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Cosmic-ray muon imaging of magma in a conduit: Degassing process of Satsuma-Iwojima Volcano, Japan

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[1] Muon radiography can provide essentially a cross section through the object parallel to the plane of the detector, on which the average density along all the muon paths is projected, somewhat like X-ray radiography. Very recently the use of emulsion films has given us a clue for visualization of the interior of volcanoes. To image a larger volcano in shorter time, we need a larger detector to collect more muon events. However, the time required for imaging will be proportional to the detection area. In order to overcome this problem, we developed a portable assembly type cosmic-ray muon telescope module to image the density distribution of magma in the conduit of Mt. Iwodake volcano, Japan. A muon detector with an area of 1 m^2 was set up at the foot of the volcano. We mapped differentially absorbed cosmic-ray muons, which depend on the varying thickness and density beneath the crater floor. We successfully imaged density distribution in the conduit as well as the conduit shape, assuming the density anomaly is localized in the vent area. The observed location of the magma head is consistent with the degassing model of rhyolitic systems proposed by K. Kazahaya et al. in 2002.
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1. Introduction

[2] Magma convection in a conduit has been proposed as a mechanism responsible for intensive and continuous degassing of magmatic volatiles from magma chambers of basaltic to andesitic volcanoes [*Kazahaya et al.*, 1994]. When a magma conduit extends to a shallow level and is allowed to degas, the upper-most part of the magma may then degas efficiently. Density of the degassed magma increases by bubble separation and melt degassing, which makes the lower part of undegassed magma buoyant, and the degassed magma descend through the conduit. *Shinohara et al.* [1995] first modeled magma convection in conduits of silicic systems. Such modelings indicate that convective degassing is possible mechanism in basaltic to dacitic volcanoes [*Stevenson and Blake*, 1998].

[3] Mt. Iwodake, the rhyolitic lava dome on Satsuma-Iwojima Island (Figure 1a), is located near the northwestern rim of the Kikai caldera (~18 km in diameter) formed 6300 years ago. Many fumaroles exist in and around the summit. The chemical composition of volcanic gases from the summit crater of Iwodake has been relatively constant since the 1950s [*Kamada*, 1964]. Isotopic compositions of the summit volcanic gases indicate that the gases have a magmatic origin [*Hedenquist et al.*, 1994]. Degassing of magma requires oversaturation of volatiles in a melt. Therefore, degassing occurs only at relatively low-pressure conditions. The highest fumarolic temperature of 900°C also supports the idea that volcanic gases were released from the magma at shallow depths. From the analogy of the volatile-poor composition measured in the Showa-Iwojima magma, it is estimated that magma degassing occurs in the upper part of Mt. Iwadake [*Kazahaya et al.*, 2002].

[4] Cosmic-ray muon radiography is similar to X-ray radiography, except penetrating muons serve in place of X-rays. The intensity of an image pixel in the detector is determined by the attenuation of incident muons caused by absorption in the object. Muon radiography using the propagation of muons 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. The muons are blocked or strongly attenuated by a higher density part and pass through a lower density part. For muon radiography, volcanoes make good study targets because they are axi-symmetric and it is reasonable to assume that the observed density variations are localized in the vent or crater area. In 2007, the internal structure of the crater and vent area of Mt. Asama volcano was imaged by muon radiography [*Tanaka et al.*, 2007b]. From such measurements, we can judge whether the vent is plugged with lava or is drained of magma to the deeper parts. This is useful for prediction of the coming consequences in volcanic eruptions. Also in 2007, muon radiography was applied to the 1944 lava dome of Usu volcano to clarify its subsurface structure [*Tanaka et al.*, 2007c]. Lava domes are one of the conspicuous topographic features in volcanic fields and should afford us important data to discuss magma risings through conduits and resultant deformations of the ground [*Tanaka and Yokoyama*, 2008]. The knowledge of subsurface structure of the lava domes is indispensable to discuss their formation mechanism. Cosmic-ray muons arrive at angles ranging from vertical to horizontal. The muon detector is placed at a

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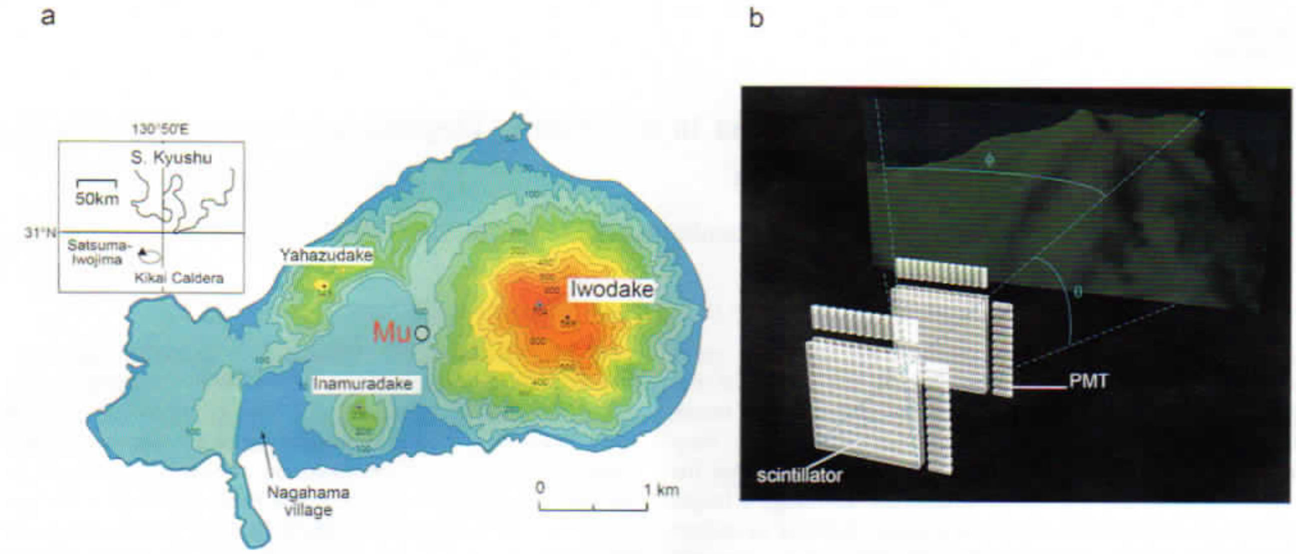

Figure 1. (a) Map of Satsuma-Iojima volcano showing the location of the cosmic-ray muon detector (Mu). (b) Portable assembly type cosmic-ray muon telescope system. The detector matrix counts 12 × 12 square pixels of 8 cm.

place pointing toward a topographically prominent feature of interest, and there will be results for any volume located above the detector. Degassing at such a low pressure in Mt. Iwodake motivates us to detect and image the degassing front of magma in the conduit by cosmic-ray muon radiography.

2. Muon Detection and Analysis

[5] The experimental arrangement for imaging the conduit of Mt. Iwodake requires that 1) the muon detection area must be large enough to collect a number of muon events, and 2) the measurement has to be performed near the volcano to achieve higher spatial resolution. In order to place the detector near the volcano, the detector must be power effective and light enough to be carried up to a mountain. One candidate would be an emulsion film because an emulsion film is a cost-effective and light muon detector [*Tanaka et al.*, 2007a, 2007b, 2007c; *Tanaka and Yokoyama*, 2008; *Tanaka et al.*, 2008]. However, large-area emulsions are difficult to scan. In order to overcome this problem, we have developed a portable assembly type cosmic-ray muon telescope module.

[6] The module comprises of a plastic scintillator, acryl light guide and power-effective photomultiplier tube (PMT) (Hamamatsu H 7724). Muons are detected by the brief flush of light when passing through a plastic scintillator. The dimension of $150 \times 8 \times 8$ cm^3 and 3.4 kg in weight is for a single module (i.e., a bar indicated in Figure 1b). 48 such modules are used to assemble the whole telescope. The detector matrix counts $12 \times 12 = 144$ pixels. At the observation site, 48 modules are arranged to make two segmented scintillation detector planes to track muon trails (a portable assembly type cosmic-ray muon telescope system). The telescope system is comprising of crossed segmented scintillator strips with a width of 8 cm pointing towards a volcano allows tracking of muons after passing through the mountain. A straight line connecting the intersecting points of muons at two detector planes determines the muon trail (Figure 1b). Since cosmic-ray muons do not arrive from the downward directions, we can distinguish "forward-directed" from "backward-directed" muon trails by choosing either positive or negative arriving angles. The distance between the telescope and the mountain surface is ~500 m, which is much shorter than the muon decay length (6000 m) for typical muon energy (1 GeV) after passing through the mountain. We therefore do not use iron plates, which is usually necessary for filtering muon-initiated soft component backgrounds [*Tanaka et al.*, 2001, 2003, 2005].

[7] The muon data are taken and analyzed by a muon radiographic imaging electronic board system (MURIEL). The system comprises of power effective comparators, an FPGA chip (field programmable gate array, Xilinx Sprtan3AN-700), a network chip (Ethernet physical layer device PHY, SMSC LAN8700i), and a switching regulator. The electronic board is 35 mm × 160 mm × 160 mm in size, and 420 g in weight. The direct output from the photomultiplier tube is directed by 5m cable to the muon read out system to convert the PMT voltage spikes into logic pulses determined by the transition from a logic-0 to a logic-1 level, which is readable by the FPGA (field programmable gate array). The FPGA chip computes a muon track by finding two simultaneous (in 200 ns) signals from two different detector planes of the telescope. If the PMT pulses from two detector planes occur within 200 ns, they are deemed to be resultant from muon passing completely through two detector planes. It is unlikely that 2 muon events occur in the same 200 ns window. The PMT signals analyzed in the FPGA chip are recorded in a number of bins representing the horizontal and vertical arriving angles of cosmic-ray muons. The data are stored in a flash memory attached to the FPGA chip as an HTML (HyperText Markup Language)-formatted histogram. The Ethernet PHY converts signals from the FPGA to meet Ethernet specifications. The network processor deals with network protocols to access the histogram from a remote PC with a web browser. The power (including a power loss of AC- to DC-conversion) required for this electronic system was

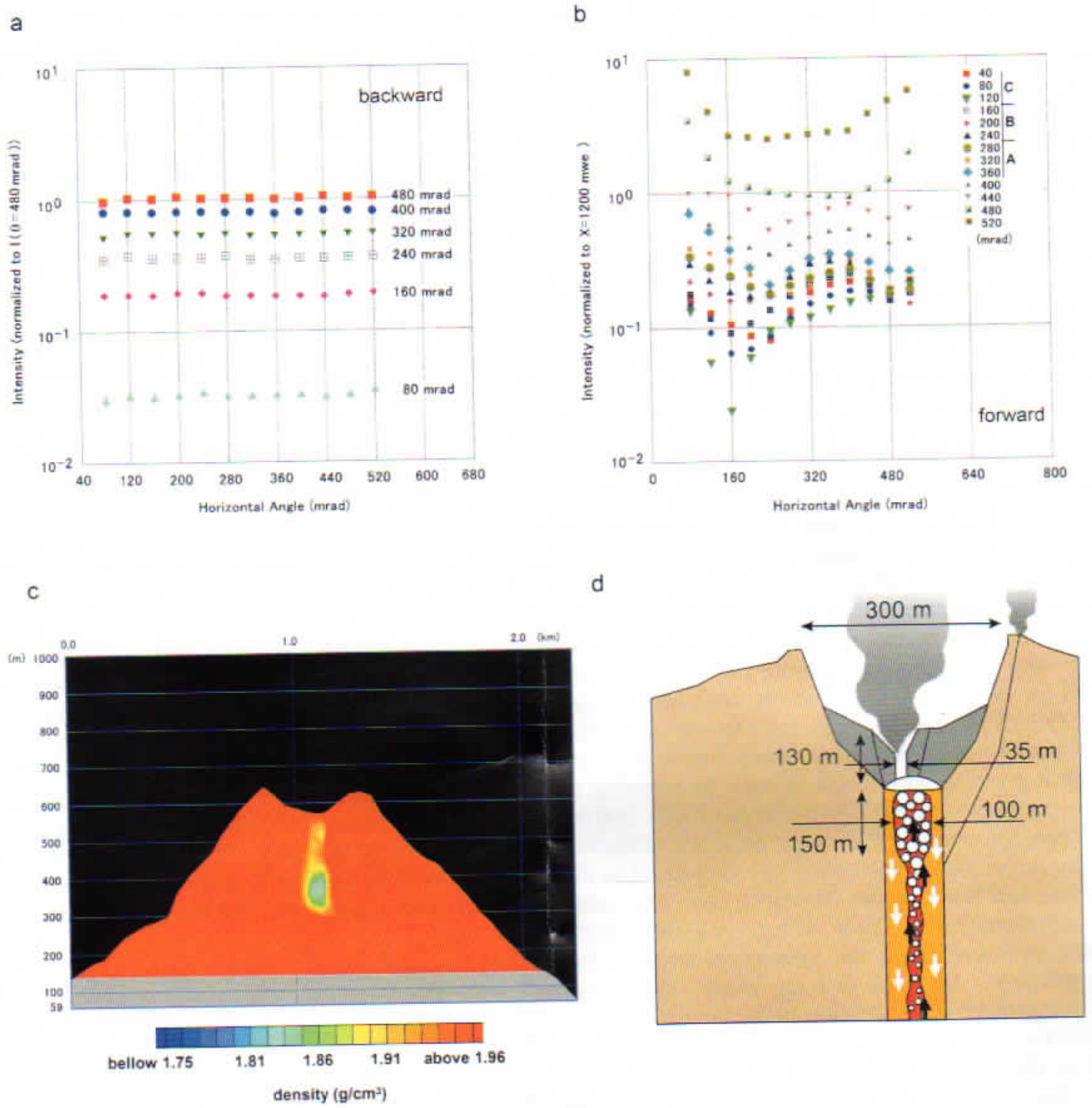

Figure 2. (a) Horizontal angle distribution of the muon events ranging from 80 to 440 mrad (4.6–25 degrees). Muon events are normalized to the events arriving from the elevation of 440 mrad (25 degrees). (b) Muon transmission intensities versus horizontal angles for different elevations ranging from 40 to 520 mrad (2.3–30 degrees). The intensities are normalized to the events passing through a rock with a thickness of 1200 meter water equivalent. (c) The average density distribution projected on the cross sectional plane that is parallel to the detector plane and that includes the crater floor of Mt. Iwodake. In order to incorporate the errors in density determination into the image, the density anomalies only below 95% of the average density are mapped. (d) Model of magma convection in a conduit at shallow depth modified after *Kazahaya et al.* [2002].

measured using a power tester (HIOKI 3334 AC/DC POWER HiTESTER). The value was 2.5 W.

[8] We use a coordinate system in which each point on a plane is determined by an angle and a distance (the distance between the detector and the object: R). The muon transmission image (muon radiograph) is therefore mapped in the angular coordinate. The angular coordinate (also known as the vertical angle or the horizontal angle denoted by θ or ϕ) denotes the positive or anticlockwise angle required to reach the point from the 0° ray. Minimum resolvable distance (spatial resolution: ΔX, ΔY) at an object is defined by minimum resolvable angle of the detector. (angular resolution: $\Delta\theta$, $\Delta\phi$) and the distance between the object and the detector (R); $(\Delta X, \Delta Y) = R \times (\Delta\theta, \Delta\phi)$. The radiograph is essentially 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.

3. Results and Discussions

[9] The muon telescope system with an area of 1 m^2 was installed at an observation point 1.2 km from the summit crater of Satsuma-Iojima volcano (Figure 1a). The observation altitude was 95 m a.s.l. The systematic error of the detection efficiency for each arriving angle was estimated from the isotropic horizontal distribution of events arriving from the backward direction (Figure 2a). The experimental

error bars were derived by fitting a linear function to the backward events and reading deviations of the data from the fitting function. The value was less than 5%. A root mean square angular resolution of the system was ±14 mrad at an interval of 40 mrad for the distance between two detector planes being 2 m.

[10] Figure 2b shows cosmic-ray muon transmission intensities versus horizontal angles for different elevations (1-month results). The data are packed into the horizontal and vertical bins being ±28 (1.6) and ±14 mrad (0.8 degrees) respectively by taking a moving average at an angular interval of 40 mrad (2.3 degrees), and are normalized to the intensity after passing through rock with a thickness of 1200 mwe (meter water equivalent). The stronger/weaker muon transmissions come from a longer/shorter path length or a higher/lower average density along the path. In Figure 2b, we can see decrease in the muon transmission for $80 < \phi < 520$ and $\theta > 440$. This corresponds to the peak of Mt. Iwodake. At $\theta = 440$ mrad, where the crater rim is located at, the increase in the muon transmission intensity can be seen between $\phi = 240$ and 480. This increase continues until $\theta = 360$ mrad, where the crater floor is located at. Below $\theta = 360$ mrad, we quantify the muon transmission rate by comparing with the GEANT4 Monte-Carlo simulations [*Agostinelli et al.*, 2003] for different uniform average densities. GEANT4 Monte-Carlo simulations give the integrated flux of muons at various zenith angles penetrating through a given density length of rock by referring to the local topographic structure [*Tanaka et al.*, 2007a, 2007b, 2007c]. Figure 2c shows the average density distribution projected on the cross sectional plane that is parallel to the detector plane and that includes the crater floor. The value of the experimental error (3% 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) may in some cases be as high as 30 m compared to the 1500 m path length. This would be 2%. Therefore, the total density length relative error becomes 3.6%. The value of these errors was incorporated into the image by neglecting the density deviations from the average that are less than 3.6%. In Figure 2c, we find two low density regions below the crater floor: (a) a region right below the crater floor and (b) a larger region below Region (a). Assuming the observed low density region beneath the dome is localized in the vent area, the region right below the crater floor is explained by a conduit diameter of 35 ± 17 m with a density of ~ 1 g/cm^3 and a larger region below Region (a) is explained by a conduit diameter of 86 ± 17 m with a density of less than 1 g/cm^3. Below Region (b) we find a higher density region (Region (c)). The density is close to the surrounding density (2.1–2.2 g/cm^3), indicating bubble-poor degassed magma. The depth of the magma head observed 130 m below the crater floor is consistent with the volatile-poor composition as observed in Mt. Iwodake, which could result from degassing at a low pressure of 0.5–3.0 MPa.

[11] We now construct a picture of the muon transmission intensity in Mt. Iwodake in order to interpret our data and arrive at an estimate for the degassing activity in the conduit. Our picture of the various depths is as follows.

[12] 1. Region between 0 and 130 m below the crater floor: This region may consist of low density collapsed materials forming a high-temperature fumarolic area at the center of the crater. The size of the pathway seems to be 30–50 m in diameter. The volcanic gas is emitted through this porous area when a magma conduit extends to a shallow level and is allowed to degas.

[13] 2. Region between 130 and 280 m below the crater floor: This region may consist of ascending extremely low density undegassed magma caused by bubble expansion and coalescence in magma. In this region, the upper-most part of the magma degases efficiently, and the degassed magma descend through the region around the low density magma as shown in Figure 2d. The size of this convection region seems to be ~ 100 m in radius

[14] 3. Region deeper than 280 m below the crater floor: This region may consist mainly of descending degassed magma.

[15] This technique only resolves the average density distribution along individual muon paths. However, by placing the muon telescope at the southern or northern flank of the volcano, one would obtain a vertical cross section that is perpendicular to that shown in this work. A comparison of the results to results from other geophysical studies is also important. Gravimetric or magnetotelluric measurements are useful to complement the muon measurements.

[16] The data presented here constitute evidence that we have imaged magma head clearly in the volcanic conduit of Satsuma Iojima volcano. The observed location of the magma head is consistent with the degassing model of rhyolitic systems proposed by *Kazahaya et al.* [2002].

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