Full waveform inversion – dealing with limitations of 3D onshore seismic data

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Summary

Full-waveform inversion is a promising technique to produce high-resolution, interpretable velocity images of the subsurface. We present one of the first results from application of full waveform inversion to a vibrator seismic land data. The results verify that full waveform inversion can be successfully applied to land seismic data after certain preconditioning procedures and with a good a priori velocity model. Updates of the shallow part of the velocity model will have an impact on better recovering of the deeper part of the migration image.

Introduction

In the past few years, full-waveform inversion (FWI) has proved to produce quantitative, high-resolution velocity models. Such models improve the quality of depth migration and thereby provide highly valuable images of complex geological structures for subsurface interpretation. FWI uses the two-way wave equation to minimize a misfit function that is defined as the difference between the modeled and observed seismic wavefields. The FWI approach has been applied successfully in 3D to marine seismic data (e.g. Sirgue et al., 2009; Ratcliffe et al., 2011) and even is beginning to become a routine. However, the application of such method has proved more challenging on 3D land data. In this paper we apply FWI to an onshore oil field to recover the shallow subsurface layers and improve the deeper part of the imaging.

The field area and acquisition

The data used in this study were acquired over an onshore field in the north-west part of the Sultanate of Oman in 1991. Located in the northern part of Oman (Figure 1), the Natih field is one of the major oil producing fields in the country. The main reservoir is a 400 m thick Middle Cretaceous sequence of chalky limestones overlaid by shale Formation as a cap rock, and the production from the reservoir is dominated by fracture network of the reservoir.

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.

Difficulties and limitations of the dataset

Obtaining a good velocity field requires the recovery of the full spectrum range including low, intermediate and high wavenumbers. There are still many limitations and challenges before a comprehensive and comprehensible method is found to solve the subsurface imaging problems. While ray-based tomography recovers the low wavenumber components of the model, full-waveform inversion uses the full range of offsets and frequencies available in the data to recover the full range of wavenumbers. However due to the non-linearity of the inverse problem, the current FWI in field data still suffers some impediments that limit the range of its applications, especially in onshore locations. Those impediments include the need for a good starting velocity model, the availability of very low frequencies in the acquired data and the necessity for long offsets in order to mitigate the inversion problem.

<u>Presence of low frequencies</u>

In order to mitigate the non-linearity of the inverse problem and to ensure its convergence to a global minimum, a good starting model is required. Because the misfit function at low frequencies suffers less ‘cycle skipping’, it is desirable to start the inversion from the lowest available frequency in the data, although a good starting velocity model can mitigate this constrain. However, the lowest frequency in the data does not always provide a good starting point if that frequency does not contain coherent arrivals. For this dataset in focus, the lowest useable frequency, in a 3D form, is 14 Hz.

<u>The starting model</u>

The starting velocity model is an important component for a successful FWI. The current approach of obtaining a starting model from ray-based traveltime tomography followed by waveform inversion works generally well and produces good results. This is due to the fact that traveltimes contain the large-scale information of the subsurface while the detailed features are held in the waveforms. However, for the current dataset we used, ray-based methods could not provide a good starting model for FWI. This is because of the complexity nature of the subsurface that exhibits a step-like phenomenon in which

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the main refraction arrival dies out and a second strong arrival, a step behind it, takes over. This occurrence repeats for at least three parallel refraction arrivals. Therefore, the group velocity is not equal to the phase velocity of parallel refraction arrivals, which might be an evidence for the existence of low-velocity layers along the profile.

Long offset

The presence of wide-angle seismic data has been demonstrated to influence the results of the seismic inversion. The presence of wide offsets provides low wavenumber information and hence produces better velocity estimates. The current inversion schemes are influenced by the acquisition geometry, with the wide-azimuth acquisition producing better velocity images compared to a narrow-azimuth survey. Moreover, even with a single frequency approach, the quality of the results depends on the range of offsets. The maximum offset of the land dataset in focus is about 2.1 km, which is not regarded as a wide-azimuth dataset. Consequently, such a range of offset would impose another challenge if a conventional FWI approach were used.

Data preparation

FWI is not yet a panacea for seismic imaging. Therefor, the input seismic data need to be treated or pre-processed prior to the FWI process. However, the main thing to be aware of during the pre-processing is to mind the gap from any process that may affect the wide-angle turning waves, or the low frequencies present in the data. Although statics can be an issue on land data, we integrated the elevation statics within the initial velocity model. In general, the pre-processing is kept to a minimum for these data (Al-Yaqoobi et al., 2011).

A top mute is applied to remove the precursor waves ahead of the first arrivals. A bottom mute is applied in order to remove any effects of the reflection arrivals, shear waves, airwaves or ground roll waves, as well as any noisy arrivals after the main signal. Bad traces and bad shots have been removed, and a low-pass filter is then applied to the data using an Ormsby filter that keeps the low frequencies but rolls off from 25 to 35 Hz. Furthermore, the first 100 m offset of all shot gathers has been excluded from the inversion to avoid the effect of ground roll at short offset. The record length of the data is limited to 1500 ms. Given that the data were produced with a vibroseis source that was correlated in the field; therefore the effective source wavelet has a zero-phase signature. Although correlation usually compensates for the phase variation of the source, the receiver phase effect could still be present. However, we assume the significance of this effect is fairly minor.

FWI procedure

Once the a priori model has been validated, it is then used for the inversion, along with the pre-processed data and the derived source signature. Input densities are derived from velocity during the inversion process using a modified empirical relation ($\rho=310V^{0.25}$) of Gardner's formula, where velocity is in m/s and density is in kg/m^3. The grid spacing of the inversion model is 12.5 m in all directions with a model size of 171 x 171 x 81 grid nodes. Although our approach assumes pressure data, we invert land data recorded using vertical geophones, holding that the effect of such assumption is minor.

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. More iterations could possibly improve the fit to the field data. However, the improvement is very marginal and the increase in the number of iterations is on the grounds of the computation expense. Such a marginal improvement might be due to the fact that there are some limitations to the acoustic forward model in the sense that it does not account for attenuation and elastic effects. This is presumably the same reason why this modeling algorithm does not match the absolute amplitude of the real data.

The proposed strategy (Al-Yaqoobi and Warner, 2013), named as the 'Opening Window Strategy', comes in an attempt to solve the problem of inverting a difficult dataset that has a poor starting model due to the intricate nature of the acquired field data. The method works in several stages where a velocity model is produced at the end of each stage, which in turn is used as a starting model for the next inversion run. Each stage of the workflow is limited to a certain offset window. The choice of the offset window is based on results verification, where it has been found that the data need to fit properly at short offset, and hence a short offset interval, in this case 100 m, is chosen for the earlier runs. Then a 200 m window was found to be satisfactory for the gradual increase in the offset window. At all stages, the frequency bandwidth, the number of frequency blocks, and the number of iterations are kept the same.

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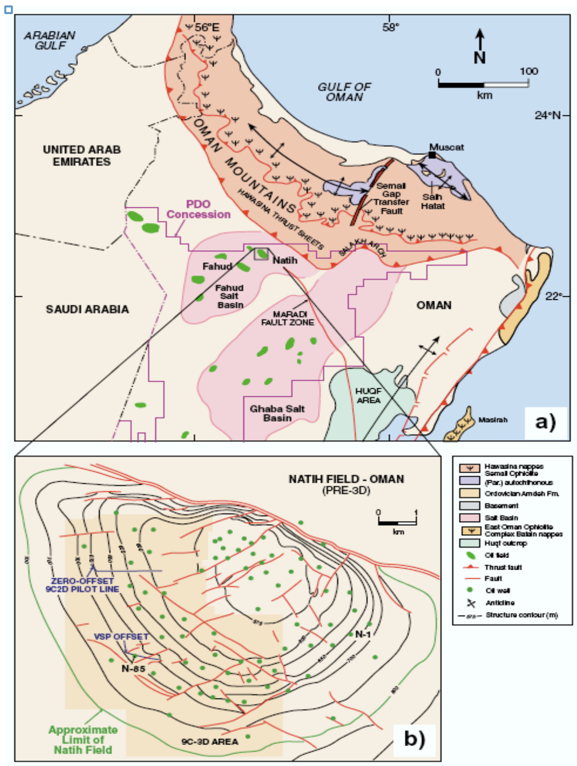

Figure 1: (a) Location map of Natih field, (b) The 3D survey area showing main faults (after Hitchings and Potters, 2000).

Results

An example of the inversion results (Figure 2) shows that there are low-velocity layers that permeate the relatively high-velocity zones. A 3D image of the FWI results (Figure 3) shows the reoccurrence of the low-velocity layers at deeper part of the model. Although the velocity generally increases with depth, those low-velocity areas could cause the propagating waves to slow at certain intervals in the near subsurface layers. Such a phenomenon complicates the near-surface structure and makes it difficult to predict the correct velocity model using the ray-based methods. This could be well related to the step-like occurrence that is seen in the field data. Consequently, traveltime tomography methods fail to produce a good starting model for FWI, and therefore conventional inversion methods might also fail if the starting model is not adequately predicted. The developed approach of the FWI methods has been able to avoid falling into local minima, by deploying a limited offset window at each stage, and repeating the inversion process at several runs to allow more data into the process at each stage till the full stretch of the data is covered. Moreover, correcting the velocity in the shallow part of the subsurface has an immense effect in the deeper parts, although the updates from the FWI model have mainly reached down to about 700 m. The 2D migrated sections (Figure 4) 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.

Detecting low-velocity anomalies

The FWI method with ‘opening window strategy’ has proved to be a successful method in detecting low-velocity layers in the near subsurface. Especially when using a 3D algorithm, the results from FWI have effectively recovered the existence of low-velocity layers in the shallow subsurface. Those relatively low-velocity horizons have velocities that range from about 1750 m/s to 2000 m/s. The presence of such alternating layers explains to a great degree the behavior of the refracted waves, which can be observed in the seismic sections of the data of this project.

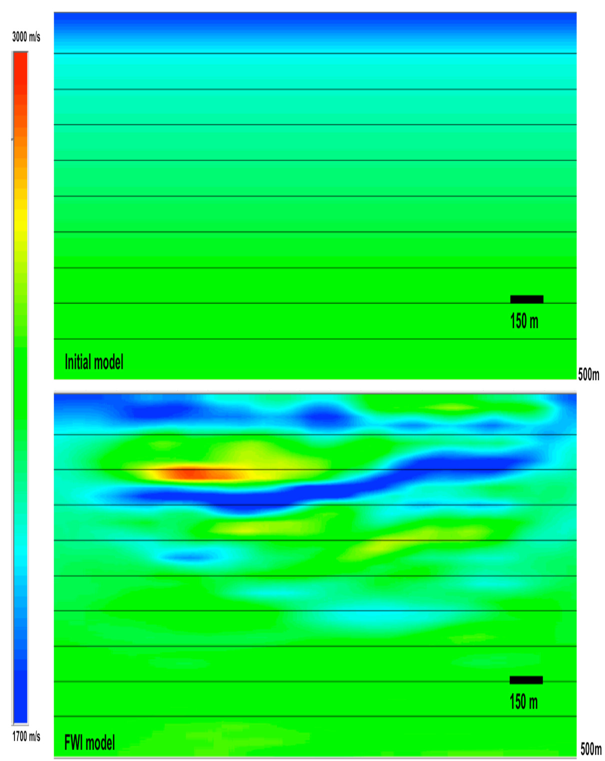

Figure 2: Vertical inline section through (a) 3D initial model, and (b) FWI 3D inversion result after inverting up to 500 m offset from the second stage of the inversion strategy.

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Conclusions

We have demonstrated the application of FWI on a 3D vibrator land dataset from an onshore field in Oman after careful pre-processing. Even with the best optimum parameters used in FWI, the method might fail if there are major issues associated with the field dataset. Using a poor initial model could yield the inversion to converge to a local minimum, and hence the final model would mismatch the field data or perhaps match the wrong arrivals. On the other hand, the developed strategy proposed in this study helps to deal with unusually difficult dataset. The method employs a limited offset window at several stages of the inversion to insure a good data fit of a certain part of the model before proceeding to fit the next parts. We have proved that such a strategy works efficiently for the dataset of this research. The choice of the offset window at each run depends on the complexity of the field dataset; where a short offset window is usually important to fit the near offset data before widen up the window for far offsets.

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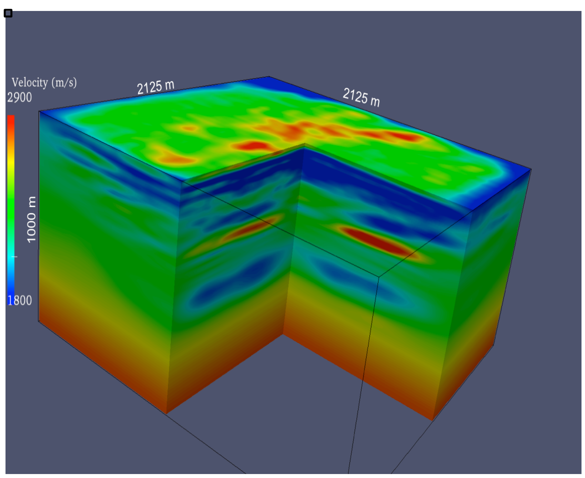

Figure 3: 3D FWI model after inverting up to 700 m offset.

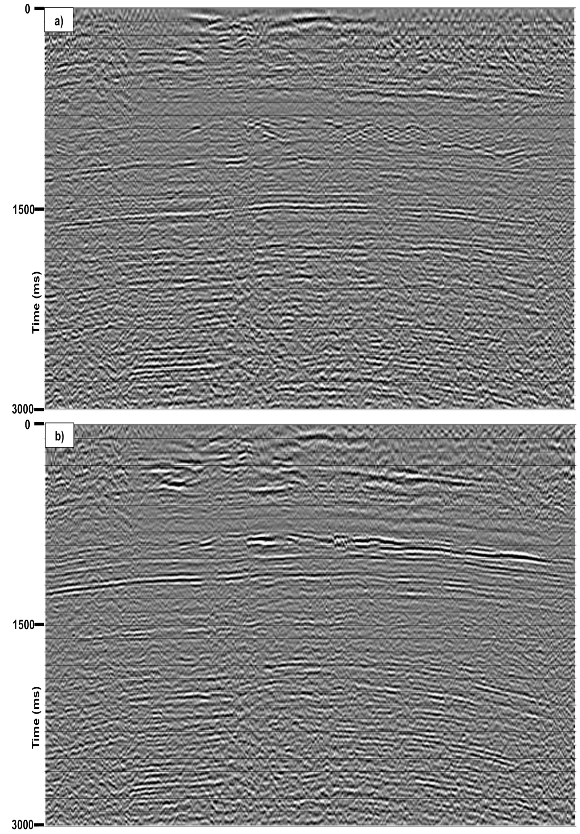

Figure 4: *2D migration images with (a) stacking velocity, and (b) FWI model. A band-pass filter of 5-10-25-35 Hz has been applied to both datasets.*

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EDITED REFERENCES

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