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Complex Structures Imaging Using Seismic Full Waveform Inversion

Navid Amini

Institute of Geophysics, University of Tehran, Tehran, Iran, Islamic Republic of Iran.

Presenting author, E-mail: navidamini@ut.ac.ir

Abstract

In this paper we address the application of seismic waveform inversion in complex structures imaging. This technique benefits from inversion of full waveform data in contrast to conventional ones which rely on attributes such as travel-times or amplitudes. As waveform data contains more information than travel-times, so puts more constraints on desired unknown parameters. On the other hand this technique use complete form of waveform hence requires solution of complete form of wave equation in contrast to travel-time approaches which rely on high frequency approximations. These characteristics improve the resolution of final images. Performing full waveform inversion and obtaining these high quality images requires high computational efforts. The theoretical base of waveform inversion as a classical inverse problem founded by Albert Tarantola and many other researchers developed theoretical aspects and applications. There is an increasing rate of full waveform inversion publication and real world implementation in recent years. In this paper we first review most common theoretical aspects and recent case studies of full waveform inversion then we test usefulness of our codes in thrust belts imaging.

Introduction

Complex structures imaging is a challenging subject in exploration seismology. In complex structures the layers are not horizontal anymore and velocity varies in all of directions. Conventional data acquisition and processing approaches based on NMO velocity analysis and stacking fail due to simple isotropic assumption of media and hyperbolic assumption of events. The complex surface and subsurface geological structures restrict the reach of the seismic waves, resulting limited seismic illumination and we will face lack of signal in our records on the other hand. So we are facing two different problems; the former problem cure is developing better imaging algorithms and latter problem solution should be seeked in the field (1) The most efficient accepted tool for imaging of complex structures is depth migration and the cure for better data is rethinking about conventional data acquisition strategies and switching to model based data acquisition approaches by capturing long wavelength components through increasing the maximum offset of gathers and broadening frequency band of receivers. Depth migration algorithms success has direct connection to correctness of velocity model and waveform inversion tries to find most precise velocity model for media. The success of waveform inversion is in direct connection with underlying assumptions in wave equation (acoustic/elastic, isotropic/anisotropic) and quality of data in terms if signal to noise ratio and uniform wavelength content of signal. The large offset data are very sensitive to velocities and play an important role in retrieving better velocity model.

Many researches employed the waveform inversion to describe complex structures in terms of velocity. Geller & Hara (2) used waveform inversion on a global scale problem to describe core-mantle boundary using earthquake data. Dessa et al. (3) used waveform inversion to image Tokai thrust in Japan. They used multi-fold ocean bottom seismometer data. Ravaut et al. (4) applied waveform tomography on a multi-fold, wide-aperture data to image Apennine thrust belt (Italy). They used first arrival travel-time tomography to generate starting smooth velocity model for waveform tomography, then by use of frequency-domain acoustic approximation they enhanced resolution of velocity model (Figure 1). Obtained results are promising and are consistent with available geological information. Brenders and Pratt (5, 6) did tests on synthetic data. They used elastic approximation on crustal scale refraction data. Jaiswal et al. (7) used a combination multiscale waveform inversion and PSDM for imaging of the Naga thrust in India. In their study they used waveform inversion results as a complement for interpretation of the PSDM image (Figure 2). Singh et al. (8) also discussed challenges of thrust belt seismic imaging in Assam Basin, India. They mentioned importance of folded thrust belts imaging due to presence of hydrocarbon reserves.

Waveform inversion

Waveform inversion (or waveform tomography) is a relatively modern tool in exploration seismology which enables us to use whole of information inside seismic traces and infer physical properties of media such as velocity, density or attenuation. Waveform tomography benefits from solving complete form of wave equation as a non-linear inverse problem and requires advanced computational facilities. Due to underlying numerical method of waveform tomography which is based on complete wave equation (in contrast to conventional travel-time tomography procedures which relays on ray approximation) and using seismic waveforms as input data (in contrast to travel-time methods which use travel-time data) this method has superior resolution. Many researchers have studied the theory and fundamentals of this method. A good review of this method was appeared in (9). The waveform inversion approach used in current study makes use of the acoustic finite-difference wave equation which is solved in the frequency-domain. As have shown by many authors with careful pre-processing of input seismic data this approximation leads to reasonable results. Modeling in the frequency-domain has some advantages comparing to time-domain especially in decimating samples of data to be inversed and easy implementation of frequency dependent attenuation mechanisms also simultaneous forward modeling of multiple sources. The discretized acoustic or elastic wave equation in the frequency-domain can be written as (10):

$$[\mathbf{K}(\mathbf{m}) - \omega^{\mathbf{2}}\mathbf{M}(\mathbf{m})]\mathbf{d}(\omega) = \mathbf{f}(\omega), \quad (1)$$

where **K** is the stiffness matrix, **M** is the mass matrix and **f** is the source term. The $\mathbf{d}(\omega)$ is the pressure wavefiled vector in the frequency domain and ω is the angular frequency. The model parameter **m** is v_p in our experiment. In the context of inverse problem one can use an iterative non-linear optimization technique such as gradient, Gauss-Newton or full Newton to minimize least-squares residuals between the measured seismic data and the forward modeled responses (10),

$$E = \left(\frac{1}{2}\right)\delta\mathbf{d}^T\delta\mathbf{d}^*, \quad (2)$$

Where $\delta\mathbf{d} = \mathbf{d}(\mathbf{m}) - \mathbf{d}_{obs}$, $\mathbf{d}_{obs}$ is the observed data and * represents the complex conjugate.

Results

We tested the performance of waveform inversion on synthetic models. One of industry well-known test models is SEG/EAGE overthrust model which is used as benchmark for imaging algorithms. We used a small portion of the model. The dimension of test model is 150*400 grids and grid spacing is 10 meters. We ran the waveform inversion for 8 different frequencies from low to high. The starting model was a smooth version of true model. The results are shown in Figure 3. As this figure shows the waveform inversion could reconstruct velocity model with a good accuracy just using 8 frequency components. The structures such as thin layers, faults and pinch outs at depth are interpretable with an acceptable resolution.

Conclusions

Waveform inversion can be used as a powerful technique for complex structures imaging. As this technique uses all of information inside recorded seismograms so results have superior resolution comparing to conventional travel-time tomography approaches. The resulted velocity map have enough resolution for interpreters to visualize geostructural objects and boundaries moreover the high resolution velocity map can be used as input for imaging techniques which are sensitive to velocity information such as PSDM.

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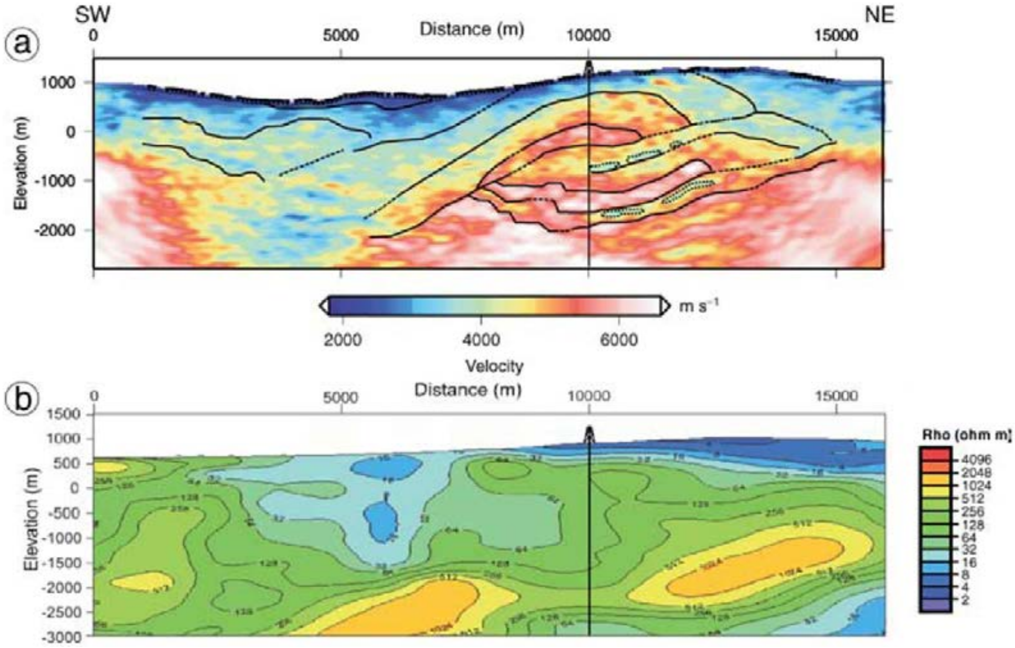

Figure 1: a) Waveform tomography result and related geostructural interpretation based on resulted velocity map. b) 2-D resistivity model obtained by inverting magnetotelluric data. There is good agreement between velocity and resistivity maps (after Ravaut et al. (4)).

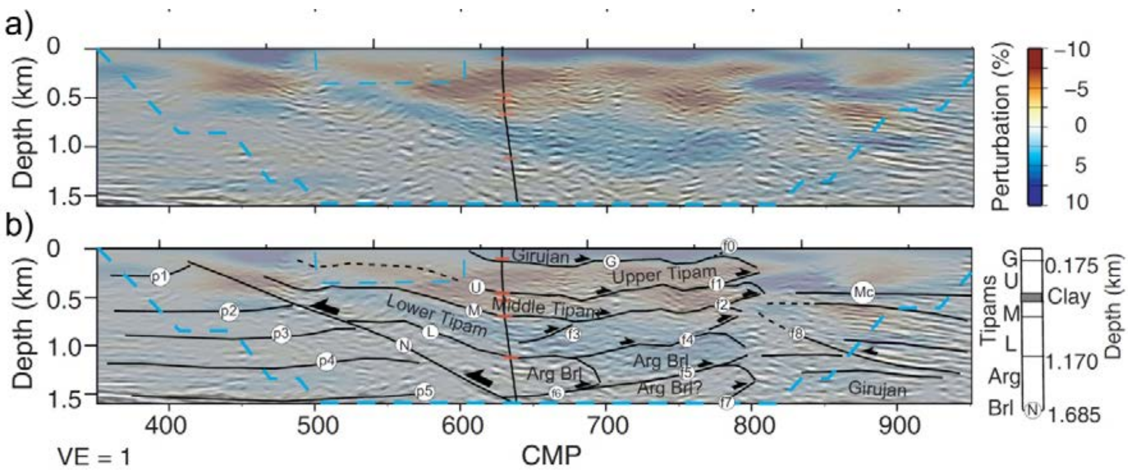

Figure 2: a) Overlay of migrated image and velocity perturbations from the final waveform tomography. b) Geological interpretation based on joint study of migrated section and velocity map along with available surface and log data (after Jaiswal et al. (7)).

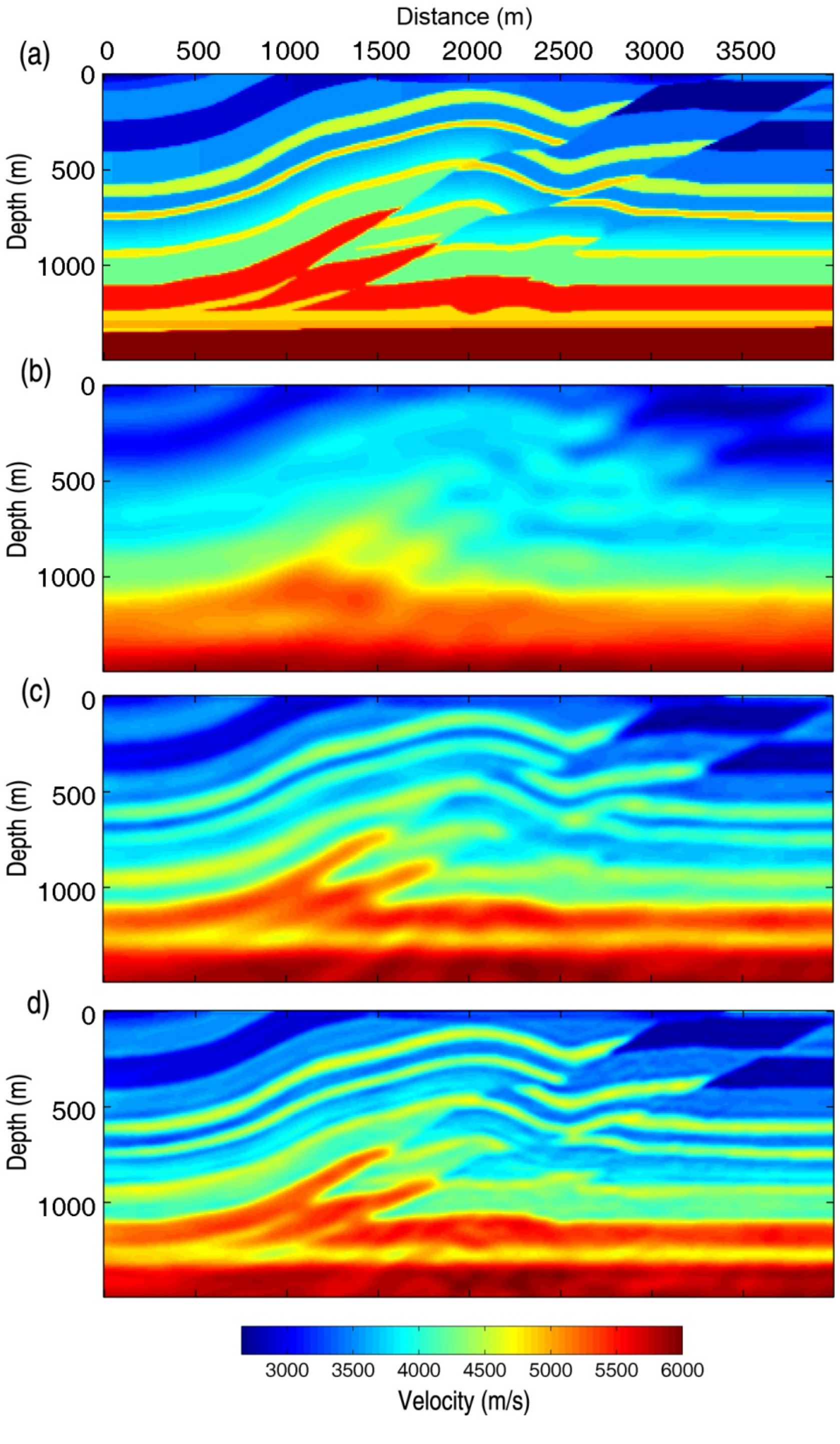

Figure 3: Results of hierarchical frequency-domain waveform tomography for a part of SEG/EAGE overthrust model. (a) True velocity model. (b) Inversion of low frequency components. (c) Inversion of middle frequency components. (d) Inversion of high frequency components.