Multi-parameter FWI imaging in the Gulf of Mexico

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Summary

Resolving illumination issues caused by the complex salt bodies in the Gulf of Mexico has been a continual challenge for seismic acquisition, processing and imaging. The long offset and rich azimuthal coverage provided by ocean-bottom node data have seen this technique become commonplace in such environments. Processing of such data requires a lengthy workflow resulting in down-going and up-going wavefields that are often migrated independently using wave-equation-based algorithms such as reverse time migration (RTM).

Multi-parameter full-waveform inversion (MP-FWI) imaging is a novel approach to seismic processing and imaging that uses the full wavefield to simultaneously determine a variety of earth parameters, including velocity and reflectivity, using minimally processed field data. The conventional processing workflow is not required since the algorithm is able to utilise aspects of the wavefield that have traditionally required attenuation prior to imaging such as ghost and multiple energy. The derived reflectivity volume is naturally formed from both up-going and down-going wavefields allowing the benefits of both to be captured in a single output. Here, we demonstrate the application of this technology for salt imaging using a deep-water OBN survey in the Gulf of Mexico and compare the results to conventional processing and imaging workflows.

Introduction

Model-building with FWI (Tarantola, 1987) applied to diving waves (diving wave FWI) is now a well-established tool. In recent years FWI has been modified to additionally use reflected events (reflection FWI) while further developments have allowed the generation of interpretable reflectivity images (FWI imaging). MP-FWI imaging aims to achieve both of these goals through the simultaneous determination of a high-resolution velocity model, a true amplitude reflectivity and optionally, other earth parameters. Separating kinematic from dynamic effects is key to establishing which are attributable to velocity and which to reflectivity. McLeman et al. (2023) proposed a scheme to address the scaling and crosstalk issues that employs an L-BFGS optimiser combined with an adaptive-gradient-like approach. MP-FWI imaging is a multi-scattering, least-squares imaging solution that uses minimally processed field data as input and, therefore, does not require the same extensive pre-processing workflow as the traditional approach.

Method

This technique has been applied to a sparse OBN dataset that was acquired in the Gulf of Mexico with water depths of approximately 2 km. The goal was to improve the imaging around the edges of, and beneath, the complex salt structures. The data were processed and imaged through a variety of workflows (as described in Figure 1) such that comparisons could be made between the MP-FWI imaging approach and conventional processing and imaging workflows.

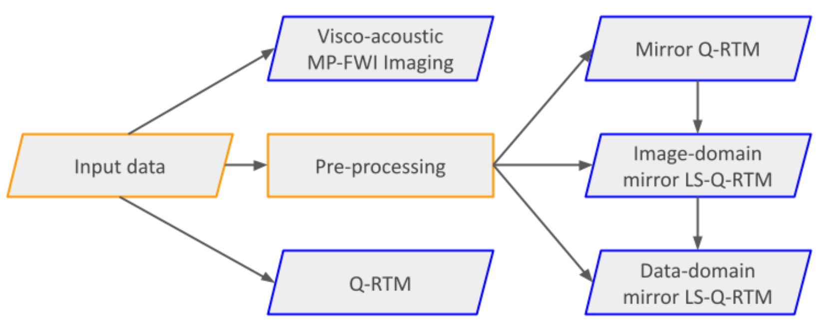

Figure 1: Processing and imaging flow chart. Items in the blue boxes are presented in this paper.

MP-FWI imaging in the Gulf of Mexico

MP-FWI imaging was run visco-acoustically to 40 Hz, simultaneously determining velocity and reflectivity. Input models consisted of a simple two-layer Q model and an existing velocity model derived through conventional techniques including diving wave FWI and reflection tomography. The input seismic data consisted of the pressure component which had been repositioned through a direct arrival analysis scheme.

The conventional approach required pre-processing of both pressure and vertical velocity components through a workflow that included node repositioning and orientation correction; Vz noise attenuation; source carpet regularisation; wavefield calibration and separation; up/down deconvolution and down/down deconvolution (Hampson & Szumski, 2020) and finally 5D regularisation of both up and down-going wavefields.

These outputs are typically migrated independently, with mirror-imaging techniques employed for the down-going wavefield. Combining the migrated results can prove challenging given the different characteristics of the datasets, especially the poor illumination of the up-going wavefield in the near-surface when nodes are sparsely distributed. It is not uncommon, as was the case here, to simply discard the up-going wavefield in favour of the down-going, mirror-imaged result. The down-going wavefield was imaged initially using Q-RTM with the output being fed into a single iteration, imagine-domain least-squares Q-RTM (LS-Q-RTM) (Guitton, 2017), the result of which was used as an initial reflectivity model for 5 additional iterations of data-domain LS-Q-RTM. The input velocity to this process was the final updated model from MP-FWI imaging and the Q model was the same as used in MP-FWI imaging. All results were generated up to 40 Hz maximum frequency.

Additionally, the same input data used by MP-FWI imaging were migrated using Q-RTM to demonstrate the issues that MP-FWI imaging was required to overcome.

Results

RTMs of the pre-processed data using the input and output velocity models to MP-FWI imaging were run to QC the FWI-derived velocity model update (Figure 2). The areas marked by yellow arrows demonstrate how the MP-FWI imaging-derived velocity model improves the sub-salt imaging with reflectors becoming more continuous and stronger in amplitude. The use of reflections in FWI to update the velocity model has provided an improvement in imaging compared to the conventional ray-based tomographic approach in this complex geological environment.

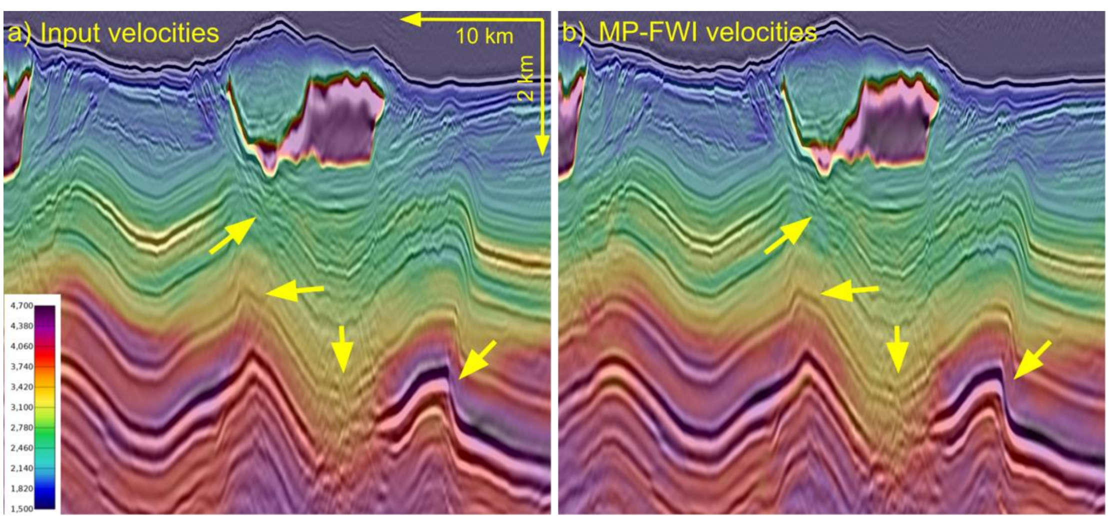

Figure 2: Input MP-FWI imaging velocity model co-rendered with a Q-RTM of pre-processed data (a) and output MP-FWI imaging velocity model co-rendered with a corresponding Q-RTM of pre-processed data (b).

Figure 3 compares conventional mirror Q-RTM (3a), image-domain LS-Q-RTM (3b), data-domain LS-Q-RTM (3c) and MP-FWI imaging reflectivity (3d). The conventional Q-RTM demonstrates clear cones of poor illumination (yellow arrows) on either side of the salt body. The two LS-Q-RTM outputs resolve this to some extent, but amplitudes remain noticeably weaker than surrounding events. The reflectivity from MP-FWI imaging shows much-improved illumination and a more consistent amplitude response through these zones.

The event highlighted by the orange arrows in the deeper section is poorly imaged in the conventional Q-RTM. The image-domain LS-Q-RTM provides a clear improvement in illumination and event continuity and a further incremental improvement is apparent in the data-domain LS-Q-RTM. However, this is at the expense of introducing noise, caused by residual multiple which is very difficult to entirely attenuate in such complex geological settings. This event and surrounding areas are significantly clearer, more continuous, and cleaner in the MP-FWI imaging reflectivity volume which is in part due to better handling of multiples than the conventional flow.

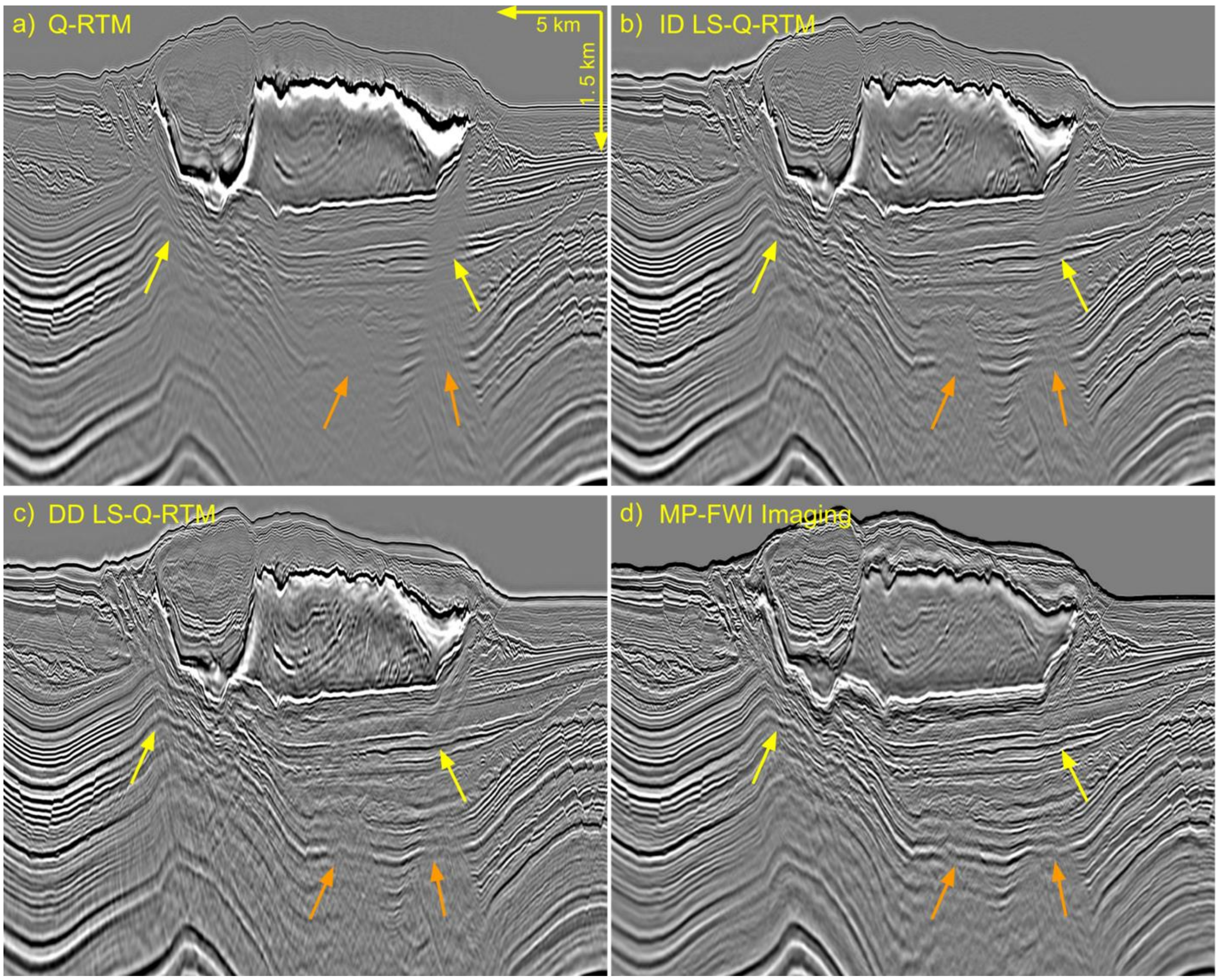

Figure 3: Mirror Q-RTM (a), image-domain LS-Q-RTM (b) and data-domain LS-Q-RTM (c) of the pre-processed down-going wavefield and MP-FWI imaging derived reflectivity (d).

A Q-RTM of the same minimally pre-processed input data to MP-FWI imaging, migrated using the up-going Green's functions, was compared to the MP-FWI imaging-derived reflectivity (Figure 4). This demonstrates the various challenges that MP-FWI imaging must automatically overcome to produce an interpretable output. The raw Q-RTM shows evidence of the source ghost, most discernibly at the seabed, poor illumination in the near-surface due to sparse node acquisition, interference in the deep section caused by the receiver ghost and evidence of an absent receiver highlighted by the yellow circle. These issues, which typically require pre-processing to resolve, have all been handled by MP-FWI imaging with its output showing a single black event at the seabed, clear illumination of the near-surface, including at the missing receiver, and deeper primaries revealed thanks to the handling of the receiver ghost. The corresponding depth slices further demonstrate the resolution of the near-surface and also reveal a clear extension of imaging well beyond the limits of the receiver carpet. Since this can only be achieved through the use of higher-order scattering (in this case the down-going wavefield), it demonstrates that MP-FWI imaging automatically uses a multi-scattering approach.

Conclusions

The successful application of MP-FWI imaging has been demonstrated on a deep-water Gulf of Mexico dataset where sub-salt imaging using conventional processing and imaging approaches can be challenging. The technique has provided a robust velocity model and reflectivity model that has improved the illumination, resolution, and imaging of key targets thanks to the use of the full wavefield. We have shown that MP-FWI imaging is able to retain and use information that is often discarded resulting in an extension of imaging well beyond the limit of the receiver carpet. Bypassing the lengthy pre-processing workflow avoids the subjective judgements required in such steps and also reduces the turnaround time of projects. MP-FWI imaging automatically uses all scattered parts of the wavefield to reconstruct the reflectivity and the kinematic earth parameters. The resulting reflectivity and the kinematic fields are optimally consistent with the field data in a least squares sense.

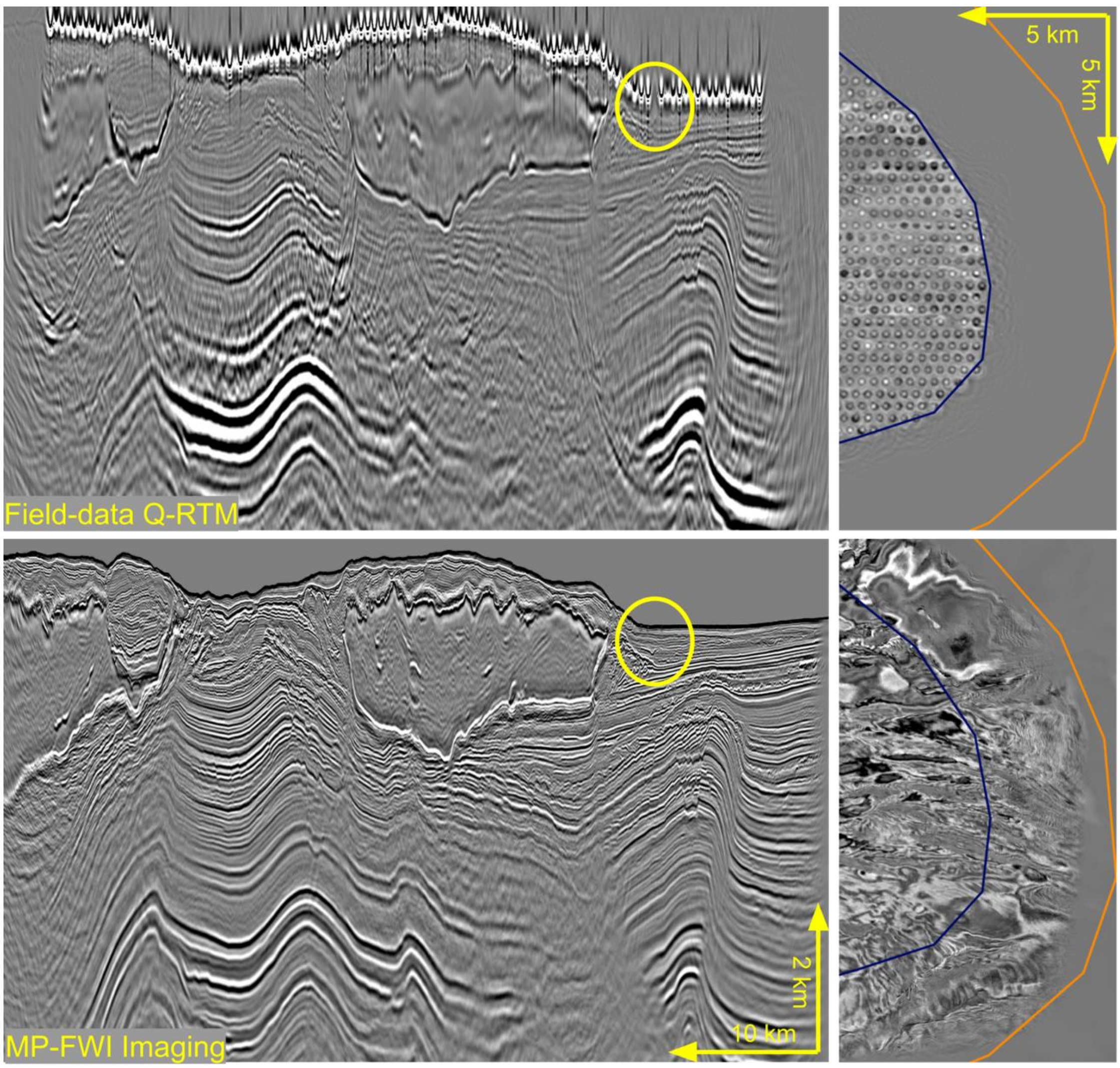

Figure 4: Section and shallow depth-slice tracking the water bottom through the Q-RTM (using up-going Green's functions) of the raw field data (top) and MP-FWI imaging reflectivity (bottom). The blue and orange lines describe the limit of the source and receiver carpets respectively.

Acknowledgements

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