Full-Waveform Inversion of Field Data in the Foothills: Results and Challenges with Long-Offset Seismic

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Summary

In the Canadian Foothills, long-offset seismic data are occasionally acquired in an effort to "undershoot" areas of steeply dipping faults and severe near-surface weathering. Since long-offsets are one method of acquiring the low-wavenumber information necessary for full-waveform inversion, these data provide an excellent opportunity for demonstrating the efficacy of full-waveform inversion in building velocity models for areas possessing large, lateral velocity variations. However, the acquisition of low-frequency field data remains a challenge. The use of MEMS accelerometers (with a broadband response in the acceleration domain) was proposed as a solution, but the results of a recent long-offset acquisition demonstrate that the records possess sub-optimal low-frequency data, dominated by instrument noise.

If seismic data are recorded with an appropriately designed survey (i.e., long-offsets and recording instruments capable of recording the low-frequencies), and sufficient, appropriate pre-processing is applied to the input data (e.g., to mitigate the effects of elastic modes), acoustic full-waveform inversion can produce complex velocity models of the sub-surface from field seismic data.

Velocity Estimation in Complex Geological Settings

Imaging and velocity model estimation in areas of complex geology, such as thrust-fold belts, remains an active area of research in the hydrocarbon exploration industry. The economic potential of these complex structures may be significant, yet many remain seismically unresolved, in part due to computational and acquisition technology limitations.

Our recent synthetic benchmark study (Brenders et al., 2008) demonstrated that seismic data in the Canadian Foothills, when acquired with long-offsets and low-frequency sensors, could potentially yield accurate, high-resolution velocity models when processed by Waveform Tomography (traveltime tomography followed by full-waveform inversion).

Over the past decade, interest in applying full-waveform inversion to wide-angle (long offset) seismic data has grown rapidly. Although challenging in practice, Waveform Tomography has proven effective in estimating velocities accurately in complex geological settings. For example, Jaiswal et al. (2008) used waveform inversion to assist in imaging a thrust fault by interpretation of a velocity model from a geologically complex area where ambiguity existed in the migrated image due to poor imaging conditions and data quality.

Acquisition of Long-Offset, Low-Frequency Seismic Data

In this study, we compare seismic data using two types of acquisition sensors: MEMS accelerometers and conventional geophones. Due to the non-linearity of the inverse problem, success in waveform inversion is dependent on acquiring both low-frequency data and on initial low-wavenumber information in the model space. An accurate starting model can provide the latter. To obtain low-frequency land seismic data, acquisition with MEMS accelerometers has been proposed (Pratt and Stork, 2006). Unfortunately, field data comparisons have shown that the low-frequencies of MEMS data are likely dominated by noise (e.g., Hons et al. (2008)).

Seismic surveys in the Alberta Foothills were designed and acquired by Talisman Energy Inc. Long-offset, 2-D seismic data were acquired from an area of active exploration: Line A is approximately 24 km long, and was acquired in an area of rough topography, including a 6 km wide section of deeply weathered carbonate outcrops. These carbonates are Mississippian in age, and overlay sequences of Cretaceous and Jurassic clastics, as well as deeper Mississippian/Devonian targets. A raw shot gather from this line is shown in Figure 1(a). A split-spread shooting geometry was used, with a maximum offset of 10 km. Shots were nominally acquired with an interval of 100 m; across the carbonate outcrop, a shot interval of 50 m was used. Shots were placed at 18 m depth; across the carbonate outcrop, shots were placed at 30 m depth to mitigate the amount of energy "trapped" in the near-surface. Receivers with a 10 Hz natural resonance frequency (OYO GS-32CT) were used, with a group interval of 25 m.

Data Preconditioning by Exponential Time-Damping

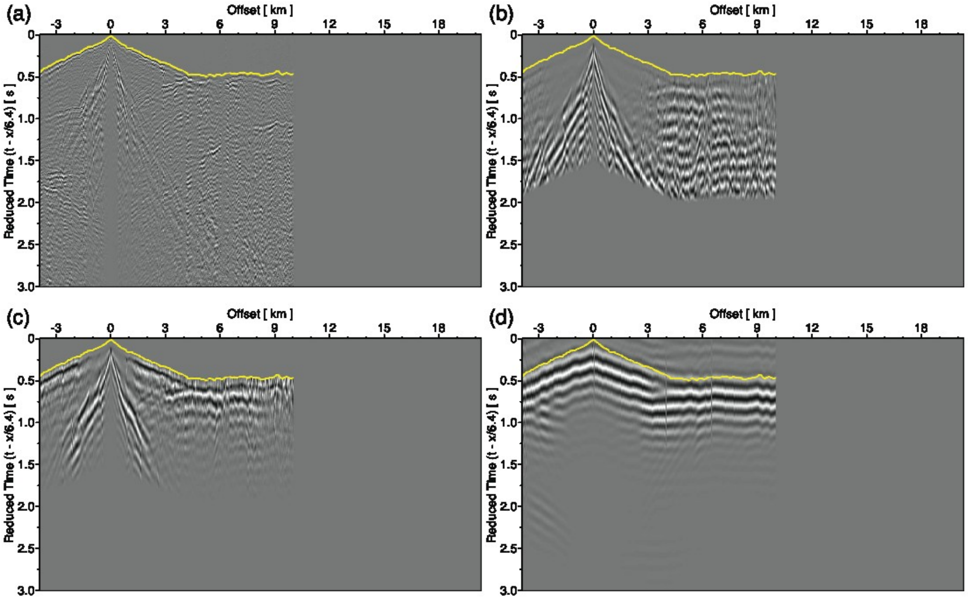

Figure 1: (a) Shot gather from a long-offset seismic line acquired in the Foothills, after (b) bandpass filtering to 8 Hz and time-windowing, and (c) with time-damping of τ =0.25s applied. For comparison, (d), the corresponding synthetic shot gather generated in the starting velocity model, also with τ =0.25s.

Before waveform inversion, the data went through a number of pre-processing steps including trace editing, t-squared scaling, bandpass filtering from 1 to 8 Hz, muting with a 1.5 s time window after the first arrival, and linear moveout. An example of a pre-processed shot gather is shown in Figure 1(b).

Waveform Tomography focuses on minimizing the misfit between the synthetic data and the early, refracted, and generally more linear portion of the full-waveform of the real data. This can be partially accomplished by inverting only a small time window of data after the first arrival. By applying an exponentially decaying time function to the input data during the inversion, we can further enhance the early-arrival energy of the diving waves. An appropriate choice of this decay constant allows us to apply "time-damping" to the input seismic data before inversion. Our pre-processed input shot gather, Figure 1(b), is shown in Figure 1(c) with time-damping applied. This time-damping approach lends itself to frequency-domain methods, since in the discrete Fourier domain, this is equivalent to using a complex-valued frequency, defined by $\omega = \omega + i/\tau$, where ω is the angular frequency and τ is a decay constant. The Fourier transform may then be replaced by

$$u(\omega') = \sum_{k}^{N_t} u(t_k) e^{i\omega t_k} e^{-t_k/\tau} \qquad (1)$$

where t_k is the time-sample and $u(\omega')$ is the complex-frequency Fourier transform of the time-damped wavefield.

Results and Challenges with Field Data in the Foothills

Comparison between observed and modelled, synthetic shot gathers in an appropriate starting model is a necessary first step for success. The starting model for Waveform Tomography was constructed by diving wave tomography using hand-picked first arrivals. A time-domain synthetic shot gather modelled in the starting model is shown in Figure 1(d), for comparison with Figure 1(c). A wide-angle reflection from the steeply dipping carbonate thrust sheet is visible at approximately 0.6 s below 3.5 to 4 km offset in both the observed and, to a lesser a degree, in the synthetic data, indicating the model is sufficiently accurate for full-waveform inversion.

By examining the data in the frequency-space domain, quality control of the input data was performed. Figure 2(a) depicts the 3.333 Hz component of the input, pre-processed data, without time-damping applied. Low-frequency, high-amplitude ground roll dominates the recorded wavefield at offsets < 3 km. Zero data indicates that a first arrival was not picked due to poor data quality. Figure 2(b) is the equivalent pre-processed 3.333 Hz real component, with $\tau = 0.25$ s applied, as in Equation 1. The importance of an appropriate τ factor to pre-processing the input data is evident: only after applying τ-compensation to the input data do coherent wavefields appear at offsets beyond those dominated by ground roll.

Examination of the panels in Figure 2 shows the variation in data quality due to near-surface geology, topography, shot coupling, etc., and allows further decisions to be made as to what data should be input into waveform inversion. For example, data at offsets dominated by ground roll were not included in the inversion. Analysis of the frequency-domain wavefield panels allows us to pick both the lowest possible starting frequency and an appropriate value of τ.

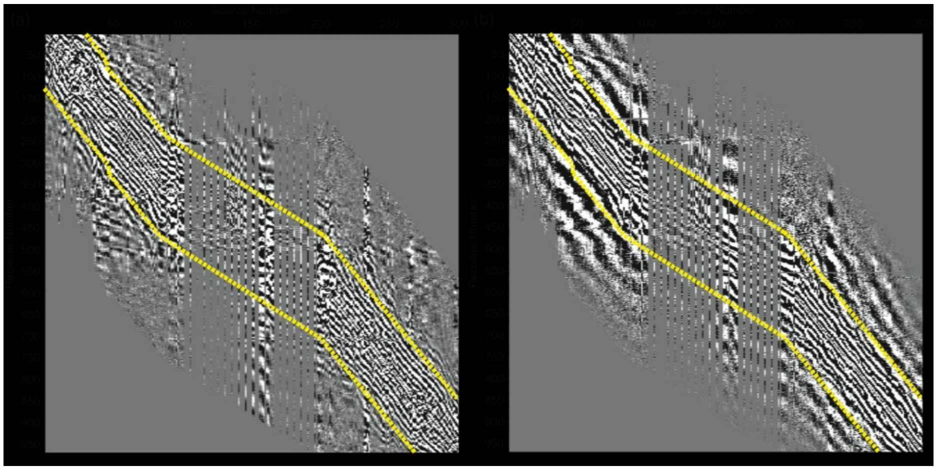

Figure 2: Frequency-domain wavefields at 3.333 Hz for picked sources and receivers (a) without and (b) with τ =0.25s applied. Below 3 km offset, the wavefields are dominated by ground roll (dashed lines).

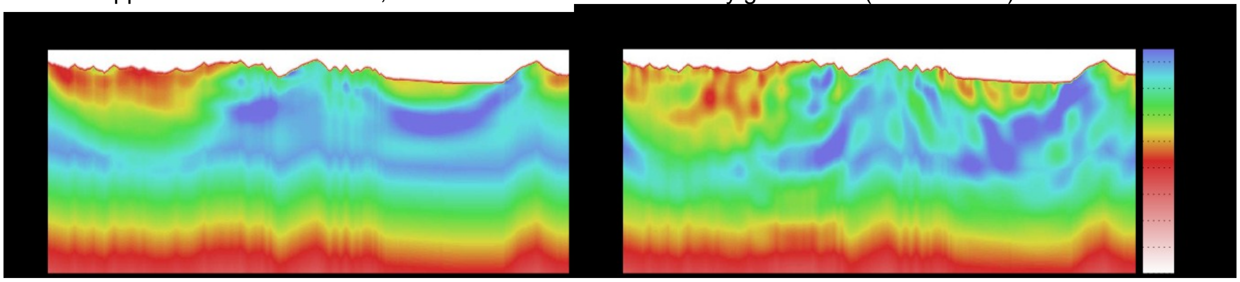

Figure 3: (a) Starting velocity model for Waveform Tomography, derived from diving wave tomography of hand-picked first-arrivals. (b) Result from full-waveform inversion of data frequencies from 2.5 to 4.0 Hz.

Using the velocity model in Figure 3(a) as a starting model, waveform inversion began at a frequency of 2.5 Hz. Groups of 3 frequencies (e.g., 2.5, 2.667, 2.833) were inverted for 5 iterations before proceeding to the next group of frequencies. Data with $\tau = 0.25$ s were initially used, followed by data with τ = 0.50 s, effectively increasing the amount of waveform input into waveform inversion. The intermediate result from full-waveform inversion, to a maximum frequency of 4 Hz, is shown in Figure 3(b).

Although a geologically interpretable velocity model was obtained in Figure 3(b), the result may have benefitted from the presence of additional low-frequencies in the recorded seismic data. Data from two additional long-offset lines were also used for full-waveform inversion. Lines B and C are both 16 km long, and were acquired in an area of rough topography, with near-surface, steeply dipping structures. Line B was acquired with geophones as in Line A, spaced every 25 m; whereas Line C was acquired with MEMS accelerometers spaced every 5 m. Comparison of 4.0 Hz wavefields from Lines B & C (Figure 4), illustrates the complete lack of high-fidelity, low-frequency data from accelerometers.

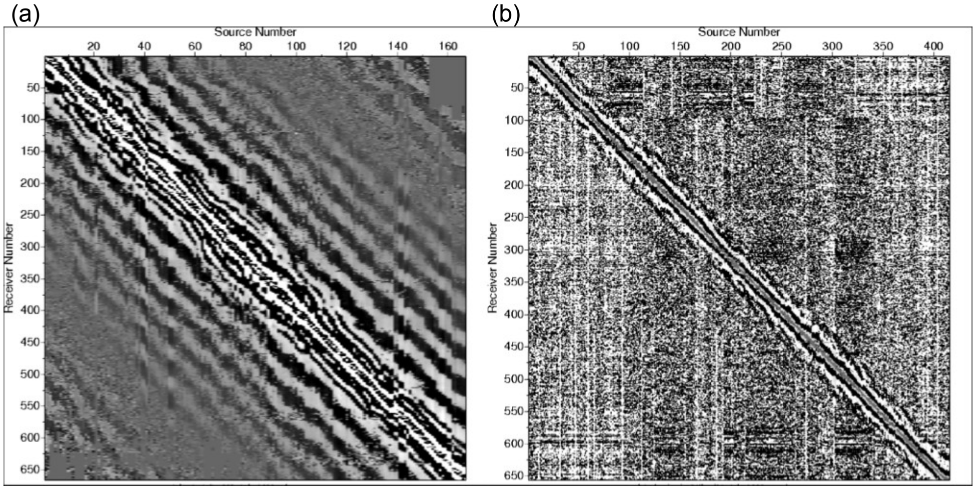

Figure 4: Frequency-domain wavefields of seismic data at 4.0 Hz for all picked sources and receivers, acquired with (a) geophones, and (b) MEMS accelerometers. Wavefields displayed with τ = 0.25 s applied.

Discussion and Conclusions

We found that geophones behaved better than MEMS accelerometers in recording low-frequency data with a usable signal-to-noise ratio. Data preconditioning is essential to successful Waveform Tomography with seismic data from the Canadian Foothills. Without sufficient time-damping applied to the input data, the inversion fails to converge to a solution.

The high-velocity carbonate thrust sheet overlying the slower clastics layers causes a sharp velocity inversion, severely limiting the depth of investigation. A better starting model coupled with low-frequency data should provide some improvement. In spite of this, Waveform Tomography of seismic data from the Canadian Foothills has succeeded in recovering a geologically interpretable velocity model.

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