Introduction

Full-waveform inversion (FWI) on marine data has been a standard of velocity model building for several years. However, application of FWI on land was more challenging to develop, due to the traditional limitations of land data. These include irregular surface sampling, lack of low frequencies and long offsets, near-surface heterogeneities, industrial noise, etc. These issues were addressed to some extent by the development of new acquisition methods, providing regular and dense surface sampling, broadband spectrum and long offsets (Mahrooqi et al., 2012). Taking advantage of these modern surveys, industrial applications of land FWI have progressed, with acoustic implementation first (Stopin et al., 2014), then towards high frequency FWI, and more recently, elastic FWI (Barthi et al., 2016). Indeed, while elastic implementation is needed in some cases to account for better physics (Solano and Plessix, 2019), Sedova et al. (2017) showed that high-resolution acoustic FWI also is achievable. This is accomplished with good quality input data, conditioned by a dedicated processing workflow for the diving and post-critical waves. More recently, progress in resolving the cycle skipping issues has been made using a multi-dimensional Optimal Transport cost-function (OT-FWI) (Sedova et al., 2019 (2)). It also results in a more geologically consistent velocity model.

The focus of this research was to push OT-FWI to higher frequencies, in order to better image complex fault structures on-shore Oman. Our workflow is adapted from the high frequency land FWI presented in Sedova et al. (2017) with, however, the replacement of conventional FWI by OT-FWI. We observed that OT-FWI up to 16 Hz results in a model that is more detailed, and updated deeper. RTM imaging using this model led to sharper graben edges and to healing of reflectors below the graben.

Input data pre-processing

The input seismic data were acquired in 2010 using an acquisition design developed by PDO and Shell (Mahrooqi et al., 2012), with distance separated simultaneous sweeping (DS3, Bouska, 2010). The broadband 3D vibroseis survey used a nine-second sweep starting from 1.5 Hz, with full-azimuth and large offsets that were processed up to 13 km. The shot sampling is dense and regular, with a 50 m increment in both x and y directions. The receiver lines are spaced 250 m apart, with 25 m spacing between receiver stations (Figure 1a).

The workflow implemented in this example uses two different sets of input data, as shown in Figure 1b. The long offset dataset, optimized for diving and post-critical waves, is used to update the velocity model from a starting frequency of 2 Hz and then up to 9 Hz. The second dataset, optimized for reflections, is then used to update the velocity model from 6 Hz up to 16 Hz.

Careful input data pre-processing is key to extracting either diving or reflected energy from the noise, especially for low frequencies. These low frequencies are essential for land FWI as they can help derive an accurate shallow velocity model, which is often not possible using conventional ray-based tomography due to noise in the data and to limited offset information from the acquisition design. The very low frequencies also help avoid cycle skipping issues that arise from not having an accurate-enough initial model. In 2018, Sedova et al. showed the benefit of using OT-FWI for low frequencies in a relatively simple geological context (flat layers in the presence of a velocity inversion), where careful input data preparation enhanced low frequency diving waves at long offsets. The pre-processing workflow implemented in this study was similar to the workflow described by Sedova et al. in 2019 (1).

We first removed the ground-roll that cannot be used in acoustic FWI. It was subtracted using adaptive surface wave attenuation. The next signal processing steps remove the interference noise coming from the DS3 acquisition, and also attenuate random and industrial noise. This is achieved with joint low-rank sparse inversion and 3D linear noise filtering, driven by a first-break guide picked on a sparse grid (Sedova et al., 2019 (1)). The first-break guide helps define the velocity trend of the diving waves, in order to protect them during the application of the de-noise process. These processes are applied in the octave domain, to optimize their parameterization for each frequency band.
Figure 1  
a) Schematic description of the acquisition layout.  
b) Workflow implemented for high-resolution OT-FWI using two input datasets, one each for diving and post-critical waves, and for reflected waves.

Figure 2  
Left: Receiver gather, raw data;  
Middle: Receiver gather after dedicated processing for diving and post-critical waves;  
Right: Receiver gather after conventional processing sequence for reflected waves, additional de-noise is applied for FWI. The blue and red lines indicate the outer and inner mutes used in FWI, respectively.

Initial Velocity Model and Wavelet

The input dataset containing reflection information comes from the conventional processing sequence used for imaging, but with additional random noise attenuation and dip filtering to remove remaining back-scattered energy. Figure 2 shows the results of the overall pre-processing sequence for the two datasets. A mute is designed for each dataset, to remove the near-offsets, which are still too noisy to be used in FWI.

The elevation is gentle in the area, so FWI was run with an assumption of flat topography. The initial velocity model used for FWI was derived from an existing pre-stack time migration RMS velocity field. The velocities were smoothed with a large operator (4 km x 4 km x 500 ms), then converted to interval velocities in the depth domain using Dix conversion. This initial velocity was scaled with constant anisotropic parameters (Thomsen), $\delta=5\%$ and $\varepsilon=7.5\%$, regional values commonly used in the area. Other methods to better estimate the anisotropy (for example, joint refraction-reflection tomography, Allemand et al., 2017) would be applicable but were not implemented on this dataset.

The input source wavelet was obtained using the auto-correlation of the pilot sweep, convolved with the geophone response, then band-pass filtered and shifted to avoid cutting energy occurring at negative times. The input data to FWI was shifted by the same amount to maintain consistency with the wavelet.
Acoustic land OT-FWI

The first stage of the FWI sequence aimed at updating the long to medium wavelengths of the velocity model, starting from a very smooth initial model (Figure 1b). We achieve this by having long-offset and low-frequency diving wave information, as described earlier, and by using the OT implementation of FWI. The benefit of OT is two-fold. Firstly, the OT cost function has a wider range of convexity than the conventional least-square cost function of FWI, which makes it less sensitive to cycle-skipping. Secondly, the multi-dimensionality of OT-FWI provides better conformity with geology, compared to least-square (Poncet et al., 2018). Diving-waves were inverted starting from 2 Hz and up to 9 Hz, as shown already by Sedova et al. 2018, in a simpler geological setting. The cross-sections shown in Figure 3 illustrate the convergence of the FWI from a very smooth model to a more detailed model. The perturbation introduced in the initial model is conformable to the geology and the faulted structure starts to be resolved (left and middle panels). We observe on the 9 Hz result a deeper update than using only diving waves would produce. Our understanding is that the pre-processing sequence applied does not fully separate diving and reflected waves, and the deeper update is then the contribution of the reflections.

![Figure 3](image)

**Figure 3** Velocity model and corresponding Kirchhoff image overlay, with the initial model (left), after 9 Hz OT-FWI using diving and post-critical waves (middle), and 16 Hz OT-FWI using reflected waves (right).

![Figure 4](image)

**Figure 4** Imaging results, Initial model (Kirchhoff) (left), 16 Hz OT-FWI (Kirchhoff) (middle), and 16 Hz OT-FWI (RTM) (right). Note the imaging uplift with RTM, when using the high-resolution FWI model.

The novelty of this study was to attempt, in a second stage, to increase the resolution of the velocity mode using OT-FWI. This was achieved by inputting the second dataset to FWI, which was optimally processed for reflections. This update of the velocity model was done from 6 Hz to 16 Hz, starting from the 9 Hz velocity model obtained in the previous step. The results of this update are shown in Figure 3, right panel. It is characterized by an overall increase of resolution in the model, as expected when running FWI to higher frequencies. The input of reflected energy also increased the effective depth of
the update which is obvious in the migration QC shown in Figure 4. Although an imaging uplift from the 16 Hz velocity model paired with Kirchhoff migration is apparent, it is only when using RTM that we see all the benefits of the high-resolution velocity model. The short wavelength detail added in the velocity model by OT-FWI is such that multi-pathing in the imaging cannot be ignored, and the high-frequency approximation of the Kirchhoff algorithm is insufficient.

Conclusions

We present in this article an application of OT-FWI in a land context, and with structurally complex geology. Two challenges inherent to land data, namely the noise content and the difficulty of building an accurate initial model, were overcome by a careful pre-processing of the input data, and by the use of multi-dimensional OT-FWI to mitigate cycle skipping issues and to provide a more geologically consistent velocity model. The inclusion of reflected waves in the FWI for higher frequency inversions up to 16 Hz helped add details in the velocity model. This resulted in significant imaging improvements when using RTM for migration. Some assumptions made during the course of the project would deserve further investigation, namely the influence of anisotropy on the result, and the impact of the FWI migration term over the tomographic term during the first stage of the model update workflow.

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References


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