# Velocity Estimation by Waveform Tomography in the Canadian Foothills: A Synthetic Benchmark Study

A. J. Brenders (Queen's University, Canada), Sylvestre Charles (Talisman Energy Inc., Canada), and R. Gerhard Pratt (Queen's University, Canada)

In the structurally complex Canadian foothills, conventional seismic data processing is inadequate, given the effects of steep dips, rough topography, and near-surface weathering. Depth imaging is often necessary, and an accurate estimation of the macro-velocity model is essential. Waveform Tomography (i.e., traveltime tomography followed by frequency-domain waveform inversion) of long-offset data provides a possible solution. In order to investigate this, we generated synthetic data in a geologically realistic model exhibiting fold-thrust sheets, steeply dipping structures, and topographically elevated carbonate outcrops. The method shows promise for resolving the near-surface geological structures in this environment. Real data acquired with long-offsets and low-frequency sensors may provide the necessary input for Waveform Tomography to succeed in the Canadian foothills.

## Main objectives:

This study illustrates a new benchmark model and dataset representative of the Canadian foothills. The imaging challenges encountered in the foothills are present in both the model and data. Using this dataset, we demonstrate the efficacy of Waveform Tomography in determining the macro-velocity model in a structurally complex geological setting.

## New Aspects Covered:

This is the first application of Waveform Tomography to seismic data representative of the Canadian foothills. The effects of the near-surface, such as topographically elevated carbonate outcrops, are investigated. We show that long-offset data containing low-frequencies allow Waveform Tomography to effectively recover the near-surface velocity structure of a Canadian foothills tectonic setting.

Submission ID: 4072

## Introduction

The Canadian foothills of the easternmost Rocky Mountains span the border between southern British Columbia and Alberta, and are an active area of oil and gas exploration. However, the dominance of complex geological structures, such as fold-thrust sheets, duplex structures, and tight box folds, combined with steeply dipping formations and rough topography, can lead to sub-standard results from conventional seismic processing. These results are often inadequate, resulting in the need for additional depth processing, such as pre-stack migration, requiring an accurate velocity model of the subsurface (e.g., Vestrum et al., (2004)).

Additional imaging challenges are present when seismic data are acquired over topographically elevated carbonate outcrops, a common occurrence in parts of the southern Alberta foothills. These carbonate outcrops, often deeply weathered, are characterized by sharp velocity contrasts between the weathered layer and underlying formations. Source energy can become "trapped" in the near-surface, reducing the amount of energy propagating to deeper targets beneath these areas, resulting in poor quality signal recorded at the surface. The lack of transmitted seismic energy is further complicated by the velocity inversion between the shallow carbonates and underlying (slower) clastics.

One solution is to "undershoot" the target area by acquiring data with long offsets. A shot gather from a 2-D line in the Alberta foothills is shown in Figure 1(a). The line was shot with longer than usual offsets (10 km split-spread), and illustrates the difficulties in acquiring clean data in areas of rough topography with significant near-surface weathering. Acquisition of long offset data presents further opportunities for improving the estimation of the sub-surface velocity model and resolution of the near-surface statics problem.

Methods of velocity estimation using refracted energy have recently attracted interest in the exploration community (e.g. Dell'Aversana et al. (2003), Pratt (2004)). Long-offset (wide-angle) methods provide extra information on the large- and medium-scale wavenumbers of the estimated velocity model, introducing stability before standard reflection processing. Previous studies of imaging with foothills-type data, such as the one described by Gray and Marfurt (1995), did not generate the long-offset data necessary for diving wave tomography methods to succeed. One promising method for velocity estimation with wide-angle data is Waveform Tomography (e.g., Brenders and Pratt (2007)).

## Waveform Tomography

Waveform Tomography combines starting models obtained from traveltime tomography with full-waveform inversion to obtain an estimate of the subsurface velocity consistent with the seismic data recorded. Implemented in the frequency-domain, waveform inversion recovers a "best fit" model by iteratively minimizing the misfit between the observed waveform data and the modelled, synthetic waveforms. Forward modelling is performed using the acoustic wave equation, and a linearised gradient method is used to iteratively converge to a solution. Capable of resolving the subsurface with a resolution of wavelength order (Pratt, 1999), Waveform Tomography is an improvement over ray-based methods.

Waveform Tomography for velocity estimation has been successfully applied in both synthetic, blind tests (Brenders and Pratt, 2007), and to real, long-offset data in an exploration setting (Operto et al., 2004). Pratt and Stork (2006) have proposed this method, when combined with digital receiver technology, as a solution to the near-surface statics problem.

Using a geologically realistic model, synthetic, long-offset data were generated by a 2-D visco-acoustic frequency domain method (e.g., Pratt, 1999). These data provide a benchmark with which to test various strategies for velocity estimation and imaging. Upon obtaining a reasonable starting model, Waveform Tomography is applied to these data to explore the ability of the method to accurately estimate a foothills velocity model.

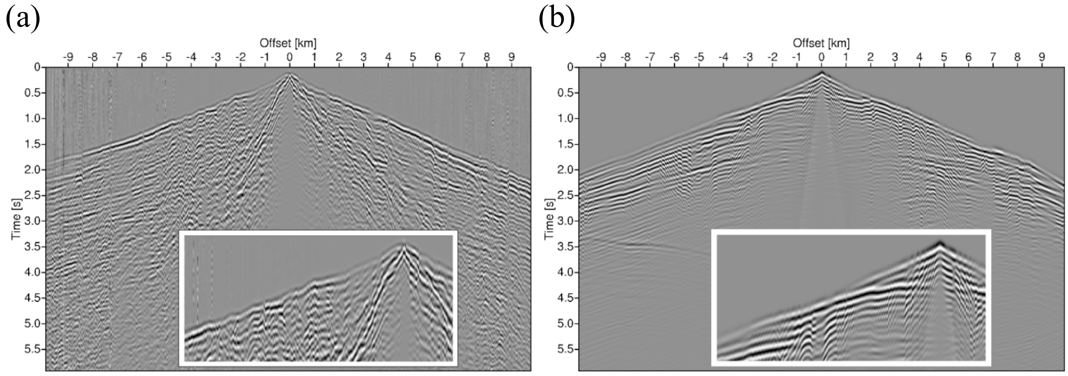

**Figure 1:** Long-offset shot gathers from (a) a real dataset collected in the Canadian foothills, and (b) a shot gather modelled in the model in Figure 2(a).

## A Synthetic Benchmark for the Canadian Foothills

A processed and structurally interpreted 2-D seismic line from an area of exploration interest was made available by Talisman Energy Inc., forming the basis of our geologically realistic foothills model. P-wave velocity and density were estimated based on available well logs. Parameters were defined on a 1 x 1m grid (Figure 2(a)), with the model extending 26025 m horizontally, and 6501 m vertically. S-wave velocities, as well as anisotropy parameters ($\delta$ and $\varepsilon$) were also specified on the same scale, for future elastic modelling. Topographic relief of 767 m is present in the model, as well as low-velocities in the near-surface representing weathering and sub-weathering layers of maximum thicknesses of 25 m and 100 m, respectively. The velocity of air (330 m/s) was specified above topography.

Economic targets within the model include a tightly folded fault-propagation structure and several duplex structures. The model is characterized by steeply dipping formations with large lateral velocity variations, and a velocity inversion near surface, with high-velocity carbonates overlaying low-velocity clastic sediments.

Ray tracing was performed within the model (see Figure 2(b)), illustrating the first-arrival ray paths of the diving wave energy within our model. Several shadow zones can be seen through which no rays pass, indicating the areas within the model most likely to benefit from Waveform Tomography. Ray tracing also illustrates the inherent difficulty of using refracted / diving wave methods in the foothills: shallow, high-velocity contrasts inhibit the early arrival energy from propagating to target depths.

## Synthetic Seismic Data

The acquisition geometry of our synthetic experiment was designed to record data with both longer offsets and denser spatial sampling intervals than in real data. Shots were spaced every 25 m along the model, at a depth of 20 m below topography. Receivers were spaced every 12.5 m, located on the topographic surface. Data were recorded for all offsets, from 0 to 26 km. Modelling was performed with a minimum-phase equivalent wavelet, in order to simulate a dynamite source signature. Using a frequency-domain, visco-acoustic method (Pratt, 1999), data were modelled from 0.0833 to 16 Hz, in steps of 0.0833 Hz, in our foothills velocity model interpolated onto a 12 x 12m grid spacing. Complex frequencies were used to reduce temporal aliasing, and the resulting frequency-domain data were transformed by discrete Fourier transform to the time-domain.

Figure 1(b) illustrates a forward-modelled shot gather with offsets ranging from -9.9 to 9.9 km, comparable to those recorded in the real shot gather in Figure 1(a). When comparing the early portions of the waveforms to those of the shot gather from a real foothills dataset (see insets, Figures 1(a) & (b)), we observe a number of the complex characteristics typically observed in foothills data, such as diffractions caused by rough topography and steeply dipping formations, albeit with a negligible amount of noise.

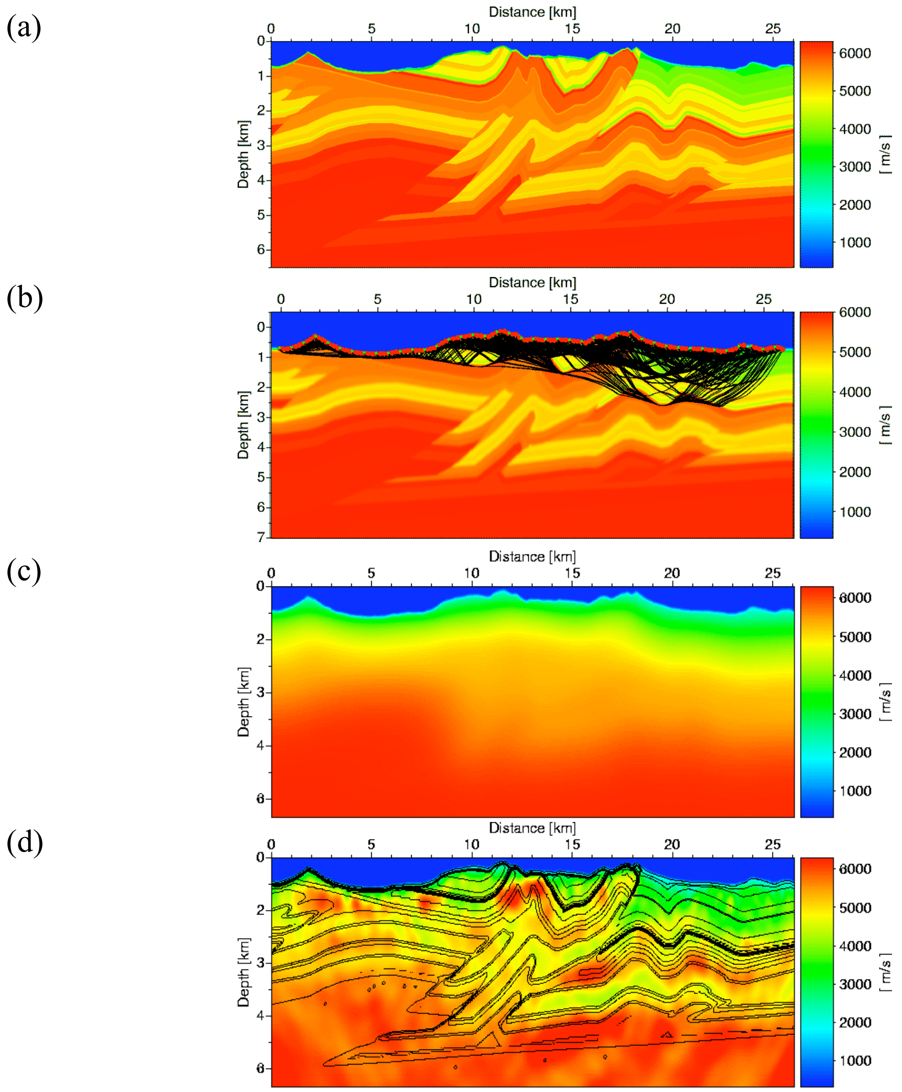

**Figure 2**: (a) A synthetic velocity model for the Canadian foothills, and (b) ray tracing within this model. (c) The starting model used for Waveform Tomography, and (d) a result from Waveform Tomography, using frequencies from 1 to 4 Hz.

## Waveform Tomography of Foothills Seismic Data

The starting model for waveform tomography is shown in Figure 2(c). It is a smoothed version of the true model; further work using starting models derived from the data is currently underway. A 2 s window of data after the first arrival was used as the input for Waveform Tomography, after increasing the shot and receiver intervals to 100 and 25 m, respectively. Figure 2(d) shows a result from Waveform Tomography of the synthetic data generated in the model. The true velocity model contours have been overlain for comparison. Frequencies from 1.0 to 4.0 Hz were inverted, in groups of 3 overlapping frequencies (i.e., 1.0 – 1.1 – 1.2 Hz). Data from offsets up to 26 km were used.

The results are promising, especially in the recovery of both the fault-propagation fold target and the anticlines overlying the duplex target structures on the right hand side of the model. Problems occur with the recovery of the high-velocity outcropping carbonates, and with the deeper, high-velocity basement. Additional preconditioning of the data or modification of the tomography strategy may provide further refinement or improvement.

## Discussion and Conclusions

Our frequency-domain modelled data were generated using an isotropic, acoustic wave equation, allowing no S-wave energy to be included in our input data. We did not explicitly model a free surface above topography. However, even with these limitations, our approximate (acoustic) method can generate synthetic data exhibiting characteristics similar to those observed in seismic data recorded in the Canadian foothills (Figure 1). In the coming months, a more realistic synthetic dataset using this model will be generated using a time-domain, anisotropic, elastic wave-equation method including the case for a free-surface above topography, such as that described by Saenger and Bohlen (2004).

The steeply dipping clastic formations of the Canadian foothills are generally known to possess anisotropy. Vestrum (2004) has demonstrated the effects of tilted transverse isotropy (TTI) on imaging in the Canadian foothills, and Charles et al. (2006) examined its impact on velocity analysis of 3-D foothills data. Recent work by Operto et. al. (2007) has extended frequency-domain waveform modelling to account for 2-D TTI anisotropic media. Implementation of this method within Waveform Tomography of a real foothills dataset is a goal of future work, and may in fact be required for accurate velocity estimation and successful imaging within the Canadian foothills.

Waveform Tomography shows promise for resolving near-surface structure in the Canadian foothills, given long offsets and low-frequency data. Real data acquired with long-offsets and sensors capable of reliably recording low-frequency energy may provide the necessary input for successful Waveform Tomography. Several questions arise: 1) Synthetic results in this paper used data from 1 to 3 Hz. Can we still obtain useful results with field data without these ultra-low frequencies? 2) Given the geological structures present in the Canadian foothills, the maximum depths of penetration for diving wave methods are limited. To what extent can accurate shallow velocity models aid in the imaging of deeper structures? These benchmark data will allow these questions to be investigated.

## Acknowledgements

We would like to thank Talisman Energy Inc. for permission to publish these results. Additional thanks to Steve Cloutier for assistance in building the foothills velocity model.

## References

Brenders, A.J. and Pratt, R.G., 2007, Full-waveform tomography for lithospheric imaging: results from a blind test in a realistic crustal model, Geophys. J. Int., **168**, 133-151.

Charles, S., Mitchell, D., Holt, R., Lin, J., and Mathewson, J., 2006, To TTI or not to TTI? Semi-automated 3D tomographic velocity analysis in the Canadian foothills: A case history, CSPG-CSEG-CWLS Ann. Conv., 58-65.

Dell'Aversana, P., Colombo D., Buia M., and Morandi S., 2003, Velociity/interface model building in a thrust belt by tomographic inversion of global offset data, Geophysical Prospecting, **51**, 23-35.

Gray, S.H. and Marfurt, K.J., 1995, Migration from topography: improving the near-surface image: Can. J. Expl. Geophys., **31**, 18-24.

Operto, S., Ravaut, C., Improta, L., Virieux, J., Herrero, A., Dell'Aversana, P., 2004, Quantitative imaging of complex structures from dense wide-aperture seismic data by multiscale traveltime and waveform inversions; a case study, Geophysical Prospecting, **52**, 625-651

Operto, S., Ribodetti, A., Grini, M., and Virieux, J., 2007, Mixed-grid finite-difference frequency-domain viscoacoustic modeling in 2D TTI anisotropic media, 77th Ann. Intl. Mtg., Soc. of Expl. Geophys., Expanded Abstracts, 194-198.

Pratt, R.G., 1999, Seismic waveform inversion in the frequency domain, Part I: Theory and verification in a physical scale model, Geophysics, **64**, 231-248.

Pratt, R.G., and A. Brenders, 2004, Frequency-domain waveform tomography using refracted arrivals: 66th Ann. Intl. Mtg., Europ. Ass. Of Geosci. & Eng., W8.

Pratt, R.G. and Stork, C., 2006, Solving static problems with ultra-low frequency data and waveform inversion, 68th Ann. Intl. Mtg., Europ. Ass. of Geosci. & Eng., A035.

Saenger, E.H., and Bohlen, T., 2004, Finite-difference modeling of viscoelasttic and anisotropic wave propagation using the rotated staggered grid., Geophysics, **69**, 583-591.

Vestrum, R., and Gray, S., 2004, Adventures in thrust-belt imaging, CSEG Annual Convention.