三代のP波速度構造のIwate火山、日本における活性地震調査

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Three-dimensional $P$-wave velocity structure of Iwate volcano, Japan from active seismic survey


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[1] The three-dimensional $P$-wave velocity structure of the Iwate volcano, northeastern Japan, is determined to depths of 2 km through an active seismic survey conducted in October 2000. Seismic tomography is applied to approximately 2700 travel-time data. The most prominent discovery is an existing of column-like high-velocity body ($V_p > 5.4$ km/s) that extends vertically for 2 km beneath the caldera. While the western part of the volcano extending from the caldera is characterized by a moderate-velocity region ($4.8 < V_p < 5.4$ km/s), the summit and eastern flank of the volcano are covered with very-low-velocity material ($V_p < 4$ km/s) which represent relatively younger volcanic edifices. The spatial difference in the velocity structures between the western and eastern parts of the volcano is explained by the evolutionary history of the volcano. And we find that the western structure may give constraints on the volcanic activity in 1998. INDEX TERMS: 7203 Seismology: Body wave propagation; 7280 Seismology: Volcano seismology (8419); 8180 Evolution of the Earth: Tomography

1. Introduction

[2] The Iwate volcano, located in the Northeastern Japan Arc (Figure 1), became highly active in 1998. This volcanic crisis associated with volcanic-tectonic (VT) and low-frequency (LF) earthquakes, volcanic tremors, very long period (VLP) events, and crustal deformation [e.g., Nishimura et al., 2000; Miura et al., 2000; Tanaka et al., 2002]. Although there has been no eruption since the crisis started, a detailed investigation of the structure of the volcano is considered to be very important. We expect that three-dimensional velocity structure of the volcano helps to determine accurate hypocenters for prediction of volcanic eruptions. Resolving anomalous bodies under volcanoes by exploration using natural earthquake sources, we sometime meet difficulty in imaging due to the source-receiver geometry. Thus seismic explorations employing active sources have been initiated in the world [e.g., Zollo et al., 1998]. Japanese researchers have carried out a large-scale active survey around volcanoes in Japan every year since 1994 under the National Project for the Prediction of Volcanic Eruptions [e.g., Kagiyama et al., 1995].

[3] The 7th seismic survey of the volcanic structure was conducted around the Iwate volcano in October 2000 in order to study the three-dimensional $P$-wave velocity in detail [Tanaka et al., 2001]. This survey is the most extensive conducted to date, in terms of the number of stations and shots and the size of the study area. Seventy scientists participated from 11 national universities of Japan (Tohoku, Hokkaido, Hirosaki, Akita, Iwate, Tokyo, Tokyo Institute of Technology, Nagoya, Kyoto, Kyushu, and Kagoshima), the National Institute of Polar Research (NIPR) and the Japan Meteorological Agency (JMA). Nine chemical explosions using dynamite charges of 200-250 kg excited seismic waves (Figure 1). Data were recorded at 330 temporary seismic stations deployed around the volcano within 20 km from the summit (study area $40 \times 40$ km$^2$). Each station consisted of a vertical short-period seismometer with a natural frequency of 2 Hz and a small data logger. More than 3000 seismograms were acquired with sampling interval of 4 ms, and they showed good signal-to-noise ratios. Additional seismograms with sampling interval of 10 ms from 33 permanent stations established to monitor volcano-seismic activity by Tohoku University, JMA and the National Research Institute for Earth Science and Disaster Prevention (NIED) are also used in the following analysis.

2. Data and Method

[4] The first arrival times of seismic waves were identified manually [Tanaka et al., 2001], giving a data set of 2676 useful readings. The numbers of readings with error less than 10 ms, 30 ms, 100 ms and more than 100 ms are 1077, 607, 572, and 420, respectively. The weights of 1.0, 0.5, 0.25, and 0.1 are assigned to the readings depending on the accuracy defined above.

[5] Prior to tomographic inversion, we constructed an initial velocity model as follows. We identified a 3-layered $P$-wave velocity structure from all the travel time (Figure 2a). A velocity model with stacked homogeneous layers is not suitable for the initial model in tomographic inversion used in this study. Therefore, the discrete velocities were smoothed in order to obtain continuous velocity structure consisting of a surface layer of 2 km thickness and a basement (Figure 2b). In order to estimate the thickness variation of the surface layer, we applied the time-term method [Scheidegger and Willmore, 1957] to the travel time data for distances greater than or equal to 7.9 km. And then we converted the time-terms to the surface layer thickness using the average velocity above the layer of the velocity of 6.0 km/s. The velocities for the top, middle and base of the surface layer are fixed as 2.5, 3.7 and 6.0 km/s, respectively. When we assigned the absolute depths of the three points of the surface layer, we considered topography.

[6] And we used TOMOG3D [Zhao et al., 1992] for tomographic inversion. TOMOG3D adopts the pseudo-bending [Um and Thurber, 1987] for ray tracing, and the damped least squares method [e.g., Aki and Richards, 1980] to invert the travel time data to velocities at grid points. As a preliminary step, we took $11 \times 14$ horizontal grid nodes with a grid interval of 0.04° (approximately
4 km) for the latitudinal and longitudinal directions and 16 vertical grid nodes at 1-km intervals. We obtained a preliminary model by iterative improvement starting from the initial model determined in the above. And then the horizontal grid interval is set to be 0.02 km (approximately 2 km). We again inverted the travel time data to focus the central area of the study region, as a final model starting from the preliminary model under the fine grid interval.

3. Results

[7] After inverting the travel time data, the weighted RMS residual is reduced from 0.36 s at the initial model to 0.18 s at the preliminary model after 10 iterations under the damping factor of 50. At the final model, the RMS residual becomes 0.17 s after 10 iteration under the damping factor of 15. The total

Figure 1. Geographical configuration of the seismic survey of the Iwate volcano. Gray stars and dots are shot points and seismic stations, respectively. Contour interval is 300 m. Insert map of Japan shows the study area.

Figure 2. Travel times and one-dimensional velocity structure. (a) Travel time plot (open circles) for all data. Times are reduced with 6 km/s. (b) Thin line with closed circles is the velocity structure estimated from the travel time data. Thick line is the smoothed structure for tomographic inversion. The travel time curve (thick line) in (a) is calculated from the smoothed velocity structure in (b).

Figure 3. Plan views of (a) tomographic image of Iwate volcano and the reconstructed images of the checkerboard tests for (b) the large grid case and (c) the fine grid case at a depth of 0 km. Topographic contour interval is 500 m. White ellipse in (a) represent caldera. The line AA’ is a location mark for the vertical cross-section of Figure 4.
The velocity region in the west of the caldera has a thickness of more than 2 km and surrounds a slightly low-velocity region (a yellow area) at a depth of 1 km (Figure 4a). Additionally, a thin, tongue-like region of the moderate velocity extends northeastward beneath the northeastern flank from the high-velocity body under the caldera (Figure 3a). In contrast with the western part of the volcano, the summit and the eastern flank are thickly covered with very low-velocity material presented by an orange area (Vp < 4 km/s) (Figures 3a and 4a).

4. Discussion

[10] We have succeeded to reveal the three-dimensional P-wave velocity structure of the Iwate volcano in detail. High reliability of the result for depths shallower than 1 km confirmed by a checkerboard test. The Iwate volcano is characterized by a relatively high-velocity body at shallow depths beneath the western part of the volcano and a thick low-velocity surface layer beneath the eastern part including the summit. High-velocity anomalies under volcanoes have been recently detected through tomographic studies at many volcanoes, e.g. Mt. Etna [Villasenor et al., 1998], Mt. Vesuvius [Zollo et al., 1998], and others [e.g. Benz et al., 1996; Nishi, 1997; Tomatsu et al., 2001]. They may be common in volcanoes. Many high-velocity anomalies are interpreted as magma solidified after intrusion [e.g., Villaseñor et al., 1998]. The high-velocity body under the western part of the Iwate volcano may be formed in the same way, because geological studies show that major volcanism in the western part started about 300 ka and already stopped at about 30 ka preceding the formation of the eastern part [e.g. Nakagawa, 1987]. Thus the high-velocity body under the caldera can be interpreted as a center of the old western volcanic edifice. On the other hand, the eastern part of the volcano including the summit has been formed since 30 ka and shows the youngest activity even in historic time [e.g. Nakagawa, 1987]. This suggests that the low-velocity materials covering the summit and the eastern flank consist of young and unconsolidated volcanic products. We can confirm quite good correlation between the pattern of three-dimensional velocity structure and the evolutionary history of the volcano.

[11] The many phenomena associated with the volcanic crisis of the Iwate volcano are mainly observed in the period from February
to August 1998. Although depths of the sources are determined with 1-D structure and should be reexamined, they are located at shallow depths comparable to the $P$-wave velocity structure obtained in this study (Figure 5). The activity of VT and LF earthquakes [Tanaka et al., 2002] started under the caldera, then migrated westward. The activity is trapped in the high- and moderate-velocity regions beneath the west of the volcano. The VLP events [Nishimura et al., 2000] stayed at the western bottom of the moderate-velocity region. The deformation sources [Miura et al., 2000] moved westward along the western lower edge of the moderate-velocity region. These suggest that the magmatic activity in the 1998 crisis received structural constraint by the old western volcanic edifice.

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