Short Communication

P-wave velocity structure beneath Asama Volcano, Japan, inferred from active source seismic experiment

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1. Introduction

A volcanic eruption is an ejection of magma transported from depth. How magma is transported from depth to the surface is thus one of the fundamental questions to understand how a volcano works. One of the effective ways to address this question is to image the magma pathway through geophysical monitoring including 1) precise earthquake relocations, 2) modeling geodetic data, and 3) exploring subsurface structure and ground deformation. The solidification of magma due to repeated intrusions is responsible for the high velocity. This thus endorses the magma pathway previously speculated by seismic and geodetic observations. These findings demonstrate that dense seismic exploration combined with geophysical monitoring is an effective way to understand the dynamics of volcanic eruptions.
related to subsurface structure. To meet this goal, we conducted a seismic exploration in October, 2006, with artificial sources and densely deployed seismometers by taking advantage of known locations and origin time of artificial sources.

2. Active seismic experiment

The seismic exploration is conducted by five dynamite sources of 250–300 kg and 464 temporary 2-Hz seismometers (Mark Products L22D) with an average spacing of approximately 150 m (Fig. 1b). Table 1 describes information on the active sources. To delineate seismic velocity structure around an area of dike intrusion during the 2004 eruptions, we constructed two lines of seismometers striking roughly north–south and east–west, respectively (Fig. 1b), crossing the area of dike intrusion. In addition, several arrays are constructed around the edifice (Fig. 1b) to observe scattered waves likely from the edifice. We do not discuss the data from these arrays here. It will be discussed elsewhere.

Precisely relocated earthquakes and geodetic modeling from dense monitoring network in Asama enabled us to gain some insights into the dynamics of magma transport beneath Asama Volcano by understanding how the magma pathway derived from geophysical monitoring is

Table 1

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<th>Shot</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Altitude (m)</th>
<th>Depth (m)</th>
<th>Date</th>
<th>Time</th>
<th>Charge (kg)</th>
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</table>

Fig. 1. (a) Tectonic setting around Asama Volcano. Plate boundary and active volcanoes are represented by solid lines and gray triangles, respectively. Asama Volcano is shown by a black triangle. PAC stands for the Pacific plate which subducts beneath Asama Volcano. Direction of plate convergence is also shown. (b) Spatial distribution of active sources (red stars) and seismometers (black dots). The summit of Asama Volcano is shown by a green triangle. Bouguer gravity anomaly with a reduction density of 2670 kg/m$^3$ (Geological Survey of Japan, 2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. P-wave velocity structure

As a first step to delineate the shallow subsurface P-wave velocity structure of the volcano, we manually picked the first arrivals of each trace. First, each author independently inspected all the traces to pick the arrival times manually, then meteo classify the first arrivals into five classes, A, B, C, D, and E, respectively, according to the accuracy of picking, where A, B, C, and D refer to the ones with picking errors of less than 0.01, 0.01–0.03, 0.03–0.1, and 0.1–0.2 s, respectively, and E refers to the ones unable to pick first arrivals within 0.2 s. Of the five classes, we left the picks of classes A, B, and C for the further analysis, resulting in a total of 346 picks along the north–south profile and 299 picks along the east–west profile, respectively. Then, we constructed P-wave velocity models to be consistent with first arrivals in each trace first by a forward modeling (Zelt and Smith, 1992) and then applying a regularized inversion of the travel times with the initial model obtained through the previous forward modeling (Zelt and Barton, 1998). The forward modeling before the inversion is required in this case because a small number of shots (only three shots per profile; see Fig. 1b) does not allow convergence to the optimum
solution in the inversion from a bad initial model. Fig. 3 shows the initial P-wave velocity and the comparison between the observed and calculated travel times. It shows that the initial velocity model is already good in terms of the fit between observed and calculated travel times notwithstanding the starting model is spatially smooth enough not to produce an arbitrary result through an inversion.

Fig. 4 shows the P-wave velocity structure for both profiles, in which Fig. 4a and b depict the comparison between observed and calculated travel times and P-wave velocity structure for the north–south profile, respectively, and Fig. 4d and e depict those for the east–west profile, respectively. Fig. 4a and d indicate that the calculated travel times fit well with the observed travel times for both profiles. Also Fig. 5 indicates that the root mean squares of the travel time residuals for north–south and east–west profiles are 0.07 and 0.10 s, respectively.

Fig. 4b clearly shows a high velocity zone around S3 (distance ≈ 0 km) at a depth of 2 km below sea level and shallower, the area of dike intrusion during the 2004 eruptions inferred from seismic and geodetic measurements (Aoki et al., 2005; Takeo et al., 2006). Fig. 4e shows a high velocity zone N 3 km to the west of the summit; combining this with the velocity along the north–south profile suggests that the high velocity zone strikes east–west with its top deepening to the east. The north–south extent of the high velocity zone is as narrow as approximately 5 km. We conclude that this is due to solidified magma resulting from repeating dike intrusions because the location of the high velocity zone roughly coincides with the area of diking associated with the 2004 eruptions. Note that the
high velocity zone is not formed by a single diking, for example, in 2004; geodetic data shows that the dike intruded in 2004 is at less than 1 m thick (Aoki et al., 2005; Takeo et al., 2006), too thin to be imaged in this analysis if the high velocity zone was formed by a single diking in 2004. Also note that we did not put a priori information that the velocity structure is the same at the intersection of north–south and east–west profiles, that is, horizontal distances of 0 km in both profiles (Fig. 4). We conclude that the velocity structure at the intersection has a reasonable agreement in the absence of a priori information (Fig. 4b, d).

Fig. 4c and f display the ray paths calculated by the bending method of Um and Thurber (1987) over the inferred P-wave velocity structure for north–south and east–west profiles, respectively. They
show that the ray coverage is good to a depth of at least 1–2 km below sea level for the north–south profile (Fig. 4c) and 1 km below sea level for the east–west profile, endorsing that a high seismic velocity at the area of inferred diking during the 2004 eruptions is a robust feature.

4. Discussion

Active and passive seismic surveys found high velocity zones in many active volcanoes (e.g., Zollo et al., 1996, 1998; Okubo et al., 1997; Tanaka et al., 2002; Yamawaki et al., 2004). We interpret the high velocity zone as solidified magma due to past intrusions, as previous studies did. Here we would like to note that the high velocity zone we found is consistent with the regional geology (Aramaki, 1963) that Quaternary volcanoes distribute roughly east–west, the eastern end and the youngest of which is Asama. Our result is also consistent with insights gained from other geophysical observations, i.e., precise earthquake locations, ground deformation, gravity anomaly, and electromagnetic structure.

Fig. 1b indicates that the spatial distribution of the Bouguer gravity in the area has east–west trending local maxima to the west of the summit, the area of high velocity, and the eastern end of which is at Asama. This saddle-shaped gravity high suggests that the high velocity zone is imaged by a high density zone, consistent with our hypothesis that the high velocity zone is due to the solidification of repeatedly intruded magma; note that when magma is cooled slowly, it will become fractureless, thus dense, rock with high seismic velocity.

Electromagnetic data depicts that the area of the high velocity zone is less conductive than surrounding areas (Aizawa et al., 2008), also consistent with our hypothesis because slowly solidified magma has low permeability, resulting in high resistivity. Aizawa et al. (2008) attributed to this high resistivity, extending up to about 1 km above sea level, as solidified magma associated with eruptions of Kurofu (Fig. 6) which has been active until 24,000 years ago (Aramaki, 1963).

Fig. 6 gives a schematic overview of magma plumbing system of Asama Volcano. The intruded dike to the west of the summit cannot migrate upward shallower than a depth of 1 km or so below sea level due to negative buoyancy; the host rock there is dense due to repeating dike intrusions and solidification associated with Kurofu eruptions. Magma then found an easier way to make the surface to the east, which formed the present magma pathway of Asama Volcano.

Our hypothesis that the high velocity zone is due to solidified magma implies that some amount of magma should fail to make the surface during eruptions. In fact, geodetic data, field observations, and Airborne Synthetic Aperture Radar observations all suggest that in the 2004 eruptions, only a small fraction of intruded magma was ejected (Nakada et al., 2005; Oki et al., 2005). We speculate that in Asama Volcano, much of the intruded magma did not make the surface but was arrested and solidified in past eruptions as well as the 2004 eruptions.

5. Conclusion

We conducted an active seismic experiment with five dynamites and more than 400 temporary seismometers to delineate the seismic structure of shallow subsurface of Asama Volcano, Japan. The analysis of first arrival times indicate that there is an area of high $P$-wave velocity to the west of the summit, the area of the dike intrusion during the 2004 eruptions delineated by earthquake relocations and modeling of geodetic data. We interpret that this high velocity zone is due to the solidification of repeatedly intruded magma. In other words, our interpretation is endorsed by the low conductivity in the area inferred from electromagnetic data. Although the observed waveforms suggest that the seismic structure below the summit may be quite inhomogeneous, our analysis using travel times only is not capable of delineating the fine structure of the magma conduit. A more sophisticated analysis using waveforms, for example, will be needed to gain more insights into the finer structure of Asama Volcano.

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References


