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Genetic waveform modeling for the crustal structure in Northeast Japan

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ABSTRACT

We propose a genetic algorithm (GA) search procedure for waveform modeling of local crustal earthquakes for optimal one-dimensional (1-D) crustal velocity model. Both waveforms and travel-time data are used for the structure determination. The use of travel times in model evaluation improves the waveform modeling performance in the sense of computation speed and accuracy. We applied this method to broadband waveforms of a local crustal earthquake (M 4.2) in Northeast Japan. P-wave velocities of the crustal model are found to be 4.95 ± 0.30, 5.9 ± 0.02, and 6.51 ± 0.20 km/s for a surface layer, upper crust and lower crust, respectively. The surface layer thickness and the Conrad and Moho depths are found to be 3.01 ± 0.8, 17.77 ± 0.4 and 34.59 ± 1.0 km, respectively. For epicentral distances <200 km, our synthetic waveforms match the observed ones generally well. Early arrivals are mainly observed at stations near the Pacific coast in the forearc area having a thinner crust. In contrast, delayed arrivals appear at stations near the volcanic front and back-arc areas where low-velocity anomalies exist due to the effect of the Pacific slab dehydration and the hot upwelling flows in the mantle wedge. In general, our results agree well with the main tectonic setting of the study area, which confirms the reliability of the proposed approach. Despite a 1-D velocity model is too simple to represent the complex crustal structure, it is still required for the conventional routine analysis of seismology, such as earthquake location and source parameter studies. The current approach is considered as a step toward the genetic full waveform modeling for the 3-D velocity model estimation.

1. Introduction

Determination of earthquake source parameters and Earth structure using waveform modeling techniques is an essential task for seismologists because they are utilized as fundamental information in various geological and geophysical researches. Waveform inversion is one of nonlinear multi-parameter optimization problems that require efficient numerical techniques to solve the non-unique problem. Many waveform modeling approaches have been developed in the last decades. In general, waveform modeling is carried out by using either a full waveform inversion technique or a forward modeling approach. The waveform inversion is a full nonlinear problem that tends to solve the wave equation with respect to crustal structure. This is considered a proper way to retrieve the crustal structure, but it requires high computational cost and memory capability. The waveform inversion studies have attracted the interests of many seismologists since the pioneering work of Backus and Gilbert (1967) on the determination of the global structure using free oscillation data of the Earth. Later, significant progress has been made in inverting seismic waveforms and travel times. In earthquake seismology, the research interest varies from the global structure of the Earth (e.g., Jordan and Anderson, 1974; Lernar-Lam and Jordan, 1983; Ishii et al., 2002; Askan et al., 2007; Zhao et al., 2013) and Moon (e.g., Zhao et al., 2008, 2012a) to tomographic imaging of the local crust and upper mantle structures (e.g., Salah and Zhao, 2003a,b; Zhao et al., 2005, 2011a; Abdelwahed and Zhao, 2007; Chen, 2005; Tromp et al., 2005; Wang and Zhao, 2012, 2013; Huang and Zhao, 2013a,b; Wei et al., 2012, 2013; Liu et al., 2013a,b, 2014; Zhao and Tian, 2013). These studies have greatly improved our understanding of seismic and volcanic activities and geodynamics.

The full waveform inversion techniques have been significantly improved and extended to conduct waveform tomography in time domain (Tarantola, 1988) or in frequency domain (Pratt and Worthington, 1988, 1990; Pratt et al., 1998; Brenders and Pratt, 2007). Askan et al. (2007) conducted full waveform inversion for seismic velocity and anelastic losses simultaneously. However,

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the full waveform inversion methods, particularly for velocity models, suffer from limitations in their applicability and the construction of differential equation matrices. Recently, iterative forward modeling techniques have been used instead. These techniques attempt to find a model that best explains the observations in a nonlinear multi-parameterization searching process within a specific modeling space (e.g., Zhao and Helmberger, 1994; Zhou et al., 1995; Stoffa and Sen, 1991; Sen and Stoffa, 1995; and others).

The forward modeling approaches mainly depend on how to calculate the ray responses and the optimization method used. The conventional methods for calculating the ray responses are, e.g., seismic ray theory (Cerveny et al., 1977), finite-difference method (Virieux, 1984, 1986; Toyokuni and Takenaka, 2012), discrete wave number (Bouchon, 1979, 1981), reflectivity method (Fuchs and Muller, 1971), and generalized ray theory (GRT) by Helmberger (1974, 1983). The forward modeling techniques suffer from several limitations. Some optimization methods have, however, such problems that computational results may converge to local minima of residuals, which require an appropriate initial model located near the global minimum. In addition, the use of systematic grid searches for waveform modeling is not practical because it is very time-consuming and requires large memory storage to involve the search through each point in the model space. In contrast, randomized searching methods such as the genetic algorithm (GA) (Holland, 1975; Goldberg, 1989; Berg, 1990) have the ability to deal with large model parameter space without falling into such local minima that tends to false parameters. Recently, the GA has been successfully applied as the searching method for solving the seismic waveform inversion problems (e.g., Zhou et al., 1995; Bhattacharyya et al., 1999; Louis et al., 1999; Stoffa and Sen, 1991; Sen and Stoffa, 1992; Sileny, 1998; Chang and Baag, 2006; Sambridge and Drijkoningen, 1992). The GA is a randomized search method that uses an analogy with biological evolution to search a model space. It is found that the GA is a powerful searching tool for the large space model parameters of waveform modeling efficiently. So far, waveform fitting and travel-time residuals have been jointly employed for estimating the velocity structure (e.g., Chang and Bagg, 2006). Despite the inadequacy of a 1-D velocity model to represent the complex crustal structure, such a 1-D model is required for various seismological studies, e.g., routine earthquake location, moment tensor inversions, and starting model for seismic tomography, etc.

In this study we adopt a forward-modeling approach for estimating the optimal 1-D crustal velocity model using local and regional broadband seismograms. The GRT method is used in conjunction with micro Genetic Algorithm (micro-GA) as a global optimization method. The advantage of the GRT technique is its ability to calculate quickly the response of a predefined set of rays individually with their corresponding travel times for a 1-D velocity model. This approach utilizes the later phase travel times together with the broadband waveform fitness for better modeling performance. We explore the sensitivity of the velocity model parameters and their effects on the modeling results to assess the feasibility of this approach. In addition, we apply this technique to broadband waveform data of a local crustal earthquake in Northeast (NE) Japan to explore the optimal crustal model under the region.

Table 1
Initial velocity model used in this study.

	Depth (km)	*Vp* (km/s)	*Vs* (km/s)	Density (g/cm^3)
Surface layer	0.0	5.0	2.9	2.45
Upper crust	3.0	5.9	3.4	2.66
Lower crust	19.0	6.6	3.8	2.83
Uppermost mantle	31.0	7.75	4.5	3.11

2. Modeling technique

In this study a forward modeling approach is developed by combining the GRT (Helmberger, 1983) and the micro-GA (Carroll, 1996). The GRT is used for constructing synthetic seismograms required for comparing with observed seismograms. The GRT technique concerns to expand the generalized ray equations in conjunction with the Cagniard-de Hoop technique. These tend to construct Green's functions for a simple crustal structure. The Green's functions are constructed by summing generalized rays for a point shear dislocation. Consider $W_i(t)$, $Q_i(t)$, and $V_i(t)$ as the vertical, radial, and transverse components of the Green's functions, respectively. The vertical $U(t)$, radial $R(t)$ and tangential $T(t)$ synthetic seismograms at the appropriate distance and source depth can be expressed as follows:

$$\begin{aligned}
U(t) &= S(t)^{*}\sum_{i=1}^{i=3} W_i(t)A_i(\theta,\lambda,\delta)\\
R(t) &= S(t)^{*}\sum_{i=1}^{i=3} Q_i(t)A_i(\theta,\lambda,\delta)\\
T(t) &= S(t)^{*}\sum_{i=1}^{i=2} V_i(t)A_{i+3}(\theta,\lambda,\delta)
\end{aligned}\tag{1}$$

where $S(t)$ is source time function, A_i are coefficients determined by the source orientation and are given by:

$$\begin{aligned}
A_1(\theta,\lambda,\delta) &= Sin2\theta Cos\lambda Sin\delta + 0.5\,Cos2\theta Sin\lambda Sin2\delta\\
A_2(\theta,\lambda,\delta) &= Cos\theta Cos\lambda Cos\delta - Sin\theta Sin\lambda Cos2\delta\\
A_3(\theta,\lambda,\delta) &= 0.5\,Sin\lambda Sin2\delta\\
A_4(\theta,\lambda,\delta) &= Cos2\theta Cos\lambda Sin\delta - 0.5Sin2\theta Sin\lambda Sin2\delta\\
A_5(\theta,\lambda,\delta) &= -Sin\theta Cos\lambda Cos\delta - Cos\theta Sin\lambda Cos2\delta
\end{aligned}\tag{2}$$

where θ is station azimuth from the source minus fault strike, δ is the fault dip, and λ is fault rake. For more details of the GRT technique, see Helmberger (1983). In this study, about 320 rays are adopted to construct synthetic seismograms. The rays represent the main crustal phases of P- and S-waves including up-going, down-going, surface reflected, and converted phases, however, the P-wave is the predominant phase. The source time function (STF) used in this study is a simple trapezoidal pulse having a width of 0.16 s. This simple STF is able to simulate the source of earthquakes with magnitudes <5.0 (Abdelwahed and Zhao, 2005; Helmberger, 1983). The pulse width is estimated by one-shot modeling for the STF width that gives the matching between the first onsets of observed and synthetic seismograms at a single station. The focal mechanism is estimated in this study using the amplitude spectra and polarities (ASPO) method (Zahradnik et al., 2001), because this method is less sensitive to the velocity model adopted. Table 3 and Fig. 3 shows the obtained focal mechanism solution of the crustal earthquake we used in this work.

Table 2
The search ranges of the model parameters adopted in this study.

Model parameter	Search range
Surface layer thickness	0.1–4.0 km
Surface layer *Vp*	4.0–5.5 km/s
Conrad depth	12.0–25.0 km
Upper crust *Vp*	5.6–6.4 km/s
Moho depth	22.0–40.0 km
Lower crust *Vp*	6.45–6.9 km/s
Vp/*Vs*	1.6–1.8