

Seismic Velocity Structure of the Crust Beneath the Aira Caldera in Southern Kyushu by Tomography of Travel Times of Local Earthquake Data

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We applied the tomography method to the P- and S-wave arrival times of 829 local earthquakes observed at 101 stations in central and southern Kyushu, and revealed the detailed three-dimensional seismic velocity structure of the crust, especially the region beneath the Aira caldera. The structure obtained beneath the Aira caldera was characterized by a compacted high Poisson's ratio zone at about 20 km depth, suggesting fluid saturation such as partial melts relating to volcanism. We also found that the low frequency earthquakes occurred so as to infill the lower crust between the high Poisson's ratio zone and the moho discontinuity beneath the Aira caldera. It was also obvious that earthquakes clearly concentrated in regions with low V_p/V_s (low Poisson's ratio) in the upper crust of the whole of southern Kyushu.

Key words: Aira caldera, Sakurajima, velocity structure

1. Introduction

Southern Kyushu (Fig. 1) is bordered by the N40° E trending Nankai Trough where the Philippine Sea (PHS) plate subducts to a direction of N50° W beneath the Eurasian plate at the rate of 4–5 cm/yr (Seno *et al.*, 1993). Associated with this subduction a nearly straight chain of active Quaternary volcanism runs almost parallel to the trough in the central part of the island. In southern Kyushu, there are four large calderas: the Kakuto, the Aira, the Ata and the Kikai calderas. Large-scale pyroclastic eruptions about 29,000 years before present in the calibrated age led to the formation of the Aira caldera (Aramaki, 1984; Okuno, 2002). Especially, Sakurajima volcano in the Aira caldera has been very active.

Using a seismic velocity inversion technique, Sadeghi *et al.* (2000) obtained a three-dimensional (3-D) seismic structure of east China and western Japan and found high velocity zones (HVZs) existed beneath Kyushu due to the subducting PHS plate, whereas low velocity zones (LVZs) existed in western Kyushu, which they cited as evidence of mantle upwelling and back-arc spreading. Yakiwara (2000) reported low P- and S-wave velocity zones beneath Unzen, Aso, Kirishima and Sakurajima volcanoes and

suggested the presence of partial melts. Meanwhile, Salah and Seno (2008), Tahara *et al.* (2008), Wang and Zhao (2006) and Xia *et al.* (2008) modeled the mantle wedge beneath Kyushu as low Poisson's ratio zones and concluded them to be due to fluid saturation from the dehydration of the subducting PHS plate. Wang and Zhao (2006) also indicated widespread low velocity zones beneath volcanoes in Kyushu. All these previous studies pointed out that the low velocity zones revealed by their 3-D tomography were closely related to volcanism in Kyushu.

In this study we focused on obtaining a detailed 3-D seismic velocity structure up to 50 km depth underneath southern Kyushu, specifically the Aira caldera, by tomography of arrival times from local earthquake data with finer grid configuration than that in the previous tomography studies. The obtained velocity structure should reveal the velocity variation related to the volcanic and seismic activity in southern Kyushu.

2. Data and Methodology

In order to reveal the crustal structure in and around the Aira caldera in southern Kyushu, we set up a wide study area with a range of 30° N–32.25° N and 129.25° E–132.

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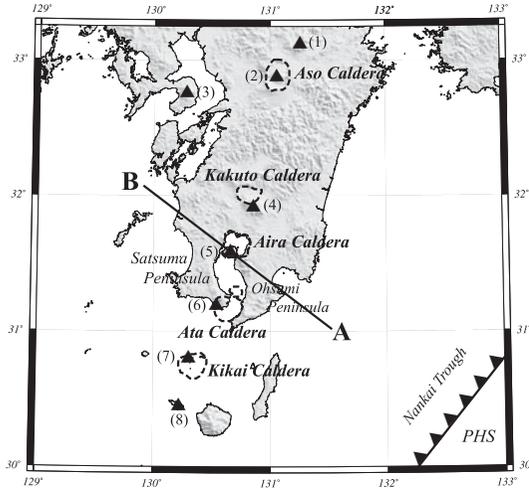


Fig. 1. A map showing the study region in Kyushu. Solid triangles are active volcanoes: (1) Kuju, (2) Aso, (3) Unzen, (4) Kirishima, (5) Sakurajima, (6) Kaimon, (7) Kikai, (8) Kuchino-erabujima. Areas enclosed by broken lines show the Aso, Kakuto, Aira, Ata, and Kikai calderas, respectively. PHS is the subducting Philippine Sea plate. A-B is a section line in Fig. 5.

25° E in a depth range from 0 to 200 km. We assigned the horizontal and vertical grid nodes with a spacing of 15 km and 10 km, respectively up to 50 km depth to get good spatial resolution in the study area. On the other hand, we allocated nodes with a spacing of 25 km in the vertical direction to the deeper regions with a depth range from 50 to 200 km.

We then selected 829 earthquakes, which were located up to 200 km depth in central and southern Kyushu, taken from the Japan Meteorological Agency (JMA) earthquake catalogue from 1997 to 2006, as shown in Fig. 2. These events were recorded by a total of 101 seismic stations deployed in the study area, belonging to JMA, National Research Institute for Earth Science and Disaster Prevention (HINET), Kagoshima University (Nansei Toko Observatory for Earthquakes and Volcanoes: NOEV), and Kyoto University (Sakurajima Volcano Observatory: SVO). P- and S-wave arrival times at all stations were picked by visual inspection and total numbers of P- and S-wave arrival time data used for the 3-D tomography were 20,302 and 13,196 in this study.

First we estimated a one-dimensional (1-D) 6-layered P-wave velocity model up to 50 km depth, which suggested the thickness of the crust at around 30–40 km, by using the 1-D inverse method (Crosson, 1976) of simultaneous damped least squares estimation of event location and velocity. This 1-D model with a constant V_p/V_s of 1.73

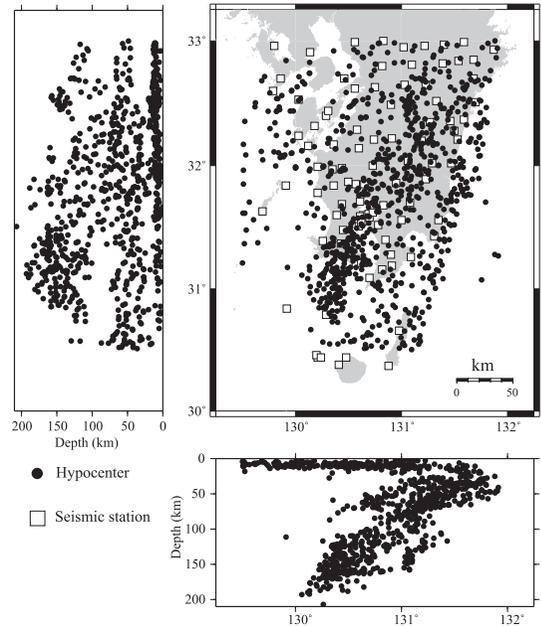


Fig. 2. Distribution of 101 seismic stations and 829 hypocenters used in the 3-D tomography.

was used as the initial velocity model for the 3-D tomography using the program package SIMULPS14 (Evans *et al.*, 1994; Thurber, 1983; Thurber, 1993; Um and Thurber, 1987). In order to ensure reliability of resolution, we adopted the derivative weight sum (DWS) at each node as an indication of ray density (Thurber and Eberhart-Phillips, 1999). As shown in Fig. 3, a minimum DWS was assigned to be 2000 or 1000 for P-waves, and 1500, 1000 or 500 for S-waves. We simply assumed that the tomography yielded reliable solutions only at nodes with DWS values larger than the minimum DWS.

3. Results

Figure 3 shows the horizontal distributions of P- and S-wave velocities, and V_p/V_s on each plane with relocated hypocenters from 0 to 100 km depth obtained by the 3-D inversion. In the shallower sections at 0 and 10 km depth (Fig. 3a and 3b), LVZs (V_p and V_s change less than -10% from the initial model) are found in the eastern part of Kyushu, where basement rocks are made up of uplifted sedimentary marine terraces (Nakada *et al.*, 2002). The figures also show that LVZs are distributed along the volcanic front between Kirishima volcano to Kaimon volcano (Fig. 1). Meanwhile, the hypocenters occurred in the inland area are obviously concentrated in regions with a relatively higher velocity and a low Poisson's ratio at a depth of 10 km. A possible reason for this concentration is that these regions are less fluid-saturated (a low Poisson's

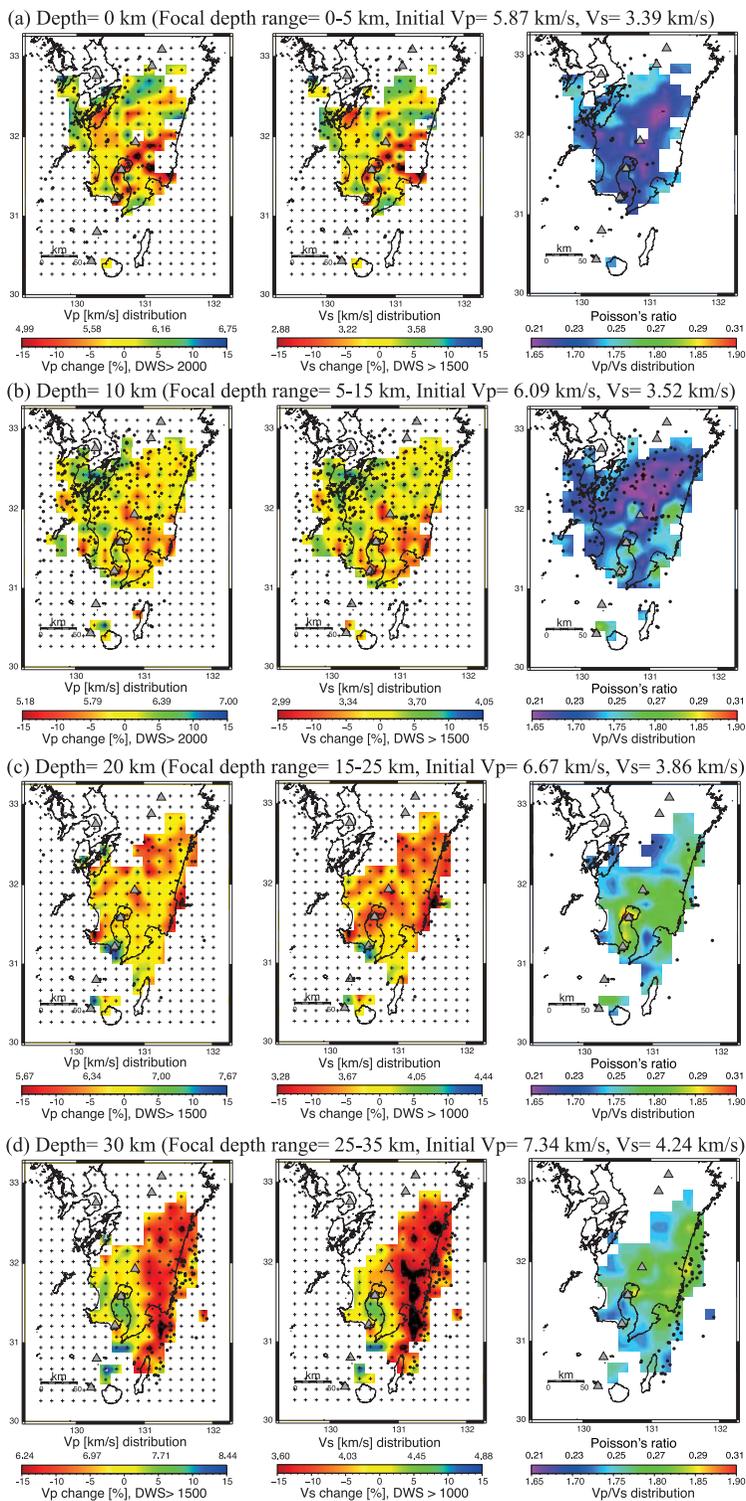
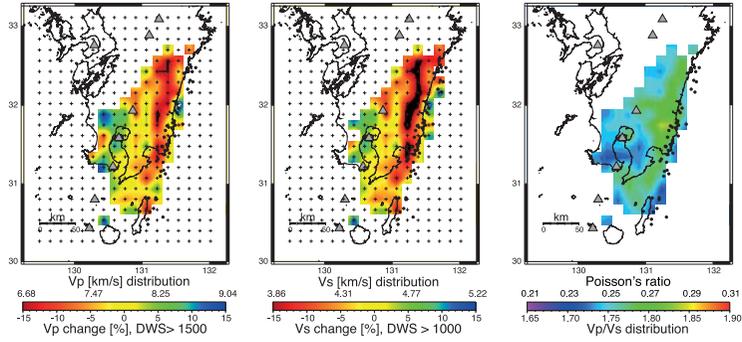
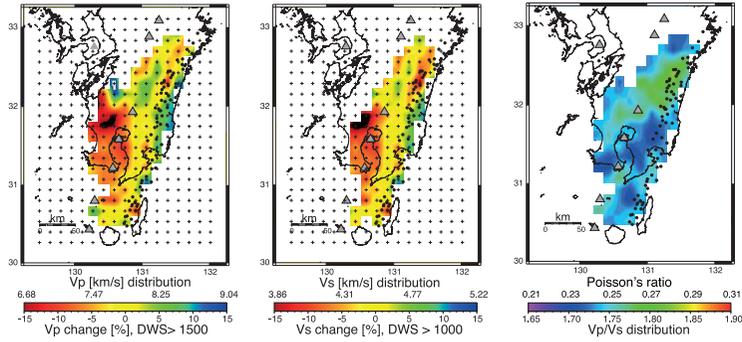


Fig. 3. Horizontal distributions of P-wave velocity (V_p), S-wave velocity (V_s), and V_p/V_s at a depth of (a) 0 km, (b) 10 km, (c) 20 km, (d) 30 km, (e) 40 km, (f) 50 km, (g) 75 km, and (h) 100 km. Solid circles, gray triangles and crosses indicate relocated hypocenters, active volcanoes and grid nodes in the 3-D model, respectively. Focal depth range of the hypocenters and the minimum value of DWS are also indicated in each section.

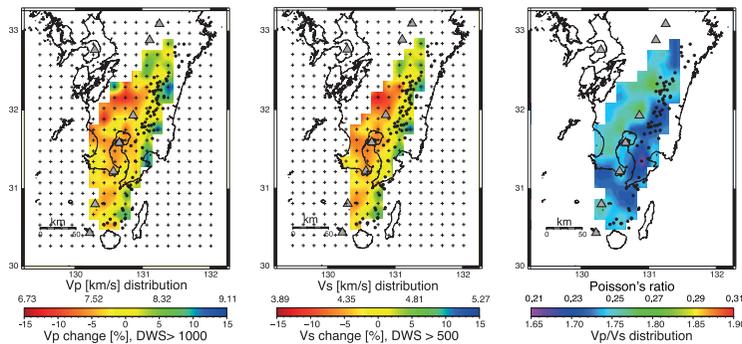
(e) Depth= 40 km (Focal depth range= 35-45 km, Initial V_p = 7.86km/s, V_s = 4.54 km/s)



(f) Depth= 50 km (Focal depth range= 45-60 km, Initial V_p = 7.86 km/s, V_s = 4.54 km/s)



(g) Depth= 75 km (Focal depth range= 60-85 km, Initial V_p = 7.92 km/s, V_s = 4.58 km/s)



(h) Depth= 100 km (Focal depth range 85-110 km, Initial V_p = 7.92 km/s, V_s = 4.58 km/s)

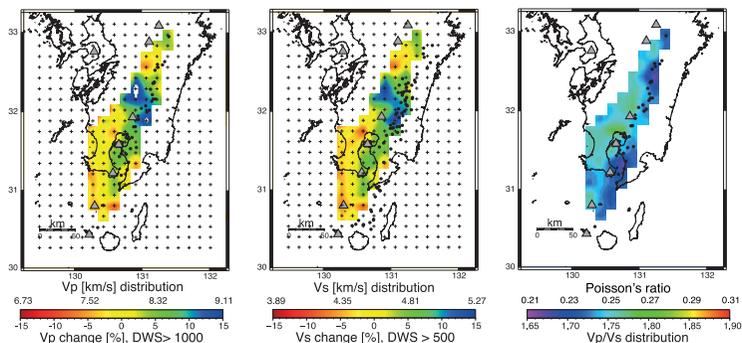


Fig. 3 continued.

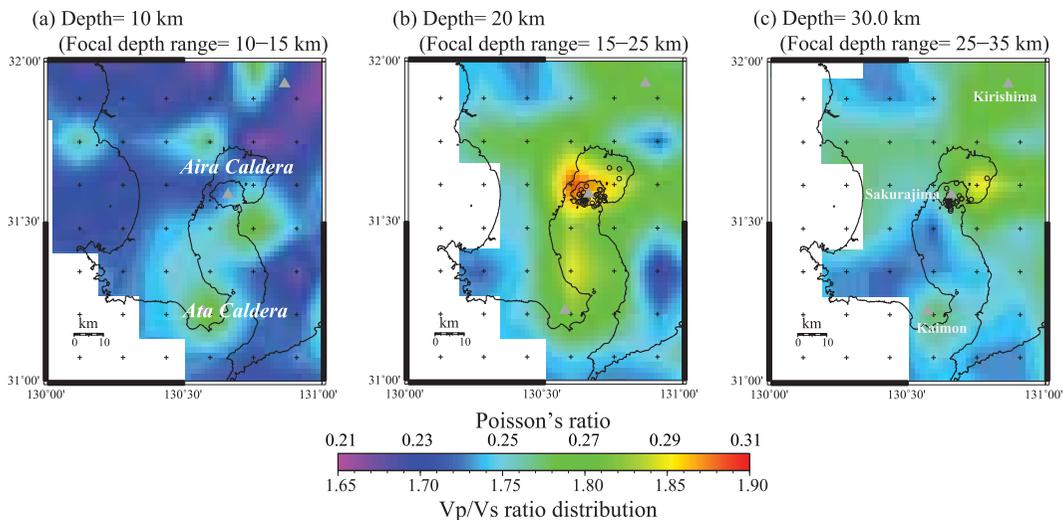


Fig. 4. An enlarged map showing the horizontal distribution of Vp/Vs around the Aira and the Ata calderas at a depth of (a) 10 km, (b) 20 km, and (c) 30 km. Open circles are the low frequency earthquakes occurred in and around the Aira caldera, which are detected routinely by NOEV. A gray triangles are Kirishima, Sakurajima and Kaimon volcanoes, respectively.

ratio is indicative of low fluid content) and thus more prone to brittle deformation.

In order to detail the particulars of the main target, the Aira caldera, we present an enlarged map showing the horizontal Vp/Vs distributions in Fig. 4. At 20 km depth (Fig. 4b), the most interesting feature is that a distinctly high Poisson's ratio zone is located exactly beneath the Aira caldera. This zone extends southward and connects the Aira caldera with the Ata caldera. As shown in Fig. 3c, it is found that large areas of low velocities exist beneath Kirishima and Sakurajima volcanoes. In contrast, there is an unusually high velocity zone beneath Kaimon volcano located at the edge of our model, and thus may not be reliable. It is noted that the earthquake distribution in the inland area is fairly sparse, as shown in Fig. 3c.

At 30 km depth in Fig. 4c, a small zone with high Poisson's ratio appears to remain beneath the Aira caldera. This small zone is assumed to be a portion of the distinctly high zone observed at 20 km depth. In Fig. 3d, the velocity distribution in the western region (Satsuma Peninsula) is quite different from that in the eastern region (Ohsumi Peninsula): the western region is characterized by high velocities of P- and S-waves, while the eastern region is characterized by low P- and S-wave velocities. At the deeper sections seen in Figs. 3e to 3g, these low velocity anomaly zones in the eastern region progressively shift westward due to the subducting PHS plate.

Hypocenters at 30 km depth are distributed along a coastal line with a NNE-SSW orientation in the eastern region, and at deeper ranges from 40 to 75 km the hypo-

centers appear to concentrate along a boundary between the high and low velocity zones. We interpret that these HVZs with low Poisson's ratios are related to the subducting PHS plate.

4. Discussion and Summary

Figure 5 shows a vertical sections of the P- and S-wave velocities, and Vp/Vs distributions along the A-B line across the Aira caldera in Fig. 1, and hypocenters of low frequency (LF) earthquakes, which occurred in and around the Aira caldera, detected routinely by NOEV are also plotted. As described in the previous section, there is an anomaly with a very high Poisson's ratio at about 20 km depth beneath the Aira caldera, possibly suggesting the presence of partial melts and the source of volcanism in the area. It is also found that LF earthquakes occur in the lower crust. A deeper part of the focal zone of these LF earthquakes appears to overlap the high Poisson's ratio zone observed at 30 km depth. These facts lead us to postulate that magma penetrating into the crust from the upper-most mantle may construct the high Poisson's ratio zone at about 30 km depth, and move upwards through the LF focal zone, and finally be stored at about 20 km depth.

Previous tomography studies such as Sadeghi *et al.* (2000), Salah and Seno (2008), Tahara *et al.* (2008), Wang and Zhao (2006), Xia *et al.* (2008) and Yakiwara (2000) have revealed the 3-D velocity structure of the southern part as well as the whole Kyushu region, and have shown that the low velocity zone is widely distributed in the crust and the upper-most mantle. Therefore, it is quite

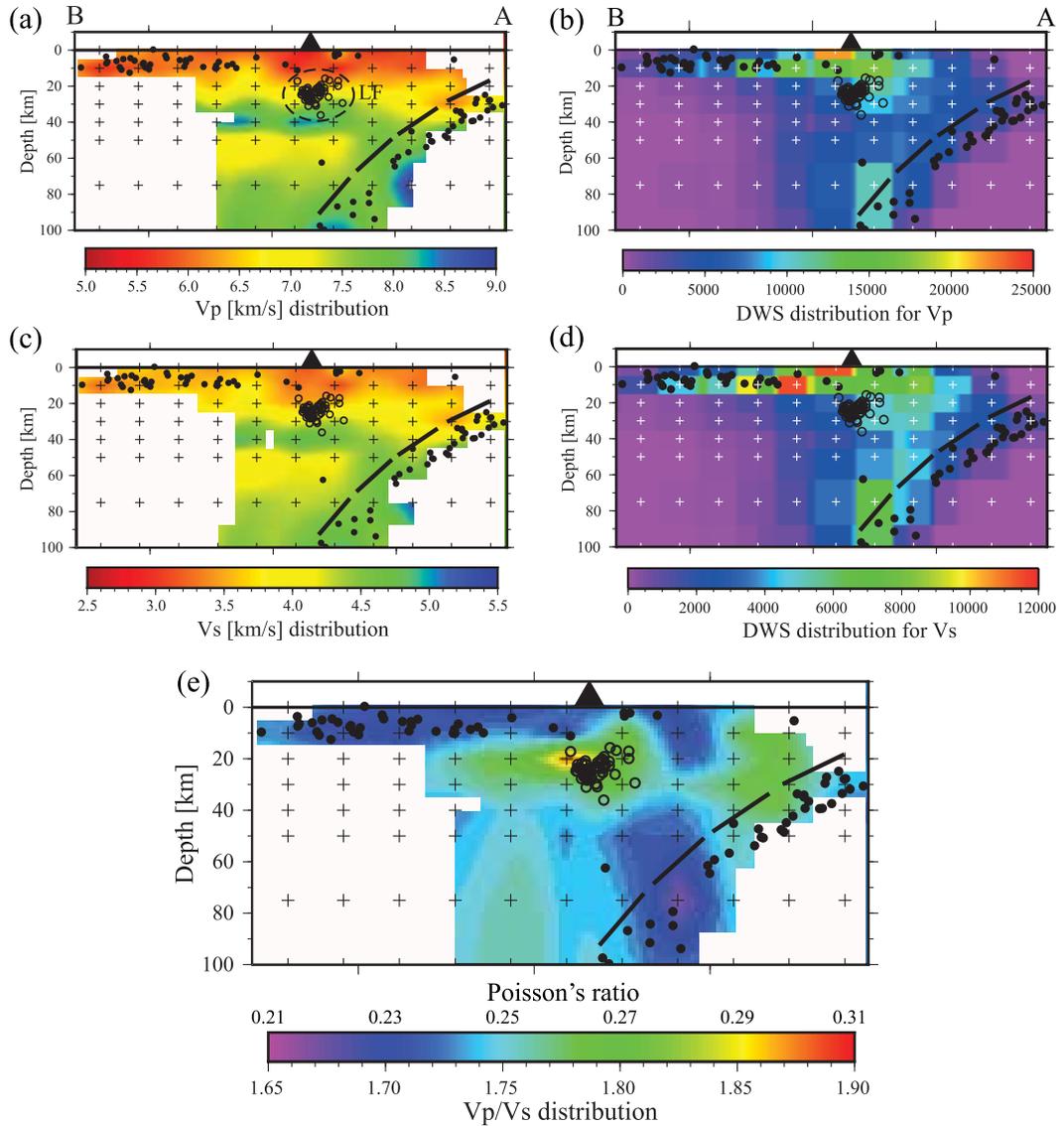


Fig. 5. Cross sections of a distribution of (a) P-wave velocity, (b) DWS for P-wave, (c) S-wave velocity, (d) DWS for S-wave, and (e) V_p/V_s , along the A-B line in Fig. 1, respectively. Solid circles, a solid triangle and crosses indicate relocated hypocenters, Sakurajima volcano and grid nodes, respectively. Open circles show the low frequency earthquakes occurred in and around the Aira caldera. Thick broken line outlines the upper boundary of the subducting PHS plate (Yakiwara, 2000).

difficult to recognize the relation between the low velocity zone and the volcanism in southern Kyushu. However, the distribution of the Poisson's ratio obtained by using the fine grid configuration in this study can specify the extent of the high Poisson's ratio zone, which suggests possibility of the existence of the magma conduit and reservoir in the crust.

Ishihara (1990) described the magma supply system of Sakurajima volcano wherein one magma reservoir is

located at about 4 km depth just beneath Sakurajima volcano and another at 8 to 10 km depth beneath the Aira caldera. Although space resolution in our tomography is insufficient to distinguish these magma reservoirs in the upper-most crust, our result puts forward a possibility of the deeper magma reservoir supplying two shallow magma reservoirs previously found.

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References

- Aramaki, S. (1984) Formation of the Aira Caldera, Southern Kyushu ~22,000 Years Ago. *J. Geophys. Res.*, **89** (B10), 8485–8501.
- Crosson, R. S. (1976) Crustal structure modelling of earthquake data 1. Simultaneous least squares estimation of hypocenter and velocity parameters. *J. Geophys. Res.*, **81** (17), 3036–3046.
- Evans, J. R., Eberhart-Phillips, D. and Thurber, C. H. (1994) User's manual for SIMULPS12 for imaging Vp and Vp/Vs: A derivative of the "Thurber" tomographic inversion SIMUL3 for local earthquakes and explosions. *U. S. Geol. Surv. Open File Rep.*, 94–431.
- Ishihara, K. (1990) Pressure sources and induced ground deformation associated with explosive eruptions at an andesitic volcano: Sakurajima Volcano, Japan. In *Magma Transport and Storage* (Ryan M. P. ed), 335–356, John Wiley & Sons, Chichester.
- Nakada, M., Tahara, M., Shimizu, H., Nagaoka, S., Uehira, K. and Suzuki, S. (2002) Late Pleistocene crustal uplift and gravity anomaly in the eastern part of Kyushu, Japan and its geophysical implications. *Tectonophysics*, **351**, 263–283.
- Okuno, M. (2002) Chronology of tephra layers in southern Kyushu, SW Japan, for the last 30,000 years. *Quaternary Research*, **41** (4), 225–236 (in Japanese).
- Sadeghi, S., Suzuki, H. and Takenaka, H. (2000) Tomographic low-velocity anomalies in the upper-most mantle around the northeastern edge of Okinawa Trough, the backarc of Kyushu. *Geophys. Res. Lett.*, **27** (2), 277–280.
- Salah, M. K. and Seno, T. (2008) Imaging of Vp, Vs, and Poisson's ratio anomalies beneath Kyushu, southwest Japan: Implications for volcanism and forearc mantle wedge serpentinization. *J. Asian Earth Sci.*, **31**, (4–6), 404–428.
- Seno, T., Stein, S. and Gripp, A. E. (1993) A Model for the Motion of the Philippine Sea Plate Consistent With NUVEL-1 and Geological Data. *J. Geophys. Res.*, **98** (B10), 17941–17948.
- Tahara, M., Uehira, K., Shimizu, H., Nakada, M., Yamada, T., Mochizuki, K., Shinohara, M., Nishino, M., Hino, R., Yakiwara, H., Miyamachi, H., Umakoshi, K., Goda, M., Matsuwo, N. and Kanazawa, T. (2008) Seismic velocity structure around the Hyuganada region, Southwest Japan, derived from seismic tomography using land and OBS data and its implications for interplate coupling and vertical crustal uplift. *Phys. Earth Planet. Inter.*, **167**, 19–33.
- Thurber, C. H. (1983) Earthquake locations and three-dimensional crustal structure in the Coyote Lake area, Central California. *J. Geophys. Res.*, **88** (B10), 8226–8236.
- Thurber, C. H. (1993) Local earthquake tomography: velocities and Vp/Vs –theory. In *Seismic Tomography: Theory and Practice* (Iyer, H. M. and Hirahara, K. ed) 563–583, Chapman and Hall, London.
- Thurber, C. H. and Eberhart-Phillips, D. (1999) Local earthquake tomography with flexible gridding. *Comp. Geosci.*, **25**, 809–818.
- Um, J. and Thurber, C. H. (1987) A fast algorithm for two-point seismic ray-tracing. *Bull. Seismol. Soc. Am.*, **77**, 972–986.
- Wang, Z. and Zhao, D. (2006) Vp and Vs tomography of Kyushu, Japan: New insight into arc magmatism and forearc seismotectonics. *Phys. Earth Planet. Int.*, **157**, 269–285.
- Wessel, P. and Smith, W. H. F. (1998) New, improved version of Generic Mapping Tools released. *EOS Trans. Amer. Geophys. U.*, **79** (47), 579.
- Xia, S., Zhao, D., and Qui, X. (2008) Tomographic evidence for the subducting oceanic crust and forearc mantle serpentinization under Kyushu, Japan. *Tectonophysics*, **449**, 85–96.
- Yakiwara, H. (2000) Three-dimensional seismic velocity structure of the crust and upper mantle beneath Kyushu, Japan, derived from local earthquake data. PhD thesis, Kyushu University.

(Editorial handling Takeshi Hashimoto)

走時データのトモグラフィーによる始良カルデラの地殻速度構造

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後藤和彦・小林励司・為栗 健・井口正人

九州の中部および南部に展開している 101 カ所の地震観測点と 829 個の自然地震から得られた P 波と S 波の走時データにトモグラフィー法を適用し、南九州、特に、始良カルデラ下の地殻速度構造を明らかにした。始良カルデラの深さ約 20 km に V_p/V_s が高い小さな領域が存在し、この領域は火山活動に関連する部分溶融領域であることを示唆している。さらに、この高 V_p/V_s 領域とモホ面を接続するように低周波地震が下部地殻中に発生していることがわかった。また、南九州の上部地殻で発生する地震は低 V_p/V_s 領域に集中していることを明らかにした。