Multi-parameter FWI imaging in shallow water: a case study from offshore Sarawak

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Summary

Common processing and imaging workflows contain a plethora of techniques such as deghosting, designature, and demultiple to suppress parts of the recorded wavefield that would be improperly mapped into the image domain by conventional migration algorithms. These pre-processing stages can be complex and time-consuming to implement due to the linear fashion they must be tested and applied. This is especially true in shallow water marine environments where strong short period multiples can obscure the desired target and are non-trivial to attenuate whilst preserving the primary amplitude. Multi-parameter full-waveform inversion (MP-FWI) imaging provides an alternative path by simultaneously determining subsurface parameters, such as velocity and reflectivity, using raw field data as input. MP-FWI imaging is a least-squares method that uses the entire recorded wavefield to deliver a higher-resolution image with improved illumination and amplitude fidelity compared against the conventional approach, which typically involves Kirchhoff preSDM. In this paper, we compare results obtained from a conventional processing and imaging sequence using Kirchhoff preSDM against the results obtained using MP-FWI imaging. We demonstrate that the MP-FWI approach essentially supersedes the conventional workflow in terms of quality of result and project turnaround time on a shallow water marine survey from offshore Sarawak, Malaysia.

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Introduction

Over the past few decades, a plethora of seismic data pre-processing techniques have been developed to carefully suppress parts of the measured wavefield which would be incorrectly translated into the image domain by conventional migration algorithms, such as Kirchhoff and reverse-time migration (RTM). Techniques such as deghosting, demultiple, designature, and regularisation are applied in linear-like workflows which are complex and time-consuming to design and execute. The resulting "primary-only" single scattering pre-processed data are then migrated and used in equally complex and time-consuming model building workflows involving reflection residual move-out (RMO) tomography to derive a low frequency estimate of the subsurface models, e.g., P-velocity. The success of each stage is judged in a largely subjective manner based on a range of parameter tests. Such a processing paradigm not only results in projects requiring many months or even years to complete, but also contains many approximations and assumptions that limit the quality of the final result.

Full-waveform inversion (FWI) imaging offers a new paradigm to supersede the conventional workflow. Traditionally, FWI has been used to produce high-resolution velocity models during conventional model building workflows using only the diving waves but its potential extends far beyond this. Multi-parameter FWI (MP-FWI) imaging can use reflection and transmission arrivals to simultaneously determine velocity along with other subsurface attributes. These include anisotropy, relative density, reflectivity, and angle dependent reflectivity for AVA analysis to determine a robust P-impedance and Vp/Vs ratio, all to high frequency using the raw field data as input (McLeman et al., 2023). Multi-parameter inversion issues such as crosstalk and relative scaling can be addressed using a novel second order quasi-Newton method (McLeman et al., 2021).

Historically, shallow water marine environments are notoriously challenging for the conventional processing and imaging workflow due to the presence of strong, relatively short period free-surface multiples obscuring key target locations. Limitations in common multiple modelling schemes (e.g., SRME (Verschuur et al., 1992)) often result in derived multiple models requiring windowed adaptive subtraction techniques to improve the match between the multiple models and the observed data, thus potentially also compromising the fidelity of the primary amplitudes. This problem is confounded with towed-streamer type acquisitions due to the lack of recorded near offset reflections. Thus, shallow water demultiple workflows are often time-consuming and complex. MP-FWI imaging, on the other hand, is a multi-scattering least-squares method using the full wavefield, which contains primaries, multiples, and ghosts of the reflection and transmission arrivals to more completely sample the subsurface during the inversion. No complex shallow water demultiple workflows are required since the multiples are correctly mapped back to the reflectors that generated them and hence are used to improve the image quality as a whole. Multi-scattering arrivals which are often seen as "noise" to be removed in a conventional workflow are instead treated as valuable signals in MP-FWI.

In this paper we demonstrate for the first time the application of 3D visco-acoustic TTI MP-FWI imaging using the method outlined by McLeman et al. (2023) in a shallow water marine environment. We use MP-FWI imaging to simultaneously determine velocity and reflectivity to a frequency of 70 Hz on a marine dataset from offshore Sarawak, Malaysia and compare these results against those obtained from a conventional processing and imaging workflow.

Method

We consider a marine towed-streamer survey located approximately 34 km North-West of Miri, Sarawak, acquired in 1999. This is a shallow water environment with a 20-80 m water depth dominated by Oligo-Miocene deltaic siliciclastic marine deposition and regional growth faults which are downthrown basin-wards to the north and northwest. The acquisition setup consisted of two sources shooting flip-flop with 18.75 m interval and six streamers with a maximum offset of 4.6 km, separation of 150 m, and a nearest inline offset of 230 m. The initial velocity model was a smoothed legacy preSTM model, and the initial anisotropic parameters were derived using the available wells in the survey area.

Two workflows were then run in parallel, the first was a conventional model building workflow which contained diving wave tomography, reflection RMO tomography, diving wave FWI up to 24 Hz using the frequency continuation strategy of 5 Hz, 6.5 Hz, 8.5 Hz, 11 Hz, 14.3 Hz, 18.6 Hz, and 24 Hz, and then finally two more passes of reflection RMO tomography. This workflow required pre-processed data in order to obtain robust RMO picks in tomography. The second workflow only made use of the raw field data and first involved several passes of diving wave only FWI applied up to 12 Hz, followed by MP-FWI using reflections to simultaneously determine an updated velocity and reflectivity. The frequency continuation strategy for MP-FWI used maximum frequencies of 16 Hz, 20 Hz, 29 Hz, 41 Hz, and then 70 Hz. Half of the available shots were used at 16 Hz and all available shots were used from 29 Hz and above. Note that due to the limited offset, the maximum depth of penetration using the diving waves was approximately 1 km.

A key step in the success of the MP-FWI approach is obtaining a robust true-amplitude source wavelet. Incorrect wavelet amplitudes result in improper use of multiples and the incorrect estimation of subsurface reflector amplitudes. Near-field hydrophones (NFHs) were not available from this survey and so an initial far field signature was obtained using gun-array modelling. This was further refined, including amplitude calibration to the streamer hydrophones, using source inversion through FWI to better match the modelled and observed data and obtain robust reflectivity amplitudes.

Results

Figure 1 demonstrates Kirchhoff 3D TTI preSDM stacks using the initial model, conventionally-derived velocity model, and the MP-FWI imaging derived velocity overlaid with their respective velocity models. A checkshot velocity trend from a well located on the line demonstrated is also shown. The MP-FWI imaging derived velocity model more closely matches the well checkshot trend. PreSDM image gathers are shown in Figure 1d, 1e, and 1f for the same three cases, where the red dashed line indicates a 35-degree angle mute. The MP-FWI imaging derived velocity model shows a clear reduction in RMO in both the shallow and the deep.

Depth slices at 3 km comparing the initial velocity model, conventionally-derived velocity model, and the MP-FWI imaging derived velocity overlaid with their respective Kirchhoff preSDM stacks are shown in Figure 2. There is an increase in detail observed in the MP-FWI imaging velocity model, with the velocity trend successfully following the trends shown by complex geological structures. This has ultimately led to the improvement in RMO and focusing of the migrated image compared with the initial model, particularly in the deeper section.

The MP-FWI imaging derived reflectivity is depicted in Figures 3 and 4. To highlight the benefit, in Figure 3 a comparison is made between a conventional Kirchhoff 3D preSDM of pre-processed data, the MP-FWI derived reflectivity, and a Kirchhoff 3D preSDM of the raw data. Both Kirchhoff migrations used the MP-FWI-derived velocity model and the input data were bandpass filtered to 70 Hz to ensure a fair comparison. Note that the MP-FWI imaging result, which was derived using the raw field data as input, shows no multiple or ghost leakage and the result is zero-phased. This is expected as the approach allows for multi-scattering arrivals to be correctly mapped back to their generating reflectors, thus improving the subsurface illumination and sampling during the inversion. The MP-FWI imaging approach is essentially performing the model building and least-squares imaging in a single step with no requirement to pre-process the input data. The yellow circle in Figure 3c highlights a multiple “noise” train when migrating the raw data with Kirchhoff.

In Figure 4, a depth slice comparison at 2 km between the Kirchhoff 3D preSDM and the MP-FWI derived reflectivity is shown. The yellow circle shows an area of poor illumination caused by the complex geology and acquisition design. This causes washed-out zones in the final image when using only the primary arrivals to construct the imaged result. The MP-FWI imaging approach however shows much better continuity through this region and an improvement in amplitude balancing as a result of the inclusion of the multiples and least-squares approach.

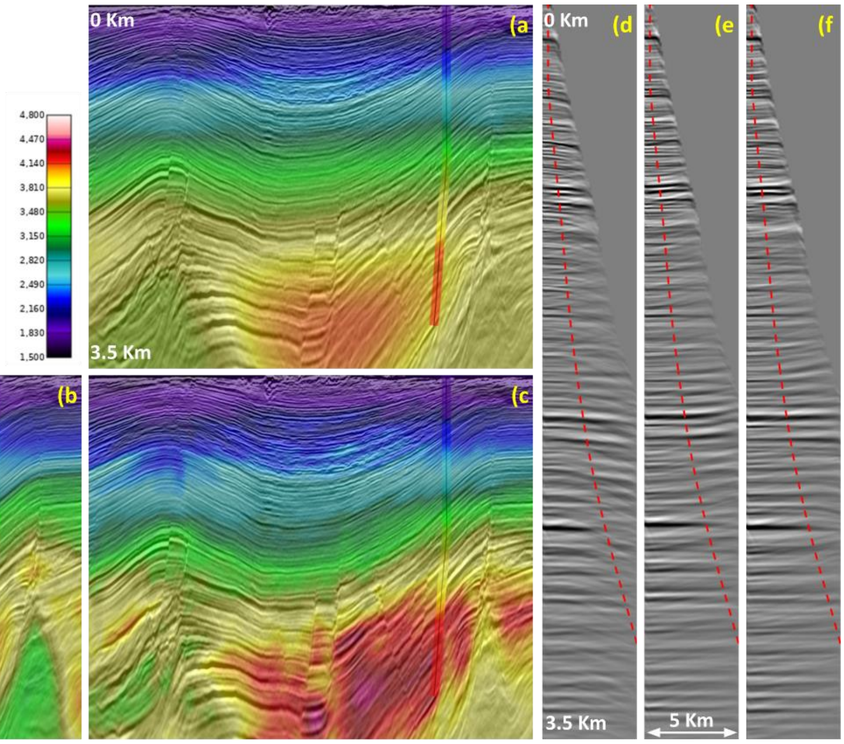

Figure 1 *3D Kirchhoff preSDM stacks comparison with velocity model overlay between a) the initial model, b) conventional workflow derived velocity model, c) the MP-FWI imaging derived velocity model. 3D Kirchhoff preSDM image gathers for a), b) and c) are shown in d), e), and f) respectively. The red dashed line indicates a 35-degree angle mute.*

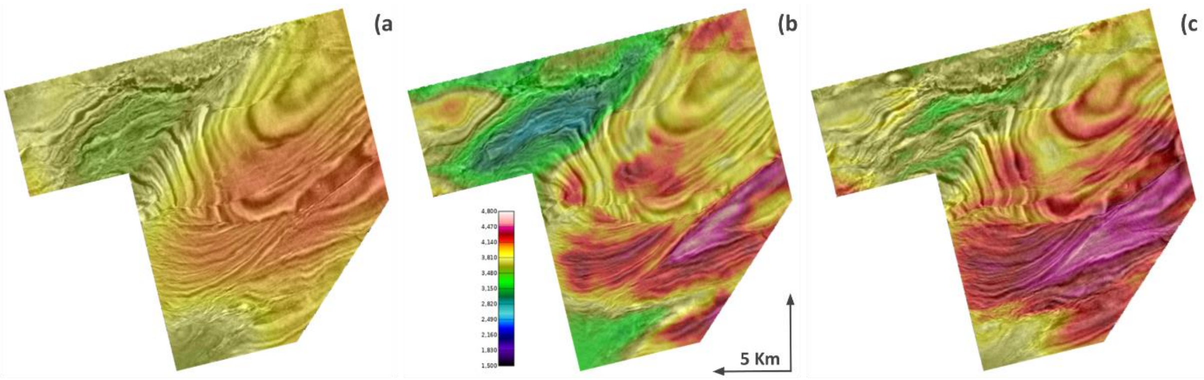

Figure 2 *Depth slice at 3 km comparing a) the initial velocity, b) the velocity derived from the conventional model building workflow and c) the final MP-FWI imaging derived velocity model, overlaid with their respective 3D Kirchhoff preSDM stacks.*

Conclusions

The MP-FWI imaging approach has demonstrated success in simultaneously deriving an updated velocity model and a reflectivity model in a shallow water marine environment. This velocity model was shown to provide an uplift in imaging with a reduction in RMO over the velocity model derived from the conventional model building workflow when used in a Kirchhoff preSDM, should such a workflow be desired. The reflectivity output from MP-FWI imaging demonstrated an improvement in subsurface illumination in the complex regions and improved amplitude balancing despite using only the raw field data as input. Furthermore, the MP-FWI imaging result was obtained in significantly less time than the conventional workflow. This further highlights the applicability of the MP-FWI approach to replace the conventional workflow.

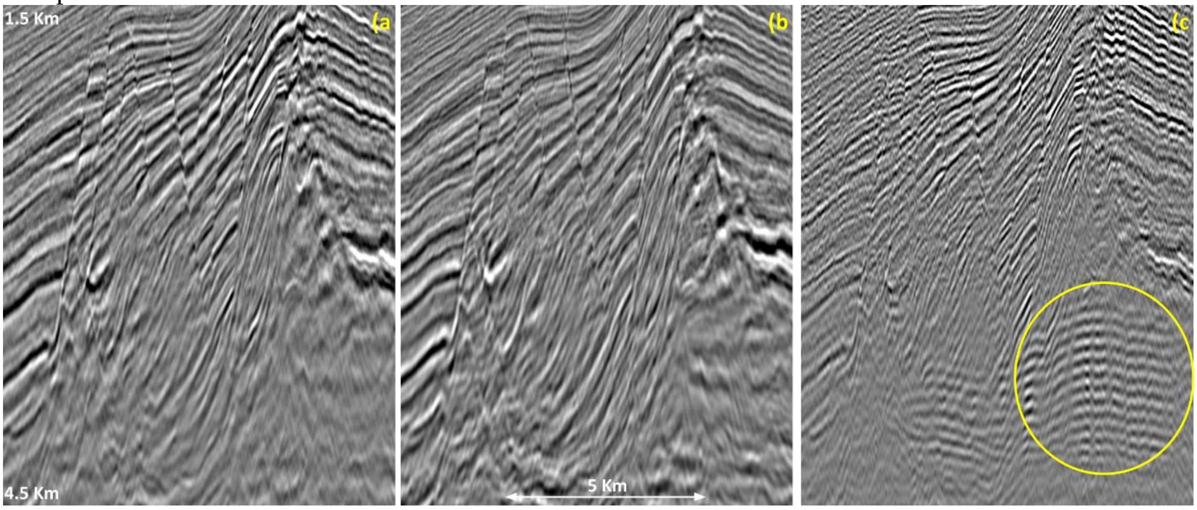

Figure 3 *A comparison between a) 3D Kirchhoff preSDM stack using pre-processed input data and the MP-FWI imaging derived velocity model, b) MP-FWI derived reflectivity using the raw field data, and c) 3D Kirchhoff preSDM stack using the raw field data as input and the MP-FWI derived velocity model.*

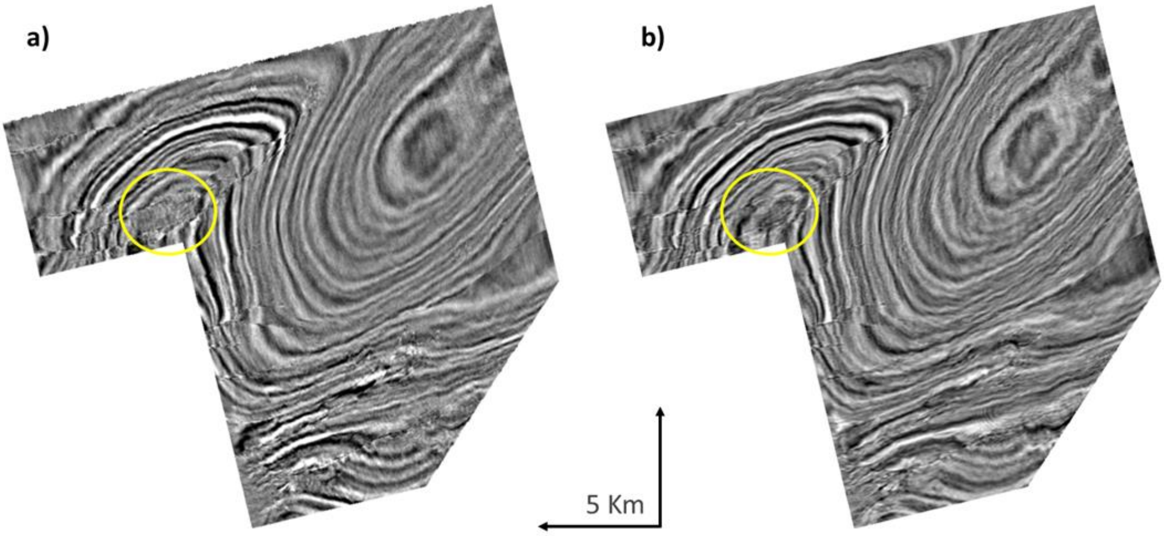

Figure 4 *Depth slice comparison at 2 km between a) Kirchhoff preSDM using pre-processed input data and the MP-FWI imaging derived velocity model, and b) MP-FWI reflectivity using the raw field data.*

Acknowledgements

The authors would like to thank DUG Technology (DUG) for permission to present this work and PETRONAS for permission to show the data examples presented.

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