HIGH-RESOLUTION FWI IMAGING - AN ALTERNATIVE TO CONVENTIONAL PROCESSING

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Summary

The inclusion of reflections in full waveform inversion (FWI) not only allows for deeper velocity model updates but also provides an opportunity to simultaneously generate an intercept-reflectivity model derived through multi-scattering least-squares imaging. We demonstrate a novel approach to simultaneously invert for velocity and intercept-reflectivity vector at high frequencies directly with FWI. These models can be achieved ahead of the conventional processing and imaging workflow and are fit for quantitative analysis. Given that FWI can use the primaries, multiples and ghosts present in the raw field data, the resulting intercept-reflectivity image is generated from signals which more completely sample the subsurface in comparison to, for example, LS-RTM or Kirchhoff which use only primaries. This yields improved illumination, a reduction in acquisition footprint and an increase in resolution. The derived velocity model is suitable for use in conventional imaging techniques, if desired, and demonstrates an improvement in image gather move-out without the need for further conventional reflection tomography. This approach is demonstrated to high frequency using a dataset from the Australian North-West continental shelf.

High-resolution FWI imaging - an alternative to conventional processing

Introduction

Full waveform inversion (FWI) using diving waves is a well-established tool in the model building workflow for producing high-resolution subsurface velocity models. The penetration depth of diving waves is, however, limited by the maximum acquired offset and geological setting. Many target reservoirs lie beneath the diving wave penetration depth so conventional reflection tomography is typically also used to achieve deeper model updates. However, such a solution is often limited in resolution, requires pre-processed data for robust residual moveout picks, and can be ineffective where ray-based approximations break down. FWI using reflections can, with special care, be a successful alternative since it is not bound by such limitations.

In addition to an updated velocity, the inclusion of reflections in FWI provides an opportunity to generate an interpretable product ahead of the conventional processing and imaging workflow. FWI can take raw field data as input and invert for a high-resolution least-squares image that is free of the source signature, source and receiver ghosts and multiples. A common method is to include reflections in a high-frequency, single parameter FWI to derive an interpretable model (Letki et al., 2019), the derivatives of which can form a pseudo-reflectivity image (Kalinicheva et al., 2020; Zhang et al., 2020). These can provide excellent fast-track structural images but *a priori* assumptions about density impose significant limitations on the amplitude fidelity of the results.

To overcome these limitations, kinematic and dynamic contributions to the FWI kernel must be separated. The method described by McLeman et. al. (2021) uses an augmented acoustic wave equation to simultaneously estimate velocity and AVA-related reflectivity. Tomographic and migration terms are discriminated by scattering angle using non-stationary filters applied as a wavenumber-domain preconditioner. Crosstalk is mitigated through an advanced quasi-Newton adaptive-gradient optimiser which has the added benefit of significantly improving the rate of convergence. This approach has two important benefits: the velocity model generated is appropriate for conventional imaging purposes if required and the intercept-reflectivity provides a kinematically correct imaging product with physically realisable amplitudes suitable for quantitative analysis.

In this paper, we continue the work of McLeman et al. (2021) to simultaneously invert for velocity and the intercept-reflectivity vector using 3D FWI up to frequencies of 85 Hz on a real dataset from the Australian North-West Shelf.

Method

The Duyfken 3D survey is a conventional towed-streamer acquisition located approximately 115 km northwest of Barrow Island. Localised channelling has resulted in rapid, lateral velocity contrasts which are difficult to resolve as part of a conventional tomographic velocity model building scheme. The data were acquired with a dual-source, 8 streamer configuration with 6 km maximum offset. An initial model was built using an existing regional model with diving-wave FWI applied to a maximum depth of approximately 2 km and a maximum frequency of 16 Hz.

Analysis of direct-arrival energy indicated that there existed a moderate level of source signature variation across the survey so per-shot signatures were derived using an FWI source-inversion scheme. FWI using reflections was then run using raw field data with a 45-degree outer angle mute applied, beginning with a maximum frequency of 16 Hz, using 1/8 of the available input shots. An increasing number of shots were input as higher frequencies were gradually introduced culminating with all shots being used at 85 Hz maximum frequency.

In this instance, anisotropy remained fixed but simultaneous velocity, intercept-reflectivity and epsilon inversion is possible as described in a companion paper (McLeman et al., 2022). Delta can be updated by calibrating well markers to picked events from the intercept-reflectivity volume.

Results

A depth slice through the initial velocity model and the 85 Hz FWI velocity model at 1.95 km depth are shown in Figure 1. There is a dramatic increase in spatial resolution of the velocity field, with localised high and low-velocity anomalies captured by the FWI model, leading to significantly improved structural simplicity of the deeper events.

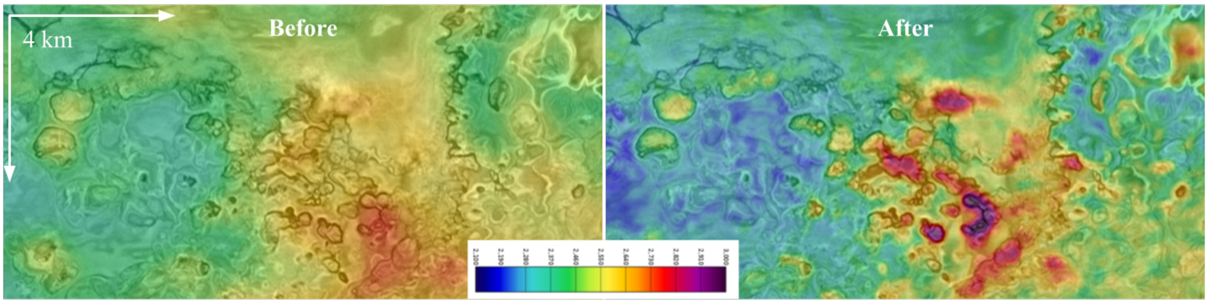

Figure 1 *1.95 km depth slices for (left) the initial velocity model before FWI overlain on a Kirchhoff preSDM stack and (right) the updated FWI model overlain on a corresponding Kirchhoff preSDM stack.*

Figure 2 demonstrates the impact that the updated model has on conventional imaging. Kirchhoff pre-stack depth migrations using pre-processed input data show that image gathers exhibit less residual move-out after the FWI update at all depths. The full-stack section has simplified structure at depth which is a result of the rapid, lateral velocity variations in the overburden being better resolved in the velocity model.

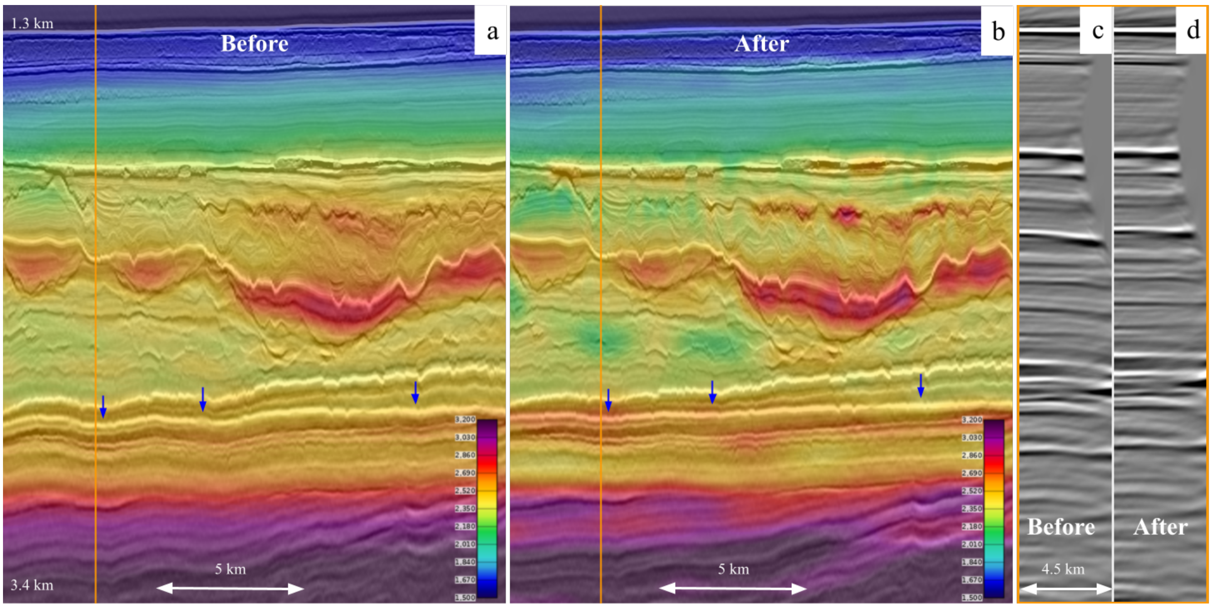

Figure 2 *(a) the initial velocity model before FWI overlain on a Kirchhoff preSDM stack, (b) the updated FWI model overlain on a corresponding Kirchhoff preSDM stack, (c) Kirchhoff preSDM gathers using the initial velocity and (d) using the updated velocity.*

The additional output from this process, the intercept-reflectivity, is presented in Figures 3 and 4. For comparison, a conventional imaging algorithm (Kirchhoff preSDM) and an advanced algorithm (image-domain least-squares RTM) are shown. Both use the field data after conventional processing, limited to 85 Hz maximum frequency for a fair comparison, as input. The least-squares RTM shows a significant increase in spatial resolution compared to the preSDM. The FWI intercept-reflectivity image, derived in an iterative least-squares manner directly from field data, delivers further improvement with additional details apparent in the depth slices and vertical sections. The FWI image is zero phase and shows no sign of the multiple or ghost energy present in the input data. We conclude that FWI has successfully handled designature, deghosting, demultiple, as well as model building and least-squares imaging.

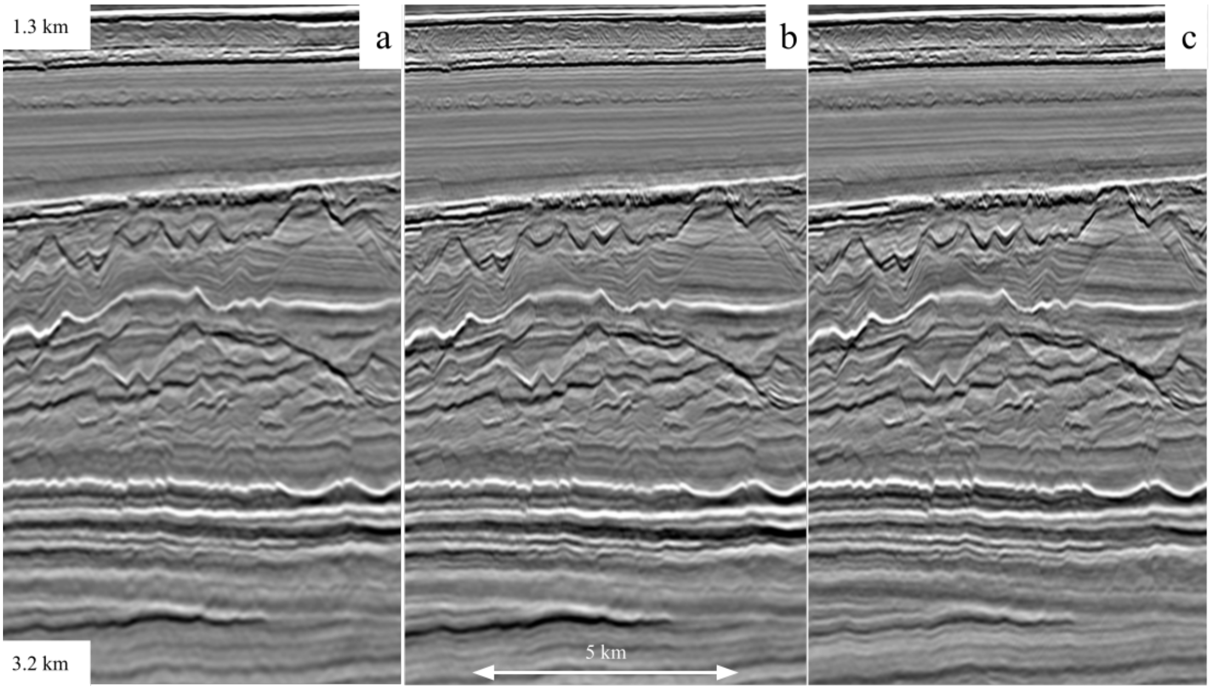

Figure 3 *a crossline section through a (a) conventional Kirchhoff preSDM, (b) least-squares RTM and (c) FWI derived intercept-reflectivity.*

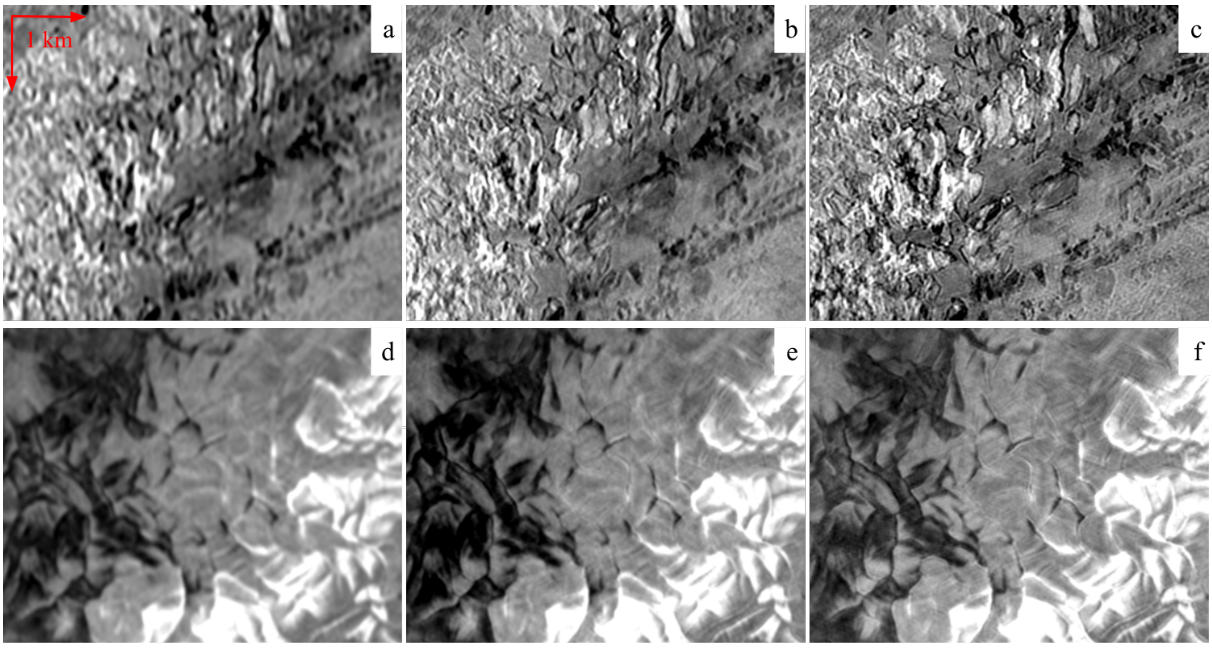

Figure 4 *depth slice at 1.5 km through (a) a conventional Kirchhoff preSDM, (b) least-squares RTM and (c) FWI derived intercept-reflectivity. Depth slice at 2.5 km through (d) a conventional Kirchhoff preSDM, (e) least-squares RTM and (f) FWI derived intercept-reflectivity.*

Geological features such as faults and channel boundaries can be readily highlighted by also examining various combinations of the components of the reflectivity vector, for example, the norm of its horizontal components. Figure 5 shows a depth slice comparing intercept-reflectivity (left) and horizontal intercept-reflectivity (right).

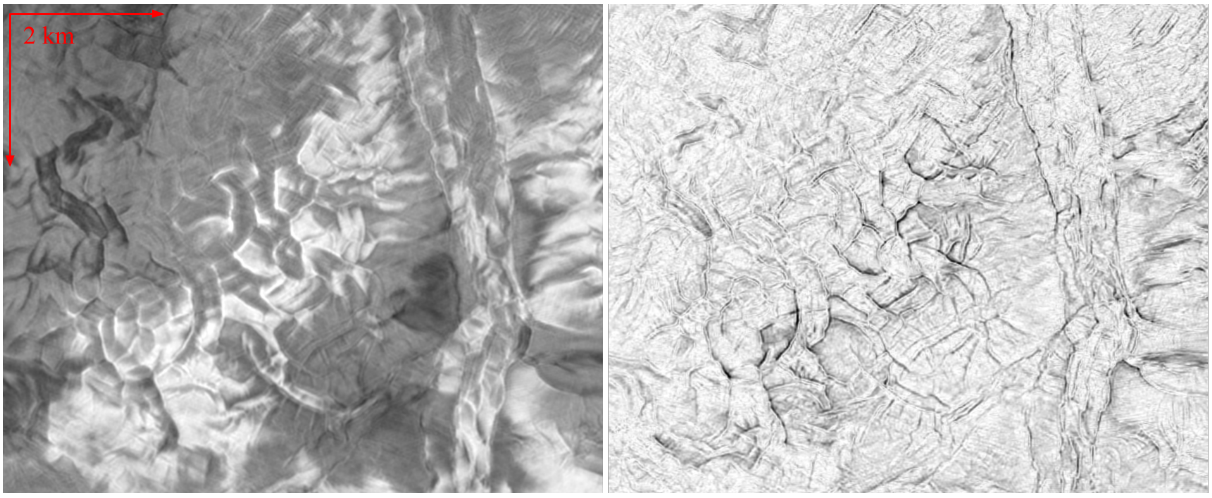

Figure 5 *a depth slice at 2.5 km through (left) the intercept-reflectivity and (right) the horizontal intercept-reflectivity.*

Conclusions

We have demonstrated high-frequency imaging using a novel, simultaneous full waveform inversion for velocity and intercept-reflectivity vector using primaries, ghosts and multiples. The separation of dynamic and kinematic effects generates a high-resolution velocity model and an intercept-reflectivity image that provides an increase in resolution compared to a Kirchhoff migration and least-squares RTM. The horizontal intercept-reflectivity can also provide additional insight into the subsurface by highlighting the change in lithology of complex fault and channel structures, further aiding interpretation.

The ability of full waveform inversion to handle traditional processing steps such as deghosting, demultiple and designature whilst inverting for a range of parameters such as velocity and intercept-reflectivity demonstrates the potential to supersede conventional approaches to processing and imaging.

Acknowledgements

We would like to thank Multi-Client Resources (MCR) for permission to use the BEX MC3D dataset and DUG Technology (DUG) for allowing us to present this work.

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