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Assessing FWI Imaging's potential to tackle illumination issues and internal multiples in the Brazilian pre-salt

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Summary

Most seismic surveys carried out in offshore Brazil consist of narrow-azimuth towed-streamer (NATS) acquisitions. In areas such as the South Atlantic offshore basins, the geological complexity results in illumination issues for NATS acquisitions, especially in the deep pre-salt section. Both Full-Waveform Inversion Imaging (FWI Imaging) and Least-Squares RTM (LSRTM) can be used to tackle this issue. Furthermore, internal multiples are a common problem. When coupled with inhomogeneous illumination, these can cause strong distortions to the geological structures and render seismic images uninterpretable. Using a data set covering a complex salt mini-basin in Campos basin, we demonstrate the capacity of FWI Imaging to naturally alleviate distortions associated with internal multiples and illumination issues. We also compare it to LSRTM and highlight some of the differences.

Introduction

The study area is in the ultradeep offshore Campos Basin, SE Brazil, with water depth greater than 2 km. According to Mohriak et al. (1995), the Aptian salt layer is dominated by contractional salt tectonics. In such context, we normally observe complex salt geometries, such as asymmetric diapirs, canopies, salt-thrusts, and narrow-deep mini-basins. In response to salt movement, syn-halokinetic post-salt layers (Cenomanian-Albian carbonates and Campanian-Turonian siliciclastics in Figure 1b) exhibit strong deformation and are heavily folded and thrusted. In contrast, above the top of the Cretaceous unconformity, the post-salt layers are less deformed and sub-horizontal. Moreover, we also observe high-amplitude inclined and saucer-shaped events crosscutting this mini-basin, which are interpreted as igneous intrusive rocks. These are normally positioned close to the top of the Cretaceous unconformity. The variety of lithologies (evaporitic, carbonatic, clastic, and igneous rocks) and structures along this narrow mini-basin result in strong lateral contrasts of acoustic properties (density and velocity). This context implies poor illumination of the pre-salt section, which is already a challenging area due to its great depths and the presence of normal faults.

The data set covering the study area was acquired using a common NATS configuration. This type of acquisition poses multiple challenges to velocity model building and to imaging in general. Diving waves have a shallow penetration depth due to limited maximum offset of 10 km. Azimuthal information is also limited, and illumination is generally inadequate. The lack of low frequencies increases the chances of cycle-skipping of FWI and poses constraints on initial velocity models. These limitations, coupled with the complexity of the overburden, resulted in an image with exploratory uncertainties during the legacy processing, without a clear definition of the base of salt and with broken events at the pre-salt (see Figure 1a).

In most data sets with complex geological settings, velocity is considered the key for obtaining a reliable image of the subsurface. However, the uplift from FWI and salt refinement seemed limited in this study area. While the accuracy of the velocity remains important, internal

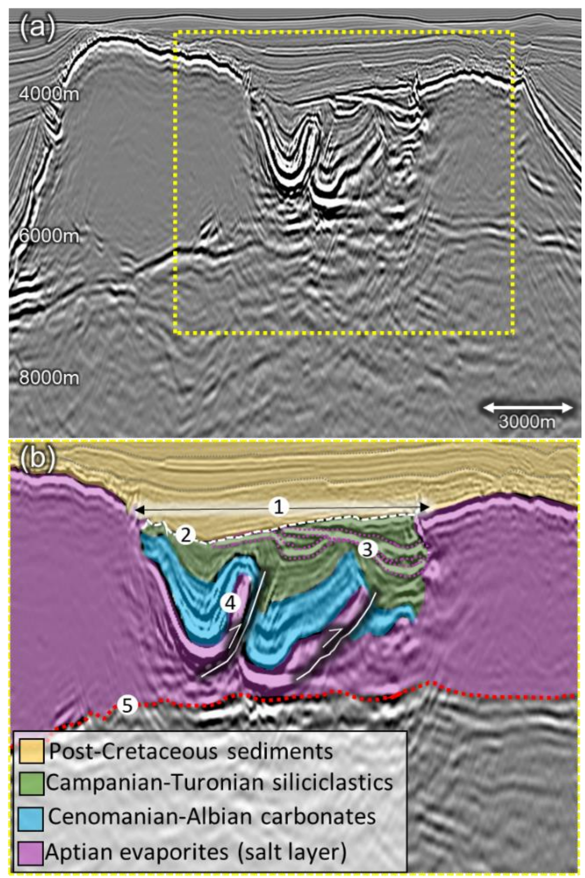

Figure 1: (a) 20 Hz legacy RTM with post-processing; (b) geological interpretation highlighting challenges related to the salt tectonics. The geological features are: mini-basin (1), top of Cretaceous unconformity (2), igneous sills (3), salt-thrusts and associated folds (4), the base of salt or top of the pre-salt section (5).

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multiples and illumination issues seem to contribute significantly to the imaging problems in this study.

This challenging context offers an interesting opportunity to test FWI Imaging (Zhang et al., 2020). This process converts high-resolution velocity models obtained by FWI into reflectivity images. Here, we show that it can address the internal multiples and illumination issues in a natural way. Comparisons with synthetic experiments, internal multiple modeling, and LSRTM were performed to understand the difficulties and gain confidence in the FWI Image.

Velocity refinement

In this study, we started from the legacy velocity model and ran Time-Lag FWI (TLFWI; Zhang et al., 2018) up to 12 Hz, coupled with refined interpretation. The updated and legacy models are shown in Figure 2. The new model captured details related to the anhydrite layer, common on top of salt mini-basins, and corrected small salt portions, such as the missing overhang pointed to in Figure 2. While these features had impact in the image, the resulting RTM showed only subtle improvements when compared to the legacy. Imaging issues persisted, such as the dimmed base of salt (BOS) and the incoherent pre-salt events.

FWI Imaging

We further iterated the TLFWI up to 20 Hz to obtain a higher resolution model comparable to the 20 Hz RTM. The resulting FWI Image is shown in Figure 3d. When compared to the RTM image (Figure 3b) generated with the same model, there is clear improvement to the definition and

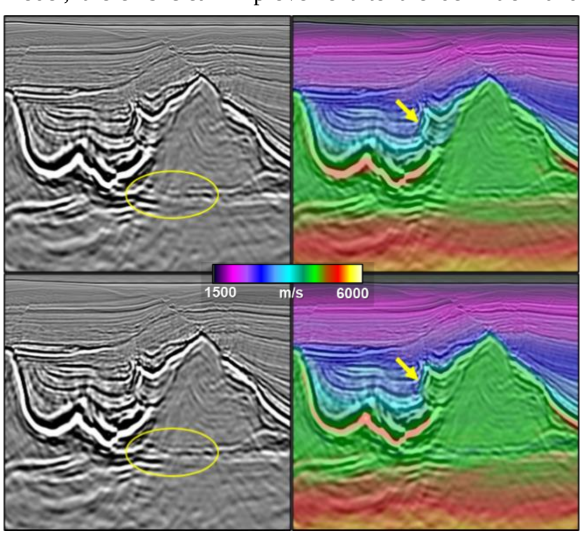

Figure 2: Top: RTM and velocity model before update; Bottom: RTM and velocity model after update. The arrow points to the updated overhang and the circle highlights the BOS improvement.

continuity of the BOS. Moreover, the FWI Image shows improvement in crossing events at the BOS as well as the broken events in the pre-salt. It is worth noting that the further increase in resolution of the velocity model did not improve the RTM image. The imaging issues lie beyond.

In order to investigate the uplift from FWI Imaging, a synthetic data set was created using the FWI velocity model as the basis for acoustic modeling. These shots were then migrated. In this case, the FWI Image plays the role of true reflectivity and any deviation from this will point to imaging problems other than velocity errors. The resulting synthetic RTM is shown in Figure 3c. While it is similar to the FWI Image (Figure 3d), it presents some of the artifacts seen in the real data RTM (Figure 3b). That is, the BOS is dimmed on the left-hand side of the mini-basin and distorted by cross-cutting events. The pre-salt also displays broken events.

Given the complexity of the geological overburden in the area, these artifacts were assumed to be internal multiples. This is confirmed with an internal multiple model that was created pre-imaging through the overburden-target separation method (Pereira et al., 2020) and migrated with RTM. The result is shown in Figure 3e, displaying good correlation with the artifacts in the RTM image (Figure 3b).

Illumination, internal multiples, and LSRTM

Internal multiples are typically not expected to be as strong as primaries since they suffer at least two extra reflections. However, in this data set, their strength is exaggerated by the illumination effects in the area. They appear much stronger than they physically are. Consequently, weaker primaries are masked, hiding important features of the structure. To investigate this further, LSRTM was applied. A prestack single-iteration implementation was used (Wang et al., 2016). It was chosen because it gives a better approximation to the inverse Hessian, due to the extra degree of freedom in the application of the curvelet-domain filters. The LSRTM result (Figure 3f) balanced the illumination and recovered some of the BOS. Internal multiples are now relatively weaker and no longer overwhelm the image.

However, after close inspection of the LSRTM image, one will notice that internal multiples are still present and have simply been reduced by illumination corrections from LSRTM. For instance, the yellow arrow in Figure 3f highlights one internal multiple still contaminating the pre-salt. Given that LSRTM operates within the framework of Born modeling and does not consider multiple reflections, a full account of the relative amplitude of internal multiples and primaries is not possible.

All these observations demonstrate FWI Imaging's capacity to attenuate internal multiple artifacts by modeling multiple

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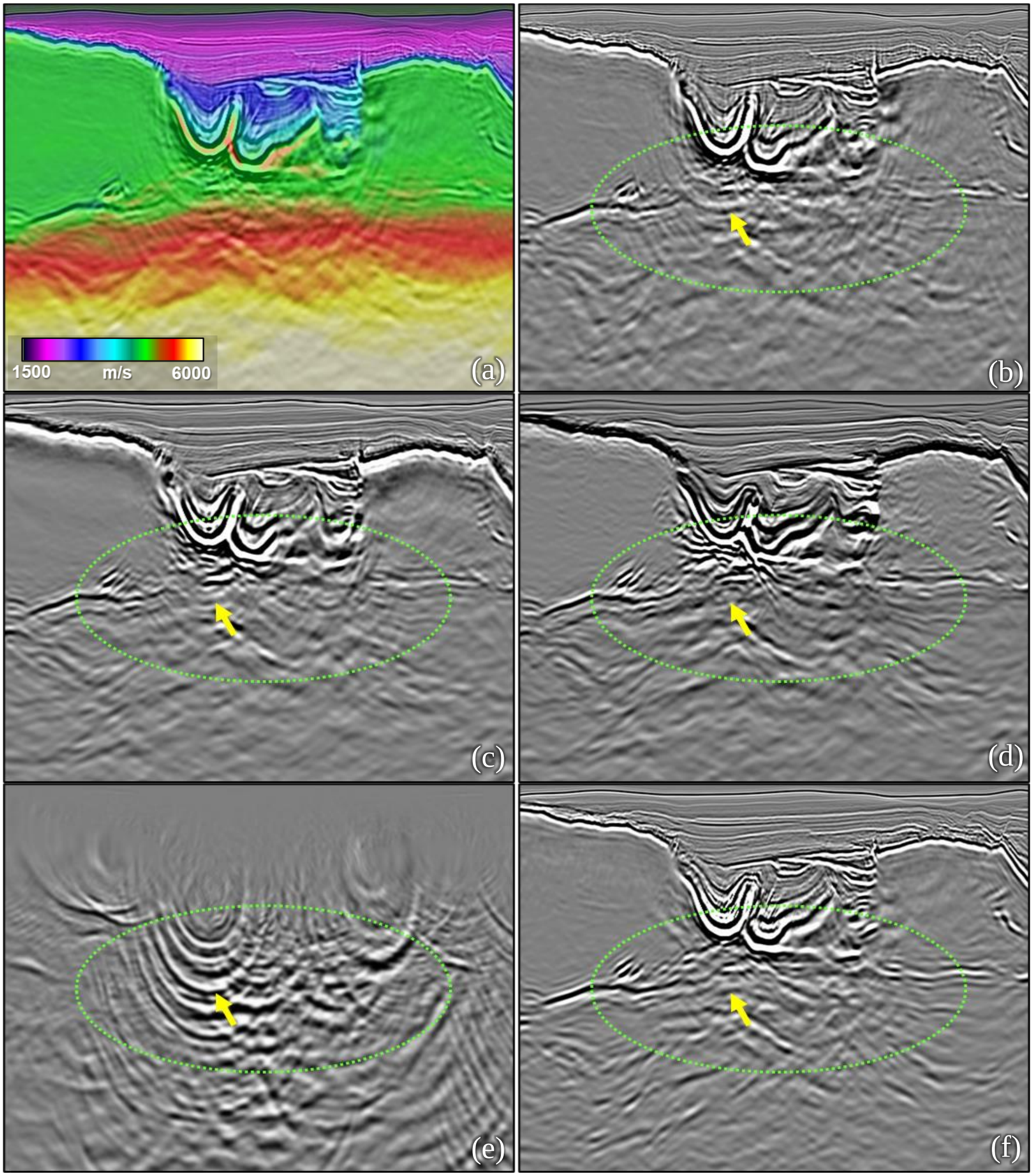

Figure 3: (a) 20 Hz FWI velocity model, (b) RTM migration using velocity model in (a), (c) synthetic RTM created with acoustic modeling using FWI velocity model, (d) FWI Image, (e) Internal multiple model, (f) Least-squares RTM. The green circle highlights the area of interest and the yellow arrow points to a particular internal multiple event at the pre-salt.

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FWI Image: illumination and multiples

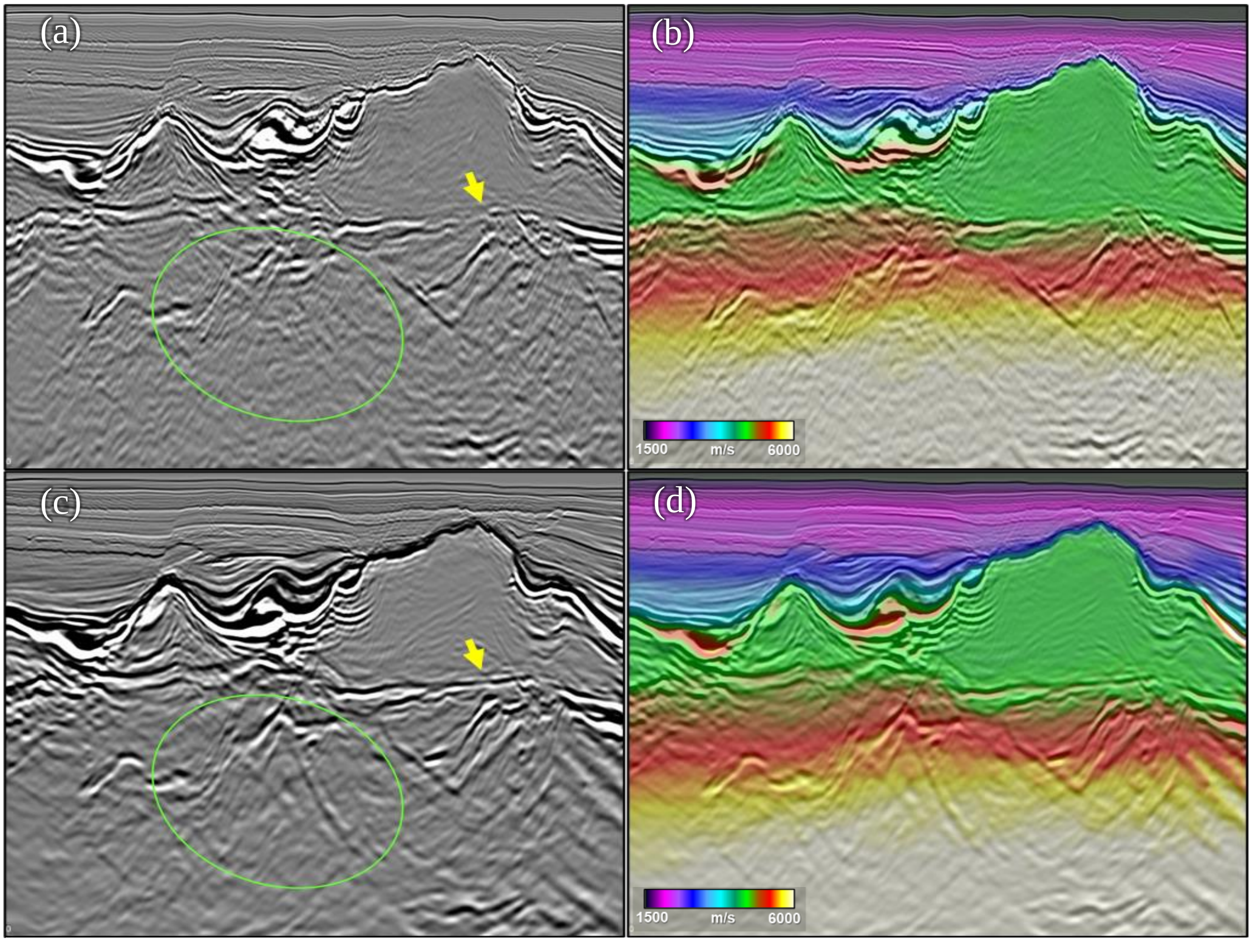

Figure 4: (a) 20 Hz legacy RTM with post-processing applied, (b) 20 Hz legacy RTM with post-processing applied and legacy velocity overlaid, (c) 20 Hz FWI Image, (d) 20 Hz FWI Image and new velocity model overlaid. The arrows show the BOS improvement, and the circles are highlighting the pre-salt faults of the rift stage which are captured by the FWI Image.

reflections and taking them into account in the inversion process. It can also overcome illumination issues, through its multi-scale iterative approach.

In Figure 4, the legacy RTM image (a) and the FWI Image (c), with their corresponding models to the right, are shown at a crossline passing through the section shown in Figure 3. Thanks to the illumination compensation of FWI Imaging, the BOS was considerably healed, and the pre-salt faults of the rift stage are better resolved.

Notice that while FWI Imaging has the potential to image internal multiples, this is not guaranteed in all cases and crosstalk may be introduced. If contrasts that generate them are far from their correct position, the process may never converge. This is critical for NATS data. For OBN data, it is expected for the process to be less sensitive. Extra information in the form of diving waves, better illumination, and low frequencies would help improve the convergence.

Conclusion

We have shown that FWI Imaging has the potential to substantially improve structural imaging in a geologically complex area using NATS data. Illumination distortions were corrected, and internal multiples were attenuated naturally through the FWI inversion.

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