Muon Imaging of Volcanic Conduit Explains Link between Eruption Frequency and Ground Deformation

László Oláh[1,9], Giuseppe Gallo[2,9], Gergő Hamar[3,9], Osamu Kamoshida[4,9], Giovanni Leone[5,9], Edward W. Llewellin[6], Domenico Lo Presti[2,7,9], Gábor Nyitrai[3,8,9], Takao Ohminato[1], Shouhei Ohno[4], Hiroyuki K. M. Tanaka[1,9], Dezső Varga[3,9]

[1]Earthquake Research Institute, The University of Tokyo, Tokyo, Japan

[2]Department of Physics and Astronomy "E. Majorana", University of Catania, Catania, Italy

[3]Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

[4]NEC Corporation, Tokyo, Japan

[5]The University of Atacama, Copiapó, Chile

[6]Department of Earth Sciences, Durham University, Durham, UK

[7]National Institute for Nuclear Physics, Catania, Italy

[8]Faculty of Natural Sciences, Budapest University of Technology and Economics, Budapest, Hungary

[9]International Virtual Muography Institute, Global

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Muographic Observation Instrument: We applied a modular MMOS system of Sakurajima Muography Observatory for this study (Oláh et al., 2018, 2019, 2021; Varga et al., 2020). The number of modules increased by the upgrade of MMOS system during the data collection period from five to eleven tracking systems. Each module was assembled with seven or eight Multi-wire Proportional chambers (MWPCs) (Varga et al., 2020). Two perpendicular wire planes were used in the MWPCs with a segmentation of 1.2 cm in both horizontal and vertical dimensions. This projective geometrical arrangement provided 1+1-dimensional positional information. The MWPCs had 96×64 segments in six modules and 64×64 segments in five modules. A length of 2 metres was set for each tracking system. Five 2-cm-thick lead plates were installed between the tracking layers to deflect or absorb the low-energy (< 1 GeV) particles that did not penetrate the volcanic edifice. This experimental setup provided an angular resolution of approx. 3 mrad. An Ar-CO_2 gas mixture was flushed through the MWPCs with a flow rate of approx. 1 liter per hour for signal generation by charged particles. The coincidence of at least three MWPCs triggered the data collection. Detector control and data acquisition were performed by a micro-computer in each module to allow autonomous operation. A local server micro-computer communicated with modules and controlled the data acquisition. The data were transferred to a remote server where automated quality assurance was performed on daily basis. We conduct the maintenance of the MMOS system every 4-6 months.

Muographic Image Processing: Data quality assurance and analysis methods have already beend presented extensively in the References (Oláh et al., 2018, 2019). Track reconstruction was performed by an event-by-event analysis for each tracking system. The reconstruction of the slopes and intersects of tracks was conducted by a combinatorial algorithm. The tracks were selected based on their chi square per number of degrees of freedom. These track cuts were set with detector simulations (Oláh et al., 2019) to reject the sub-GeV muons. The muon flux was calculated by dividing the number of tracks with acceptance of tracking system and effective data collection time for each $\Delta(\tan(\theta_\mathrm{X})) \times \Delta(\tan(\theta_\mathrm{Y}))$ bin. In the last step, the flux calculated for different modules were weighted with their relative flux errors and averaged to quantify the flux of MMOS system. The average densities were calculated by means of comparisons of measured and modeled fluxes on angular bin by angular bin basis. The modeled fluxes were calculated for different density-lengths (quantity given by densities integrated along the paths of muons) by integrating the differential muon spectra (Tang et al., 2006) from the threshold energies that were required for muons to penetrate across the volcanic edifice. The threshold energies were calculated by taking into account the stochastic energy loss processes of muons (Lipari & Stanev, 1991; Oláh et al., 2021). The digital elevation model of Sakurajima volcano with a mesh size of 50 m $\times$ 50 m was used to calculate the path-lengths through the volcanic edifice. The systematic density error of 0.06 $\mathrm{g cm^{-3}}$ were originated from the following sources (Oláh et al., 2021; Oláh & Tanaka, 2022): atmospheric temperature and pressure effects on muon production, instrumental effects (e.g., variation of gas amplification, malfunctioned electronics channels, etc.), the multiple scattering of muons through the volcanic edifice, in air and in the MMOS, the energy cut of the MMOS, as well as the modeling of muon spectra.

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