Two vs three-dimensional FWI in a 3D world

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Summary

Three-dimensional anisotropic acoustic FWI has become a relatively routine component of depth-model building for PSDM and shallow-hazard identification, and is increasingly being used for pore-pressure prediction and reservoir characterization. However, 3D FWI is relatively resource intensive, especially at higher frequencies. Consequently 2D FWI can provide a low-cost option when extensive initial testing is required for parameter selection and quality control of starting models. In addition, during early exploration, full 3D coverage may not be available everywhere, and long 2D lines are not uncommonly used to tie new 3D surveys to more-distant wells and provide regional context. In these circumstances, 2D FWI may have a role to play as part of a larger 3D FWI workflow.

Here we apply both 2D and 3D FWI to the same field datasets to explore the utility, accuracy and limitations of the former. We show that 2D FWI applied to long regional lines has exploration benefit and that the additional benefit of applying full 3D FWI to this type of data is limited. We also demonstrate that early testing may be rapidly and usefully performed using 2D FWI ahead of full-3D production FWI with a consequent saving in both time and cost. Initial 2D testing can be especially relevant ahead of cost-sensitive decisions to run FWI to higher frequencies where the 2D results can provide a low-cost initial indication of the potential benefits of increased bandwidth in 3D.

Introduction

3D FWI allows the use of velocity models that vary in three dimensions, but it also allows sources and receivers to be properly distributed in space and it allows those sources and receivers to act as points rather than the lines that 2D wave propagation assumes. The latter changes both the amplitude and phase spectra of the predicted data and influences its temporal decay. Consequently, 3D simulation provides different results and is superior to 2D modelling of the same data. Some of these differences can be mitigated during 2D FWI and some cannot.

Most algorithms that are used to simulate the seismic wavefields required for FWI scale as n^3 in 2D and as n^4 in 3D for a single source where n is a measure of the linear dimensions of the model in mesh points. In addition, 3D modelling requires additional source coverage in the third dimension so that in 3D the number of sources required scales as n^2 whereas in 2D it scales as n. Consequently the computational cost of 3D FWI is around n^2 times greater than is 2D FWI; typically n is a few hundred or more.

In practice, depending in part upon the acquisition geometry, it is often possible to reduce the source density in 3D FWI below that required in pure 2D so that this scaling is not quite as severe as suggested, but 3D FWI is always significantly more expensive than 2D. In addition, as the maximum frequency of the data increases, the number of mesh points required to capture the wavefield accurately also increases so that the difference in cost between 2D and 3D FWI becomes more marked.

Field data

We have applied both 2D and 3D FWI to two datasets from the Carnarvon basin on the NW Australian shelf. In the first dataset, an 80-km 2D line was acquired using a single source and single streamer. Data acquisition was optimized for FWI by employing a 10,000-m cable, towed at 25-m depth, and a large low-frequency source array towed at 10-m; the shot interval was 50 m. For this survey, the shallow velocity model was reasonably benign for FWI but there are thin high-velocity igneous intrusions in the deeper section. The water depth ranged from 600 to 1600 m. Figure 1a shows a typical shot record; there are strong water-bottom multiples, significant refracted energy at longer offsets, and good signal-to-noise at low frequencies.

The second dataset was taken from a conventional 3D narrow-azimuth towed-streamer survey designed principally to enhance spatial resolution rather than for improved FWI. The survey used flip-flop sources and eight cables. The cable length was 5500 m., towed at 6-m depth, and the sources were towed at 5-m depth with an 18.75 shot interval. The underlying velocity model was more complicated than for the first survey with several generations of buried channels, mini-basins and velocity inversions, and this velocity model is difficult to recover without assistance from extensive reflection tomography. The water depth is around 1400 m. Figure 1b shows a typical shot record; there is less refracted energy, less low-frequency signal, and more noise than in Figure 1a.

We applied acoustic VTI anisotropic 2D and 3D FWI on both datasets with minimal preprocessing. Both refracted and reflected arrivals were used throughout, and surface ghosts and multiples were retained within the field data. We took no explicit account of attenuation or elastic effects, but our FWI code is designed to be robust against systematic amplitude variations in the field data that do not match our acoustic assumptions. We used regional values for anisotropy and held these values constant during FWI.

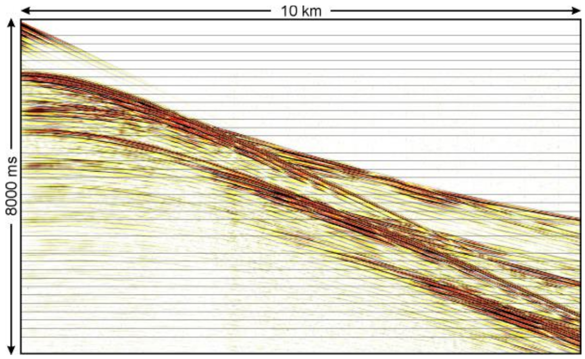

Figure 1a: Dataset one, shot record, filtered below 30 Hz.

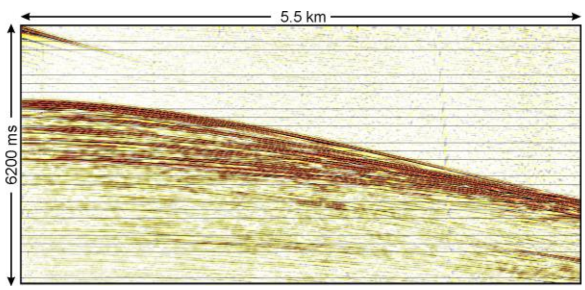

Figure 1b: Dataset two, shot record, filtered below 30 Hz.

The source wavelet required for FWI differs between 2D and 3D. The appropriate wavelet was obtained using an initial estimate to model the direct arrival through the water, subsequently using a Wiener filter to match this to the observed direct arrival. This approach automatically corrects the phase and amplitude spectra of the source for 2D, and also deals correctly with the surface ghost.

We did not explicitly correct the temporal decay of amplitude for 2D FWI. Instead we correct this heuristically by matching RMS amplitudes between predicted and observed data, suitably stabilized, at each time slice within each shot record. This forms part of our default parameterization for marine field data where it is designed principally to deal with the amplitude effects of anelasticity and sub-grid-cell scattering, but it has the useful side effect of also dealing reasonably effectively with the amplitude differences introduced by 2D simulation.

Results – dataset one

We began the inversion at 2.5 Hz using a starting velocity model based upon smoothed PSTM stacking velocities, Figure 2a. We ran 2D inversion to a maximum frequency of 24 Hz. For this inversion, the data were collapsed onto a 2D line, preserving source-receiver offset; the maximum feathering of the 10-km cable was 650 m.

The final 2D FWI-derived velocity model is shown in Figure 2b, and overlain by the 2D PSDM section in Figure 2c. The strong irregular reflections in the lower half of the section are from basaltic intrusions; these appear as high-velocity features in the FWI velocity model. Both the FWI velocity model and the PSDM pick out a major unconformity that traverses the section, and both show shallow channels in the upper parts of the section. Figure 3 shows a close-up of both the FWI model and the PSDM where the detailed correlation between the two sections is clear.

To assess the accuracy of the 2D FWI velocity model, surface-offset common-image gathers generated using 2D Kirchhoff PSDM were generated, Figure 4. Figure 4a uses the starting model, Figure 4b uses the results of isotropic 2D FWI, and Figure 4c uses the results of anisotropic 2D FWI. It is clear from these gathers that purely 2D FWI is able to produce a velocity model that is sufficiently accurate to migrate these data. The gathers are flatter following 2D FWI, and even though the inversion is only in 2D, it is clear that the inclusion of anisotropy during FWI improves the outcome.

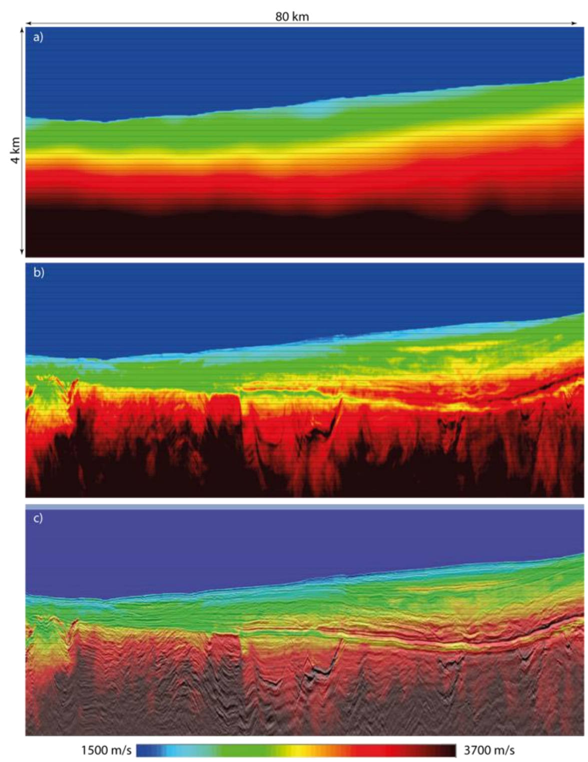

Figure 2: a) Starting velocity model. b) Anisotropic 2D FWI-derived velocity model at 24 Hz. c) FWI velocity model overlapped with PSDM section.

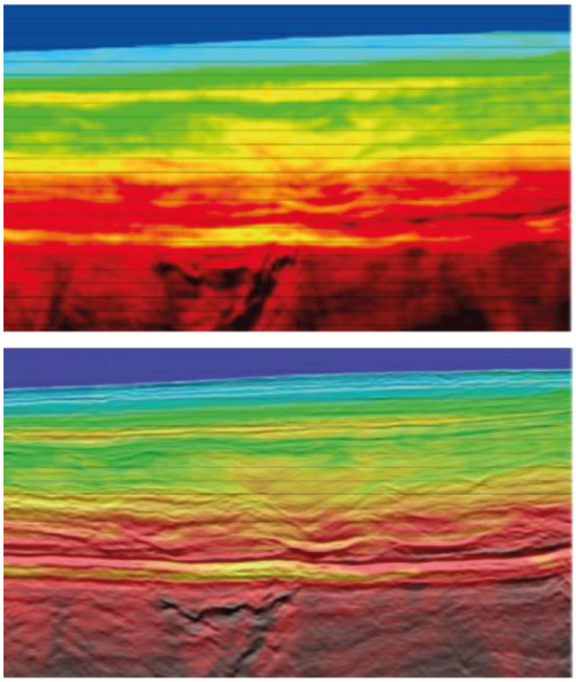

Figure 4: Close up of Figure 3; lateral extent is 18 km.

The migration is not perfect; both FWI and PSDM were here performed in 2D, and cable feathering and cross-line velocity changes are not dealt with correctly by either method. Nonetheless, it is clear that 2D FWI migrates the data better than the starting model. For long regional tie-lines, 2D FWI clearly provides benefit.

We repeated the inversion of this 2D line using full 3D FWI run to a maximum frequency of 12 Hz. Since there is little control over cross-line variations in velocity provided by this 2D dataset, we regularized the model strongly in the cross-line direction during FWI. Apart from this regularization, the inversion was fully in 3D with sources and receivers placed in their true positions.

Figure 6 shows a comparison between the velocity models obtained using 2D and 3D FWI. These models are not identical, but they are remarkably similar. The local absolute velocities do not always agree but we could ascertain no systematic differences between them. Sometimes one and sometime the other model appears to be better resolved and to match the PSDM more closely.
There are significant differences between the two results in the area circled in Figure 6. Here the streamer was not straight, the feathering was larger than normal, and the 2D assumption was more significantly in error. Unsurprisingly, in these circumstances, using the full 3D geometry leads to a significantly improved outcome for FWI.

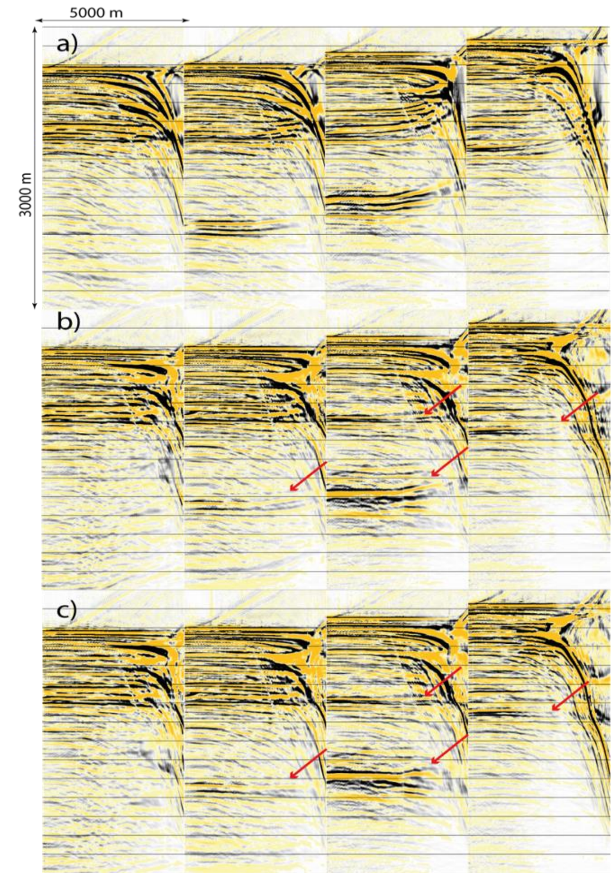

Figure 5: CIGs generated using: a) the starting model, b) isotropic 2D FWI, c) anisotropic 2D FWI.

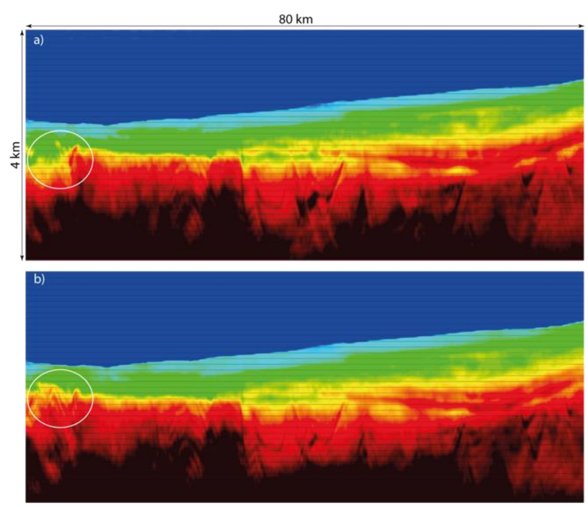

Figure 6: FWI velocity model at 12 Hz: a) 2D, b) 3D. The 3D result is about 400 times the cost of 2D FWI.

Results – dataset two

Unlike dataset one, here the data were acquired with full 3D acquisition. Consequently the main role of 2D FWI in this survey is in early parameter testing and in assessing the commercial value of more-expensive algorithms, for example extending FWI to higher frequencies. This can be especially relevant when production runs are performed on the cloud and early testing is performed using more-limited local resources.

Figure 7 shows the start model and results of 2D and 3D anisotropic FWI for this survey. FWI was run between 3.6 and 7.8 Hz; similar parameterization was used for both inversions. In dataset one, 2D FWI used a single source and single cable so that cable feathering becomes an issue. In dataset two, we have full 3D acquisition, and so are able to select a subset of sources and receivers from multiple cables that closely match a true 2D geometry; this match is not perfect because of the finite cross-line spacing of both sources and receivers, but it is much closer than can normally be obtained by using data from a single cable.

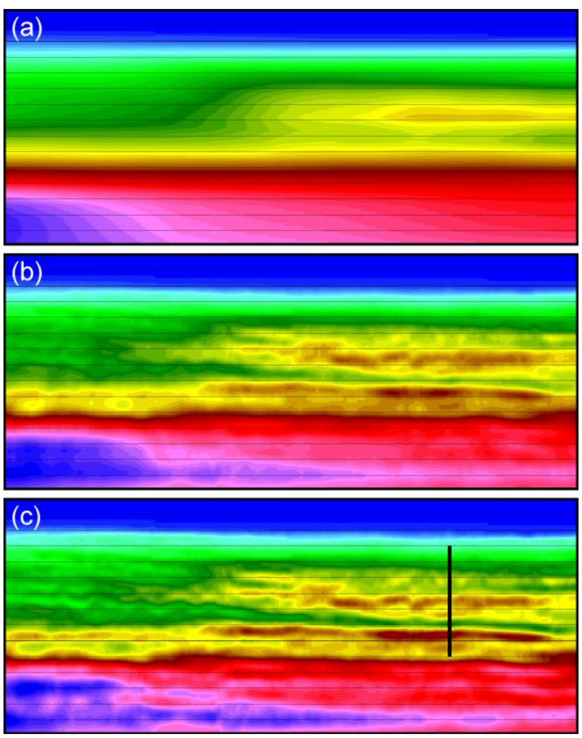

Figure 7: (a) Starting model, (b) 2D FWI, (c) 3D FWI. The inversion is to a maximum frequency of 7.8 Hz. The base of the section is at 4 km below the sea surface. Vertical line shows well from Figure 8.

Qualitatively the 2D and 3D results are similar, but the velocity anomalies introduced by FWI are almost always more intense in the 3D model. It is not clear why that should be the case. Significantly more data is used to generate the 3D result, and this additional data will act to reduce the effective signal-to-noise ratio during FWI. This dataset has high noise levels at low frequencies because of the shallow tow depth, and we speculate that the amplitudes of the velocity updates during 2D FWI are suppressed by these higher noise levels acting to compromise the data fit.

For this survey, we used extensive testing with 2D FWI to design the optimal parameterization for subsequent 3D inversion. This is a difficult dataset to invert, and previous attempts have relied heavily on reflection tomography. We found the initial 2D testing to be invaluable in developing the full 3D workflow. Figure 8 demonstrates that the final anisotropic 3D result matches check-shot data at the well, and serves to validate this approach to 3D FWI.

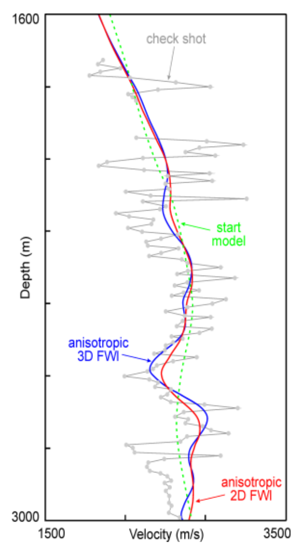

Figure 8: Comparison of check shots, starting model, and 2D and 3D anisotropic FWI models. The location of the well is shown in Figure 7.

Conclusions

We have successfully applied anisotropic full-waveform inversion to marine-streamer datasets in both 2D and 3D. We have shown that 2D FWI applied to regional 2D tie-lines appears to work as well as full 3D FWI provided that the acquisition geometry is approximately two-dimensional. We have also shown that 2D FWI of conventional 3D NATS data can provide velocity models that are qualitatively similar to those generated by full 3D FWI. We have also shown that 2D FWI proves to be useful for early parameter testing while working with 3D datasets.

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EDITED REFERENCES

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REFERENCES

No references.