

Z-99 Velocity Models from Frequency-Domain Waveform Tomography: Past, Present and Future

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Introduction

The author recently contacted a number of leading research groups, many of whom provided examples of the success of the frequency-domain approach to waveform inversion. Apart from the use of the frequency-domain, a key common factor in all of these studies is the tomographic use of large-offset, transmitted, refracted arrivals. In this respect we refer to such work as *waveform tomography*. Large offset data are very sensitive to velocities; waveform tomography provides a way to unravel the complexities of the refracted arrivals in order to yield well constrained velocity models. In contrast, the CMP reflection survey is less sensitive to the macro variations in seismic velocity, and wide angle, refracted arrivals are generally ignored in the conventional processing scheme.

Waveform tomography is an extension of waveform inversion methods first developed in the early 1980's (e.g., Lailly, 1983 and Tarantola, 1984). The frequency-domain version of waveform inversion developed in the 1990's (e.g., Pratt and Worthington, 1990) has now emerged as an efficient imaging tool, capable of being used on a production basis for large scale 2D problems.

The examples of frequency-domain waveform tomography herein image the Earth's interior successfully on a wide range of scales. We can therefore anticipate a rich future for the waveform tomography approach and it is very likely that part of this future lies in the oil and gas industry. Ultimately surveys should be specifically designed for waveform tomography. The industry will need to re-discover the importance of the refracted wavefield and the equal importance of low frequencies. On the processing side, major challenges remain to move the 2D implementations into the 3D world, to properly account for shear waves, mode conversions and multi-component data, and to incorporate the critical second order effects of anisotropy and attenuation.

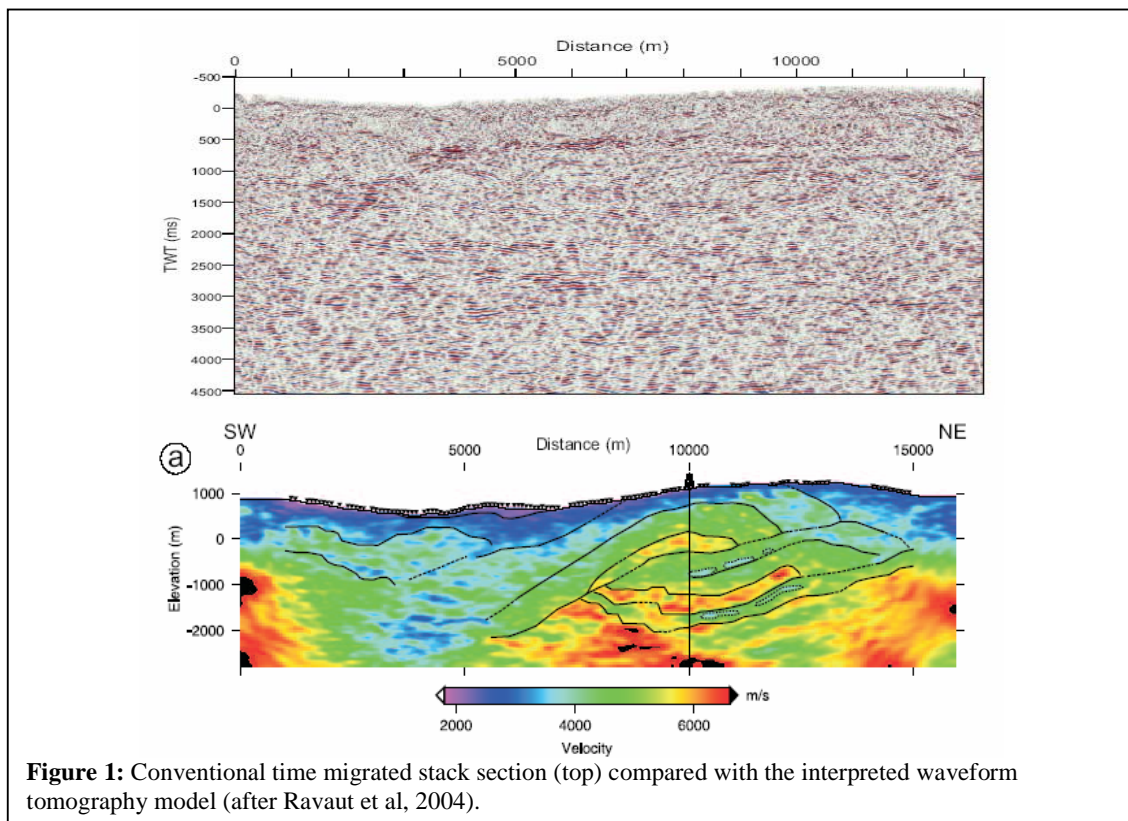
Data examples

The data examples below are arranged roughly in order of decreasing scale length and increasing data frequencies. They range from the global scale, to the crustal scale, to the exploration scale, and to the small scales required in near-surface engineering applications. At the very smallest scale, waveform tomography has also been used to image georadar data.

1. 3-D seismic structure of the Earth's interior on a global scale (R. Geller¹, T. Hara², N. Takeuchi¹, K. Kawai¹): Geller and his associates invert earthquake teleseismic and surface wave data on a global scale (e.g., Geller and Hara, 1993); their frequency-domain modelling algorithm is known as the Direct Solution Method (e.g., Geller and Takeuchi, 1995); their inverse approach is equivalent to that of Tarantola (1984). They have used their approach, for example, to show that the scale of hot, upwelling structures originating at the core-mantle boundary becomes smaller as the hot material ascends to the mid-mantle.

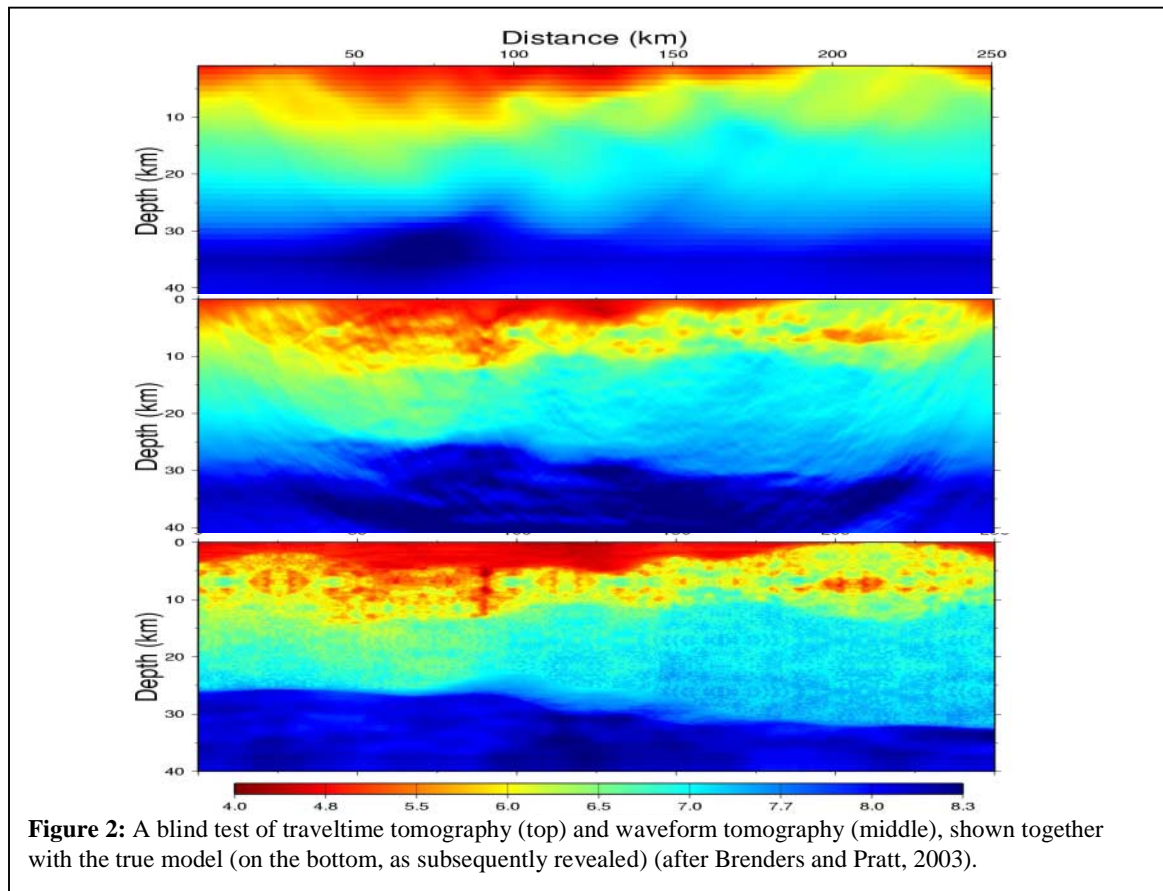
2. Multi-fold OBS data Eastern Nankei Trough, offshore Japan (J.X. Dessa³, S. Operto³, S. Kodaira⁴, A. Nakanishi⁴, G. Pascal⁵, K. Uehira⁶, Y. Kaneda⁶): A major marine experiment involving 100 OBS receivers at a 1 km spacing was inverted using combined traveltimes tomography and prestack depth migration (Dessa et al., 2004). The authors are now using frequency-domain waveform tomography; their initial results indicate an improved ability to image the low velocity zone representing the Tokai thrust.

3. Multi-fold wide-aperture data, Southern Apennines, Italy (C. Ravaut³, S. Operto³, L. Imbrota⁷, J. Virieux³, A. Herrero⁷, P. Dell'Aversana⁸): An application of frequency-domain waveform tomography to dense onshore refraction data recorded in a complex geological setting (Ravaut et al., 2004). The study demonstrates that the combination of first-arrival traveltimes and waveform tomography is a promising approach, solving some of the problems in developing macro-velocity models when only near-vertical reflection data are considered. Two images from this study are shown in Figure 1.



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4. Synthetic Elastic, Crustal Refraction data in a blind test (D. Brenders⁹, R.G. Pratt⁹): Brenders and Pratt (2003) processed data from a blind test: their results and the true model (now revealed) are shown in Figure 2. The synthetic survey comprised 2-D elastic wide angle data from 51 shots, each recorded at 2779 receivers, spanning a 250 km interval.



5. Efficient selection of Frequencies (Marmousi Model data) (L. Sirgue^{9,3}, R. G. Pratt⁹): Sirgue and Pratt (2004) showed that as few as only three frequencies are sufficient to yield an accurate velocity model from a wide-angle version of the Marmousi model data.

6. Alternative objective functions (Marmousi Model data) (C.S. Shin¹⁰): Shin (2004) has developed methods for a suite of objective functions based on the complex phase of the data.

7. Gulf of Mexico: Tomostatic Waveform Tomography (J. Sheng¹¹, A. Leeds¹², K. Osypov¹³, G. T. Schuster¹¹): These authors use a time-domain multi-grid scheme to alternately restrict the solution to long and short wavelengths; this considerably improves efficiency. They apply this to resolve near-surface velocity statics from the refracted wavefield.

8. Near-offset and wide-angle data: imaging under basalts (M. Warner¹⁴): Conventional imaging beneath a sill complex is poor in an example from an area west of Britain. Imaging using waveform tomography with very long-offset surface streamer and ocean bottom data show both the sill complex, as well as (apparently) a deeper igneous complex below.

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9. One-way and two-way wave equation migration (W.A. Mulder¹⁵, R.E. Plessix¹⁵): Mulder and Plessix, (2003) are using the frequency-domain approach for migration. For 2D problems this approach is an order of magnitude faster than the time-domain approach, to the extent that two-way wave equation migration is competitive with one-way wave equation migration.

10. Waveform tomography at a ground water contamination site (F. Gao¹⁶, A. Levander¹⁶, R.G. Pratt⁹, C. Zelt¹⁶): Engineering scale, seismics, comprising a suite of two VSP and 45 parallel, surface refraction lines were analyzed by traveltimes and waveform tomography (Gao et al., 2003). The waveform tomography results yielded a 3D image of a paleo-channel.

11. Hydrate dissociation imaging from crosshole seismic data (T. Watanabe¹⁷, S. Shimizu¹⁸, E. Asakawa¹⁹ and T. Matsuoka²⁰): Differential data from a time lapse crosshole tomographic survey were analyzed by waveform tomography to locate the velocity alterations caused by the thermal stimulation of gas hydrates (Watanabe et al., 2004)

12. Crosshole GeoRadar on a rock glacier in eastern Switzerland (J. Ernst²¹, K. Holliger²¹): Crosshole georadar measurements with a 22 MHz radar-system were carried out on the Muragl rock glacier in eastern Switzerland (Musil et al., 2004). Small-scale features were found by using waveform tomography on three sets of frequencies.

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