Introduction

The Tertiary basins of South Asia host several highly productive petroleum systems. Their stratigraphy is characterized by multiple stacked carbonate units interbedded with sandstones and shales, forming a series of alternating carbonate–clastic successions. These intervals extend from shallow depths, near the basin top, down into the deepest and earliest phases of basin fill (Lunt and Madon, 2017). The presence of the high-impedance carbonate layers with complex geometry poses significant challenges for imaging, related to strong mode conversions, scattering effects and attenuation of the wavefields. Earlier imaging studies with borehole data (3-component vertical incidence Vertical Seismic Profiling [VSP] and 3D Distributed Acoustic Sensing [DAS] VSP) have shown that elastic effects are significant in this area and need to be accounted for during the VMB sequence, (Alai et al., 2024) and (Alai et al., 2026).

In this study, we make use of an OBN dataset from offshore Malaysia to build an elastic velocity model for the underlying streamer data with elastic Dynamic Matching (DM) FWI (Mao et al., 2020 and Liu et al., 2024). The streamer dataset was acquired and processed few years ago and was primarily used for the FWI model validation (image domain QC). Furthermore, we explore FWM, leveraging all orders of multiples, with the raw wavefield-separated data to increase the sub-surface illumination compared to conventional mirror migration with the down-going wavefields. The OBN data was acquired with 135 nodes, separated 100x300 [m] combined with two different source vessels; an air gun with 50x50 [m] shot sampling and a low frequency Tuned Pulse Source (TPS) with 100x100 [m] shot sampling.

Methodology – elastic FWI

To resolve the model complexity in this area, we make use of an elastic modeling engine in FWI, combined with an amplitude robust norm based on Dynamic Matching (DM), which maximizes the local windowed cross-correlation between observed and modeled data. This norm has proven robust against cycle-skipping and low Signal-to-Noise Ratio (SNR), while being less sensitive to amplitude variations, making the inversion primarily phase-driven. The optimization leverages a quasi-Newton (L-BFGS) method, which enhances convergence, particularly when improved physics (elasticity) is incorporated into the modeling.

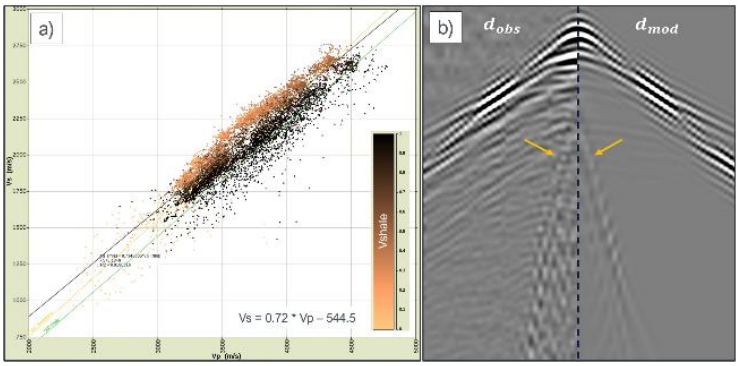


Figure 1*: a) Vp-Vs cross plot and linear regression done in the sub-carbonate section and b) comparison of observed and elastic modeling.*

A pressure-wave velocity (Vp) model had previously been derived from conventional tomography using an underlying streamer acquisition. This velocity model was conditioned with global smoothing and served as an initial long wavelength background model for FWI. The shear-wave velocity (Vs) model was built based on a linear relationship between Vp and Vs from the well information for the sub-carbonate interval and further adjusted in the shallow section based on elastic modeling results. Figure 1a shows the linear regression of the Vp-Vs cross plot derived from the well log and Figure 1b shows the data alignment of the near surface converted waves after tuning the shallow Vs model. The orange arrows annotate the near surface converted events with velocities around 400 [m/s]. For the density model, Gardner's equation was utilized. The Vs and density model were subsequently updated during the inversion process based on changes in the Vp model.

The data conditioning prior to FWI was limited to de-bubbling and denoise. The two sources (air gun and TPS) were implicitly inverted during the FWI process, enabling usage of all the OBN recorded data simultaneously. This was achieved by sorting the common receiver gather into two sets of files, corresponding to the two sources, followed by a data-reconstruction approach in FWI (Zuberi et al., 2023). The reconstruction computes and applies

a global matching filter for each node using synthetic data as the target. This process does not alter the kinematics of the observed data since the same filter is applied to all traces within the node. Furthermore, it will address uncertainties in the source wavefield and allows us to use the raw mix-phased data directly in the inversion. The inversion was performed in frequency stages up to 16 [Hz], where the data selection was gradually increased with the improved modeling results, allowing the inversion to resolve the model from shallow to deep.

Methodology – FWM

Full Waveform Migration (FWM) is a flavor of wave equation migration where the recorded down-going wavefield is utilized as the "virtual source wavefield" at every receiver position, effectively increasing the source side illumination (Lu et al., 2015). In addition, FWM will forward-propagate a full wavefield in contrast to conventional wave-equation migration with primaries that utilizes a single point source. When applied to OBN data, under the reciprocity assumption, the illumination can potentially extend to the full source carpet. Compared to conventional mirror migration, that utilizes a single order of multiples in the migration process, FWM makes use of all orders of multiples which further increases the sub-surface illumination. Preprocessing for FWM is limited to wavefield separation and denoise, which enables imaging much earlier than for conventional preprocessing and migration, and can offer full bandwidth resolution with an early velocity model in contrast to FWI derived reflectivity that requires significant number of iterations to higher frequencies (FWI Imaging). The de-signature process can also be mitigated when FWM is implemented with a deconvolution Imaging Condition (IC), which is effectively a division of the wavefields and hence produces a zero-phased output reflectivity. The challenge with multiple imaging can be crosstalk, which is caused by the undesired interactions between the up and down going wavefields. Crosstalk gets significantly reduced when applying the deconvolution IC rather than conventional cross-correlation, but further suppression can be obtained through crosstalk prediction or through an iterative least-squares migration process (Lu et al., 2018). Figure 2 shows the concept of FWM compared to imaging of primaries, illustrated for a multi-component streamer acquisition.

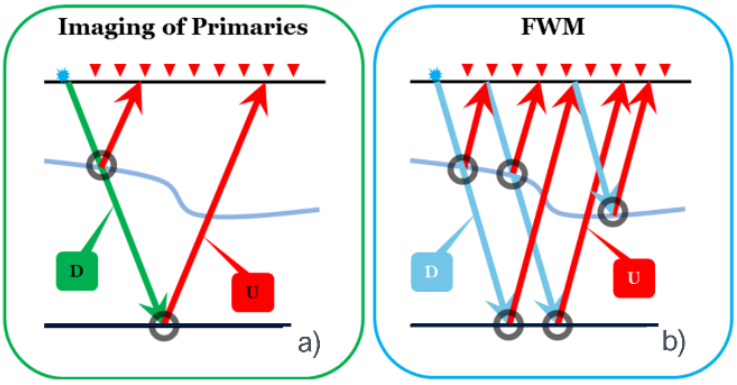


***Figure 2**: Illustration of the FWM concept compared with conventional primary-only migration for a streamer acquisition. For OBN data, under the source–receiver reciprocity assumption, this approach can potentially extend illumination to the full source layout.*

Results

Figure 3 shows an inline section and depth slice from the initial velocity model (Figures 3a and 3d) and the updated FWI model (Figures 3b and 3e). The total velocity perturbation, displayed with the migrated streamer seismic data overlaid, is presented in Figures 3c and 3f. The inversion transforms the originally smooth carbonate interval into a highly heterogeneous unit by introducing localized velocity increases and decreases required to match the recorded data. This behavior aligns with the regional stratigraphic interpretation, in which several carbonate units are stacked and interbedded with sandstones and shales. The depth slice through the main carbonate level further illustrates how both the inverted model and its associated perturbation conform to the underlying seismic structure, demonstrating the improved geological fidelity achieved through the FWI update. Figures 3g and 3h show the migration results obtained using the initial and updated velocity models, respectively. Imaging with the updated FWI model leads to noticeably improved reflector focusing and a simplified base carbonate event (blue arrow), as well as enhanced continuity of the subsequent reflectors (shallow orange ellipse and arrows). These improvements in the shallow section propagate downward and positively impact image of deeper target reflectors (deep orange ellipse and arrows). In addition, the updated

model yields clearer reflector termination against the major fault (left of the blue arrow) that originates within the carbonate section and extends into deeper stratigraphy.

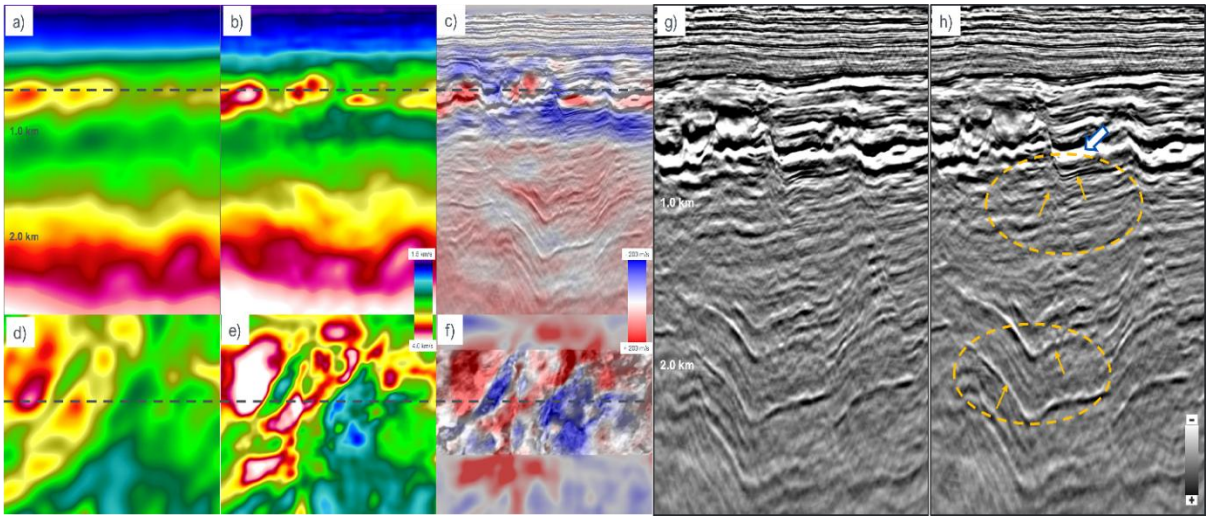


Figure 3: *Inline section and depth slice from the initial velocity model (Figure 3a and 3d) and the updated FWI velocity model (Figure 3b and 3e). The total velocity perturbation from FWI, overlaid on the migrated streamer data, is shown in Figures 3c and 3f. Migration with the initial model (Figure 3g) is compared with migration using the elastic FWI model (Figure 3h)*

Figure 4a and 4c show an inline section and depth slice through the carbonate interval obtained from the OBN mirror migration, while Figures 4b and 4d present the corresponding results from FWM. The FWM clearly improves and extends the illumination both vertically and laterally compared to the conventional mirror migration result. The shallow seafloor at approximately 50 [m] depth is only visible in the FWM image. Furthermore, the FWM result reveals significantly more intra-carbonate complexity (green box) than the mirror-migration output. Improvements provided by FWM are also evident for the deeper target reflectors (orange ellipse and arrows). However, some reflectivity around 1.5 km depth (red arrows) becomes less coherent, which may be related to residual crosstalk between the up- and down going wavefields, as described in the FWM methodology section. The depth slice, with the well projection annotated in yellow, confirms the laterally extended illumination and the overall imaging improvements achieved with FWM. It is worth noting that FWM requires only minimal preprocessing, in contrast to the extensive processing sequence necessary to produce the mirror-migration image.

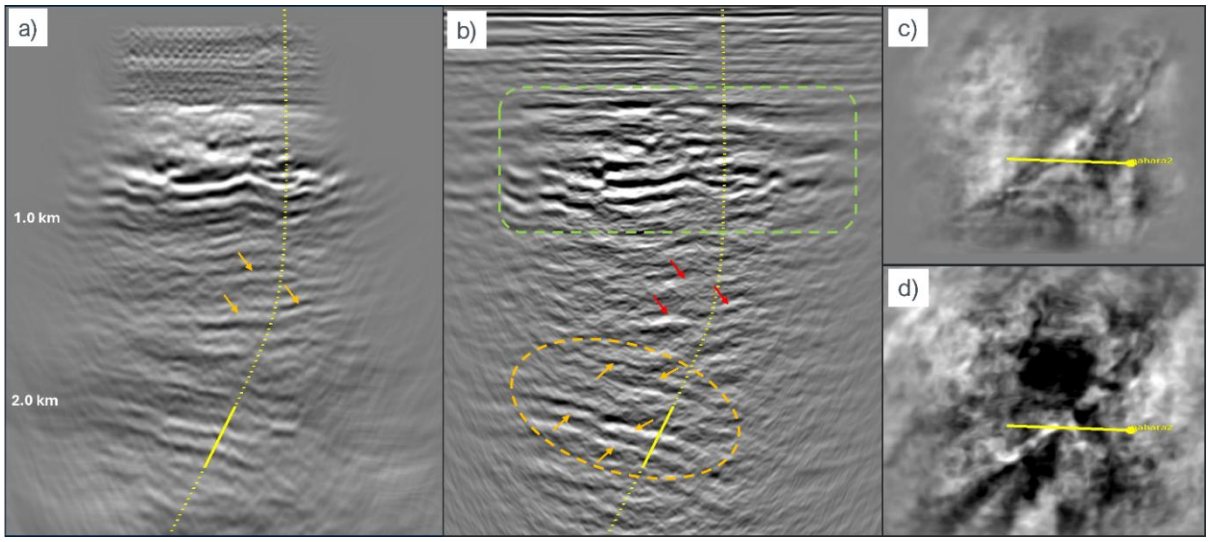


Figure 4*: Inline section and depth slice through the carbonate interval obtained from OBN P-down mirror migration (Figures 4a and 4c) and the corresponding results from Full Wavefield Migration (Figures 4b and 4d).*

Conclusions

With OBN data from offshore Malaysia, we have demonstrated how elastic Dynamic-Matching FWI can resolve the model and image complexities associated with the strong lateral and vertical heterogeneities within the rugose carbonate interval and substantially improve imaging of the underlying streamer data. Our approach makes use of a data-reconstruction approach within FWI that implicit inverts for the two different set of source wavelets with a global matching filter for each node using synthetic data as the target. Furthermore, we demonstrate the increased and extended illumination achieved with FWM using the OBN data over conventional mirror imaging.

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