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High-resolution Land Full Waveform Inversion - A Case Study on a Data Set from the Sultanate of Oman

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Summary

Land full waveform inversion (FWI) is hindered by the presence of surface waves, near-surface heterogeneities, topography, and elastic effects. Broadband and large offset data acquisitions have been developed with the aim of investigating FWI as a tool for velocity model building in land environments. FWI using minimally-processed refractions and diving waves provides an efficient solution to recover long spatial wavelengths in the velocity model. This method has been proposed as a means to enhance standard reflection-based methods. Rather than settle for the recovery of long-to-intermediate spatial wavelengths, we incorporate reflection data in the FWI and move to higher frequencies (up to 13Hz) with the aim of recovering a level of model resolution that is comparable to marine case studies. By incorporating reflection data we recover details such as channels and fault structures and see improved imaging results over conventional migration velocity analysis. We outline a data preprocessing sequence tailored for improving data quality at low frequencies and long offsets and describe the FWI workflow. We show the resolution uplift over refraction-based FWI and compare migrated stacks generated with the standard tomography model to that generated with the high frequency FWI result.

Introduction

Subsurface imaging in land environments remains a challenging problem: standard reflection-based model building suffers from a general reduction in data quality relative to marine, and land applications of full waveform inversion (FWI) are hindered by the presence of surface waves, near-surface heterogeneities, topography, and elastic effects. Following the strategy proposed by Baeten et al. (2013), Petroleum Development Oman (PDO) has acquired broadband 3D wide-azimuth (WAZ) vibroseis data sets with the aim of improving regional subsurface imaging. These acquisitions have led to successful FWI case studies (Plessix et al., 2013; Stopin et al., 2014) which illustrate how minimally-processed refractions and diving waves recover the long-to-intermediate spatial wavelengths of the subsurface model. In these applications it is proposed that the FWI result be used as an improved input model to reflection-based traveltime tomography. In this study we aim not only to recover the long spatial wavelengths using FWI, but also the intermediate-to-short spatial wavelengths which provide a subsurface model resolution that is comparable to marine applications. Using a two-stage FWI approach, initially focusing on refractions/diving waves and subsequently incorporating reflection data, we obtain a significant improvement in structural detail which surpasses that achieved by refraction/diving wave FWI and migration velocity analysis.

Data acquisition and preprocessing

The study area is located in the Sultanate of Oman, acquired in 2014 by a broadband 3D WAZ vibroseis survey using a 9 second sweep of 1.5 to 86Hz (Mahrooqi et al., 2012). The acquisition design is that of recent regional case studies (Stopin et al., 2014): a shot spacing of 50 m by 50 m and a receiver spacing of 250 m by 25 m. The subsurface volume in this study spans 800 square kilometers in surface area and 5 km in depth. FWI was run in two stages. In the first stage we applied refraction/diving wave FWI using a maximum offset of 15 km, and in the second stage we applied FWI to both refractions and reflections together using a maximum offset of 8 km. Data preprocessing was designed for transmitted data quality in the first stage and reflected data quality in the second. On refractions and diving waves we applied adaptive surface wave attenuation (Le Meur et al., 2008), joint low-rank sparse inversion (Sternfels et al., 2015), and 3D linear noise filtering (Hugonnet et al., 2012) and tuned the preprocessing operators at each frequency octave (Retailleau et al., 2014). Figure 1 illustrates the level of noise attenuation/signal enhancement obtained in the bandwidth of 2-4 Hz. Details of the reflection data preprocessing can be found in Retailleau et al. (2014) and Retailleau (2015).

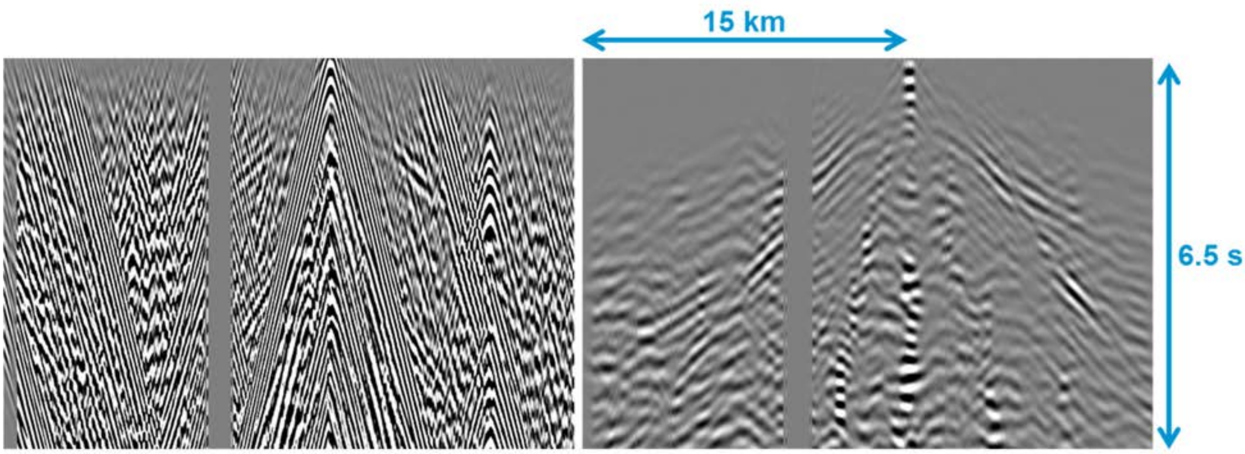

Figure 1 *On the left is a receiver line of the input data, filtered to frequency octave 2-4 Hz. On the right is the corresponding preprocessed data for this frequency range.*

Land FWI workflow

We applied an acoustic VTI formulation, parameterized in pressure, and computed gradient updates for the P-wave velocity. Density was empirically linked to P-wave velocities, and the anisotropy parameters for VTI modeling were obtained from well analysis and kept fixed. The acoustic approximation to land data is indeed a severe one. With proper data preprocessing and a sufficiently smooth starting model, the acoustic approximation can be made valid for land data (Plessix et al., 2010, 2012; Perez Solano et al., 2013; Stopin et al., 2014). To compare the vertical velocity geophone data with the modeled pressure wavefield, we artificially increase the receiver depths by a few meters as outlined in Plessix et al. (2012). The same approach is used to convert the vertical displacement vibroseis source to a pressure increment.

The FWI starting model was obtained from an existing pre-stack time migration velocity model, heavily smoothed and converted to depth. The elevation horizon was approximated by a flat and uniformly dipping surface. Elevation differences between this surface and the source and receiver depths (maximum difference of 22m) were used to compute small statics corrections which were applied to the seismic traces prior to FWI. We first ran FWI using refractions/diving waves with an increasing maximum frequency from 3 Hz to 9Hz, incrementing by 1 Hz intervals, with seven iterations in each frequency band. Similarly to Stopin et al. (2014), we did not obtain a significant uplift above 9 Hz. This FWI result was used as a starting model for a subsequent FWI application on both refractions and reflections from 9 Hz to 13 Hz, also incrementing by 1 Hz and with seven iterations in each frequency band. In this second stage of FWI we delineate structures such as channels and high-resolution faulting. Figures 2 and 3 illustrate two different depth slices, at 850 m and 1450 m respectively, of the FWI result using refractions only (9 Hz result) versus the final 13 Hz result. We compare migrated stacks generated using a model obtained by ray-based migration velocity analysis to migrated stacks generated with the 13 Hz FWI result. A section of a cross-line stack is shown in Figure 4. We observe improved reflector continuity and flatness particularly below faulted structures and at depth, and resolve deeper faulting structures that are not apparent using the conventional velocity model building approach.

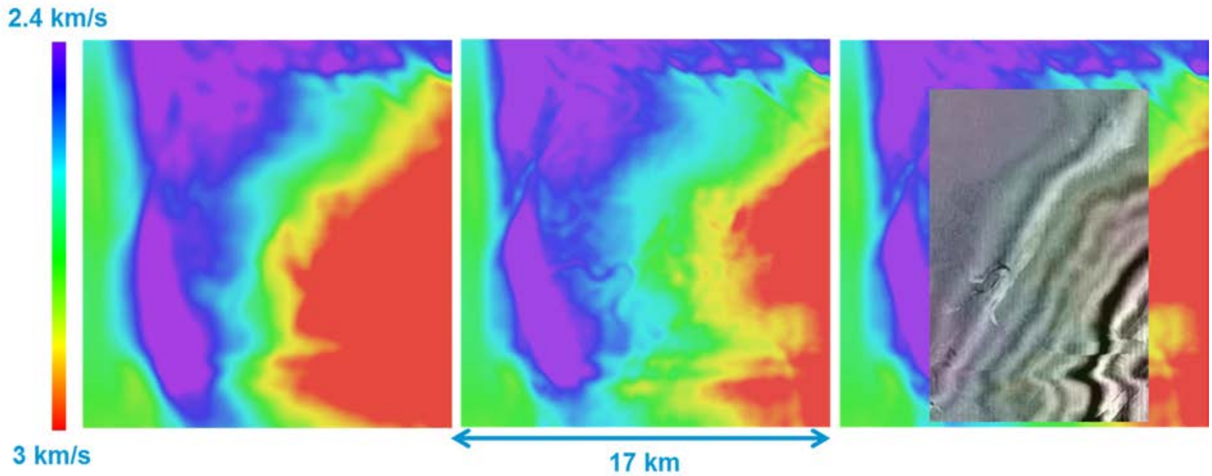

Figure 2 *Depth slice at 850 m. Left: refraction/diving wave FWI result at 9 Hz. Middle: 13 Hz FWI result which incorporates reflections. Right: including corresponding migrated stack depth slice overlay.*

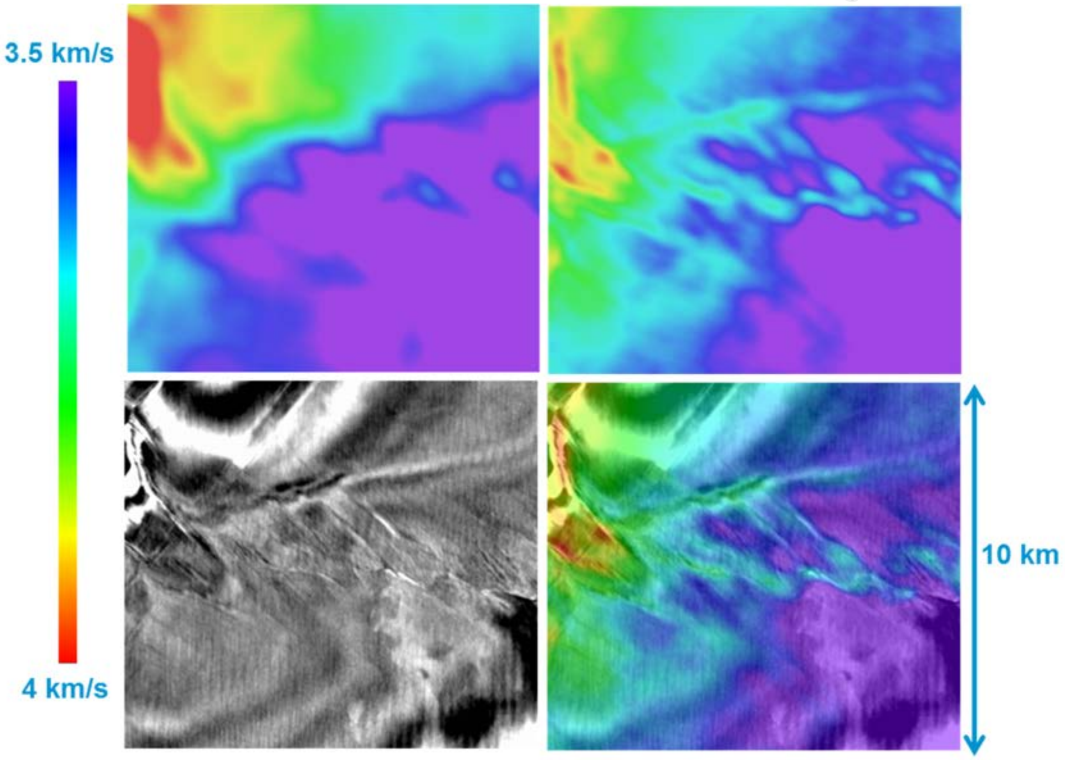

Figure 3 *Depth slice at 1450 m. Top left: refraction/diving wave FWI result at 9 Hz. Top right: 13 Hz FWI result which incorporates reflections. Bottom left: corresponding migrated stack depth slice. Bottom right: 13 Hz FWI result with migrated stack overlay.*

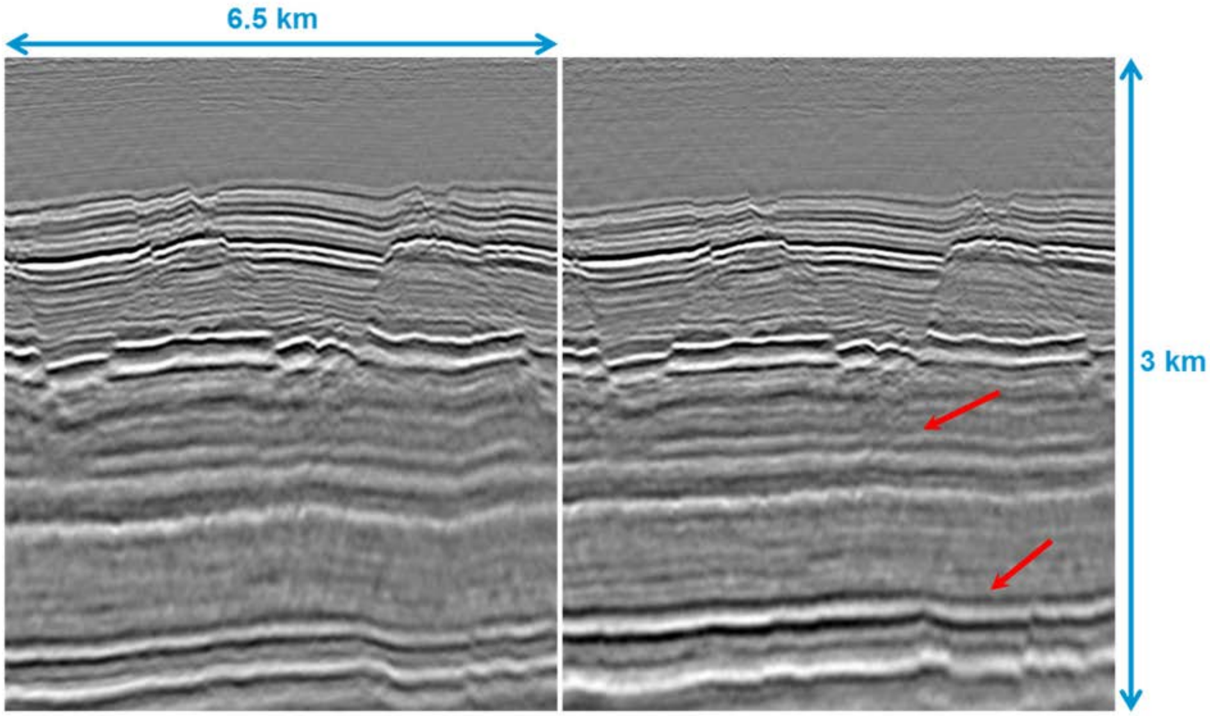

Figure 4 *Left: A section of a migrated stack cross-line using ray-based migration velocity analysis. Right: the same section of a migrated stack generated with the 13Hz FWI result. We observed*

flattened, compressed and continuous reflectors beneath faulted structures and improved image quality of faulting depth.

Conclusions

The recent developments in vibroseis acquisition design, recovering very low frequencies (down to 1.5 Hz, not easily obtained in marine acquisitions) and long offsets, offer promising opportunities for land FWI. We outline a FWI-oriented data preprocessing sequence for vibroseis data and detail a two-step FWI workflow which incorporates both transmitted and reflection data. We observe a significant uplift in structural detail and resolution following the inclusion of reflection data which we do not attain with refractions/diving waves alone, even when inverting at higher frequencies (Stopin et al., 2014). Finally, we observe imaging improvements over conventional migration velocity analysis and obtain a subsurface model resolution that is comparable to offshore studies.

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