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FWI with Scaled-Sobolev Preconditioning Applied to Short-Offset Vibroseis Field Data

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Summary

We present an application of seismic full-waveform inversion (FWI) with scaled-Sobolev preconditioning (SSP - after Zuberi and Pratt, 2016) to a field seismic dataset. The data were collected over a crooked line with rough topography, using only short offsets, and no low frequency content. As is often the case with land data, this presents a number of challenges for processing with FWI. The reservoir of interest is the Utica Shale in eastern Ohio, USA, which sits at depths between 2.2 km and 2.5 km in the study area. We limited our inversions to approximately 0.6 km in depth, due to the narrow range of offsets. Constraining the velocity structure in the very near surface is essential to recovering the velocity structure at greater depths through subsequent migration processing. The FWI results are validated by a comparison of forward-modelled data to field data, and by a scrutiny of the coherencies of the recovered source signatures.

Introduction

Successful imaging of deeper subsurface structures requires an accurate representation of the seismic velocities in the very near-surface (Armstrong et al., 2001). It is uncommon to apply full-waveform inversion (FWI) to land seismic data, due to the challenges imposed by near-surface effects, statics, and terrain issues (Smithyman and Clowes, 2012). Some of these challenges can be met where there is access to very large offsets (eg. Kamei et al., 2015) and/or low frequencies (eg. Malinowski et al., 2011). Without low frequencies it is difficult for conventional FWI to converge on global minimum solutions (Virieux and Operto, 2009). To mitigate convergence problems 'multi-scale' approaches are often used in which strong wavenumber filtering is employed as a preconditioner in the beginning stages of FWI to produce low-wavenumber updates. However, such multi-scale approaches often unnecessarily eliminate high-wavenumber features early on in the inversion scheme. We apply an alternative approach based on a scaled-Sobolev preconditioning (SSP - Zuberi and Pratt, 2016; Zuberi and Pratt, 2017) that avoids the need for scale separation. This approach allows us to successfully apply FWI to a land seismic dataset with only a limited offset range and no low frequency content.

Seismic Survey and Data Preconditioning

The Utica Shale reservoir in eastern Ohio, USA is a common area of hydraulic fracturing for oil and gas. In 2013, a 3-component land seismic acquisition survey was carried out on a crooked line, called 'Firestone 2D-3C.' Figure 1 shows a map view of the crooked seismic line, the projected coordinates for 2D FWI, and nearby oil and gas wells.

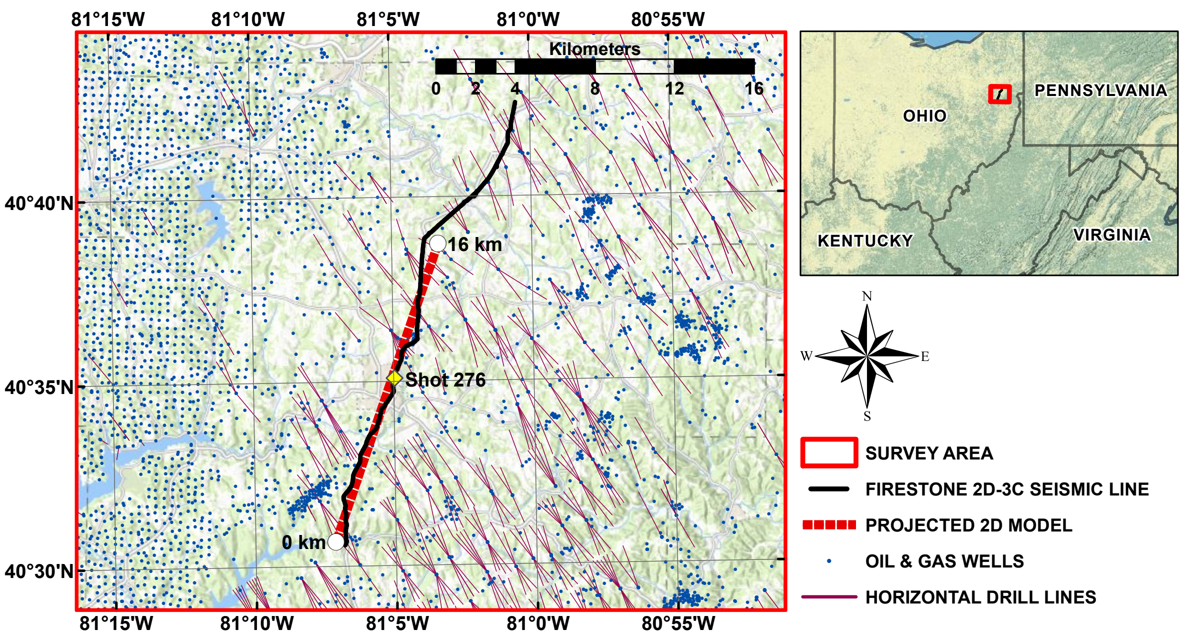
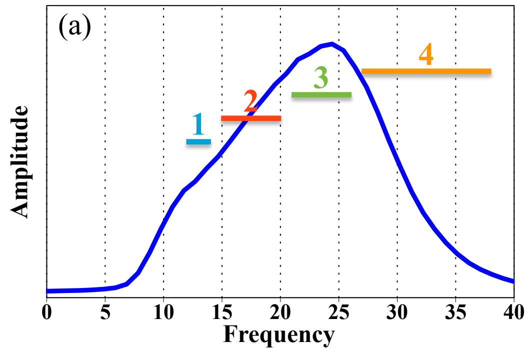


Figure 1 *Map of Firestone 2D-3C seismic line. The 'projected 2D model' corresponds to the results displayed in Figure 3 (a) - (e). Shot #276 in yellow corresponds to the shot gathers displayed in Figure 4 (a) - (c). Map data from Ohio Department of Natural Resources - Division of Oil and Gas Resources Management (2016); Esri (2016); and U.S. National Park Service (2009).*

We applied 2D FWI to a 16 km portion of the line, with 501 unique source positions, and 995 unique receiver positions. The sources were vibroseis trucks sweeping from 6 to 120 Hz over a time record of 8000 ms. The source spacing was 33 m. Within each source group, two vibroseis trucks were spaced apart by 24 m. The receivers were 10 Hz resonant 3-component geophones spaced at 17 m. The data were collected with standard offsets for the purpose of conventional reflection seismic processing: a typical shot had 438 active receivers deployed in a split-spread configuration, with a maximum offset of approximately 3.5 km (Figure 4 (a)). Because FWI relies on transmitted or refracted events (Virieux and Operto, 2009), our results are limited by these offsets to a depth of 0.6 km. We thus do not image the Utica Shale reservoir, which lies at depths between 2.2 km and 2.5 km in the study area. Recovering the velocities in the near surface, however, is essential to accurately imaging subsurface features during subsequent migration.

A projection of a crooked line onto a 2D plane creates errors in traveltimes of seismic data. In 2D modelling, 3D wave propagation is not accounted for and the actual time a wave takes to get from shot to receiver in an (x,y,z) world is different than its projected-(x,z) counterpart. To mitigate the resulting errors, we discarded all data where the difference between the new projected offset value and the original offset value was greater than 3%.

Further data preconditioning was completed in VISTA Seismic Processing software and included (1) isolating the vertical P-wave component of recorded seismic data (from 3 components); (2) applying an FK filter to suppress the effects of ground roll; (3) applying a zero-phase Butterworth filter with corner frequencies 6-12-20-40 Hz; (4) muting the data 30 ms before the first-break picks; (5) eliminating the farthest offsets (greater than 2.5 km) in the early stages of inversions; and (6) eliminating the near offsets (less than 0.6 km) throughout all stages of inversions (Figure 4 (a) - (c)). Figure 2 shows the amplitude spectrum of the field data following preconditioning, and our frequency-domain inversion strategy.



(b)

Block	Frequencies (Hz)	# Iterations
1	12, 13, 14	100
2	15, 16, 17, 18, 19, 20	100
3	21, 22, 23, 24, 25, 26	100
4	27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38	50

Figure 2 *(a) Frequency content of field data after FK filter, bandpass filter (corner frequencies 6-12-20-40 Hz), and trace muting. (b) Frequency-domain FWI strategy.*

FWI with Scaled-Sobolev Preconditioning

We generated the starting model for FWI by performing 3D traveltime tomography in TomoPlus (Zhang and Toksoz, 1998) software on the crooked line with the original (x,y,z) coordinates. We then projected to (x,z) coordinates and smoothed the result for 2D FWI (Figure 3 (a)). When the background velocity of the model is accurate, the use of the Born approximation in FWI is sufficient. However, where the background velocity is less accurate this may lead to nonlinearity in the FWI objective function (Ma and Hale, 2013). In order to mitigate this nonlinearity, we constrained the wavenumber scale of the velocity updates by applying scaled-Sobolev preconditioning (SSP) to the gradient of the least-squares objective functional during model updates (Zuberi and Pratt, 2016; Zuberi and Pratt, 2017). SSP applies an image-constrained smoothing kernel to the gradient. The SSP smoothing kernel allows local high wavenumber perturbations to be retained in the gradient, but also amplifies low wavenumbers elsewhere. The strength of the high-wavenumber features included in the velocity updates is controlled by choosing appropriate SSP scale factors.

We applied FWI using only the phase of the data, following Kamei et al. (2014). A strong attenuation of $Q = 1$ was used in the air layer to suppress wave propagation; and a weaker attenuation of $Q = 400$ was used in the subsurface to allow for adequate wave propagation. Laplace-Fourier domain damping was used ($\tau = 0.35$ s) to emphasize early arrivals, and to suppress later arrivals.

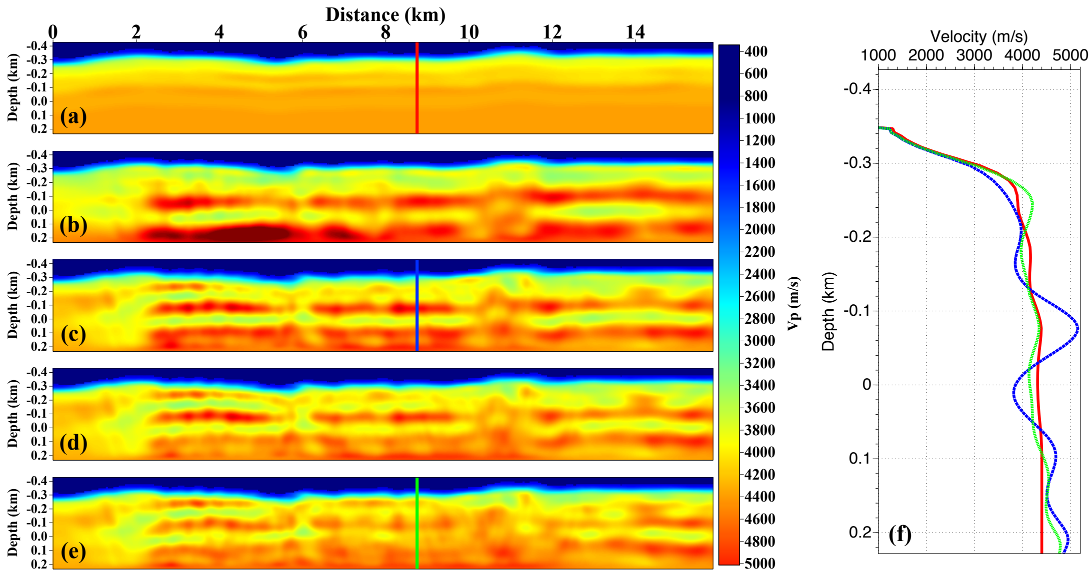


Figure 3 *Progression of P-wave velocity model from FWI with SSP. Negative depth values indicate elevation above mean sea level. (a) Starting model for FWI - smoothed 2D line of the 3D result from traveltime inversion. (b) Model after block 1: 12-14 Hz. (c) Model after block 2: 15-20 Hz. (d) Model after block 3: 21-25 Hz. (e) Final model after block 4: 26-38 Hz. (f) 1D velocity plot at shot #276 (8.7 km) from the starting model (red), the block 2 model (blue), and the final model (green).*

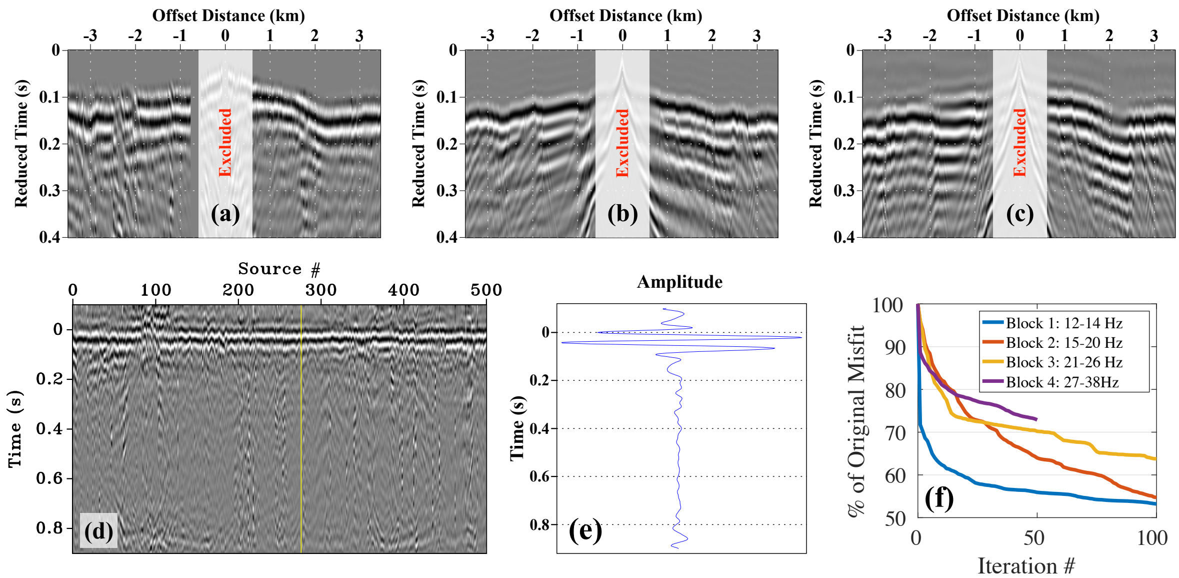


Figure 4 *(a) Field data after preconditioning. (b) Forward-modelled data from starting FWI model. (c) Forward-modelled data from final FWI model. (d) Source inversion after final FWI model; yellow line indicates shot used in plots (a) - (c). (e) Average of all sources. (f) Objective function reduction. Trace balancing was applied to plots (a) - (d).*

Figure 3 shows the progress of the velocity models during FWI with SSP. We observe the largest visible change in the velocity model from the starting model (a) to the result after 12-14 Hz (b). In the absence of sonic well log data, we validate our final result by comparing forward-modelled data to the original field data, and by reviewing the final ensemble of source inversions for each source location (Figure 4 (d)). The final forward-modelled data results in Figure 4 (c) show a good correlation with the phase of the field data in Figure 4 (a). Decreases in the misfit between forward-modelled data and field data are displayed in Figure 4 (f) and further show convergence throughout all frequency blocks. The recovered source signature for the 501 sources in Figure 4 (d) and their average in Figure 4 (e) show a coherent estimation of a mixed-phase wavelet appearing close to 0 s. There is a noticeable amount of noise present in the individual source estimates. Nevertheless, the coherency of these estimates gives us confidence in the velocity model.

Conclusions

Our study presents, to our knowledge, the first application of 2D FWI with scaled-Sobolev preconditioning (SSP) to a field dataset. The ability to simultaneously update the low- and high-wavenumber features through the SSP method is an invaluable asset to the FWI algorithm, and particularly to this dataset, where low frequency content below 12 Hz was unavailable. By using the SSP approach, we successfully applied FWI to a field dataset without requiring a separation of scales during the inversion.

Acknowledgements

This work is supported in part by a NSERC Discovery Grant to R. Gerhard Pratt, and an Ontario Graduate Scholarship to Benjamin P. Consolvo. We would like to thank TGS for the seismic data used in this study. We also thank Brendan R. Smithyman, Hugh D. Geiger, and Shaun M. Hadden for their review of the abstract. The figures were generated using Madagascar, Seismic Unix, MATLAB, and ArcGIS.

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