

Shallow water multi-parameter FWI imaging in Equatorial Guinea

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Summary

We use multi-parameter full-waveform inversion (MP-FWI) imaging up to a maximum frequency of 50 Hz to produce a step-change improvement in imaging of both the very shallow and the deep subsurface offshore Equatorial Guinea, using a hydrophone-only towed streamer dataset acquired in 1999. When compared to the legacy Kirchhoff pre-stack depth migration (KDM), the MP-FWI imaging derived reflectivity produces a more structurally plausible, easier to interpret image of the deeper subsurface without the extensive pre-processing of the conventional workflow. Illumination of the shallow is significantly improved through the use of the full wavefield, which includes all ghosts and multiples. This shows MP-FWI imaging can enhance imaging from legacy datasets without requiring conventional reprocessing in parallel.

Introduction

Conventional seismic processing techniques have been developed and refined for decades to produce the best possible image using primary-only migration algorithms. This means that large parts of the wavefield are treated as noise e.g. source and receiver ghosts, sea surface and internal multiples, and, in the case of Kirchhoff migration, multi-pathing arrivals. However, these aspects of the wavefield contain valuable additional information about the subsurface.

Multi-parameter full-waveform inversion (MP-FWI) imaging can make use of these arrivals that would be discarded in conventional processing by using near-row shot gathers to simultaneously determine V_p and reflectivity using the full wavefield (McLeman et al., 2023). This produces a P-wave velocity field and true amplitude least-squares reflectivity image from the data with minimal processing applied. This can breathe new life into legacy seismic datasets by extracting additional information that would have to be discarded in the conventional workflow. This is true over the entire subsurface but is particularly appealing in shallow water environments where the use of ghosts and multiples to generate the image can dramatically improve near-surface illumination.

In this paper, we show how MP-FWI imaging can be used to produce a step-change improvement in the quality of the subsurface image at depth and in the very shallow subsurface on a dataset from offshore Equatorial Guinea

without the requirement to perform conventional processing in parallel.

Method

Block EG-01 offshore Equatorial Guinea poses processing and imaging challenges. There is a shallow water (~8 m) region on the shelf and then a steep rugose water bottom down to ~1.5 km water depth from the shelf break. The post-Albian sediments have significant faulting, and there are complex carbonate and salt structures below the top Albian unconformity (red dashed line in Figure 3) at a depth ranging from ~1 km depth in the shallowest water to a maximum of ~5 km. The most recent re-processing was a conventional Kirchhoff pre-stack depth migration (KDM) velocity model build and migration in 2015. The goal was to obtain an image of the very shallow subsurface, enhance the structural understanding of the reservoir targets above the top Albian unconformity and improve understanding of the complex salt and carbonate structures beneath that unconformity.

Pressure data from a towed-streamer dataset acquired in 1999 with 10 4.5 km long streamers separated by 100 m and a near offset of 250 m was used to perform diving wave FWI to update the P-wave velocity model up to a maximum frequency of 16 Hz, using a frequency stepping approach. Minimal pre-processing was applied to the data before input to the inversion - mild swell noise attenuation, receiver motion correction, and tidal statics. The initial velocity model was created by smoothing the legacy interval velocity model, and anisotropy models were based on the available well data. A modelled source signature was generated using the available gun array information and then updated using an FWI-based source inversion methodology. Visco-acoustic MP-FWI imaging was then implemented up to a final maximum frequency of 50 Hz, using a frequency stepping approach. This provided an updated V_p model and full offset reflectivity image down to a maximum depth of 7 km. Additionally, 40 Hz true-amplitude angle reflectivity volumes for near (4-16 degrees), mid (16-28 degrees) and far (28-40 degrees) angles were generated by MP-FWI imaging for AVA analysis.

Since the conventional workflow utilized by the legacy processing and imaging uses only primary reflections, it was anticipated that by using the full wavefield in MP-FWI imaging significant improvements could be made.

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Shallow imaging improvements

The minimum water depth in the shallowest portion of the survey of approximately 8 m was very close to the tow depth of the streamers (7 m). The wide sail lines led to limited resolution in the water depth information acquired during shooting and also meant that near-angle primary reflection illumination in the shallow water was very poor. In the final processed legacy stacks, the data is muted above ~100 m depth due to contamination by stretch and post-critical energy. For a fair blind comparison purpose only, the shots used as input to MP-FWI imaging were passed through a fast-track processing flow of deghosting,

demultiple, and designature for use in a Kirchhoff migration. Figure 1 shows a comparison of the legacy KDM stack, the KDM stack using the fast-track processed data migrated with the MP-FWI imaging velocity model, and the MP-FWI imaging reflectivity using the full wavefield. A significant improvement in the illumination of the near surface is clearly apparent. In the MP-FWI imaging derived reflectivity (Figure 1c), reflectors at and immediately beneath the seabed can be identified even where they could not be reliably interpolated from the acquisition water depth data or identified in the conventionally migrated images (Figure 1a and 1b).

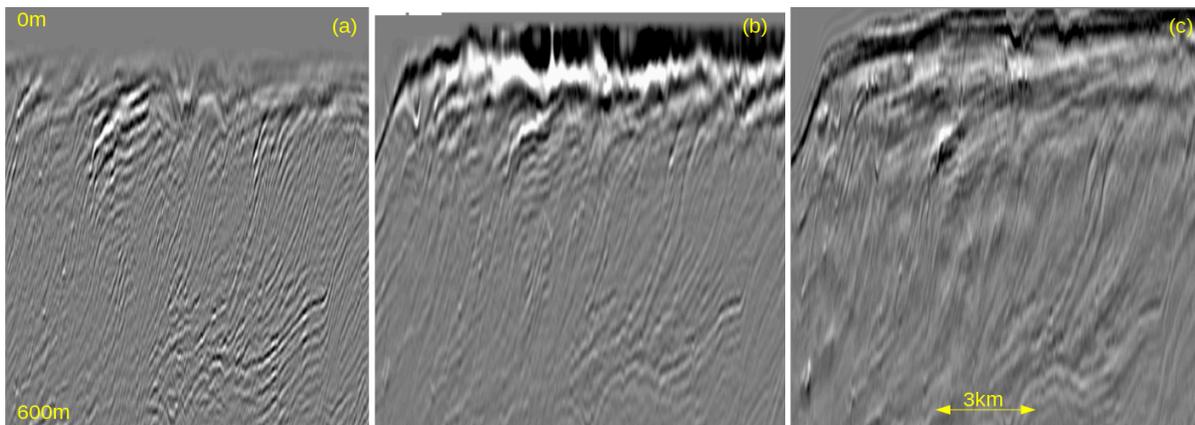


Figure 1: A comparison of a) the legacy KDM stack, b) KDM stack of the fast-track processed data with a 30-degree outer mute, and c) the MP-FWI imaging reflectivity.

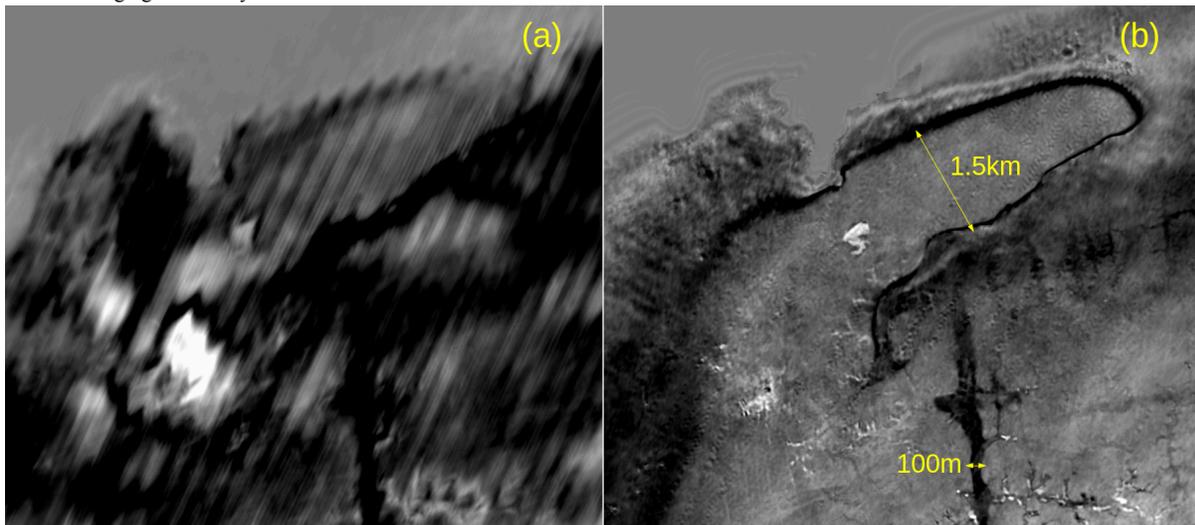


Figure 2: A depth slice at 50m depth through a) a 30-degree KDM stack of the fast-track processed data and b) the MP-FWI imaging reflectivity using unprocessed input data.

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This improvement in shallow illumination is even more apparent in Figure 2, where depth slices through the stack produced from the KDM of the fast-track data and the MP-FWI imaging reflectivity is demonstrated. The fine structural detail in the MP-FWI imaging result is evident, whereas the conventional image contains primarily acquisition footprint and migration stretch. MP-FWI imaging is able to achieve this improvement through the use of ghosts and multiples to fill in the missing information in the primary-only conventional image.

Target-level imaging improvements

The MP-FWI imaging full offset reflectivity demonstrates a noticeable uplift in imaging at all depths when compared to the legacy KDM. Figure 3 shows images of this comparison — note the improvement in structural clarity in

the MP-FWI imaging volume, along with the reduction in the dimming in the shallow washout zone (yellow circle) compared to the legacy KDM. We attribute this to the correct compensation for illumination effects in the MP-FWI image.

Above the top-Albian unconformity (red dashed line), fault resolution is improved, with some faulting becoming visible that was not evident in the legacy image (white arrow). In the Albian below the unconformity, the structure is simplified, with fault blocks and salt structures imaged that were not interpretable on the legacy image (yellow arrows). This improvement is due to the enhanced fidelity of the velocity model, combined with the benefits of a full-wavefield least-squares imaging solution — honouring all P-wave modes, including free-surface and interbed multiples.

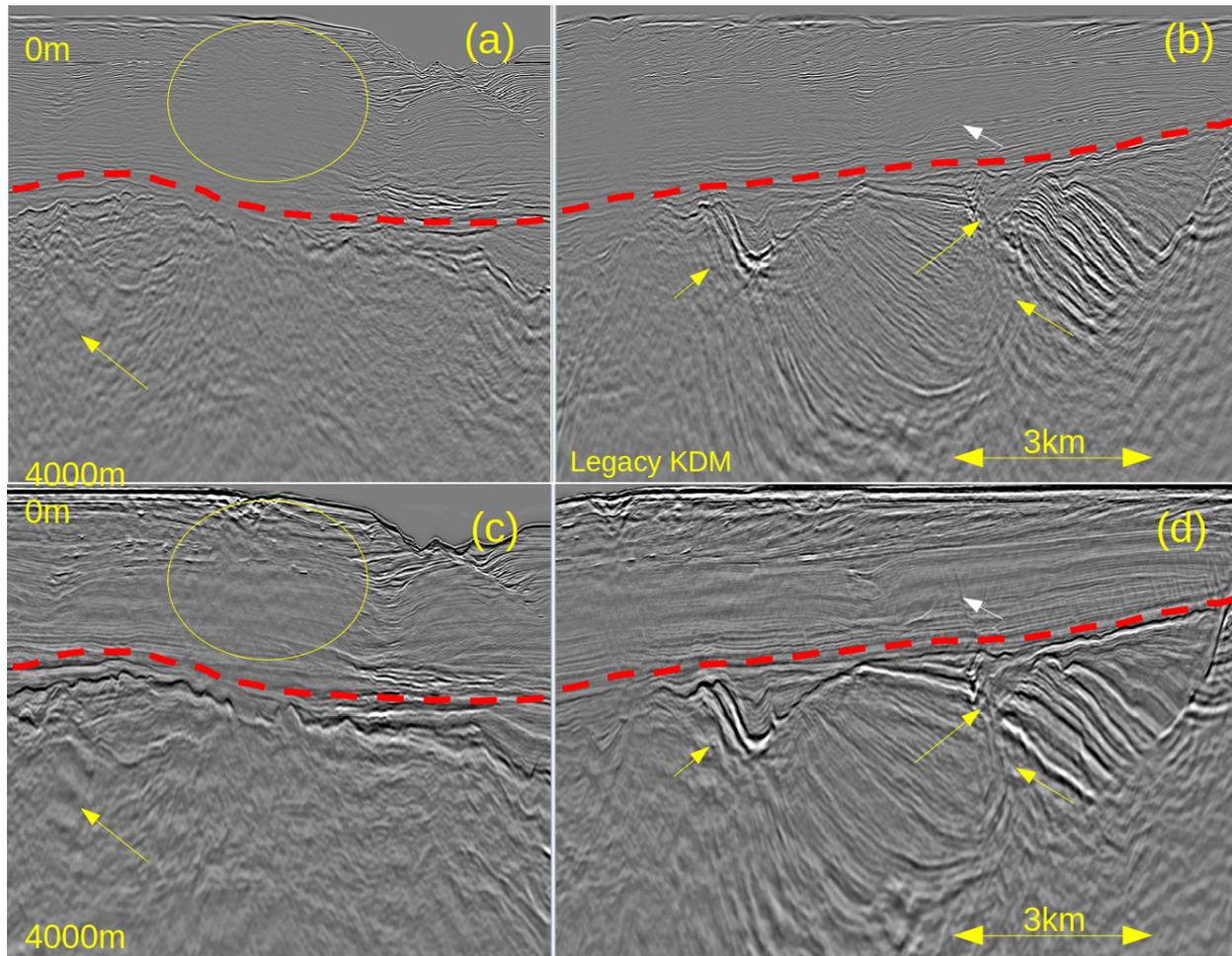


Figure 3: A comparison of an inline (a and c) and crossline (b and d) through the legacy KDM image and full offset MP-FWI imaging reflectivity.

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In addition to the full offset reflectivity, three true amplitude angle reflectivity volumes were produced for AVA analysis. These were generated by holding the velocity fixed while reflectivity was updated to produce 3 MP-FWI imaging derived angle stacks. Figure 4 demonstrates that these outputs are effective in describing the expected AVA behaviour as determined from the well information. This is further highlighted by the correlation coefficient, quantifying a good match between the well predicted AVA trend and the MP-FWI imaging derived reflectivity with angle.

Conclusions

MP-FWI imaging has produced a significant improvement in imaging compared to the legacy KDM without the extensive pre-processing of the conventional workflow.

This demonstrates its suitability as a data-driven replacement for the conventional processing flow, even when using data acquired more than 20 years ago.

The improvement in structural imaging is significant at all depths, and angle reflectivity volumes show a good tie to well synthetics. The use of the full wavefield, including ghosts and multiples at all stages of the inversion, has produced a dramatic improvement in the imaging of the very shallow subsurface.

Acknowledgements

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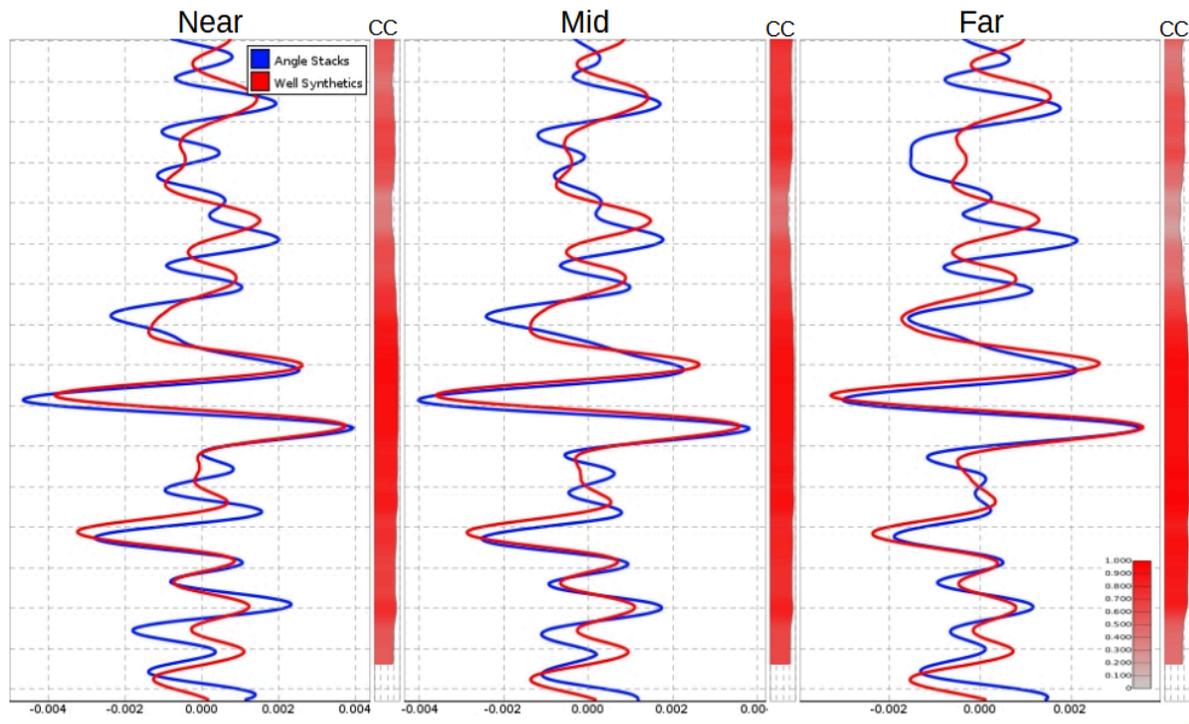


Figure 4: Traces from the near, mid, and far MP-FWI imaging angle reflectivity volumes (blue) and well synthetic traces (red) for an example well, with the cross-correlation coefficient plotted alongside.