Imaging complex geology offshore Angola through integration of one-sided WAZ acquisition, low frequency sources and Elastic DMFWI model building

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Summary

While parts of the Lower Congo Basin offshore Angola have mature plays, deeper sub-salt and pre-salt frontier opportunities remain underexplored, mainly due to imaging challenges caused by complex salt. This makes high-resolution imaging critical for prospect de-risking.

A recent Narrow Azimuth (NAZ) 3D multi-client survey across Blocks 33, 49, and 50 using one-sided wide-azimuth (WAZ) streamer configuration, low-frequency sources combined with an Elastic Dynamic Matching Full Waveform Inversion (E-DMFWI) workflow enabled robust velocity model building yielding improved subsalt imaging despite offset limitations. Using elastic modeling combined, we achieved a reasonable uplift in imaging quality in the post-salt and sub-salt by refining carbonate and salt geometries.

The integrated solution discussed in this paper provided an efficient solution for early-stage exploration in Angola's salt provinces, paving the way for future discoveries and reinforcing Angola's role as a key energy hub in West Africa.

Introduction

In 2025 a 3D Multiclient acquisition and imaging project was acquired in an exploration setting offshore Angola where no 3D legacy imaging existed. It spans over blocks 33, 49, and 50, with a total survey area of 8,681 km^2. The project was designed to address complex subsurface challenges associated with salt structures by using advanced acquisition technology (multi-sensor streamers and low frequency sources) in a hybrid NAZ and one-sided WAZ streamer configuration (Figure 1) while deploying modern earth model building technology such as elastic full waveform inversion.

Acquisition was conducted using twelve multi-sensor 10 km cables spaced 150 meters apart, two low-frequency triple sources ($3 \times 8{,}000$ in^3). One source was located behind the streamer boat and another behind the source boat roughly 5 km down the cable and 800m to the side (Donaldson *et al.*, 2024 and Widmaier *et al.*, 2025). This allowed for acquisition of data orthogonally to the survey direction at the same time as the nominal direction. The bin size was 6.25 meters inline by 25 meters crossline, with an east–west line azimuth optimizing spatial resolution for imaging steeply dipping structures and complex salt geometries present in those blocks.

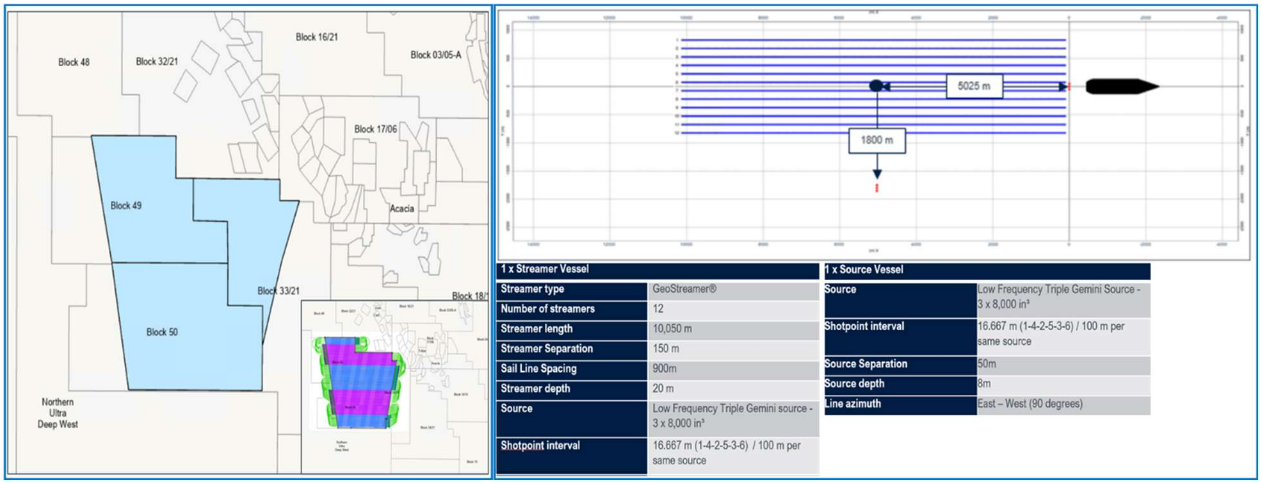

Figure 1: Survey location map (left) and acquisition geometry (right)

Geological overview and petroleum system

The Lower Congo Basin offshore Angola (Figure 2) is a rifted passive margin formed during the Early Cretaceous breakup of Gondwana. Initial syn-rift half-grabens filled with continental clastic and lacustrine facies were later overlain by marine shales and carbonates during post-rift subsidence. A regionally extensive Aptian salt acts as a major detachment surface driving basin-scale gravitational gliding and genesis of the subsequent extensional, translational, and compressional domains. The post-salt region developed when huge amounts of Oligo-Miocene clastic sediments flowed quickly from the Congo River, creating layers as thick as 7 km and forming a widespread deepwater turbidite fan system. This system now serves as the main reservoir suite and also caused the salt to shift, shaping the allochthonous salt bodies (Marton, *et. al.*, 2000).

Accurate mapping of the salt framework is critical for evaluating the petroleum system as the salt tectonism is at the origin of many complex trap geometries found in the basin, particularly around salt flanks and in sub-allochthonous salt settings. A Neogene deepwater turbidite fan system forms the primary reservoir suite, characterized by stacked channel complexes and basin-floor fans with significant heterogeneity and are controlled by salt-related structural segmentation. The main source rock is a pre-salt lacustrine shale, charging both pre-salt and post-salt reservoirs. Finally, hydrocarbon migration and trap integrity are also dependent on salt tectonics and depositional architecture, making high-resolution seismic imaging and advanced processing critical for exploration and prospect derisking. While the Oligo-Miocene play is mature, deeper post-salt and pre-salt petroleum systems remain underexplored, offering future potential.

Our study area can be subdivided into three distinct salt domains (Figure 2) based on structural style and depositional context: 1) The simple salt diapir province (East) features NW–SE trending salt walls compressed between elongated post-salt basins characterized by prominent salt diapirs. It contains the thickest Cenozoic section, indicating significant post-salt accommodation. 2) The Salt-Suture province (central) is defined by apical suture lines seen on the Top Salt map. This domain exhibits major shortening of the Cretaceous section and associated mini basins. Salt suturing occurs near diapir crests because of intense compression. 3) Lastly, the Salt nappe province (West) is characterized by inflated salt that has been expelled basin-ward across a fault step onto oceanic crust, creating an extensive salt sheet or nappe. Its distal edge marks the limit of salt advance, halted by sediment accumulation in the peripheral basin.

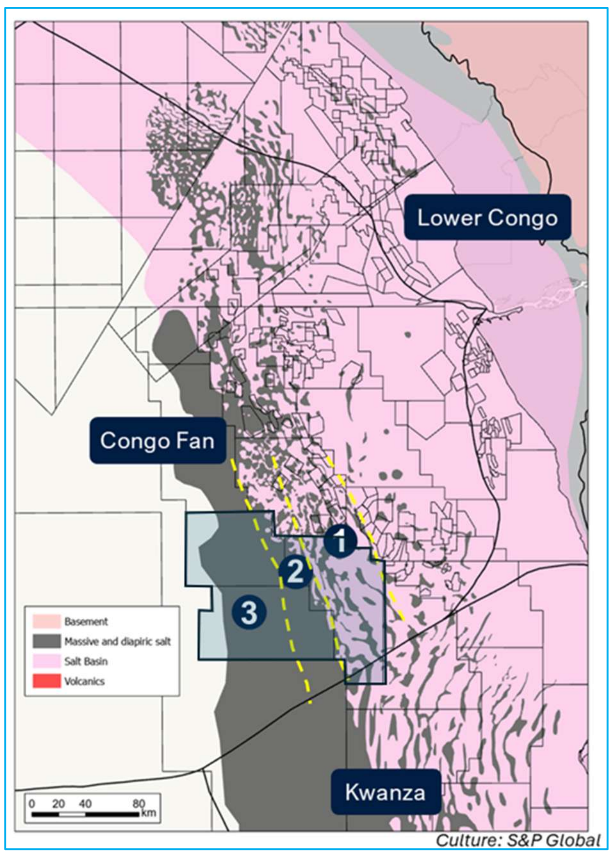

Figure 2: Salt domains (1, 2 and 3) based on structural style and depositional context over the survey area

Acquisition Design and Inversion Synergy

The adoption of a hybrid NAZ and one-sided WAZ streamer acquisition geometry—utilizing multi-sensor streamers and low-frequency triple sources—enabled efficient data acquisition for the exploration survey. This configuration provided enhanced subsurface illumination and improved spatial and temporal resolution, both of which are essential for accurately imaging complex salt structures prevalent in the study area. In comparison, an Ocean Bottom Node (OBN) survey could deliver similar imaging benefits but would require substantially higher costs and operational complexity, particularly in early-stage exploration scenarios where economic efficiency is critical.

Incorporating one-sided WAZ shots into the Full Waveform Inversion (FWI) workflow further improved the overall imaging outcome. These additional azimuths increased subsalt illumination, especially in regions beneath salt overhangs where coverage from standard streamer geometries is limited. The inclusion of these shot points in FWI contributed to better-constrained velocity model updates in structurally complex areas, supporting a more reliable characterization of the subsurface. Figure 3 highlights the improvements on images and CDP gathers with the yellow arrows.

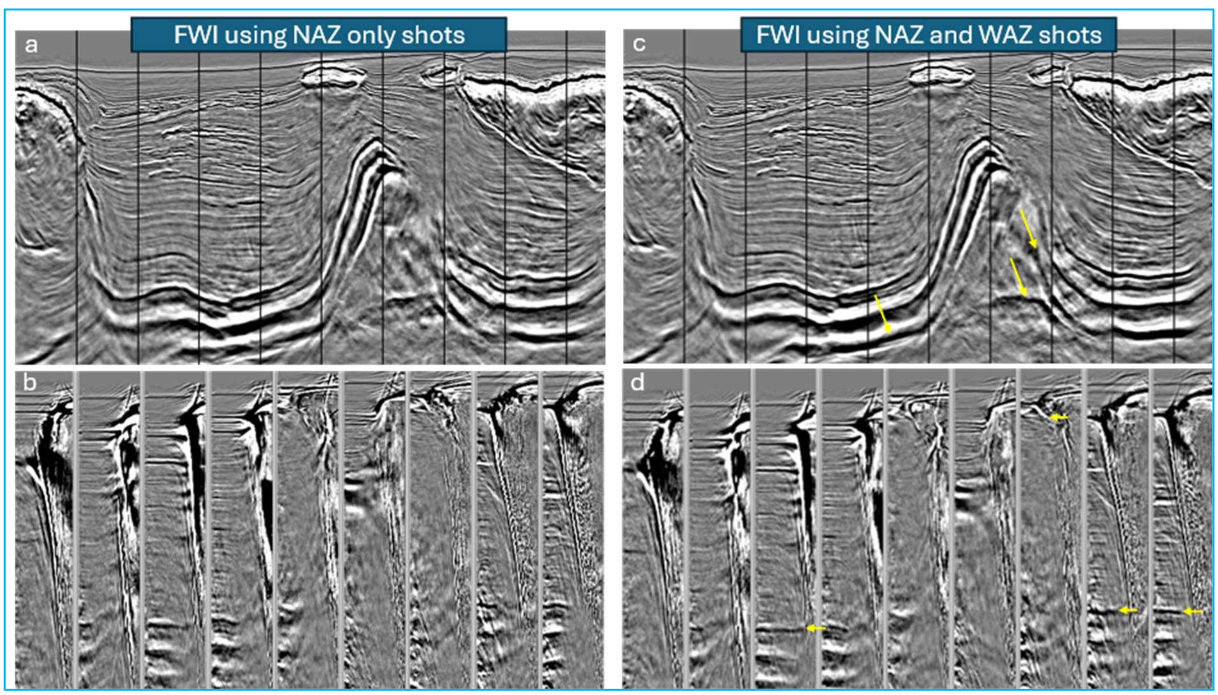

Figure 3: image and gathers after FWI using NAZ shots only (a) and (b) respectively, versus image and gathers after FWI using both NAZ and WAZ shots (c) and (d).

The deployed energy source has large single chamber of 8000 in^3. It provides extended low frequency without compromising the high frequency needed for high-resolution imaging. Because it is not an array of guns with various volumes (Figure 4), it is considered as point source up to 128Hz. As industry practice, FWI uses an inverted 1D wavelet per each input survey and usually uses minimally processed data under the assumption of low source directionality effects at the low frequency bands. Therefore, using these single-point sources fit into the 1D wavelet assumption of the FWI, besides the low frequency gain needed to stabilize the inversion. These directionality effects are phase and amplitude and if not corrected for, it may translate incorrectly to velocity information under the 1D wavelet assumption for relatively higher inversion frequency bands.

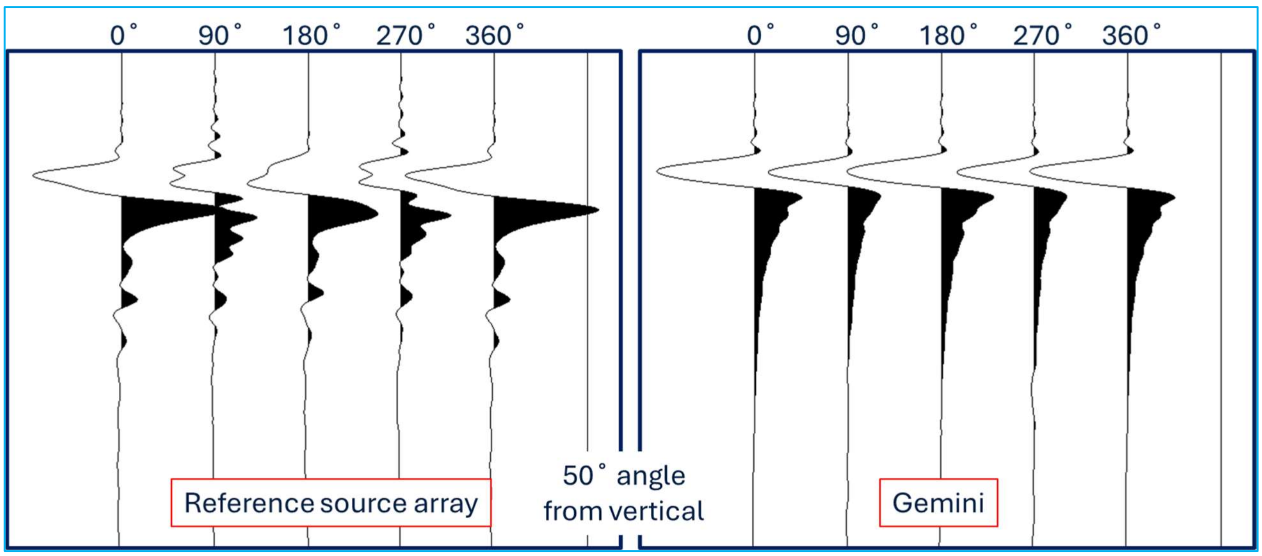

Figure 4: Modeled source wavelets for reference source array (left) and the extended low frequency source used in this project (right). Notice the similarity of all the modeled wavelets in all directions in the Gemini case compared to the reference array.

Velocity Model Building overview and results

Briefly, our data-driven elastic FWI VMB workflow (Figure 6), consists of three interconnected elements: a fit for purpose initial model, E-DMFWI and geological QCs and inversion guided interpretation of the salt framework for continuous iteration towards a robust model.

To capture true subsurface physics, we use elastic modeling to effectively capture phase changes across angles and azimuth where the acoustic assumption breaks down. Furthermore, to take full advantage of the elastic modeling we calibrated our elastic relationships using neighboring wells (Figure 5), so our model remains geologically grounded.

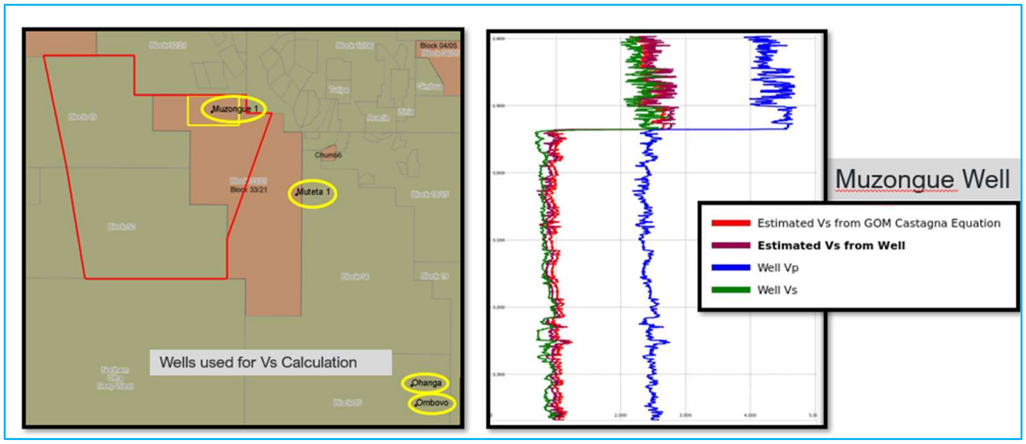

Figure 5: Well calibration of the Vp/Vs relationship

The initial water column velocity model was developed by scaling the average TSDip profile. A preliminary sediment model was subsequently generated through regularization and interpolation of 2D velocity profiles across the area, followed by three-dimensional smoothing. Further refinement involved three iterations of tomographic processing to resolve medium-wavelength velocity anomalies down to 2 km depth. Due to the absence of well data for deeper sedimentary basins, the legacy anisotropy function was applied and referenced from the water bottom horizon. This framework constituted the pre-FWI sediment background model used in the interpretation of the top of salt. To expedite impactful preliminary results, an initial salt body, featuring provisional overhangs, and the regional base of salt were interpreted from a single salt flood. A smoothed version of this complete salt velocity model, combined with the sediment background, served as the input for the first sequence of elastic FWIs, which spanned frequencies from 3 Hz to 6 Hz and utilized both NAZ and WAZ data to enhance illumination of salt geometries.

The initial E-DMFWI sequence, applied up to 6Hz, established the foundational background velocity essential for accurate kinematic modelling of the data. Insights gained from this phase guided a revision of the salt framework, which informed the development of an updated model for the subsequent E-DMFWI sequence (up to 12Hz). This iterative approach enabled further refinement of critical geological features, including salt and carbonate bodies, thereby improving structural imaging and enhancing the resolution of the velocity model. The aim was to perform kinematic adjustment to the post salt sediment model and more importantly to establish in a data driven way a robust salt geometry yielding the model used for the Fast-Track imaging.

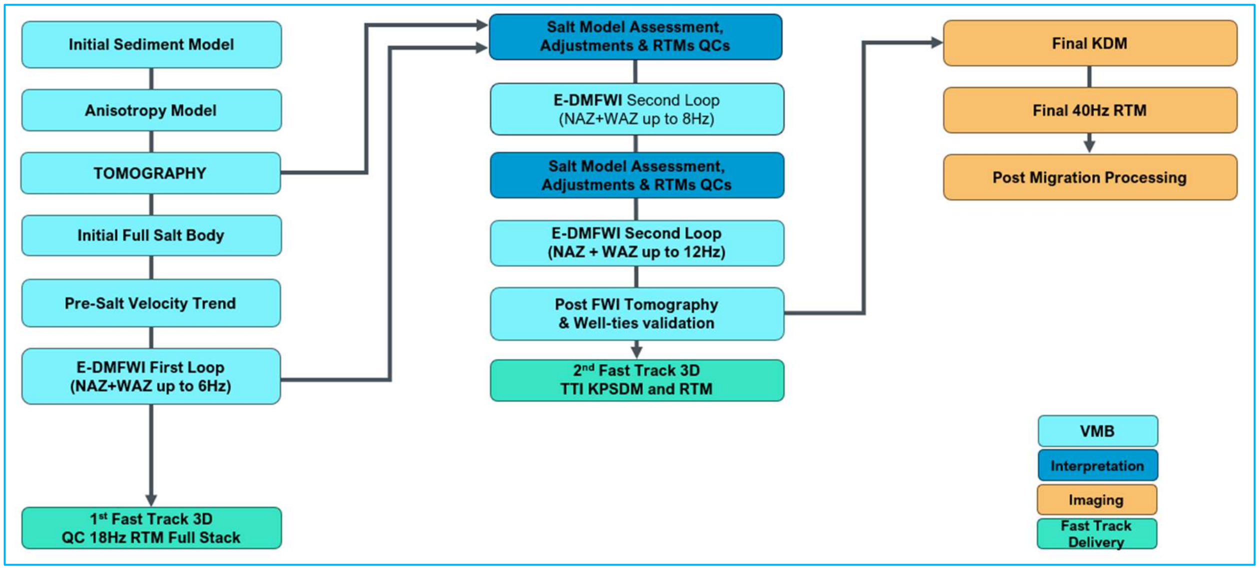

Figure 6: Velocity Model Building and Imaging workflow

In tandem with the accelerated completion schedule, scenario testing informed by inversion outcomes, incorporating additional salt and overhang floods, was undertaken within the central salt province's most complex survey areas. Insights gained from these scenarios were integrated into the salt framework developed during the initial phase of E-DMFWI. This process resulted in the formulation of an updated salt model, which was applied in the second and final E-DMFWI sequence, operating across frequencies ranging from 1.5 Hz to 12 Hz. The work remains underway as part of the full integrity project track; however, preliminary comparisons (see Figure 7) already highlight the influence of the adopted E-DMFWI VMB methodology.

The results indicate that, notwithstanding offset constraints, E-DMFWI has effectively enhanced the delineation of carbonate and salt geometries within the velocity models by utilizing the full wavefield down to depths of 5 km. This approach facilitated robust updates reliant solely on reflection data, extending to the regional base of salt or basement, thereby substantially improving imaging quality at those depths.

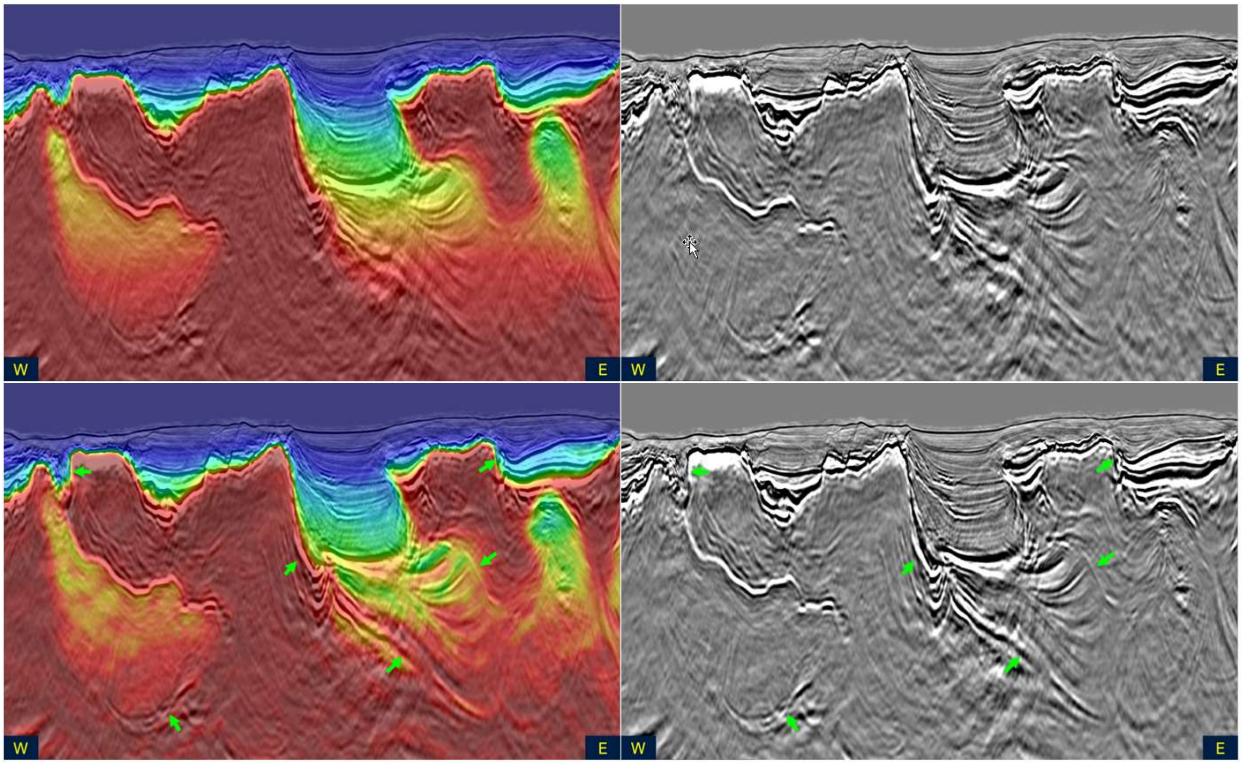

Figure 7: 18Hz RTM QC stacks with respective model overlays comparison using the initial model (top) and the latest velocity model after E-DMFWI sequence 2 (bottom).

Conclusions

This case study illustrates that combining one-sided wide azimuth (WAZ) acquisition with low-frequency sources and a cascaded Elastic Dynamic Matching Full Waveform Inversion (E-DMFWI) workflow effectively addresses subsalt imaging challenges in the complex salt provinces of Angola. The approach enhances imaging beneath salt and pre-salt layers by refining salt and carbonate geometries and improving velocity model precision. The robust elastic implementation accurately captures wavefield behavior in regions of pronounced velocity contrast, yielding images that support more dependable interpretation and reduce exploration risk in previously underexplored areas. In summary, this methodology offers a cost-efficient solution for early-stage exploration and establishes a foundation for future high-resolution imaging and prospect assessment throughout Angola's frontier plays.

Acknowledgement

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