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Unravelling Structural Complexities with High Resolution Imaging in Santos Sul 3D Survey

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Abstract Summary

The Santos Basin has proven to be a highly prolific basin over the past few decades, with extensive exploration activities leading to the drilling and production of numerous wells. The Santos Sul 3D seismic survey is situated in the southernmost, and less explored region of the basin (Figure 1). Although this area is generally characterized by reduced structural complexity due to the relative absence of extensive salt bodies, high resolution imaging has remained as challenging. Key geological and geophysical challenges include water-bottom canyons, near-surface mass transport complexes (MTCs), polygonal faulting, carbonate build-ups, salt "fingers", and deep-seated volcanic intrusions.

To address these challenges, we propose an integrated velocity model building workflow incorporating information from the underlying legacy 2D seismic data, anisotropy calibration, tomographic inversion, and Dynamic Matching Full Waveform Inversion (DM FWI). The application of this approach has resulted in significant improvements in imaging quality, both in shallow and deep sections, including enhanced resolution of sub-basement structures.

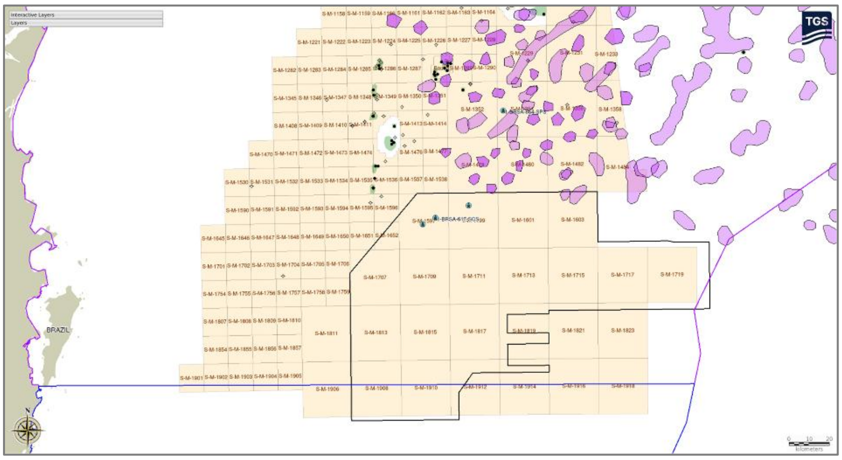

Figure 1: Map of Santos Sul 3D survey outline (black), Santos Basin outline with salt features (purple), and Pelotas Basin outline (blue).

Introduction

The Santos Sul 3D seismic survey was acquired using a configuration of 12 to 14 dual-component streamers spaced at 112.5 meters, with a maximum offset of 8 kilometers. A triple-source array deployed at a depth of 9 meters, combined with receiver depths of 20 meters, facilitated the acquisition of high-fidelity seismic data. The dataset underwent AVO-compliant broadband processing, incorporating wavefield separation, source deghosting, directional designature, 3D surface-related multiple elimination (SRME), and 4D regularization.

Dynamic Matching Full Waveform Inversion (DM FWI) has demonstrated significant potential as a velocity model updating methodology. Mao et al. (2020) illustrated its effectiveness on datasets characterized by long offsets and wide azimuth coverage. Recent studies by Yong et al. (2023)

have shown that DM FWI can still yield high-quality results even when applied to suboptimal datasets in terms of maximum offset and azimuthal coverage.

Geologic Setting

The survey area is situated north of the Florianópolis Fracture Zone and south of the main salt province in the Santos Basin. Seismic imaging indicates significant early-stage crustal deformation affecting the magmatic basement, which serves as the economic basement in this region (Reuber et al. 2025, submitted). During Albian, carbonate platforms developed in a shallow marine environment under thermally buoyant lithospheric conditions. As the margin transitioned into thermal subsidence, sedimentation shifted toward the accumulation of predominantly clastic deposits. Exploration efforts in the area are primarily targeting Upper Cretaceous (Aptian) turbidite fan systems along with Middle Cretaceous (Albian) source rocks.

Methodology

The full-depth imaging workflow for the Santos Sul 3D survey involved a series of steps to generate a high-fidelity depth-migrated seismic volume. An initial depth velocity model was constructed using a regional 2D seismic data library, supplemented by interpreted major geological horizons such as water bottom, top of Cretaceous (top K) and regional basement surface. This foundational dataset was instrumental in capturing regional velocity trends and establishing a more geologically consistent starting interval velocity model. Temperature-salinity (TS) dip measurements conducted in the water column during acquisition enabled derivation of an average water velocity function, providing additional calibration for the near-surface velocity field.

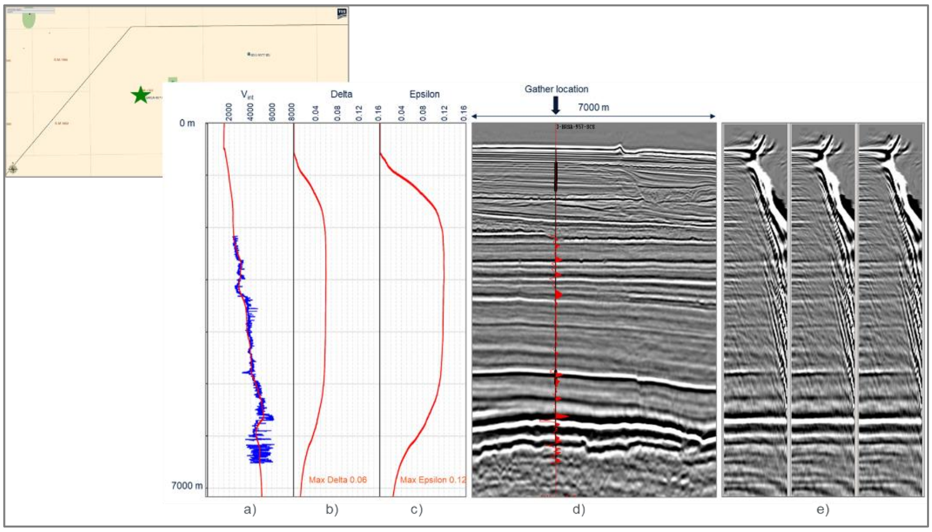

Figure 2: Well 3-BRSA-957-SCS (location marked with green star) with a) sonic (blue curve) and calibrated velocity (red curve), b) calibrated delta, c) calibrated epsilon, d) stack with well location and synthetic, and e) gathers after calibration at the well location.

Three wells located in the northern portion of the survey area (1-BSS-0077-BS, 1-BRSA-617-SCS, and 3-BRSA-957-SCS) facilitated pre-inversion anisotropy calibration. The partially overlapping TGS Picanha 3D survey was also leveraged to calibrate Thomsen anisotropic parameters, specifically delta (δ) and epsilon (ε), at well control points (Figure 2). Once the entire Santos Sul 3D seismic data was acquired and became available, validation was performed by comparing the modeled velocities to sonic logs, assessing the alignment between synthetic seismograms and stacked seismic data, and evaluating gather flatness at farther offsets. The calibrated δ and ε fields were then spatially propagated along key stratigraphic markers including the water bottom, Top K, and basement horizons.

Detailed analysis of gather flatness across the survey revealed the necessity of introducing a spatially variable epsilon field, with values ranging from a maximum of 5.9% in the western part of the survey to 6.8% in the east. This spatial variability was critical in achieving optimal seismic imaging across the full survey area.

Following the generation of the initial velocity model, two iterations of Tilted Transverse Isotropy (TTI) tomographic inversion were performed, along with final iteration targeting deep velocity updates at the basement level and below. These updates enhanced the accuracy of the model prior to the application of Dynamic Matching Full Waveform Inversion (DM FWI) in TTI mode.

DM FWI was conducted in four frequency bands, with a final maximum frequency of 12 Hz. This frequency threshold enabled the resolution of kinematic details and improved imaging of a wide range of geological features that would have otherwise remained unresolved at lower frequencies.

Results

Push-downs (or structural sags) caused by water-bottom canyons have been effectively resolved following the application of DM FWI, resulting in a marked improvement in the imaging of subsurface geological structures. Post-velocity update, gathers exhibit increased flatness, indicating enhanced velocity model accuracy, which translates into structurally conformant geologic horizons. Figure 3 illustrates a comparative example of stacked seismic images and corresponding offset gathers before and after the application of DM FWI.

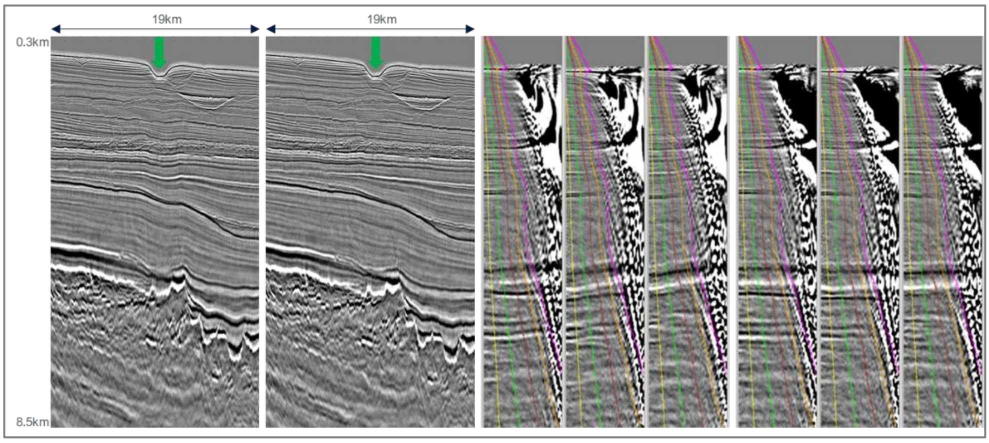

Figure 3: Stacks and gathers (location marked with green arrow) before (left) and after (right) DM FWI updates. Angles displayed on gathers are for reference and the range is from 10 – 50 degrees in increment of 10 degrees.

Mass transport complexes (MTCs) observed across most of Santos Sul survey area, represent large-scale sedimentary accumulations generated by submarine landslides and gravity-driven depositional processes. These MTCs significantly influence basin morphology and have implications for hydrocarbon prospectivity. From the velocity model building standpoint, MTCs are characterized by rapid lateral velocity variations. If inadequately captured in velocity model, these heterogeneities can introduce localized structural distortions in deeper sections. The application of DM FWI has proven effective in resolving these features, thereby improving imaging fidelity.

In the northeastern sector of the survey, two prominent salt diapirs mark the southernmost extent of the Santos Basin salt province. These diapirs define a mini-basin configuration, with carbonate accumulations observed onlapping the salt flanks. The eastern salt structure, in particular, is characterized by carbonate bodies draping over salt fingers and flanks. The velocity model construction followed a conventional sequence involving TTI sediment tomography, top salt horizon picking, salt flooding, and base salt delineation. DM FWI was initiated using a smoothed tomography-derived velocity model (500 m smoothing in all three spatial directions) with soft salt boundaries. The inversion was conducted using four frequency bands, progressively increasing up to a maximum of 12 Hz under a TTI assumption. Incorporating accurate carbonate velocities prior to the DM FWI stage was critical. A comparative analysis before and after DM FWI demonstrates significant enhancements in salt body definition, including improved delineation of salt flanks, identification of internal salt fingers, and clearer imaging of the base of salt and underlying pre-salt structures (Figure 4). These details in salt definition would not be possible with classic salt interpretation workflow and can be attributed to robust DM FWI updates.

The deeper sections of the Santos Sul survey area exhibit evidence of volcanic activity, manifested as volcanic calderas, necks, sills, and dikes (Reuber et al, 2025, submitted). These features are now imaged with improved clarity due to high-resolution velocity updates. Given their depth range (~5.0–6.5 km) and the maximum seismic offset limitation (8 km), it is evident that these updates stem predominantly from the reflection wavefield component of DM FWI, as diving waves do not reach such depths.

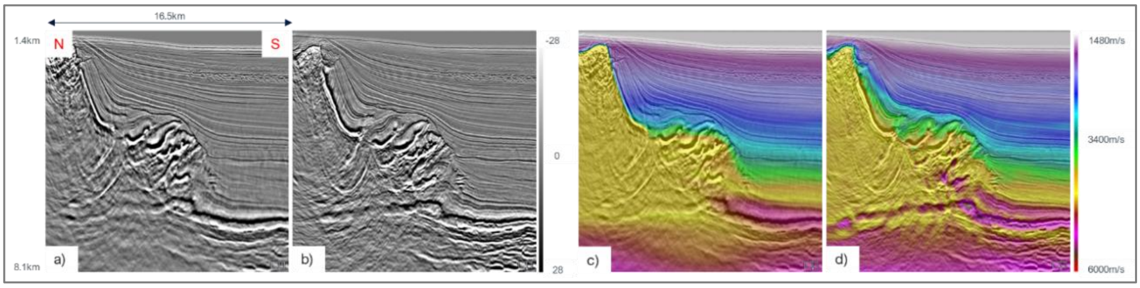

Figure 4: a) KPSDM (75 Hz) stack after TTI tomographic updates, b) KPSDM (90 Hz) stack after DM FWI updates, c) KPSDM (75 Hz) stack after TTI tomographic updates with velocity overlay, and d) KPSDM (90 Hz) stack after DM FWI updates with velocity overlay.

Conclusions

Anisotropic velocity model building, incorporating a tilted transversely isotropic (TTI) framework and leveraging Dynamic Matching Full Waveform Inversion (DM FWI) as the principal inversion engine, resulted in a seismic image that exhibits excellent correlation with well control in the northern portion of the survey area. This alignment with well data enhances confidence in the depth accuracy across the broader survey extent. The comprehensive and robust velocity model building workflow effectively resolved geologically complex structures, leading to significant improvements in seismic image continuity, structural coherence, and interpretability.

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