Resolving imaging challenges in the Niger Delta with seismic methods (FWI) assisted by potential fields

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Summary

The 2021 update to the Nigerian Petroleum Industry Act (PIA) has sparked a surge in exploration activity in the deepwater Niger Delta, particularly within the lesser explored shale diapir zone where imaging of complex mobile shale structures has historically proven challenging. In areas like this, new 3D seismic acquisition in combination with modern processing workflows is required to de-risk exploration and evaluate potential new plays. Acquisition of approximately 11,500 km2 3D seismic data was completed in February 2024, marking the first modern multi-client 3D seismic acquisition offshore Nigeria in the last decade. The seismic data for this case study were acquired with triple source, 10 streamers and 10km cable modern acquisition. A state-of-the-art seismic model building workflow, which included tomography for background updates and Dynamic Matching Full Waveform Inversion (DM™ FWI) for finer details, was used in conjunction with gravity and magnetic modelling to build a geologically plausible model over the entire area. Gravity and magnetic data were recorded during the same multi-client seismic acquisition program.

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Geological Setting

The Niger Delta was formed during the Late Cretaceous to Quaternary and is characterised by a thick, laterally extensive sequence of progradational deltaic clastics overlying marine shales. The Niger Delta is sub-divided into two lobes (NW & SE) by a basement high along the Charcot Fracture Zone. High sedimentation rates since the mid-late Miocene have resulted in differential sediment loading across the delta lobes, leading to extensional faulting inboard and compressional deformation in the outboard. A range of structural domains are present across the Niger Delta including an extensional domain, inner and outer fold & thrust belts and a shale diapir zone (Cobbold et al., 2009). The Akata formation marine shales represent a thick over-pressured shale unit and the main source rock in the basin. These are overlain by a sequence of deltaic clastics known as the Agbada formation, which form the reservoir targets. There is stacked reservoir potential within the Agbada formation, particularly within compressive structural traps. New plays involving sub-thrust trapping require high quality modern PSDM seismic data to resolve the margins of shale bodies and image sediments below the thrusts.

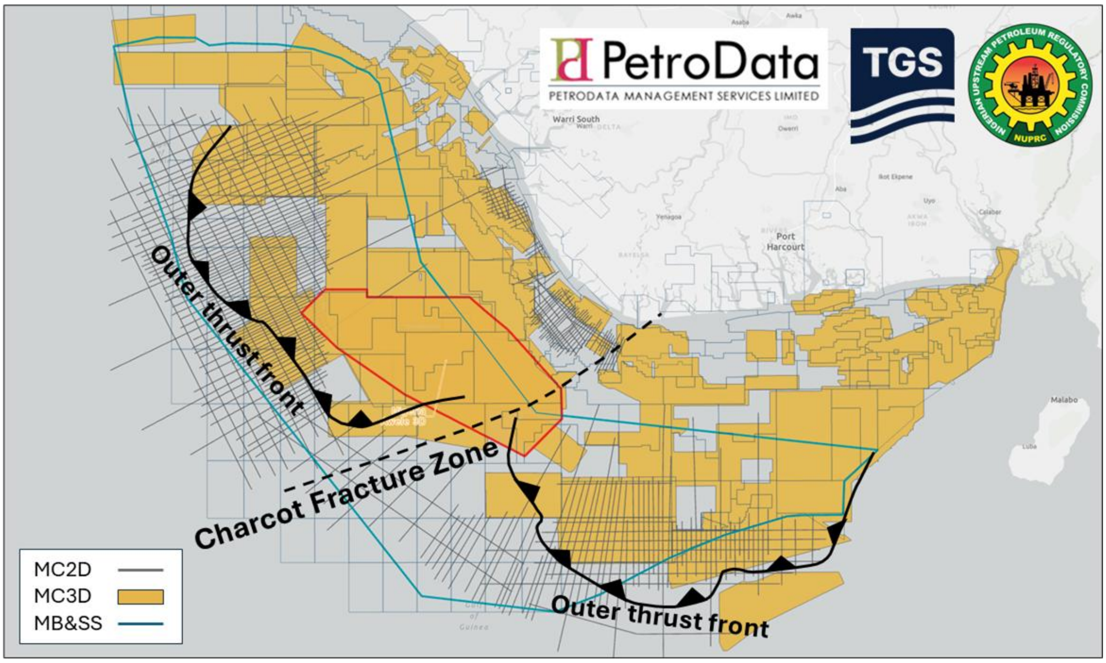

Figure 1 *Location map of multi-client 2D and 3D datasets in the Niger Delta with structural elements highlighted after Cobbold et al., 2009. The study area is outlined in red.*

Method / Workflow

The approach to velocity model-building (VMB) in the Niger Delta must consider the main tectonic driving force in the area; the mobilized shale of the Akata formation. On its path to the surface the mobile shale deforms the more competent units of the Agbada formation and thereby introduces a high degree of lateral and vertical variability in structure and velocity. Seismically the mobile shale unit is mostly void of coherent events; not even the top of the mobilized mud is an interpretable event and as the shale spreads laterally, the structure is inherently complex (multi-z picking required). Locally the mobile shale penetrates the seabed as a mud-volcano. This poses serious challenges to any data-driven seismic inversion technique, be it tomography or FWI, which rely on seismic events with good signal-to-noise (S/N).

The most promising seismic model-building workflow to address this challenge must therefore rely to some extent on other methods, such as gravity modelling and interpretation. However, a significant amount of valuable seismic work can be accomplished beforehand. Several iterations of tomography will improve the high reflectivity (and high S/N units) from a smooth regional starting model to a large extent. We can also use refraction FWI to insert lithologically relevant detail (high velocity for competent rocks, low velocity for mobile shale) into the shallow section.

At this stage however, the model needs to be continued downwards in a geologically sensible manner. This can be done by interpreting a simplified top mobile shale that follows the termination of coherent surrounding sediment as there isn't an actual phase associated with the top. One can also use a byproduct from tomography, which is the stack semblance as an indicator volume for the mobile shale. This will allow the seismic processor to insert typical mud velocities into the low semblance areas and below the interpreted top shale. Velocity profiles from a global study of mobile shale (Soto et al., 2021) were used successfully in this case study as a starting point for scanning. In the Niger Delta the basement is a very strong event in areas with little mobile shale contribution and a weak and deformed event in areas with a thick mobile shale cover. The velocity scanning will be able to use the regional basement as a quality indicator.
Potential fields can also help in validating seismic models and more importantly, in pointing the processors to areas where the seismically derived densities contradict the measured gravity or the depth of the basement, which in the Niger Delta is the top of the oceanic crust, contradicts the independently verified magnetic basement. These areas most likely require revisiting and model alterations performed at a deeper level where S/N is inappropriately low for data-driven seismic methods.

Results

Here, we present results from an intermediate VMB stage following an initial round of two tomography iterations and a more advanced stage after mobile-shale scenarios, additional tomography updates and FWI up to 12Hz. The aim of the tomographic update shown in the top panel of Figure 2 was to improve the regional background model to a degree where the residual moveout measured on depth gathers was generally within ±5%. We can also see a reasonable structural coupling in the high S/N areas (Agbada formation) and a rough differentiation between the more coherent events of the Agbada formation and the low coherency Akata mobilized shale. At this stage we had not updated the deep model below 7km from the smooth regional background. The lower panel of Figure 2 shows the result of scanning for the optimal mobile shale velocity, based on the quality/deformation of the basement, tomography updates and DM™ FWI using both refraction and reflections up to 12Hz.

The resulting image shows a much better resolved shallow section and improved definition between the two main lithologies (Agbada sediment and Akata shale). It also reveals enhanced reflectivity in the pre-Akata section below 7km depth and a much-improved basement, with better continuity and relief.

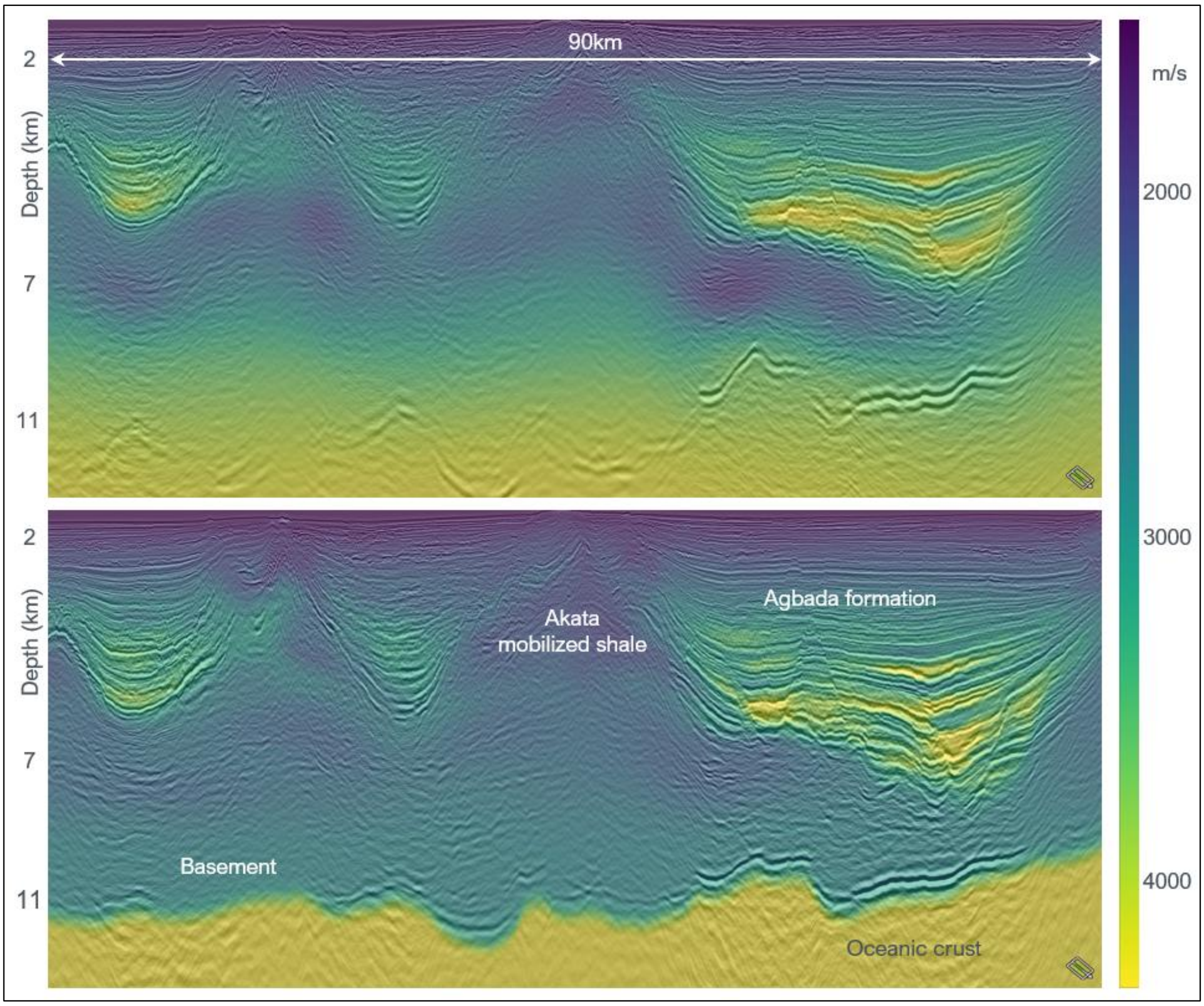

Figure 2 *Velocity and stack from intermediate VMB stage prior to FWI (top) and after 12Hz* DM FWI. *Note the better resolved Agbada formation in the lower section due to FWI, the improved definition of the Akata mobilized shale and the enhanced basement. The deformation of this event was used as an indicator for problems with the overburden model.*

Our FWI strategy and parametrization was defined to take advantage of the 10km-long streamer. At an early stage of seismic processing, refraction FWI for the lower bandwidth of up to 9Hz was performed to improve the shallow resolution inserted by the first pass of tomography. The more refined model after scenario testing and further deep tomographic updates was then input to reflection FWI.

At this stage FWI benefitted from a fully deghosted and demultipled seismic input and was run in 4 steps from the low bandwidth 3.5-5Hz up to a maximum of 12Hz over the entire 11,500 km^2 area. The quality of this inversion can be best seen in slice view.

Figure 3 shows a shallow slice at 400m below a smooth seabed. Compared to the pre-FWI tomography, the 12Hz FWI model shows a great amount of fine detail such as channels and circular gas pockets, some of which are being observed as pock marks in the high-resolution multi-beam bathymetry.

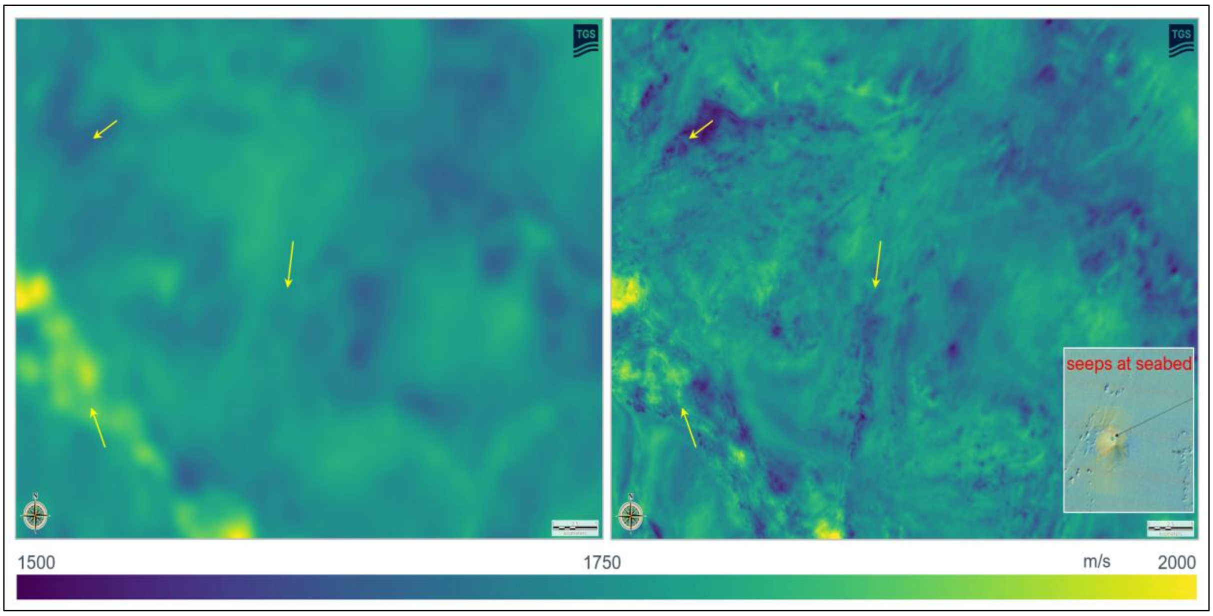

Figure 3 *Shallow velocity slices at 400m below a smooth seabed from an intermediate VMB stage prior to FWI (left) and after 12Hz DM FWI (right). A great amount of fine detail has been captured by FWI including channels (yellow arrows) and circular gas pockets very similar in density to the pockmarks shown in multi-beam data from the seabed (inset).*

Conclusions

The complex imaging challenges of the Niger Delta can best be tackled with a multi-method approach, where seismic processing and modelling is being supported by interpretation and potential fields modelling. We demonstrated how data-driven methods such as Tomography and FWI, require the input from other methods to overcome the low S/N, almost opaque seismic character of the main tectonic driver in this area, the mobilized shale of the Akata formation. Interpretation of an approximative top mobile shale and potential field inversions have assisted the seismic methods with valuable data that helped achieve a geologically plausible model from the seabed to the Moho.

The interpretation of the basement horizon was also very helpful for guiding VMB, as some of its relief (deformation) can be caused by model problems in the overburden. Where the mobile shale is a thick layer up to 7-8km in this area) the model uncertainty is greatest, and the basement is the only coherent event that can be used to steer VMB.

Acknowledgements

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