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Active-source Seismic Exploration of Fuji Volcano in 2003

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Abstract

In 2003, a controlled seismic exploration was conducted around Fuji volcano, Japan. First-motion data obtained with a seismic refraction analysis reveal the following seismic structure. The first layer, with a P-wave velocity of 2.5–3.5 km/s, extends for approximately 40 km around the summit to a depth of 1–2 km. The second layer, with a velocity of 4.0–5.5 km/s, is 2–5 km thick to the west of the summit and 1–2 km thick to the east, forming a dome-like shape below the summit. The third layer, with an upper surface velocity of 5.7 km/s has a dome-like shape slightly to the east of the summit; it is related to the part of the second layer that lies directly beneath the peak of the volcano and climbs upward on the east side of the volcano, corresponding to the thickness of the second layer. These structures reflect the formation of the crust within the special tectonic setting around Fuji volcano and the repeated intrusion of active magma from the deep crust.

Keywords: Fuji volcano, seismic structure, active-source seismic exploration, seismic refraction analysis

1. Introduction

Fuji volcano is the largest basaltic stratovolcano in Japan: its height is 3,776 m and the volume of the body of the mountain is about 400 km^3. Volcanic activity in the area of the volcano began approximately 80,000 years ago in the vicinity of Komitake volcano, forming the Older Fuji volcano. The Older Fuji volcano is currently covered by volcanic products that erupted from the Younger Fuji volcano, which first became active about 10,000 years ago. Although the eruption history can be divided into a period of eruption from the summit crater and a period of eruption from the flank area, flank eruptions on the northwest and southeast sides of the volcano have occurred repeatedly over time. Since the seventh century, 10 eruptions have occurred at intervals of about 120 years; however, the most recent event, the Hoei eruption, occurred 300 years ago in 1707.

Fuji volcano is exceptionally large compared to other volcanoes in Japan because its magma effusion rate is between two and 10 times greater than that of other stratovolcanos (Fujii, 2001). Moreover, most volcanoes in Japan are andesitic, being rich in silica and containing only a small proportion of basalt, if any. Fuji volcano, in contrast, is unique in that it is composed mainly of basalt (Tsuya, 1971). The volcano is located close to plate boundaries where the Philippine Sea Plate subducts beneath the North American and Eurasian Plates, and where the Izu Peninsula collides with mainland Japan. The complex structure of the crust and upper mantle around Fuji volcano creates a special tectonic setting that may

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influence the peculiar nature of volcanic activity from Fuji volcano. The task of deciphering the subsurface structure of this volcano and its surrounding area is of vital importance in understanding its volcanic activity. In the field of seismological research, several studies have been conducted on the seismic velocity structure. Nakamichi et al. (2007) clarified the 3-D seismic velocity structure around Mt. Fuji up to a depth of about 20 km using seismic tomography and found the low P-wave velocity and low Vp/Vs ratio zone. Using a receiver function analysis, Kinoshita et al. (2015) showed that there is a low-velocity region at a depth of 13–26 km. They also found a velocity contrast at 40–50 km. Tsutsui et al. (2007) identified several reflective surfaces from just below the summit to a depth of 15 km using artificial seismic survey data.

2. Outline of Observations

In 2003, from the end of August until the beginning of September, an artificial earthquake survey, based on the Sixth Prediction of Volcanic Eruption Plan of Japan, was performed focusing on Fuji volcano. The objectives of the survey were to: (1) determine the two-dimensional velocity structure across Fuji volcano from west-southwest to east-northeast, to about 10 km in depth, and (2) detect reflected and scattered waves from an anomalous region of seismic structure directly beneath the volcano, as well as estimate the distribution of the anomalous region. A detonation of 500 kg of dynamite (at 80 m depth) was used as the artificial earthquake source; explosions were carried out at the five sites indicated by crosses (S1, S2, S3, S4, and K1) in Fig. 1. Seismographs with an eigenfrequency of 2 Hz were used for the observations, as positioned along a transect connecting S1 and K1, and passing through the summit of the volcano; the total length of the transect was 87 km. 469 observation points were established with three-component seismometers installed at 60 of the sites. The intervals between observation points were about 250 m between S2 and S4 and approximately 500 m between S1 and S2 and between S4 and K1. On-site data were saved to data loggers. The sampling interval was 4 ms, and the explosions were conducted from 13:02 on September 11, 2003, at five-minute intervals. In November, a data-analysis team drawn from the authors analyzed the initial data.

3. Data

The seismic traces are arranged with the distance from S1 to the observation point on the vertical axis and

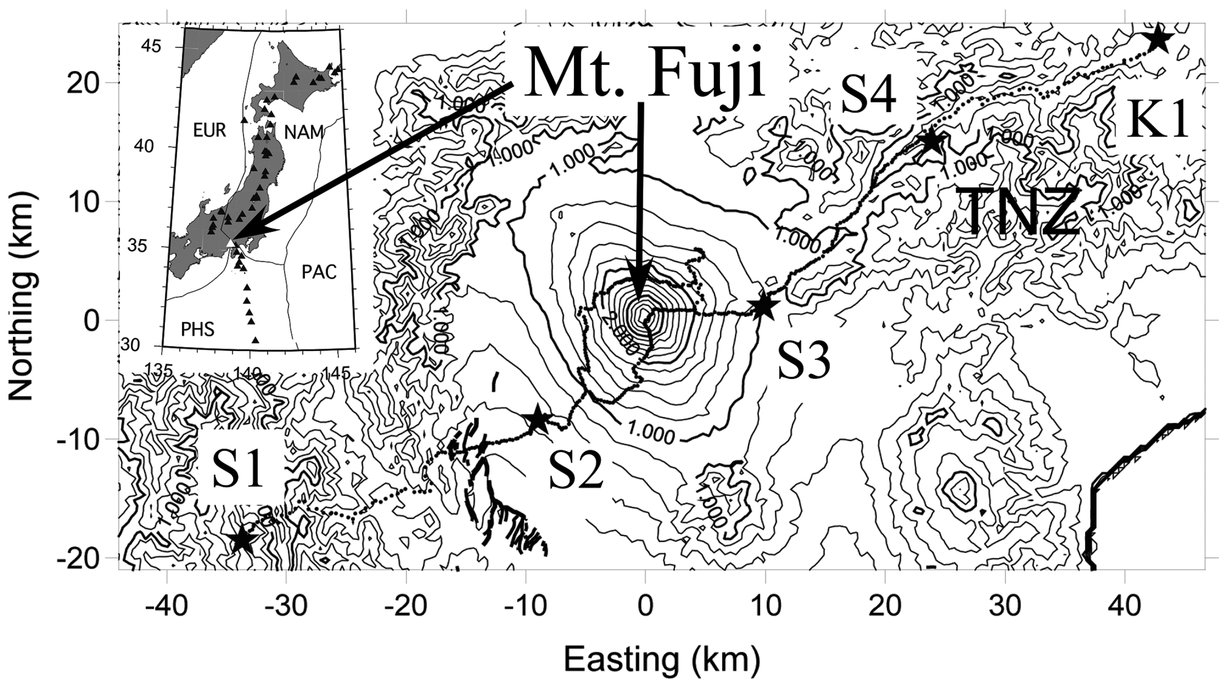


Fig. 1. Geographical configuration of the 2003 seismic exploration survey at Fuji volcano. Stars and dots indicate shot points and observation points, respectively. TNZ indicates Tanzawa Mountains. The origin is at the summit of Mt. Fuji (35.35688 N, 138.73487 E).

the travel time from the shot point on the horizontal axis (Fig. 2). The amplitude of each trace is normalized by its maximum value. The seismic wave appears to have disappeared on the way to K1; this is because the explosion was ineffective, producing a wave motion with only a small amplitude. The first motion was picked from these waveforms as basic data, based on the following criteria:

A rank: The initial motion is determined within ±10 ms, and the polarity is known.

B rank: The initial motion is determined within ±30, and the polarity is known.

C rank: The initial motion is determined within ±100, and the polarity is known.

D rank: The initial motion is determined within ±100, and the polarity is uncertain.

L rank: The initial motion is identified, but cannot be categorized in terms of ranks A–D.

X rank: The initial motion cannot be confirmed.

Travel-time plots corresponding to each explosion are shown in Figure 3 as a function of the distance from S1 (for rankings A–D). The number of data (rankings A–D) among the total of 469 observation points are 350 at S1, 229 at S2, 314 at S3, 378 at S4, and 89 at K1. Oikawa et al. (2007) summarizes coordinates of the active sources and temporary seismic sites and the hand-picked arrival times.

4. Analysis and Results

Initial motion data used were derived from a seismic refraction analysis to obtain the two-dimensional seismic velocity structure directly beneath a traverse line running across Fuji volcano from west-southwest to east-northeast. The slope of the time–distance curve in the vicinity of the shot points corresponded to the seismic velocity directly beneath the observation line; the seismic velocity was approximately 4 km/s near S1, S4, and K1, and 2.5 km/s near S2 and S3 (Fig. 3). The analysis was performed based on the following assumptions:

- the seismic velocity structure around Fuji volcano is assumed to be a layered system;
- the body of the mountain, including S2 and S3, is the first layer;
- the area including that directly beneath S1, S4, and K1 is the second layer;
- the remainder comprises the third and fourth layers.

First, the seismic velocity and depth of the upper surface of the second and third layers were estimated using the Time-term Method (Sheidegger and Willmore, 1957); other appropriate parameter values were used in assembling the initial model. Next, the theoretical travel time was calculated using ray tracing with a program developed by Zelt and Smith (1992). Here, the theoretical and observed travel times were compared, and the velocity structure was modified to correct for the difference. The calculation and correction of the theoretical travel time was repeated until the theoretical travel time was almost identical to the observation travel time. The P-wave velocity structure obtained with this forward modelling is shown in Fig. 4. Fig. 5 shows the theoretical ray path, theoretical travel time, and observed travel time for each shot based on the seismic velocity structure obtained in this study. The vertical axes show depth, while the horizontal axes show the distance from S1; the curves are theoretical ray paths. The vertical axes in the lower figures show travel time reduced to 6.0 km/s; the lines are observed values, with line lengths indicating the degree of error corresponding to the designated ranking; the points indicate the theoretical travel time. Finally, the inversion process of the program was applied. The P-wave velocity structure obtained in the inversion is shown in Fig. 6 and Fig. 7 shows the theoretical ray path, theoretical travel time, and observed travel time for each shot.

The characteristics of the P-wave velocity structures obtained with forward modelling and the inversion process are as follows.

(1) The first layer extends over a length of about 40 km, centered approximately on the summit of Fuji volcano, and with a thickness of 1–2 km. The P-wave velocity is 2.5 km/s for the upper surface of the layer (ground level) and 3.5 km/s for the lower surface.

(2) The P-wave velocity for the second layer is 4.0 km/s for the upper surface and 5.5 km/s for the lower surface. The thickness of the layer is 2–5 km on the west side of the volcano and just 1–2 km on the east side. The layer forms a dome-like shape, with a peak altitude of 2000 m directly below the summit.

(3) The third layer with a P-wave velocity of 5.7 km/s for the upper surface has a dome-like shape slightly to the east of the summit and is related to that part of the second layer that lies directly beneath the peak of the volcano. The layer rises slightly on the east side of the volcano, corresponding to the thick-

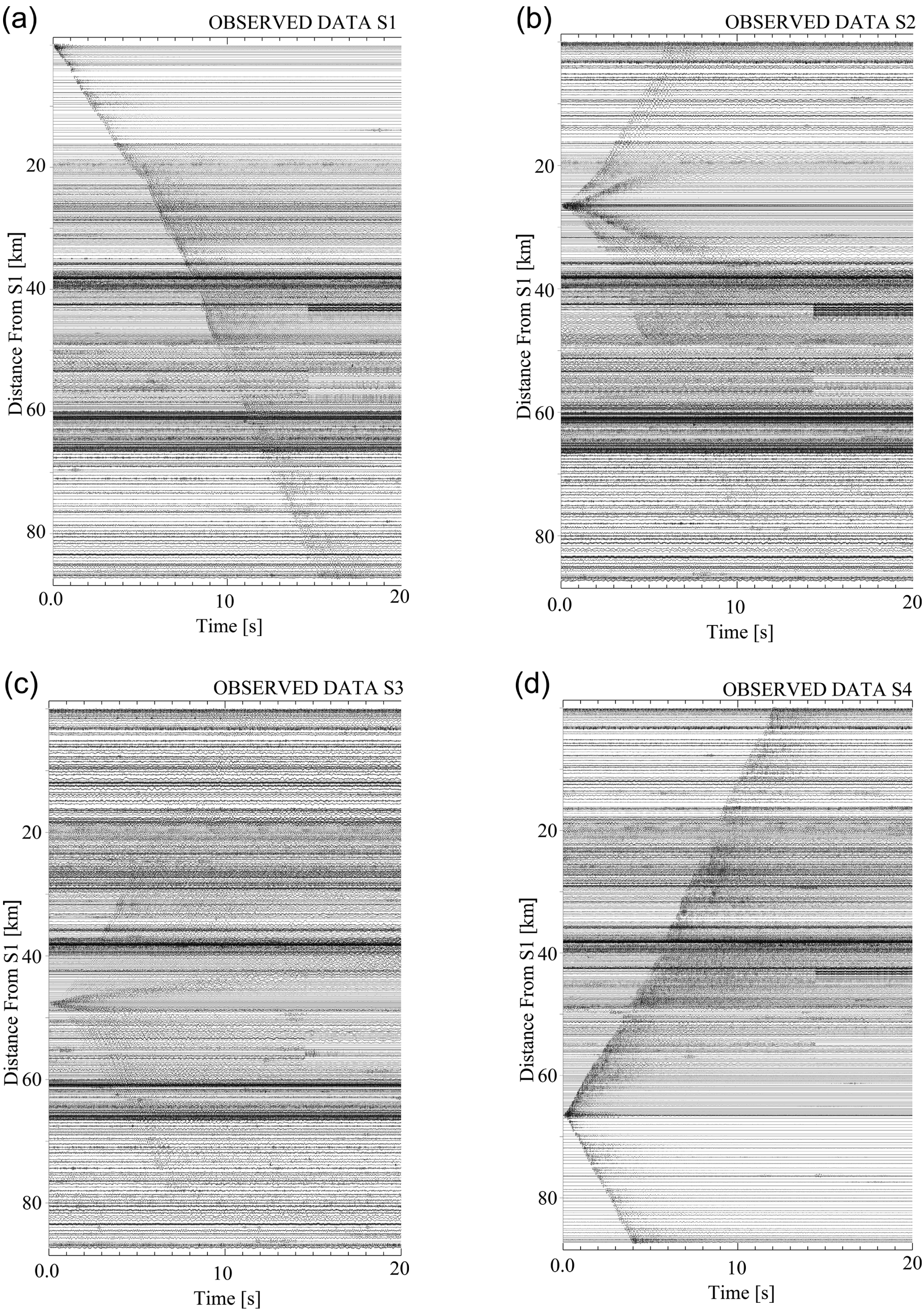


Fig. 2. Seismic traces along the observation line for (a) S1, (b) S2, (c) S3, (d) S4, and (e) K1. Vertical axis is distance from shot S1 and horizontal axis denotes travel time.

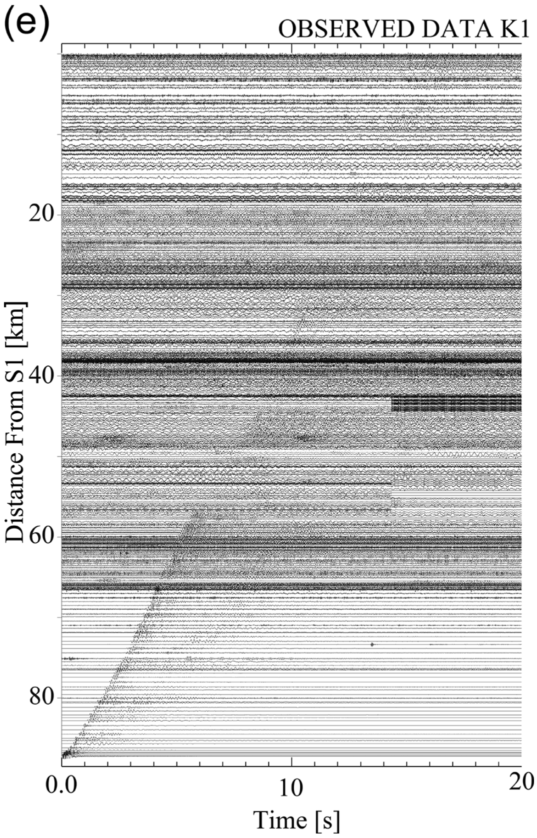


Fig. 2. Continued.

ness of the second layer.

A comparison of the theoretical travel times and the observation travel times of each shot shows them to be quite consistent, but with some small deviations. Among them, the deviation between 60 km and 70 km in S3 seems to be systematic and large. Compared to the structure, this deviation seems to correspond to the swelling of the third layer directly below, but the swelling is a necessary structure to explain the travel time due to other shots. It is possible that the actual ray path from S3 to the observation point between 60 km and 70 km passes through low-velocity layers and blocks that could not be represented in the assumptions of this study.

5. Discussion

The contrasting crustal structures observed on the east and west sides of Fuji volcano are consistent with the results of geological surveys and gravity data. In the vicinity of S4, on the east-northeast side of the volcano, the Tanzawa Mountains contain exposures of Tertiary tonalite-granite. At this site, it was expected that a high-density basal layer reaches ground level. Furthermore, a large positive gravity anomaly extends from this range to Fuji volcano, indicating a high-density area in the

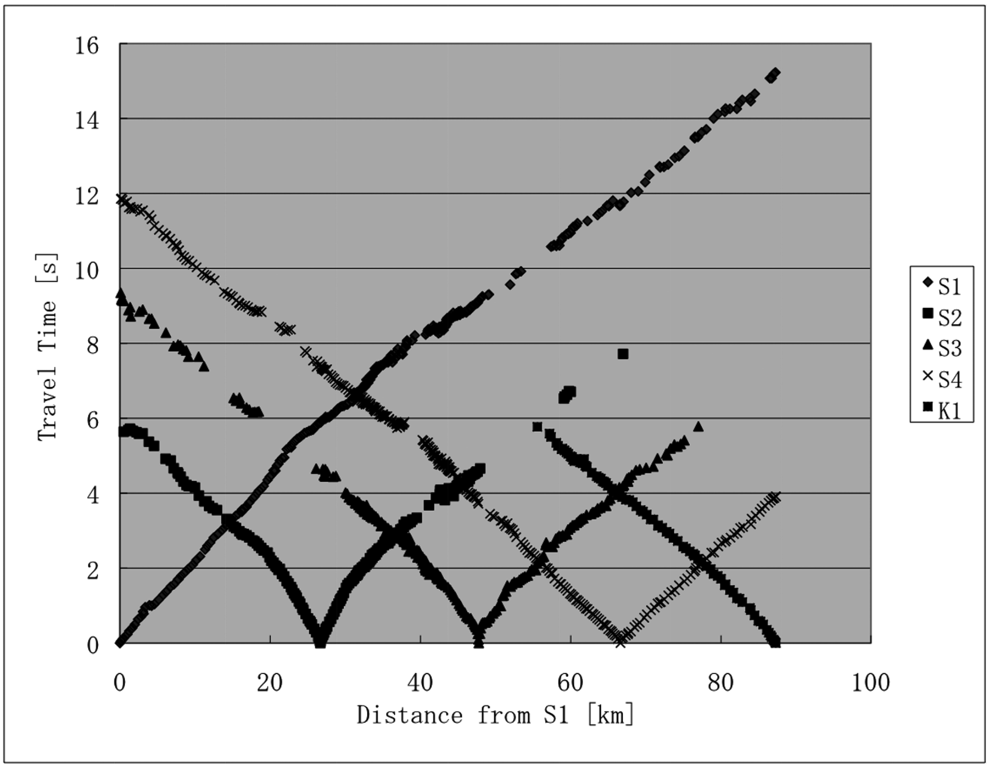


Fig. 3. Travel-time curves for all shots. Vertical axis indicates travel time and horizontal axis is distance from S1.

shallow subsurface (Komazawa, 2000; Komazawa, 2003). The results of the present study indicate that a layer with high seismic velocity has risen close to the surface on the east side of Fuji volcano, although qualitatively a high seismic velocity corresponds to high density. This means that the structure represented by the gravity anomaly was also identified as a seismic velocity structure.

The structure that consists of a layer with high seismic velocity and that rises to the east side of Fuji volcano is largely due to the process of crustal formation in the area around the volcano, especially on the east-northeast side. As noted in the Introduction, Fuji volcano is located slightly back from the site where the Philippine Sea Plate subducts beneath the Eurasian Plate and where the Izu Peninsula collides with the

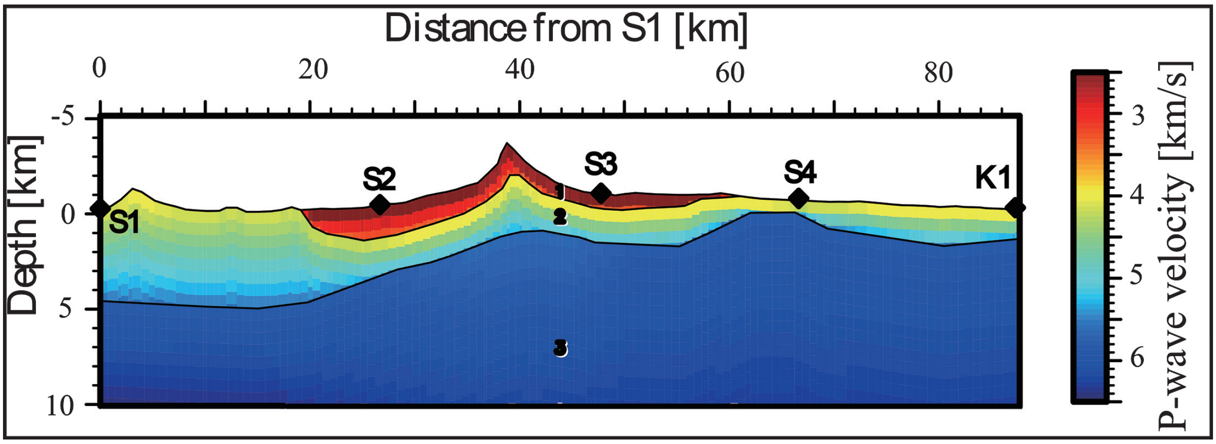


Fig. 4. Two-dimensional velocity structure obtained with forward modelling revealed by the 2003 seismic exploration survey at Fuji volcano. Vertical axis denotes depth below sea level and horizontal axis is distance from S1.

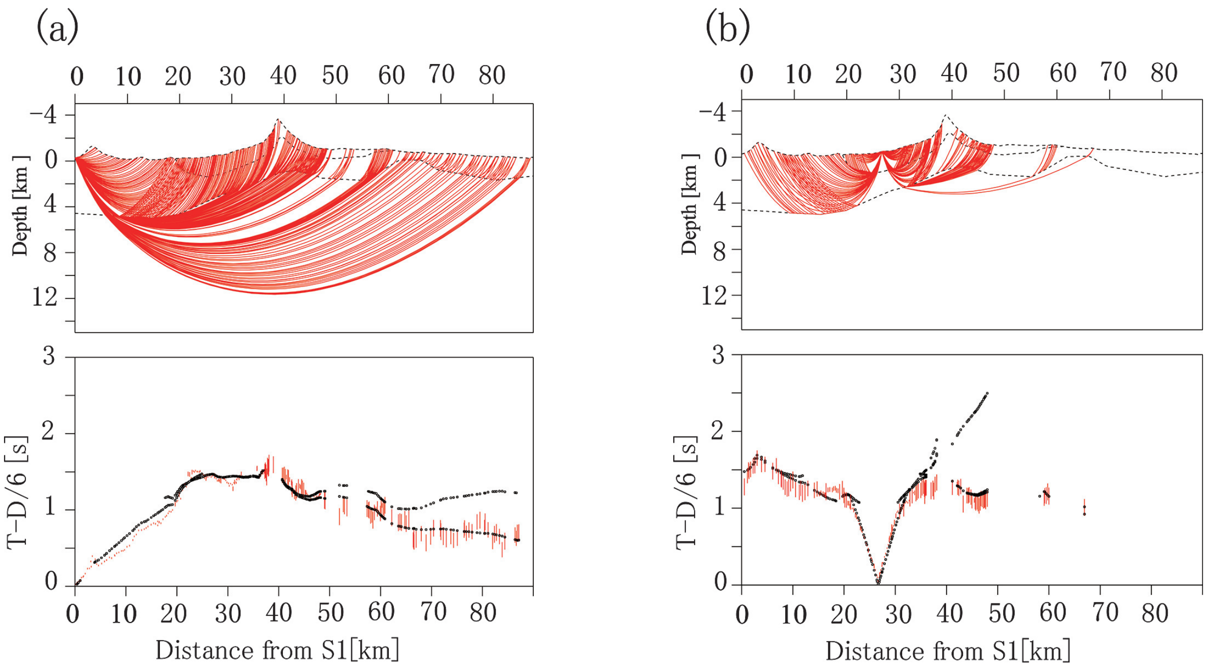
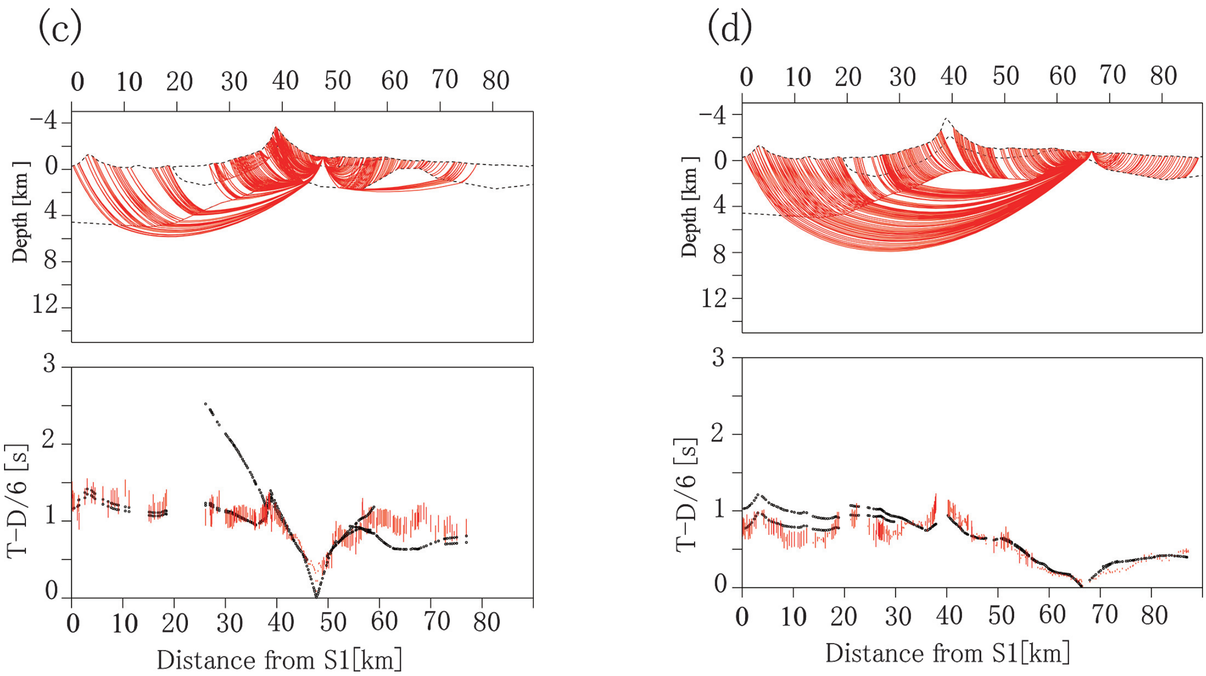


Fig. 5. Ray path diagrams (upper) and travel-time comparisons (lower) for (a) S1, (b) S2, (c) S3, (d) S4, and (e) K1 obtained with forward modelling. Vertical axes in ray path diagrams denote depth below sea level, and horizontal axes represent distance from S1. Curves are theoretical ray paths. Vertical axes in travel-time comparisons indicate travel time reduced to 6.0 km/s, and horizontal axes represent distance from S1. Observed data are indicated by vertical bars, the heights of which represent errors corresponding to the rank of the data. Travel times associated with ray traces are indicated by dots.



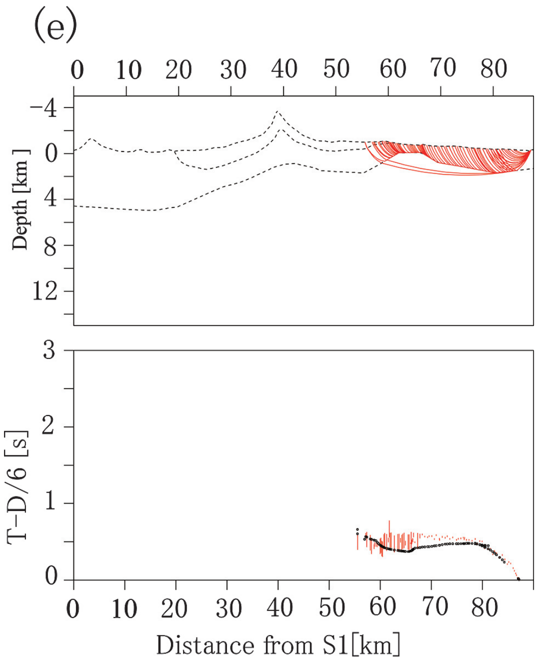


Fig. 5. Continued.

Japanese mainland (e. g., Nakamura, 1989). Matsuda (1962) suggests that Fuji volcano lies on the same uplifted body as the Tanzawa Mountains to the east, which is formed by a subduction-related collision with the Izu Peninsula. It is presumed that these led to the uplift of the high-velocity bedrock layer.

The dome-like structure of the base of the second and third layers appears directly beneath the volcano's summit and reaches an altitude of approximately 2,000 m. Similar dome-like geometries have been reported from directly beneath other volcanoes such as Iwate volcano (Tanaka et al., 2002) and Bandai volcano (Yamawaki et al., 2004). Such dome-like structures are considered to result from the accumulation and solidification of magma as it repeatedly intrudes from the deep crust to shallow levels throughout the duration of volcanic activity. In other words, the dome-like shape of the base represents the magma feeder system directly beneath Fuji volcano. This can be considered to be a structure that corresponds to the early activity of the volcano, leading to the subsequent formation of Komitake volcano, Old Fuji volcano, and the present-day Fuji volcano.

6. Conclusion

An artificial earthquake survey undertaken along a transect line crossing Fuji volcano from west-southwest to east-northeast reveals the following structure, assuming a layered system beneath the volcano.

(1) The first layer extends about 40 km around the summit area of the volcano. It has a thickness of 1–2 km, and a P-wave velocity of approximately 2.5 km/s on the upper surface and 3.5 km/s on the lower surface.

(2) The second layer has a P-wave velocity of 4.0 km/s

on the upper surface and 5.5 km/s on the lower surface, with a thickness of 2–5 km on the west side of the volcano and just 1–2 km on the east. Furthermore, a dome-like structure centered beneath the summit area attains an altitude of 2,000 m.

(3) The third layer with a P-wave velocity of 5.7 km/s on the upper surface has a dome-like shape slightly to the east of the summit; it is related to the part of the second layer that lies directly beneath the peak of the volcano and climbs upward on the east side of the volcano, corresponding to the thickness of the second layer.

These structures reflect crustal formation within the active tectonic setting around Fuji volcano and an active supply of magma from the deep crust.

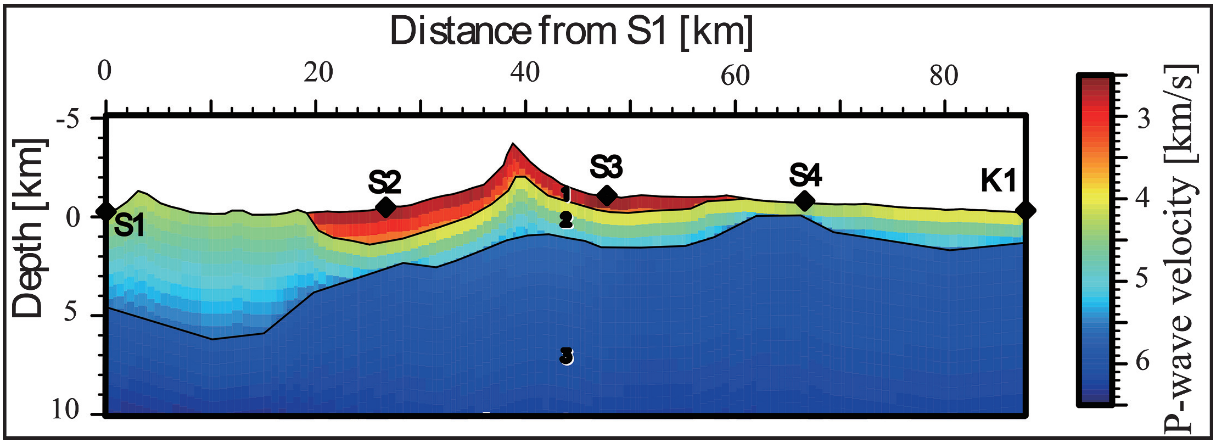


Fig. 6. Two-dimensional velocity structure obtained in the inversion of travel times revealed by the 2003 seismic exploration survey at Fuji volcano. Vertical axis denotes depth below sea level and horizontal axis is distance from S1.

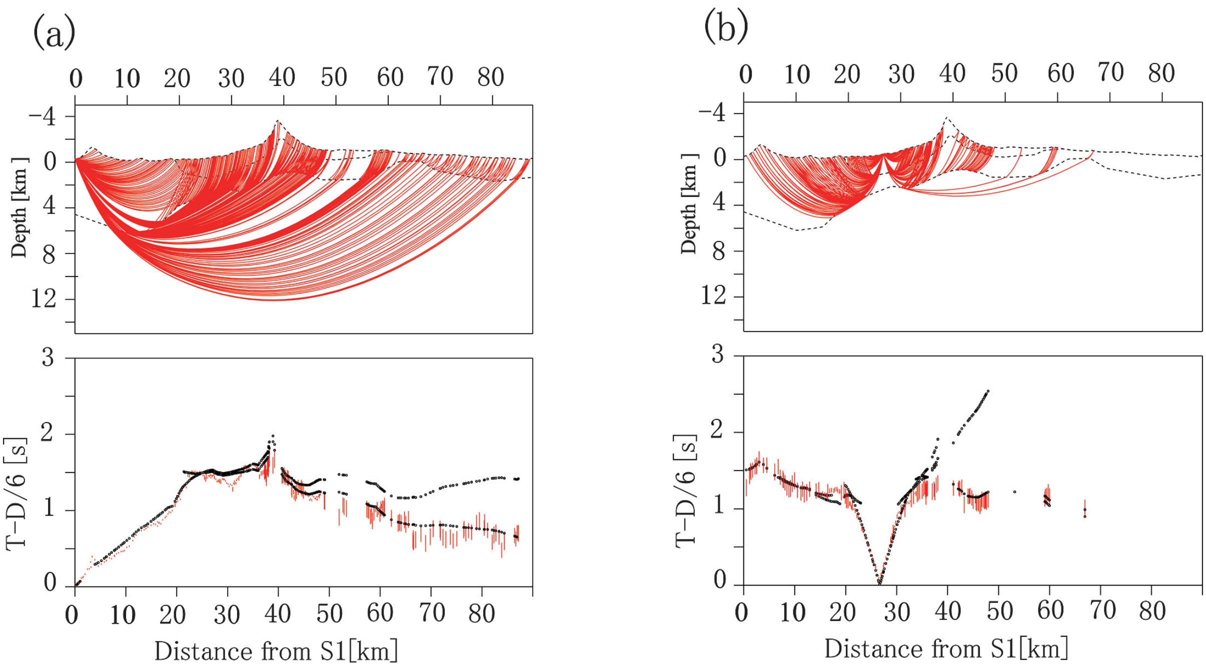
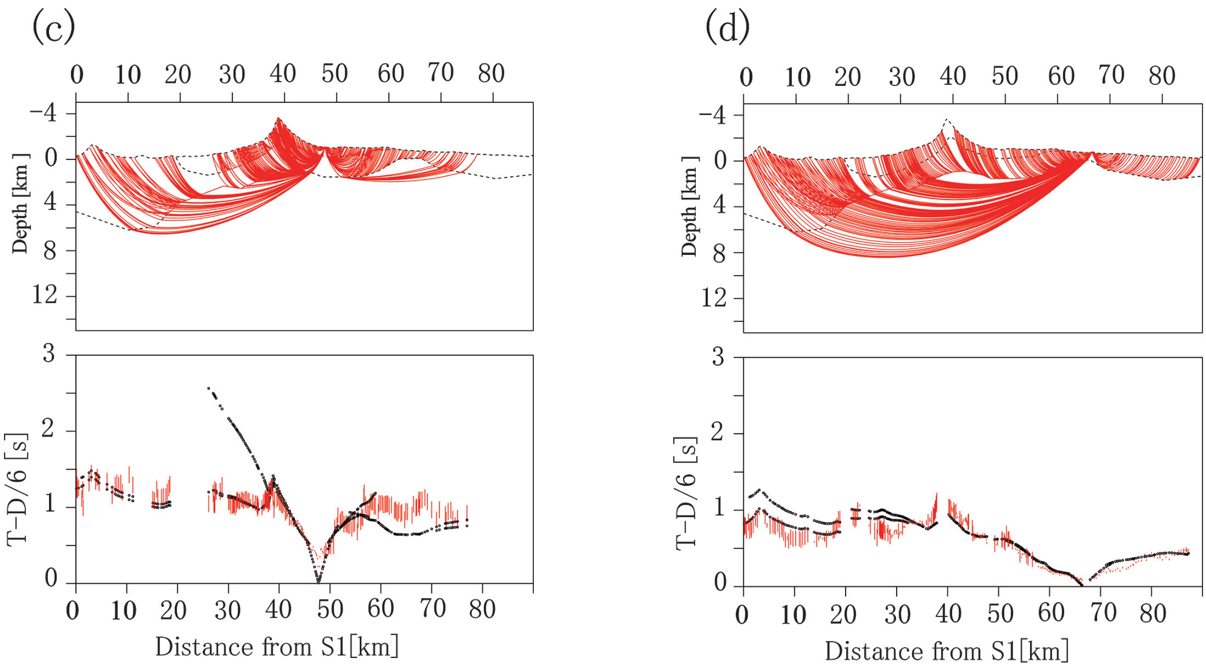


Fig. 7. Ray path diagrams (upper) and travel-time comparisons (lower) for (a) S1, (b) S2, (c) S3, (d) S4, and (e) K1 in the inversion of travel times. Vertical axes in ray path diagrams denote depth below sea level, and horizontal axes represent distance from S1. Curves are theoretical ray paths. Vertical axes in travel-time comparisons indicate travel time reduced to 6.0 km/s, and horizontal axes represent distance from S1. Observed data are indicated by vertical bars, the heights of which represent errors corresponding to the rank of the data. Travel times associated with ray traces are indicated by dots.



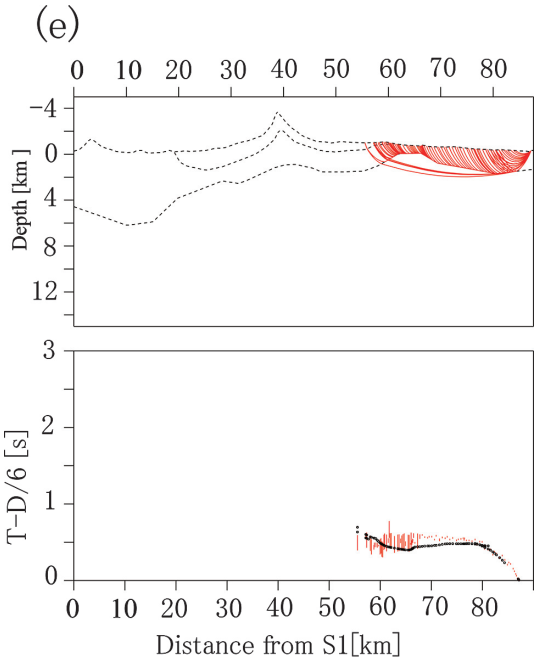


Fig. 7. Continued.

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