Combining automatic carbonate detection with Dynamic Matching FWI to improve imaging of Jurassic reservoirs, Timor-Leste

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Summary (max. 200 words)

In shallow water environments where usable offsets are limited, Full Waveform Inversion (FWI) has become a tool-of-choice to generate high-resolution velocity updates. Traditional approaches such as refraction and reflection traveltime tomography can struggle with capturing sharp lateral and vertical velocity variations responsible for structural distortions deeper in the section. Classical implementation of FWI works at its best when very low frequencies and long offsets are recorded. This allows the inversion scheme to start from a smooth initial velocity model. However, the absence of quality low frequencies below 4 Hz and offsets limited to 6000 m in this project meant that the initial model built from legacy stacking velocities had to be improved prior to running FWI.

We first demonstrate a methodology to automatically detect the top of the shallow carbonate platforms and pinnacle reefs present near the seabed. The small-scale velocity variations added to the starting model bring immediate structural improvement down to the reservoir level and enable FWI to start at a higher frequency band. Alternating between passes of FWI and conventional reflection tomography leads to an updated velocity model conforming to the complex geology. The resulting depth migration enables better fault positioning and mapping of key reservoir horizons.

Introduction

The Kyranis 3D narrow-azimuth reprocessing project covers an area of 9024 sqkm and sits on the border between Timor-Leste and Australia. The survey lies in water depths of 50-100 m with the Bayu-Undan gas field to the west, and Greater Sunrise Development to the north. It includes the Chuditch gas discovery drilled in 1998. Reservoir and source are thought to be Jurassic Plover sand formation around 3000 m depth. Adjacent undrilled traps have been identified but the definition of the prospects and leads remains unreliable because of shallow geological variations impacting seismic signal and creating large structural distortions at the target depths.

Challenges for seismic imaging include the presence of Lower Tertiary and younger shallow carbonate platforms and pinnacle reefs scattering the signal, as well as seabed channels and recent shallow faulting causing major distortion and shadowing due to sharp lateral velocity contrasts. The shallow complexities dramatically reduce signal penetration and produce uncertainties in mapping the gas zones and possible reservoirs. Therefore, a geologically conformable and high-resolution velocity model needs to be built to capture the near surface velocity heterogeneities and allow a Pre-Stack Depth Migration (PSDM) scheme to correctly position the shape and size of the potential prospects.

Data and methodology

The towed streamer seismic survey was acquired in 2012 with conventional source and receiver depths (6 m and 7 m respectively) which limit the access to good low frequency seismic content. Migrated stack and gathers using the initial model built from legacy stacking velocities were used to run reflection tomography to update the long to medium wavelength velocity model features. This led to improved gather flatness and better structural conformity. Yet, this approach struggled to appropriately update the velocity model in the shallow section exhibiting high velocity contrasts between the clastic sedimentary rocks and carbonates. To improve both the lateral and vertical resolutions of the velocity model, Full Waveform Inversion (FWI) was implemented on this project (Lailly, 1983; Tarantola, 1984). Classic implementation of FWI relies on using very low wavenumber information in the seismic data (Mora, 1987) or formulated differently the lowest frequency having coherent phase. This is to ensure convergence towards a meaningful solution of the FWI problem before gradually increasing the frequency range (Bunks et al., 1995). Phase stability maps based on instantaneous phase were created across the full survey on decimated shots and using the maximum cable length (6000 m) to assess the lowest usable frequency in the observed shot gathers (Figure 1).

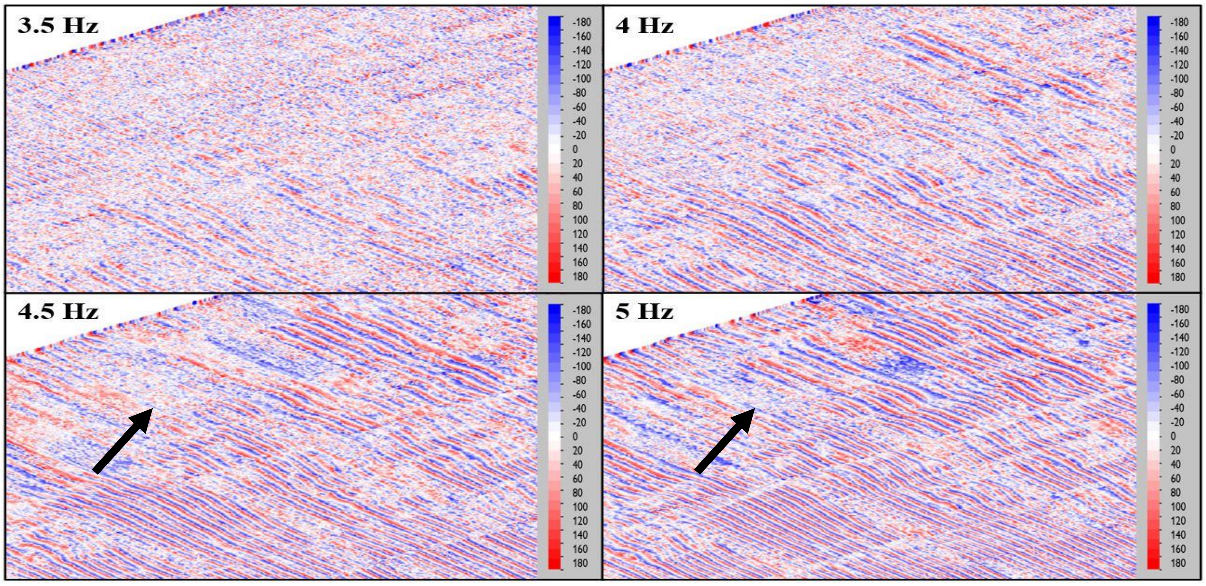

Figure 1 – Phase stability maps generated between 3.5 Hz and 5 Hz showing a lack of stable low frequencies for FWI in areas with shallow carbonate platforms (indicated by arrows)

While parts of the survey show a possible starting frequency around 3.5 Hz, areas with shallow carbonates contain little usable frequency below 5 Hz. The recorded shot gathers at those locations exhibit strong evidence of guided waves that could explain for the higher minimum low frequency underneath the carbonate platforms due to dispersion effects.

Forward modelled shots were generated using the input velocity model to FWI at maximum frequencies from 3.5 Hz up to 5 Hz. Time Shift (TS) and Cross-Correlation (XC) values were derived from the results of the synthetic shots along with the observed shots. The velocity errors present in the input model to FWI result in large kinematic errors between observed and modelled shot gathers at those frequencies which are beyond the acceptable cycle-skipping limit. This led the initial FWI tests to not recover the appropriate velocity perturbation in the very shallow section.

The input velocity model to FWI had to be improved. This was done by designing a workflow to generate an accurate automated Top Carbonate pick using data conditioning and amplitude snapping (Figure 2). The amplitude snapping iteratively fits to the time of the maximum amplitude value around an initial estimate (in this case, around Top Carbonate) and convert the result into a surface for velocity flooding tests. Several scenarios were created using different carbonate velocities extracted from first break picking. “Pseudo” Base Carbonate horizons were also tested as this interface is not clearly apparent on the stack volume. These velocity models were then used to run Kirchhoff PSDM and to output target lines. Results were analyzed in the image domain (migrated gathers and stacks) and in the data domain (modelled vs. observed shots). The velocity model leading to the best structural image and minimizing the data misfit between modelled and recorded shots was selected as input to FWI.

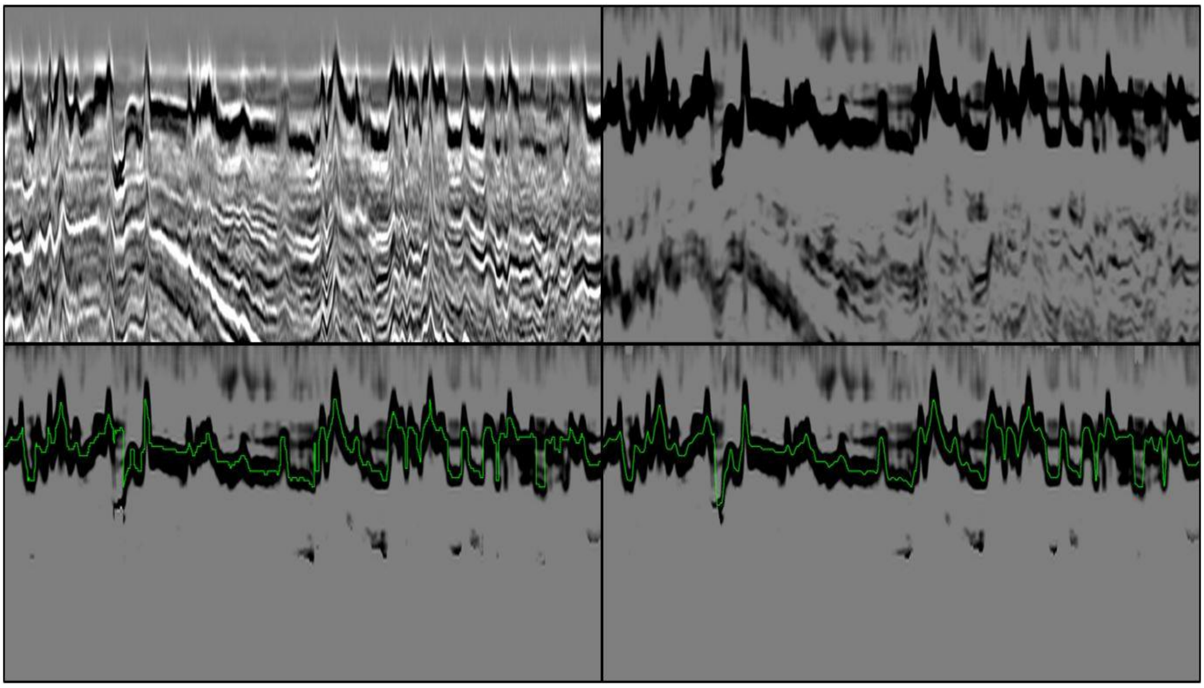

Figure 2 – Input and conditioned stacks for automatic Top Carbonate detection (top left and right); first and second pass of automatic Top Carbonate picking (bottom left and right)

With a better starting velocity model, passes of reflection tomography at different resolutions based on density of residual moveout picks, ray-tracing grid, and smoothing applied in the inversion, were alternated with iterations of FWI initially driven by diving waves. We used a multi-channel local cross-correlation objective function approach focusing on the phase difference between the recorded and modelled shots (Mao et al. 2020). The Dynamic Matching FWI (DM FWI) can use both refractions and reflections present in the data, is less sensitive to cycle skipping, and is more robust to data with low signal to noise ratio. The frequency range was progressively increased to reach a maximum of 14 Hz to extend the resolution of the velocity model especially around the main carbonate geo-bodies.

Results and observations

Capturing the reef pinnacles velocity was paramount to dramatically reduce the pull-ups seen on the initial depth migration. The lateral velocity variations in the shallow section were responsible for the large distortions visible down to the low relief prospective areas. With the shallow velocities in place, reflection tomography updated the long to medium-wavelength background velocity model. While this technique moved the velocity in the right direction it took the DM FWI several iterations at increasing frequencies to accurately refine the shallow carbonate velocities as well as the Late Tertiary carbonate platform. This later unit started as a blurry velocity increase in the initial model coming from a smoothed legacy model before DM FWI managed to reveal its spatial and vertical extent (Figure 3).

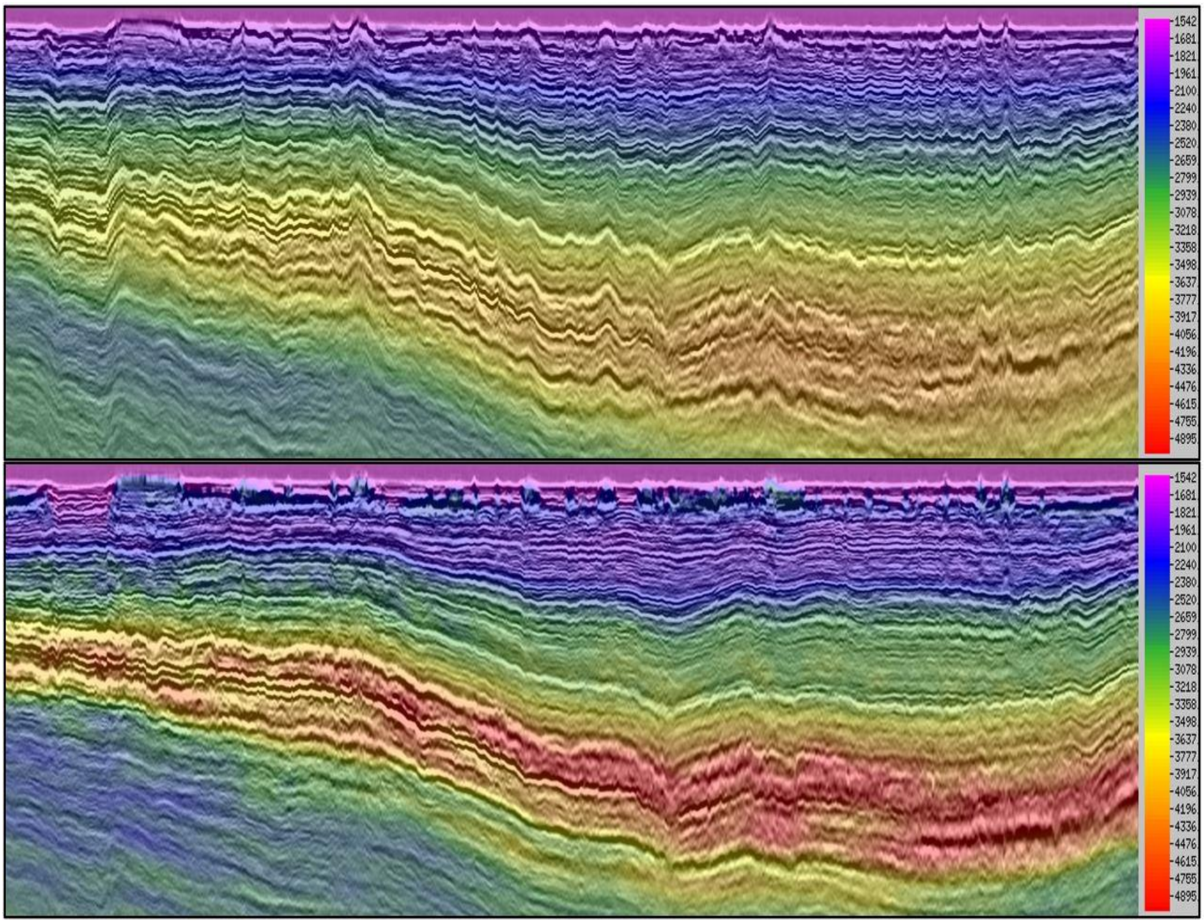

Figure 3 – Initial migrated stack and velocity (top) vs. final migrated stack and velocity (bottom)

With this geo-body positioned in the model, the structural image and gather flatness at and below the platform were improved. The tilted block faulting in the crossline direction was enhanced as were the reflector termination points. Previously estimated anisotropic parameters delta and epsilon (Thomsen, 1986; Alkhalifah and Tsvankin, 1995) were validated with good matching between the migrated seismic events and key well markers. The final velocity model conforms to the main geological events observed and captures the velocity trend measured at the wells.

Conclusions

With limited access to low frequency, and presence of shallow and sharp velocity variations, a methodology was established to derive a better starting point for high-resolution Velocity Model Building (VMB) alternating between passes of reflection traveltime tomography and Dynamic Matching FWI at increasing frequencies. Capturing the velocity related to carbonate platforms and reef pinnacles was the key to resolve the structural distortion observed at the beginning of the VMB exercise.

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References

Alkhalifah, T., and Tsvankin, I. [1995]. Velocity analysis for transversely isotropic media. *Geophysics*, **60**, 1550–156.

Bunks, C., Saleck, F., Zaleski, S. and Chavent, G. [1995]. Multiscale seismic wave-form inversion. *Geophysics*, **60** (5), 1457-73.

Lailly, P. [1983]. The seismic inverse problem as a sequence of before stack migrations: Conference on Inverse Scattering, Theory and Application. *Society for Industrial and Applied Mathematics, Expanded Abstracts*, 206–220.

Mao, J., Sheng, J., Huang, Y., Hao, F. and Liu, F. [2020]. Multi-Channel dynamic matching full-waveform inversion. *SEG Annual Meeting Extended Abstract.*

Mora, P. R. [1987]. Nonlinear two-dimensional elastic inversion of multi-offset seismic data. *Geophysics*, **52**, 1211-1228.

Tarantola, A. [1984]. Inversion of seismic reflection data in the acoustic approximation. *Geophysics*, **49**, 1259–1266.

Thomsen, L. A. [1986]. Weak elastic anisotropy. *Geophysics*, **51**, 1954–1966.