Mitigating Structural Uncertainty: Early Insights from OBN FWI Imaging - A Santos Basin Case Study

Abstract

Full Waveform Inversion (FWI) yields high-fidelity velocity models for enhanced seismic imaging in complex geological settings. FWI-Derived Reflectivity (FDR) offers rapid subsurface reflectivity reconstruction with improved illumination and turnaround over conventional methods. In structurally complex areas, high-quality seismic data are crucial for FWI. Ocean Bottom Node (OBN) data—characterized by rich low-frequency content, long offsets, and broad azimuth coverage—significantly enhances the resolving power of Full Waveform Inversion (FWI) for building accurate velocity models. The resulting FDR images exhibit higher resolution and improved illumination, providing clearer imaging and reduced structural uncertainty compared to Multi-Azimuth (MAZ) datasets, and enabling more reliable geological interpretation. This Santos Basin case study highlights a significant reduction in structural uncertainty by integrating OBN data with an FWI imaging workflow.

Introduction and Geological Setting

The Santos Basin, a major offshore hydrocarbon province in southeastern Brazil, has been a focal point for pre-salt exploration since the early 2000s. These deepwater reservoirs—located around 5 km below the seabed beneath 2 km of water and thick salt layers—pose significant imaging challenges due to complex pre-salt geology and the distorting effects of the overburden, caused by the large lateral velocity variations in the post-salt mini basins, salt thickness and intra-salt heterogeneity. High-resolution seismic imaging is therefore critical for accurate characterization of these complex carbonate reservoirs.

This case study is from a key ultra-deepwater development located in the Santos Basin. The field consists of elongated structural traps at the base of salt with thinning sedimentary sequences towards the apex. Its heterogeneous carbonate reservoirs, composed of karst-modified mounds at these structural highs, require detailed understanding for effective management. A key challenge is the substantial structural uncertainty caused by the thick overlying salt, which degrades seismic data and hinders accurate imaging of faults, horizons, and reservoir geometry.

Legacy MAZ reprocessing

In 2021, a Multi-Azimuth (MAZ) reprocessing project aimed to generate a more accurate and reliable subsurface image, particularly within the complex pre-salt formations and at the reservoir level, to reduce structural uncertainties. This project integrated data from three narrow-azimuth (NAZ) acquisitions (oriented NW-SE at 123°, a similar orientation at 158°, and E-W) and one full-azimuth (FAZ) acquisition acquired in 2011 using a coil method. Despite these reprocessing efforts, persistent structural uncertainties remain within the area of interest, especially at the reservoir level. These challenges are fundamentally rooted in the basin's inherent geological complexity, complicating the development of an effective velocity model capable of significantly reducing exploration uncertainty.

Recent Ocean Bottom Node (OBN) Survey Acquisition

To overcome limitations of legacy data, a high-density Ocean Bottom Node (OBN) seismic survey was acquired in 2024. This survey used a variable orthogonal receiver grid optimized for subsurface sampling. In the main area, receiver lines (IL) were spaced at 466 m with 538 m receiver spacing (XL), while coverage expanded with 932 m (IL) and 1076 m (XL) spacing in the outer area. A triple source array with 48 m separation fired at a dense 17.33 m shot point interval for high fold and illumination. This geometry provided consistent ~12 km offset coverage across all azimuths and up to ~32 km inline, crucial for robust velocity model building and FWI.

FWI beyond velocity

While FWI is primarily used to build high-resolution subsurface velocity models, these accurate models can also be directly leveraged for superior seismic imaging, a process known as FWI Imaging (Wang et al., 2021). A common and efficient approach to generate an FWI image, frequently referred to as FWI-Derived Reflectivity (FDR), involves computing the spatial gradient or divergence of the FWI velocity model. This resulting image approximates a conventional migrated seismic section, with amplitudes corresponding to acoustic impedance contrasts. The benefits of FWI imaging are significantly amplified when combined with advanced seismic acquisition techniques such as OBN data, which provide rich low-frequency content and broad subsurface illumination.

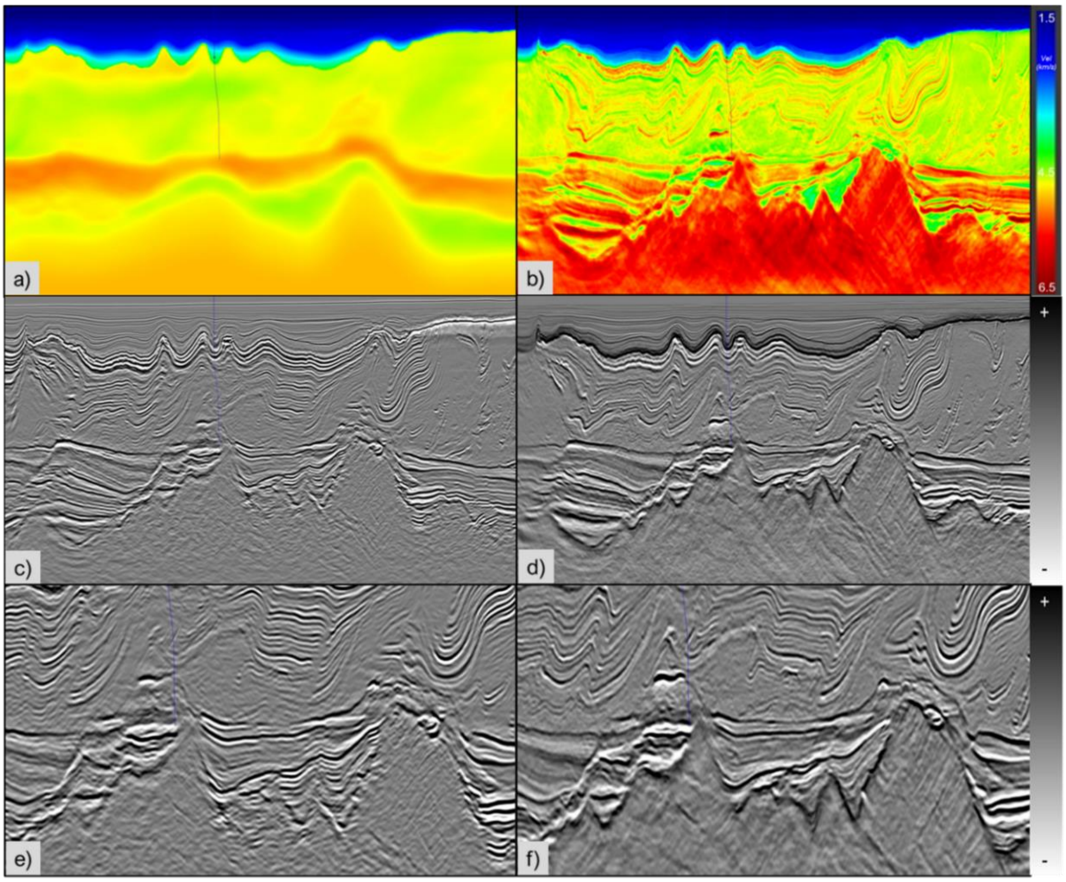

Figure 1: FWI beyond velocity. Vp model from a) legacy MAZ reprocessing and b) OBN 30 Hz acoustic FWI. The Vp model in a) was used to produce the final 30 Hz RTM shown in c) and e) for a full section and a zoomed pre-salt section, respectively, in the legacy MAZ project. The 30 Hz FWI model in b) was used to generate the FDR images shown in panels d) and f).

Early insights from OBN FWI Imaging

To rapidly gain early insights into the pre-salt structures using the newly acquired OBN data, a fast turnaround acoustic FWI imaging product was prioritized, employing a Dynamic Matching FWI (DM FWI) algorithm (Mao et al., 2020; Sheng et al., 2020). DM FWI uses multidimensional local cross-correlation to maximize the similarity between observed and dynamically matched synthetic seismic data, reducing sensitivity to noise and amplitude discrepancies through local amplitude normalization. Leveraging this robust DM FWI approach with the rich low-frequency and long-offset content of the OBN dataset, our efficient workflow initiated at 2.5 Hz. The strategy focused initially on quickly updating the background sediment velocity and reconstructing key salt geometries using the sensitivity of refracted and diving waves. Subsequent iterations exploited the full wavefield to refine the velocity model and improve resolution up to 30 Hz. This accelerated workflow was crucial for delivering a timely product for interpretation of the pre-salt architecture.

The enhanced fidelity and resolution achieved through the application of OBN FWI are illustrated in Figure 1, which compares the velocity (Vp) model derived from legacy MAZ reprocessing (Figure 1a) with the Vp model obtained from the OBN 30 Hz acoustic FWI (Figure 1b). While the legacy MAZ Vp model (Figure 1a) was utilized to generate the final 30 Hz RTM images, presented as a full section (Figure 1c) and a close-up in the pre-salt zone (Figure 1e), the higher-quality OBN 30 Hz FWI velocity model (Figure 1b) enabled the creation of FDR images shown in Figure 1d and Figure 1f. Notably, these resulting FDR images exhibit superior subsurface illumination and a substantial increase in resolution, leading to a marked improvement in the imaging of both intra-salt and crucial pre-salt structural elements. Figure 2 further demonstrates the effectiveness of FDR in mitigating structural uncertainty. Compared to legacy MAZ RTM inline (2a) and crossline (2b) sections, corresponding FDR sections (2c, 2d) reveal a significantly improved definition of fault systems and a clearer termination of steeply dipping pre-salt beds. Figure 3 highlights another advantage of OBN FWI in a pre-salt depth slice. The FDR image (3b) provides better continuity and termination of reflectors with a higher signal-to-noise ratio and fewer imaging artifacts than the legacy MAZ RTM depth slice (3a), resulting in a cleaner and more interpretable image.

Conclusions

This case study demonstrates a significant advancement in our ability to image and understand the structurally complex pre-salt formations of the Santos Basin through the application of OBN-based FWI imaging. The resulting FDR volumes provide a substantial uplift in image quality compared to those derived from legacy MAZ reprocessing, revealing previously obscured details in both the overburden salt and the underlying carbonate reservoirs. The improved definition of key structural elements directly contributes to a reduced level of structural uncertainty, facilitating more accurate geological interpretations and ultimately supporting better-informed decisions regarding exploration, appraisal, and production activities in this challenging deepwater setting. The efficiency of the fast turnaround workflow further emphasizes the practical benefits of integrating OBN data with advanced FWI imaging techniques for rapid subsurface evaluation.

Acknowledgments

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References

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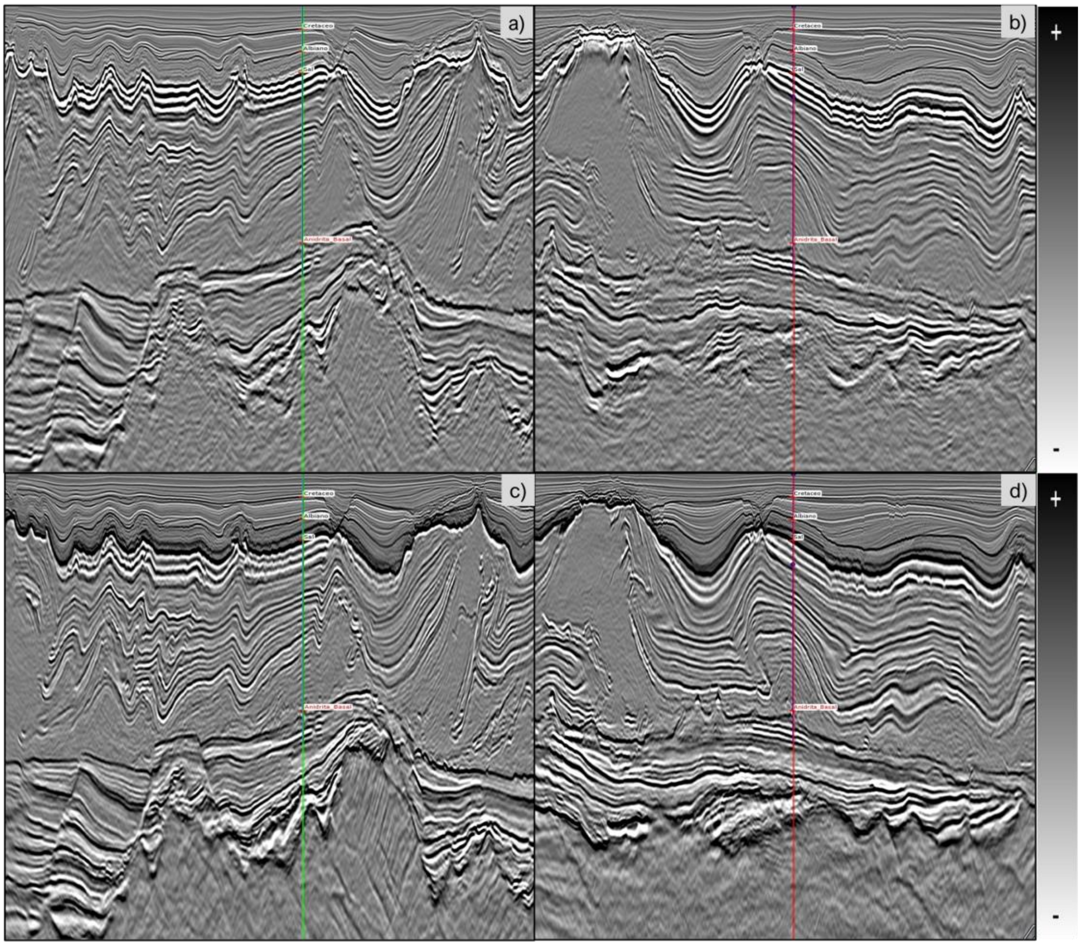

Figure 2: Mitigating Structural Uncertainty. 30 Hz RTM from legacy MAZ volume for a) an inline section and b) a crossline section. 30 Hz FDR for corresponding a) inline and b) crossline section.

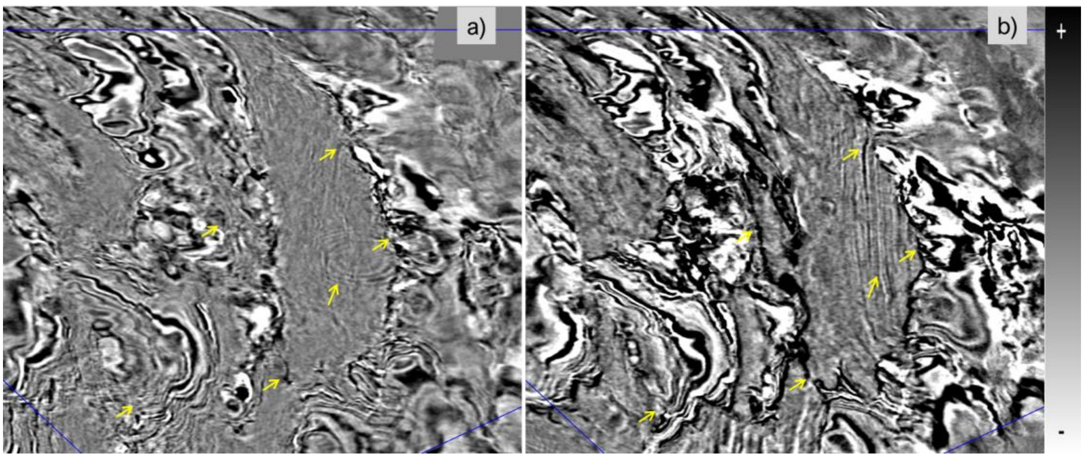

Figure 3: Mitigating Structural Uncertainty. a) Depth slice section in the pre-salt of 30 Hz RTM from legacy MAZ volume. b) the corresponding depth slice in 30 Hz FDR.