Application of multiscale waveform tomography for high-resolution velocity estimation in complex geologic environments: Canadian Foothills synthetic data example

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Seismic imaging in compressional belts such as the Canadian Foothills is very challenging due to complex geological structures, rugged surface topography, and highly variable near-surface conditions. Seismic sections across the Canadian Foothills are usually progressively more distorted when approaching the Canadian Foothills region. Figure 1 shows the degree of structural complexity and topographic variations which are in part responsible for the deteriorated imaging in the thrust belt. Accurate velocity models of subsurface structures are critical for improving seismic images of thrust belts in both the time domain (e.g., tomostatics) and the depth domain (e.g., prestack depth migration).

Figure 1. *An outcrop in the Canadian Foothills showing the rugged surface topography and complex near-surface structures.*

Velocity estimation methods using refracted waves, e.g., refraction traveltime tomography, can be ineffective because this energy is trapped by the complex near-surface structures and consequently has limited depth penetration. In contrast, waveform tomography, which uses both refraction and reflection energies, can accurately estimate both near-surface and deep velocity structures. Time-domain multiscale waveform tomography is used in this work to investigate potential for velocity estimation in complex environments because it is simple to implement; there is no need to solve a large, sparse linear system of equations; and, thus, less computer memory is required even for 3D cases. Furthermore, free-surface boundary condition and surface topography can be easily handled with the time-domain formulation.

Synthetic acoustic data were generated from a geologically realistic velocity model to test the potential of waveform tomography to reconstruct velocity models in complex areas. Results show that multiscale waveform tomography can provide an accurate and highly resolved velocity tomogram. This test also validates that waveform tomography can effectively handle rugged surface topography.

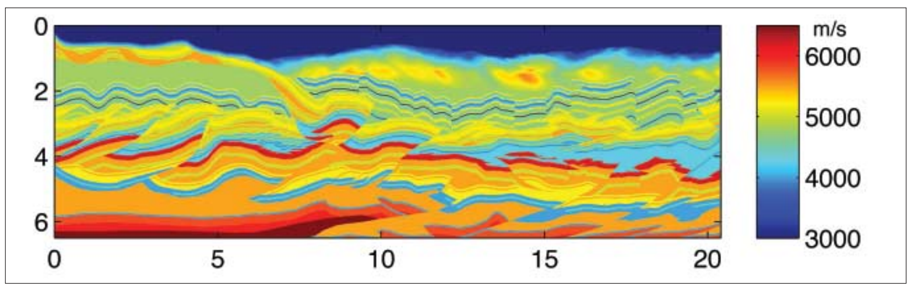

Figure 2. *The velocity model used to generate acoustic synthetic data. Vertical axis = depth (km). Horizontal axis = horizontal position (km).*

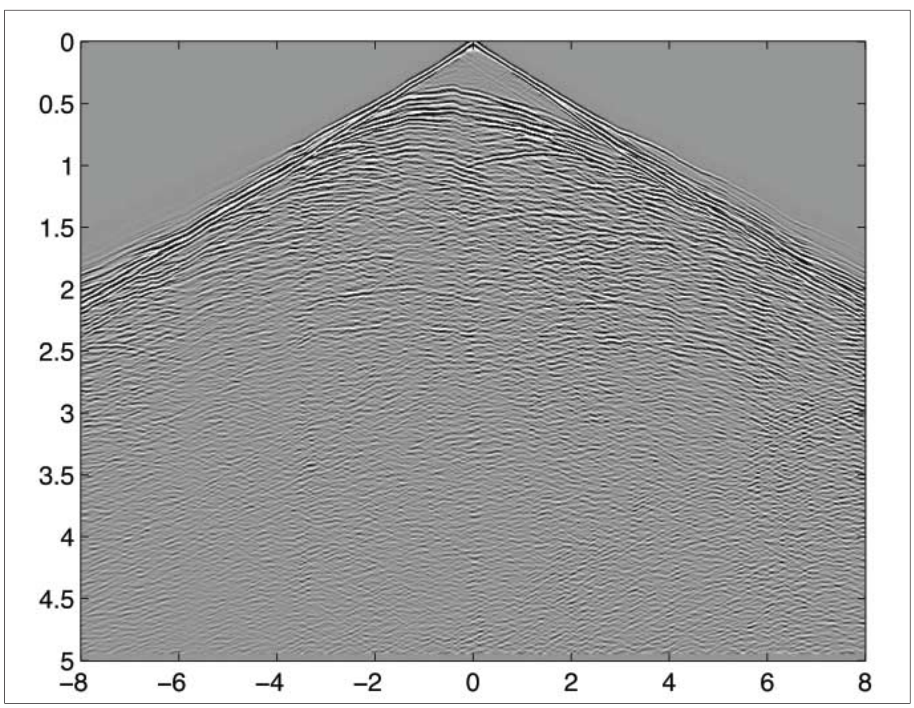

Figure 3. *A synthetic shot gather generated by using the model in Figure 2. Vertical axis = time (s). Horizontal axis = offset (km).*

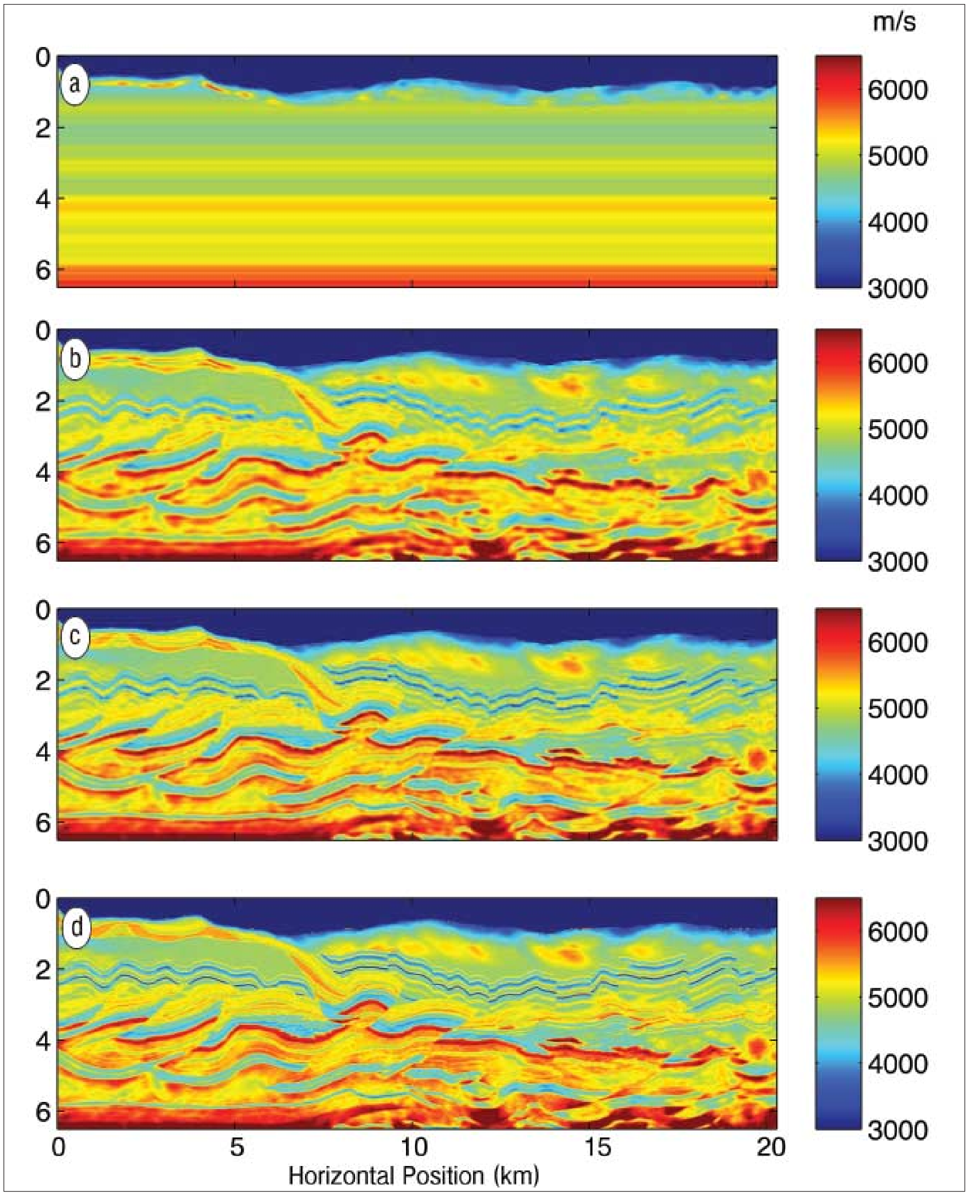

Figure 4. *(a) Initial velocity model. Waveform tomogram after the inversion using (b) data with a peak frequency of 5 Hz, (c) data with a peak frequency of 10 Hz, and (d) data with a peak frequency of 20 Hz. Vertical axis = depth (km). Horizontal axis = horizontal position (km).*

Time-domain multiscale waveform tomography

Tarantola (1984) pioneered the development of acoustic waveform tomography for accurate and high-resolution velocity estimation. In complex velocity models, the local minima problem usually prevents waveform tomography from converging to the global minimum. To solve this problem, Bunks et al. (1995) proposed a multiscale method in the time-domain. Their method was successfully validated by the well-known Marmousi model. To improve the computational efficiency of the method of Bunks et al., Boonyasiriwat et al. presented efficient low-pass filters and a strategy for choosing optimal frequency bands (a modified version of a frequency-domain strategy proposed by Sirgue and Pratt in 2004). Their method has been tested on both synthetic data and field data.

In the time-domain multiscale waveform tomography method, the seismic data and the estimated source wavelet are low-pass filtered to various low-frequency bands. This allows the inversion to proceed sequentially from low-frequency data to high-frequency data in the time domain. Since the misfit function at low frequencies is more linear than at higher frequencies, multiscale waveform tomography has a better chance to reach the global minimum. Inversion of low-frequency data recovers low-wavenumber components of velocity models while inversion of high-frequency data recovers higher-wavenumber components. Accurate large-scale or low-wavenumber components of velocity models are crucial for successful recovery of high-wavenumber components.

The velocity model used to generate synthetic data for this study was based on actual surface geology, topography, seismic, and well data from the Canadian Foothills (Figure 2). Synthetic, long-offset, split-spread, acoustic data were generated from this model. A representative shot gather is shown in Figure 3. A 20-Hz Ricker wavelet was used to generate 204 shots with 1601 receivers per shot. Sources and receivers are located 10 m below the topographic surface with source and receiver intervals of 100 m and 10 m, respectively. Each shot gather has a maximum offset of 8 km and a total record length of 5 s.

Waveform tomography results

An initial model was obtained by combining a traveltime tomogram, which provides the near-surface velocity structure, and a 1D average of the true model (Figure 4a). The refraction energy is trapped in the near-surface area and does not provide a good starting model for the deep region. Full-waveform data with three frequency bands (peak frequencies of 5 Hz, 10 Hz, and 20 Hz) were used in multiscale waveform tomography without any time window, i.e., the entire gather was used in the inversion. The inversion results are shown in Figure 4b–d. Comparing to the true model (Figure 2), the final tomogram (Figure 4d) is accurate and highly resolved. Thin-layer structures in the near surface and the thrust-fold structures are accurately recovered. Another objective of this

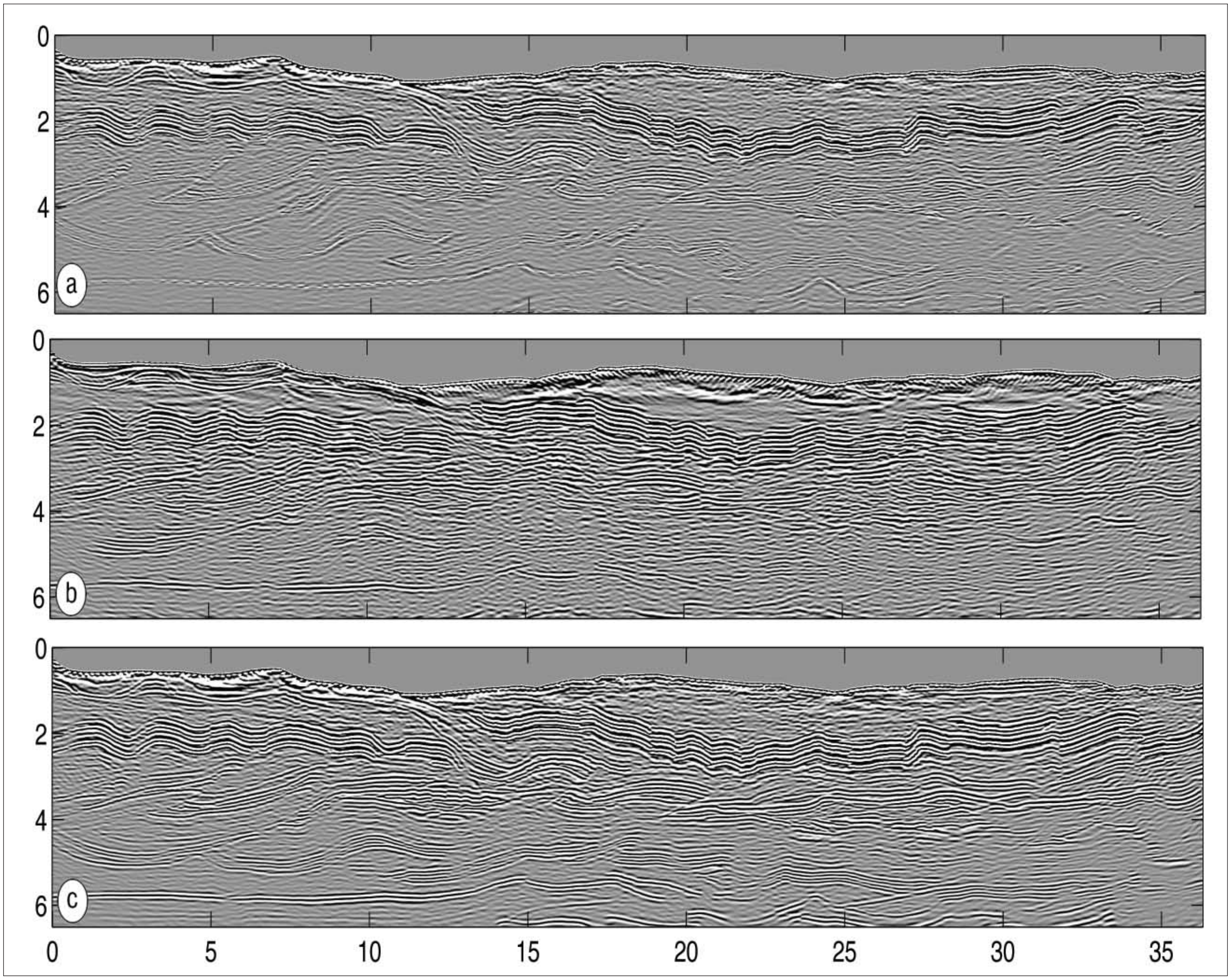

Figure 5. *(a) RTM migration using true velocity model. (b) RTM migration using ray tomography model. (c) RTM migration using waveform inversion velocity model. Vertical axis = depth (km). Horizontal axis = horizontal position (km).*

study is to determine the influence of the velocity model on generating migration images. We applied reverse time migration (RTM) to the data using zero-lag cross-correlation. The RTM image using the true velocity model shown in Figure 5a compares well with the RTM image obtained using the full-waveform velocity model in Figure 5c. The improvements in the migrated image using the full-waveform velocity model in Figure 5c compared to Figure 5b clearly demonstrates the value of full-waveform inversion in imaging complex structures.

Conclusions

We successfully applied time-domain multiscale waveform tomography to velocity estimation in a synthetic, complex environment. Both near-surface and deep, complex structures are accurately recovered. These promising results show that waveform tomography can be a method of choice for velocity estimation in complex environments. In field data cases, there are additional challenges, including random noise, surface waves, nonuniform source radiation, elastic effect, attenuation, and anisotropy, which make waveform tomography extremely difficult to work. In such circumstances, early arrival waveform tomography and intensive data preprocessing will be strongly required.

Suggested reading. "Inversion of seismic reflection data in the acoustic approximation" by Tarantola (Geophysics, 1984). "Multiscale seismic waveform inversion" by Bunks et al. (Geophysics, 1995). "Efficient waveform inversion and imaging: A strategy for selecting temporal frequencies" by Sirgue and Pratt (Geophysics, 2004). "An efficient multiscale method for time-domain waveform tomography" by Boonyasiriwat et al. (submitted to Geophysics). "An application of time-domain multiscale waveform tomography to marine data" by Boonyasiriwat et al. (SEG 2008 *Expanded Abstracts*). "Early arrival waveform tomography on near-surface refraction data" by Sheng et al. (Geophysics, 2006). TLE

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