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Muographic monitoring of hydrogeomorphic changes induced by post-eruptive lahars and erosion of Sakurajima volcano

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ABSTRACT

Post-eruptive destabilization of volcanic edifices by gravity driven debris flows or erosion can catastrophically impact the landscapes, economies and human societies surrounding active volcanoes. In this work, we propose muography as a tool for the remote monitoring of hydrogeomorphic responses to volcano landscape disturbances. We conducted the muographic monitoring of Sakurajima volcano, Kyushu, Japan and measured continuous post-eruptive activity with over 30 lahars per year. The sensitive surface area of the Multi-Wire-Proportional-Chamber-based Muography Observation System was upgraded to 7.67 m²; this made it possible for the density of tephra within the crater region to be measured in 40 days. We observed the muon flux decrease from 10 % to 40 % through the different regions of the crater from September 2019 to October 2020 due to the continuous deposition of tephra fallouts. In spite of the long-term mass increase, significant mass decreases were also observed after the onsets of rain-triggered lahars that induced the erosion of sedimented tephra. The first muographic observation of these post-eruptive phenomena demonstrate that this passive imaging technique has the potential to contribute to the assessment of indirect volcanic hazards.

Introduction

Volcanic gases, ashes, rocks and other debris ejected by explosive eruptions of stratovolcanoes reach the surrounding lands by pyroclastic flows, tephra falls, syneruptive lahars and debris avalanches. The deposition of volcanic ejecta can disturb the drainage basins on volcano slopes, valleys and streams and pose indirect hazards to the surrounding landscape, economy and population within a distance approximately 30 kilometers¹. Preservation, erosion and secondary transport of the sedimented ejecta depend on the bulk density and the thickness of deposits, the steepness of the land, the geomorphic environment and the vegetation². Wind and water driven erosion processes can destabilize and mobilize the deposited materials before they become fully incorporated into the soil. For example, the wind induced erosion of unstable newly deposited tephra from Eyjafjallajökull volcano created dust storms that seriously affected the air quality within a distance of a few hundreds of kilometers during the first summer after eruption 2010³. Post-eruptive lahars were generated even several years after the disturbance of drainage basins⁴ due to heavy (typically a few tens of mm per hour) rainfalls^{5–7}, flooding of volcanic lakes, post-eruptive erosion of volcanic edifices, gravitational collapse of weakened structures and earthquakes^{8,9}.

The generation and dynamics of lahars are controlled by the local topography, the volcanic activity,

the amount and composition of tephra as well as the intensity and duration of rainfall^{5,10–12}. The flows of multi-tons of material mixtures with typical volume of 10^4 – 10^8 m³ and speed of a few tens of meters per second can even reach a distance of a few tens of kilometers from the volcanic edifice¹³. Compared with pyroclastic flows that occur within a few minutes, the lahars travel for a relatively long time: from a few tens of minutes to a few hours¹⁴. The speed of lahars and volume of transferred materials decrease as the distance traveled increases. The transferred materials transform to an almost hardened state after the stoppage of the flow.

Lahars can catastrophically impact the environment, such as river valleys or flood plains, human-made infrastructures, and human populations by making the lands around volcanoes uninhabitable^{11,15–17}. Continuous monitoring of the amount of sedimented volcanic ejecta would allow researchers to observe the occurrence of erosion processes before the destabilization of the volcanic edifice and onset of post-eruptive lahars. Although various remote sensing techniques, such as airborne synthetic aperture radar¹⁸ or airborne laser scanning¹⁹, are utilized for measurement of long-term changes (from few months to few years) in the thickness of volcanic ejecta deposits, the monitoring of short-term (from few hours to few weeks) erosion processes has not yet been realized due to the constraints on observational time and cost.

Muography can depict the amount of materials and its changes through geological edifices and human-made structures by means of the measurement of the flux of penetrated cosmic-ray muons flux—similar to the technique used for radiography of the human body²⁰. Cosmic-ray muons are naturally occurring elementary particles that are created in the atmosphere at the altitudes of 10–15 km above sea level as decay products of hadronic particle showers. This process originates from the collisions of primary cosmic rays with atmospheric nuclei. These elementary particles can penetrate through geological structures with the thicknesses of beyond a kilometer with only a few milliradians of deflections along their paths. The applicability of muography has already been demonstrated for volcano imaging thanks to the recent progress in the development of observation instruments^{21–30} and imaging techniques^{31–34}. Various volcanic phenomena, such as magma ascent and descent³⁵, the degassing process³⁶, plug formation³⁷, magma intrusion into lava domes³⁸, tectonic evolution³⁹, hydrothermal processes^{40,41} or long-term tephra deposition⁴², have already been measured with muographic imaging.

In the latter muography campaign, Tanaka (2020)⁴² measured the amount of tephra on the Sakurajima volcano, Kyushu, Japan between December 2014 and November 2016 with 3 time-sequence experiments, each lasting 240 days. The transmission rate of muons decreased more than 2 standard deviations between the 1st and 3rd time sequences due to the deposition of tephra fallouts with a mass of approx 0.4 Mt. Although this muographic measurement of tephra thickness demonstrated that muography could provide useful input for the determination of the magnitude and intensity of eruptions, the limited time resolution of the experiment was not sufficient to reveal the hydrogeomorphic changes which occurred on the volcanic edifice. In this work, we exploit the technological advantages, specifically the upgraded detection acceptance and angular resolution, of the Multi-wire-proportional-chamber (MWPC)-based Muography Observation System (MMOS)^{33,37,43} of Sakurajima Muography Observatory (SMO)^{33,34,37,42} to observe the short-term erosions of the volcanic edifice that can weaken and destabilize the upper parts of the volcano. Muographic monitoring of hydrogeomorphic responses to the disturbances of volcano landscapes may contribute to the assessment of the threats posed by indirect volcanic hazards.

Results

Data collection

Figures 1A–1C show the location and topography of the selected experimental site at Sakurajima volcano⁴⁴. The Sakurajima volcano is one of the world's most active stratovolcanoes connected to magma from the

71 Aira caldera located underneath the Kagoshima Bay⁴⁵. Multiple craters, namely Central Craters (Vent
 72 A and B) and Showa Crater, show alternate eruptive activity with a few hundred explosive eruptions per
 73 year^{46,47}. Volcano vegetation has already been damaged on the volcanic edifice due to deposition and
 74 transportation of volcanic ejecta.

Figure 1. The map of the measurement site and the schematic drawing of the experimental arrangement. (A) The map of Kyushu, Japan is shown with the location of Sakurajima volcano (white star)⁴⁴. (B) The elevation map of Sakurajima volcano is shown based on the data of Geospatial Information Authority of Japan⁴⁴. The location of Sakurajima Muography Observatory (SMO) is shown by a filled white star. The dashed white lines show the orientation and angle of view of SMO. The coloured solid lines show selected cross-sections across the Central Craters (CC), Showa Crater (S) and Arimura Basis (AB), and Arimura Middle Reaches (AMR), respectively. The locations of lahar observation stations are shown by empty white stars. (C) The selected cross-sections of Sakurajima volcano are shown across the blue-coloured, cyan-coloured and gray-coloured lines of panel B. The coloured lines indicates three selected angular regions in the vertical direction for muographic observation of the volcanic edifice.

75 Central Crater showed persistent activity since 2018 and a series of explosive eruptions have produced
 76 tephra deposition in the crater and downstream from the volcanic edifice with a typical mass of a few Mt
 77 per year^{48–50}. Heavy rainfalls mobilized this tephra deposition and induced several lahar events in recent
 78 years^{48–50}. Rain, strain and ultrasonic gauges, wire and pressure sensors, and load cells from the Japan
 79 Meteorological Agency (JMA) are measuring the debris flow rate and velocity, as well as the accumulated
 80 debris volume present in downstream areas of Sakurajima volcano^{51,52}. We used the wire sensor data that
 81 were collected from the Arimura and Furusato rivers by in-situ lahar monitoring sensors⁵⁰. The locations
 82 of these lahar sensors are shown by empty white stars in Figure 1B. The occurrence of the aforementioned

83 volcanic phenomena was the reason that Sakurajima volcano was an appropriate target for studying the
84 hydrogeomorphic responses to volcano landscape disturbances.

85 We applied the MMOS for muographic observation of Sakurajima volcano between 15th March 2019
86 and 17th December 2020. The MMOS was installed in the SMO that is located at 31.557° N, 130.650° E at
87 150 m above sea level at a distance of approx. 2,800 m from the to southern peak of the volcano (indicated
88 with the filled white stars in Figures 1A and 1B). The MMOS is an autonomously operating modular
89 muographic observation system which is serving real-time (a few-hour-time-scaled) data. A photograph
90 of three MMOS muon tracking systems is shown in Figure 2. The MMOS system collected data with
91 seven tracking systems (total area of 5.31 m^2) for 157 days between March and August 2019 and with ten
92 tracking systems (total area of 7.67 m^2) for 462 days between August 2019 and December 2020. The data
93 collection procedure was stopped from the 19th to the 28th of August 2019 due to installation of the three
94 new tracking systems. Further technical stops were performed three times with a maximum of 2 days for
95 maintenance work. All of the tracking systems were housed inside the SMO building and oriented towards
96 the active craters of Sakurajima volcano, specifically 30.25° from the North, during the measurement
97 campaign as shown by dashed white lines in Figure 1B.

Figure 2. Photograph about three tracking systems of Multi-Wire-Proportional-Chamber-based Muography Observation System (MMOS). Ten MMOS operated in the Sakurajima Muography Observatory during the data collection period.

98 Data analysis

99 Since the analysis methods will be detailed in the "Methods" section of this paper, in this section the
100 principles will be described in a nutshell. Muography exploits the relationship between the energy

dependent attenuation of muons and the amount of materials along muons' paths⁵³. A projection image, called a muogram, is derived by means of angular dependent counting of the measured muon tracks. The angular dependent flux reflects the yield of penetrated muons that is quantified by normalizing of the muogram with the effective detection acceptance and data collection time. Average density-length and mass reflect the amount of materials that the muons have traveled through. These are derived by modeling or simulating of the initial angular, energy and location dependent fluxes of muons⁵⁴ and their penetration rate through the imaged structure⁵³. Based on measurements of muographic tephra monitoring campaigns, expectations are that the deposition of volcanic ejecta increase the mass of the surface region of the volcano and consequently the muons' penetration rate and the flux decrease from this direction. In contrast, erosion processes decrease the mass of the volcanic edifice and therefore the muons' penetration rate and the flux increase.

Figure 3. The southern peak of Sakurajima volcano is shown with the designated regions. (A) A photograph of the southern peak that was captured at the muography observatory. (B) The measured muon flux is shown as a function of horizontal ($\tan(\theta_x)$) and vertical ($\tan(\theta_y)$) directions with an angular resolution of $5.5 \text{ mrad} \times 5.5 \text{ mrad}$ for a period of 227 days. The white shaded regions without flux values represent very large thicknesses with inpractically low penetrated muon count. The coloured rectangles show the designated angular regions for Central Crater (CC, blue), Showa and Arimura Basin (S and AB, cyan) and Arimura Middle Reaches (AMR, gray), respectively.

In this work, an event-by-event off-line data analysis was utilized in order to reconstruct the trajectories of detected charged particles³³. The muon flux was calculated in a $\tan(\theta_x)$ - $\tan(\theta_y)$ coordinate system, where $\tan(\theta_x)$ and $\tan(\theta_y)$ track slopes were determined relatively to the horizontal and vertical orientations of MMOS, respectively^{33,37}. Four angular regions were selected for studying the muon flux changes and revealing the underlying volcanic phenomena. In Figure 3A, coloured rectangles indicate the selected

regions that were selected based on the convex shape of the volcanic edifice in a photograph of Sakurajima volcano and Figure 3B shows a muographic image that was captured with an angular bin size of $5.5 \text{ mrad} \times 5.5 \text{ mrad}$ with the MMOS system during a period of 227 days. A reference region (RR, red rectangle) was designated with an open sky measurement to investigate the change of muon flux without any volcanic phenomena. Three further angular regions, namely the Central Crater vents (CC, blue rectangles), Showa and Arimura Basin (S and AB, cyan rectangles) and Arimura Middle Reaches (AMR, gray rectangles), were designated through the southern peak of Sakurajima volcano. Figure 1C shows the cross-sectional view of Sakurajima for different directions. The thickness of materials through the selected volcano regions were ranged from 1,030 meter-water-equivalent to 2,630 meter-water-equivalent and the land deformation due to the volcanic activity was negligible. We did not expect the muon flux to change as it transversed through the three volcano regions due to internal volcanic activity: neither due to magmatic plug formation³⁷ nor explosion³⁴ because we focus on the surface region. The fluxes were averaged in each angular region for time sequences of 4 days, and the averaged fluxes were smoothed by applying a moving average calculated from the previous ten consecutive time sequences, i.e. over a period of 40 days. In the following section, we refer to this quantity as averaged muon flux.

Figure 4. The averaged muon fluxes are shown with 1 standard deviation for the Reference Region (red-coloured band), Central Craters (blue-coloured band), Showa Crater and Arimura Basin (cyan-coloured band) and Arimura Middle Reaches (gray-coloured band), respectively.

Muon flux reduction due to tephra sedimentation

Figures 4 and 5 show respectively the averaged muon fluxes and the relative averaged muon fluxes through the four selected angular regions with 1 standard deviation bands from 21st April 2019 to 1st December 2020. As it was expected, the variation of relative averaged flux in the reference region (red error bands) did not exceed the flux changes of 1.5 % due to the atmospheric temperature and pressure changes, except for July to October 2020 when muon flux was observed to have decreased significantly from 3 % to 6 % due to an uncorrected loss of detector acceptance due to noisy electronic channels. After September 2019, the relative averaged flux decreased through the volcano regions from 10 % to 40 % which were well above either the expected atmospheric effects or expected flux decrease due to uncorrected instrumental effects. The significant decrease of muon flux reflects the change of volcanic ejecta mass that

142 was measured to approx. 0.25 Mt between April and September 2019 and approx. 2 Mt from September
 143 2019 to July 2020^{48,49}.

Figure 5. The variations of averaged muon fluxes (F) relatively to the fluxes measured at the first time sequence (F₀). The relative flux changes are shown with 1 standard deviation bands during the data collection period for the Reference Region (red-coloured band), Central Craters (blue-coloured band), Showa Crater and Arimura Basin (cyan-coloured band) and Arimura Middle Reaches (gray-coloured band), respectively.

144 Discussion

145 Since averaged muon fluxes measured through the three volcano regions (Figures 4) showed a similar
 146 overall trend throughout the data collection period, we quantified the total mass through these regions
 147 to present our observations on hydrogeomorphic responses to the disturbances of Sakurajima volcano.
 148 The total mass includes the mass of volcanic edifice and the mass of deposited tephra. The total mass
 149 was measured to approx. M₀ = 12.08 Mt for the 1st time sequence. Figures 6A-6C show the variations
 150 of total mass relative to M₀ (M-M₀) with 1 standard deviation (green-coloured bands), the daily number
 151 of lahars (orange-coloured impulses), the daily total precipitation (blue-coloured impulses) and hourly
 152 maximum precipitation (red-coloured impulses), as well as the daily frequency of eruptions occurred
 153 from the Central Crater vents (yellow impulses) between 21st April 2019 and 1st December 2020. The
 154 comparison of the timelines of different quantities suggested that the onsets of lahar events were triggered
 155 by the heavy rainfalls with hourly maximum precipitation of above 10 mm per hour instead of the total
 156 daily precipitation. This is being consistent with the generation of post-eruptive lahars on Merapi⁵, Volcán
 157 de Colima⁶, and Pinatubo⁷ volcanoes. Furthermore, there was no correlation between the onset of lahars
 158 and the eruptive frequency.

159 We found that the mass deposition rate did not correlate with the frequency of explosive eruptions.
 160 This observation is found to be consistent with the muographic observation of Showa cater conducted
 161 between 2014 and 2016 which suggested that the amount of ejected materials per eruption is larger when
 162 the interval between the eruptions is longer⁵⁵. In spite of the continuous deposition of erupted tephra,
 163 the mass deposit showed significantly decreasing trends through various periods, e.g. from November

164 2019 to January 2020, during March 2020 and October 2020. The observed muon flux increases are
 165 interpreted as follows. (i) The volcanic sediments were transported from the selected peak regions to
 166 downstream regions of the volcano by the onset of rain-triggered lahar events. It is worth noting that the
 167 muon flux increases did not reflect all lahars. These lahar events were assumed to have been initiated in
 168 the downstream region after the erosion of peak region. (ii) Further mass decreases were observed without
 169 the occurrence of lahar events, e.g. after mid-September 2020. This observation suggests the water driven
 170 erosion of the peak region of Sakurajima volcano. These processes were induced by rain falls that were
 171 observed continuously during the typhoon season from August to October 2020.

Figure 6. The relative variation of total mass measured through the three volcano regions is shown relative to the total mass measured in the 1st time sequence as a function of time. The relative mass values (black lines) are plotted with 1 standard deviation error (green-coloured bands) and its variation is compared to the variations of the daily number of lahar events (orange-coloured impulses in panel **A**), total daily precipitation (blue-coloured impulses in panel **B**), maximum hourly precipitation (red-coloured impulses in panel **B**) and daily number of eruptions (yellow-coloured impulses in panel **C**), respectively.

172 In conclusion, we propose muography as a tool for monitoring of the hydrogeomorphic responses to

the disturbance of the landscape of Sakurajima volcano. The sensitive surface area of the MMOS system was upgraded up to 7.67 m^2 to detect muons within a total acceptance of $1.36 \text{ m}^2\text{sr}$. This drastically decreased the time required to measure the volume of materials, either tephra deposition or transportation, through the crater regions from 240 days to 40 days. The measured muon flux and mass deposit changes reflected the tephra deposition which occurred due to the ejection of approx. 2 Mt tephra after October 2019, as well as tephra transport by post-eruptive lahars and rain-triggered erosion of the volcanic edifice. These results demonstrate the applicability of muography for the measurement of erosion processes at a shorter duration which may contribute to improved modeling of the erosion of the volcanic edifice and assessment of volcano hazard levels.

Methods

Observational instruments. The design, operation and performance of the MWPCs and the tracking systems are presented extensively in Refs.^{28,33,43}, therefore here just a brief description is provided. Each tracking system was assembled with seven or eight MWPCs comprising a total surface area of 0.64 m^2 or 0.96 m^2 . The length of each tracking system was set to approx. 2 m. The total effective acceptance of ten tracking systems was $1.38 \text{ m}^2\text{sr}$. Figure 7 shows the merged acceptance of MMOS system as a function of track slopes. Five 2-cm-thick lead plates were installed between the tracking layers to deflect or absorb the low-energy particles. This setup of MWPCs and lead plates provided angular resolutions of approx. 3 mrad for both horizontal and vertical directions³³.

Figure 7. The total acceptance of ten tracking systems is shown as a function of horizontal and vertical tracks slopes with a bin size of approx. $5.5 \text{ mrad} \times 5.5 \text{ mrad}$. Coloured lines highlight equal values at the acceptance of $0.5 \text{ cm}^2\text{sr}$ (yellow), $1 \text{ cm}^2\text{sr}$ (cyan), $1.5 \text{ cm}^2\text{sr}$ (pink), $2 \text{ cm}^2\text{sr}$ (blue) and $2.5 \text{ cm}^2\text{sr}$ (green), respectively.

Micro-computer-based detector control and data acquisition systems were installed in each tracking system to achieve autonomous operation. The data collection was triggered by a coincidence of at least three MWPCs. The triggering efficiency was found above 99 % for each tracking system and trigger was blocked for a few hundreds of microseconds during the data readout. This resulted in a dead time of approx. 0.2 % for each tracking system during the data collection period. A local server micro-computer communicated with the micro-computers of tracking systems and controlled the data collection and

management. The collected data were transferred to a remote server where data storage and quality assurance were performed. The maintenance of the MMOS was required regularly every 4-6 months.

Track reconstruction and flux measurement. Track reconstruction and selection performed by an event-by-event analysis independently for each MMOS module³³. A pre-analysis was applied for exclusion of noisy readout channels and alignment of detector layers. The tracks were reconstructed by means of two independent line fits on the reconstructed cluster centroids in horizontal and vertical directions. The tracks were selected from the reconstructed set based on the chi-squares of fitted lines^{33,37}. The flux of the module (F_{mod}) was calculated for each $\tan(\theta_x)$ - $\tan(\theta_y)$ angular bin as follows.

$$F_{\text{mod}} = \frac{N_{\text{tracks}}}{A \times \Delta t} , \quad (1)$$

where N_{tracks} is the number of selected tracks, A is the acceptance of tracking system, Δt is the effective data collection time. The horizontal orientations of different tracking systems were found within an angle of 12 mrad relative to a reference one, namely MMOS01, by means of minimization of relative flux differences³⁷. These corrections were also taken into account in the track reconstruction procedure. In the last step of flux calculation, the F_{mod} were weighted with the relative flux errors and averaged to quantify the merged flux of MMOS system (F).

Mass calculation. The X density-lengths were determined by means of the comparison of measured and modeled fluxes. The latter ones were derived to various density-lengths up to 3,000 meter-water-equivalent with a step of 2 meter-water-equivalent as follows.

$$F_{\text{calc}}(90^\circ - \theta_y, L) = \int_{E_{\text{thr}}(L)}^{\infty} f_{\text{diff}}(E, 90^\circ - \theta_y) dE , \quad (2)$$

where $E_{\text{thr}}(L)$ is the threshold energy that is required to muons to penetrate L density-length. The fluctuations of radiative energy loss processes dominate the energy loss of muons⁵⁶ that are being able to penetrate the volcanic edifice. For parametrization of $E_{\text{thr}}(L)$, muons were generated with realistic muon spectra and their penetration strengths were simulated through silicon dioxide walls with different density-lengths in GEANT4 framework⁵⁷. The extracted threshold energies were fitted in $(1-7) \times 10^5$ gcm⁻² density-length range with a third-order polynomial function: $E_{\text{thr}}(L) = p_0 + p_1 L + p_2 L^2 + p_3 L^3$, where the L is given in gcm⁻² units and $p_0 = -186.6760$, $p_1 = 0.0051$, $p_2 = -7.6098 \times 10^{-9}$, $p_3 = 2.3328 \times 10^{-15}$. Figure 8A shows the $E_{\text{thr}}(L)$ in silicon dioxide for GEANT4 and continuous-slowing-down-approximation (CSDA)⁵³. Figure 8B shows the survival rates of 1-TeV-muons through standard rock ($\rho = 2.65$ gcm⁻³, $A = 22$, $Z = 11$) for the data generated by GEANT4 (red circles) and a simulation presented in Ref.⁵⁶ (black line). Data produced by different simulations were found in agreement; this result validated the simulation presented in this work. $f_{\text{diff}}(E, 90^\circ - \theta_y)$ differential muon energy spectra were modeled by a modified Gaisser parametrization⁵⁴. The L density-lengths were extracted when differences between the measured and modeled fluxes were found to be minimal. The average masses, M , through the designated volcano regions were estimated using the following formula⁴²:

$$M = N \times D^2 \times \Delta \tan(\theta_x) \times \Delta \tan(\theta_y) \times L , \quad (3)$$

where N is the number of angular bins that were involved in the designated region, $D \approx 2,700$ m is the distance between the MMOS and volcanic edifice, as well as $\tan(\theta_x) \ll 1$ and $\tan(\theta_y) \ll 1$.

Figure 8. The threshold energies of muons were quantified with GEANT4 simulation. **(A)** The continuous-slowing-down-approximation⁵³ (CSDA, black line) and the simulated threshold energies (red line) are shown for silicon dioxide. **(B)** The survival rates of muons with an energy of 1 TeV through standard rock were found in agreement for data produced by Monte Carlo simulations presented in Ref.⁵⁶ (black line) and GEANT4 (red circles). Black arrow shows the range of 1 TeV muon in standard rock quantified by CSDA.

Atmospheric effects of muon production. Changes in atmosphere's thermal state affect the muon production⁵⁸ that has to be taken into account in muographic monitoring⁴⁰. The ΔF change from the F muon flux due to pressure and temperature changes can be quantified with the following empirical formula:

$$\frac{\Delta F}{F} = \beta \Delta p + \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}}, \quad (4)$$

where β is the barometric coefficient, Δp is the pressure change from the average pressure that is measured at the observational site, α_T is the temperature coefficient that depends on amount of transferred materials and T_{eff} is the weighted average of temperatures measured under different atmospheric pressures. The temperature weights describe the propagation of pions and kaons through the atmosphere⁵⁹. The pressure and effective temperature changes were quantified using the atmospheric weather data that were collected above the Kagoshima Bay⁶⁰. The average pressure was found to be 986 hPa with a change of $\Delta p < 10$ hPa. The β was estimated below 10^{-5} hPa^{-1} for TeV muons⁶¹, thus the barometric effect was estimated to well below 1 %. The effective temperatures were quantified with the procedure that was proposed in Ref.⁵⁹. The energy threshold and the zenith-angle parameters were set to 500 GeV and 75° . The seasonal variation of effective temperature is shown by blue dots in Figure 9. These were fitted with a cosine function (solid red line) and an effective temperature variation of 4 °K was quantified around the average effective temperature of 223.5 °K. The corresponding coefficient was approximated to $\alpha_T \approx 1$ using that

219 data that was compiled in Ref.⁵⁹. Therefore, a relative muon flux variation of 1.5 % was estimated for our
 220 campaign due to atmospheric pressure and temperature effects.

Figure 9. The effective temperatures are shown for the data collection period. The T_{eff} values were calculated using the balloon-borne measurements performed above the Kagoshima Bay⁶⁰. The cosine fit shows an average seasonal variation of 4 °K around the average value of 223.5 °K.

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Author contributions statement

H. K. M. T. and L.O. conceived the study. L.O, G.H. and H. K. M. T. conducted the data collection. L. O. performed the data analysis. L. O. prepared the figures. L. O. and H.K.M.T. wrote the manuscript text. All authors reviewed the manuscript.

Additional information

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Figure 1. The map of the measurement site and the schematic drawing of the experimental arrangement. (A) The map of Kyushu, Japan is shown with the location of Sakurajima volcano (white star)⁴⁴. (B) The elevation map of Sakurajima volcano is shown based on the data of Geospatial Information Authority of Japan⁴⁴. The location of Sakurajima Muography Observatory (SMO) is shown by a filled white star. The dashed white lines show the orientation and angle of view of SMO. The coloured solid lines show selected cross-sections across the Central Craters (CC), Showa Crater (S) and Arimura Basis (AB), and Arimura Middle Reaches (AMR), respectively. The locations of lahar observation stations are shown by empty white stars. (C) The selected cross-sections of Sakurajima volcano are shown across the blue-coloured, cyan-coloured and gray-coloured lines of panel B. The coloured lines indicates three selected angular regions in the vertical direction for muographic observation of the volcanic edifice.

Figure 2. Photograph about three tracking systems of Multi-Wire-Proportional-Chamber-based Muography Observation System (MMOS). Ten MMOS operated in the Sakurajima Muography Observatory during the data collection period.

Figure 3. The southern peak of Sakurajima volcano is shown with the designated regions. **(A)** A photograph of the southern peak that was captured at the muography observatory. **(B)** The measured muon flux is shown as a function of horizontal ($\tan(\theta_x)$) and vertical ($\tan(\theta_y)$) directions with an angular resolution of $5.5 \text{ mrad} \times 5.5 \text{ mrad}$ for a period of 227 days. The white shaded regions without flux values represent very large thicknesses with inpractically low penetrated muon count. The coloured rectangles show the designated angular regions for Central Crater (CC, blue), Showa and Arimura Basin (S and AB, cyan) and Arimura Middle Reaches (AMR, gray), respectively.

Figure 4. The averaged muon fluxes are shown with 1 standard deviation for the Reference Region (red-coloured band), Central Craters (blue-coloured band), Showa Crater and Arimura Basin (cyan-coloured band) and Arimura Middle Reaches (gray-coloured band), respectively.

Figure 5. The variations of averaged muon fluxes (F) relatively to the fluxes measured at the first time sequence (F_0). The relative flux changes are shown with 1 standard deviation bands during the data collection period for the Reference Region (red-coloured band), Central Craters (blue-coloured band), Showa Crater and Arimura Basin (cyan-coloured band) and Arimura Middle Reaches (gray-coloured band), respectively.

Figure 6. The relative variation of total mass measured through the three volcano regions is shown relative to the total mass measured in the 1st time sequence as a function of time. The relative mass values (black lines) are plotted with 1 standard deviation error (green-coloured bands) and its variation is compared to the variations of the daily number of lahar events (orange-coloured impulses in panel A), total daily precipitation (blue-coloured impulses in panel B), maximum hourly precipitation (red-coloured impulses in panel B) and daily number of eruptions (yellow-coloured impulses in panel C), respectively.

Figure 7. The total acceptance of ten tracking systems is shown as a function of horizontal and vertical tracks slopes with a bin size of approx. $5.5 \text{ mrad} \times 5.5 \text{ mrad}$. Coloured lines highlight equal values at the acceptance of $0.5 \text{ cm}^2\text{sr}$ (yellow), $1 \text{ cm}^2\text{sr}$ (cyan), $1.5 \text{ cm}^2\text{sr}$ (pink), $2 \text{ cm}^2\text{sr}$ (blue) and $2.5 \text{ cm}^2\text{sr}$ (green), respectively.

Figure 8. The threshold energies of muons were quantified with GEANT4 simulation. **(A)** The continuous-slowing-down-approximation⁵³ (CSDA, black line) and the simulated threshold energies (red line) are shown for silicon dioxide. **(B)** The survival rates of muons with an energy of 1 TeV through standard rock were found in agreement for data produced by Monte Carlo simulations presented in Ref.⁵⁶ (black line) and GEANT4 (red circles). Black arrow shows the range of 1 TeV muon in standard rock quantified by CSDA.

Figure 9. The effective temperatures are shown for the data collection period. The T_{eff} values were calculated using the balloon-borne measurements performed above the Kagoshima Bay⁶⁰. The cosine fit shows an average seasonal variation of 4 °K around the average value of 223.5 °K.