GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L17302, doi:10.1029/2009GL039448, 2009

Detecting a mass change inside a volcano by cosmic-ray muon radiography (muography): First results from measurements at Asama volcano, Japan

Hiroyuki K. M. Tanaka,[1,2] Tomihisa Uchida,[3] Manobu Tanaka,[3] Minoru Takeo,[1] Jun Oikawa,[1] Takao Ohminato,[1] Yosuke Aoki,[1] Etsuro Koyama,[1] and Hiroshi Tsuji[1]

Received 15 June 2009; revised 14 July 2009; accepted 29 July 2009; published 2 September 2009.

[1] A visual detection and monitoring of volcanic eruptions is the most essential information. In February 2, 2009, Asama volcano, Japan erupted and a large amount of volcanic ash was ejected from the vent. We have observed the activity at Asama since October 12, 2008. For eruption monitoring we used cosmic-ray muon radiography (muography), a new volcano monitoring system recently developed by Tanaka et al. (2009). We measured a quantitative mass loss inside the crater during the eruption event although no changes were found below the crater. The measured value of 30,780 tons is consistent with a model calculation of volcanic ash flow as observed on February 2, 2009. The obtained radiographic image suggests that a "boiling liquid expanding vapor explosion" occurred and a part of an old lava mound was exploded. This picture is consistent with the analytical result of the volcanic ash ejected on February 2, 2009. **Citation:** Tanaka, H. K. M., T. Uchida, M. Tanaka, M. Takeo, J. Oikawa, T. Ohminato, Y. Aoki, E. Koyama, and H. Tsuji (2009), Detecting a mass change inside a volcano by cosmic-ray muon radiography (muography): First results from measurements at Asama volcano, Japan, *Geophys. Res. Lett.*, *36*, L17302, doi:10.1029/2009GL039448.

1. Introduction

[2] The Volcanic Explosivity Index, or VEI, was proposed in 1982 as a way to describe the relative size or magnitude of explosive volcanic eruptions [*Newhall and Self*, 1982]. The VEI uses several factors to assign a number, including mass of erupted material, etc. In general, it is difficult for us to directly measure a mass movement inside and below the crater. Minakami estimated the total mass of ejecta as the sum of ejecta exploded from the inside of the crater and bombs hurled out around the crater by the explosion. The volume of erupted material inside the crater was estimated by repeated triangulation surveys of the crater bottom [*Minakami*, 1937, 1942]. In 2004, airborne synthetic aperture radar (AirSAR) was applied to measuring the topography on the summit crater floor of Mt. Asama [*Urabe et al.*, 2006]. AirSAR is a useful method to measure the amount of erupted material inside the crater when thick volcanic fumes cover the crater. However, such optical measurements can be difficult to monitor the mass movement below the crater. In this paper, we report how muography is useful to measure the mass movement inside and below the crater.

[3] Muography is the use of muons to view inside structure of volcanoes [*Tanaka et al.*, 2003]. Muography uses a well known energy spectrum for muons arriving at different zenith angles, a well understood muon detector, and a specific muon propagation model through matter. If the Earth structure along the muon path is unknown, the information from counting muon events in the detector at different arriving angles can be used to infer the properties of the matter through which the muons travelled. This technique is utterly independent of the geophysical model, and directly measures the density length (*density* × *path length*). Muography has been applied to several volcanoes, such as Asama [*Tanaka et al.*, 2007a; *Tanaka and Yokoyama*, 2008], Usu [*Tanaka et al.*, 2007b, 2008], and Satsuma Iwojima [*Tanaka et al.*, 2009].

[4] Muography technique only resolves the average density distribution along individual muon paths. However, when we determine the mass changes in the crater, two-dimensional muon radiographs as obtained before and after the eruption event would suffice. The reason is as follows: (1) a cross section through the volcano parallel to the plane of the detector, on which the average density along all the muon paths is projected, is obtained with muography. (2) By multiplying a small change in the average density length $\Delta\langle\rho\rangle L$ and the area A, $\Delta\langle\rho\rangle LA$ gives the mass changes in the crater.

[5] Asama Volcano on the Japanese island of Honshu is located at the junction of the Izu-Marianas and NE Japan volcanic arcs. The modern cone of Maekake-yama forms the summit of the volcano and is situated east of the remnant of an older andesitic volcano, Kurofu-yama Maekake-yama, capped by the Kama-yama pyroclastic cone that forms the present summit of the volcano, is only a few thousand years old. Maekake-yama has had several major plinian eruptions, the last two of which occurred in 1108 and 1783 AD. recently produced a small eruption at 1:51 am on February 2. Volcanic ash fall near the crater was found with a surface mass density of 400–500 g/m^2, and it extended much further toward the south east ($\gtrsim$20 km). Total mass of ash can be estimated by integrating the surface density of the ash-fall distribution over the area where the ash fell. The value was 2.0–2.4 × 10^7 kg. This is a half of the amount measured in the 2004 eruption (S. Nakada, private communication, 2009). Volcanic ash was collected on February 2, 2009 and was analyzed in order to find fresh volcanic glass

[1]Earthquake Research Institute, University of Tokyo, Tokyo, Japan.
[2]Atomic Physics Laboratory, RIKEN, Wako, Japan.
[3]Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, Tsukuba, Japan.

0094-8276/09/2009GL039448$05.00

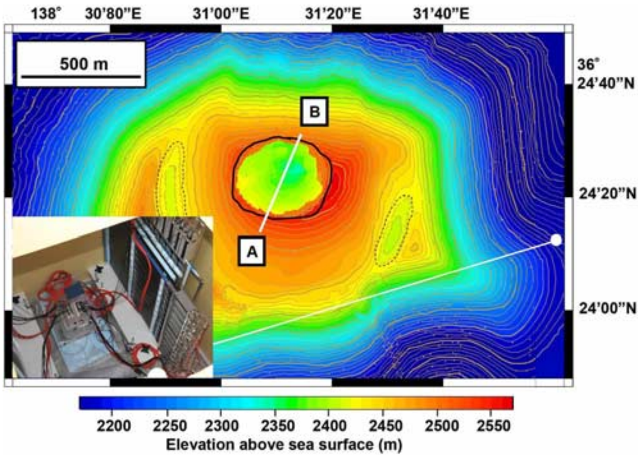

Figure 1. Map of Asama volcano showing the location of the cosmic-ray muon detector. The inset shows a photograph of the cosmic-ray muon telescope system in an underground vault.

with bubbles, which is thought to be magma-like substance. Coarse particles (35% of total) with a diameter above 1 mm did not include any magma-like substance. On the other hand, 7 magma-like particles were found in 3798 fine particles (1.4% in total) with a diameter of 125–250 μm. Most of the volcanic ash were debris particles from old lava deposited at the bottom of the crater (Y. Suzuki, private communication, 2009). Here we report a visual detection and a quantitative estimation of a mass movement inside and below the crater during the 2009 eruption.

2. Real-Time Muon Monitoring System

[6] For a real-time muon monitoring system, we used a portable assembly type cosmic-ray muon telescope module system [*Tanaka et al.*, 2009]. The telescope system consists of crossed segmented scintillator strips with a width of 7.8 cm pointing towards a volcano and allows tracking of muons after passing through the mountain. The PMT output consists of a series of electric pulses, each one representing the passage of a muon through the scintillator. Such pulses can be converted to logic pulses to be interpreted as trajectories of muons. We can distinguish "forward-directed" from "backward-directed" muon trails by choosing positive or respectively negative angles, because muons arriving from below are negligible. The telescope system was installed in an underground vault constructed 1.2 km from the peak (Figure 1) so that showers and multi-muon events are rejected. The distance between two segmented scintillation detector planes is 128 cm so that the angular resolution becomes ~60 mrad. This angular resolution corresponds to the spatial resolution of ~72 m at the center of the crater.

[7] The muon data are taken and analyzed by a power effective muon read out system [*Uchida et al.*, 2009]. Total weight of the muon read out system is 420 g. The PMT signals are recorded in a number of bins representing the horizontal and vertical arriving angles of cosmic-ray muons. The histogram is generated as an HTML (HyperText Markup Language) file. At the observation site, a wireless LAN was installed so that the muon telescope system can be monitored via internet. These data can be directly read by the network processor when a remote PC access to the board.

3. Results and Discussions

[8] A preliminary test measurement with the telescope system has been performed on campus without a target object, and the integral muon intensity and its zenith-angular dependence have been confirmed. The systematic error of the detection efficiency for each arriving angle was estimated from the isotropic horizontal distribution of events. There the horizontal distribution at a certain elevation (θ_1) is normalized to the different horizontal distribution at a different elevation (θ_2) (normalized events). The experimental error bars were derived by fitting a linear function to the normalized distribution and reading deviations of the data from the fitting function. The value was about 6%. The effective vertical angle is $-720 < \theta < 720$ mrad and the effective azimuth angle is $-720 < \varphi < 720$ mrad.

[9] The data are analyzed between (1) October 12th and February 1st, (2) January 6th and February 1st, and (3) February 2nd and February 8th. In Figure 2, horizontal distributions of cosmic-ray muon intensities are compared between (1) and (2), and (2) and (3) for elevations of $\theta = 60 \pm 30$ mrad, $\theta = 120 \pm 30$ mrad, $\theta = 180 \pm 30$ mrad, and $\theta = 240 \pm 30$ mrad. Muon intensity can be normalized to the muons not passing through any substance to give the relative muon intensity (vertical axis). (A) An elevation of $\theta = 240 \pm 30$ mrad corresponds to the region between the upper edge of the crater and a place at half depth. Therefore, an increase in the muon intensity can be seen at the crater region. (B) An elevation of $\theta = 180 \pm 30$ mrad corresponds to the region between a place at half depth and the bottom of the crater. This region corresponds to the region where the lava mound was formed in 2004 eruption. (C) An elevation of $\theta = 120 \pm 30$ mrad corresponds to the region between the bottom of the crater and the region right below the crater. (D) An elevation of $\theta = 60 \pm 30$ mrad corresponds to the region deeper than (C). If we compare the data for each elevation between (1) and (2), and between (2) and (3), we find an interesting feature. Although any statistically significant difference in the muon intensity cannot be found between (1) and (2) for any elevations, we find some deviation between (2) and (3) for $\theta = 180 \pm 30$ mrad. This region corresponds to a place near the north edge of the crater. The muon flux measured in this region before the eruption differs by ~10% in comparison to that measured after the eruption. This difference corresponds to ~3-% reduction in thickness of 700-m rock.

[10] Figure 3 shows the average density distribution projected on the cross sectional plane that includes the crater floor. A topographic cross section is superimposed. GEANT 4 Monte-Carlo simulations [*Agostinelli et al.*, 2003] give the integral flux of muons at various zenith angles penetrating through a given density of rock by referring to the local topographic structure. The value of experimental error (<1% for (A), 1% for (B), and 2% for (c) at $\theta = 180 \pm 30$ mrad in determining the density length) was evaluated from the systematic error of the detection efficiency for each arriving angle. The errors raised by the path length estimation using the topographic map (1/25000)

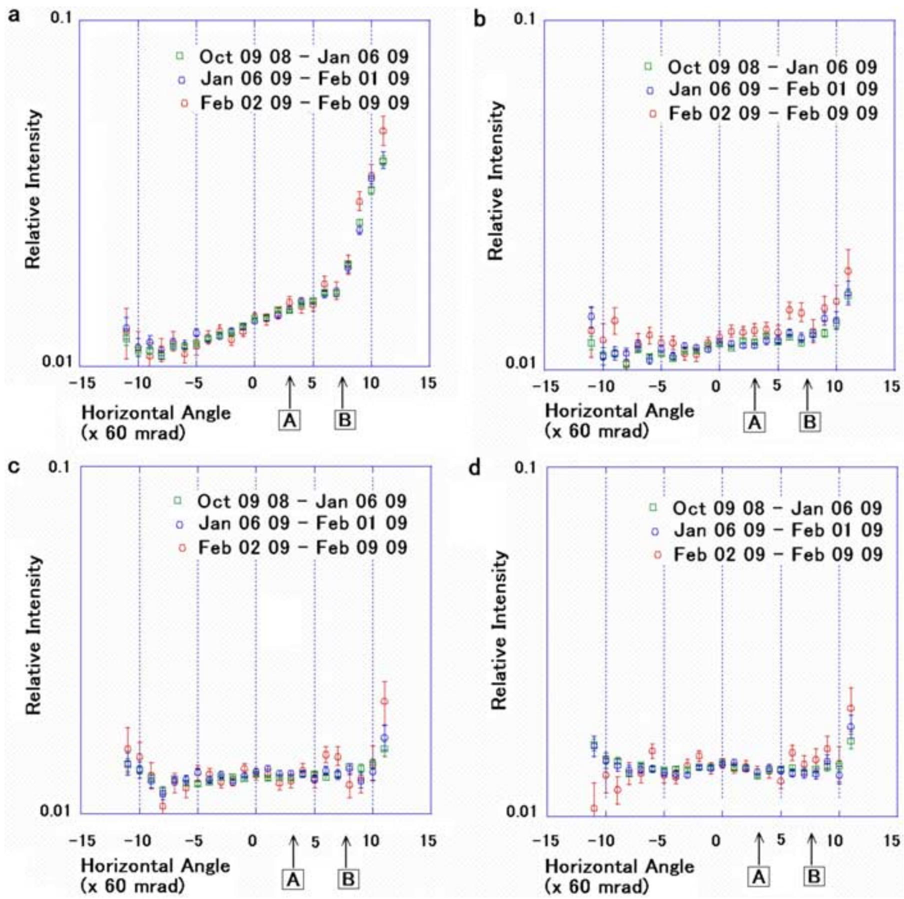

Figure 2. Horizontal distributions of cosmic-ray muon intensities. Data are compared between October 12th and February 1st (green square) and January 6th and February 1st (blue circle), and February 2nd and February 8th (red circle). (a) An elevation of $\theta = 240 \pm 30$ mrad; (b) an elevation of $\theta = 180 \pm 30$ mrad; (c) an elevation of $\theta = 120 \pm 30$ mrad; (d) and an elevation of $\theta = 60 \pm 30$ mrad. The labels A and B are corresponding to the south and north edges of the crater, as shown in Figure 1.

may in some cases be as high as 10 m compared to the 700 m path length ($\theta = 180 \pm 30$ mrad). This would be 1.4%. Therefore, the total errors would be ∼1.5% for (A), ∼1.7% for (B), and ∼2.4% for (c) at $\theta = 180 \pm 30$ mrad in determining the density length. Dotted lines indicate the shape of the crater floor before 2004 eruption, and the solid lines indicate the shape of the one after 2004 eruption [*Urabe et al.*, 2006].

[11] The increase in the muon intensity found in the region (B) indicates a certain mass loss during the 2009 eruption in the region between a half depth of the crater and the bottom of the crater. On the other hand, because statistically significant changes were not found, there seem no movements of a large mass below the crater. Our picture of the 2009 eruption is as follows: A "boiling liquid expanding vapor explosion" occurred and as a result old lava at the bottom of the crater was exploded. The mass loss at the crater bottom can be estimated quantitatively by referring to the observed increase in the muon intensity. Taking a spatial resolution of ±35 m and a density resolution

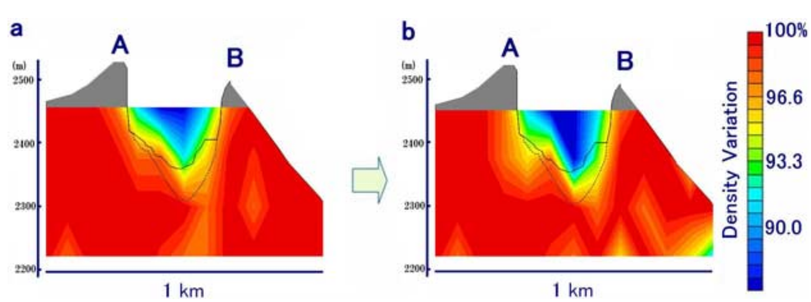

Figure 3. Average density distribution projected on the cross sectional plane that is parallel to the detector plane and that includes the crater floor of Asama. (a) Data collected between January 6th and February 1st; and (b) data collected between February 2nd and March 5th.

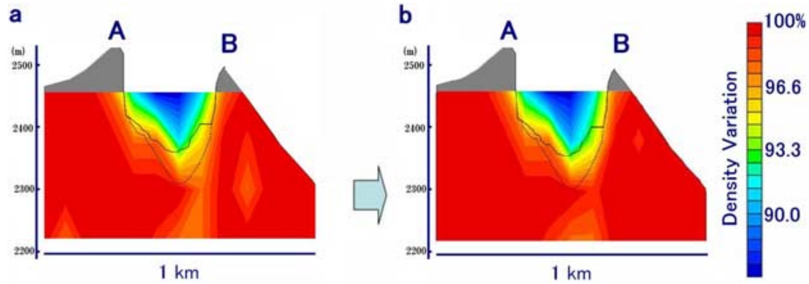

Figure 4. Average density distribution projected on the cross sectional plane that is parallel to the detector plane and that includes the crater floor of Asama. (a) Data collected between January 6th and February 1st; and (b) data collected between February 2nd and February 8th.

of ±2% into account, the changed area A as a cross section through the volcano parallel to the plane of the detector is 58 ± 35 m (in width) × 50 ± 35 m (in height), and a difference in the average density length $\Delta\langle\rho\rangle L$ is 22.5 ± 15 tons m^{-2}, respectively. Therefore, the minimum value of the mass change in the crater at 1σ confidence level is 2,588 tons, the mean value is 65,250 tons, and the maximum value at 1σ confidence level is 302,812 tons. The total volume of ash and other volcanic ejecta due to the eruption of February 2, 2009 was estimated to be ~50,000 tons (S. Nakada, private communication, 2009). The mass loss measured by cosmic-ray muography is consistent with the amount estimated from volcanic ash studies.

[12] The data presented here constitute evidence that we have visually detected mass movement inside the crater due to volcanic eruptions with muography. At the present stage it takes one week to visualize the difference due to the limited flux of cosmic-ray muons. However, this time can be easily reduced by enlarging the size of the detection area. Inversely, if we expose the detector for a longer period of time we obtain more accurate image. Figure 4 shows a comparison between (2) January 6th and February 1st, and (4) February 2nd and March 5th. No significant difference can be clearly seen below the crater floor. The mass change in the crater can be computed to be 30,780 tons with a lower and upper limit of 11,305 tons and 68,503 tons respectively. The observed amount is consistent with the result, as obtained with the volcanic ash studies.

[13] **Acknowledgments.** Special funding arrangements by S. Okubo, K. Nakatsuka, and related people of ERI, JSPS (Japanese Society of Promotion of Science) and JST (Japan Science and Technology Agency) are acknowledged. T. Koyaguchi of ERI, K. Nagamine of UCR, I. Yokoyama, M.J.A., Y. Yamashina, and S. Steigerwald are also acknowledged for their valuable suggestions. This work is greatly benefited from useful comments by two reviewers of this manuscript.

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Y. Aoki, E. Koyama, J. Oikawa, T. Ohminato, M. Takeo, and H. Tsuji, Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo, Tokyo 113-0032, Japan.

H. K. M. Tanaka, Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan. (ht@riken.jp)

M. Tanaka and T. Uchida, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan.