FWI Imaging: the future or merely derivative?

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Summary

Creating images from high-resolution FWI models by taking some form of the spatial derivative of the velocity has quickly become a popular way to generate reflectivity images, typically called FWI Imaging. FWI imaging offers the possibility of high-quality and high-resolution in a more simplified workflow compared to the conventional processing, model building and imaging workflow. Such images are being increasingly used as alternatives or even replacements of the conventional, or least-squares, Kirchhoff and RTM products.

Using data examples of FWI imaging we demonstrate its benefits; after drawing conclusions we consider some of the challenges of working with FWI imaging that have formed the basis of ongoing or recently completed work.

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Introduction

Creating images from high-resolution FWI models by taking some form of the spatial derivative of the velocity has quickly become a popular way to generate reflectivity images, typically called FWI Imaging. FWI imaging offers the possibility of high-quality and high-resolution in a more simplified workflow compared to the conventional processing, model building and imaging workflow. Such images are being increasingly used as alternatives or even replacements of the conventional, or least-squares, Kirchhoff and RTM products (Jones et al., 2023).

FWI imaging has developed rapidly over the last few years. Kalinicheva et al. (2020) demonstrated that the 1D derivative of a high-resolution FWI velocity model creates an estimate of reflectivity that exhibits improved imaging compared to conventional imaging techniques. Zhang et al. (2020) improve the imaging of dipping events by employing a 3D derivative along the normal to the dominant dip direction. McLeman et al. (2021) invert directly for the intercept-reflectivity as part of a multiparameter full waveform inversion.

Here we present examples from two projects in which FWI imaging was applied to high-resolution FWI velocity models. The FWI images are computed using a plane wave destructor method that is functionally equivalent to taking the 3D derivative. Using these examples, we demonstrate the benefits of FWI imaging; after drawing conclusions we consider some of the challenges of working with FWI imaging that have formed the basis of ongoing or recently completed work.

Results: Brazil

The first example comes from a narrow azimuth towed streamer survey from the Campos Basin, offshore Brazil. Dynamic matching FWI (Mao et al., 2020), utilising diving waves and reflections, was used to build a velocity model incorporating post-salt, salt and pre-salt. The maximum offsets in the data are 10 km and the FWI was run to a maximum frequency of 14 Hz. The final velocity model is shown in Figure 1.

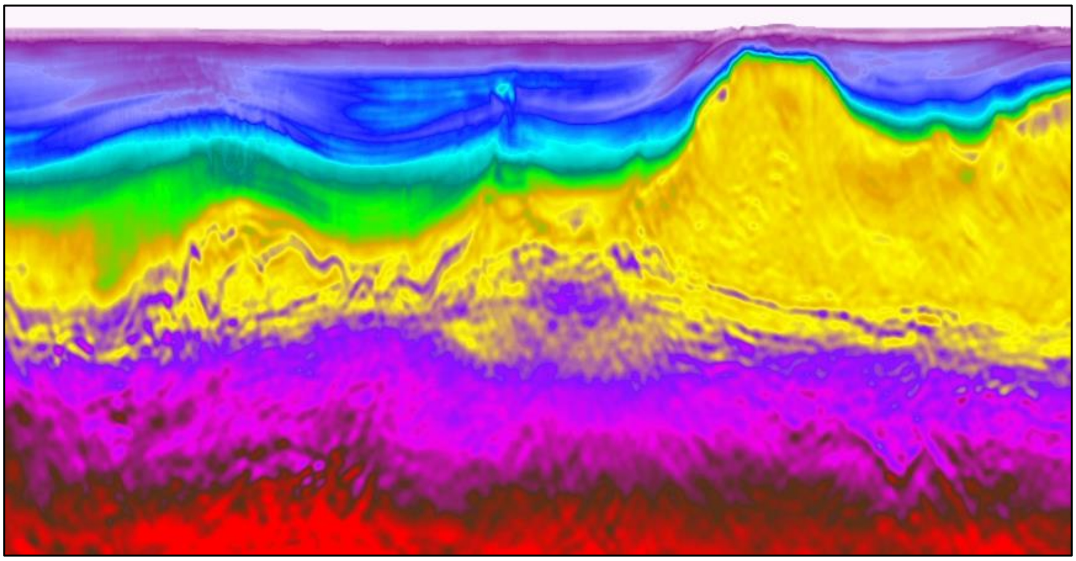

Figure 1*: Final DM FWI velocity model, Campos Basin, Offshore Brazil*

Figure 2 shows a detail from the velocity model (Figure 2a) in conjunction with the FWI image (figure 2b) and a reverse time migration (RTM, figure 2c). The green arrows in figure 2b pinpoint an area where the FWI image picks out greater complexity in faulting that is not well illuminated in the RTM image. This comparison nicely illustrates the capabilities of FWI to improve areas of poor illumination, which derives from the non-linear nature of full-waveform inversion.

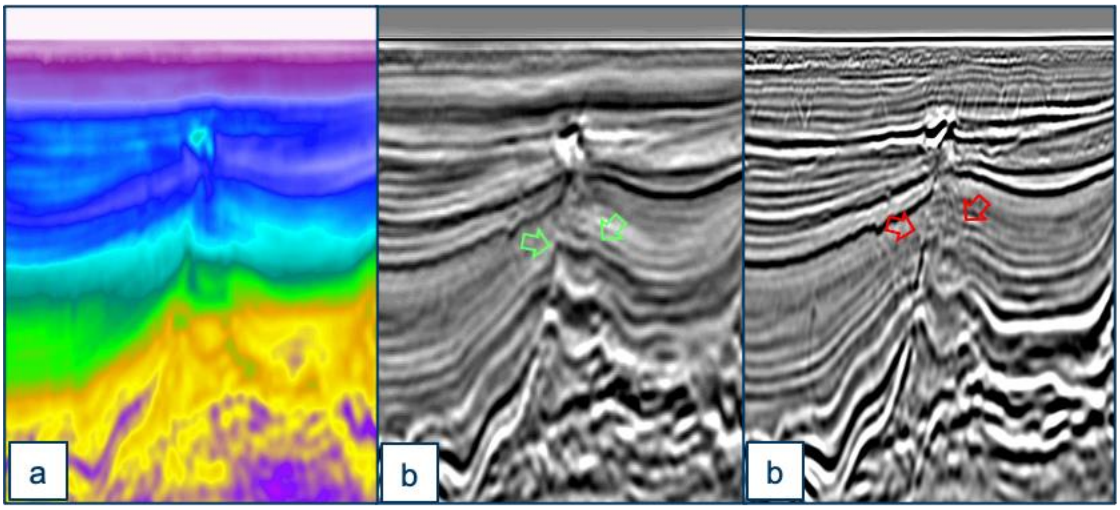

***Figure 2**: a) detail from the DM FWI model shown in figure 1; b) 3D FWI image derived from the model in panel a); b) RTM image.*

Figure 3 shows a comparison of the pre-salt section, traditionally a challenging environment because of the effect of the complex salt structures on the seismic wavefield. FWI imaging can compensate for these effects as can be seen in the areas highlighted by the green arrows on Figure 3a, which indicates places where the FWI image has improved the illumination and imaging of rotated fault blocks and fault planes in the pre-salt section, compared to the RTM image.

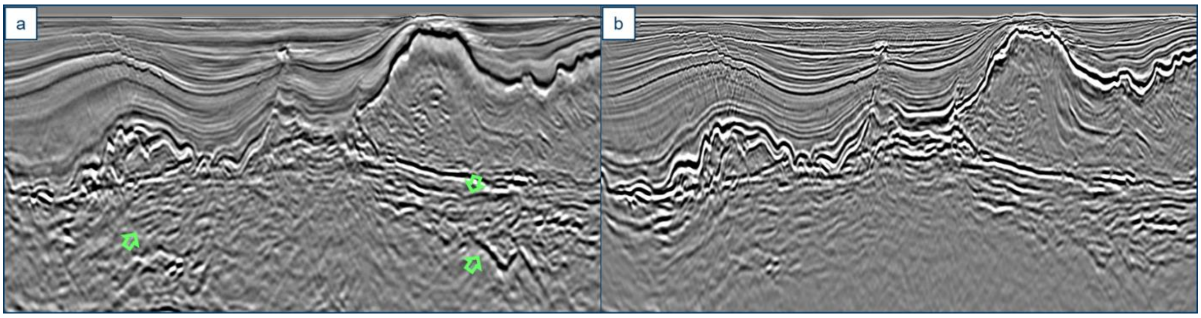

Figure 3: a) *3D FWI Imaging using the DM FWI model in figure 1; b) RTM image.*

Results: West of Shetlands

The second example comes from the North Sea (Wang et al., 2021). The challenge here was to build a high-resolution velocity model using dense OBN data acquired over the Clair field in the West of Shetlands region of the North Sea. The source sampling was 25 m x 25 m and the receiver spacing was 50 m x 100 m.

Figure 4) shows the results of the final FWI model (figure 4b), compared to the initial model (figure 4a). FWI effectively resolves the shallow high-resolution high-velocity anomalies and brings improvement to the deeper structures. These improvements to the model are reflected in the RTM images shown in figures 4c and 4d. In figure 4d (the RTM image using the updated FWI model) the shallower events exhibit less undulations and are better focussed while deeper reservoir events are also more geologically reasonable (less 'wavy') and better focussed.

Figure 5 compares an RTM (figure 5b) with a 3D FWI image derived from the FWI model in figure 4b. Comparing the results, we can see that the FWI image is sharper and possess greater clarity over the

RTM image. Furthermore, the FWI image has less migration artefacts and a greater signal to noise ratio. In addition, the FWI image appears to contain some meaningful reflectors that are absent from the RTM image.

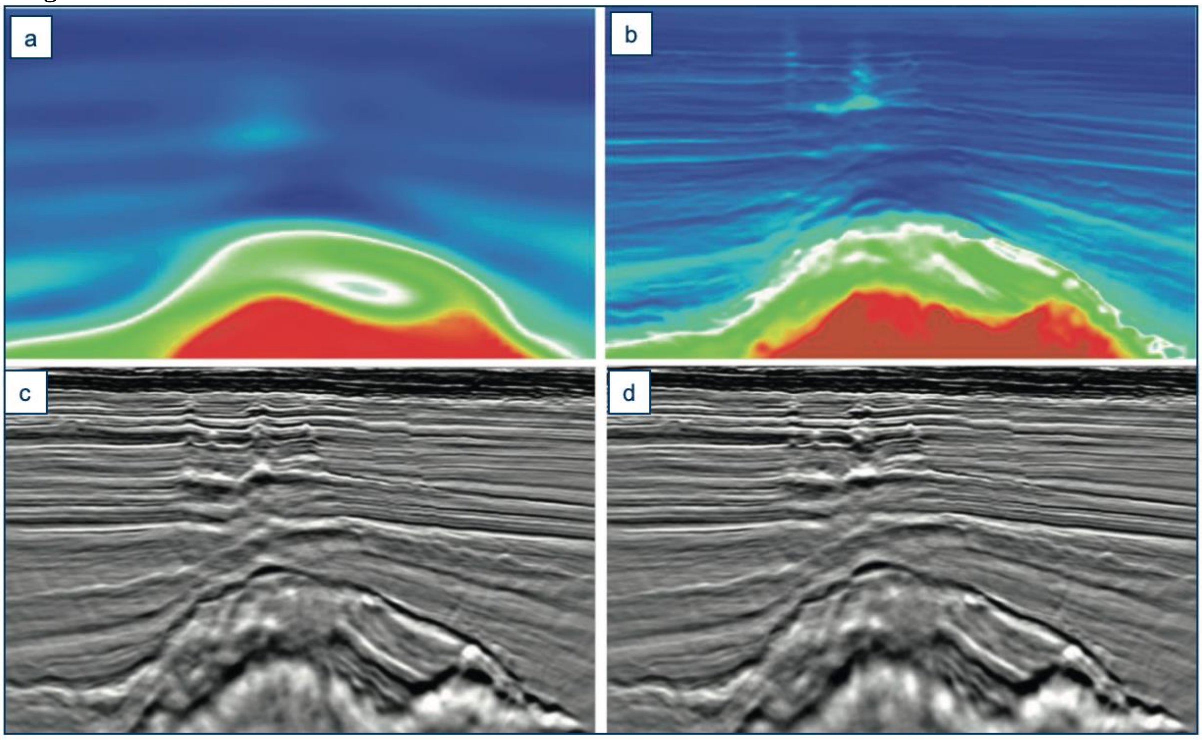

Figure 4 *(from Wang et al, 2021): a) initial velocity model; b) final DM FWI velocity model; c) RTM with initial model; d) RTM with final FWI model.*

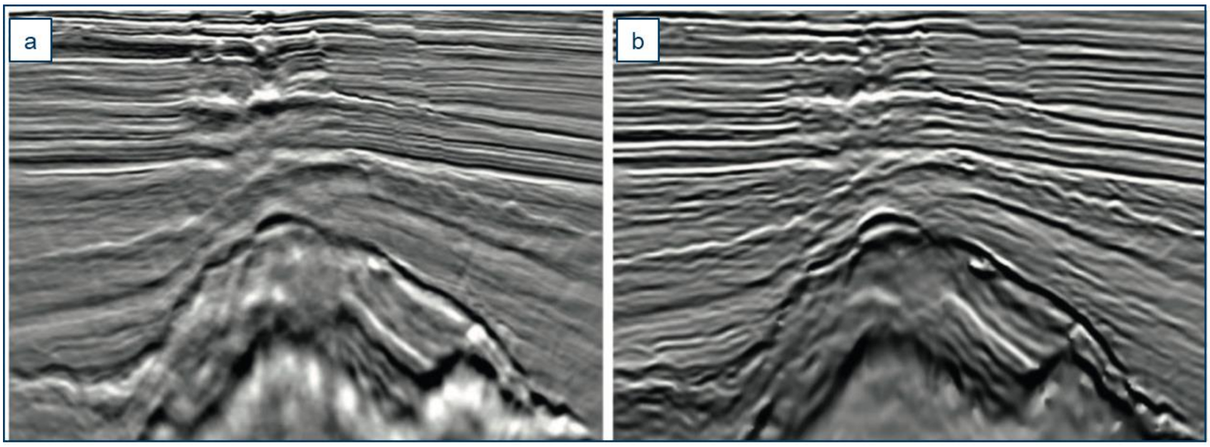

Figure 5 *(from Wang et al, 2021): a) RTM with final velocity model; b) 3D FWI Image of the model in figure 4b.*

Conclusions

We have shown results from FWI imaging using data from two different geological settings and acquisition styles: pre and post salt sediments from narrow azimuth towed streamer acquisition offshore Brazil and shallow water North Sea high density OBN data. In both cases 3D FWI imaging using high resolution FWI velocity models is able create images as good or better than RTM images using the same model. The FWI images show improved focussing, S/N ratio, resolution and illumination compensation compared to RTM.

These examples demonstrate the clear benefits that follow from applications of FWI imaging. However, several questions remain and an understanding of them is being developed in work currently underway.

One of these relates to the pre-processing applied to the data. For example, multiple energy, especially interbed multiple, can create artefacts in the FWI model, which then appear in the FWI image. These artefacts can be addressed by application of interbed multiple removal, but to do so challenges the assumption that high quality FWI images can be produced quickly from raw data without significant pre-processing.

As FWI is run to higher frequencies traditional QC approaches, especially those that rely on gather flatness and image QCs are reduced in effectiveness. Alternative QCs such as cross-correlations or NRMS between the RTM and FWI image can provide additional assurance that the FWI model is developing in a good direction or highlight areas for further investigation.

Warner et al. (2022) have shown that AVO information can be extracted from acoustic FWI run on data divided into limited offset ranges, however certain types of AVO anomaly, for example class 2p anomalies that exhibit a polarity reversal as offset increases, pose challenges to acoustic FWI and prompt a consideration of the role of density or pseudo-density in the inversion and of the portion of the wavefield to be inverted (e.g. near or far angle ranges).

Acknowledgements

The authors would like to thank TGS multiclient for permission to publish the Brazil data examples and Leon Ge and Seet Li Yong for their work on the project.

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