Improved imaging through application of elastic FWI in the Nile Delta

M. Romanenko[1], V. Valler[1], M. Hart[1], J. Fruehn[1], L. Saxton[1], Q. Li[2], I. De Lemos[2]

[1] TGS; [2] BP

Summary

The 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 provided 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.

The final VMB workflow included multiple passes of eFWI up to 10 Hz, followed by high-frequency acoustic passes up to 20 Hz. The final velocity model provided enhanced subsurface details, resulting in clearer Kirchhoff migrations and structurally accurate representations of the pre-Messinian layers. FWI Image generated from final velocity model is a cleaner, higher-resolution product compared with traditional Kirchhoff migration with fewer illumination issues, making it a valuable tool for hydrocarbon exploration in challenging geological settings.

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Introduction

The Nile Delta is a region of high hydrocarbon potential, particularly for gas exploration, due to its vast reserves. However, the complex geology of the area poses significant challenges for seismic imaging. The post-Messinian section contains mud volcanoes and small gas pockets, leading to lateral variability in rock properties that complicate imaging. The Messinian layer, which consists of a mix of sands, shales, and evaporites, is particularly challenging due to its disruption by faults and mobile shale. This complexity is further compounded in the pre-Messinian section, where the overlying geological features create difficulties in accurate velocity model building and 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 Elastic Full-Waveform Inversion (eFWI). This method has proven to be beneficial for 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 seismic data.

Method

Acoustic FWI (aFWI) has been a key step of the standard VMB workflow over the recent years. Although it is effective in relatively simple geological environments, it might struggle in areas with complex geology and/or high velocity contrast. eFWI provides significant advantages over aFWI in such areas. 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 waves (P-waves) 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 shot gathers across the strong velocity contrast in the Messinian layer in the very complex part of the section. The acoustically modelled shot gather does not include elastic effects for P 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.

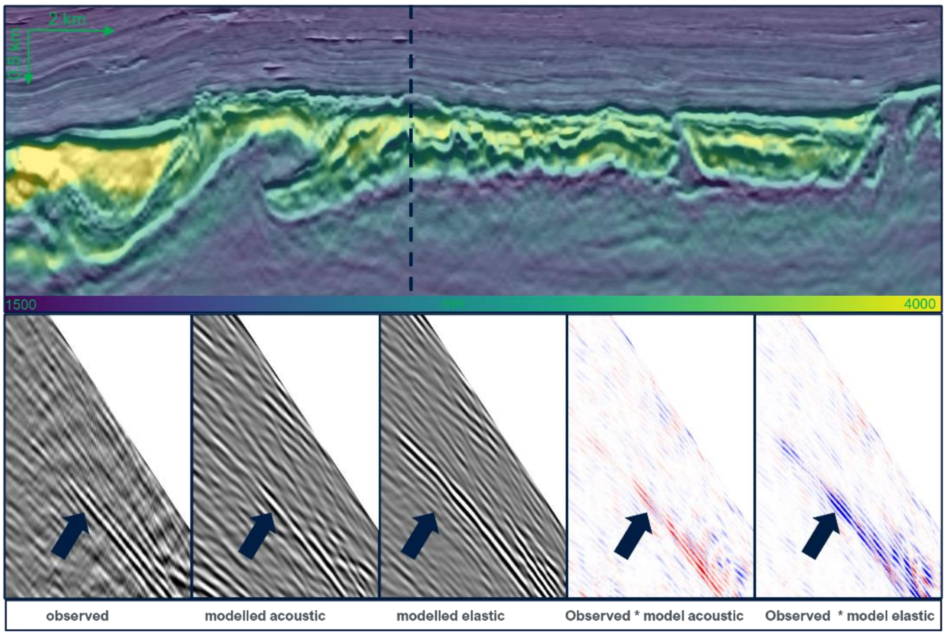

Figure 1 *Kirchhoff migration overlaid with final velocity model (top) and shot gather (bottom). Blue colour shows good match between observed and modelled data.*

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 produces unfocused interfaces, leading to inaccuracies in the velocity model. eFWI sharpens these boundaries, resulting in clearer and more accurate subsurface images. This improved resolution leads to better velocity models, more precise imaging of complex structures, and enhanced reservoir 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 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 a simpler geological structures of 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.

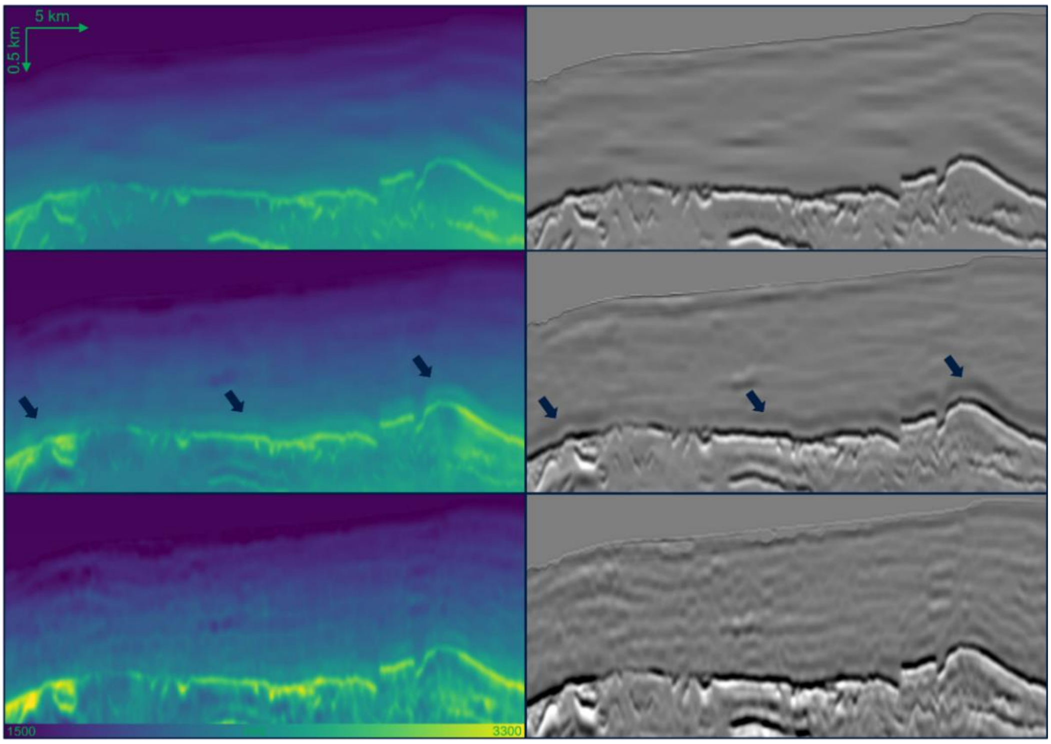

__Figure 2__ Velocity model and FWI Image, Input to FWI (top), after 7Hz aFWI (center), after 7Hz eFWI (bottom).

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 at 15 Hz and 20 Hz were run in acoustic mode. The input dataset was changed from raw hydrophone data to a pre-processed dataset to avoid potential multiples imprints 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.

The final velocity model is highly detailed in the post-Messinian, with FWI capturing fine small-scale features such as mud volcanoes, channels, and small gas pockets (Figure 4c) It represents a significant improvement over the legacy model overall, providing much more details at all levels, including fault blocks, Messinian velocity contrasts, and small-scale features within the Messinian (Figure 5). 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 migration. The final velocity model also produces a highly detailed FWI Image that is cleaner, with fewer illumination issues and higher resolution comparing with Kirchhoff migration, offering a valuable alternative or complementary product to the standard RTM and Kirchhoff volumes.

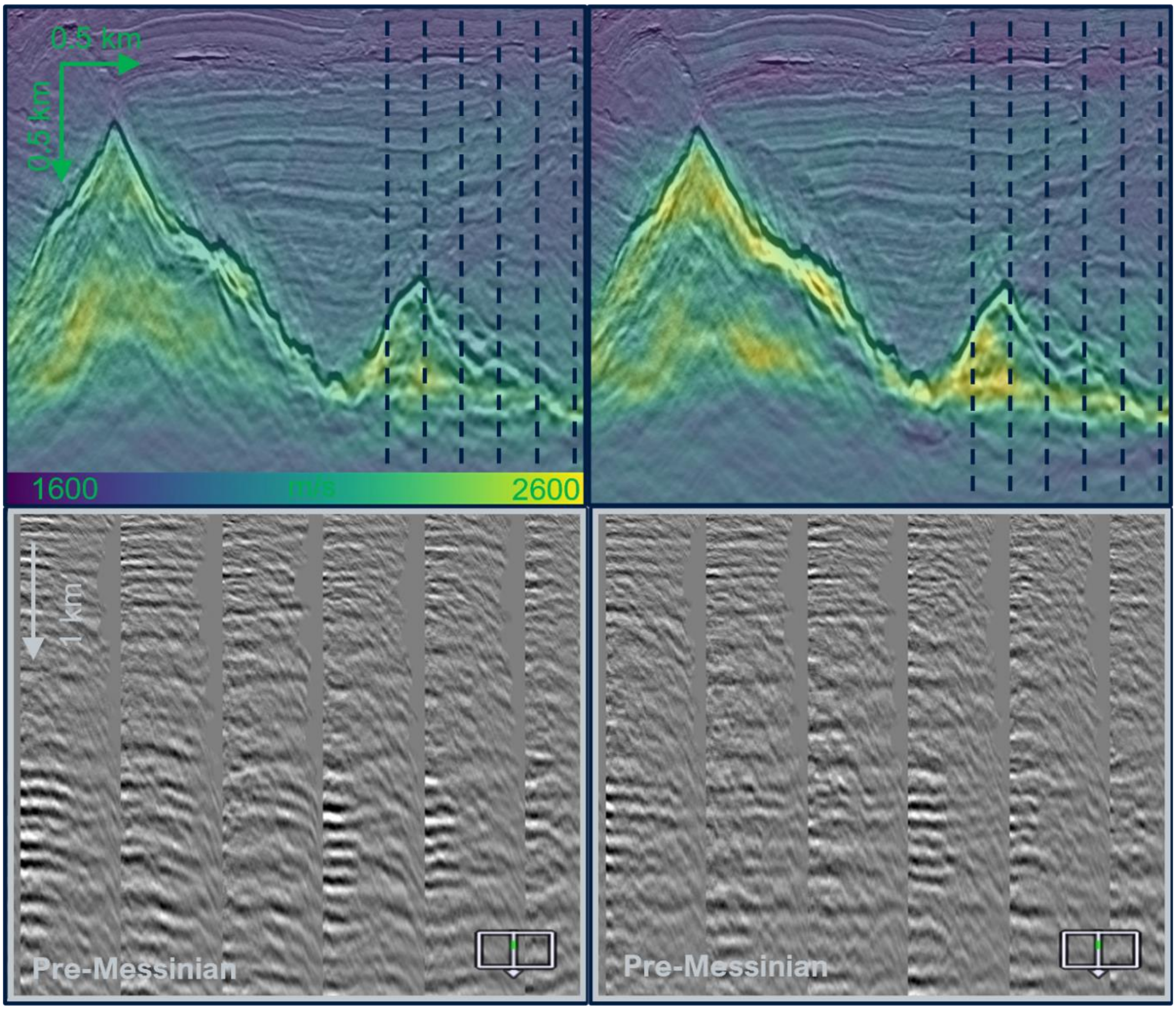

Figure 3 *Velocity model and Kirchhoff migration, 7 Hz aFWI(left) and 7 Hz eFWI(right).*

Conclusions

In conclusion, the application of eFWI to Multi-Azimuth streamer seismic data has demonstrated substantial improvements in imaging the complex geological features 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.

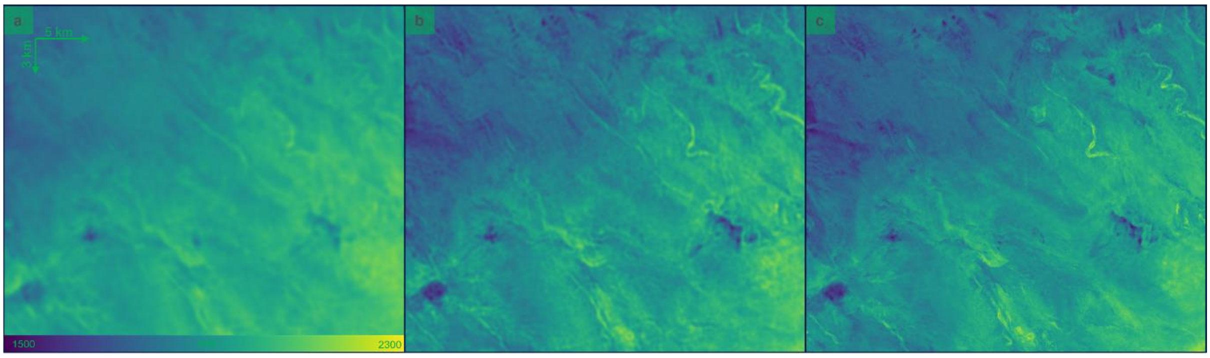

Figure 4 *post-Messinian velocity model depth slice 2000m, 7 Hz aFWI(a), 7 Hz eFWI(b), final model (10 Hz eFWI +20 Hz aFWI)(c).*

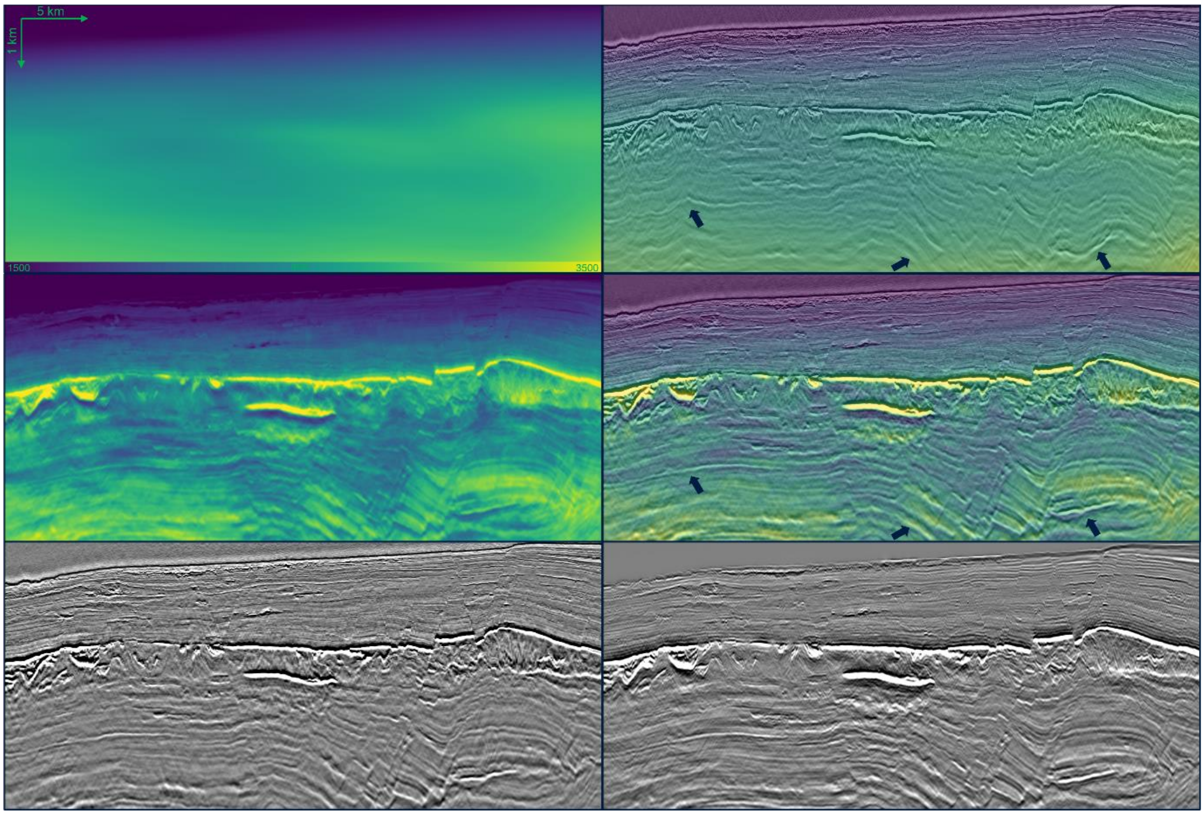

Figure 5 *Velocity model and Kirchhoff migration - legacy (top) and final (center), Kirchhoff migration (bottom left) with final model and FWI Image (bottom right).*

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