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Full Waveform Inversion - A Strategy to Invert Cycle-skipped 3D Onshore Seismic Data

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SUMMARY

Building a velocity model for onshore subsurface is a nontrivial problem. Full-waveform inversion is a technique that seeks to find a high-resolution high-fidelity model of the Earth's subsurface that is capable of matching individual seismic waveforms, within an original raw field dataset, trace by trace. We have developed an inversion scheme in which only data from the shorter offsets are initially inverted since these represent the subset of the data that is not cycle skipped. The offset range is then gradually extended as the model improves. The final 3D model contains a strongly developed low-velocity layer in the shallow section. The results from this inversion appear to match p-wave logs from a shallow drill hole, better flatten the gathers, and better stack and migrate the reflection data. The inversion scheme is generic, and should have applications to other similar difficult datasets.

Introduction

Full-waveform inversion (FWI) is a technique that seeks to find a high-resolution high-fidelity model of the Earth's subsurface that is capable of matching individual seismic waveforms, within an original raw field dataset, trace by trace. The method begins from a best-guess starting model, which is then iteratively improved using a sequence of linearized local inversions to solve a fully non-linear problem. In principle, FWI can be used to recover any physical property that has an influence upon the seismic waveform, but in practice the technique has been used predominantly to recover P-wave velocity, and this is the route that is followed here.

Although the underlying theory of FWI is well established, its practical application to 3D land data, and especially to seismic data that have been acquired using vibrators, in a form that is effective and robust, is still a subject of intense research. We have applied 2D and 3D FWI techniques to a vibrator dataset from onshore Oman. Both the raw dataset and the subsurface model cause difficulties for FWI. In particular, the data are noisy, have weak early arrivals, are strongly elastic, and especially are lacking in low-frequency content. The Earth model appears to contain shallow low-velocity layers, and these compromise the use of first-arrival travel-time tomography for the generation of a starting velocity model.

Challenges in Land Seismic Data

Full-waveform inversion is not yet a one-click method in the sense that it cannot take the raw field data and simply produce a good velocity model. There are many challenges and assumptions that need to be accounted for prior and during the inversion process. Such challenges become even more difficult when considering land seismic data. Among other impediments facing such data, three main difficulties are tackled in this paper: obtaining an adequate starting model, mitigating the absence of low frequencies in the early arrivals, and dealing with first arrivals that appear to be dispersive.

The latter has proven to be particularly troublesome; the phenomenon is illustrated schematically in Figure 1. This shows a first arrival that is composed of a sequence of high-frequency parallel phases; these die out successively with increasing offset, and as each phase dies, the next in line replaces it to form the first arrival. Consequently the local phase velocity and the group velocity are not the same. This "shingled" pattern is common on land data, and it is very likely evidence for the existence of shallow low-velocity layers along the profile.

This pattern of first arrivals is unlikely to be reconstructed successfully by conventional ray-based traveltime tomography methods which do not account for finite-frequency effects. The high-frequency asymptotic approximation on which the traveltime tomographic algorithm is based, tries to map an average smooth first-arrival time which will provide a good fit to the average group velocity, Figure 1. This group-velocity model though will always predict cycle-skipped arrivals when it is used to synthesize finite-frequency data since the real arrivals are not parallel to the group velocity. Hence first-arrival traveltime tomography is not expected to be able to generate an adequate starting model for FWI for these data.

Opening Window Strategy

With the many challenges persisting for the land field data, there is a need for a different route to handle the FWI method. Our new strategy uses a starting model that is not cycle skipped at the shortest offsets only, and we limit the input data to include only these shortest offsets. We start from the lowest useable frequency that shows a coherent pattern in the early arrivals, which is not necessarily the lowest frequency present in the data – our early arrivals are much higher in minimum frequency than are later reflected arrivals. As the inversion proceeds, we successively open the offset window, seeking to limit the data at each stage only to that portion that is not cycle skipped.

Survey Parameters & Pre-processing

The 3D seismic survey area covers 28 km^2 and is divided into three blocks that comprise a total of 9072 sources and 288 receivers per source. Each swath in the survey comprises 4 source and 4 receiver lines. Each source line has 27 source points, and each receiver line has 72 3-component stations. The nominal source spacing is 100 m inline and 50 m crossline, while the receiver spacing is 25 m inline and 200 m crossline. The sweep frequency of the vibrator source is 5-60 Hz. The subset area consists, if the full range of offset is deployed, of a total of 806 sources and 200,392 receivers. However, when a limited offset is used at each stage of the inversion process, the total number of sources and receivers is reduced. The maximum offset at any point is about 2.1 km.

The subset has undergone a minimal pre-processing sequence. Such pre-processing is similar to that shown in Al-Yaqoobi et al., (2011). Ground roll and non-acoustic arrivals have been removed with an offset mute in order to enhance the signal-to-noise ratio. A top mute has also been applied to remove any precursor arrivals. Bad shots and noisy traces have been eliminated prior to the inversion process. Traces of less than 100 m offset have been excluded to avoid the effect of strong ground roll at short offset. Finally a low-pass filter is applied to the data, which rolls off from 25 to 35 Hz while retaining the low frequencies.

FWI Procedure

The input elements for the inversion are the preconditioned data, a source wavelet extracted from the data, and a starting velocity model. We use a 3D acoustic time-domain FWI approach described in Warner et al., (2010). This approach solves the acoustic wave equation using a finite-difference iterative solver in the time domain. We assume an absorbing boundary, and apply spatial preconditioning of the gradient in order to mitigate the non-linearity effect of the inversion. The FWI is run with a bandwidth of 14-33 Hz, and a total of 50 iterations. Note the high minimum-frequency of 14 Hz used in these inversions – lower frequencies were not evident in the early arrivals, though they are present later in the data. The model size is 171 x 171 x 81 with a grid spacing of 12.5 m. This model size is equivalent to a coverage area of 2125 x 2125 x 1000 m. Sources and receivers are placed at their correct locations inside the initial model, relative to a datum of 229 m above MSL. The densities are derived from the velocities with aid of a modified equation of Gardner's formula.

Results

The recovered velocity model using only short-offset data, shows a strong shallow low-velocity layer, Figure 2. It is this feature, and its deeper analogues that can be seen in 3D in Figure 3, that we believe produce the shingled early arrivals, and that limits the lower bandwidth of the early arrivals. The low-velocity zones have been successfully recovered using FWI, and they cannot of course be modeled by first-arrival travel-time tomography.

Figure 4 shows the starting and final FWI model compared to the well. Although the velocities measured in the well are consistently lower than those in the starting and final seismic models, the reconstructed velocities have same trend. The starting model is just a simple gradient, but the final FWI model shows long-wavelength structure that is similar to the trend in well log. Our inversions assume no anisotropy; however anisotropy in a vertical plane is very likely to affect this strongly layered sedimentary sequence. Velocities measured in the well are vertical velocities, whereas those recovered by FWI, applied to early arrivals, are dominated by the horizontal velocities. We strongly suspect therefore that the offset between the well and the models is fully explained by anisotropy.

If this is the case, then the magnitude of the assumed anisotropy can be estimated; the fractional difference between vertical and horizontal velocities is approximately equal to the anisotropy parameter, ε. Calculating the median anisotropy of the parameter ε gives a value of about +7%. This is not a high value for a layered sedimentary sequence that contains alternating thin beds and aligned anisotropic minerals such as clays and shale, where ε can often reach values above 20%.

Sections migrated only in 2D (Figure 5) illustrate the noticeable improvements in the shallow part where extra layers can be seen. Sharper images and less conflict between dips, in the deeper part, are produced by FWI velocity. However, the FWI model is not able to obtain a thorough improvement for the entire migrated section, possibly due to the effect of 3D structure in 2D imaging. Improvements of the results can also be seen in the NMO sections (Figure 6), where the FWI model has better flattened the gathers compared to the stacking velocities.

Conclusions

We have proposed a new strategy to invert difficult 3D land seismic data. We have demonstrated the application of this strategy on a 3D vibrator land dataset from an onshore field in Oman. The results confirm the presence of low-velocity layers that might cause the step-like early arrivals that are observed in the field data. In the case of complex field data and with the lack of a good starting model that fits the field data to a less than half a cycle, the 'Opening Window Strategy' could be adapted to overcome such a deficiency. Instead of falling into a local minimum, the adopted strategy has the ability to drive the inversion process to the right direction. It is not so much where the starting model stands but in what direction the inversion is moving.

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References

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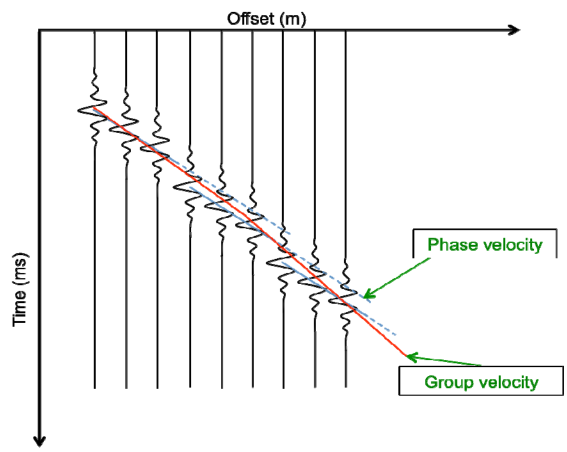

Figure 1 *A schematic diagram showing shingled first arrivals. The phase velocity of a single event continues to a certain offset, before it dies out, and another stronger event takes over. The red line shows the group velocity that might be predicted using first arrival traveltime tomography.*

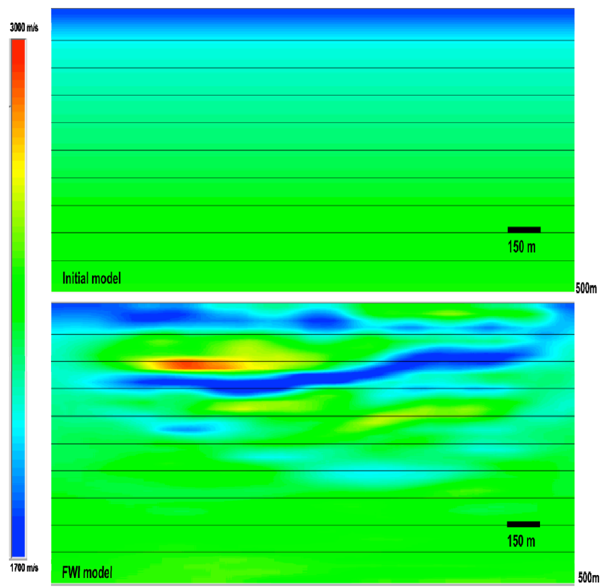

Figure 2 *Start model (top), and FWI result (bottom) using up to 500 m offset from the second stage of the inversion process.*

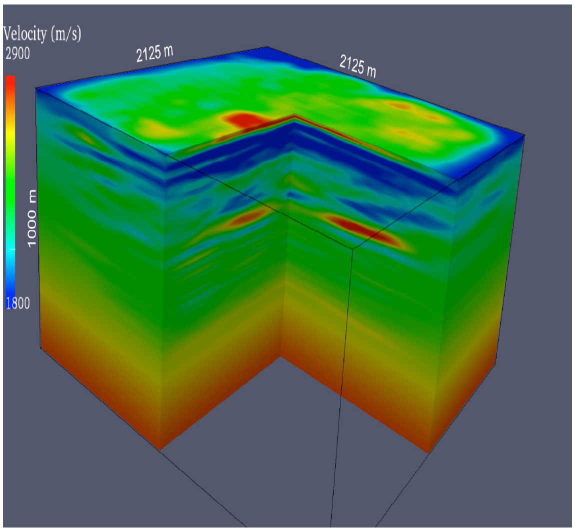

Figure 3 *3D FWI model after inverting up to 700 m offset.*

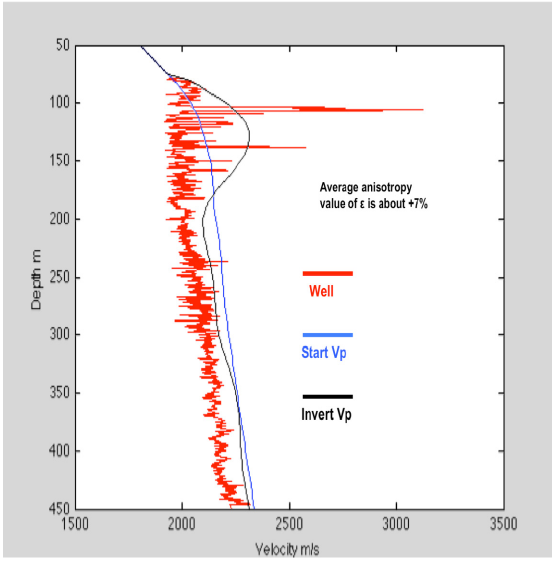

Figure 4 *Starting model, 3D FWI model after inverting up to 700 m offset, and well-log sonics.*

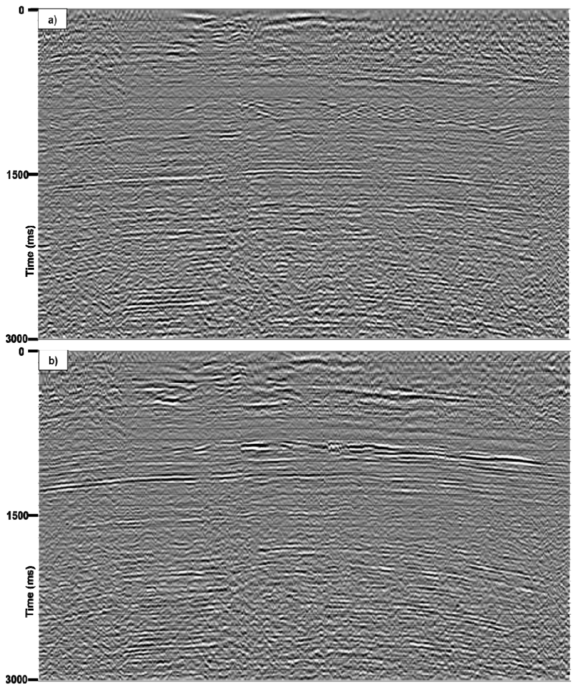

Figure 5 *2D migration images with (a) stacking velocity, and (b) FWI model. A band-pass filter of 5-10-25-35 Hz has been applied to both datasets.*

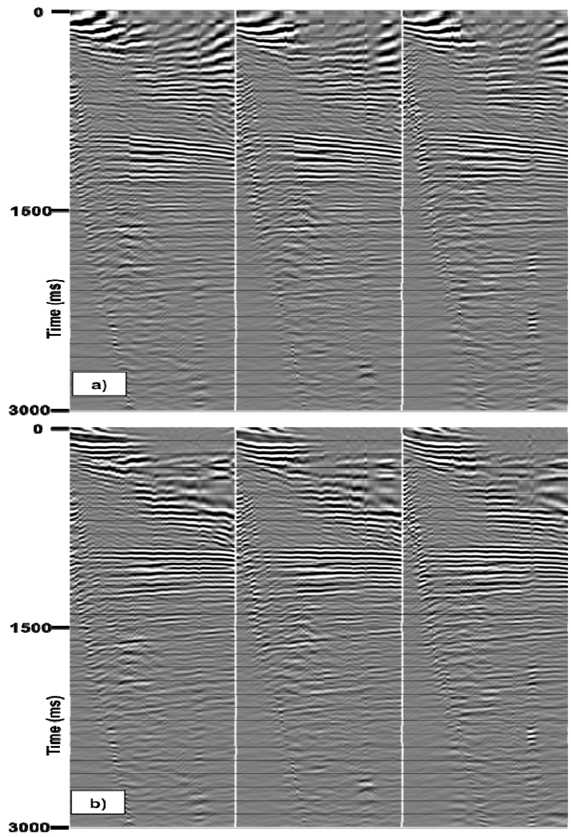

Figure 6 *CDP gathers of the 2D data with NMO correction. (a) Stacking velocity, and (b) FWI model. A band-pass filter of 5-10-25-35 Hz has been applied to both datasets.*