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High-Resolution Reflection FWI

M. Warner* (S-Cube), T. Nangoo (S-Cube), A. Umpleby (S-Cube), N. Shah (S-Cube), G. Yao (S-Cube)

Summary

We demonstrate reflection FWI on a less-than-ideal 3D narrow-azimuth towed-streamer dataset that contains little refracted energy and that is deficit in low frequencies. We begin from a very simple starting model built rapidly from stacking velocities. We fist use an FWI scheme that alternates between a migration-like and a tomography-like stage, showing that this can both recover the background velocity model and generate high vertical resolution. We follow this by using global inversion to build the long-wavelength anisotropy model. Finally, we use more-conventional reflection-based FWI to introduce the full range of wavelengths into the recovered velocity model, and show that this both migrates the reflection data and is structurally conformable with the reflections.

Introduction

Currently, there are broadly two flavours of full-waveform inversion in widespread commercial use. The more usual of the two is driven principally by low-frequency minimally-processed amplitude-normalised long-offset refracted arrivals, and it is typically used to build full-bandwidth high-resolution relatively shallow p-wave velocity models for improved depth imaging and hazard identification. The less-usual but still widely used version of FWI is driven principally by higher-frequency short-offset pre-processed sub-critical true-amplitude de-ghosted de-multipled primary reflections, and is designed typically to build high-wavenumber impedance models for high-resolution quantitative reservoir characterisation. The first approach is exemplified in Warner et al. (2013), and the second in Routh et al. (2017). Both these approaches rely upon conventional velocity-model-building tools in order to build a high-quality starting model including anisotropy.

In this paper, we demonstrate a third approach to FWI in which the aim is to dispense with the need for a high-quality starting model, building the entire velocity and anisotropy model from scratch using FWI applied directly to reflection-dominated data recorded only to moderate offsets without significant pre-processing. The intention is to build a velocity model, using reflection FWI, that recovers all wavenumbers present in the model including both the low wavenumbers that would more usually be generated using reflection tomography, and the intermediate wave numbers that would more-usually be recovered by FWI using refractions. Our approach differs from most other practical reflection FWI algorithms (Gomes & Chazalnoel, 2017; Vigh et al., 2017) which aim to make small adjustments to a final model that already provides a good fit to the data.

Method

In this demonstration, we begin from a simple, smooth, isotropic velocity model that approximately predicts moveouts on time-migrated gathers. Such a velocity model can be built for most datasets within a few days of the data becoming available for processing. When more accurate legacy models are already available, then these can also provide a ready starting point.

The first stage is to use a form of reflection FWI that seeks to match the kinematics of primary reflections in the data to build a long-wavelength background velocity model. We do this principally by separating the migration-like and tomography-like aspects of conventional FWI, alternating between the two. In one iteration, we build reflectors into a smooth model; in the next iteration, we use the moveout predicted for those reflectors to update the smooth model. In doing this, it is important to fully separate the two aspects of FWI without compromising spatial resolution. It is also important to take proper account of the non-linear interaction between the two iterations since absolute reflection travel times change when the smooth background model is updated. Raw primary amplitudes are affected by density, attenuation, elasticity and anisotropy as well as velocity, so it is also important at this stage that the FWI algorithm is robust in the presence of unmatched amplitude anomalies. We operate with raw field data containing multiples, so the FWI algorithm must also be able to match the kinematics and dynamics of multiples accurately. We demonstrate the efficacy of the first-stage algorithm on a simple synthetic before applying the full scheme to a 3D field dataset.

The second stage is to build the initial anisotropy model. We do this using global FWI to build a smooth anisotropy model, simultaneously using local gradient-descent FWI to refine the corresponding higher-resolution velocity model. We have previously demonstrated this form of global inversion on other field datasets (Debens et al., 2015) and do not discuss it further here. The third and final stage is to apply more-conventional reflection-based FWI to the full dataset, introducing the difficult intermediate wavelengths below the depth of the deepest refracted energy while also taking advantage of the migration-like characteristics of conventional FWI to introduce the shortest wavelength contrasts into the velocity model. Throughout the inversions shown here, we impose Gardner’s law to model density, and we do not explicitly invert for or model attenuation or elasticity. In the field example shown, we have not sought to adjust delta in the anisotropy model to match wells though it is straightforward to do this when well information is available.

Synthetic example

Figure 1 shows an example of the first stage of pure-reflection FWI applied to a simple synthetic example without multiples. Figures 1a and 1b show the starting and true models respectively. The problem here is to recover the velocity structure represented by the missing layers as shown in Figure 1c using FWI applied to pure reflection data – this is a difficult problem to solve. The synthetic data were acquired using a finite-offset two-sided array moving across the top of the model. Figure 1d shows a single shot record from the synthetic dataset generated by the true model – this is the input to reflection FWI. The input dataset contains only primary reflections; direct and refracted arrivals have been muted. The velocity anomalies to be recovered lie largely outside the bandwidth of the input data; they must therefore be recovered using the kinematics of the reflection data and cannot be generated simply by migrating the reflections into the starting model. The deepest reflector is very weak so that it will be difficult to obtain any information about the deepest missing layer.

Figure 1e shows the first iteration of migration-like FWI applied to the input data using the smooth starting model. The finite extent of the reflectors is produced by the finite extent of the acquisition. Figure 1f shows the background velocity update generated by the first iteration of tomography-like FWI. Iterating this procedure generates the final cumulative velocity update shown in Figure 1i, and the final migrated boundaries shown in Figure 1h. The accuracy of the final result can be seen by comparing Figures 1c and 1i, and by examining Figure 1g closely; the latter shows Figure 1c superimposed on Figure 1h. The reflectivity model is designed such that, in Figure 1g, the top of the red layer, and the base of the blue layer, should correspond exactly to a polarity change from white to black in the reflectivity – this match is extremely close.

In this inversion, there is no explicit feature that encourages velocity anomalies to be conformable with reflectors or that causes anomalies to have sharp edges. It is gratifying therefore to see that the inversion correctly builds accurately located conformable edges to the updates. We know of no other version of reflection FWI that can even approache this degree of vertical velocity resolution.

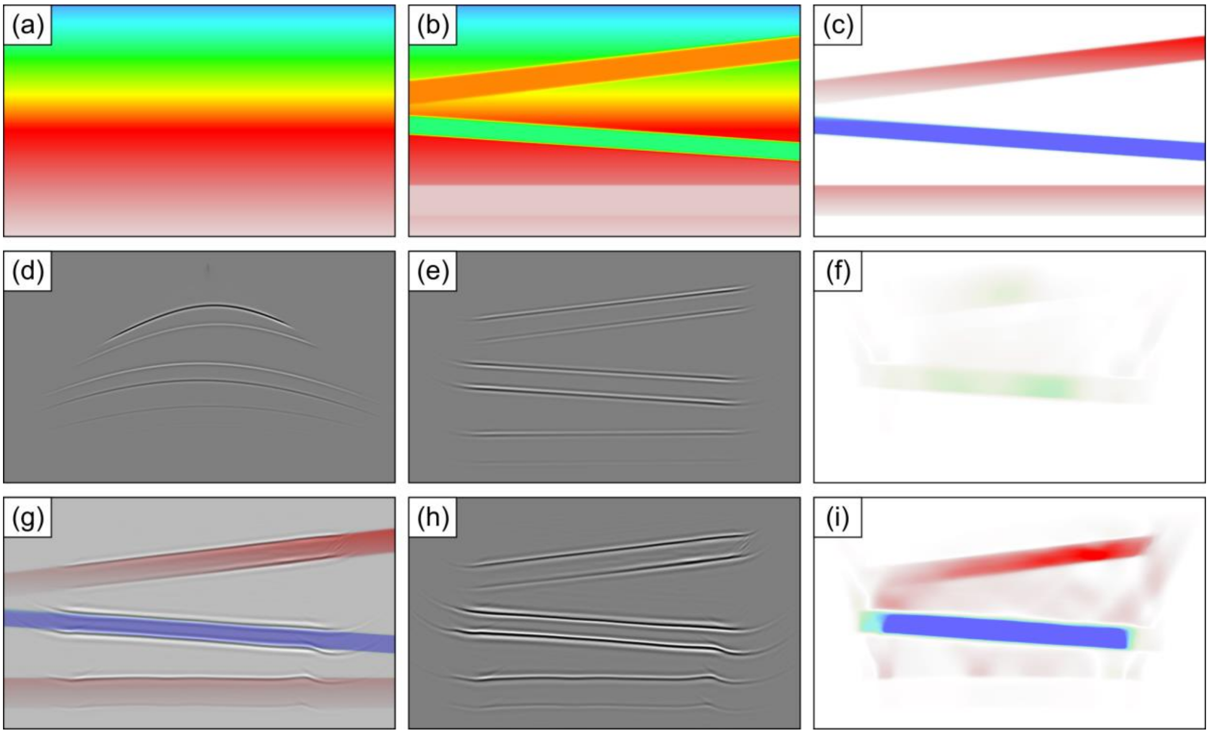

Figure 1 *Synthetic models and data used to demonstrate reflection FWI – see text for details of individual panels. The model measures 11.2 × 5 km. Seismic data, recorded to 6000 ms, have a dominant frequency of 23 Hz. The maximum useable offset is approximately equal to reflector depth.*

Field example

We demonstrate the full approach to reflection FWI on a less-than-ideal narrow-azimuth towed-streamer marine 3D field dataset, beginning from the simplest possible isotropic starting model. The data are from a public-domain data set acquired on the NW Australian shelf in about 1300 m of water.

The source depth was 5 m, receiver depth 6 m, maximum offset 5550 m. Figure 2 shows a typical shot record from this dataset. The data contain very little refracted energy and are deficient in low frequencies; they are dominated by sub-critical reflections and their multiples. This is a difficult dataset for conventional FWI, and it will only be possible, using FWI, to update the long and intermediate-wavelength velocity model if the FWI algorithm used is able to make proper use of the kinematics of the primary reflections.

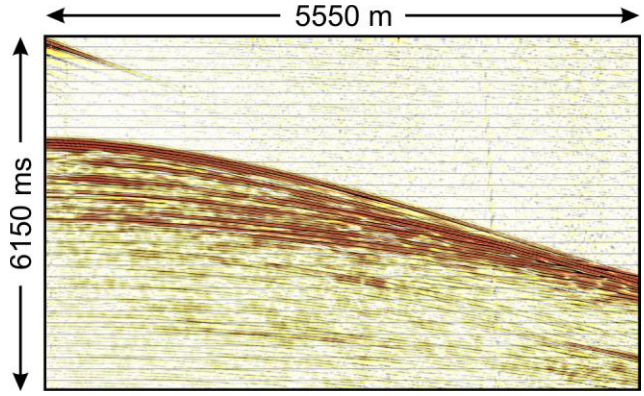

Figure 2 *Reflection-dominated shot record.*

Figure 3 shows a vertical depth slice through the 3D models and migrations generated at various key stages during the inversion of this dataset. Figure 3a shows the initial isotropic velocity model; this was generated by picking moveouts on time-migrated gathers, smoothing those stacking velocities heavily, and converting them to smooth interval velocities. This simple model contains just three regions: a faster one-dimensional region on the right of Figure 3a containing a low velocity zone, a slower one-dimensional region on the left without a clear LVZ, and a central region of smooth transition; the model varies minimally in the third dimension. Such a model is trivial to construct directly from the field data. It serves as the starting model for first stage of reflection FWI.

Figure 3b shows the anisotropic starting model used as the starting point for the third stage of reflection-based FWI. This model was obtained after both global inversion to determine anisotropy and the first stage of pure-reflection FWI; both stages are highly regularised. After these stages, the long-wavelength velocity model is largely correct, as is the long-wavelength anisotropy model.

Figure 3c shows the model after more-conventional reflection-based FWI to a maximum frequency of 5 Hz. By this stage, the velocity model should be adequate for Kirchhoff depth migration of the reflection data; the corresponding migration is shown in Figure 3e. The velocity model is now correct at long-wavelength, and has recovered a significant portion of the intermediate-wavelength structure. If Kirchhoff migration is sufficient, and if there is no direct interest in the velocity model itself, then FWI can cease at this point.

Figure 3d shows the final velocity model after continued conventional reflection-based FWI extending up to 23 Hz. This represents the final velocity model for this dataset. The model should now be correct at all length scales down to about half a wavelength at 23 Hz. This model can be used for direct interpretation, both for drilling hazards and for reservoir characterisation. We have not here used local inversion to introduce shorter wavelength structure into the anisotropy model, but it is straightforward to do this given that global inversion has already generated the long-wavelength anisotropy structure. This model is now too detailed for Kirchhoff migration, and a wave-equation-based migration, such as rtm, is required to use it properly for migration.

Figure 3f shows the comparison of the 5-Hz migration with the final 23-Hz velocity model. The velocity model contains high and low-velocity channels at multiple depths, and there is good structural concordance between the migration and the velocity model throughout the depth range. The final model also flattens gathers, at both long and short wavelengths, and accurately predicts the raw field data. The final velocity model does not display any contamination by multiples.

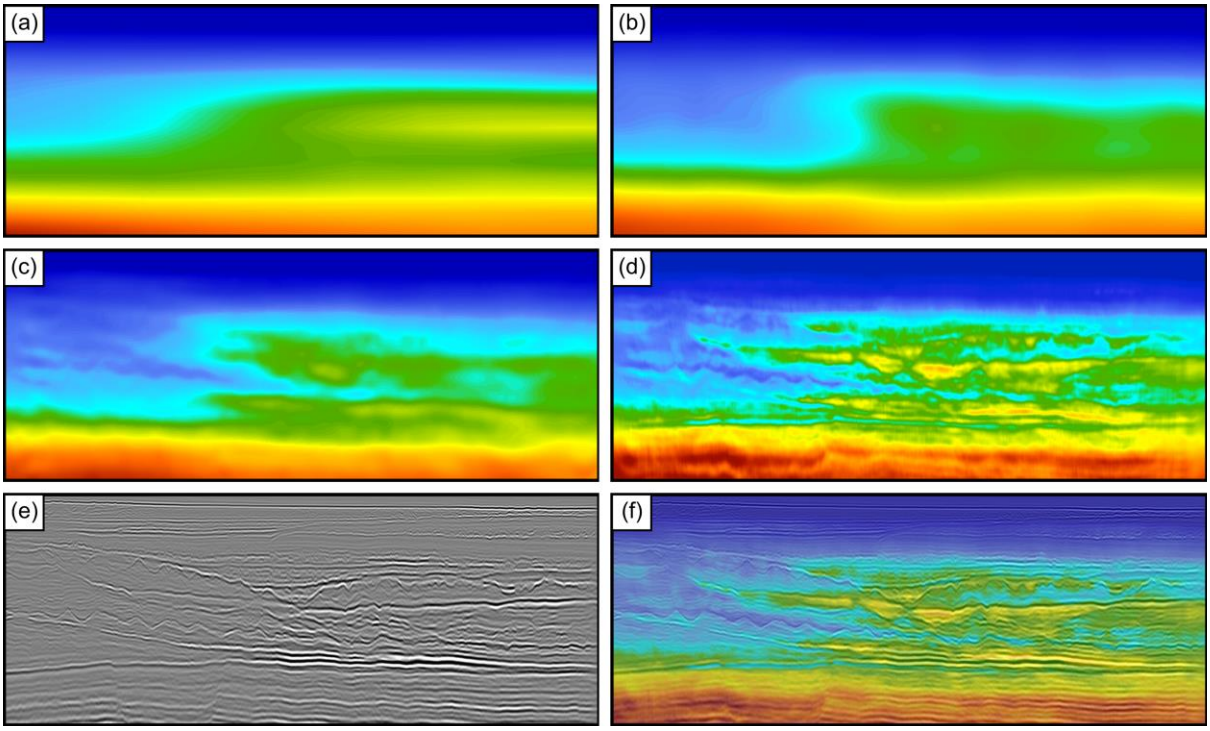

Figure 3 *(a) Isotropic start model obtained from PSTM moveout. (b) Anisotropic start model obtained after reflection FWI and global inversion for epsilon. (c) FWI model at 5 Hz. (d) FWI model at 23 Hz. (e) Kirchhoff depth migration using 5 Hz FWI model. (f) Overlay of (d) and (e). The panels shown are 25 km wide, and extend in depth from 1200 to 3400 m.*

Conclusions

We have shown that pure reflection FWI, employing an alternating migration-like and tomography-like FWI algorithm, can recover the long-wavelength velocity model starting only from a simple smooth model. This approach to reflection FWI can recover velocity models with sharp vertical boundaries, and with good vertical resolution. Following this form of reflection FWI with global inversion to recover anisotropy, and with more-conventional reflection-based local FWI for velocity, can then recover the full high-resolution velocity model at all length scales. This scheme is shown to work well on a difficult narrow-azimuth towed-streamer 3D field dataset. The advantages of this approach are clear – the final velocity model is available as soon as the reflection data are ready for depth migration, and minimal human effort is required to build that velocity model.

References

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