Awele-3D, an integrated seismic and potential fields study from the Niger Delta

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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. Acquisition of approximately 11,500 km^2 3D seismic data in 2024 marks the first modern multi-client 3D seismic acquisition offshore Nigeria in over a decade. The seismic data for this case study were acquired with a triple source, 10 streamers single-sensor configuration, with each streamer being 10 km in length.

Gravity and magnetic data were recorded during the same multi-client seismic acquisition program. A state-of-the-art seismic processing and model building workflow, which included Dynamic Matching Full Waveform Inversion (Mao et al, 2020), was used in conjunction with gravity and magnetic modelling to build a geologically plausible velocity model over the entire area.

Additionally, monitoring data integrity throughout the seismic processing sequence, ensuring consistency across a large input area, was essential to the success of a project and for the requirements of optimal reservoir characterization. For this purpose, quality control (QC) processes were designed to expedite the full survey QC and an increased confidence in the output.

Geological Setting

The Niger Delta was formed during the Late Cretaceous to Quaternary and is characterized by a thick, laterally extensive sequence of progradational deltaic clastics overlying marine shales. 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. 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 unexplored 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.

Introduction

The newly acquired seismic data have been processed using the most current implementations of deblending, deghosting, demultiple and regularization techniques. However, ensuring consistency across the large input area was a focus for all processing steps. An amplitude continuity attribute, based on normalized amplitude differences around the N+1 region, was developed to assess the performance of the deblending process. Capturing residual, or signal leakage, the process was successfully optimized to remove the blended energy masking the basement, and crustal structures, which would have otherwise been uninterpretable with this expedited, explorative acquisition configuration.

Acquisition-supplied receiver depths initially guided the deghosting process. Although a well deghosted dataset was achieved the wavelet width QC attribute revealed stripes correlating to inaccurate information for some cables, causing errors in the starting point for the inversion process. Revising these depth headers for affected cables, by notch picking within frequency domain and rerunning the deghosting, produced a width QC showing a consistent response across the survey giving confidence in the new results.

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, as it introduces a high degree of lateral and vertical variability in structure and model attributes (velocity, anisotropy, Q). Seismically, the mobile shale unit is mostly void of coherent events; the top of the mobilized mud is widely a non-interpretable event. The most promising seismic model-building workflow to address this challenge must therefore rely to some extent on other geophysical data, such as gravity/magnetic modelling and depositional interpretation.

Method / Workflow

The data were deblended using an inversion scheme (Sun et al., 2022). A QC attribute was developed to assess the performance of the deblending process designed to capture residual or signal leakage. The scheme is based on the normalized difference in RMS amplitudes measured above and below the N+1 region of a shot record. This measure assumes amplitude continuity in the underlying signal across the N+1 overlap region. The attribute values range from +1 to -1. Positive values tending to +1 suggest overlapping shot residuals in the deblended result while negative values tending to -1 suggest a loss of signal. For optimal deblending, values close to 0 are expected. This provided a quantitative approach for converging the testing procedure, increasing confidence in the deblending output.

A 3D sparse Tau-p inversion method (Seher et al., 2021) was used to perform both source and receiver side deghosting. Acquisition supplied receiver depths were used to guide the process. After an initial run of deghosting, a 3D stack volume was created over which the wavelet width QC attribute was generated. The width of the embedded wavelet is defined as the distance from the peak to a specified fraction of the amplitude of the trace envelope measured at a determined horizon, typically the water bottom.

Overall, a well-deghosted dataset was achieved; however, the wavelet width QC revealed stripes of higher values in the attribute slice. Close inspection of the crossline shows evidence of ringing in the data at specific locations. Further investigation of the data revealed the supplied receiver depth headers to be inaccurate for some cables and that the starting point for the inversion was too much in error. Revising these depth headers, by notch picking within frequency domain, and rerunning the deghosting produced a consistent response across the survey giving confidence in the new results.

Model-building in the Awele area was mostly based on seismic methods. Several iterations of tomography were used to improve the high reflectivity (and high S/N) units

from a smooth regional starting model. We have also used refraction FWI to insert lithologically relevant detail into the shallow section. Interpreting a simplified top mobile shale horizon that follows the termination of coherent surrounding sediment can be helpful to continue the model downward. Additionally, a byproduct from tomography, the stack semblance provided an indicator volume for the mobile shale. Both products allowed the seismic processor to insert typical mud velocities below the interpreted top shale prior to further velocity scanning and tomography.
Potential-field data were used to help validate seismic models and more importantly, to indicate areas where the seismically derived densities contradict the measured gravity response or the depth of the basement. In the Niger Delta the seismic basement is the top of the thinned transitional and largely oceanic crust. Comparing this horizon with the independently derived magnetic basement helped adjust the model at deeper levels, where the S/N is inappropriately low for data-driven seismic methods.

Examples

From the deblending process we present the amplitude continuity attribute calculated and mapped for every shot over a subset of the Awele project with histograms showing the distributions. Before deblending a distribution close to +1 is seen. After deblending the values shift towards 0.
However, there clearly is a variation in the values ranging from the Southeast of the survey (where the attribute becomes negative but is close to 0) to the Northwest (where values tend to be still quite positive). This is seen in the multimodal distribution of the attribute after deblending. A bathymetry map of the survey showed a trend from deep to shallow water running roughly Southeast to Northwest. This indicates that the deblending has worked optimally in the deep-water area whilst some remnant noise remains in the shallower water regions. A cross plot of the attribute with water depth is presented in Figure 1, which shows a clear trend of increased residual noise with decreasing water depth.
This result is not obvious when visually inspecting the deblended results in the section view of Figure 1, demonstrating the value of attribute-based areal QC. In these areas, as identified by the amplitude continuity attribute, the residual overlap noise can be addressed by extending the inversion to further iterations.

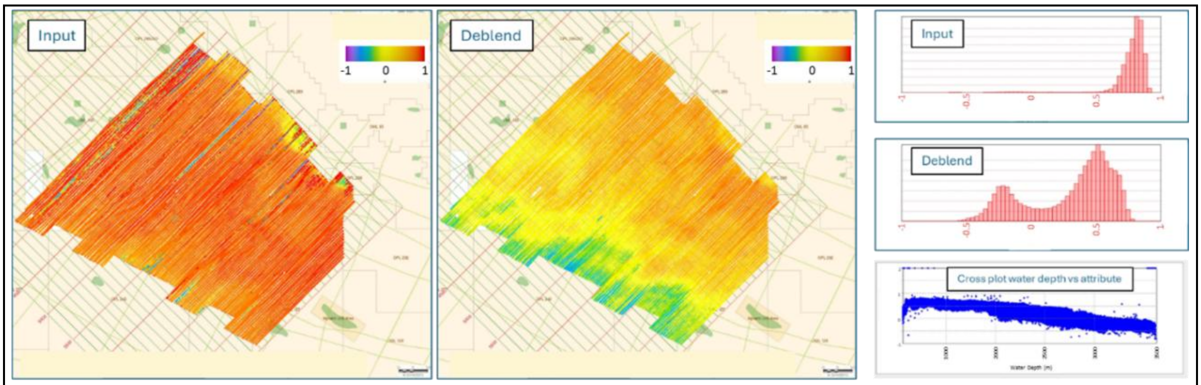

Figure 1: The deblending QC RMS ratio attribute mapped over a subset of the Awele Survey before & after deblending with corresponding distributions (histograms in red). A cross plot of the attribute after deblending against water depth is also shown.

From the deghosting process we present the wavelet width QC attribute. Figure 2a shows this QC as an attribute slice after the initial deghosting with 2b showing an example crossline through the stack. Overall, a well-deghosted dataset was achieved. However, the wavelet width QC reveals stripes of higher values in the attribute slice. Close inspection of the crossline shows evidence of ringing in the data at specific locations (highlighted by the arrows).
Further investigation of the data revealed the supplied receiver depth headers to be inaccurate for some cables and that the starting point for the inversion was too much in error. Revising these depth headers and rerunning the deghosting produced the resulting attribute analysis shown in Figure 2c with the corresponding crossline in Figure 2d. In the new results the wavelet width QC shows a consistent response across the survey, giving confidence in the new results. The QC attribute shown in Figure 2a highlights where problems may exist and allows for targeted remedial efforts.

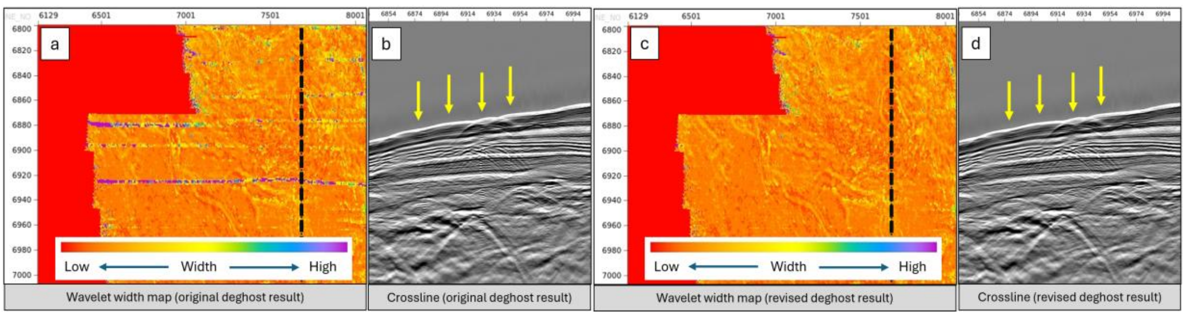

Figure 2: (a) The wavelet width QC attribute slice over initial deghost result. (b) Crossline through initial result. (c) The wavelet width QC attribute slice over revised deghost result. (d) Crossline through revised result. Yellow arrows indicate regions of inaccurate cable depth headers.

From the model-building stage of the processing we present here a typical cross-section from the Awele area and an example from full-waveform inversion (FWI). Figure 3 shows an example from an initial round of tomography iterations (top) and a more advanced stage (bottom) after mobile-shale scenarios, additional tomography updates and FWI up to 12Hz. We can 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 mobilized shale. The lower panel of Figure 3 shows the result of scanning for the optimal mobile shale velocity, based on the quality and 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 depositional layers. It also reveals enhanced reflectivity in the pre-shale section below 7km depth and a much-improved basement, with better continuity and relief.

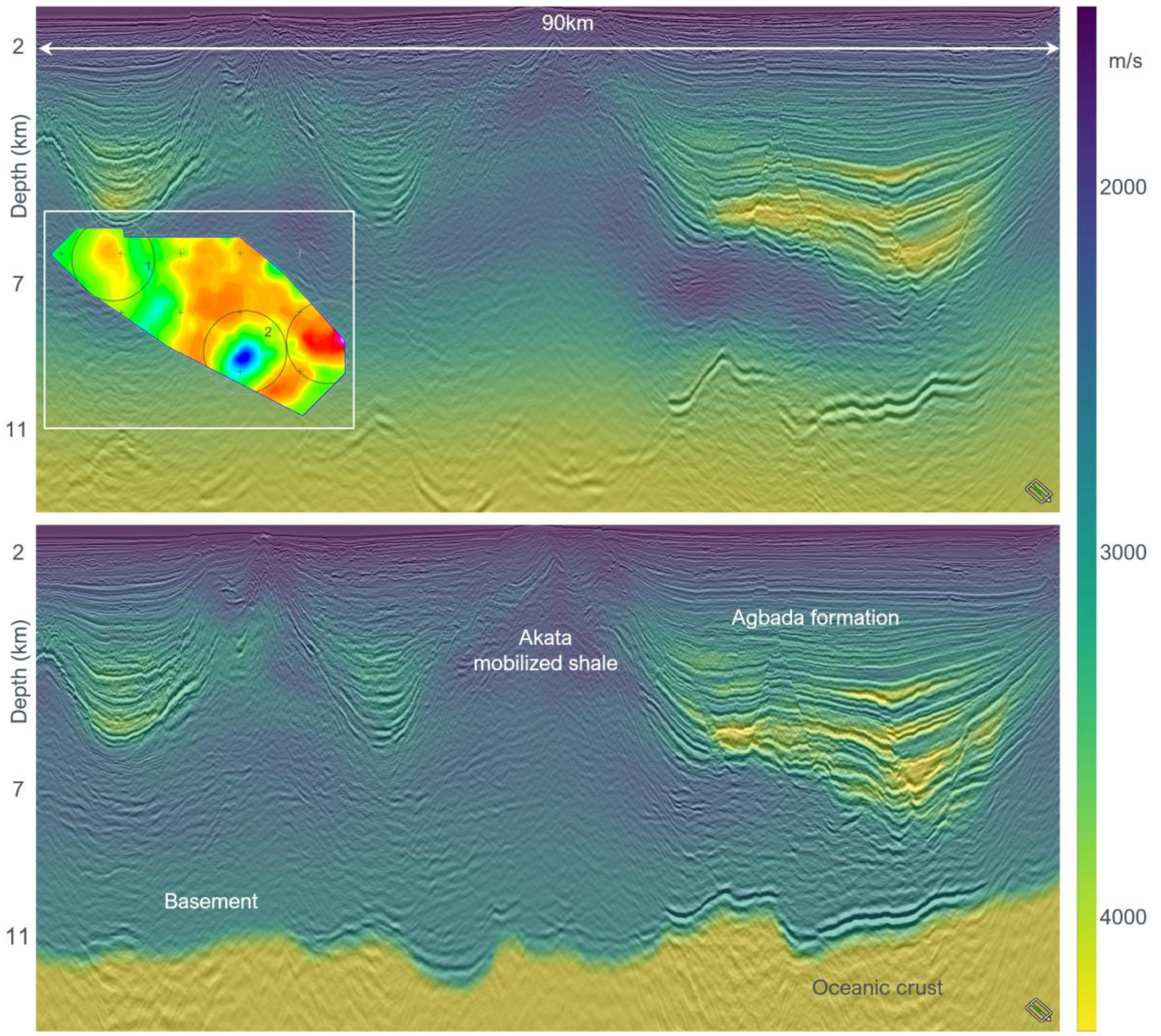

Figure 3: - Velocity and stack from intermediate VMB stage prior to FWI (top) and after 12Hz DM FWI. Note the better resolved Agbada formation in the lower section due to FWI, the improved definition of the Akata mobilized shale and the enhanced basement. The deformation of this event was used as an indicator for problems with the overburden model. Inset shows difference between observed and calculated gravity with anomalous areas highlighted. This map was very helpful in the seismic VMB route as it pointed the imager to areas that might require further model updates.

Converting seismic depth/interval velocities to densities using the Gardner relationship allowed imagers to validate the model by comparing the calculated densities to the observed values. The map shown in Figure 3 helped improve the velocity model in areas where the seismic S/N is poor due to predominant mobilized shale occurrence. Additional gravity inversion work and re-conversion to velocities gave a good indication on the velocity range of the shale areas.

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 band-width 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 used as 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 4 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.

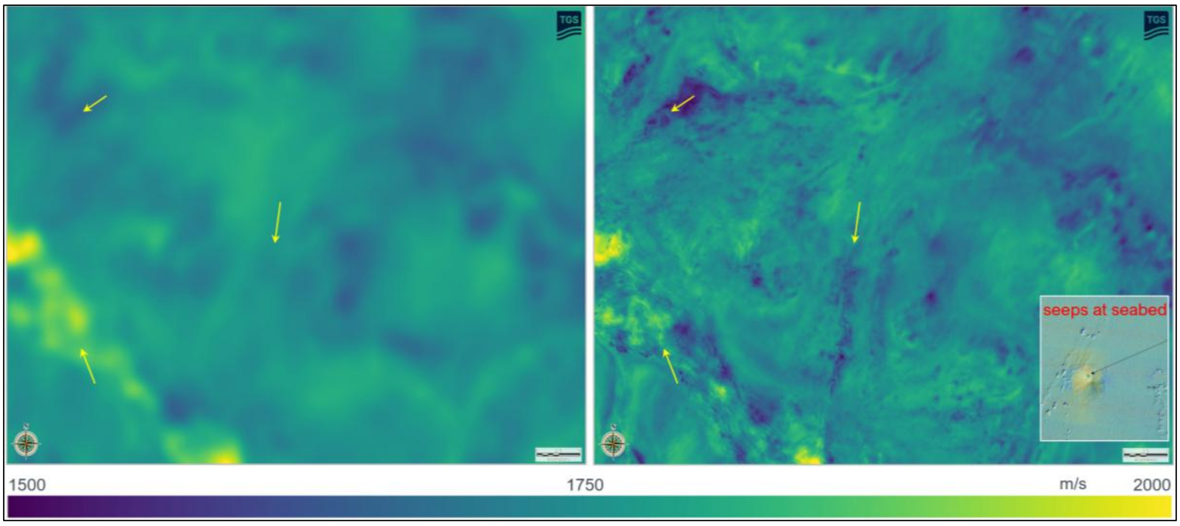

Figure 4: Shallow velocity slices at 400m below a smooth seabed from an intermediate VMB stage prior to FWI (left) and after 12Hz DM FWI (right). A great amount of fine detail has been captured by FWI including channels (yellow arrows) and circular gas pockets very similar in density to the pockmarks shown in multi-beam data from the seabed (inset).

Conclusions

Monitoring data integrity throughout the seismic processing sequence, ensuring consistency across a large input area, is essential to the success of a project. Attribute-based QC procedures were able to expedite the full survey QC in the Awele area and influence testing procedures, resulting in an increased confidence in the output.

QC of seismic data was enhanced by generating attributes designed to capture the key characteristics of specific processes. In the case of deblending, using the amplitude continuity attribute revealed the variation in the result with varying water depth. This was the result of deploying a single parameterization over the entire survey area; for future cases we could incorporate this attribute to enable a data-dependent parameter convergence, accounting for variable water depth, rather than simple QC.

In deghosting, the wavelet width method revealed an inconsistency due to inaccuracies in the assumed cable depths. The attribute lent itself more readily to map-based and statistical analyses providing a more comprehensive and efficient QC procedure. This work highlighted the requirement for better elevation detection prior to the deghosting process or enable a global search within the process to more easily account for variations.

The imaging challenges of the Niger Delta are best addressed by a multi-method approach, where seismic processing and modelling is being supported by potential fields modelling and interpretation. We demonstrated how data-driven methods such as tomography and FWI require the input from other geophysical data to overcome the low S/N, almost opaque seismic character of the mobilized shales. Interpretation of an approximative top mobile shale and potential field inversions have assisted the seismic methods with valuable confirmation and helped achieve a geologically plausible model from the seabed to the Moho.
The interpretation of the basement horizon was very helpful for guiding the VMB, as some of its relief (deformation) can be caused by model challenges in the overburden. Where the mobile shale is a thick layer of 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. Significant uplift has been brought to the interpretable volume through the progression of processing technologies and modern acquisition.

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