High-frequency MP-FWI imaging and AVA for shallow targets: Barents Sea

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Summary

Multi-parameter full-waveform inversion (MP-FWI) imaging to simultaneously determine velocity and reflectivity offers an attractive alternative to the conventional pre-processing and imaging workflow for seismic data. The conventional approach involves the sequential application of many steps to remove multiples, ghosts, etc. Velocity model building in such a typical flow requires numerous iterations of tomography using RMO picking on migrated pre-processed gathers. MP-FWI imaging, on the other hand, can use minimally processed raw field data, including all multiples and ghosts, and a simple initial velocity model. In this paper, we apply 3D visco-acoustic MP-FWI imaging to a dataset from the Wistings area of the Barents Sea. Starting from a simple initial velocity from well information and minimally processed field shots, diving wave FWI and MP-FWI imaging alone were used to simultaneously update velocity and reflectivity to a maximum frequency of 110 Hz. Additionally, AVA-reflectivity volumes were generated using MP-FWI imaging to a maximum frequency of 85 Hz. For comparison, the velocity model generated from MP-FWI imaging was used to conventionally migrate a pre-processed version of the same field data. The results demonstrate that MP-FWI imaging provides higher-resolution images and improved AVA compared to the equivalent, conventionally processed data.

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Introduction

The development of multi-parameter full-waveform inversion (MP-FWI) imaging to simultaneously determine velocity and reflectivity offers an improved and attractive alternative to the conventional pre-processing and imaging workflow for seismic data. The conventional approach involves the sequential application of many subjective, challenging, and time-consuming steps. These steps are designed to remove components of the wavefield that do not satisfy the assumptions of conventional migration algorithms such as multi-scattering arrivals. Velocity model building in such a typical flow is similarly tortuous, with numerous iterations of tomography, each requiring carefully parameterised residual move-out (RMO) picking of pre-processed migrated gathers.

In contrast, MP-FWI imaging uses minimally processed field data and a simple initial velocity model. Separating the FWI kernel into kinematic and dynamic contributions (McLeman et al., 2023) allows the simultaneous determination of velocity and reflectivity. Crosstalk and relative scaling issues typical of multi-parameter inversions are addressed using a combination of an adaptive gradient scheme and L-BFGS (McLeman et al., 2021). Importantly, the inversion uses the full wavefield, including all multiples and ghosts that would typically be discarded during conventional pre-processing. MP-FWI imaging yields improvements over the primary-only approach, particularly in complex geological areas and in shallow water, where regions of sub-optimal imaging due to poor illumination can be resolved using the multiples.

In this paper, we apply 3D visco-acoustic MP-FWI imaging to a dataset from the Wistings area of the Barents Sea with shallow targets of 600-800 m depth. Starting from a simple initial velocity model derived from well information and a 2-layer Q model, diving wave FWI and MP-FWI imaging were used to simultaneously update velocity and reflectivity to a maximum frequency of 110 Hz. Additionally, MP-FWI imaging derived AVA-reflectivity volumes were generated to a maximum frequency of 85 Hz. For comparison, the velocity model generated from MP-FWI imaging was used to migrate a conventionally processed version of the same field data. The results demonstrate that MP-FWI imaging provides higher resolution images and improved AVA outputs compared to the equivalent, conventionally processed data.

Method

The Wistings area of the Barents Sea presents numerous processing and imaging challenges. The area is characterised by strong multiple generators including a hard, rugose seabed and a very shallow unconformity with a strong impedance contrast. The primary target is a heavily faulted, shallow reservoir that requires a high degree of resolution for accurate imaging. Water depths within the survey area ranged between 400-475m.

We consider data from two near orthogonal surveys acquired in a single campaign using a novel 'Half-Seis' configuration (Dhelie et al., 2023), which tows 12 × 4000 m long streamers (separated by 50 m) with four sequentially fired 625 cu. in. sources spaced 62.5 m apart, positioned above and 250 m behind the first receiver group. The small volume, compact source and shot interval of 6.25m provides data with fine spatial sampling, while the source positioning over the cables provides near and genuine zero-offset information which is typically missing in a conventional towed streamer set-up. While these acquisition features are tailored to address the challenges of the survey area, realising these benefits using a conventional pre-processing and imaging flow remains challenging, time-consuming, and still limited by primary-only imaging algorithms. In order to explore potential imaging improvements with this bespoke dataset, MP-FWI imaging was pursued in parallel to the conventional approach.

The initial velocity and anisotropy models used to begin FWI were derived from available well information and extrapolated across the survey area. The input seismic data were field data with minimal pre-processing applied. As a result, the final velocity model produced was entirely derived using only well information and FWI without any of the conventional processing and velocity model building steps.

We applied diving wave FWI to a maximum frequency of 18 Hz to constrain shallow sharp lateral velocity variations. The 4000 m streamer provided diving wave penetration deeper than the shallow targets. MP-FWI imaging was then carried out to simultaneously determine velocity and reflectivity models stepping up in frequency through 18 Hz, 22 Hz, 30 Hz, 45 Hz, 60 Hz, 85 Hz, and 110 Hz. In addition to the full offset reflectivity volume, true-amplitude angle reflectivity volumes were produced for AVA analysis at 85 Hz for near (0-15°), mid (15-30°), and far (30-45°) angle ranges.

Results

The development of the velocity model from a simple, well-derived trend, through to the final MP-FWI model using up to 110 Hz is shown in Figure 1. Improvements in the resolution of the velocity field are immediately clear, with sharp lateral features conformable to the faulting, subtle velocity inversions within the fault blocks, and an improved tie to the well check-shot velocities being observed. The improvement in gather flatness is obvious in Figure 1 c) and d).

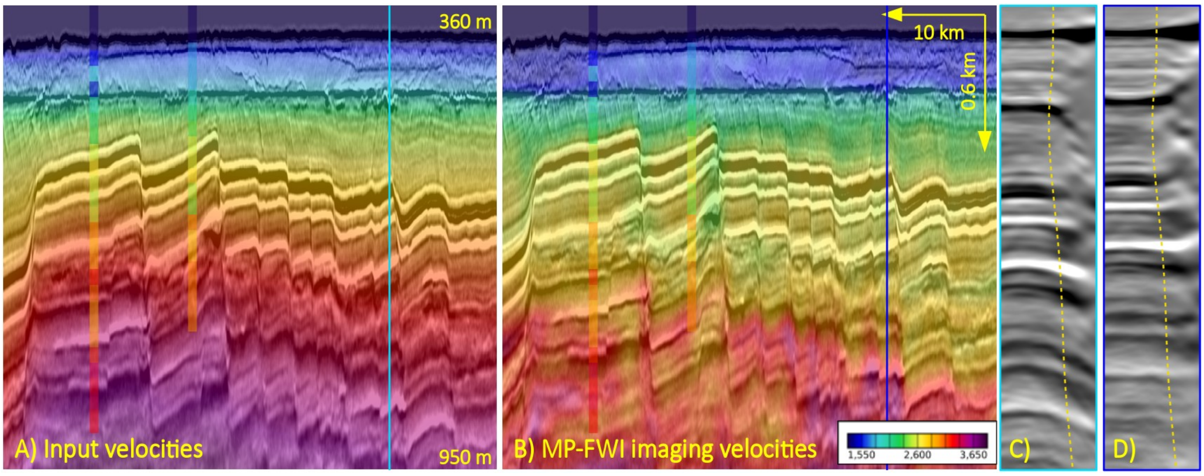

Figure 1 (a) *The initial velocity model before FWI overlain on its Kirchhoff preSDM stack and two check-shot velocity profiles, (b) the updated 110 Hz MP-FWI imaging velocities overlain on its corresponding Kirchhoff preSDM stack, (c) Kirchhoff preSDM image gathers using the initial velocity, and (d) with the updated 110 Hz MP-FWI imaging velocities. A 35 degree mute is annotated. The improvement in gather flatness from the initial gather (cyan) to the 100 Hz MPFWI gather (dark blue) is clear.*

The reflectivity output from MP-FWI is presented in Figures 2 & 3. A Kirchhoff preSDM, migrated using the MP-FWI imaging velocities and conventionally pre-processed input data limited to 110 Hz maximum frequency, is also shown. The MP-FWI reflectivity, generated from field data using a much-simplified workflow relative to the conventional Kirchhoff preSDM, shows imaging improvements in the vertical section as well as noticeably sharper fault delineation on the depth slices.

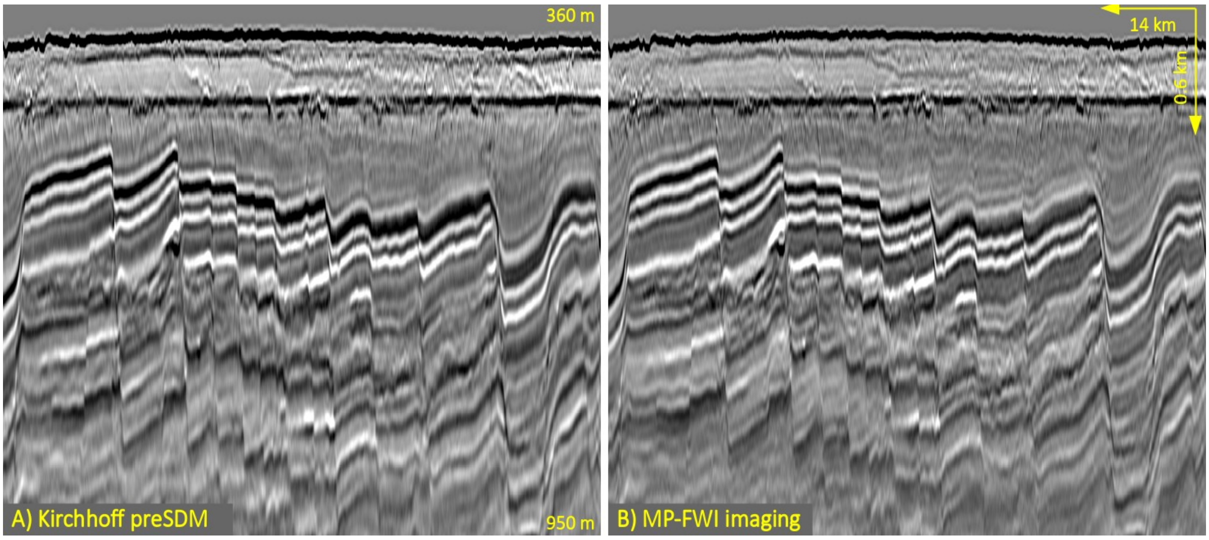

Figure 2 (a) *Arbitrary line section for (a) conventional Kirchhoff pre-SDM migrated using 110 Hz filtered input data, and (b) 110 Hz MP-FWI imaging reflectivity.*

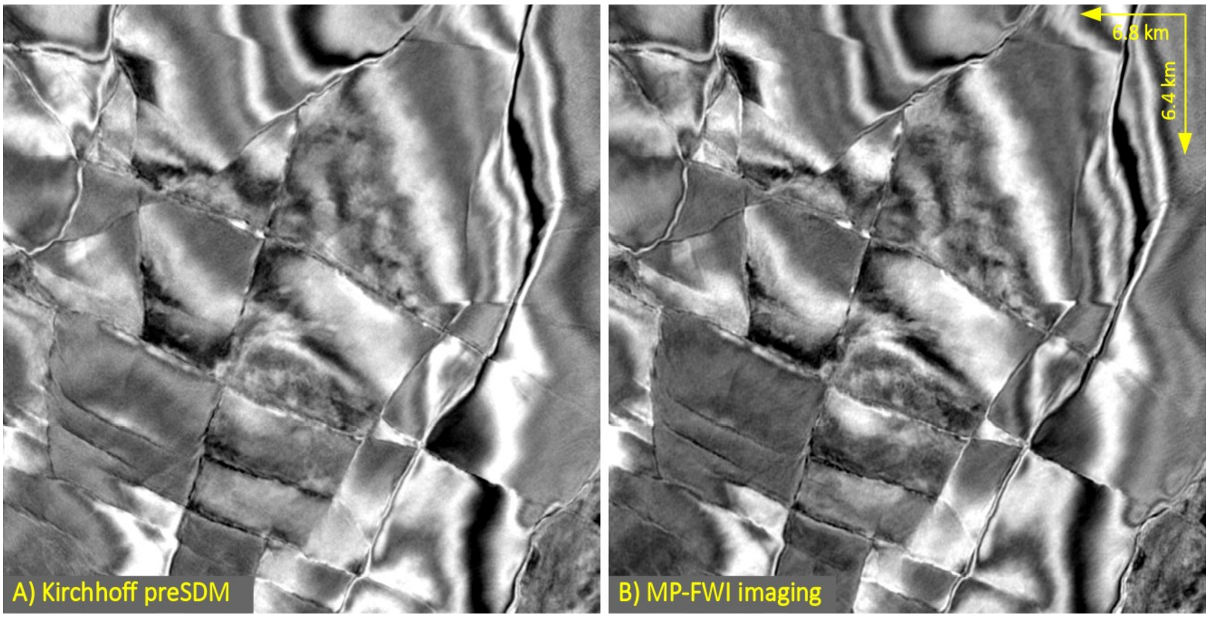

Figure 3 (a) *660 m depth slice for (a) conventional Kirchhoff preSDM migrated using 110 Hz filtered input data, and (b) 110 Hz MP-FWI imaging reflectivity.*

An analysis of the angle-reflectivity is shown in Figure 4 comparing well-based AVA synthetics to both the corresponding Kirchhoff preSDM stack and the MP-FWI imaging angle-reflectivity. Both the Kirchhoff preSDM and MP-FWI imaging show good ties to the synthetic for the near and mid-angle range, while the far-angle MP-FWI imaging result shows an improved tie compared to the Kirchhoff preSDM.

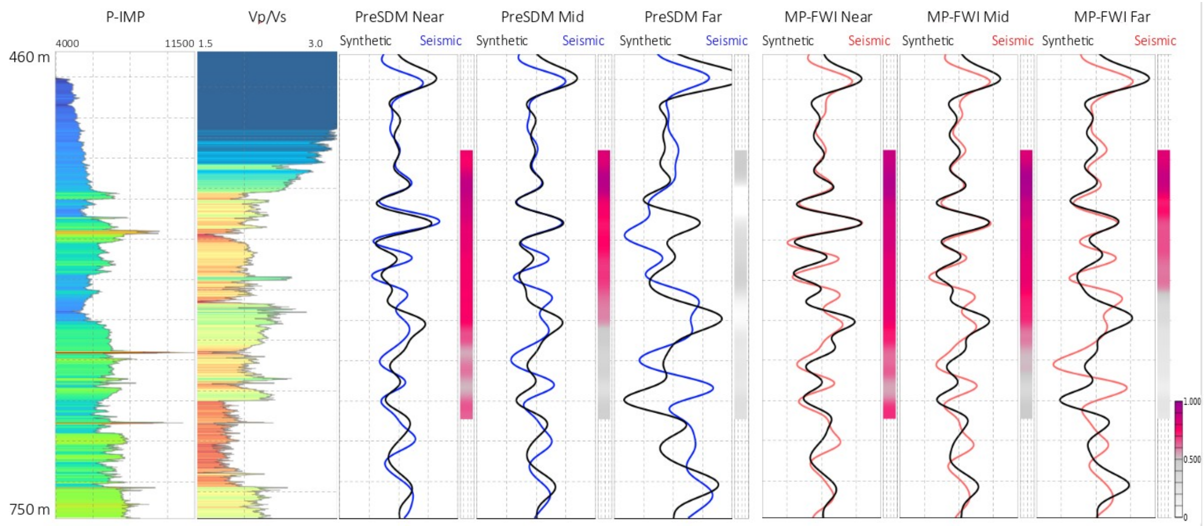

Figure 4 (a) *Well logs and AVA synthetics (black) compared to Kirchhoff preSDM (blue) and MP-FWI imaging (red) responses for near, mid, and far angle ranges. Cross correlation coefficients are shown alongside and display an improved match between the MP-FWI imaging and the corresponding well synthetics, particularly for the far angle range.*

Conclusions

Diving wave FWI and 110 Hz MP-FWI imaging has successfully generated a robust velocity model starting from a simple, well-derived input without the need for pre-processed or legacy seismic data as part of the model-building workflow. The reflectivity output from MP-FWI imaging provides an increase in image quality, particularly in lateral resolution, relative to an equivalent conventional Kirchhoff preSDM. The MP-FWI imaging angle-reflectivity volumes show an improved match to well-synthetic traces.

The ability of MP-FWI imaging to produce high-resolution velocity and reflectivity models starting from minimally processed field data and very simple initial models demonstrates that it can produce results better and faster than conventional processing approaches.

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