

Precise hypocenter locations of midcrustal low-frequency earthquakes beneath Mt. Fuji, Japan

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Midcrustal low-frequency earthquakes (MLFs) have been observed at seismic stations around Mt. Fuji, Japan. In September–December 2000 and April–May 2001, abnormally high numbers of MLFs occurred. We located hypocenters for the 80 MLFs during 1998–2003 by using the hypoDD earthquake location program (Waldhauser and Ellsworth, 2000). The MLF hypocenters define an ellipsoidal volume some 5 km in diameter ranging from 11 to 16 km in focal depth. This volume is centered 3 km northeast of the summit and its long axis is directed NW-SE. The direction of the axis coincides with the major axis of tectonic compression around Mt. Fuji. The center of the MLF epicenters gradually migrated upward and 2–3 km from southeast to northwest during 1998–2001. We interpret that the hypocentral migration of MLFs reflects magma movement associated with a NW-SE oriented dike beneath Mt. Fuji.

Key words: Low-frequency earthquake, hypocenter, focal mechanism, Fuji.

1. Introduction

Low-frequency (LF) earthquakes have been commonly observed at many volcanoes. Most of them originate at depths less than 3 km and are associated with magma migration and magmatic interactions with hydrothermal systems. LF earthquakes have been observed at mid to lower crustal depths and in the uppermost mantle beneath volcanoes (Hasegawa *et al.*, 1991; Pitt and Hill, 1994). Although these LF earthquakes indicate deep magmatic activity, quite a few of them seem to have occurred independently of volcanic eruptions or other signs of unrest. In some cases, however, occurrence of LF earthquakes have also been found to correlate with volcanic activity, for example, CO₂ emissions (Hill, 1996), shallow high-frequency (HF) earthquakes (Nakamichi *et al.*, 2003) and eruptions (White, 1996). Therefore, LF earthquakes are useful for evaluating volcanic subsurface activity and must be investigated.

Mt. Fuji, the most famous active basaltic stratovolcano in Japan (Fig. 1), has experienced major historical eruptions in 781, 800–801, 826, 864–865, 937, 999, 1033, 1083 and 1707 (Tsuya, 1971). It has not erupted about 300 years since the 1707 Hiei Eruption. Mt. Fuji has a larger eruption rate than most other island-arc volcanoes by one order of magnitude (Fujii, 2001). Mt. Fuji has erupted mostly basaltic products, although it is an island-arc type volcano (Tsuya, 1971). These features may be due to the unique

tectonic setting of Mt. Fuji, which is located near three converging plates, the Eurasia (EUR), North American (NAM) and Philippine Sea (PHS) plates (Fig. 1). The region around Mt. Fuji is a zone of crustal collision where the Izu block (Izu Peninsula) collides with the Honshu block (EUR and NAM), which pushes in the NW direction. More than half of the parasitic craters of Mt. Fuji are located on the NW and SE flanks of Mt. Fuji, which is manifested by numerous magmatic-dikes running parallel in the NW-SE direction (Tsuya, 1971). This direction is strongly related and influenced to regional stress field (Nakamura, 1977).

Seismic observations around Mt. Fuji have been conducted since the 1980s by the Earthquake Research Institute, University of Tokyo (ERI), the National Research Institute for Earth Science and Disaster Prevention (NIED) and the Japan Meteorological Agency (JMA) (Fig. 1). No intense seismic activity or remarkable crustal deformation has been observed around Mt. Fuji before 2000. However, midcrustal low-frequency earthquakes (MLFs) have been detected at Mt. Fuji since the early 1980s (Kanjo *et al.*, 1984; Ukawa and Ohtake, 1984; Shimozuru *et al.*, 1986). About 700 MLFs occurred beneath Mt. Fuji, mainly in two periods during September–December 2000 and April–May 2001. In these periods, the occurrence rate of MLFs was 20–70 per month, which is ten times higher than the background level (Ukawa, 2003). Besides the extremely high occurrence rate of the MLFs, there was no accompanying or following unusual shallow seismic activity or crustal deformation around Mt. Fuji (Ukawa, 2003). Therefore, the MLFs are the only information we have to infer magmatic activity beneath Mt. Fuji.

Precise hypocentral locations and focal mechanisms allow us to interpret the volcanic process that generates MLFs beneath Mt. Fuji. In this paper, we precisely locate the

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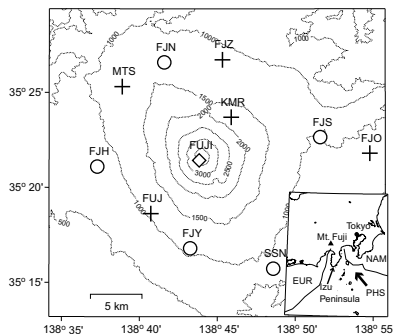


Fig. 1. Location map showing the seismic stations near Mt. Fuji and the location of Mt. Fuji (inset map). The solid lines in the inset map indicate plate boundaries. EUR, NAM and PHS represent the Eurasian, Northern American and Philippine Sea plates, respectively. The plate boundary between EUR and NAM is not shown, because the boundary is under debate. The thick arrow indicates the direction of Philippine Sea plate motion. We use the data from 58 seismic stations within 100 km from Mt. Fuji. Stations within 15 km from the summit are shown. Dotted lines show elevation contours at 500 m intervals. Crosses: permanent stations maintained by ERI; Diamond: station in the Mount Fuji Weather Station on the summit maintained since 1987 by JMA; Open circles: stations maintained by NIED. Stations FJH, FJN, FJS and FJY have borehole type tiltmeters and seismometers installed at 200 m depth. All stations are equipped with three-component short-period seismometers.

hypocenters of the MLFs during 1998–2003, combining the seismograms independently recorded by NIED, ERI and JMA.

2. Data and Analysis

Figure 2(a) shows three-component seismograms of a MLF event on April 30, 2001, which is the largest event we have observed since 1990. Seismograms of MLFs differ from the much more common broadband signature of HF earthquakes (see Fig. 2(b)) in their relatively low energy at frequencies above 5 Hz and their ringing coda. Their onsets are sometimes impulsive with relatively clear P and S phases, unlike those of shallow LFs, but are more commonly rather emergent. P and S waves of the MLFs are often associated with high-frequency (> 5 Hz) waves at close stations (e.g., FJN, FJY and FJH). An additional feature of the MLFs was their unusual tendency to occur in swarm in which the largest events occurred between the middle and end of the sequence.

Each organization has routinely located MLFs using its own seismic network. We firstly combined data of the three organizations collected during 1998–2003, picked up arrival times of MLFs with careful identification of phases and determined their hypocenters precisely. We limited the arrival time data to stations with epicentral distance smaller than 100 km. The number of events with an acceptable signal-to-noise ratio was 80, about 16% of all events in the MLFs catalog routinely obtained by NIED for this time period. We carefully measured the arrival times of P and S phases of MLFs on the three-component seismograms and obtained 1744 P and 2424 S picks. We repeated the repick procedure several times in a short time to reduce bias of reading the arrival times. The reading accuracies of P and S wave arrival times are better than 0.20 s.

We relocated the selected 80 MLFs that occurred during

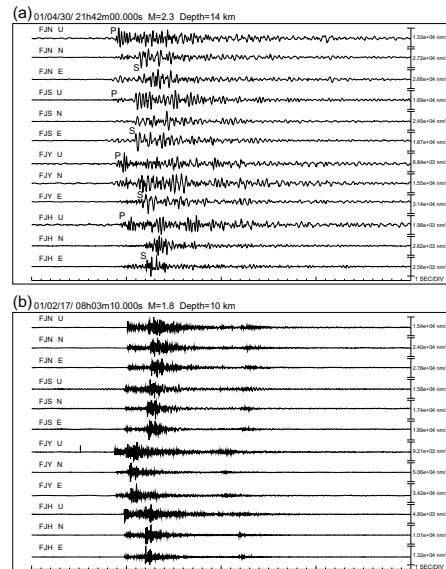


Fig. 2. (a) Three-component waveforms for the MLF event at 21:42 Japan standard time (JST) on April 30, 2001. This MLF has the best signal-to-noise ratio and clearest P and S waves of those recorded since 1998. U, N and E: vertical, north-south and east-west components. (b) Three-component waveforms for the high-frequency (HF) event at 8:03 JST on February 17, 2001. This HF event occurred beneath the south flank of Mt. Fuji.

Table 1. Velocity structure used for hypocenter determination.

Depth (km)	V_P (km/s)	V_S (km/s)
0–4	5.50	3.18
4–15	6.10	3.53
15–32	6.70	3.87
32–	8.00	4.62

1998–2003 beneath Mt. Fuji, using the hypoDD earthquake location program of Waldhauser and Ellsworth (2000) and the arrival time readings. The hypoDD program minimizes the residuals between observed and calculated travel time differences for pairs of earthquakes at common stations by iteratively adjusting the hypocenters. Thus, the hypoDD program minimizes the effects of unknown earth structure without the need for station corrections. We obtain travel-time differences for each event pair with a separation distance less than 4 km at stations located within 100 km of the cluster centroid. Travel-time differences were weighted based on the quality of the arrival time picks. RMS travel-time residuals for the used stations are between 0.08 s and 0.36 s and the average is 0.21 s. The velocity structure used for the hypocenter relocation is shown in Table 1. We also calculate hypocenters using several velocity structures with low velocity top layers for considering volcanic surface structure. No significant (over 1 km) difference of the hypocenter distribution between the velocity structures.

We also estimate the source mechanism of the largest MLF event (see Fig. 2(a)) using body-wave ratio method (Nakamichi *et al.*, 2003). 21 P wave polarities and 10 SH/P amplitude ratios are used for the source mechanism estimation. The obtained source mechanism is shown in Fig. 3.

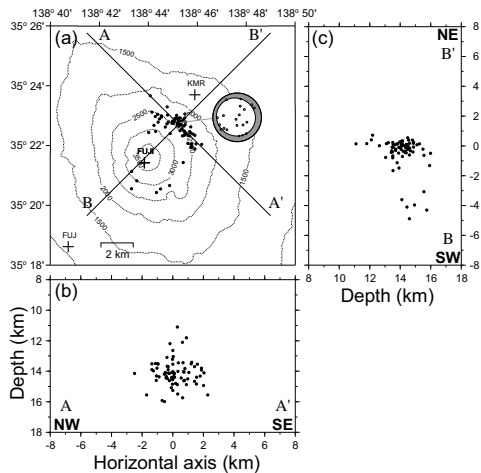


Fig. 3. Hypocentral distributions of the MLFs, as determined by the hypoDD program. (a) Map view of relocated hypocenters. The source mechanism of the largest MLF (M2.3) is also shown. Lower focal hemisphere is shown in equal-area projection, with compressional fields shaded. Open circles on the source mechanism indicate inward motion. (b) Cross-section A-A' in (a). (c) Cross-section B-B' in (a). Cross-sections A-A' and B-B' include earthquake hypocenters projected from 10 km on either side of the cross-section line.

3. Location Results

The resulting distribution of hypocenters of the MLFs (Fig. 3) has several striking features. Hypocenters of the MLFs occupy an ellipsoidal volume roughly 5 km in diameter with its center offset 3 km to the northeast of the summit of Mt. Fuji. The long axis of the volume is oriented NW-SE. The relocated hypocenters are mainly aligned on a 1 km thick vertical disk with an elliptical shape at depths of 11–16 km. The relative error ranges of the hypocenters relocated here are from 100 to 500 m horizontally and from 200 to 700 m vertically obtained from Monte Carlo numerical simulations with the presumed errors in reading travel-times. No elongated structure in the direction of the observed NW-SE strike is observed in the simulations, indicating that the observed strike is not an artifact of the relocation procedure. The extent of this depth range is also supported by the spread in *S-P* readings for individual earthquakes. *S-P* arrival time differences for well-recorded MLFs at station KMR range from 1.9 to 2.4 s, verifying that MLFs beneath Mt. Fuji span a depth range of at least 4 km, and are not confined to a very small volume.

We compared the hypocenters located in this study with the hypocenters of the same MLFs used for the relocations, routinely obtained by NIED (Ukawa, 2001), and observed a clear improvement in the location accuracy with the procedure in this study (Fig. 4). The hypocenters of MLFs by NIED are distributed in a larger volume and not along a particular plane. The hypocenters of MLFs in this study are much more concentrated and are located in a NW-SE direction. The focal depths of MLFs obtained by NIED range from 10–20 km, while the depths obtained in this study range from 11–16 km. Therefore, good station distribution and careful picking arrival times of phases are effective for accurate location of MLFs, as well as selection of clear events.

Figure 5 shows the spatial and temporal variations of

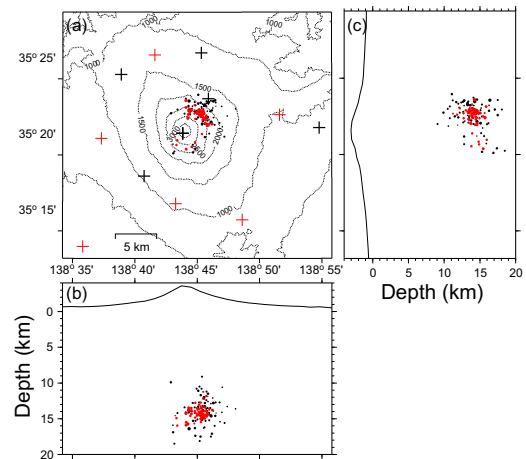


Fig. 4. Comparison between the hypocenters of the MLFs by this study (red circles) and the routine processing at NIED (black circles). (a) Map view of hypocenters. (b) Cross-section of E-W. (c) Cross-section of N-S.

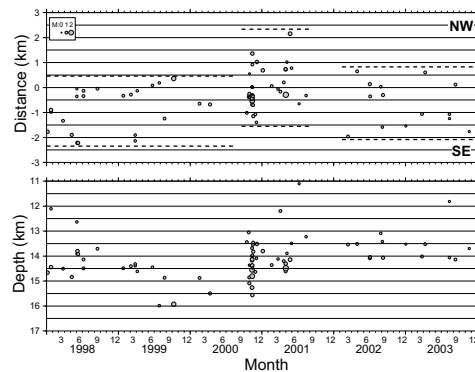


Fig. 5. Spatial and temporal variations of the hypocenters of MLFs. (a) NW-SE horizontal locations. The origin is the cross point of A-A' and B-B' in Fig. 3. (b) Focal depths.

MLFs in (a) NW-SE-vs-time and (b) depth-vs-time plots. A potentially significant observation is a temporal change in earthquake locations. The locations of MLFs in the active period during 2000–2001 are shifted 2–3 km northwest from those located in 1998–1999 and 2002–2003. This is supported by the fact that the *S-P* arrival time differences at FJN, which is located on the northwest flank of Mt. Fuji, are about 0.3 s shorter in 2000–2001 than those in 1998–1999 and 2002–2003. The temporal variation in depth is somewhat complex. The focal depths of MLFs in 1998–1999 were 12–16 km and seemed to move deeper gradually. MLFs in the active periods of September–December 2000 and April–May 2001 occurred in the depths of 13–15.5 and 12–14.5 km, respectively. The focal depths of MLFs in 2002–2003 were at 12–14 km. This depth variation is supported by the fact that *S-P* arrival time differences vary within 0.5 s at KMR, which is located just above the focal region of MLFs. As suggested for the cases of migration of hypocenters of LF earthquakes at Mt. Iwate, Japan (Nakamichi *et al.*, 2003), here the migration of hypocenters of the MLFs is considered to be a manifestation of recharge and migration of magma and/or readjustments of stress to magma movement around the hypocentral region.

4. Discussion

The long axis of the hypocentral volume of MLFs is oriented NW-SE, which coincides with the orientation of flank craters on the slopes of Mt. Fuji (Tsuya, 1971). The distribution of flank craters generally agrees with the preferred direction of dikes, which are controlled by the maximum compressional stress axis (Nakamura, 1977). The maximum compressional stress axis around Mt. Fuji directs NW-SE (Ukawa, 1991). The coincidence of the orientation of MLF hypocenter distribution and the flank craters suggests that both phenomena relate to dike-intrusion processes.

Although the source model of the MLF has not been established, it is reasonable to consider that the MLF is closely related to magma activity because of the proximity in swarm locations. Tomographic images of *P* and *S* waves indicate a low velocity zone below 25 km beneath the Mt. Fuji (Lees and Ukawa, 1992). A large low electro resistive anomaly exists beneath Mt. Fuji at depths greater than 20 km (Aizawa *et al.*, 2004). These results show a possible location of major magma reservoir beneath the source region of MLFs. The hypocenter zone of the MLFs is located above the low velocity and resistive zone. We speculate that the upward movement of magma causes the MLFs.

The source mechanism solution of the largest MLF (M2.3) is obtained (Fig. 3). All the measured *P* wave polarities are compressive and their distribution is not explained by a double-couple solution. The moment tensor of the mechanism is decomposed (Knopoff and Randall, 1970) and has a large CLVD (72%) and volumetric (21%) components, and a small double-couple (7%) component, indicating that MLFs could be caused by magmatic fluid.

As we do not have enough data for estimating the focal mechanisms of other MLFs, we obtained *SH/P* amplitude ratios of several stations for five MLFs with corrections for free surface and attenuation effects in order to further discuss the source mechanisms of MLFs. Most amplitude ratios are between 1 and 4 and the average amplitude ratios are 1.7 to 2.8, suggesting a difference from the focal-sphere averages for single-force (4.2) or double-couple (6.4) mechanisms with a Poisson solid, although these mechanisms are not completely excluded.

One of the characteristics of the MLF events at Mt. Fuji is the variety of focal processes estimated from the range of *SH/P* amplitude ratios. The amplitude ratios at stations for five events range from 1 to 4, indicating a wide difference in source processes. From a cross-correlation analysis of MLFs and the amplitude ratios, we conclude that the MLFs cannot be characterized as earthquake families, even though the MLFs are clustered in a region of approximately 2 km in radius as described before. This indicates that a complex process occurs within a small region beneath Mt. Fuji.

5. Conclusions

We have determined the hypocenter locations of MLFs using the hypoDD program and repicked arrival times from the seismic networks of ERI, JMA and NIED in and around Mt. Fuji between 1998 and 2003 including the active periods from September 2000 to May 2001. The main results are summarized as: (1) Hypocenters of MLFs define an ellipsoidal volume, 5 km in diameter ranging from 11 to 16

km in focal depth. (2) This volume is centered at 3 km northeast of the summit and its long axis is oriented NW-SE. This orientation coincides with the major axis orientation of tectonic compression around Mt. Fuji. (3) The center of the MLF epicenters migrated upward and 2–3 km from SE to NW in 1998–2001.

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References

- Aizawa, K., R. Yoshimura, and N. Oshiman, Splitting of the Philippine Sea Plate and a magma chamber beneath Mt. Fuji, *Geophys. Res. Lett.*, **31**, L09603, doi:10.1029/2004GL019477, 2004.
- Fujii, T., Detecting the activity of Mt. Fuji, *Kagaku*, **71**, 1595–1600, 2001 (in Japanese).
- Hasegawa, A., D. Zhao, S. Hori, A. Yamamoto, and S. Horiuchi, Deep structure of the northeastern Japan arc and its relationship to seismic and volcanic activity, *Nature*, **352**, 683–689, 1991.
- Hill, D. P., Earthquakes and carbon dioxide beneath Mammoth mountain, California, *Seismol. Res. Lett.*, **67**, 8–15, 1996.
- Kanjo, K., I. Karakama, and R. S. Matsuura, Seismic activities of Mt. Fuji region detected by continuous observation of micro-earthquakes, *J. Phys. Earth*, **32**, 463–468, 1984.
- Knopoff, L. and M. J. Randall, The compensated linear-vector dipole: A possible mechanism for deep earthquakes, *J. Geophys. Res.*, **75**, 4957–4963, 1970.
- Lees, J. M. and M. Ukawa, The south Fossa Magna, Japan, revealed by high-resolution P- and S-wave travel time tomography, *Tectonophysics*, **207**, 377–396, 1992.
- Nakamichi, H., H. Hamaguchi, S. Tanaka, S. Ueki, T. Nishimura, and A. Hasegawa, Source mechanisms of deep and intermediate-depth low-frequency earthquakes beneath Iwate volcano, northeastern Japan, *Geophys. J. Int.*, **154**, 811–828, 2003.
- Nakamura, K., Volcanoes as possible indicators of tectonic stress orientation—principle and proposal, *J. Volcanol. Geotherm. Res.*, **2**, 1–16, 1977.
- Pitt, A. M. and D. P. Hill, Long-period earthquakes in the Long Valley Caldera region, eastern California, *Geophys. Res. Lett.*, **21**, 1679–1682, 1994.
- Shimozuru, D., N. Osada, and T. Miyazaki, Seismic and tilt monitoring of Mount Fuji during the period from October 1982 to December 1984, *Bull. Earthq. Res. Inst.*, **61**, 587–613, 1986 (in Japanese with English abstract).
- Tsuya, H., Topography and geology of volcano Mt. Fuji, Results of the co-operative scientific survey of Mt. Fuji, Fuji Kyuko Co. Ltd., Tokyo, 1971 (in Japanese with English abstract).
- Ukawa, M., Collision and fan-shaped compressional stress pattern in the Izu block at the northern edge of the Philippine Sea plate, *J. Geophys. Res.*, **96**, 713–728, 1991.
- Ukawa, M., Low-frequency earthquakes, forecasting and disaster mitigation of eruption of Mt. Fuji, *Chikyu Monthly*, **23**, 784–790, 2001 (in Japanese).
- Ukawa, M., Activity of Fuji volcano, Reports on volcanic activities and volcanological studies in Japan for the period from 1999 to 2002, 18–22, 2003.
- Ukawa, M. and M. Ohtake, Peculiar microearthquake activity just beneath Mt. Fuji, *Zisin*, **37**, 129–133, 1984 (in Japanese).
- Waldhauser, F. and W. L. Ellsworth, A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am.*, **90**, 1353–1368, 2000.
- White, R. A., Precursory deep long-period earthquakes at Mount Pinatubo: Spatio-temporal link to a basalt trigger, in *Fire and Mud Eruptions and Lahars of Mount Pinatubo, Philippines*, edited by C. G. Newhall and R. S. Punongbayan, Philippine Institute of Volcanology, 1996.