Solving the imaging complexity via application of elastic FWI in the Nile Delta

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Summary

This study highlights the application of Elastic Full-Waveform Inversion (eFWI) to address imaging challenges in the complex geological structures of the Nile Delta. Unlike acoustic FWI (aFWI), eFWI incorporates both P- and S-wave physics, effectively handling significant velocity contrasts, such as those found in the Messinian layer, and reducing boundary smearing at salt-sediment interfaces. The application of eFWI to multi-azimuth streamer data provides superior imaging of mud volcanoes, small gas pockets, and channels in the post-Messinian, as well as improved resolution of complex Messinian and pre-Messinian layers.

Introduction

The Nile Delta is recognized for its high hydrocarbon potential, particularly in gas exploration. The area has attracted significant drilling activity; notably, within the first two months of 2025 two major operators drilled wells in different parts of the region, both reporting gas discoveries. However, the complex geology of the area poses significant challenges for seismic imaging.

The post-Messinian section features mud volcanoes and small gas pockets, creating lateral variations in rock properties that complicate imaging. The Messinian layer, composed of sands, shales, and evaporites, poses additional difficulties due to faulting and mobile shale, further disrupting subsurface interpretation. These complexities are even more pronounced in the pre-Messinian section, where overlying geological formations add to the challenges of velocity model building and accurate imaging.

To address these challenges, new acquisition techniques and advanced seismic processing methods, including Velocity Model Building (VMB) and cutting-edge imaging technologies, are essential (Baptiste, et al., 2024, Davies, et al., 2024). One of the most promising technologies to resolve imaging problems is eFWI. It has already demonstrated its advantages in the inversion of large-offset OBN data (Macesanu et al., 2024; Jiang et al., 2024). In this paper we will discuss its application on Multi-Azimuth streamer data.

Method

Over the past few years, aFWI has been a key step of the standard VMB workflow. While effective in relatively simple geological settings, it can encounter challenges in regions with complex subsurface structures and high velocity contrasts. In such cases, eFWI offers significant advantages. Since the aFWI approach employs the acoustic approximation for the underlying media, it struggles in regions with significant impedance contrasts, such as near salt bodies or hard rock layers, where elastic effects on compressional wave (P-wave) propagation play a crucial role. By incorporating both P-waves and S-waves, eFWI captures the full seismic wavefield and better represents the physics of wave propagation in such challenging environments like the Nile Delta. Figure 1 shows observed and modelled shot gathers across the strong velocity contrast in the Messinian layer in a very complex part of the section. The acoustically modelled shot gather does not include elastic effects for P-wave events, potentially leading to discrepancies between the real and synthetic data and resulting in errors during the velocity update. In contrast, the elastically modelled shot gather incorporates the correct physics, providing a better match with the observed data and resulting in more accurate velocity model updates.

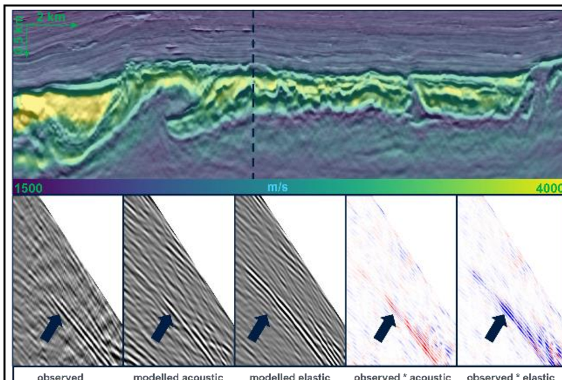

Figure 1: Kirchhoff migration overlaid with final velocity model (top) and shot gather (bottom). Blue colour shows good match between observed and modelled data.

Acoustic vs Elastic FWI: results comparison

One of the main benefits of eFWI is its ability to reduce boundary smearing, particularly at salt-sediment interfaces such as top Messinian with its salt, anhydrite and evaporite bodies where the P-wave velocity can be as high as 6000 m/s. Since waves propagating near the salt-sediment boundary are sensitive to elastic effects, aFWI often struggles to maintain interface sharpness, leading to inaccuracies in the velocity model. In contrast, eFWI enhances the definition of these interfaces, delivering sharper and more precise subsurface images. This improved resolution leads to better velocity models, more precise imaging of complex structures, and enhanced reservoir

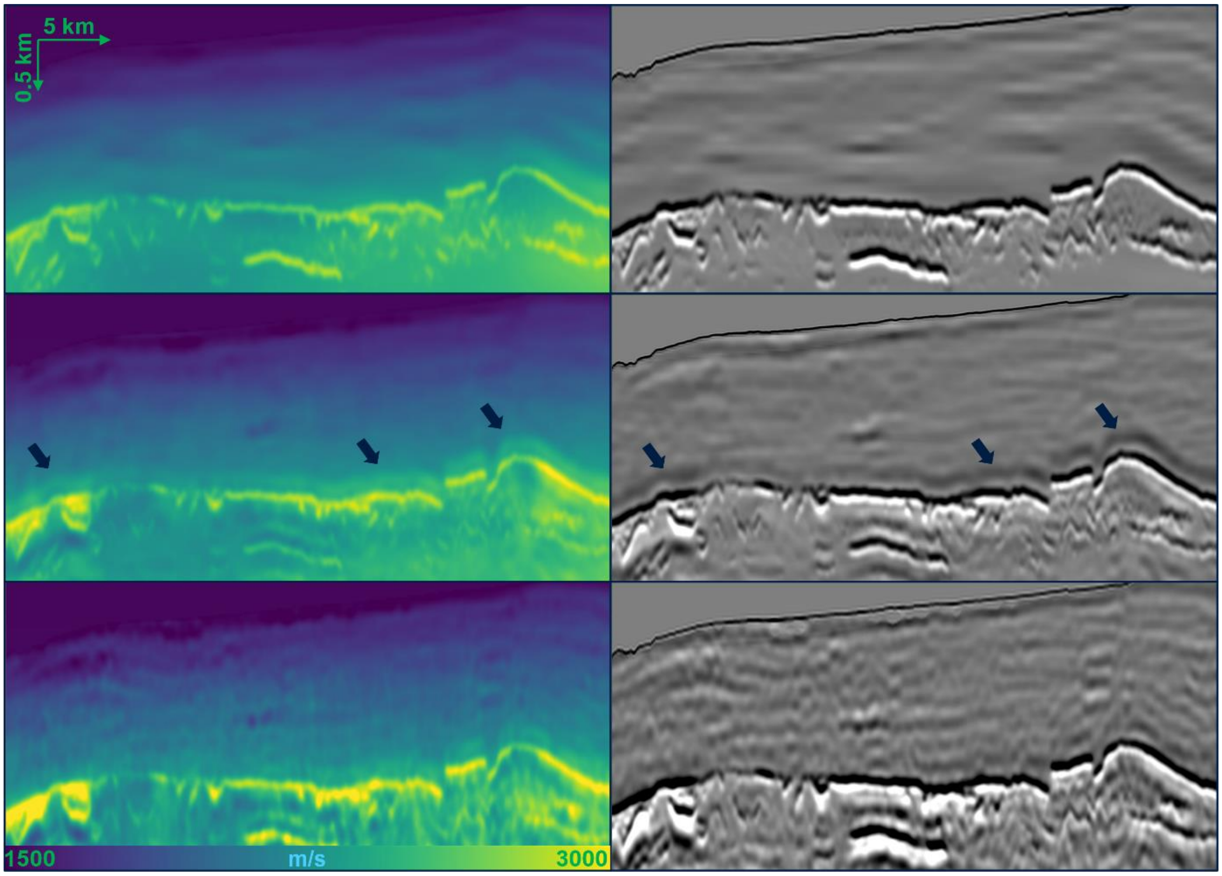

Figure 2: Velocity model and FWI Image, Input to FWI (top), after 7Hz aFWI (center), after 7Hz eFWI (bottom).

characterization for exploration and development. Figure 2 presents a comparison of the velocity model and FWI Image between the input to FWI (top), 7 Hz aFWI (centre), and 7 Hz eFWI (bottom). While aFWI enhances model details, it introduces a pronounced 'halo' effect above the top Messinian layer (indicated by dark arrows), resulting in a false low-frequency horizon in the corresponding FWI Image and potential interpretation errors.

The eFWI velocity model not only offers more details than the acoustic model but also significantly reduces the 'halo' effect, improving the FWI Image quality. eFWI effectively captures the top and base Messinian velocity contrasts, as well as small-scale features within the Messinian, providing a superior resolution of this complex layer compared to the acoustic model (Figure 3, top). As a result, the gathers in the pre-Messinian (Figure 3, bottom) are less complex and flatter, leading to a better stack response and simpler geological structures in the target layer. Figures 4a and 4b show depth slices through the post-Messinian layer for the 7 Hz aFWI and eFWI velocity models. The elastic model more clearly defines two mud volcanoes in the bottom left corner, as well as improves the imaging of channels in the top right. Additionally, eFWI captures small gas pockets that are not visible in the aFWI model.

Final results review and discussion

The final VMB workflow employed for this project involved several passes of eFWI up to 10 Hz, followed by tomography to further refine the model. To add more details into the model two additional passes of aFWI at 15 and 20 Hz were run. For these higher frequency updates the input dataset was changed from raw hydrophone data to a pre-processed dataset to avoid potential multiples imprinting on the velocity model and FWI Image. FWI parameters were adjusted to focus on near offsets, enhancing model resolution and introducing more details, while also reducing the impact of elastic effects, which are generally more significant at large offsets/angles.

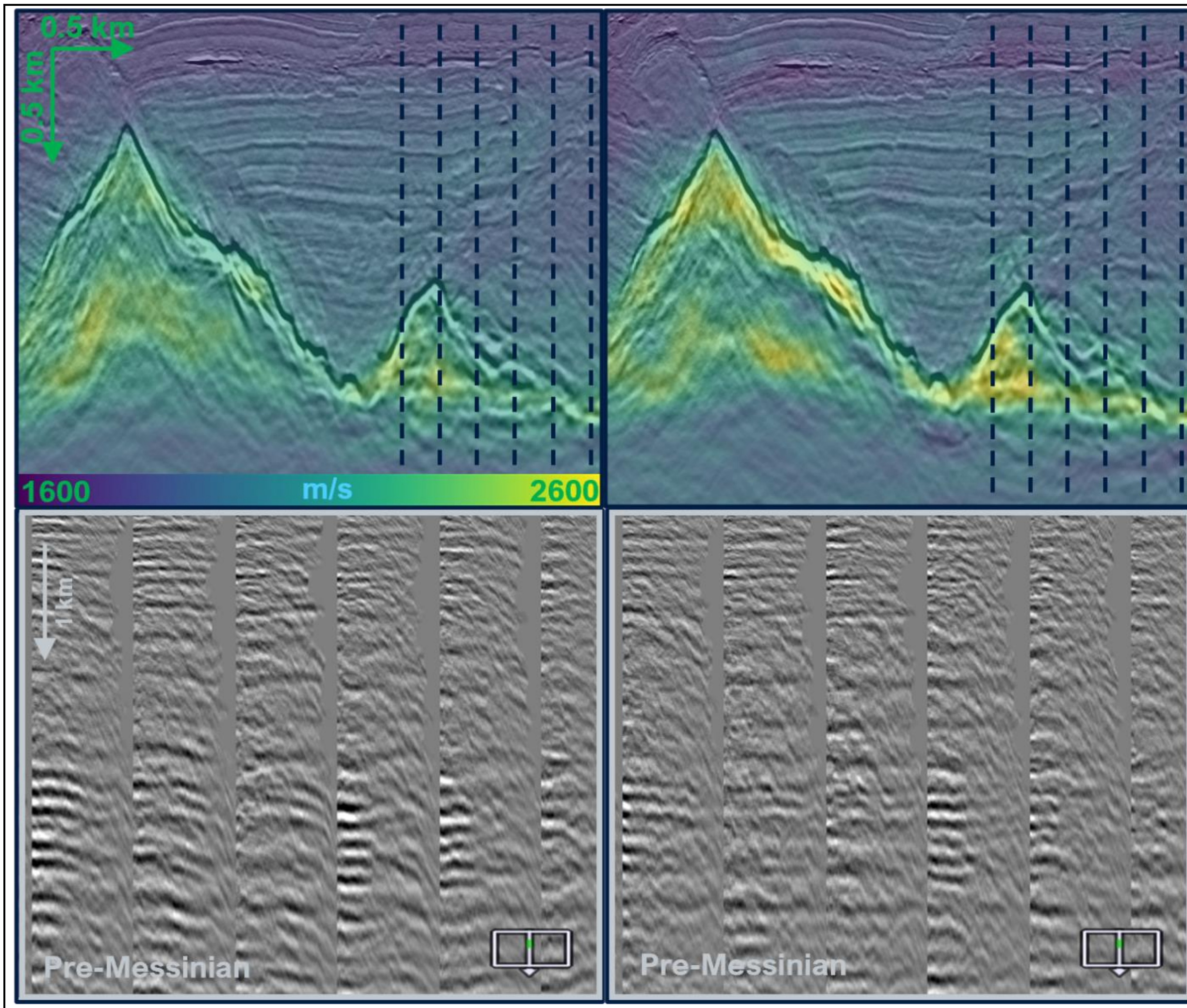

Figure 3: Velocity model and Kirchhoff migration, 7 Hz aFWI(left) and 7 Hz eFWI(right).

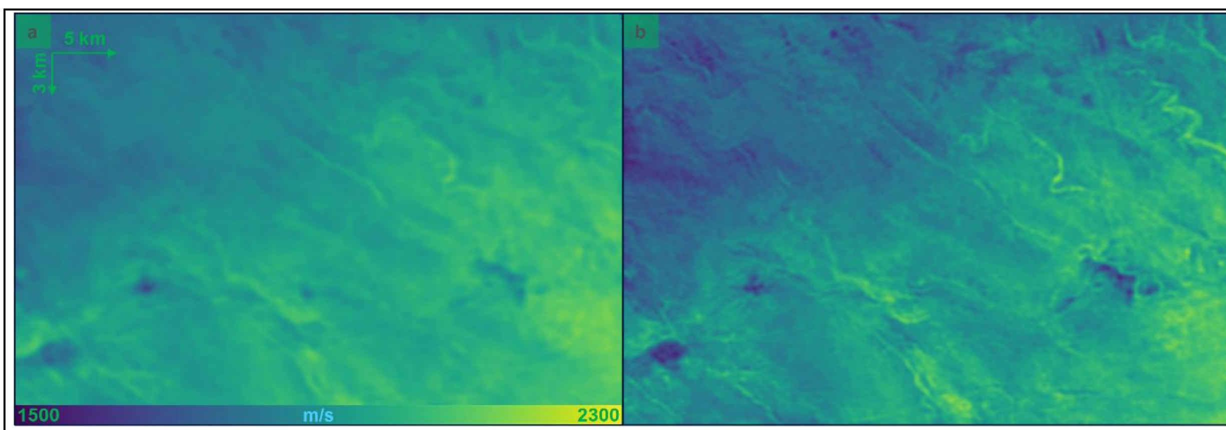

Figure 4: post-Messinian velocity model depth slice 2000m, 7 Hz aFWI(a), 7 Hz eFWI(b)

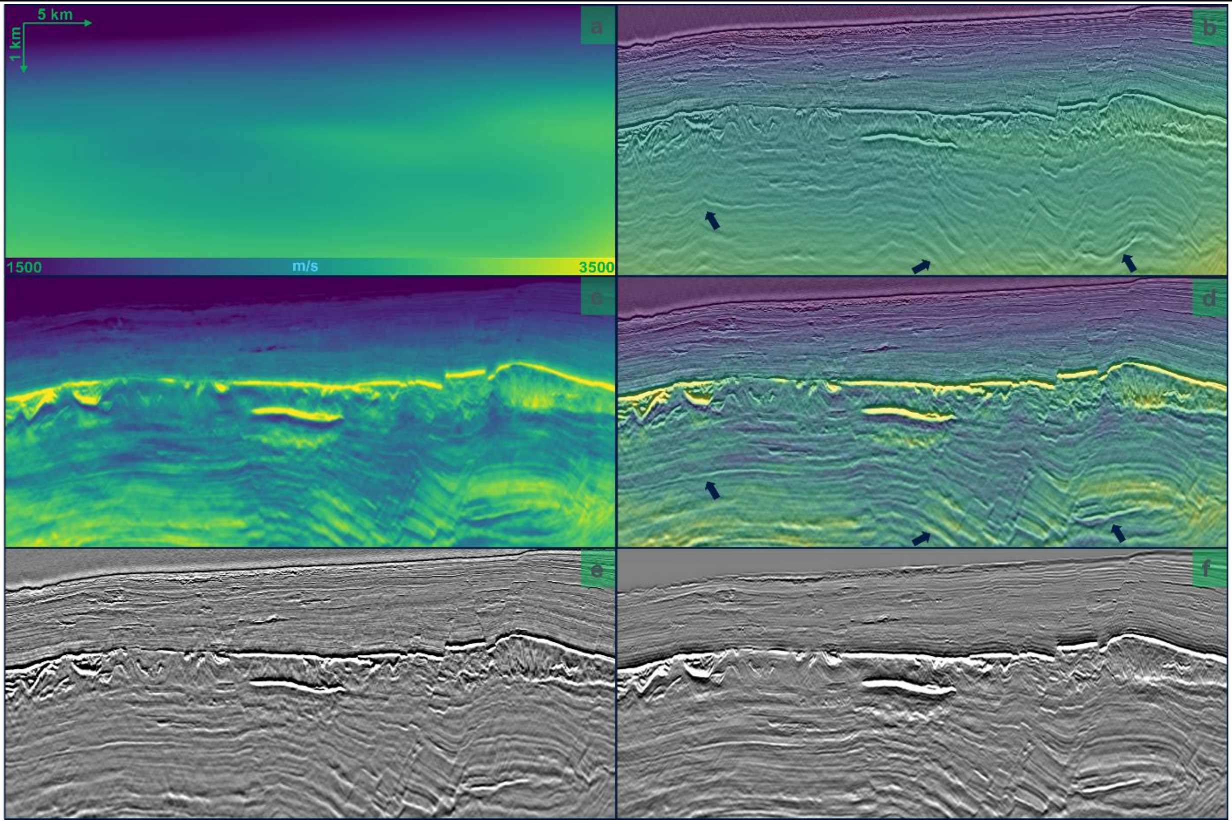

Figure 5: Velocity model and Kirchhoff migration - legacy (a,b) and final (c,d), Kirchhoff migration (e) with final model and 20 Hz FWI Image (f). Black arrows show examples of better stack continuity with the final model.

The final velocity model is highly detailed in the post-Messinian, with FWI capturing fine small-scale features such as mud volcanoes, channels, and gas pockets (Figure 5c). It represents a significant improvement over the legacy model (Figure 5a) overall, providing much more details at all levels, including fault blocks, Messinian velocity contrasts, and small-scale features within the Messinian.

Migration using the final velocity model shows clear improvements compared to the migration with legacy model, resulting in a simpler, geologically plausible structure in the pre-Messinian, with good conformity between the velocity model and the migration image (Figure 5b, 5d). The 20 Hz FWI Image (Figure 5f) generated from the final velocity model reveals small scale details in the Messinian, sharpens faults blocks in the pre-Messinian, has higher resolution with fewer illumination issues compared to the Kirchhoff migration (Figure 5e) and generally looks cleaner, thus providing a valuable alternative or complementary product to the standard RTM and Kirchhoff volumes.

Conclusions

In summary, applying eFWI to Multi-Azimuth streamer seismic data has led to significant advancements in imaging the complex geological structures of the Nile Delta. By incorporating elastic effects for both P and S waves, it enhances the accuracy of velocity models and reduces boundary smearing. The final velocity model provides detailed imaging of mud volcanoes, small channels and gas pockets in the post-Messinian, a highly detailed complex Messinian layer, and a structurally improved pre-Messinian. This results in more accurate representation of subsurface structures, offering a valuable tool for hydrocarbon exploration in challenging geological settings.

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