Correcting severe image distortion via multi-azimuth FWI in offshore Senegal

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Summary

High-quality depth images typically require accurate high-resolution representations of the earth model. Full-waveform inversion (FWI) has recently justified its value throughout the industry in providing high-resolution velocity models. However, obtaining an accurate FWI velocity model using narrow-azimuth streamer data can still be challenging in complex geologic environments. The uncertainties, often caused by relatively low resolution perpendicular to the shooting direction and weaker illuminations areas, instill less confidence for reservoir delineation and depth mapping. In this case study from offshore Senegal, we present a joint velocity (Vp) and epsilon (ε) multi-azimuth FWI workflow to construct a high-resolution model to overcome severe image distortion. The updated model improved event focusing and gather flatness and demonstrated significant imaging uplifts consistent with our understanding of the geology in the area.

Introduction

The study area is located in the Rufisque, Sangomar, and Sangomar Deep Blocks, covering a combined area of 2290 km² within the Senegalese portion of the Mauritania-Senegal-Guinea Bissau Basin. In this area, the water bottom depth varies steeply from 50 to 3000 m (Figure 1). The shallow overburden geology is complex, including Mio-Pliocene canyon deposits and a complex fault system (Figure 4a), as well as Tertiary carbonates with strong anisotropy. Deeper sections consist of carbonate layers and fault systems. These compounded geological complexities are known to present challenges for seismic imaging in the area.

Two narrow-azimuth (NAZ) towed-streamer surveys were acquired in the East-West (EW) direction in 2007 and 2015, with streamer lengths of 6 km and 8 km, respectively, and with a 3 Hz low cut applied. The two surveys cover all 3 polygons in Figure 1. The most recent legacy processing on this EW NAZ data set was performed in 2017. The final legacy model, derived from high-definition tomography (Guillaume et al., 2011), produced reasonable imaging for understanding the regional geology. However, visible undulations are still observed at the target level and deeper sections (Figure 4a). The remaining uncertainties in reservoir delineation and depth mapping result in less confidence for a new drilling plan.

An initial FWI trial was performed using the EW NAZ input in an effort to address this issue. It gave reasonable improvements overall but was still not satisfactory for drill planning. To further improve the model accuracy and image quality, a new multi-azimuth (MAZ) acquisition was designed and conducted in 2019, covering the area with 3 azimuths: North-South (NS), Northeast-Southwest, and Northwest-Southeast. All of the new azimuth data were acquired with an 8 km streamer length and a 3 Hz low cut applied. When combined with the legacy EW data, we have a complete MAZ coverage over the area. In the following sections, we demonstrate that MAZ FWI can greatly improve velocity model accuracy over single-azimuth FWI. Benefits from MAZ FWI and a joint velocity and epsilon inversion further refine the details in the velocity and epsilon, thus better correcting image distortions and improving structural focusing.

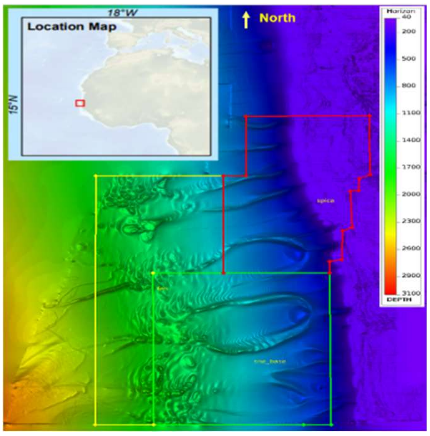

Figure 1: Survey location and water bottom map.

MAZ FWI

Full-waveform inversion (FWI) has proven to be the algorithm of choice for building high-resolution velocity models in complex geologic settings (Mancini et al., 2016). However, the effectiveness of FWI and the fidelity of the FWI model are limited by input data quality and constraints, such as available low frequencies, azimuth, and offset coverage. The fundamental limitations of NAZ streamer data in illuminating the complex subsurface combined with less velocity sensitivity in the direction perpendicular to the shooting direction often result in non-optimal FWI applications. These limitations of NAZ FWI are more pronounced when attempting to resolve strong anomalies that are highly variable in 3D, as is the case for offshore Senegal. The partially-resolved model tends to cause imaging issues in the direction perpendicular to the NAZ shooting direction.

For this study, we ran 12 Hz FWI using the EW NAZ data, the NS NAZ data, and the MAZ data. In our first test, we

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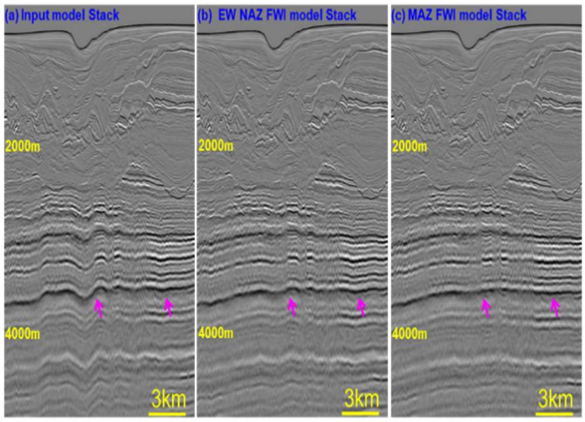
used the EW NAZ data as migration input and compared a NS section of the migrated data using the input model before FWI (Figure 2a), the EW NAZ FWI model (Figure 2b), and the MAZ FWI model (Figure 2c). Compared to the image without FWI (Figure 2a), which had severe undulations at around 3-5 km depth, the EW NAZ FWI (Figure 2b) provided decent uplift in relieving some of these undulations. However, some obvious undulations remained, indicating that the EW NAZ FWI was unable to fully resolve the velocity anomalies with adequate resolution and accuracy along the NS direction (perpendicular to the shooting direction). As shown in Figure 2c, the MAZ FWI clearly gave the best outcome and succeeded in addressing the undulations.

Next, the same experiments were conducted, but with the NS NAZ data as the migration input. The NS NAZ FWI (Figure 2e) improved the images when compared with the input model (Figure 2d), but it still left undulations along the EW direction (perpendicular to the shooting direction) beneath the carbonate and fault area, as illustrated in Figure 2e (pink arrows). Again, MAZ FWI (Figure 2f) further corrected the undulations. Through the two NAZ FWI and MAZ FWI comparisons, we illustrated that complete illumination in the azimuth direction and sufficient offset coverage are important for maximizing the benefits of FWI. MAZ FWI outperforms NAZ FWI in resolving velocity details in higher resolutions, which in turn corrects structural artifacts in the seismic images.

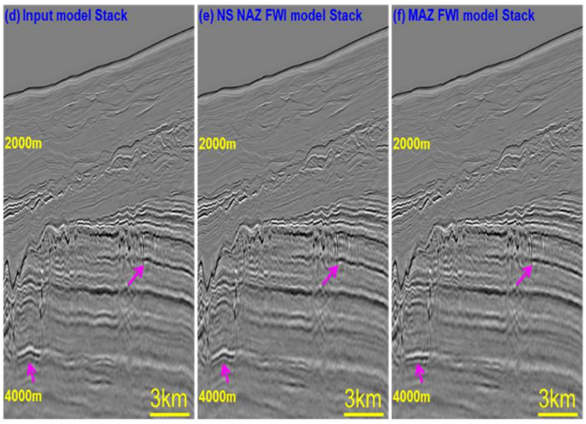
Joint velocity and epsilon FWI

Even after 12 Hz MAZ FWI using the data from all four azimuths, some suspicious undulations were still visible (left panel in Figure 3a). By comparing real and synthetic shots (left panel in Figure 3c), we see that while the kinematics are well matched overall, there is some mismatch between reflection events (pink arrows) with short traveltimes below an epsilon anomaly. Based on prior geologic knowledge, we speculate that this may be related to unresolved anisotropy. Crosstalk between velocity and anisotropy in the FWI inversion is a well-known issue. Decoupling them in FWI requires not only very good large-angle constraints from seismic data for the full domain in consideration, which are barely met even with modern dense OBN data, but also a multi-parameter scheme with full Hessian, which is impractical for industrial 3D data sets. Therefore, it remains common practice to build a smooth anisotropy background model with well calibrations while inverting for velocity only in FWI.

Recently, practical approaches for jointly inverting velocity and anisotropy were attempted with some success (Haacke et al., 2019). We employed a similar method to allow FWI to update both the velocity and epsilon and observed encouraging improvements (Figure 3). Compared with the initial epsilon model (middle panel of Figure 3a), the FWI-updated epsilon model (middle panel of Figure 3b) exhibited more geologically consistent variations. Although we see hardly any observable differences in the corresponding velocity models (right panels of Figures 3a and 3b), the velocity and epsilon models jointly updated by FWI further corrected the residual undulations on the seismic images (left panel of Figure 3b) compared with the velocity-only FWI and initial epsilon models. The new synthetic shot also better matches with the real shot at both near and far offsets (Figure 3c), solving the conflict between reflections and diving waves.



(a) to (c): PSDM crossline stack of EW NAZ data (perpendicular to its shooting direction) using: (a) input model, (b) EW NAZ FWI model, and (c) MAZ FWI model



(d) to (f): PSDM crossline stack of NS NAZ data (perpendicular to its shooting direction) using: (d) input model, (e) NS NAZ FWI model, and (f) MAZ FWI model

Figure 2: PSDM crossline stack of NAZ data using: input model, NAZ FWI model, and MAZ FWI model.

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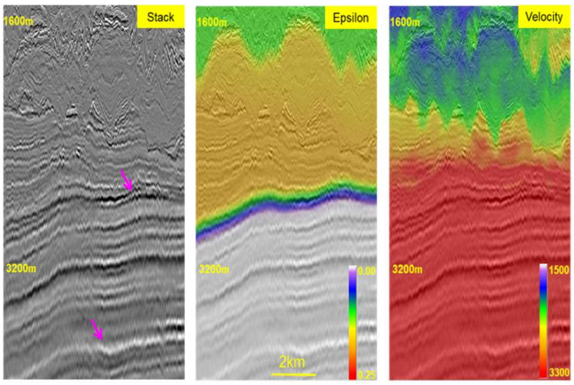
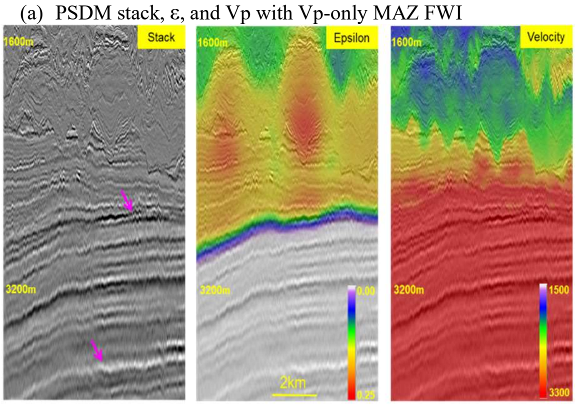
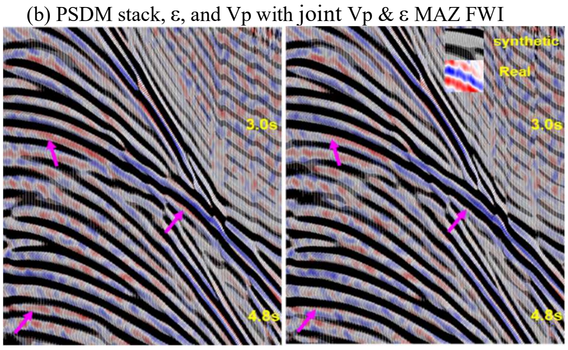


(a) PSDM stack, ε, and Vp with Vp-only MAZ FWI



(b) PSDM stack, ε, and Vp with joint Vp & ε MAZ FWI

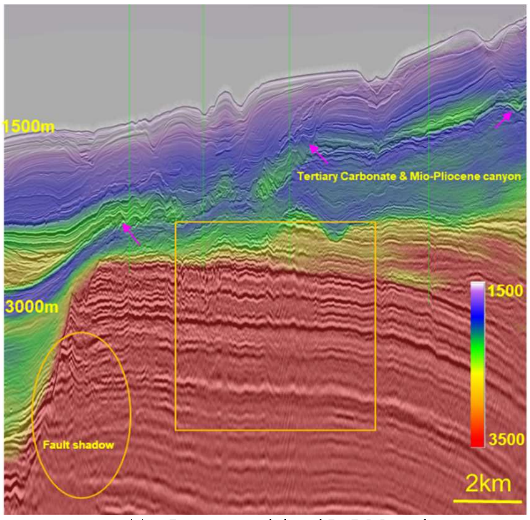


(c) Synthetic and real shot comparion: Vp-only MAZ FWI (left) and joint Vp & ε MAZ FWI (right): less red means better matching

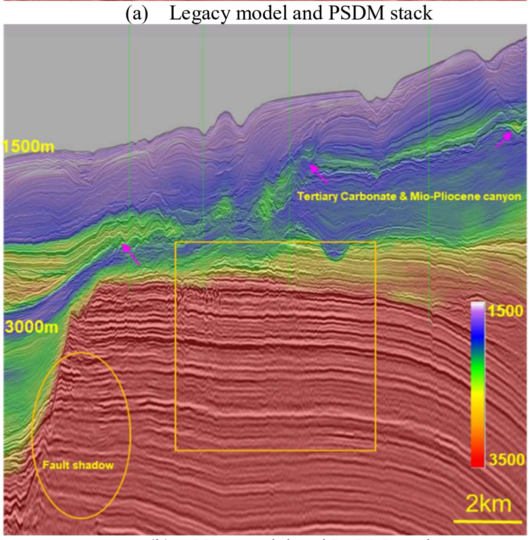
Figure 3: Joint Vp & ε FWI PSDM examples with Vp-only MAZ FWI model and stack (a), joint Vp & ε MAZ FWI model and stack (b), and synthetic and real shot overlay comparison (c).

Final results

By incorporating MAZ data and jointly inverting velocity and epsilon in FWI, our velocity model building flow yields a high-resolution, high-fidelity model. As shown in Figure 4a, the legacy 2017 image suffers from severe undulations at the reservoir depth caused by unresolved complex overburden velocity anomalies. In contrast, the new MAZ FWI model better follows the geology, as shown in Figure 4b. It clearly delineates small canyons, carbonate layers in the overburden, and rotated blocks, as highlighted by the pink arrows. Image distortions were greatly diminished, thus reducing image artifacts and enhancing event continuities (orange box in Figure 4b). In addition, higher S/N is observed beneath the main escarpment (orange ellipse), and the fault shadow is well mitigated.



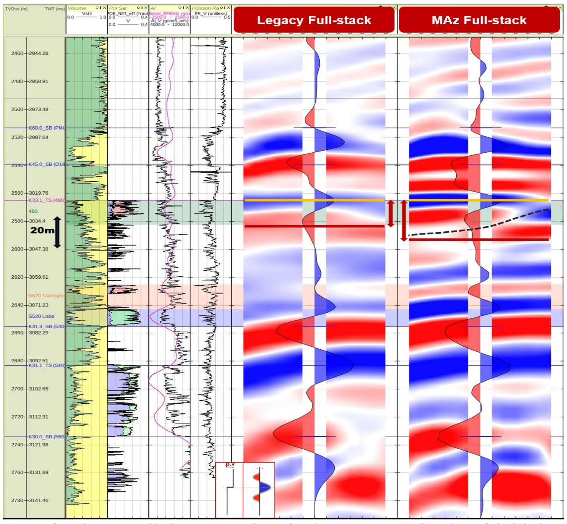
(a) Legacy model and PSDM stack



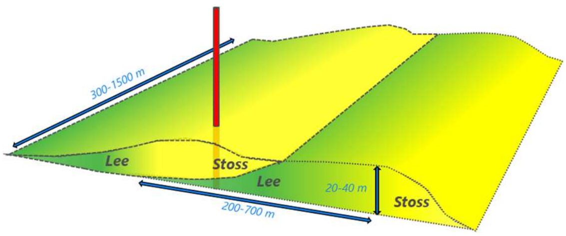
(b) New model and PSDM stack

Figure 4: New result shows significant improvement on seismic image.

The MAZ surveys also allow for noise reduction and enable bandwith extension to work, resulting in substantially improved resolution. One of the key insights from the new data set is the detail of the sediment wave features, calibrated at some key wells (Figure 5a as an example). The previous interpretation based on the legacy image assumes that all of the wells penetrate the crest of the waves, but with a higher resolution image, we can confidently conclude that some of the lee sides have been logged (Figure 5b). Besides providing valuable information for geosteering modeling, this also means that the base of the reservoir package can be pushed deeper in some areas, increasing the gross volumes.



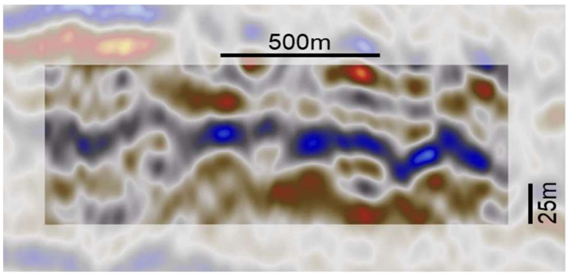
(a) Seismic to well tie comparing the legacy 3D seismic with higher resolution MAZ full stack



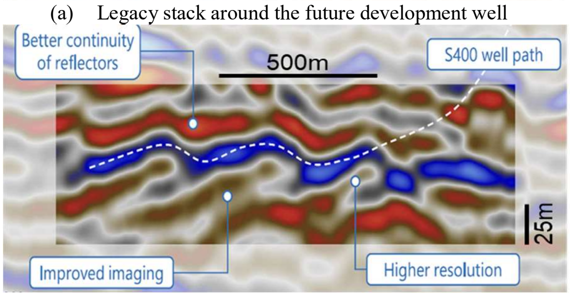
(b) Schematic diagram of sediment wave reservoir to illustrate the gross thickness change

Figure 5: Seismic to well tie comparison (a), and schematic diagram of sediment wave reservoir (b).

The improved image also provides a better understanding of the reservoir, resulting in higher confidence in the development drilling program. When compared with the legacy stack (Figure 6a), the new image (Figure 6b) shows clearer reservoir distribution, enabling well optimization.



(a) Legacy stack around the future development well



(b) New stack around the reservoir

Figure 6: Comparison of the legacy 3D seismic (a) with the recent products (b) along a planned horizontal trajectory.

Conclusions

Senegal data suffers from severe image distortions caused by canyon systems and shallow, fast carbonate layers. This velocity complexity, along with the limitations of NAZ towed-streamer data, leads to uneven illumination coverage, which can cause directional sensitivity in FWI applications. On the other hand, MAZ data can reduce the sensitivity and thus stabilize the FWI application. We demonstrated how joint Vp and ε FWI using MAZ data can produce a more accurate model that better conforms to the geology. Specifically, the resulting FWI model significantly improves the model resolution, delineates small shallow anomalies, and reveals the strong anisotropic carbonate layer. It corrects the image distortions at the reservoir level, thus leading to a high-quality seismic reservoir image that helps de-risk the new drilling program. The success of this case study demonstrates the value of MAZ acquisition, especially where shallow geology is complex. This workflow may be implemented in other areas with similar geologic or acquisition conditions.

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