REFLECTION SEISMIC IMAGING BY VISCOELASTIC FULL WAVEFORM TOMOGRAPHY

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ABSTRACT

The issue of seismic inversion/imaging can be generalized to find the velocity field and reflectivity that provides the best explanation for seismic data. Theoretically, migration is the first iteration in the inversion process, but not the solution that minimizes the difference between observed and model-predicted wavefield. Full waveform tomography (FWT) seeks to find the true elastic parameter field (seismic velocities, densities, attenuation) by directly solving the partial differential viscoelastic wave equations. The full elastic wavefield is inverted in an iterative tomographic approach. All wave phenomena like multiple reflections, refractions, mode converted waves (P-S) and surface waves can be considered. The imaging principle is the same as in Kirchhoff pre-stack depth migration. The resolution of FWT is in the order of the seismic wavelength and thus comparable to pre-stack depth migration methods. The inversion strategy is an iterative linear approach. An adequate starting model is required that can be obtained by conventional traveltime tomography or migration based velocity analysis. The inversion requires the solution of two times as many forward calculations as there are source locations in each iteration step. Although this is a big task, viscoelastic 2-D FWT is within the capabilities of present day parallel clusters. First applications to synthetic and real data sets published in recent years show the great potential of this method.

INTRODUCTION

Traditional seismic imaging methods treat the seismic velocity model and the seismic reflectivity image as if they were two different represenations of the subsurface. The seismic velocity model generally is a very smooth low resolution representation required for successful imaging, while the reflectivity image contains the structural details with high resolution.

In order to combine these two views and to come to a consistent and an uniform image of the subsurface, we must use inverse methods that are able to use the complete wavefield, i.e. every wiggle on every trace from every shot gather in the survey. This is the goal of seismic waveform inverse methods. They are seeking and analyse the class of models that fully explain the full wavefield, thereby combining aspects of both the velocity model and the reflectivity image. They account for all wave types such as multiples, mode converted P-S waves, and wide-angle reflections and refractions.

By full waveform tomography (FWT), we define the inverse methods that utilize the full waveform of seismograms recorded over a broad range of frequencies and apertures. The basic idea of FWT is to use the full information content of the seismic signals in a tomographic approach to derive 2-D and 3-D multi-parameter images of the subsurface. For wide-aperture geometries, FWT allows for a mapping of very large to small-scale structures where the latter can be smaller than the seismic wavelength, hence providing a tremendous improvement of resolution compared with traveltime tomography.

FWT is generally a highly nonlinear inverse problem which requires the definition of a starting model. This macromodel is often developed by traveltime tomography or migration-based velocity analysis. It is thus important to note that FWT cannot replace traveltime tomography and/or pre-stack migration since the results from these methods must serve as starting models. In fact, FWT is a late step in the imaging sequence that should be capable of imaging smaller structures at sub-wavelength scale and deriving additional parameters of the subsurface, e.g. densities, S-velocities, absorption, and anisotropy. An often applied approach to derive such additional elastic parameters is the inversion of reflection amplitudes with offset (AVO). FWT should be superior because it takes into account lateral heterogeneities of the reflector and the overburden. In addition, it does not require the identification of distinct events, since it considers all wave phenomena, such as multiple reflections or converted waves.

Although first implementations in the 1980's were conducted in the time-domain, the frequency-domain version of waveform tomography 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 main advantage of the frequency-domain approach is the possibility of starting the inversion at low frequencies (large-scale structures) and then moving to higher frequency components (smaller scales), hereby realizing a multi-scale approach. This frequency selection also helps to mitigate the non-linearity of the inverse problem. However, the time-domain approach should not be neglected because it is much better adapted to modern cluster type computers.

The routine application of FWT to 2-D subsurface models has just started in the recent years. Because of the current rapid growth in the number of available seismic sensors in the research community, the improving quality of seismic data, and the increasing computer power, we can anticipate a bright future of full waveform tomography to analyze both active and passive seismic experiments.

WAVEFORM AND TRAVELTIME TOMOGRAPHY

In conventional tomography approaches the input consists of attributes extracted from specific events like traveltime, amplitudes or other properties of the signal. As an example, first arrival traveltime tomography utilises first arrivals only. Inverse scattering methods also use traveltimes of later arrivals. These methods account for specific wavefield properties of distinct events (mostly P-wave events). They are termed as traveltime tomography in the following. For the traveltime-based methods, the maximum resolution is related to the width of the first Fresnel zone:

$$(Width\ of\ first\ Fresnel\ zone) = \sqrt{\lambda L} \tag{1}$$

where λ is the dominant seismic wavelength and L is the propagation distance. The resolution of full waveform tomography is approximately λ. The resolution of FWT does not depend on the source receiver distance L. The potential improvement in resolution, when using waveform inversion, can thus be estimated as:

$$\frac{\sqrt{\lambda L}}{\lambda} = \sqrt{\frac{L}{\lambda}} = \sqrt{N_\lambda} \tag{2}$$

where N_λ is the number of dominant wavelengths between source and receiver. Thus, waveform methods have a potential resolution limit that is approximately $\sqrt{N_\lambda}$ smaller than for traveltime methods. The reasons for this improved resoltion are the following:

1. The input data consist of the seismic waveforms themselves and not of attributes like traveltime, amplitudes, etc.

2. The underlying numerical method is adopted from the full wave equation and not from a ray or Born approximation.

3. The calculation of residuals differs: in traveltime tomography the backprojection of traveltime residuals is calculated, whereas in waveform tomography the backpropagation of waveform residuals is computed.

WORKING METHOD

The development and application of 2-D and 3-D FWT methods are currently the main goal of the research team at TU BAF that has been established in 2006/2007. We implement new 2-D/3-D time-domain strategies in which we use the viscoelastic finite-difference method of Bohlen (2002) that is highly optimized

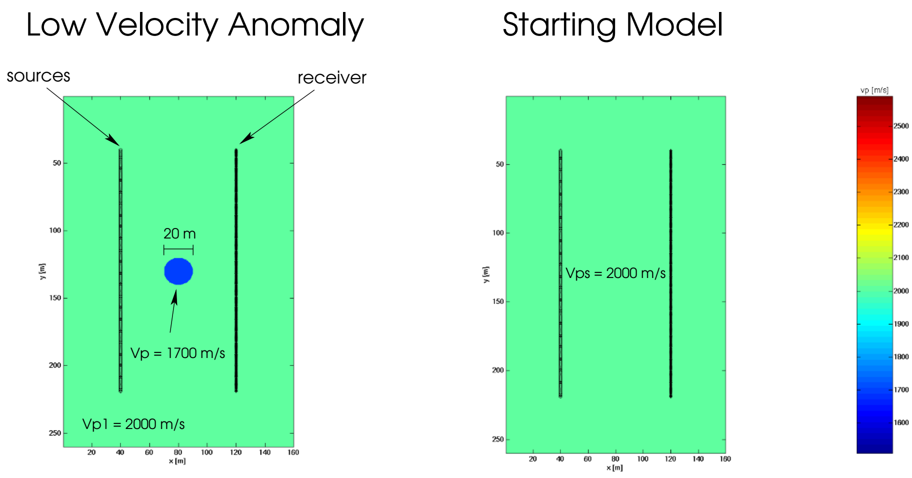


Figure 1: A simple cross-well synthetic example to illustrate the full waveform tomography method. A sperical low velocity inclusion is located in between the source line (left) and receiver line (right). The right image shows the homogeneous starting model for FWT.

for modern cluster technology. In the following we illustrate the working method of FWT for a cross-well acquisition geometry using a simple inclusion model and a heterogeneous random medium model.

Spherical inclusion

Let us first consider a cross-well acquisition geometry with a spherical low velocity zone (P-wave velocity V_p = 1700 m/s) embedded in an homogeneous background medium (V_p = 2000 m/s) (Figure 1, left).

We chose a homogeneous medium with V_p = 2000 m/s as a starting model (Figure 1, right). As described for example in Tarantola (2005), the model parameter m_n at iteration step n can be improved by using a steepest-descent gradient method:

$$m_{n+1} = m_n + \mu_n d_n, \tag{3}$$

where d_n denotes the steepest-descent direction of the misfit function and μ_n the step length. The gradient d_n can be effectively calculated by a zero-lag crosscorrelation between the forward modelled and backpropagated residual wavefield and a summation over these cross-correlations of every shot (Figure 2). By multiplying the gradient with an optimal step length μ_n, the change in material parameters can be calculated. After only five iterations the shape and velocity of the low velocity anomaly fit quite well (compare left most images of Figures 1 and 2, respectively).

Random Medium Example

In the following example acoustic 2-D FWT is applied to reconstruct the P-wave velocity field of a heterogeneous medium. We use the same acquisition geometry as in the previous example (cross-well geometry). The heterogenous medium between the source and receiver vertical lines is a self-similar random medium, which was generated by using a van Karmann autocorrelation function (Figure 3, middle). The velocity perturbations have a standard deviation of 8 per cent around a mean value of 2000 m/s. The starting model (Figure 3, left) is a smoothed representation of the true model that corresponds to the result of a first arrival travel time tomography. The result of FWT is shown on the right hand side of Figure 3. After 50 iterations, the result of the time-domain FWT code shows a lot of small scale features, which can also be found in the true model. Note also how well the seismic sections for a central shot are fitted by FWT (Figure 4). The FWT is able to fit (scattering) events that arrive later than the direct P-wave.

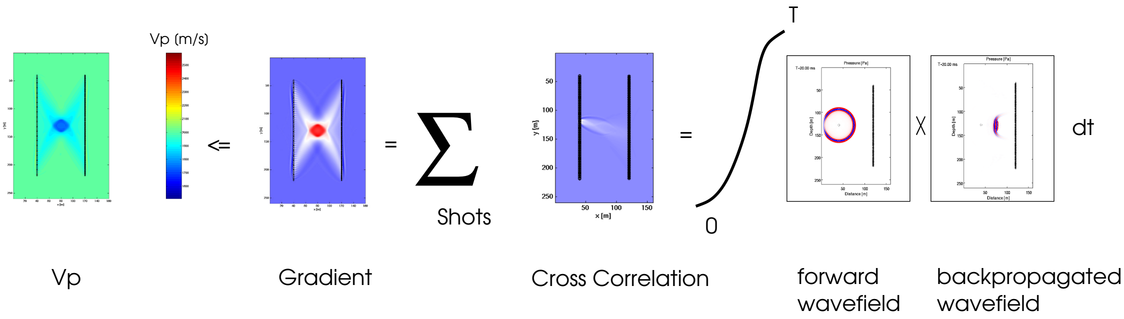


Figure 2: The working method of time domain full waveform tomography. The required calculations for each iteration step are shown. From right to left: for each shot two wavefield simulations are performed. One simulation propagates the wavefield forward in time, the second simulation back-propagates the data residuals (misfit between model predicted wavefield and real data). A zero-lag cross-correlation between these two wavefields is performed. The summation of all cross-correlations for all shots yields the gradient (sensitivities) for the acquisition geometry. This gradient is used to update the actual model according to equation 3.

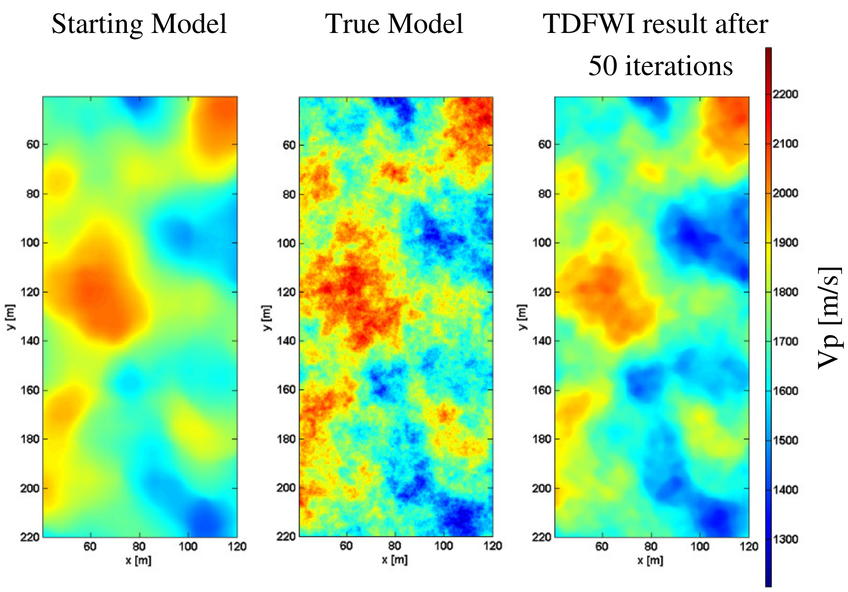
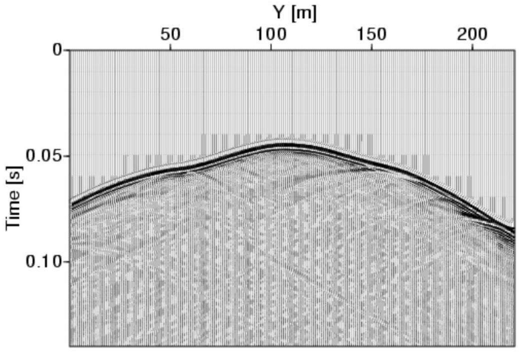
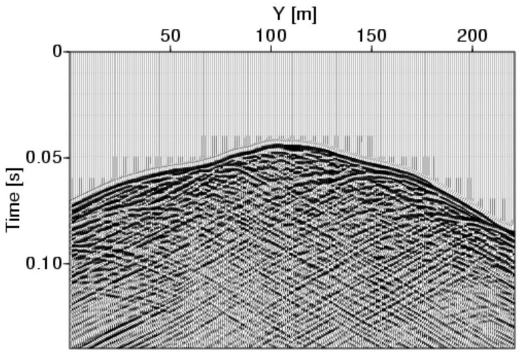


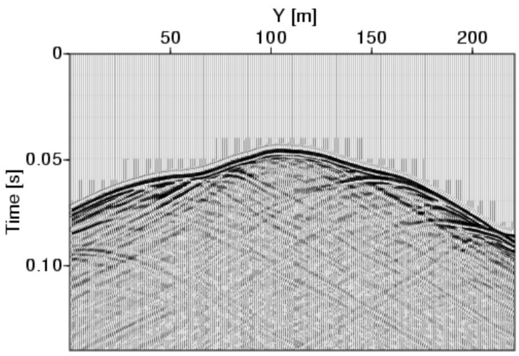
Figure 3: FWT applied to a random medium. The starting model (left), the true model (center) and the time domain FWT result after 50 iterations.



travel time tomography model (starting model)



true model



Result of FWT

Figure 4: Shot-gathers of the pressure field (from top to bottom) for the starting model (Figure 3, left), the true model (Figure 3, middle), and FWT model (Figure 3, right).

OUTLOOK

As mentioned, the recent developments and current computer power make the application of FWT feasible for 2-D reflection seismic surveys. The application to real data and the comparison of FWT images with (conventional) pre-stack depth migration results should thus be the main focus in the next years.

Major challenges for future methodological improvements of the method are

- the optimization of our 2-D and 3-D viscoelastic time domain implementations
- the comparison of the performance of frequency domain (Pratt and Worthington (1990)) and our time domain FWT
- the joint-inversion of multi-parameter images, e.g. P-wave velocities, S-wave velocities, densities, and attenuation from multi-component (geophone) data.

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