Introduction

FWI is widely used to generate high-resolution models of sub-surface physical properties, especially p-wave velocity. Although FWI-generated velocity models have a variety of possible applications, they are most often used as part of a wider velocity-building workflow for subsequent pre-stack depth migration using Kirchhoff or wave-equation based migration. However, in the early development of FWI, a key strategic objective was also to replace conventional seismic processing, velocity-model building and migration entirely by running FWI on raw data to full seismic bandwidth. In the event, the full capabilities of FWI have not yet been exploited in the way that its early champions envisioned. In this paper, we demonstrate the practicality of their vision applied to deep-water marine field data.

In principle, with enough compute power and with a sufficiently accurate inversion algorithm, there should be no need to process seismic data. Instead it should be possible to create a model of the sub-surface that predicts the unprocessed raw seismic data to within the noise level, and that consequently acts as a direct replacement for a conventional PSDM volume. In this paper, we demonstrate exactly that outcome, applying FWI at 100 Hz directly to unprocessed field data from a towed-streamer marine dataset. We differentiate the resultant FWI velocity model vertically in space, and compare the result of this directly with the results of conventional PSDM. Our full-bandwidth FWI result is broader band than the PSDM section at both high and low frequencies, and appears to be better resolved vertically. When run on the cloud, this approach is capable of generating a full high-quality PSDM volume for narrow-azimuth towed-streamer data within a few days of data acquisition.

Method

We demonstrate our approach using the Pivot dataset (Mancini et al., 2015) acquired on the NW Australian shelf over the Northern Carnarvon Basin. This narrow-azimuth long-offset towed-streamer survey was acquired in water depths of around a kilometre over a dipping seabed. It used a single deeply towed streamer at a depth of 25 m, and a single large airgun source of 5040 cu in, towed at a depth of 10 m. The shot interval was 50 m, and the group interval was 12.5 m. The active cable length was 10,050 m, and the data were recorded without a low-cut filter applied in the field. The survey parameters were designed specifically to enhance low frequencies and to reduce ambient noise for subsequent FWI. We inverted a 50-km section along a single shot line from this survey.

In a conventional PSDM workflow, operations to de-noise, de-ghost, de-multiple, zero-phase, build a velocity model, remove refracted arrivals, depth migration primary reflections, minimise residual moveout and generate a final stacked depth volume are all explicit, and are typically separate operations. In contrast, using FWI, these operations are all implicit within a single algorithm. Before applying FWI, we bandpass filtered the data between 3 and 100 Hz, and we muted the data ahead of the first arrivals; this was the only pre-processing applied to the field data. The high-cut filter rolls off rapidly so that there is effectively no energy retained in the filtered data above about 120 Hz.

We determined the source wavelet using the direct arrival at short offset. We used the starting velocity model shown in Figure 1a to begin FWI. This model was obtained by picking moveout on coarsely space PSTM gathers, and following this by two rounds of low-intensity reflection tomography. In practice, most of the detail introduced by the tomography was overwritten subsequently by the FWI. There are no wells on this line. We used a regional model of VTI anisotropy in which epsilon values were around 5% in the upper section above a major unconformity, and increased to about 15% at a depth of 4000 m. Delta values were set to two thirds of epsilon.

We ran time-domain, acoustic, VTI, variable-density FWI in stages, opening up the bandwidth progressively from 3 to 100 Hz in a total of 64 steps. We used a 25-m grid spacing to 20 Hz, a 12.5-m grid spacing to 40 Hz, and 5-m grid spacing to 100 Hz. Our finite-difference code is tenth-order in space and fourth-order in time, and is accurate down to about 2.6 grid points per wavelength. Below 40 Hz, we used the full 10-km offset of the data, and inverted refractions, reflections, ghosts and multiples together. Above 40 Hz, we restricted the maximum offset to 2.5 km which effectively excluded refracted arrivals. We used half the available shots at each alternate iteration.
Figure 1 (a) Starting Vp model used for FWI. (b) Final 100-Hz FWI velocity model. (c) FWI reflectivity model – the vertical differential of the FWI velocity model. (d) Conventional PSDM section as generated by processing contractor #2. The strong continuous event that crosses the entire section is a major unconformity. The strong deep upward-concave events are basaltic intrusions.
RESULTS

Figure 1b shows the final velocity model produced by FWI to 100 Hz. During FWI, the macro velocity model continued to evolve systematically to 40 Hz. Above 40 Hz, the offset range was restricted to reduce compute cost, and the macro model did not thereafter continue to evolve; the model though did continue to sharpen and increase in spatial resolution all the way to 100 Hz.

Figure 1c shows the result of differentiating the final FWI velocity model vertically in space. We used variable-density FWI to make the velocity model, tying velocity and density together using Gardner’s law. The differential of the velocity model therefore provides acoustic reflectivity excluding a scaling factor that depends upon the local velocity, Gardner’s law and local dip. This factor is straightforward to calculate to transform this section into a true-amplitude reflectivity section.

Figure 1d shows the equivalent conventional PSDM section generated by the second of two processing contractors. Figures 1 c and d are clearly broadly similar; they are compared in detail in Figure 2. For the PSDM section, the data have been deghosted and demultipled, and the velocity model used for the migration involved both tomography and conventional-bandwidth FWI. For the FWI reflectivity section, the raw data are used, and there is no explicit deghosting or demultiple involved. Instead, the free surface is included in the model, and the finite-difference simulation adds ghost and multiples to the predicted data rather than attempting to remove these features from the field data. The result is a model that is free of the effects of ghosts and multiples.

Figure 2 shows close-up sections of a portion of the FWI and PSDM reflectivity images; sections are shown in both colour and monochrome because different features are apparent in the two formats. The original data was processed by two different contractors; we did not have direct access to the contractors’ PSDM results for this paper, and so there will likely be differences in plotting parameters between the different sections. Contractor #1 did not apply FWI as part of the velocity model building, whereas contractor #2 used both tomography and conventional FWI to build the velocity model, and had access to the first contractor’s result. In these data, nominal receiver-ghost notches occur at multiples of 25 Hz, and the source notch appears at 75 Hz. Consequently careful deghosting of the data is required for a conventional PSDM workflow; the deghosting applied by the two contractors was evidently different, and the second version appears to be superior. Using FWI, full deghosting occurs implicitly, and no such considerations apply.

Figure 2a shows the colour PSDM image from contractor #2. Figure 2b shows the equivalent FWI reflectivity image at full bandwidth. It is apparent that the FWI image is broader band than the PSDM image. At the high end, it appears to have significantly higher vertical resolution than the PSDM image, and has fully captured the 100 Hz data into the model. At the low end, the PSDM is band limited because it is an image only of the reflection data which has no energy below about 3 Hz, whereas the FWI image is open at the bottom end, extending the reflectivity model way below the frequency of the lowest reflections. It is able to do this because the kinematics of the high-frequency data contain velocity information at longer wavelengths. In the FWI reflectivity image, the often discussed “gap” in resolution bandwidth between tomography and migration is not seen at all, and the model contains all wavelengths from DC to 100 Hz.

Figure 2c shows the 100-Hz FWI model low-pass filtered approximately to match the vertical resolution of the PSDM image. The filter used here was a vertical running average over a 15-m window. After low-pass filtering the FWI image, Figures 2a and 2c are rather similar except the FWI image also clearly contains longer wavelengths that are not apparent in the PSDM image. The retention of these longer wavelengths is sufficient in some case to change the apparent polarity of some shorter-wavelength reflections.

Figures 2d and 2e are the monochrome equivalents of Figures 2a and 2b, and show some features more clearly. Figure 2f is the equivalent PSDM section generated by contractor 1. The differences between this figure and the nominally equivalent PSDM in Figure 2d are larger than the differences between the low-pass filtered FWI reflectivity in Figure 2c and the PSDM image in Figure 2a.
Figure 2  Detailed section from the FWI and PSDM reflectivity models.  (a) Final PSDM image generated by contractor #2.  (b) Full-bandwidth 100-Hz FWI reflectivity image.  (c) FWI reflectivity low-pass filtered to match approximately the bandwidth of the PSDM image.  (d) Monochrome PSDM image generated by contractor #2.  (e) Monochrome Full-bandwidth 100-Hz FWI reflectivity image.  (f) Final PSDM image generated by contractor #1.  The principal difference between the two conventional PSDM sections appears to be in the deghosting.

DISCUSSION

It is clear that FWI can be used, for this deep-water survey, to generate a final PSDM-like depth image without any recourse to the normal processing and migration tools. The result of such a process is a reflectivity image which is better resolved vertically and broader band at both high and low frequencies than conventional PSDM. For a deep-water, narrow-azimuth, towed-streamer survey, where the wavelet and starting velocity model can be pre-generated onboard, and FWI tested and optimised on a few early swaths while acquisition proceeds, a full-bandwidth final FWI depth image at least equivalent in quality to a conventional PSDM volume can be realistically generated within a few days of the final shot being fired. The FWI tools required to achieve this already exist, and the largest cloud providers have the hardware resources needed to make it a practical reality. Even when speed is not at a premium, most interpreters will want access to section 2b even if section 2a is also available. FWI has now reached a level of maturity where it can begin to replace conventional processing workflows in their entirety in just the way that its inventors originally foresaw.

REFERENCES