Monitoring pre-salt reservoirs with hybrid acquisitions and 4D FWI

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Summary

Many fields in the Brazilian pre-salt have been historically imaged with narrow-azimuth towed-streamer (NATS) data and only recently have been surveyed with ocean bottom nodes (OBN). Some cases of time-lapse 4D seismic monitoring are limited to hybrid pairs of data, where a NATS baseline acquisition was performed before production start and an OBN data set was acquired later for monitoring. This leads to low repeatability, imposing many challenges for extracting reliable 4D signal, especially in the context of the subtle changes expected from pre-salt carbonate reservoirs. Considering this, we developed a novel joint 4D full-waveform inversion (FWI) formulation to attenuate the adverse effects of low repeatability due to diverse acquisition geometries. Results are demonstrated using field data from the Santos Basin, revealing potentially genuine 4D anomalies.

Introduction

Time-lapse monitoring has become a standard for the development of fields and optimizing oil recovery (Lumley, 2001). It consists in measuring changes of properties of the subsurface throughout a period of production. The quality of the extracted 4D signal, which corresponds to the changes in the subsurface, is dependent on the quality and repeatability of the baseline and monitor data sets. For this reason, OBN/OBN configurations are ideal.

In the Brazilian pre-salt, however, many fields were assessed with NATS data at the early exploration stages. Less than a decade ago, OBN data started being acquired. Thus, it is the case for several fields to have NATS data acquired before production, whereas OBN data are acquired years later for monitoring purposes. Deriving 4D information in this hybrid NATS/OBN configuration is challenging, due to the low repeatability. Moreover, in carbonate pre-salt fields, only subtle 4D differences are expected. Cypriano et al. (2019) and Cruz et al. (2021) reported the results of the first 4D seismic imaging for Brazilian pre-salt reservoirs, comparing data from two OBN acquisitions. The level of the 4D information obtained was around 2%.

Figure 1 shows a section from a pre-salt field in Santos Basin. The baseline is a NATS data set acquired in 2012 and the monitor is an OBN data set acquired in 2021. The baseline 45Hz RTM and LS-RTM (Wang et al., 2016) images are shown in Figures 1a,b. These illustrate some of the region's geological complexity where deep reservoirs lay below stratified evaporitic deposits. Figure 1c shows the 4D

difference related to RTM migration images. Despite having a 4D pre-processing which includes matching, binning and deghosting, it shows strong unrealistic amplitudes due to differences in the acquisition geometries. With the image-domain single-iteration LS-RTM approach, 4D noise is largely attenuated as seen in Figure 1d. It better highlights a potential 4D anomaly below the base of salt, near a well (green line). This is due to the illumination correction and attenuation of geometrical properties of LS-RTM (Wang et al., 2017). However, the background noise is still above 10% at reservoir depth, possibly hiding true 4D signal.

In recent years, there has been an increase in the use of FWI for extracting valuable information of the subsurface and imaging purposes (Zhang et al., 2020). This has been demonstrated by Brando et al. (2023) on pre-salt fields. Moreover, applications of FWI to time-lapse projects show promising results and demonstrate benefits compared to LS-RTM (Bortoni et al., 2021). To benefit from the properties of FWI while overcoming repeatability issues for hybrid 4D datasets, we developed a novel joint 4D FWI formulation. This formulation explicitly accounts for differences in the acquisition geometry of the baseline and monitor surveys, thus increasing the reliability of the inversion result.

Method

Many strategies for tackling the challenges of time-lapse 4D FWI have been explored (see Fu and Innanen, 2023 for an overview). The most common is the parallel strategy (Plessix et al., 2010), in which both vintages are inverted independently starting from the same initial model. But the limitations of the different acquisitions still have considerable impact on the inversion result, leading to additional 4D noise (Rudrigues et al., 2024).

To overcome the dependency on acquisition geometry and attenuate its effects, our joint 4D FWI constrains the updates of the baseline and monitor models, m_B and m_M, at every iteration, such that each contains information of the acquisition geometry of the other. The update for each iteration can be written as preconditioned gradients:

$$\Delta m_B = -P_B g_B, \qquad \Delta m_M = -P_M g_M, \quad (1)$$

where the preconditioners P_B and P_M represent approximate inverses of the respective Hessian operators, and g_B and g_M represent the gradients over m_B and m_M, respectively. Furthermore, these preconditioners satisfy the constraint

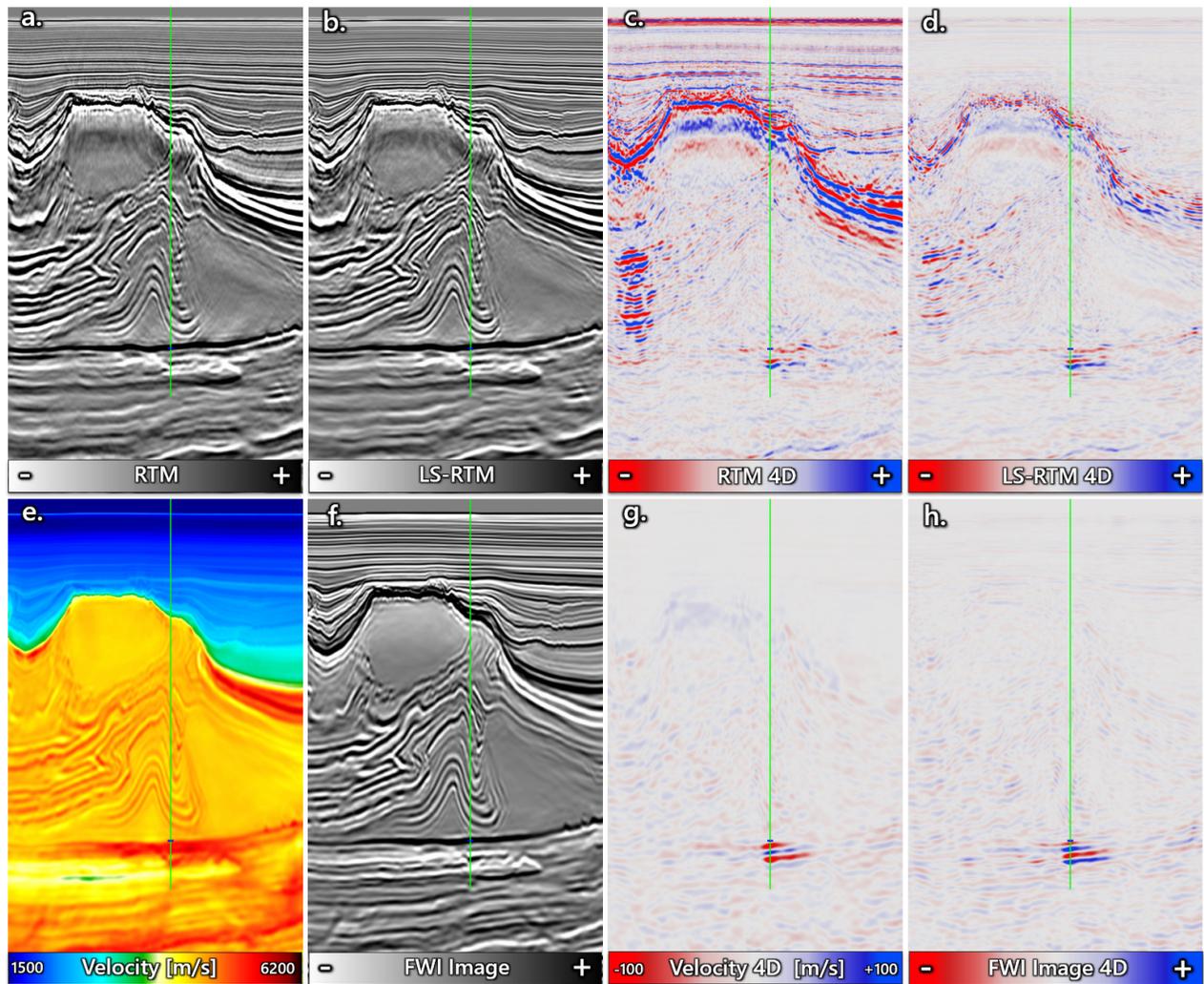$$P_B H_B \gamma = P_M H_M \gamma, \quad (2)$$

Figure 1: (a) RTM image of the NATS baseline data. (b) LS-RTM image of the NATS baseline data. (c) RTM image 4D difference. (d) LS-RTM image 4D difference. (e) Baseline velocity model obtained with the joint 4D FWI. (f) Baseline FWI Image obtained with the joint 4D FWI. (g) Velocity 4D difference. (h) FWI Image 4D difference. Well is shown as green line.

for a given search space direction γ representative of the current iteration. H_B and H_M are the Hessians over m_B and m_M. As the Hessians include effects related to acquisition geometry, the constraint limits the effects of geometrical differences on the updates.

Revealing pre-salt changes with joint 4D FWI

We tested the joint 4D FWI formulation for the same pre-salt NATS/OBN hybrid data set used to obtain the RTM/LS-RTM results. The baseline NATS data was obtained with a dual-source configuration and 12 receiver cables, with maximum offset of 8km. The monitor OBN data was also obtained with a dual source configuration and nodes spacing of 425m, reaching offsets greater than 20km. To maximize the similarity between the data sets, we limited the OBN data to the same azimuth and offset range as the NATS data. We conducted a 30Hz joint 4D FWI, based on a time-lag cost function (TLFWI, Zhang et al., 2018). The initial model was obtained through a separate 3D FWI based on the full-azimuth OBN data.

Figure 1e shows the baseline velocity model obtained with the joint 4D FWI approach. The velocity model has high resolution, showing layered structures from post-salt to pre-salt depths. Figure 1f shows the corresponding baseline FWI Image, for the same line view. Figure 1g shows the 4D

difference between the monitor and baseline velocity models. A clear isolated velocity 4D anomaly can be observed at the reservoir depth, around the well path. Figure 1h shows the 4D difference between the monitor and baseline FWI Images. As in the velocity case, a clear isolated 4D anomaly can be observed in the image domain. A comparison between Figures 1d and 1h indicates that the two imaging methods can detect a potential 4D anomaly in the reservoir level. However, the joint 4D FWI approach leads to significantly less 4D noise than LS-RTM. Strong 4D noise around top of salt and intra-salt vanish in the joint 4D FWI case.

Another example of the effectiveness of the joint 4D FWI in recovering time-lapse information is shown in Figure 2. It shows an arbitrary line passing through selected wells in the study area. Figure 2a depicts the baseline FWI Image overlaid on its corresponding velocity model, with the well

trajectories shown as green lines. The combination of image and velocity reveals geological complexities, such as post-salt mini basins, salt geometry variability, intra-salt stratifications and pronounced pre-salt heterogeneities (including faults and velocity variations at reservoir-level). Figure 2b shows the obtained FWI Image 4D difference for the same line view. Despite all geological complexities and acquisition differences, the joint 4D FWI reveals prominent 4D anomalies concentrated at reservoir depths and around wells, exhibiting inter-connection between some of them. The joint 4D FWI Image led to the lowest NRMS values within all imaging techniques tested in this study case (about 4% at the reservoir level).

The continuity of 4D information can be better visualized in Figure 3, in which a perspective view of the 4D intensity attribute is shown. This attribute represents the absolute amplitude of the 4D difference extracted on an intra-
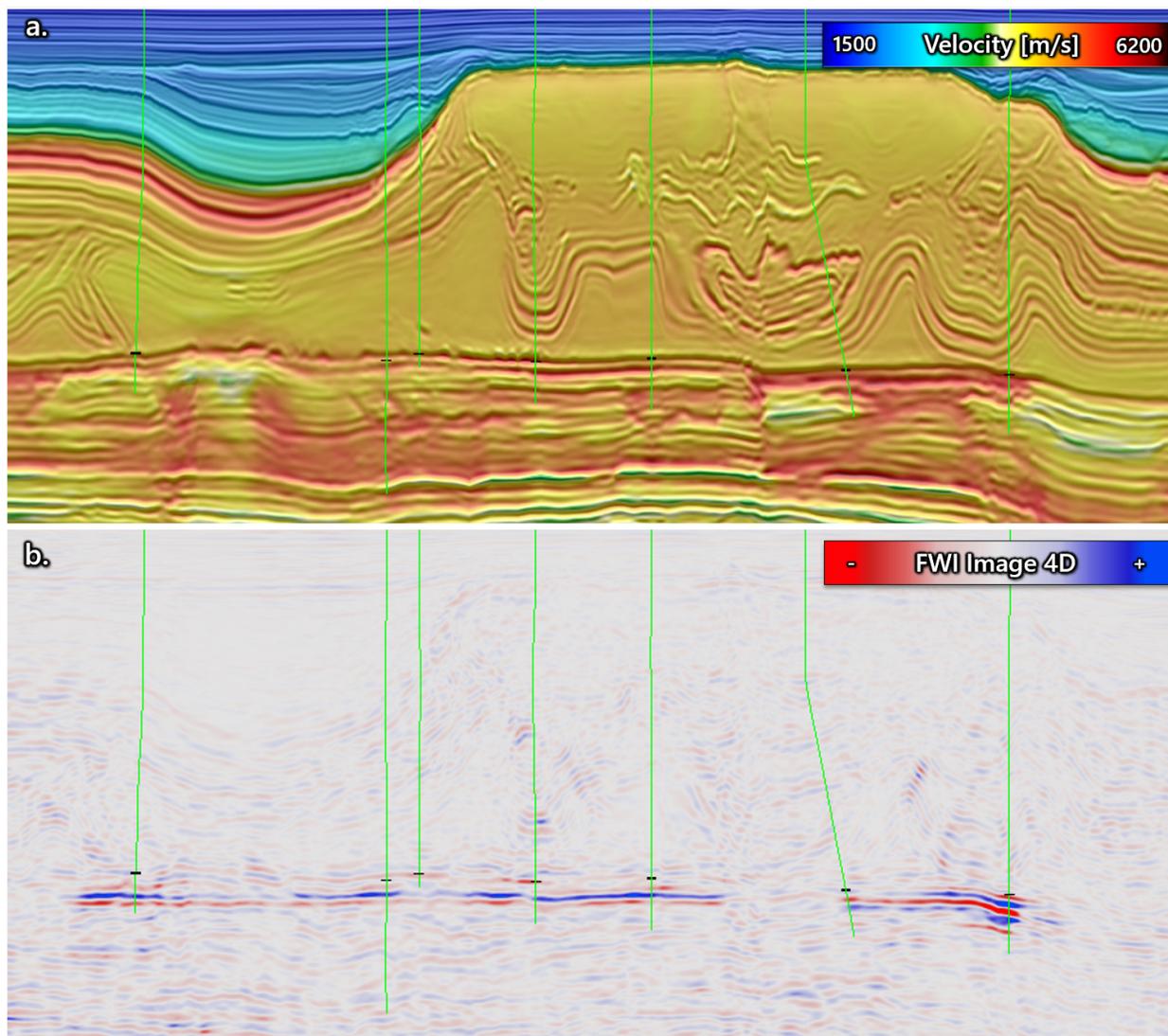

Figure 2: Arbitrary line passing through wells of the study area for (a) the baseline FWI Image overlaid by its corresponding velocity model and (b) the FWI Image 4D difference. Well trajectories are show as green lines.
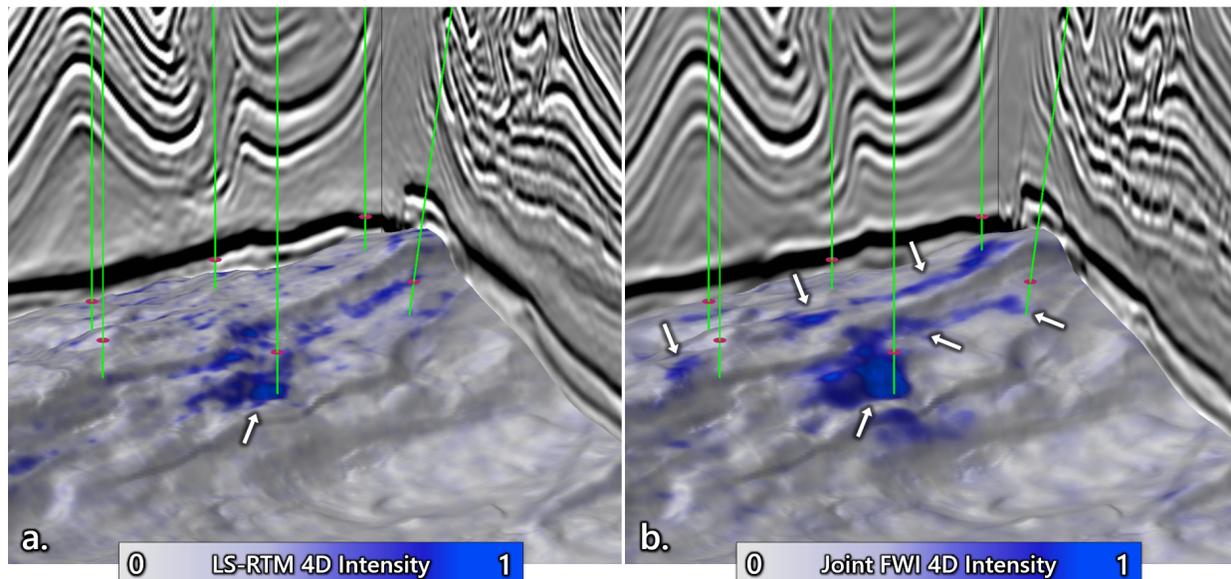
Figure 3: 3D view of an intra-reservoir horizon exhibiting the 4D intensity attribute (absolute amplitude of 4D differences) for (a) the LS-RTM data set and (b) the FWI Image data set. Different well trajectories are shown as green lines. The attribute values are normalized (0 to 1). White arrows indicate regions of potential 4D anomalies.

reservoir horizon (normalized between 0 and 1). Six drilled wells are shown as green lines for reference. One clear anomalous region can be observed in the LS-RTM result, near a well path position (white arrow in Figure 3a). Beyond this single localized anomaly, the LS-RTM 4D intensity distribution is discontinuous, with low correlation with other wells. On the other hand, the FWI Image 4D intensity distribution reveals pronounced and continuous anomaly paths (white arrows in Figure 3b). A high correlation with well sites is identified and some level of connectivity between the wells can be observed.

The obtained results indicate that the interpretation of 4D information can benefit from the joint 4D FWI velocities and images. Izeli et al. (2024) make a preliminary analysis of these results with promising conclusions for the future of time-lapse processing for the Brazilian pre-salt.

Conclusions

The development of technologies to deal with 4D seismic monitoring under complex acquisition and geological conditions is necessary for areas like the Brazilian pre-salt, which has predominantly NATS data before production and OBN data during production. In this work, we showed the challenges of extracting reliable 4D information from a hybrid pair of acquisitions. Accordingly, we developed a new joint 4D FWI formulation that mitigates the effects of acquisition differences. Our results showed that the proposed joint 4D FWI is more robust than other imaging techniques, such as LS-RTM, in this application. However, 4D FWI still benefits from the typical 4D pre-processing steps used for obtaining consistent results between baseline and monitor data sets.

With significantly reduced 4D noise, the joint 4D FWI allows identification of time-lapse changes in both velocity and image domains. It reveals 4D anomalies at reservoir depths exhibiting high correlation with wells within the study area. Although repeatable data sets would ultimately provide results with the highest confidence – in the context of this study – the presented method has the potential to deliver time-lapse analysis that can bring value to reservoir planning and future monitoring activities.

For the next steps, we aim to test the new joint 4D FWI with different data sets in different geological settings. It is noted that regions with even more complicated geological aspects can be found within the Brazilian pre-salt or in a worldwide context.

Acknowledgments

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