Imaging challenges in Foz do Amazonas Basin – a case study.

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Abstract

Located in the northwest of the Brazilian equatorial margin, the Foz do Amazonas (FDA) Basin has become a place of high exploration interest in the recent years. This attractiveness is due to the exploration success in the nearby basins in French Guiana and Suriname.

Like other basins in early stages of exploration, data availability can be limited and only narrow-azimuth-towed-streamer (NATS) datasets are available. However, conventional imaging techniques applied to this NATS dataset struggle to provide a satisfactory image below the complex carbonate platform where illumination issues are observed.

In this work, we demonstrate how new technologies in seismic processing and imaging, such as time-lag FWI (TLFWI) and FWI imaging, can reduce exploration risks by mitigating geological uncertainties.

Introduction

The offshore Brazilian equatorial margin is a region still underexplored but of growing interest, especially after the recent significant discoveries in French Guiana and Suriname. The Foz do Amazonas (FDA) basin presents a rapidly varying water bottom (200 - 2500 m), deep canyons, channels structures, gas pockets, as well as a steep and shallow carbonate platform with strong impedance contrasts (Figure 1). All these geological elements make the imaging process and velocity model building quite challenging, limiting the value of prospectivity studies below the carbonate platform. In this paper, we present how novel technologies can revamp a 2014 NATS dataset in FDA basin in comparison to legacy processing.

For the pre-processing, a 3D de-signature and de-ghosting methodology was applied, more suitable for environments with the presence of canyons and out-of-plane reflections. Then, a joint SRME-MWD de-multiple flow was implemented to tackle the strong multiple contamination generated by the high impendence contrast of the carbonate layer.

Foz do Amazonas basin displays strong lateral velocity variations causing distortions in the image (push-downs and pull-ups) if not correctly captured in the velocity model; therefore, velocity resolution, both vertical and lateral, is a key element to obtain an accurate image. The velocity model was built with an iterative workflow combining time-lag full-waveform inversion (TL-FWI), (Zhang et al., 2018), geological interpretation and ray-based tomography.

Even with good signal-to-noise ratio data and a detailed migration velocity, there were regions in the image with strong lateral amplitude variations due to the uneven illumination of the NATS acquisition. The application of a single-iteration depth image domain least-squares migration was the enabler to improve the image in these areas.

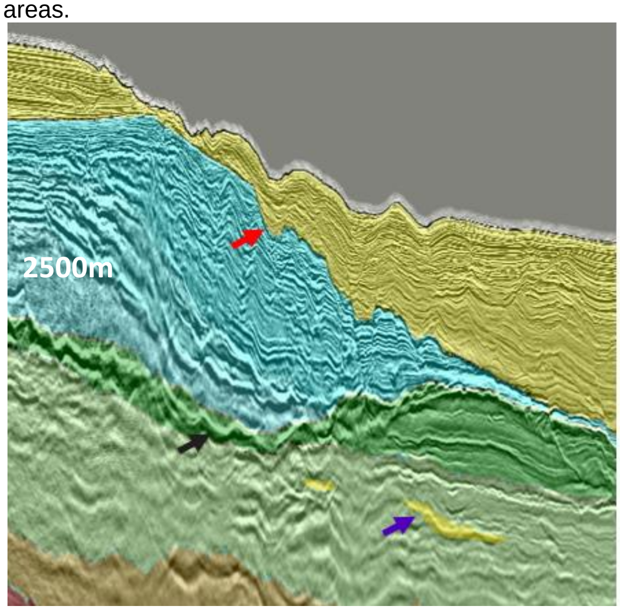

Figure1 *- The complex geology of FDA Basin shown as interpretation on a representative seismic section. The yellow layer represents the Amazon cone sediment layer above the thick carbonate platform represented in light-blue.*

Pre-Processing

The de-signature and de-ghosting steps are important processing in the estimation of Earth's reflectivity. The legacy processing applied 1D de-signature and 2D source and receiver de-ghosting. These methodologies give acceptable results for data recorded from near-offset and inner cables. However, since the source directivity is known to be anisotropic, their effectiveness is reduced for far-offset and outer cables, leading to poor bubble attenuation and loss of resolution in the data. The new workflow uses a full 3D approach (Wang et al., 2014, Poole et al., 2015). This methodology takes advantage of $\tau - p_x - p_y$ transform, where the source anisotropy and the take-off angles are considered for signature and ghost modelling.

The surface related multiple elimination (SRME) relies on primary reflections to predict multiples, which can be a constraint for shallow water regions, since the incidence angles of mid-offsets can exceed the critical angles, compromising the efficacy of the algorithm. Other technologies, such as the model-based water layer de-multiple (MWD), were applied to mitigate the limitations of SRME. Proposed by Wang et al., (2011), this approach models the Green's function of the water-layer primary reflections (WLPRs), based on a known water-layer model, and then convolves them with the recorded data to obtain the water-layer related multiples (WLRMs). Besides being able to model the shallow water bottom multiples, MWD also overcomes the bandwidth limitation of SRME, due to the double wavelet effect when convolving the data with itself, giving modelled data with better low and high-end frequency content (Huang et al., 2016).

The presence of a shallow carbonate platform, in addition to the very shallow seafloor, leads to strong multiple contamination, which could not be totally removed by the legacy processing, mainly in the intra- and sub-carbonate regions. In the reprocessing, a joint subtraction of SRME and MWD models in the curvelet domain was applied to address the complex multiples of the region and obtain an effective attenuation.

Figure 2 shows the comparison between legacy (a) and reprocessing (b) data migrated with the same velocity to evaluate the improvements from pre-processing. It is noticeable how the 3D de-signature/de-ghost was able to better recover the low frequency of the data, leading to improved events, especially on the top of the carbonate (dashed red arrow), whereas the 2D approach shows limitations due to the complexity of the area. In the sub-carbonate area, it is possible to observe the benefits of both the 3D de-ghosting and the joint de-multiple workflows. The attenuation of cross-cutting events, indicated by the yellow arrows leads to an increased continuity of the primaries.

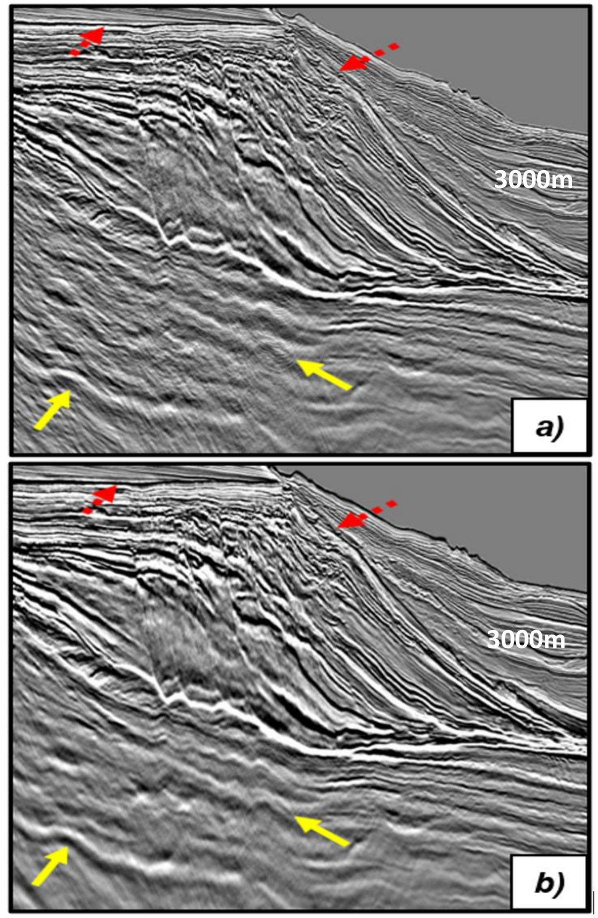

Figure 2 - *Comparison between (a) legacy and (b) reprocessed data, migrated with the same velocity to evaluate only the pre-processing improvements.*

Velocity Model and imaging

Besides being a challenging area for data processing, the Brazilian Equatorial Margin presents several geological complexities for velocity model building (Pereira et al., 2018). The legacy model was built only using tomographic updates and it was not able to resolve the complex velocity field required for good imaging, especially when considering the acquisition and processing limitations, which also affected the reliability of the common image gathers used for the tomographic inversion.

In the Foz do Amazonas reprocessing, an iterative flow combining TL-FWI up to 12Hz with ray-based tomography was used to improve the velocity model.

In Figure 3, the new velocity (3d) is compared with the tomography-based legacy model (3b). The TL-FWI increased the resolution of the velocity model, describing more appropriately the geological structural behavior, reducing depth distortions inside and below the carbonate platform, as indicated by the yellow arrows (3c). Moreover, the lateral continuity of the events was enhanced.

The advances in preprocessing combined with the improvement in the velocity model using the TL-FWI, improved the migrated image, however, the azimuthal limitation of the data resulted in areas where the results were not satisfactory. Therefore, after conventional Kirchhoff migration, there were still some unbalanced amplitude zones, principally around the base of carbonate platform, due to its high impedance contrast and heterogeneity, in addition to intrinsic migration effects, such as swings and amplitude losses.

A possible solution to deal with these remaining challenges is a single-iteration least-squares Kirchhoff migration (LSKM), in which the subsurface reflectivity is better recovered by approximating the inverse of the Hessian matrix using a curvelet-domain matching filter (Wang et al., 2017).

In Figure 4, a comparison between legacy (a), reprocessed Kirchhoff (b), and reprocessed LSKM (c) is displayed. The improvements of the pre-processing and the velocity model, visible in 3b, are further highlighted by the LSKM, which was able to recover the poorly-illuminated areas, while reducing the migration artifacts related to the sparseness of the NATS acquisition.

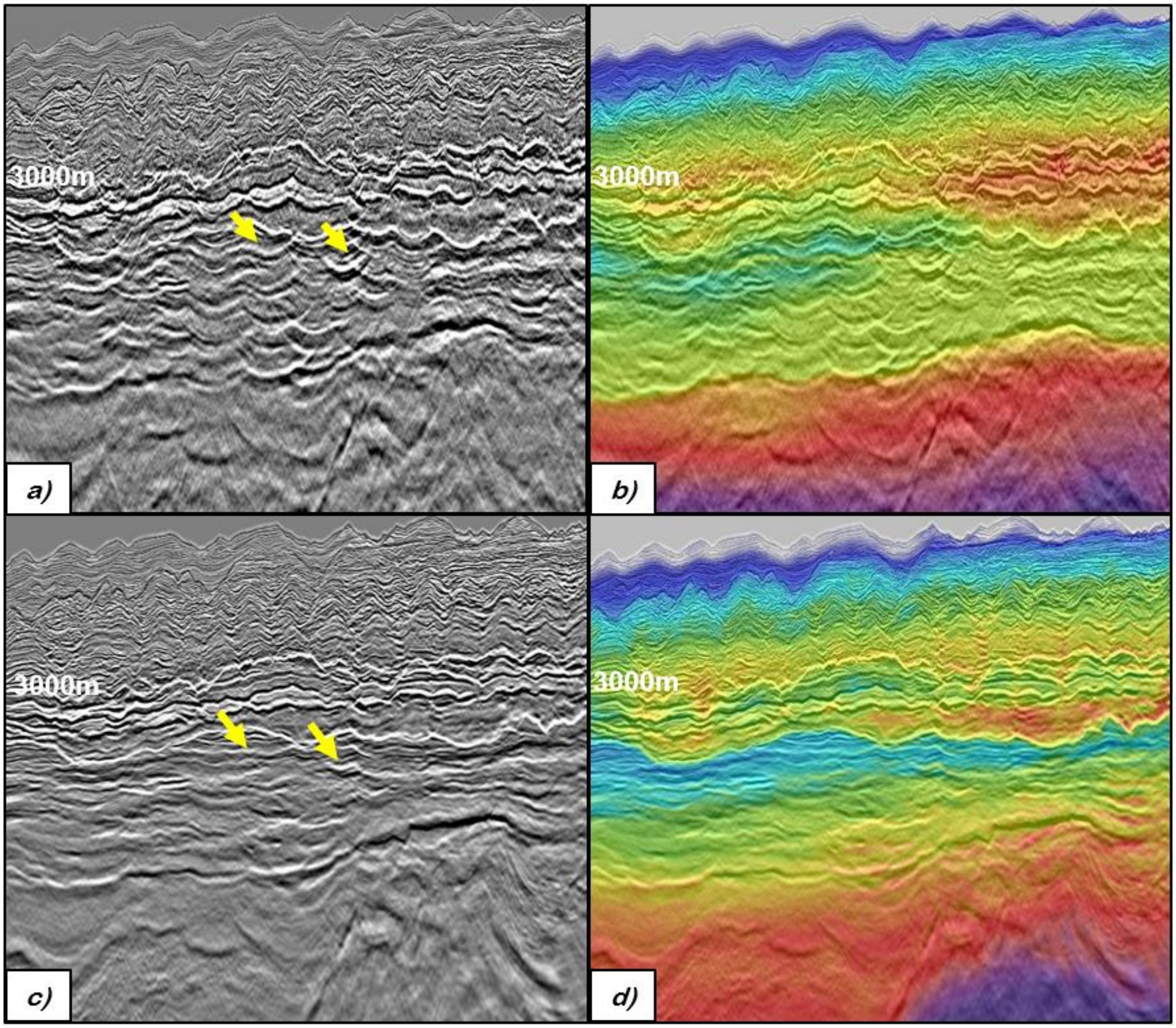

Figure 3 - *Comparison between legacy (a) and reprocessed (c) seismic data, using the corresponding velocity models (b) and (d). The yellow arrows in the seismic data show the push-down effect due to wrong velocity inside the carbonate platform.*

Another expected improvement brought by LSKM is the AVO behavior. Since there are no wells available to perform a direct measurement of the expected AVO, we perform a quantitative analysis of the similarity between the AVO model and the real data (Coléou, 2012). This analysis gives the quality indicator attribute of the dataset and consists of cross-plotting NRMS and correlation coefficients. Since these two attributes are strongly anti-correlated, we observe a cloud of points with a lower boundary shown on Figure 5b. As we ascend on this curve, we are increasing similarity between real data and the AVO model which indicates an improvement on AVO response of the LSM dataset (Figure 5d).

FWI Imaging

Despite all aforementioned improvements, the single-scattering limitation of the Kirchhoff migration still poses a challenge to proper illuminate complex regions below the carbonate platform. To address this limitation, an FWI image was produced (Huang et al., 2021). This methodology calculates the directional derivative perpendicular to the dips of the geology of the FWI velocity model. Thanks to the use of the full wavefield, including multiples and least-squares data fitting, the FWI image can achieve an enhanced illumination and higher S/N in complex regions.

We carried out a study in a complex geological area to assess the efficiency of the methodology.

As a starting model, we used a smooth velocity obtained by few iterations of tomographic velocity update. TL-FWI ran up to 25Hz to generate the velocity model shown in Figure 6d.

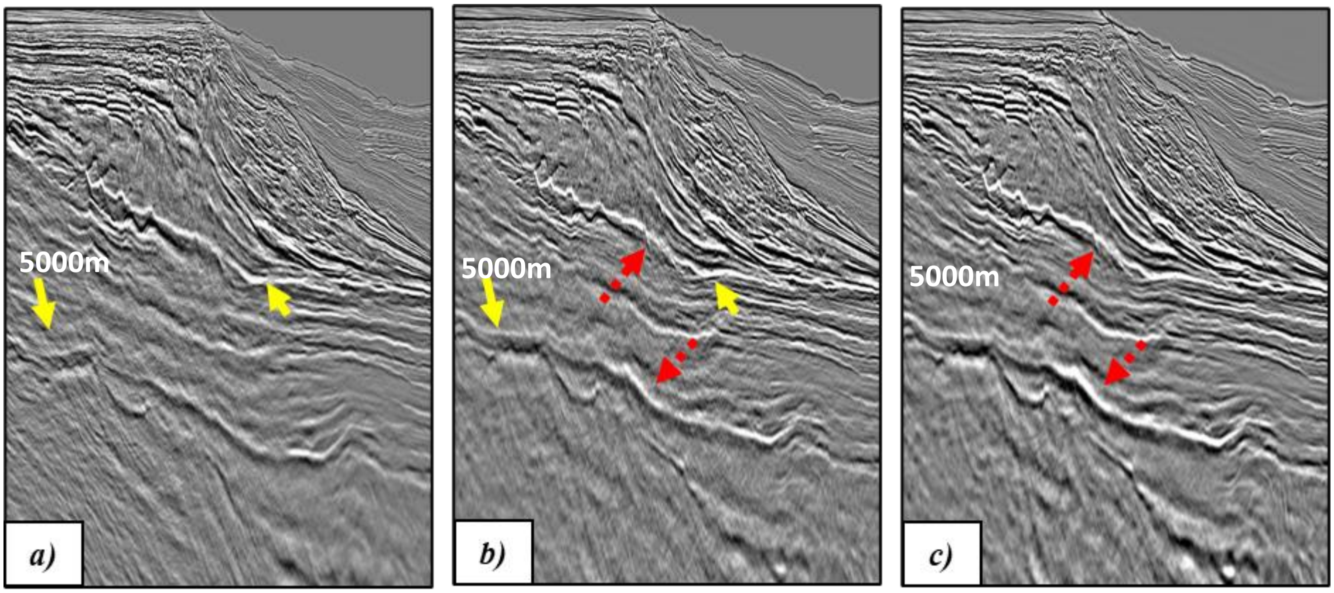

Figure 4 *- Comparison between (a) legacy, (b) Kirchhoff reprocessing and (c) LS Kirchhoff migration.*

We can observe that the conventional imaging algorithms like LSKM (6a) and RTM (6b), fails to illuminate complex intra- and sub-carbonate events indicated by the yellow and green arrows respectively, however the FWI image recovers those events in poor illuminated zones (6c).

Conclusions

Recent advancements of processing and imaging technologies allowed the successful reprocessing of a legacy NATS data to overcome some imaging challenges posed by the complex geology of the Foz do Amazonas basin. The application of 3D de-signature and de-ghosting, in addition to the joint MWD and SRME curvelet subtraction demultiple, had a significant impact on the pre-processing.

The combination of the pre-processing with TL-FWI and LSKM workflows reduced the depth distortions (pull-up / push-down), providing a more reliable representation of the complex geological structures and improved the quantitative analysis of the data.

FWI imaging confirmed its capability to utilize the full wavefield producing an improved image, with respect to conventional imaging techniques, like LSKM or RTM. In one (iterative) inversion, FWI imaging addresses usual imaging challenges like velocity inaccuracies, migration artifacts, noise and multiples.

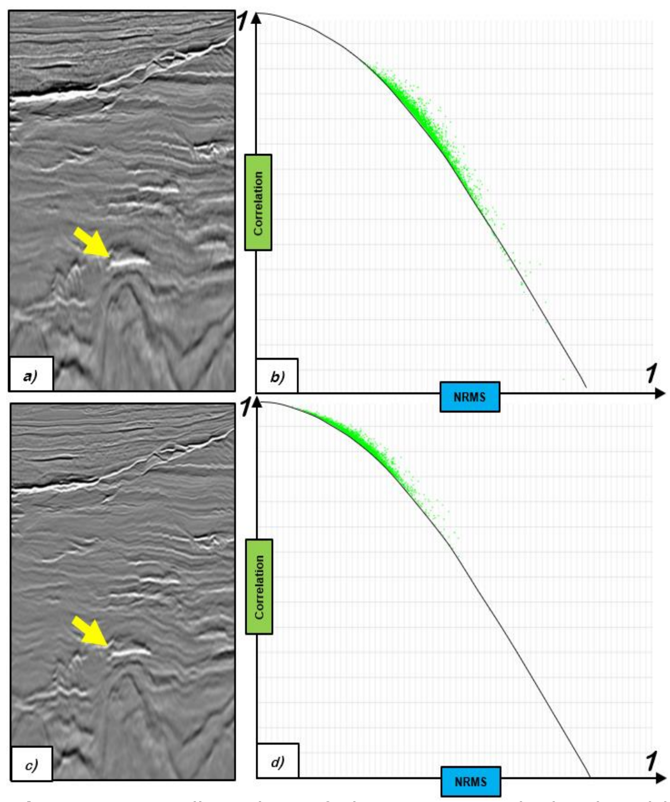

Figure 5 *Crossline view of the target sand showing (a) Kirchhoff Migration and (c) LSM. Panel (b) and (d) shows the cross-plot of cross-correlation and NRMS around the sand, for both migrations.*

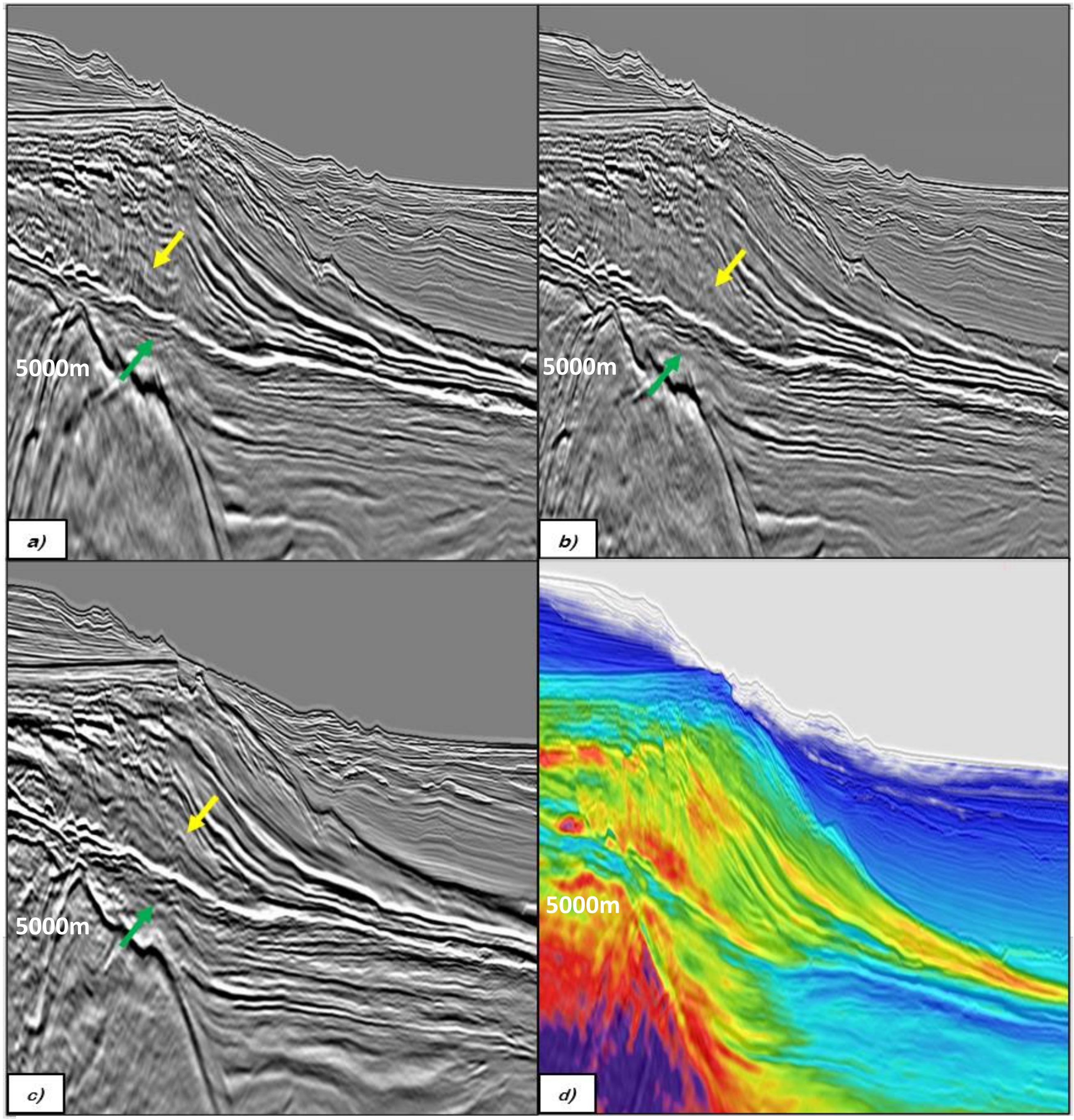

Figure 6 – Inline View of *a) LSKM, b) RTM Image, c) FWI image and d) 25Hz TL-FWI velocity model.*

Acknowledgments

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