Illuminating the near surface using the full wavefield in ultra-shallow water via MP-FWI Imaging

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Summary

Conventional seismic processing techniques treat large parts of the wavefield as noise e.g. source and receiver ghosts, sea surface and internal multiples, and, in the case of Kirchhoff migration, muti-pathing arrivals. These arrivals contain valuable information about the subsurface, which, if harnessed, can provide dramatic improvements in the illumination of the ultra-shallow. 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 in a towed streamer dataset offshore Equatorial Guinea. When compared to the legacy Kirchhoff pre-stack depth migration, the MP-FWI imaging reflectivity produces a clearer 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. It is shown that MP-FWI imaging can produce significant improvements in imaging of legacy datasets through the use of information that would usually be discarded in the conventional processing flow.

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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, muti-pathing arrivals. However, these aspects of the wavefield contain valuable additional information about the subsurface that is absent from the primary-only wavefield.

Multi-parameter full-waveform inversion (MP-FWI) imaging can make use of these arrivals that would be discarded in conventional processing by using near-raw shot gathers to simultaneously determine Vp 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 this technology can be used to produce a step-change improvement in the quality of the subsurface image at depth and in the very shallow 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 at a depth ranging from ~1 km TVDSS in the shallowest water to a maximum of ~5 km. The most recent re-processing was a conventional Kirchhoff pre-stack depth migration (KpreSDM) 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 up to a maximum frequency of 16 Hz using a frequency stepping approach. 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 a source inversion in FWI. Visco-acoustic MP-FWI imaging was then implemented up to a final maximum frequency of 50 Hz, again using a frequency stepping approach. This gave an updated Vp model and full offset reflectivity image down to a maximum depth of 7 km. 40 Hz true-amplitude angle reflectivity volumes for near (4-16 degrees), mid (16-28 degrees) and far (28-40 degrees) angles for AVA analysis were also generated.

Due to the restrictions of using only primary information in the conventional workflow, limiting what was achievable with such an approach, it was deemed that only the MP-FWI imaging approach, utilising the full wavefield, would be used to address the imaging challenges.

Shallow water 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 bathymetry data acquired during acquisition and also meant that near-angle illumination in the shallow was very poor. In the final processed legacy stacks, the data is muted above ~100 m TVDSS 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 KpreSDM stack, the KpreSDM 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 image, the water bottom reflector can be identified even where it could not be reliably interpolated from the bathymetry data or identified in the conventionally migrated images.

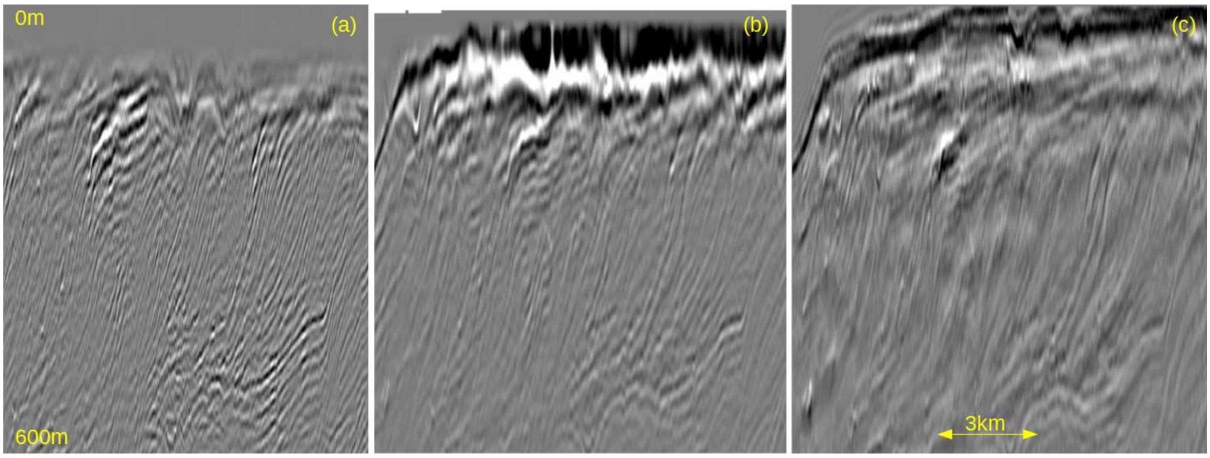

***Figure 1** A comparison of the legacy KpreSDM stack (a), a KpreSDM stack of the fast-track processed data with a 30-degree outer mute (b), and the MP-FWI imaging reflectivity (c).*

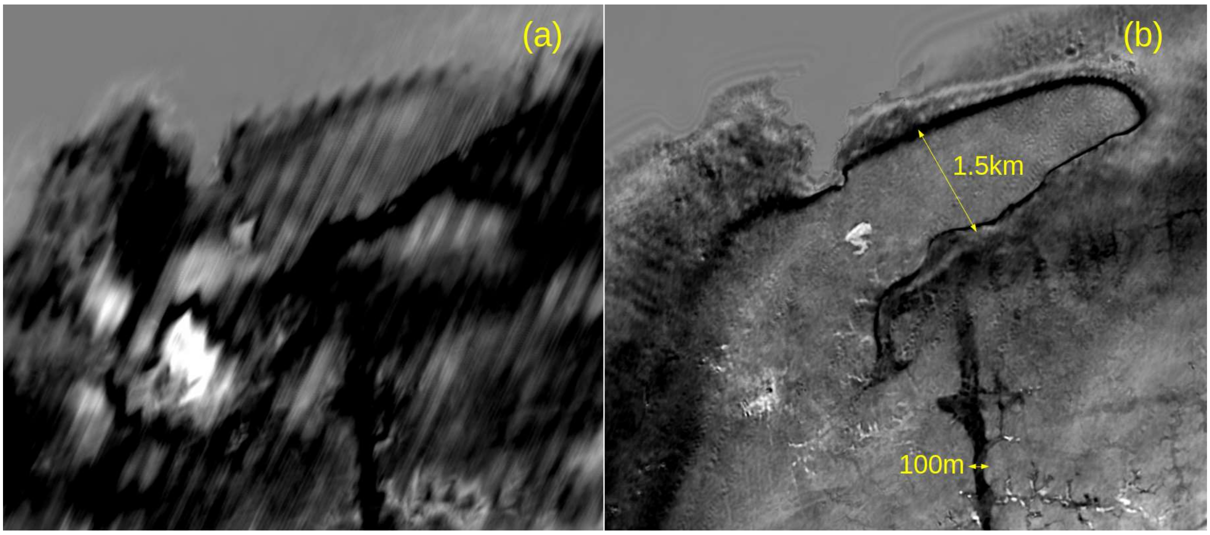

***Figure 2** A depth slice at 50m TVDSS through a 30-degree KpreSDM stack of the fast-track processed data (a) and the same depth slice through the MP-FWI imaging reflectivity using unprocessed input data (b).*

This improvement in shallow illumination is even more apparent in Figure 2, where depth slices through the images produced by the KpreSDM of the fast-track data and the MP-FWI imaging reflectivity show fine structural detail in the MP-FWI imaging result, 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 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 KpreSDM. 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 apparent dimming in the shallow washout zone (circled) compared to the legacy KpreSDM. We attribute this to the improved compensation for illumination effects in the MP-FWI image.

Above the top-Albian unconformity, fault resolution is improved, with some faulting becoming visible that was not evident in the legacy image (blue arrow). At the Albian and below, 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 improved fidelity of the velocity model, combined with the benefits of a full wavefield least-squares imaging solution - honouring all P-wave modes, including sea surface and interbed multiples.

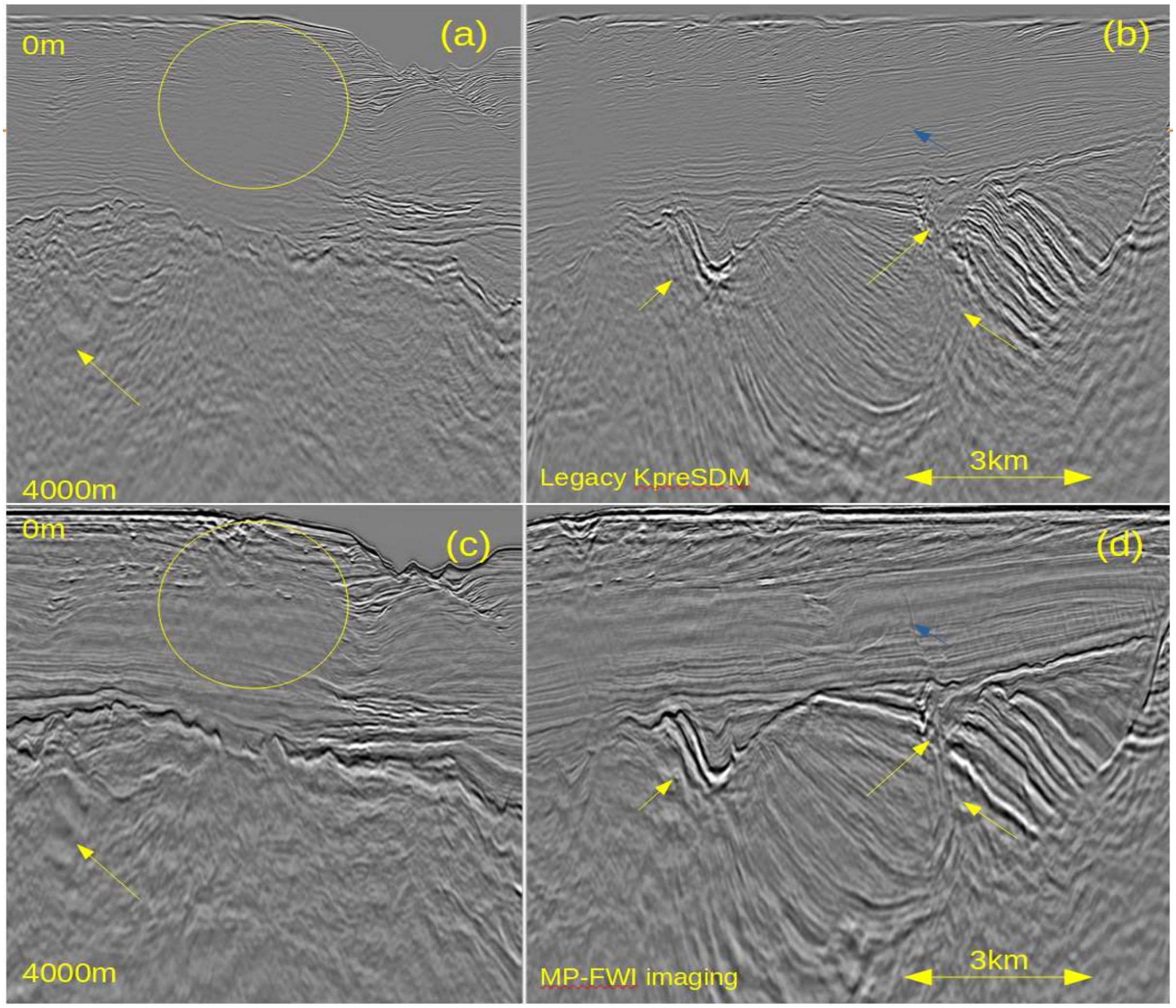

Figure 3 *A comparison of an inline (a and c) and crossline (b and d) through the legacy KpreSDM image and full offset MP-FWI imaging reflectivity.*

In addition to the full offset reflectivity, three true amplitude angle reflectivity volumes were produced for AVA analysis. These were generated via three independent inversions where velocity was held fixed while reflectivity was updated using input data divided into discrete angle ranges. Figure 4 demonstrates that these outputs are effective in describing the expected AVA behaviour as determined from the well information.

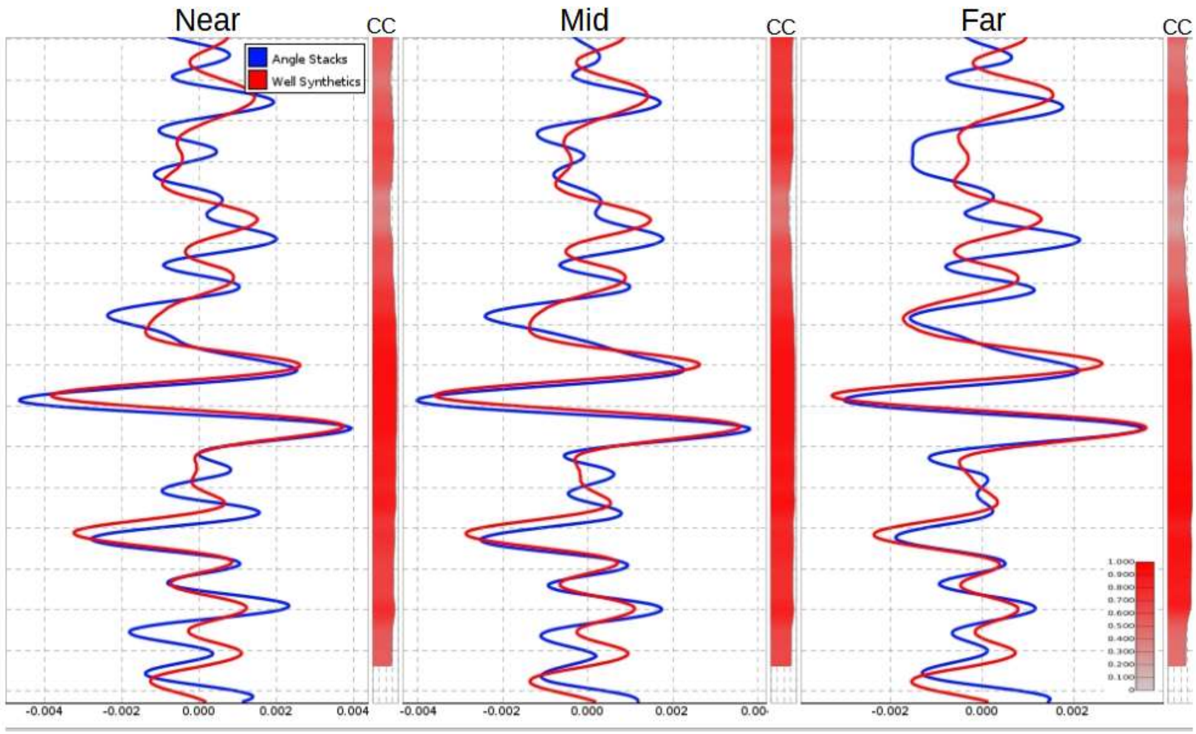

Figure 4 *Traces from the near, mid and far MP-FWI imaging angle reflectivity volumes (blue) and well synthetic traces (red) for an example well with cross-correlation coefficient plotted alongside.*

Conclusions

MP-FWI imaging has produced a significant improvement in imaging compared to the legacy KpreSDM 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.

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References

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