Illuminating Santos Basin's pre-salt with OBN data: Potential and challenges of FWI

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Summary

Over the last ten years, Santos Basin has become one of the most prospective oil provinces in the world. Multiple giant pre-salt oil and gas fields have been discovered. Due to the geological complexity of this basin, ocean-bottom-node (OBN) acquisition has naturally emerged as an imaging solution. Besides imaging, the full-azimuth and long-offset from OBN data are ideal for full-waveform inversion (FWI), particularly the recently-developed time-lag FWI (TLFWI) formulation, which provides an approach suitable for the complex geologies of the Santos Basin. We show herein that given the right data, provided by OBN acquisition, a reliable FWI engine such as TLFWI, and a good starting model, we are able to derive a velocity model with enough resolution to impact the imaging of salt and pre-salt regions. This offers a significant improvement compared to models derived from narrow-azimuth (NAZ) streamer data. However, some challenges remain. FWI is highly dependent on the initial velocity model, due to the difficulty of recording reliable extra low frequencies. Multi-parameter FWI anisotropy update also continues to be a complicated task, as decoupling velocity from the anisotropy term remains arduous. Overcoming these challenges is not a trivial task. Better acquisitions together with multi-parameter FWI may help for solving these challenges.

Introduction

The Santos Basin is well known for its giant pre-salt oil and gas fields. Since 2006, pre-salt oil discoveries have rapidly elevated this province to one of the most prospective in the world. Today, pre-salt fields contribute to half of Brazil's national production. Prospecting these plays is not without its challenges, as pre-salt reservoirs usually lie around 5 km depth, below a thick layer of stratified salt. The pre-salt region is complex, with fast carbonates, slow sediments, volcanic layers, and large fault systems.

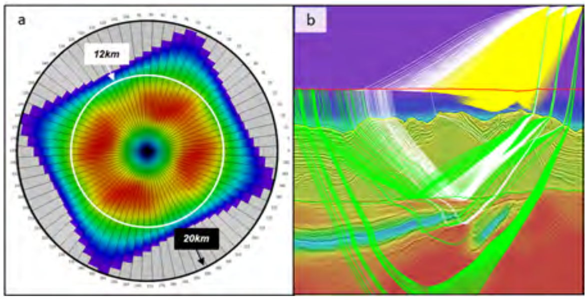

Figure 1: (a) Rose diagrams of mid-point fold from all nodes, with the inner and outer circumferences indicating 12 and 20 km offset, respectively. (b) Diving rays through the updated velocity model, with the water bottom horizon in red. Yellow rays (offsets from 4 to 8 km) cannot penetrate deeper than top of salt. White rays (from 8 to 12 km) can reach base of salt and some pre-salt layers. Green rays (from 12 to 18 km) show penetration in all pre-salt formations.

The majority of seismic data in this basin has been acquired by narrow azimuth (NAZ) towed streamer surveys. These acquisitions offer imaging that is reasonable for understanding the regional geology, but lacks enough range in offset and azimuth to fully-illuminate the complex pre-salt prospects. As a result, velocity model building has relied on involved workflows including layer stripping, multiple passes of reflection tomography, shallow full-waveform inversion (FWI) to update the sediments, top-of-salt (TOS) interpretation, salt-flood migration for base-of-salt (BOS) interpretation, and tests with numerous salt scenarios. This approach is time consuming and susceptible to inaccuracies caused by human misinterpretation (Dellinger et al., 2017).

Ocean-bottom-node (OBN) data contain rich low frequency signal, full-azimuth coverage, and long-offset illumination, which are ideal for building a good velocity model using FWI (Tarantola, 1984). The long offsets allow for deeper penetration of diving waves, which mainly drive the FWI updates. The full azimuth coverage better constrains the inversion and improves its reliability, and the rich low frequency content alleviates some of the inaccuracies of the starting model (Michell et al., 2017; Shen et al., 2017).

Santos Basin data share many of the challenges of Gulf of Mexico data, namely complexity of salt bodies with sharp impedance contrasts and deep targets. Another feature of the Santos Basin is salt stratification. These complex geological features of the Santos Basin bring many challenges for conventional FWI applications, even with OBN data, and a relatively good starting velocity model. Recent applications of time-lag FWI (TLFWI) (Zhang et al., 2018, Wang et al., 2019) in the Gulf of Mexico have shown great potential for salt velocity update and subsalt image improvement in geological settings similar to Santos Basin.

In the following sections, we illustrate the use of TLFWI to build an accurate velocity model with OBN data from the central Santos Basin. Results show valuable improvement compared to NAZ-derived results for model building and pre-salt imaging.

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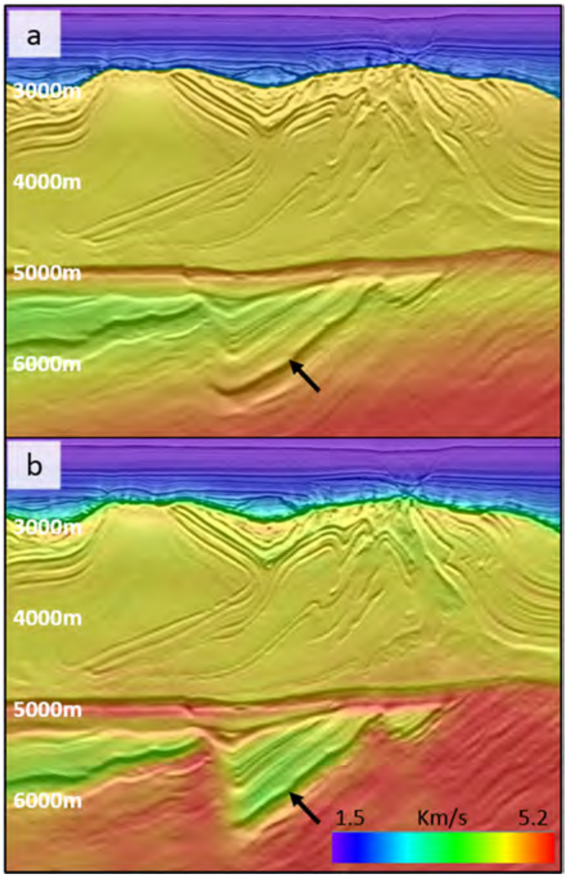

Figure 2: Crossline section with the velocity overlaid on a 45 Hz RTM stack for (a) initial model, and (b) output model from 15 Hz TLFWI.

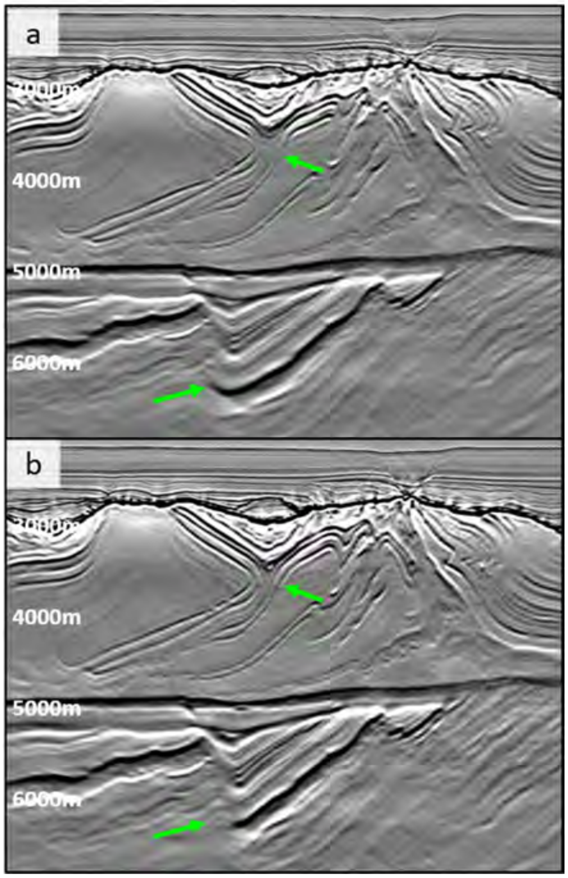

Figure 3: Crossline 45 Hz RTM stack sections for (a) initial model and (b) output model from 15 Hz TLFWI. The arrows point to improvements of imaging after FWI; pre-salt layers are more geologically consistent.

Geology, OBN and FWI

The data set is located in the Santos Basin, south of Rio de Janeiro. It is characterized by a water bottom at ~2 km and a pre-salt reservoir lying around a depth of 5 km. In the post-salt region, a fast Albian layer covers most of the eastern area. Multiple intricate stratification patterns are present within the salt. The pre-salt region is complex with fast carbonates, slow sediments, volcanic layers, and a large fault system.

Approximately 1000 nodes covered the area, with a 400 m by 400 m separation and a shot spacing of 50 m by 50 m. Thanks to the 16 km maximum offset OBN data (Figure 1a), diving-wave ray tracing analysis (Figure 1b) showed adequate diving-wave penetration within the pre-salt layer.

In the presence of sharp velocity contrast like salt, volcanic intrusions or carbonates, FWI can fail for two main reasons: cycle-skipping and amplitude-discrepancy between field and modelled data. Misplaced rapid velocity transitions such as between sediments and salt can induce large timing differences between synthetic and real data beyond the half-cycle criteria, leading FWI to fall into local minima. Furthermore, the amplitude distribution of synthetic data and field data can be very different. This is caused by poorly described changes in density and elastic effects that are not captured accurately with acoustic modelling. Such amplitude changes can be interpreted as velocity errors by FWI, leading to erroneous velocity model updates.

To mitigate these issues and to take full advantage of the properties of OBN data, TLFWI (Zhang et al., 2018) utilizes a traveltime cost function that focuses mostly on the kinematics of the data, thus reducing the sensitivity to amplitude discrepancies. It also uses a frequency-dependent windowing scheme and a cross-correlation based weighting function to better utilize the low-frequency data, where the signal-to-noise ratio (S/N) is often low. These attributes make TLFWI a suitable candidate for Santos Basin geology, particularly for the velocity update of the salt and pre-salt regions.

The potential of FWI

The input to TLFWI is the raw OBN data without any additional preprocessing. The initial velocity model is a smoothed legacy model built using NAZ towed streamer data. TLFWI is used to simultaneously invert for the post-salt, salt, and pre-salt sections. The velocity inversion started from 1.6 Hz and ran up to 15 Hz. The anisotropic models remained unchanged.

Even though the legacy velocity model already provided a reasonable image, the TLFWI velocity update led to structural improvements at the pre-salt level, as shown in Figure 2. The low frequency updates (1.6 to 6 Hz) produced a geologically consistent image, correcting the regional salt velocity, enhancing the BOS, and improving fault definition in the pre-salt by capturing a low velocity layer (black arrow in Figure 2). The high frequency (6 to 15 Hz) updates provided details in the stratified salt, the post-salt, and pre-salt carbonates.

Figure 3 shows a 45 Hz RTM stack from the initial model and after the 15 Hz TLFWI velocity update. The more noticeable changes in imaging after FWI are in the salt and pre-salt (green arrows). Reflectors are more focused and continuous, pre-salt faults are better defined, and resolution below the BOS is improved. Figure 4 displays depth slices, one in the salt and one in the pre-salt, with the initial model (Figures 4a-b) and the 15 Hz TLFWI model (Figures 4c-d). TLFWI captured the intra-salt velocity variation induced by salt stratification, offering a data-driven solution to resolve the salt velocity complexity. The depth slice in the pre-salt section (Figures 4b-d) highlights the lateral velocity variation in the pre-salt. Figures 5a-b show the TLFWI model updates by comparing to available well logs at two locations. The updates reasonably match the low wavenumber part of the sonic logs.

Remaining challenges and discussions

Some issues that we encountered remain challenging for FWI to solve on its own. For this testing, anisotropy was kept unchanged throughout the inversion, as velocity was the major focus. However, this limits the accuracy of the updated model. Figures 6a-b display the velocity and epsilon profiles at a well location for the initial model, the TLFWI updated model and a final model that includes anisotropy updates by tomographic well calibration and TLFWI. In the pre-salt section, comparison to sonic logs shows that the initial anisotropy model used for TLFWI limited its ability

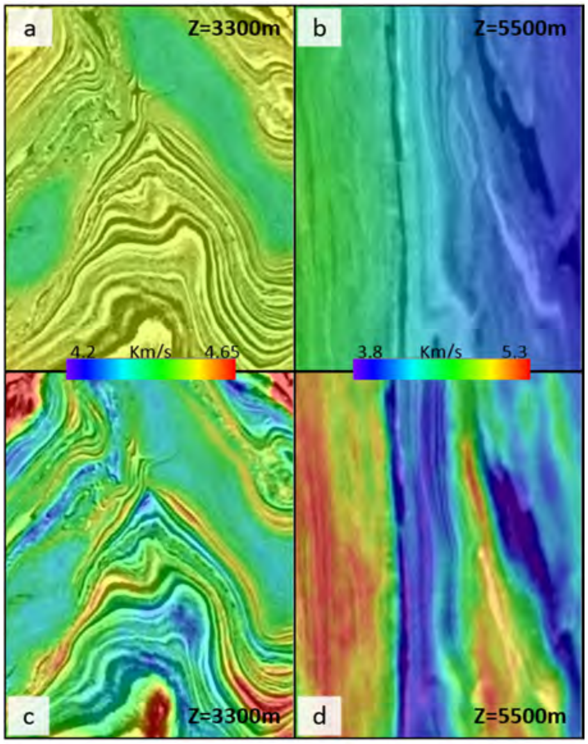

Figure 4: Depth slices, in the salt (3300 m) and pre-salt (5500 m), with the velocity overlaid on Kirchhoff stacks for initial model (a) & (b), and output model from 15 Hz TLFWI (c) & (d).

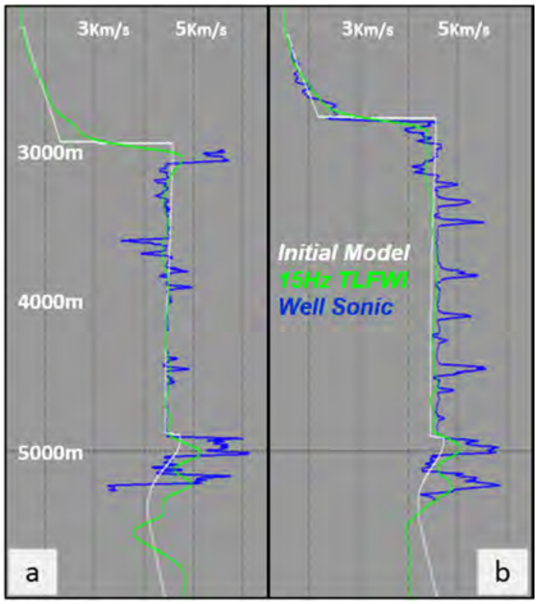

Figure 5: (a) & (b) Velocity profiles at two well locations; blue profile corresponds to the sonic log, white profile to the initial velocity model, and green profile to the 15 Hz TLFWI model.

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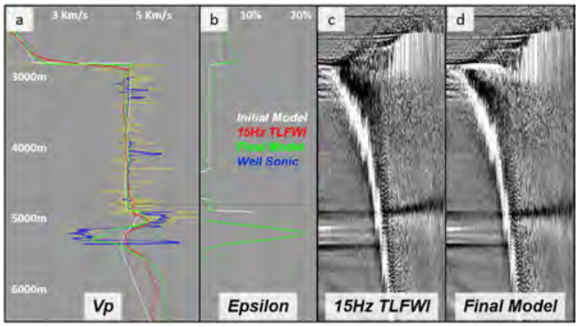

Figure 6: (a) Velocity profiles at a well location: blue profile corresponds to the sonic log, yellow profile to checkshot data, white profile to the initial velocity model, red profile to the 15 Hz TLFWI model, and green profile to the tomographically updated final model. (b) Epsilon profiles at a well location: white profile corresponds to the initial epsilon model and green profile to the updated final epsilon model. (c) & (d) Snail gathers of 12 km offset migrated with the 15 Hz FWI and the final models.

to converge to an accurate solution in the slow velocity layer around 5000 m depth, while the final model with improved anisotropy produced a low-velocity layer that better matches with the sonic log. Figures 6c-d display snail gathers up to 12 km offset at a well location, in which it is clear that the final model, with improved anisotropy, offers flatter events in the post-salt, salt, and pre-salt sections.

In the current state of FWI technology, multi-parameter inversion remains challenging. Prieux et al. (2011) discuss some of the difficulties. More developments are required for FWI to be able to decouple anisotropy and velocity as well as other subsurface parameters. This is an active research field as seen in the work of Da Silva et al. (2016), and Djebbi and Alkhalifah (2019). Joint reflection and refraction inversion using extra-long offsets (>20km) could facilitate the decoupling between anisotropy and velocity terms (Allemand et al. 2017).

The OBN data used here offer rich low frequency signal compared to streamer data. Phase analysis of the OBN data (Figures 7a-b) shows that the signal-to-noise ratio at ~1.6 Hz is relatively low. More reliable signal is present at ~2 Hz. Having this low frequency content as well as a reasonable initial model, our application of FWI was fully data-driven with almost no human intervention. Looking ahead at other areas where good initial models might not be available, FWI only may not be sufficient. In an effort to achieve a fully automatic FWI workflow, Dellinger et al. (2016) performed recent experiments in Gulf of Mexico with an ultra-low frequency source. The low wave-number updates provided in this case may further reduce FWI's reliance on initial velocity models.

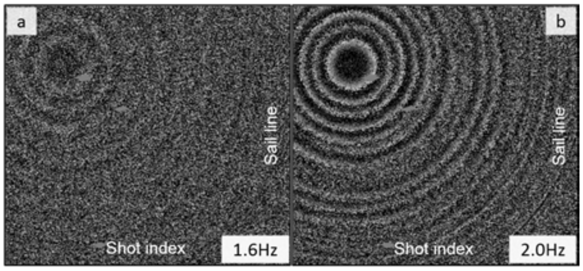

Figure 7: Phase extracted at a) 1.6 Hz and b) 2.0 Hz, for all of the traces of a single OBN receiver gather.

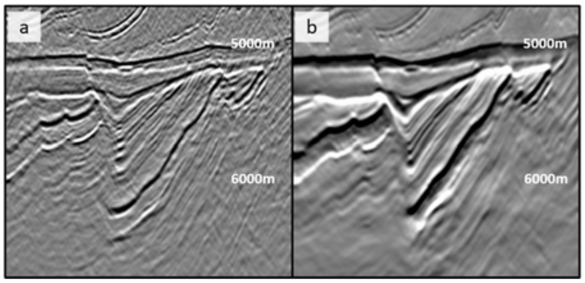

Figure 8: a) Stack of the legacy streamer data migrated with the legacy model, and b) stack of the down-going OBN data migrated with the 15 Hz FWI model.

Even with these remaining challenges, the benefits of OBN data combined with FWI are substantial. Figures 8a-b compare NAZ data migrated with the NAZ-derived legacy model to the OBN data migrated with the OBN-derived FWI model. The comparison is not meant to be fair due to the large difference in the processing sequences of NAZ and OBN data, but is simply demonstrative of the potential benefits that can be provided by OBN data for pre-salt targets in the Santos Basin.

Conclusions

With the benefits of OBN data and a reliable FWI formulation, imaging uplifts are achievable in complex geological settings like the Santos Basin. Having low frequency, long offset and wide azimuth data was a key factor to the successful application of TLFWI in the pre-salt. This offers an impactful data-driven solution for reservoir characterization and interpretation. For more complex geological settings, a good starting model with improved acquisition will be necessary to obtain a similar quality of results. Acquisitions with ultra-low frequencies and ultra-long offsets, combined with a reliable multi-parameter anisotropic FWI will be the main ingredients to obtaining data-driven solution for Santos Basin prospects.

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REFERENCES

Allemand, T., A. Sedova, and O. Hermant, 2017, Flattening common image gathers after full-waveform inversion: The challenge of anisotropy estimation: 87th Annual International Meeting, SEG, Expanded Abstracts, 1410–1415, doi: https://doi.org/10.1190/segam2017-17736527.1.

Da Silva, N. V., A. Ratcliffe, V. Vinje, and G. Conroy, 2016, A new parameter set for anisotropic multiparameter full-waveform inversion and application to a North Sea data set: Geophysics, **81**, no. 4, U25–U38, doi: https://doi.org/10.1190/geo2015-0349.1.

Dellinger, J., A. J. Brenders, J. R. Sandschaper, C. Regone, J. Etgen, I. Ahmed, and K. J. Lee, 2017, The Garden Banks model experience: The Leading Edge, **36**, 151–158, doi: https://doi.org/10.1190/tle36020151.1.

Dellinger, J., A. Ross, D. Meaux, A. Brenders, G. Gesoff, J.T. Etgen, J. Naranjo, G. Openshaw, and M. Harper, 2016, Wolfspar®, an "FWI-friendly" ultralow-frequency marine seismic source: 86th Annual International Meeting, SEG, Expanded Abstracts, 4881–4885, doi: https://doi.org/10.1190/segam2016-13762702.1.

Djebbi, R., and T. Alkhalifah, 2019, Frequency domain multiparameter acoustic inversion for transversely isotropic media with a vertical axis of symmetry: Geophysics, **84**, no. 1, C1–C14, doi: https://doi.org/10.1190/geo2017-0564.1.

Michell, S., X. Shen, A. Brenders, J. Dellinger, I. Ahmed, and K. Fu, 2017, Automatic velocity model building with complex salt: Can computers finally do an interpreter's job?: 87th Annual International Meeting, SEG, Expanded Abstracts, 5250–5254, doi: https://doi.org/10.1190/segam2017-17778443.1.

Prieux, V., R. Brossier, Y. Gholami, S. Operto, J. Virieux, O. I. Barkved, and J. H. Kommedal, 2011, On the footprint of anisotropy on isotropic full waveform inversion: The Valhall case study: Geophysical Journal International, **187**, 1495–1515, doi: https://doi.org/10.1111/j.1365-246x.2011.05209.x.

Shen, X., I. Ahmed, A. Brenders, J. Dellinger, J. Etgen, and S. Michell, 2017, Salt model building at Atlantis with full waveform inversion: 87th Annual International Meeting, SEG, Expanded Abstracts, 1507–1511, doi: https://doi.org/10.1190/segam2017-17738630.1.

Tarantola, A., 1984, Inversion of seismic reflection data in the acoustic approximation: Geophysics, **49**, 1259–1266, doi: https://doi.org/10.1190/1.1441754.

Wang, P., Z. Zhang, J. Mei, F. Lin, and R. Huang, 2019, Full-waveform inversion for salt: A coming of age: The Leading Edge, **38**, 204–213, doi: https://doi.org/10.1190/tle38030204.1.

Zhang, Z., J. Mei, F. Lin, R. Huang, and P. Wang, 2018, Correcting for salt misinterpretation with full-waveform inversion: 88th Annual International Meeting, SEG, Expanded Abstracts, 1143–1147, doi: https://doi.org/10.1190/segam2018-2997711.1.

10.1190/segam2019-3215027.1