京 都 大 学 防 災 研 究 所 年 報　第47号 B　平成16年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 47 B, 2004

Three Dimensional Seismic Velocity Structure beneath the Otake-Hatchobaru Geothermal Area at Kuju Volcano in Central Kyushu, Japan

Miyuki YOSHIKAWA, and Yasuaki SUDO*

* Graduate School of Science, Kyoto University

Synopsis

We studied the three-dimensional seismic velocity structure of the Otake-Hatchobaru geothermal area in central Kyushu, Japan, using the tomographic method of Zhao et al. (1994). As a result of that, we could find a velocity structure imaging a geothermal structure of the area. A low Vs and low Vp/Vs region relating to the old magma body of volcanoes around of the geothermal area was located at the depth deepter than 5 km. At the upper part of this low anomalous region, the high Vs and low Vp/Vs region (Z=3.5 km depth) showing the granitic basement rock was found. There were low Vp and Vs regions at 1 km depth over the high Vs region, which were associated with a volcanic deposite zone and a fracture zone at this area.

Keywords: velocity structure, the Otake-Hatchobaru geothermal area, Kuju Volcano

1. Introduction

The Otake-Hatchobaru area at the northwest part of Kuju Volcano in Central Kyushu, Japan is a well-known geothermal area in Japan. The geothermal area characterized by a vapor-dominated geothermal system and a fractured reservoir has one of the major geothermal power plants in Japan with a total output of 122.5 MW (12.5 MW at the Otake area, 110 MW at the Hatchobaru area).

Volcanoes around of the Otake-Hatchobaru geothermal area formed during from 0.2Ma to 0.1Ma (Fujino et al. 1985). Mt. Sensui and Mt. Kuroiwa at southeast of the geothermal area spilled out lava flows until 10,000 years ago, whose volcanic activities related to the heat source of the geothermal area (Inuyama et al. 2002). A reservoir of the geothermal area is formed by fractures. A lot of fractures including faults are located at this area. NW-trending faults such as the Hatchobaru fault and the Komatsuike fault are dominant in this area, along which hot springs, fumaroles and altered zones are found (Yamasaki et al. 1970). The geothermal reservoirs also are found along these NW-trending faults (Manabe and Ejima 1980). Geothermal fluids circulate between surface and the granitic basement rock at 2.0 km depth from surface (700 m below sea level) in the Hatchobaru area (Manabe and Ejima 1984).

In the Otake-Hatchobaru geothermal area the underlying structures have been discussed by various investigations. Kamata (1968) found a high gravity anomalous region connecting to the uplifted zone of the basement rock. Onodera (1973) indicated negative anomalous regions of the self-potential related to geothermal reservoirs at the Otake and the Hatchobaru area. Kubotera (1988) showed an uplifted zone of the basement rock at 1 km depth below the sea level by a interpretation of a shallow seismic velocity structure using a time-term method. Sudo and Matsumoto (1998) found a high Vp region related to the uplifted zone at 4 km depth and a low Vs region related to a magmatic body at 7.0 km depth from the three dimensional P-wave velocity structure using the tomographic method.

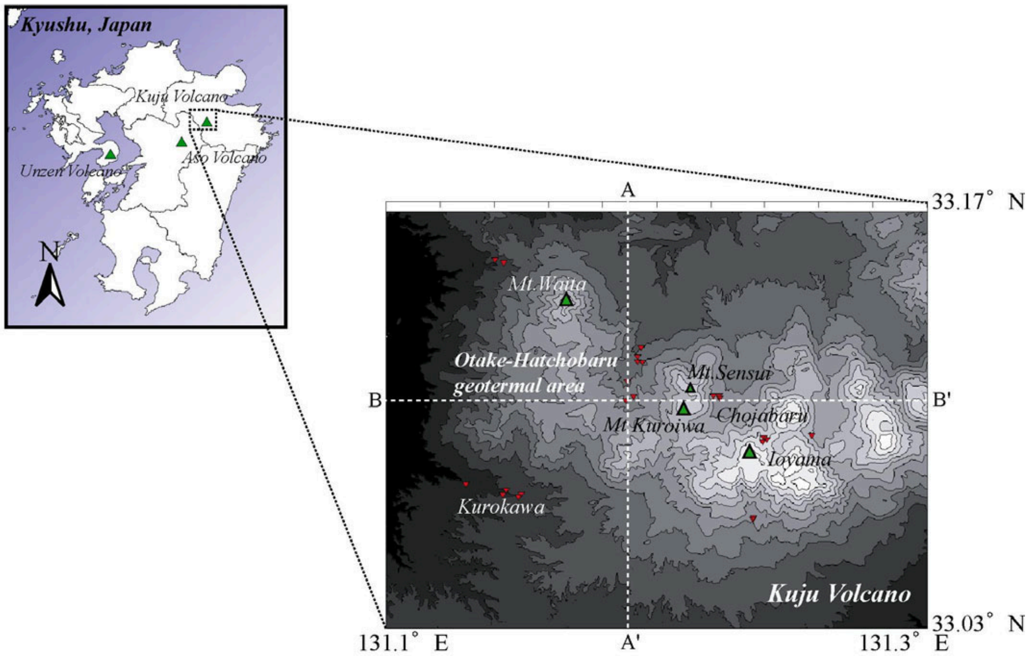

Figure 1 Maps of the Kyushu in Japan and study area. The study area is the right-hand map. Triangles and inverted triangles on maps indicate top of mountains and hot springs, respectively. Cross views of Figure 3 indicate along broken lines (A-A', B-B') on the right-hand map.

The geothermal structure in the Otake-Hatchobaru area has been discussed often shallower than 2.0 km depth below sea level as above mentioned, since this shallow geothermal structure has been emphasize for a geothermal development. However, a realization for a whole structure including a deeper part should be important in order to know a geothermal system, because a heat source of a geothermal area is expected at the deeper part.

In this study we discuss the deeper geothermal structure in and around of the Otake-Hatchobaru area using the tomographic method of Zhao et al. (1992) for exploring the geothermal structure.

2. Data and Method

Aso Volcanological Laboratory (AVL) of Kyoto University has established a seismic network to be constructed by 47 permanent and temporary stations in the central part of Kyushu (Fig.1). 5,850 well located earthquakes were selected from the period 1981 to 2002 in the region 32.6° N - 33.5° N x 130.6° E - 131.5° E wide, and 43530 P- and 31408 S- arrival times were used for this analysis. The initial model for P-wave velocity is calculated with VELEST program using 1966 best-recorded earthquakes from the AVL network (Table 1), and basic model which is an one-dimensional velocity structure of the Aso volcanic region shown by Sudo (1981). S-wave velocity was used what P-wave velocity divided by Vp/Vs ratio, 1.64.

Before the tomographic inversion was performed, P and S travel time residuals for every earthquake are calculated and the average travel time residuals for each station was used as a station corrections. Appling the station corrections for deciding seismic sources, RMS error significantly decreased from 0.174 to 0.136 sec.

This study area is the region 33.03° N – 33.17° N x 131.10° E – 131.30° E wide and from 0 to 30 km depth. Carrying out this inversion on this study volume, we adopted a 0.02° spacing of nodes in horizontal planes at Z = 1 km, 3.5 km, 5 km, 8 km, 11 km and 20 km depth (Z = 0 km indicates sea level).

3. Results

In order to evaluate the influence of the size of grid on the resolution of the velocity inversion, the checkerboard resolution test (CRT) for P- and S-wave was carried out. We computed synthetic P- and S-wave travel times for CRT model, with ±5 % velocity perturbations alternately at grid nodes to check the resolution. Good CRT results were obtained around Otake-Hatchobaru area for depths from 1 km

Table 1 Model of P wave velocity structure

Depth (km)	P wave velocity (km/sec)	
	Initial	Inverted
-9.00	3.300	3.300
1.00	4.126	3.430
3.50	5.260	4.140
5.00	5.723	5.560
8.00	6.133	6.040
11.00	6.490	6.590

to 3.5 km, and in the eastern region of Mt. Sensui for the layers at 5 and 8 km depths. However, at 11 km depth, there is no resolution. Therefore we can only discuss results of the tomographic inversion for layers shallower than 8 km.

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

Figures 2 and 3 show results of the inversion for P- and S-wave, respectively. In Figures 2 and 3, a low V_P and V_S region is located at 1 km depth beneath Otake-Hatchobaru area. Under the low V_P and V_S region, there are widely a high V_S region at 3.5 km depth and a low V_S region at deeper than 5 km. The low V_S region connects with Kurokawa geothermal area. At east of the low V_S region, a low V_P region linearly distributes from east of Kurokawa area to Otake-Hatchobaru area (low V_P line).

Figure 4 shows N-S and E-W cross-sections of P- and S-wave velocity perturbation. We can find clear contrasts of seismic velocity. There are contrasts among the low V_P and V_S region, the high V_P region and the low V_S region at 1 km and 3.5 km depths and deeper than 5 km beneath Otake-Hatchobaru area, respectively.

4. Discussion and Conclusion – the deep geothermal structure

As inversion results for 0.02° nodes spacing, we found a low V_P and V_S region in the north and a high V_P and V_S in the south at 1 km depth, a high V_S region at 3.5 km depth beneath Otake-Hatchobaru area. Several researches show that the surface seismic velocity is correlated with the surface geology. Londono and Sudo (2002) showed that a high V_P region was correlated to lava flows, and a shallow low V_P region to pyroclastic rocks at Nevado del Ruiz Volcano. It is also known that cracks, fractures, altered rocks and cracks filled with fluids reduce seismic velocities (e. g. Moos and Zoback 1983). The velocity structure at 1 km depth seems to be related with the surface geology. The high V_P and V_S region and the low V_P and V_S region at Otake-Hatchobaru area which appeared at 1 km depth are correlated to lava flows and pyroclastic deposits, respectively. On the other hand, at the low V_P and V_S region, Hayashi (1973) confirmed many faults and altered rocks. This low V_P and V_S region is with low V_P/V_S. Therefore, it is possible that the low V_P and V_S region at 1 km depth shows a fracture zone and it filled with gas because of low V_P/V_S.

There is a high V_S region at 3.5 km depth under the low V_P and V_S region. The high V_S region follows with low V_P/V_S. At a part of the high V_S region low V_P is located near Otake-Hatchobaru geothermal area, where seismic activity level is high. Figure 4 shows cross section views of P- and S-wave velocities. The figure shows uplifted region of S-wave velocity beneath Otake-Hatchobaru area. About P-wave velocity, while a low velocity region is found near the geothermal area, some researchers revealed an existence of high V_P region around Otake-Hatchobaru area. Kubotera (1988) mentioned at Otake-Hatchobaru area an uplifted region of P-wave velocity using a time-term analysis. Sudo and Matsumoto (1998) showed three-dimensional P-wave velocity structure around Kuju Volcanic area and a high V_P region at 3 km depth around Otake-Hatchobaru area. In case of our study, we cannot confirm a high V_P region, since a region where the CRT results is good is narrow. But it is possibility that the high V_P region exists because of results by Kubotera (1988) and Sudo and Matsumoto (1998). The possibility is supported by distributing high V_P regions around the low V_P region near the geothermal area.

Seismic velocity is compared with gravity data. At a region where seismic velocity is high, positive anomaly of gravity is often located. At first, a characteristic of gravity is that there is a negative Bougure anomalous region suggested as Kuju Caldera

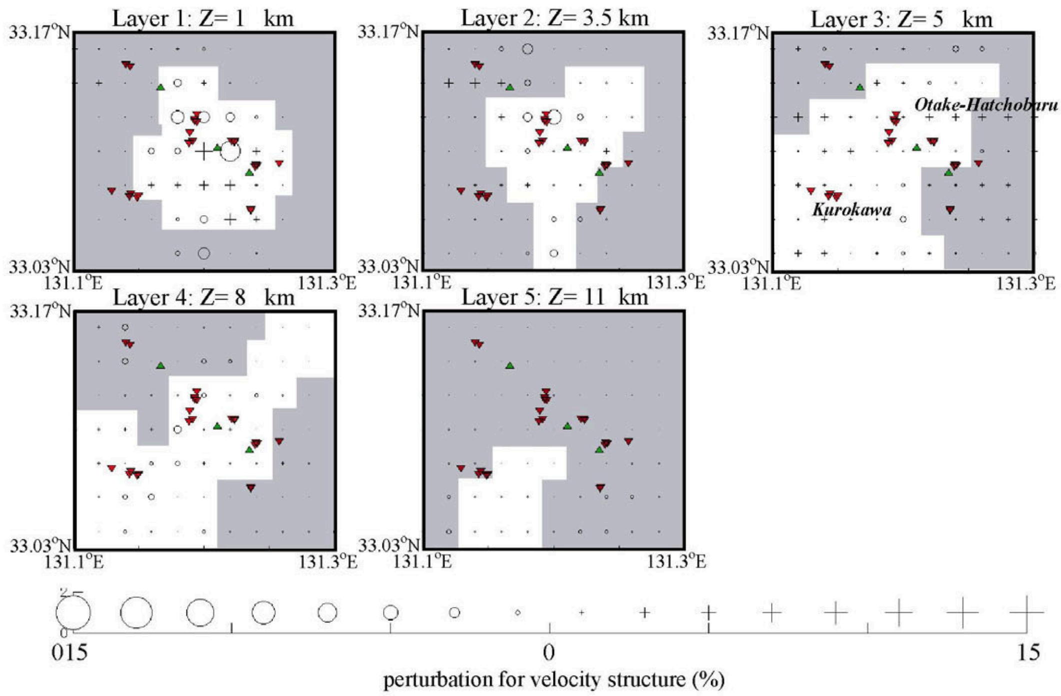

Figure 2 Plane views of seismic velocity perturbations for P-wave velocity. Shadow areas show regions where CRT results are bad. Triangles and inverted triangles show tops of notable mountains and geothermal manifestations, respectively.

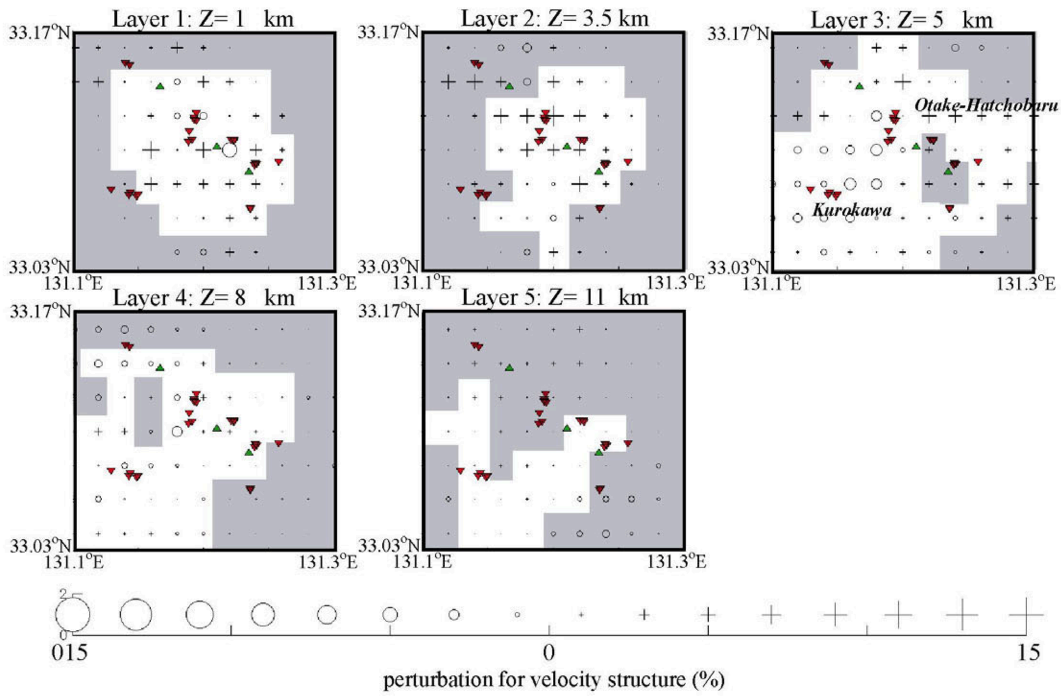

Figure 3 Plane views of seismic velocity perturbations for S-wave velocity. Shadow areas show regions where CRT results are bad. Triangles and inverted triangles show tops of notable mountains and geothermal manifestations, respectively.

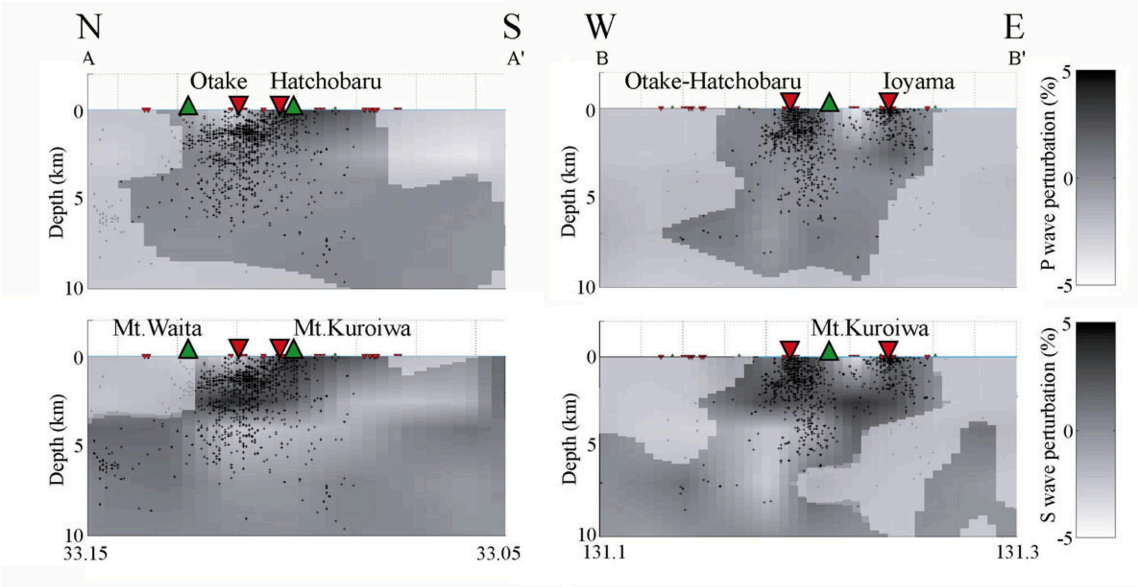

Figure 4 Cross views on A-A' and B-B' lines of perturbations of P wave and S wave velocities rounding off ±5% and hypocenter distribution near cross sections. Triangles inverted triangles and pluses on maps indicate top of mountains, hot springs and hypocenters, respectively. White zones indicate areas where CRT results are not good.

by Matsumoto (1979) and Kubotera et al. (1969) at northeast of Otake-Hatchobaru geothermal area, and there is a relatively positive anomalous region at the geothermal area. A boundary between these Bougure anomalous regions corresponds to a northeastern margin of the high V_S region. At the high V_S region we can locate the positive Bougure anomalous region.

At Otake-Hatchobaru area, the granitic basement rock was confirmed at shallower level of depth (700 m below sea level) by drilling data (Manabe and Ejima, 1984). The positive Bougure anomalous region and the uplifted P-wave velocity region was suggested the uplifted zone of basement rock by Kubotera (1988). Sudo and Matsumoto (1998) also suggested the high V_P region as the uplifted zone. Therefore we can consider that the high V_S region relates the uplifted zone. And we suggest that the low V_P region near Otake-Hatchobaru area shows a fracture zone inside the basement rock, since a lot of earthquakes occur at the low V_P region.

Under the high V_S region, there is a low V_S region with high V_P/V_S at deeper than 5 km (Fig. 3, Z=5 and 8 km). The low V_S region continues to Kurokawa geothermal area. Comparing between the low V_S region and the hypocenter distribution, there is a seismic gap at the low V_S region. In cross-section view (Fig. 4), hypocenters distribute along the eastern side of the low V_S region at deeper than 5 km.

Londono and Sudo (2002) suggested that a low V_S region with high V_P/V_S indicated an old degassing magma body at Nevado del Ruiz Volcano. They also showed that volcano tectonic earthquakes (VT earthquakes) occurred around the low V_S region. Volcanoes around Otake-Hatchobaru geothermal area formed during from 0.2 Ma to 0.1 Ma (Fujino et al. 1985). Moreover, Mts. Sensui and Kuroiwa located to the southeast of the geothermal area, spilled out lava flows until 10,000 years ago, whose volcanic activities are believed to be a heat source of the geothermal area (Inuyama et al., 2002). Therefore, it is possible that the low V_S region with high V_P/V_S means the fracture zone keeping high temperature or an old magmatic body, which is the heat source for Otake-Hatchobaru geothermal area.

Acknowledgments

Thanks to Prof. D. Zhao of Ehime University, Japan for his comments and for providing his software. Thanks to J. Kiyosaki of Fukuoka University, Japan, all staff of Aso Volcanological Laboratory at Kyoto University, Japan, Assistant Prof. T. Tsusui of Akita University and M. Tanaka for the seismic observation. And thanks to many others for supports in various ways.

References

Fujino, T., Hayashi, M. and Watanabe, K. (1985): Geothermal History of the Otake-Hatchobaru Geothermal Field. Jnl. Geotherm. Res. Soc. Japan, Vol. 8(2), 195 (in Japanese).
Hayashi, M. (1973): Hydrothermal Alteration in the Otake Geothermal Area, Kyushu. J. Japan Geotherm. Energy Assoc., Vol. 10, 9-46.
Inuyama, F., Matsumoto, T., and Fujino, T. (2002): Review on the Historical Change of Conceptual Model of the 35 years in Otake Geothermal Field. J. Japan Geotherm. Energy Assoc., Vol. 39, 30-59.
Kamata, S. (1968): Gravity Survey in Otake Geothermal Area. Jnl. Geotherm. Res. Soc. Japan Special Issue, (14), 24-30 (in Japanese with English abstract).
Kubotera, A. (1988): Seismicity of the Geothermal Field. Jnl. Balneolog. Soc. Japan., Vol. 38, 23-29 (in Japanese with English abstract).
Londono, J. M., Sudo, Y. (2002): Velocity structure and a seismic model for Nevado del Ruiz Volcano (Colonbia). Jnl Volcanol Geotherm Res., Vol. 119, 61-87.
Manabe, T. and Ejima, Y. (1984): Tectonic Characteristics and Hydrothermal System of Fractured Reservoir at the Hatchobaru Geothermal Field. Jnl. Geotherm. Res. Soc. Japan., Vol. 21(2), 101-118 (in Japanese with English abstract).
Matsumoto, Y. (1979): Some problems on volcanic activities depression structures in Kyushu, Japan. Mem. Geol. Soc. Japan. Vol. 16, 127-139 (in Japanese with English abstract).
Moos, D., Zoback, M. D. (1983): In Situ Studies of Velocity in Fractured Crystalline Rocks. Jnl. Geophys. Res. Vol. 88(B3), 2345-2358.
Onodera, S. (1973): Self-potential Measurements at the Otake Geothermal Field. J. Geotherm. Res. Soc. Japan. Vol. 10(2), 25-29 (in Japanese with English abstract).
Sudo Y (1981): Seismic activities at the western region of the Aso caldera. Bull. Volcanol. Soc. Japan, Vol. 23, 263-279 (in Japanese with English abstract).
Sudo, Y and Matsumoto, Y. (1998): Three-dimensional P-wave velocity structure in the upper crust beneath Kuju Volcano, central Kyushu, Japan. Bull. Volcanol. Vol. 60, 147-159.
Yamasaki, T., Matsumoto, Y. and Hayashi, M. (1970): The geology and hydrothermal alteration of the Otake geothermal area, Kujyu volcano group, Kyushu, Japan. Geothermics, Special Issue, (2), 197-207
Zhao, D., Hasegawa, A., Horiuchi, S. (1992):

三次元地震波速度構造から推定された
九重火山北西部地域（大岳・八丁原地熱地域）の地熱構造

吉川美由紀・須藤　靖明*

*京都大学理学研究科

要旨

大岳・八丁原地域の深部地熱構造について地震波速度構造と地震活動からの検討をおこなった。その結果，大岳・八丁原地域の深さ1kmにおいてlow Vp and Vs領域がみられた。Low Vp and Vs領域の下部，深さ3.5kmには基盤岩を示すと考えられるhigh Vs領域が分布し,Vp/Vsはlowを示した。この下，深さ5kmから8kmにかけてはlow Vs領域が大岳・八丁原地熱地域から南西の黒川地熱地域まで分布する。火山地域においてLow Vs領域はしばしば古いマグマと関係づけられ，この場合も同様のことが示唆される。

キーワード:速度構造，大岳・八丁原地熱地域，九重火山