THREE DIMENSIONAL SEISMIC VELOCITY STRUCTURE IN THE OTAKE-HATCHOBARU GEOTHERMAL AREA IN CENTRAL KYUSHU, JAPAN

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SUMMARY - We studied the three-dimensional seismic velocity structure in and around the Otake-Hatchobaru geothermal area in central Kyushu, Japan, using the tomographic method of Zhao et al. (1994). A low Vs with high Vp/Vs region, suggesting a cooling magma body beneath the volcanoes around the geothermal area, is located between 4.0 km and 7.0 km depth. Above an anomalous low Vs region at 2.5 km depth, a high Vs with low VpNs region exists indicating the granitic basement rock. Most of seismic sources relating to the movement of geothermal fluids were found at shallower depths (<2.5 km) and at the boundary between the low and high Vs regions. We suggest fluid movements in Otake-Hatchobaru geothermal area are associated with the high Vs region at 2.5 km depth and the low Vs region deeper than 4.0 km.

1. INTRODUCTION

The Otake-Hatchobaru area is one of the well-known geothermal areas in Japan, located at the northwestern part of Kuju Volcano in central Kyushu (Fig. 1). The geothermal area is characterized by a water-dominated system with a fractured reservoir. Two geothermal power plants have been operating with a total output of 122.5 MW (12.5 MW at the Otake area, 110 MW at the Hatchobaru area).

Volcanoes around the Otake-Hatchobaru geothermal area formed during the period of 0.2Ma to 0.1Ma (Fujino et al. 1985). Mt. Sensui and Mt. Kuroiwa in the southeast produced lava flows until about 10,000 years ago. These volcanic activities related to the present day heat source of the geothermal area (Inuyama et al. 2002). NW-trending faults such as the Hatchobaru fault and the Komatsuike fault are dominant in this area, along which hot springs, holes and alteration zones are distributed (Yamasaki et al. 1970). The geothermal reservoirs are also arranged along these NW-trending faults (Manabe and Ejima 1980). Water circulates from the surface down to the granitic basement at 2.0 km depth (700 m below sea level) (Manabe and Ejima 1984).

The underlying structures of the study area have been discussed in various reports of geophysical investigations. Kamata (1968) found a high gravity anomaly region connected to the uplift zone of basement rock. Onodera (1973) showed that the geothermal reservoirs are associated with negative self-potential anomalies. Kubotera (1988) showed an uplift zone of basement rock at 1.0 km depth below sea level from a seismic velocity structure determined using a time-term analysis. Sudo and Matsumoto (1998) described a high Vp region relates to the uplift zone at 4.0 km depth, and a low Vp region relates to a magma body at 7.0 km depth, based on a 3D P-wave velocity structure seismic tomography.

In this study we describe a 3D seismic velocity structure in and around the Otake-Hatchobaru area determined using the tomographic method of Zhao et al. (1994).

2. DATA AND METHODS

Aso Volcanological Laboratory (AVL) of Kyoto University has established a seismic network which includes 47 permanent and temporary stations in central Kyushu. Of all the well located earthquakes in the 32.6% - 33.5°N and 130.6°E - 131.5°E region, 5850 were selected from the period of 1981 to 2002 for the inversion analysis, and 43530 P and 31408 S arrival times were used.

The initial model for the P wave velocity is calculated with the VELEST program (Kissling 1994) using 1966 sets of the best-recorded earthquakes from the AVL network. The base model for the VELEST program is the one-dimensional velocity structure of the Aso volcanic region shown by Sudo (1981). The S wave velocities of this model were estimated from the P wave velocities using a VpNs ratio of 1.64.

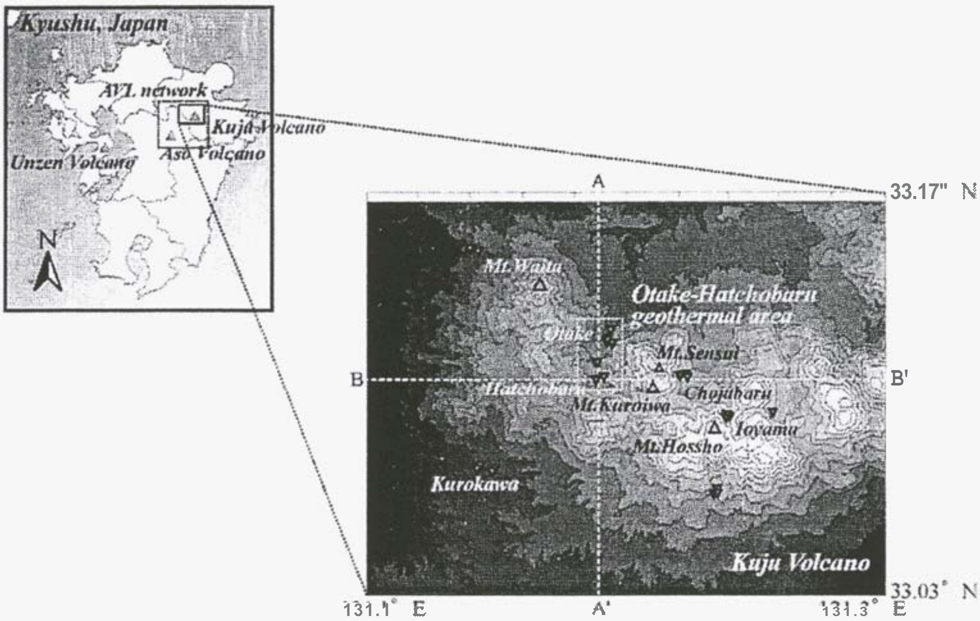

Figure 1 Maps of the Kyushu in Japan, AVL seismic network area and study area. The study area is the right-hand map. Triangles and inverted triangles on maps indicate top of mountains and hot springs, respectively.

Prior to the tomographic inversion, P and S travel time residuals for every earthquake were calculated. The average travel time residuals for each station was used as a station correction. When seismic locations were calculated using the corrected travel times, the average of RMS errors with the corrected travel times, 0.136 sec, was significantly less than the average given by the original travel times, 0.174 sec.

The study area covers a region of 32.6°N-33.5°N x 130.6°E-131.5°E, from 0 to 30 km depths (Figure 1). For the tomographic inversion, we adopted a 0.02 □ spacing of nodes in horizontal planes at Z = 0.0 km (Z = 0 km indicates sea level), 2.5 km, 4.0 km, 7.0 km, 10.0km and 20.0 km depth.

3. RESULTS

To check the influence of the grid size on the resolution of the velocity inversion, the checkerboard resolution test (CRT) for the P wave and the S wave was carried out. Synthetic P and S waves travel times were computed using a CRT model which assigned positive and negative velocity perturbations of +3% alternately to grid nodes. Good CRT results can be obtained around the Otake-Hatchobaru area for depths from 0 km to 2.5 km, and in the east region of Mt. Sensui for layers at 4 and 7 km depths. However, at 10 km depth, no resolution was shown by the CRT. Therefore we can only use the tomographic inversion for layers shallower than 7 km.

The velocity inversion was carried out with a damping value of 10 chosen by trial and error. The first inversion RMS errors are 0.123 sec for the P wave and 0.168 sec for the S wave. The final results of inversions were obtained after 7 iterations for the P wave and 10 iterations for the S wave. The final inversion RMS errors are 0.116 for the P wave and 0.157 for the S wave. These errors were about 7% less than before the first inversion.

Results of the inversion reflecting the CRT results on the individual layer are shown in Figures 2 and 3.

In Figure 2, a low Vp and low Vs region at 0.0 km depth extends fiom Mt. Waita to the Chojabaru area. To the south of this low velocity region, a high Vp and high Vs region at 0.0 km depth occurs around Mt. Sensui, Mt. Kuroiwa and Mt. Hossho. A region of high Vs at 2.5 km depth is located around the Otake-Hatchobaru area. Under this high Vs region, there is alow Vs region at 4.0 and 8.0 km depths, extending fiom the Otake-Hatchobaruarea to the Kurokawa area.

Figure 3 shows N-S and E-W cross sections along lines A-A' and B-B' in Figure 1. There is a clear contrast between the low Vs region deeper than Z=4.0 km and the high Vs region at Z=2.5 km in the Otake-Hatchobaru area. On the E-W cross section a high Vs region showing a W shape is found from 0.0 km to 2.0 km depth. Under the high Vs region, a low Vs region deeper than 4.0 km is located from the Otake-Hatchobaru area to

Mt. Hitome. On the N-S cross section there is a high Vs region between the low Vp and low Vs region in the shallower part and the low Vs region in the deeper part. The high Vs region and the low Vs region in the deeper part rise gradually from north to south.

4. CORRELATION WITH OTHER DATA

Seismic velocities often correlate with geology. Londono and Sudo (2002) showed a high Vp correlates with lava flows and a low Vp correlates with pyroclastic rocks. The presence of cracks, fractures, altered rocks and fluids reduces the seismic velocities (e.g. Moos and Zoback 1983).

The velocity structure in the study area at 0.0 km depth (sea level) seems to be related to the surface geology. The high Vp and Vs region and the low Vp and Vs region in the Chojabaru area at 0.0 km depth are correlated with mapped lava flows and pyoclastic deposits, respectively. In the Otake-Hatchobaru area, the low Vp and Vs region correlates with numerous faults and altered rocks.

A high Vs with low Vp/Vs region is located at 2.5 km depth. While andesites are the most common rock type in this area, granites are the basement rocks. Christensen (1996) showed that granite has a higher seismic velocity but lower Vp/Vs than andesite. As the granitic basement was confirmed at 700 m below sea level by drilling (Manabe and Ejima 1984), the high Vs with low VpNs region is interpreted to be the basement rock.

A low Vs with high VpNs region under the high Vs region is located deeper than 4.0 km. Earthquakes occurred beside the low Vs region on Figure 3. Londono and Sudo (2002) showed that volcano tectonic earthquakes (VT earthquakes) occurred around the low Vs region relating to the degassing old magma. The volcanoes around the Otake-Hatchobaru geothermal area were formed from 0.2Ma to 0.1Ma (Fujino et al. 1985). Mt. Sensui and Mt. Kuroiwa in the southeast of the geothermal area were active until 10,000 years ago (Inuyama et al. 2002). Thus the low Vs region may represent an old magma body of the volcanoes which could be the heat source of the geothermal area.

5. DISCUSSION AND CONCLUSION – THE DEEP STRUCTURE AND A MODEL OF THE GEOTHERMAL SYSTEM

The low Vs with high VpNs region located deeper than 4.0 km in the Otake-Hatchobaru geothermal area is interpreted to represent the heat source of the geothermal system. The high Vs with low Vp/Vs region from 0.0 km to 2.5 km depth might represent the granitic basement rock.

In the Otake-Hatchobaru area earthquake swarms relating to the geothermal fluids (Kubotera 1988) are very common. Following the suggestion by McNutt (2000) that VT earthquakes can show the movement of geothermal fluids, these earthquake swarms may indicate a circulation of geothermal fluids.

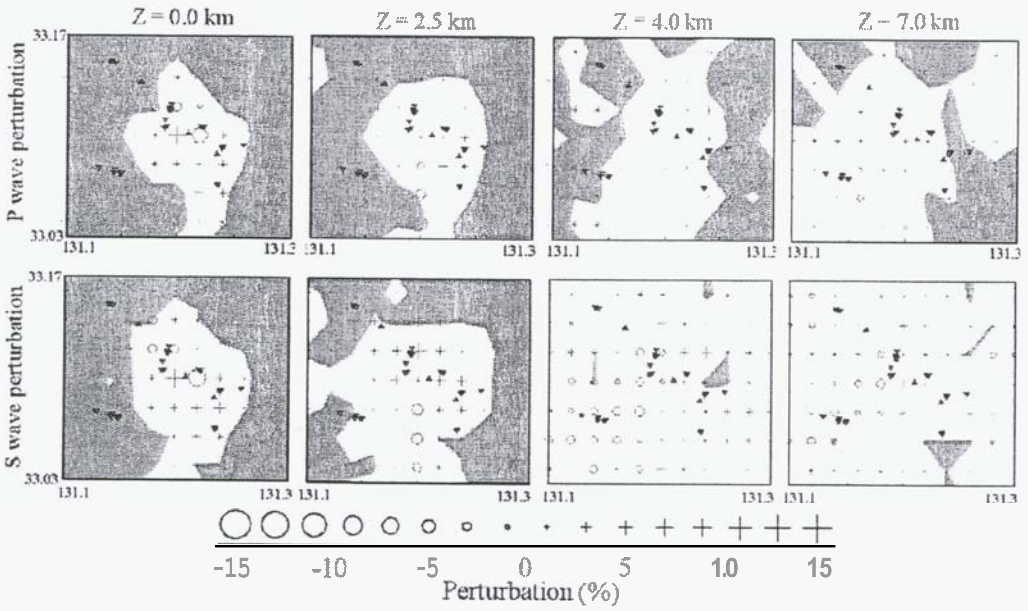

Figure 2 Plan views of perturbations of P wave and *S* wave velocities. Triangles and inverted triangles on maps indicate top of mountains and hot springs, respectively. Shadow zones indicate areas where CRT results are not good.

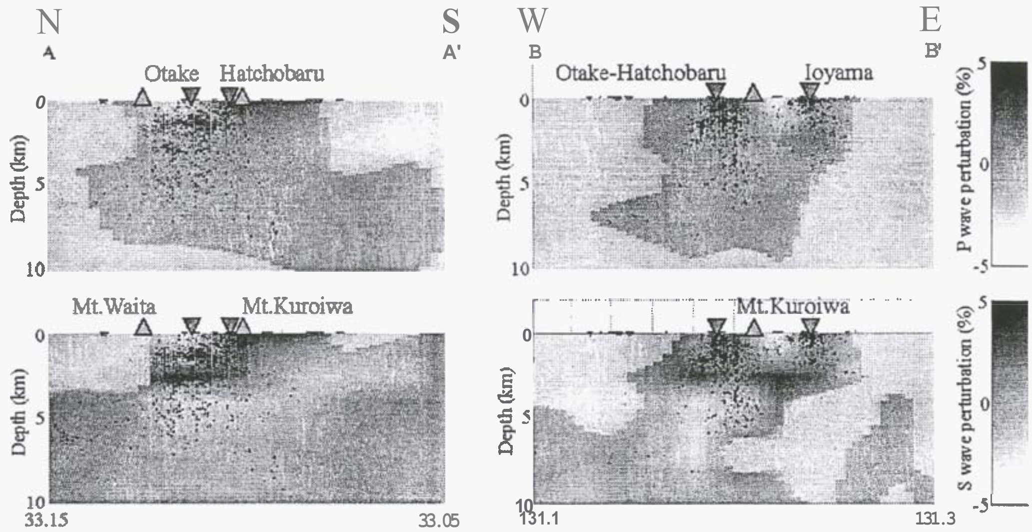

Figure 3 Perturbations of P wave and S wave velocities rounding off +5% and hypocenter distribution on cross sections on A-A' and B-B' lines in Figure 1. Triangles, inverted triangles and pluses on the figures are top of mountains, geothermal areas and hypocenters, respectively. White shading zones indicate areas where CRT results are not good.

On the N-S cross section, hypocenters occur above the upper part of the low Vs with high Vp/Vs region. The hypocenter distribution zone rises from its deeper part in the north Otake area to the surface in south Hatchobaru area.

On the E-W cross section, hypocenters distribute along the boundary between the low Vs with high VpNs region and the high Vs with low VpNs region deeper than 4.0 km. Above the boundary, hypocenters distribute to the west of the high Vp and high Vs region. The hypocenter distribution makes a line from the deeper part to the surface.

Two flow regions of geothennal fluids can be imaged from these hypocenter distributions. One flow region is associated with geothermal fluids above the high Vs and low VpNs region rising toward the southeastern part of the Hatchobaru area; the other is associated with the low Vs and high VpNs region deeper than 4.0 km where geothermal fluids move along the boundary between the low Vs and high Vp/Vs region and the high Vs and low VpNs region. Manabe and Ejima (1984) suggested that surface water infiltrating along faults was heated to about 300 degrees C by uplifted granitic basement rocks along NW-trending faults, such as the Hatchobaru fault and the Komatsuike fault, and that fluids from the deeper geothermal reservoir rose along NW-trending faults. They also suggested that the main up-flow area is in the southeast region of Hatchobaru, south of Mt. Kuroiwa. Therefore we suggest that the Otake-Hatchobaru geothermal system is controlled by the high Vs region at 2.5 km depth relating to the granitic basement rock and the low Vs region deeper than 4.0 km depth relating to the old magma of the Kuju Volcanic complex.

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