Revisiting the Brazilian Equatorial Margin with FWI and its impact on interpretation in an exploratory frontier

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Summary

Recent technology advancements have enabled us to revisit the Foz do Amazonas (2014) and Barreirinhas (2016) narrow-azimuth towed-streamer (NATS) seismic surveys and tackle specific imaging challenges in a way that the legacy processing could not. In an exploratory frontier such as the Brazilian Equatorial Margin (BEM), the petroleum system knowledge is limited, with few wells and no significant commercial discovery in the area yet. Thus, high-quality seismic data is crucial for reducing risk in the initial exploration phases.

Motivated by important discoveries in the West African margin and most recently in the nearby Equatorial Guianas, we revisited the exploratory frontier of the BEM with a combination of manual interpretation and time-lag FWI (TLFWI).

Results exhibit significant uplift in the image, making interpretation less ambiguous and more geologically consistent, which in turn improves our understanding of the petroleum system, including comprehension of its structural framework and channel-fan system distribution at Late Cretaceous/Paleogene reservoir units.

Introduction

The Foz do Amazonas (FDA) and Barreirinhas (BAR) basins exhibit a complex evolutionary history related to the combination of extensional and strike-slip tectonics, which culminated in the opening of the Equatorial Atlantic Ocean during the Early Cretaceous (Montenegro et al., 2021). In addition, episodes of gravitational tectonics are common in the BEM. We can observe many regional and local gravity-driven slides, mass transport deposits, and shale-dominated thrust systems.

Both surveys present near-seafloor complexity, including irregular seafloor morphology due to canyons, the high-contrast and heterogeneous Neogene carbonate platform (Amapá Formation in FDA and Ilha de Santana Formation in BAR) also incised by paleo-canyons, as well as channel-fan systems down to the Late Cretaceous.

In response to this shallow complexity, the legacy images display distinctive pull-up and push-down distortions indicative of small to-mid scale inaccuracies in the velocity model. Such distortions accumulate with depth, creating wave-like artefacts in the sub-carbonate and sub-channel reflectors (Figure 1). Interpretation-wise, it creates false anticline structures and non-geological boundaries at the reservoir interval and into the deeper rift section. It also undermines lateral amplitude distribution and reliability, compromising any amplitude characterization in the stacked image of the channel-fan facies and their enveloping/contrasting shale seals. For example, we identified intra-reservoir “ghost channels” that are imprints of velocity contrasts from the real channels immediately above (Figure 1).

Deep in the main potential source rock interval (Late-Aptian lacustrine shales from Codó Formation, see Figueiredo et al., 2007 and Trosdtorf Jr. et al., 2007), where the images are already compromised by loss of frequency content and illumination issues, these depth distortions hinder the recognition of discontinuities related to faults rooted in the rift and their role as migration pathways to the Late Cretaceous. This is particularly true in BAR survey, where sedimentary overburden may reach 10 to 12 km of isopach.

Advances in FWI

Past approaches for velocity model building were based on a non-linear multi-layer TTI tomography workflow (Guillaume et al., 2012), with the carbonate platform being manually interpreted as a separate layer.

As shown in Figure 1, the resolution of the tomographic inversion was not able to catch required details in the velocity in the shallow section (e.g., seafloor canyons, carbonate platform heterogeneities, and channel-fan systems). Moreover, short-period multiples, as well as limited offset reflections, decrease the reliability of the RMO information, which in turn limits the robustness of the tomographic inversion inside and right below the carbonate platform. Lastly, manual interpretation of the carbonate platform interface limited the accuracy of the multi-layer workflow.

The lack of long offsets (8 km maximum offset), low-frequency content, and azimuthal information typical of NATS data can severely hinder the stability and robustness of FWI. In this area, diving waves only penetrate as deep as the seafloor canyons and part of the carbonate platform, not reaching the base of the carbonate platform in thick portions nor the channel-fan systems in the Late Cretaceous (around 4–5 km deep). Conventional FWI has been tested on these datasets in the past with no success. The rugosity of the water bottom and the complex shallow overburden make FWI prone to cycle skipping. High impedance contrasts, for example at the top of carbonate, can also create amplitude

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discrepancy issues between field data and synthetics. However, TLFWI (Zhang et al., 2018; Wang et al., 2019) uses a time-lag cost function to mitigate these issues related to cycle skipping and amplitude. It can therefore yield more reliable updates when compared with conventional FWI.
A regional seismic interpretation of the key strata was performed to smooth the legacy model along the interpreted horizons. We obtained a smooth and geologically consistent model, from which TLFWI was performed.

Results and Discussion

We show here that the use of TLFWI together with a geologically consistent, interpretation-guided initial model can partly overcome the identified challenges and provide

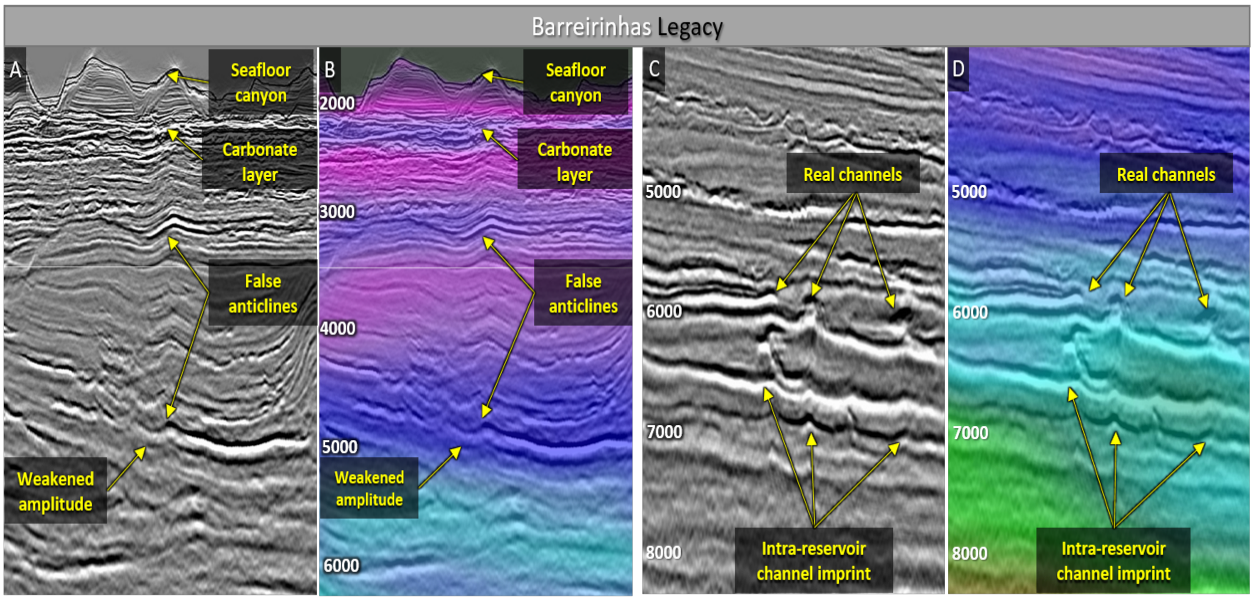

Figure 1: Summary of imaging challenges with the legacy model: Kirchhoff migrations depicting (a) and (b) depth distortions; (c) and (d) channel imprint artefacts immediately below real channels at the reservoir interval.

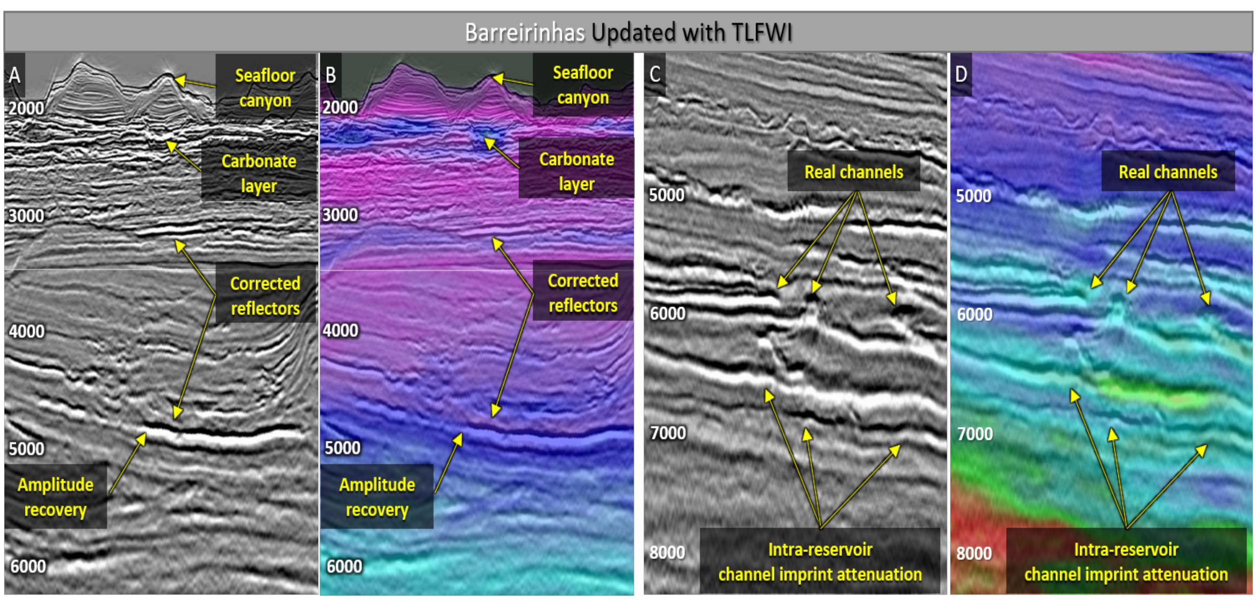

Figure 2: Summary of imaging challenges after 6 Hz TLFWI: Kirchhoff migrations depicting (a) and (b) mitigation of depth distortions; (c) and (d) channel imprint attenuation at the reservoir interval.

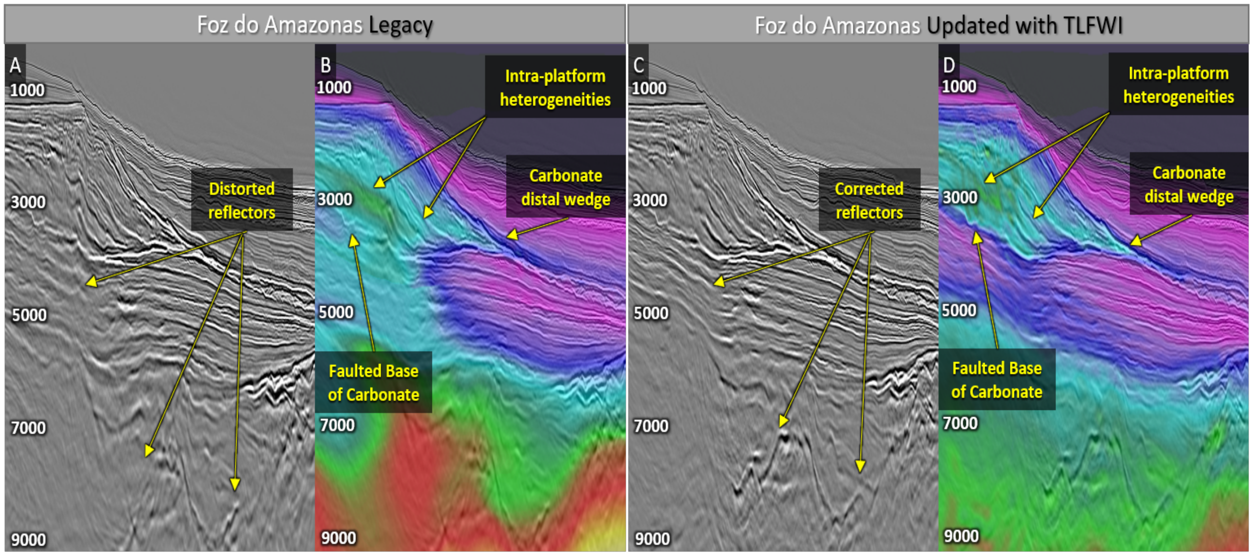

Figure 3: Comparison between legacy and updated images after 6 Hz TLFWI: RTM stacks (a) and (c); with respective models overlaid (b) and (d).

meaningful updates. After a few iterations of TLFWI up to 6 Hz, shallow velocity errors that were causing depth distortions (Figure 1) are now diminished (Figure 2).

In Figure 1a, the bright anomalies highlighted by the yellow arrows are interpreted to be fan-systems. After TLFWI, a false anticline in Figure 1a is better interpreted as a possible stratigraphic trap against an onlap surface in Figure 2a. In the case of the deeper fan anomaly, the repositioning of the bright reflector also recovered amplitudes and increased lateral continuity, affecting reservoir characterization and volumetrics.

The updated image in Figure 2c shows an attenuation of the channel imprints when compared to Figure 1c, despite the fact there are residual artefacts. We believe that TLFWI's ability to capture the subtle lateral velocity variations between the channel sand facies and contrasting enveloping shale facies reduced the distortions, but we still need higher frequency iterations than the result achieved with 6 Hz to delineate this more clearly.

In Figure 3d, the updated velocity captured sharper contrasts when compared to Figure 3b, both at the faulted base of carbonate and at the thin distal wedge. It also captured heterogeneities inside the platform which are coherent with seismic facies distribution. The deeper rift-section is now coherent with expected geometries for such tectonic settings, where what once was a distorted and dimmed syn-rift layer in Figure 3a now exhibits thickness growth against the rift faults in Figure 3c. Considering the syn-rift (Late Aptian) as the main source rock, changes in thickness and continuity

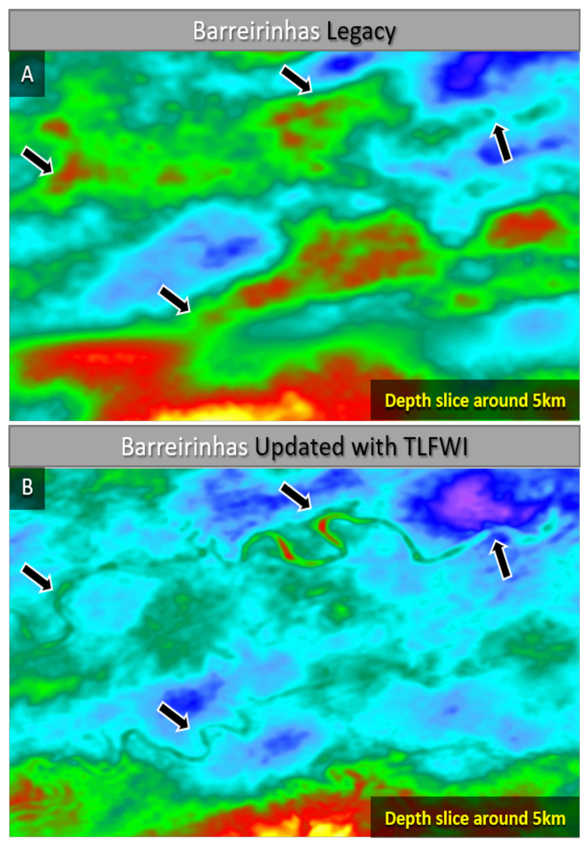

Figure 4: Comparison between legacy model (a) and a 6 Hz TLFWI update (b). Black arrows indicate specific lateral velocity variations before and after the update.

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and shifts in depth of the reflectors would affect petroleum system modeling and consequent risk assessment of maturation and migration processes.

As seen in Figure 4, the update was able to capture detailed lateral velocity variations and demarcated submarine-channel features even deeper than the reach of the diving wave contributions. In Figure 4a, the tomography-based legacy model seems to capture important long-wavelength components but with insufficient resolution for the evaluation of these kinds of exploration targets. On the other hand, Figure 4b shows that the updated model has enough resolution to aid the identification of contrasting architectural elements, which are important for the prediction of deep-water depositional systems (e.g., submarine channel complexes, lateral splays, sheet sand lobes, terminal fans).

The resulting higher resolution model also managed to distinguish internal velocity variations in reservoir candidates, as shown in Figure 5. A package interpreted to be turbidite (highlighted by the black arrow), where the reflectivity at the channel-base drape is a strong white trough, shows poor velocity resolution in Figures 5a and 5c. The updated velocity in Figures 5b and 5d captured highly localized lateral and vertical variations through the turbidite, indicating a high-velocity channel core. Moreover, internal events are sharper and flatter in the updated Kirchhoff migration, supporting a more accurate architectural element analysis of the turbidite. This higher resolution TLFWI model may also assist the analysis of important differences in reservoir acoustic properties related to facies association in sand-rich deposits (e.g., mud content, grain-size, cementation, compaction).

Conclusions

Supported by several examples, we demonstrated that the adopted workflow was able to successfully capture shallow velocity details, significantly reducing depth and amplitude distortions that were present in the legacy images based on reflection tomography.

The effectiveness of TLFWI in addressing these issues has eased interpretation by reducing ambiguities in reflector positioning in depth, seismic facies characterization, and amplitude variations, especially at sub-carbonate layers.

The uplift in the image has impacted the identification of the main erosive surfaces by improving the recognition of reflector terminations. At the reservoir level, it has eased the characterization of vertical stacking and lateral offset of channel-fan systems, and therefore reduced risks in reservoir volumetric estimations. In the deeper section, it brought new insight at the structural framework connecting source rocks to reservoir intervals.

Altogether, such image upflifts have increased the confidence level in geological interpretation and modeling for Barreirinhas and Foz do Amazonas plays and may impact risk assessment/decision-making for exploratory efforts in the Brazilian Equatorial Margin.

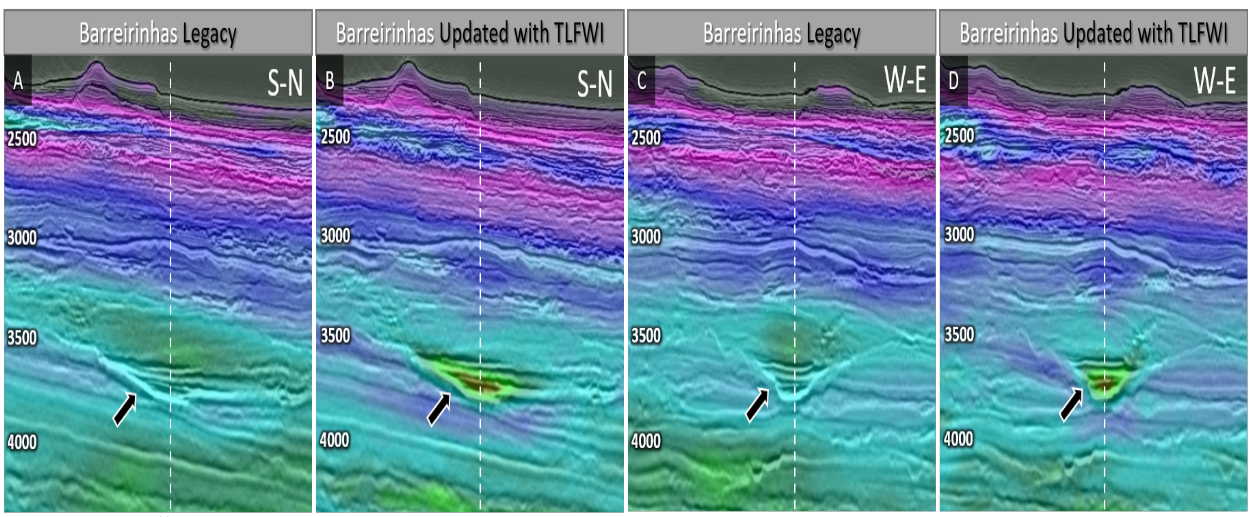

Figure 5: Kirchhoff migrations with velocity model overlaid. Panels (a) and (b) are South-North oriented. Panels (c) and (d) are West-East oriented. Dashed white line indicates the intersection of the sections. Black arrows highlight a strong channel-base drape reflector.

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