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TRANSFORMATIVE SCIENCE
FOR LIFE & EARTH

Cosmic-Ray Muon Imaging for the Structural Characterization of Volcanic Slopes

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29 May 2026



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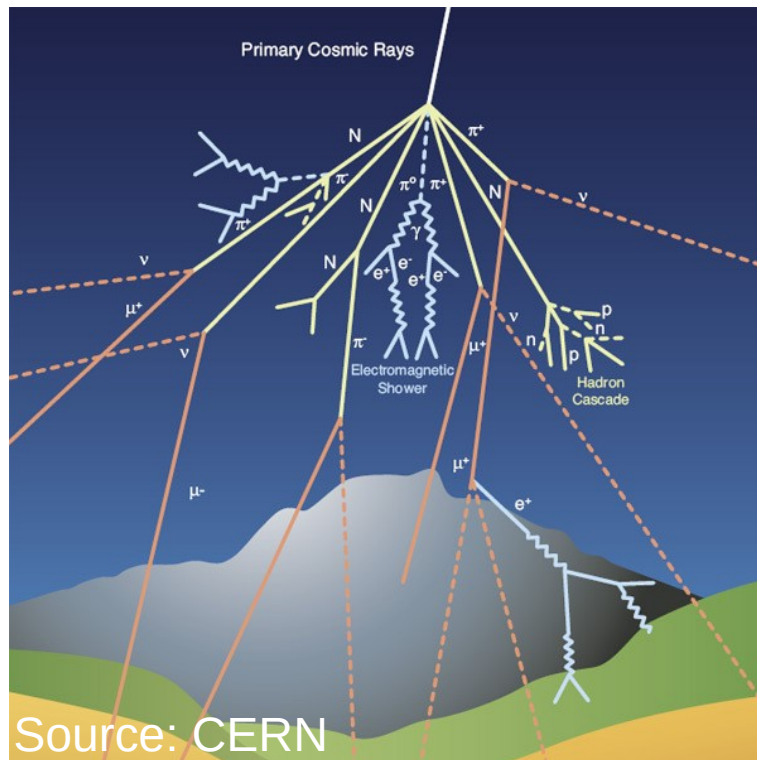


Outline

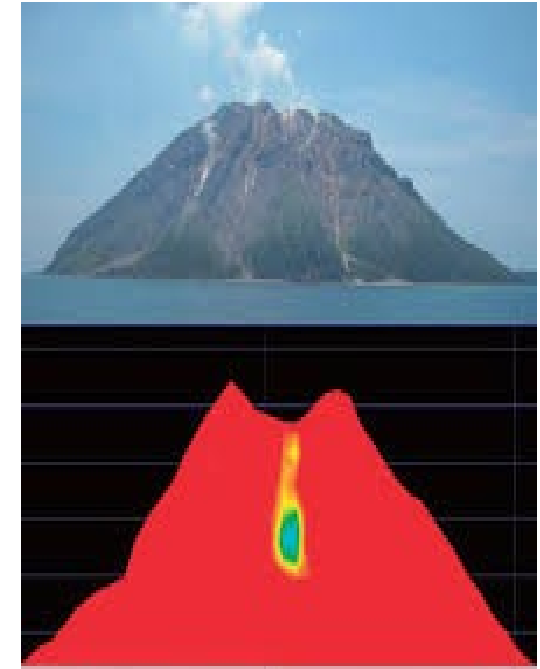
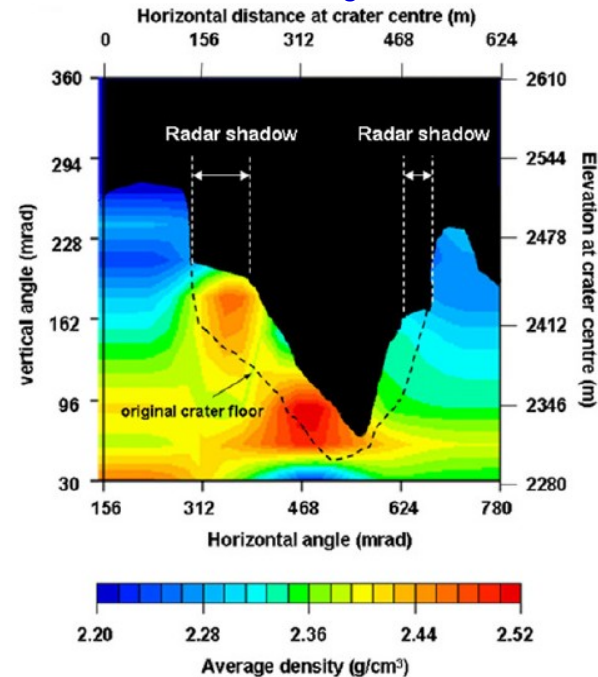
- I. Introduction: Muography as a Complementary Technique for Structural Characterization of Volcanoes**
- II. Hydrogeomorphic Changes Observed on the Active Sakurajima Volcano**
- III. Structural Characterization of Mount Unzen**
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I. Introduction: Muography as a Complementary Technique for Structural Characterization of Volcanoes

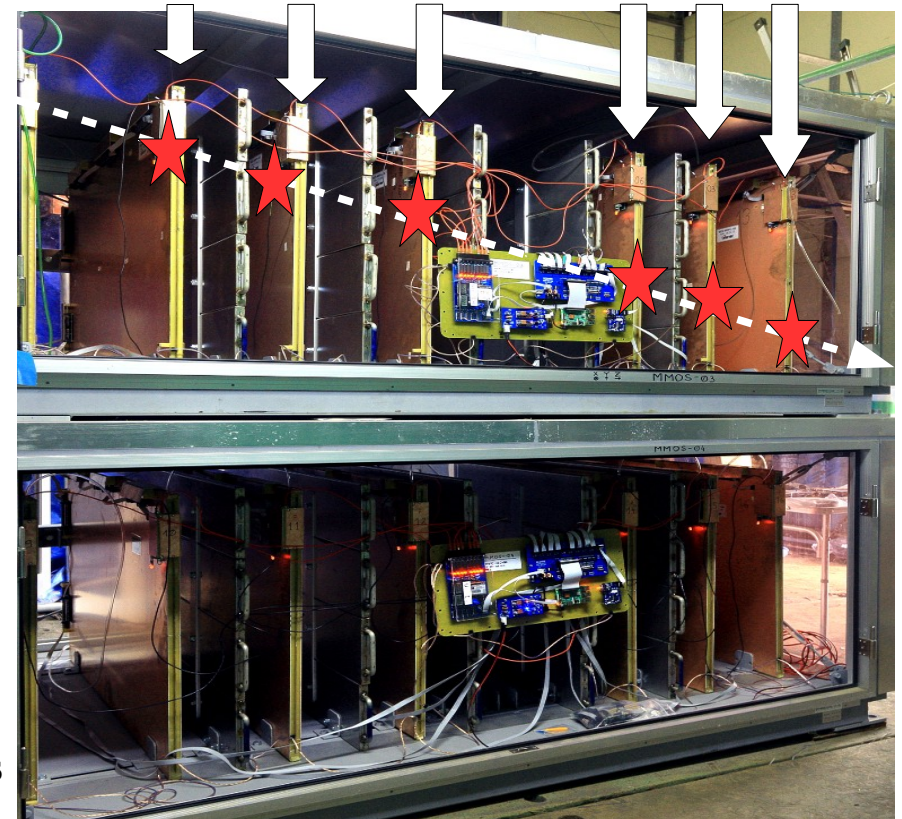
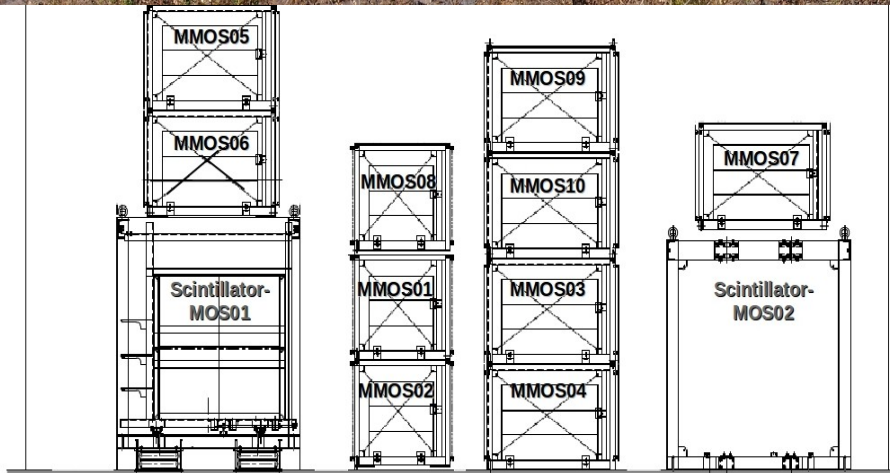
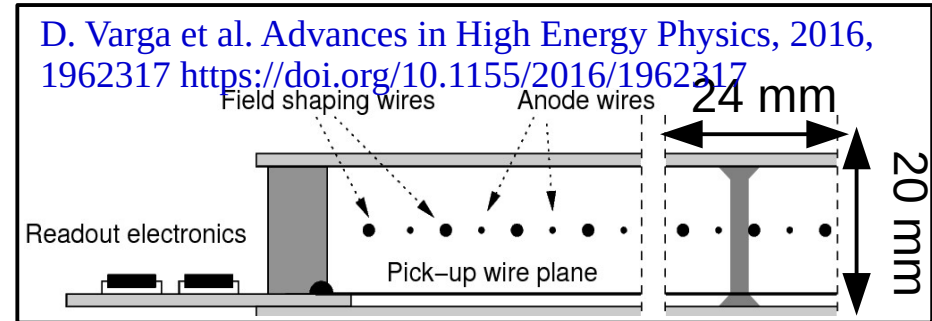
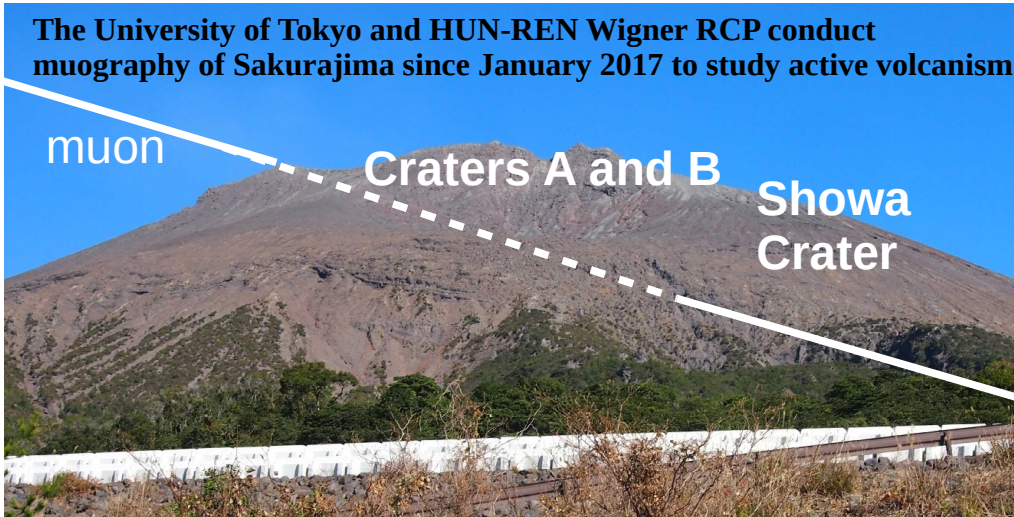
- Cosmic-ray muons are **continuously produced in the atmosphere** and are observed everywhere on Earth. Muons are **highly penetrative particles** that can travel through even a few kilometers of rock. The flux of transmitted muons depends on the thickness and density of the penetrated media.
- **Muography:** "X-raying" of large structures via tracking of cosmic-ray muons → **passive, remote, high-resolutational imaging of the subsurface structure of volcanoes**
- Muographic density imaging allows (1) the monitoring of the evolution and movement of magma, (2) reconstructing of upper conduit structures, (3) **the monitoring of the mass of tephra deposition and erosion**, (4) **localizing weak zones**, etc.



First muon images of volcanoes by H.K.M. Tanaka et al. (mid 2000s)



Muography Observation System (MOS)



- **Modular infrastructure for volcano muography** (8 MWPC-based trackers cover 8 sqm surface area)
- **Micro-computer controlled** → real-time DAQ & analysis
- **Power consumption:** ~ 6 W per MMOS

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Muographic Observation Instrument WO2017187308
<https://patentscope2.wipo.int/search/en/detail.jsf?docId=WO2017187308>

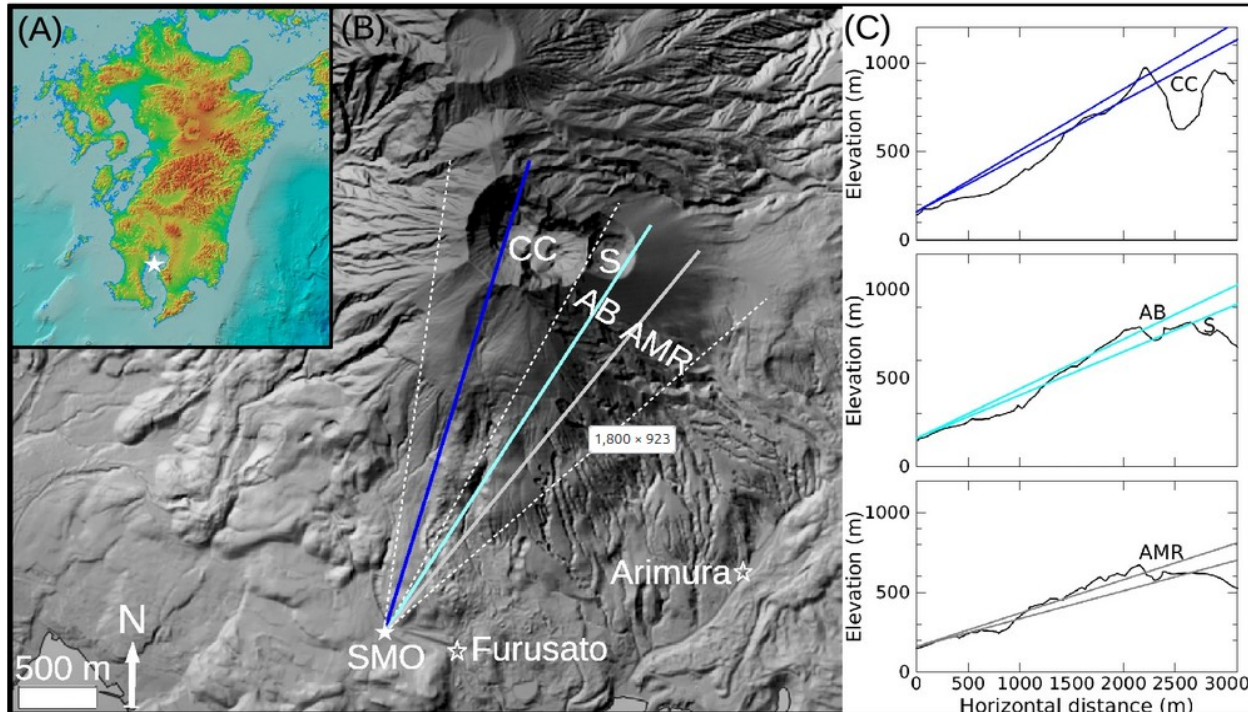
L. Oláh et al. *Scientific Reports*, 8, 3207, 2018,
<https://doi.org/10.1038/s41598-018-21423-9>

D. Varga et al. *Nucl. Instrum. Meth. A* 958, 162236, 2020
<https://doi.org/10.1016/j.nima.2019.05.077>

II. Hydrogeomorphic Changes Observed on the Active Sakurajima Volcano

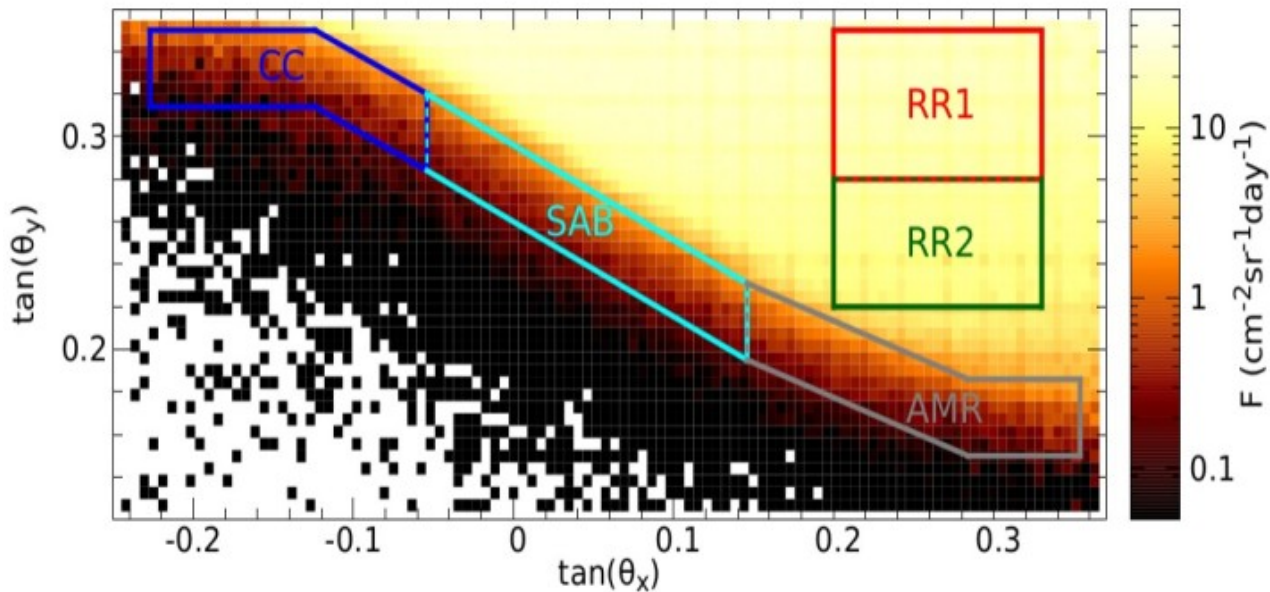


- Lahars are fast-moving gravity-driven flows of mixture of volcanic rocks and water occurred either during eruptions or when the volcano is dormant.
- Wind and water driven erosion processes can destabilize and mobilize the tephra deposition before they become fully incorporated into the soil.



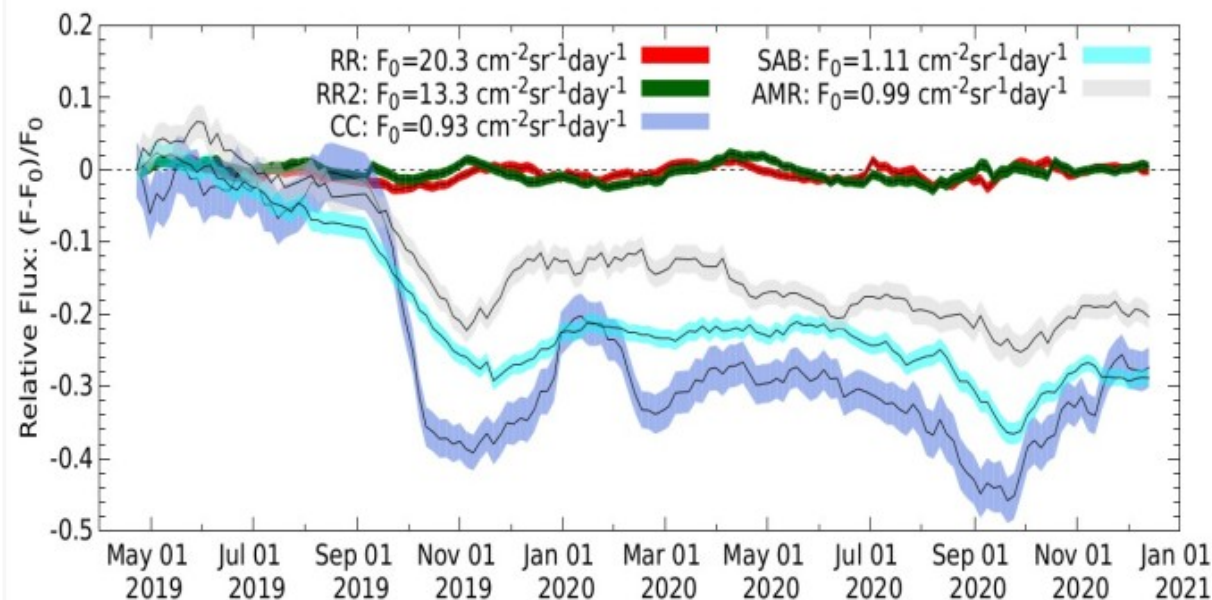
- The generation and dynamics of lahars are controlled by the following factors:
 - (i) local topography,
 - (ii) volcanic activity,
 - (iii) amount and composition of tephra,
 - (iv) intensity and duration of rainfall.
- Muography has potential to measure the amount (mass and thickness) of tephra deposition and topographical changes that controlling the onset of post-eruptive lahars.

Muon Flux Reduction due to Tephra Deposition



- Muon flux was monitored through the
 - Central Craters (CC),
 - Showa and Arimura Basin (SAB),
 - Arimura Middle Reaches (AMR),
 - two reference regions (RR1, RR2).

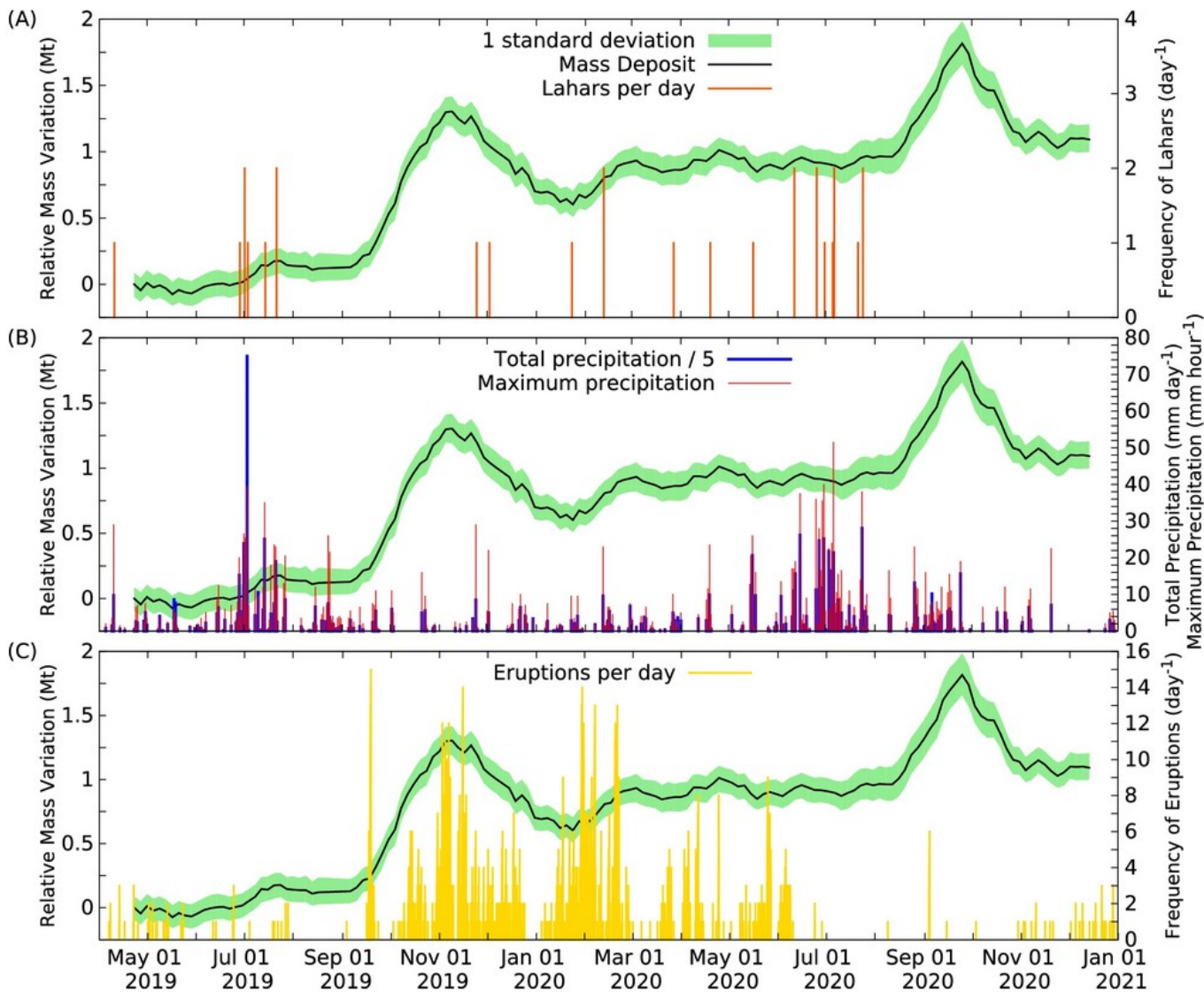
- The fluxes were averaged in each angular region for time-intervals of 4 days, and the averaged fluxes were smoothed by applying a moving average calculated from the previous ten consecutive time-intervals, i.e. over a period of 40 days.



- After September 2019, the relative averaged fluxes (measured relatively the flux of the first time sequence, F_0) decreased through the volcano regions from 10 to 40%.

- Change of volcanic ejecta mass that was measured to approx. 0.25 Mt between April and September 2019 and approx. 2 Mt from September 2019 to July 2020 by the Japan Meteorological Agency.

Mass Losses due to Lahars and Erosion



- The total mass (volcanic edifice and tephra) was measured to $M_0 = (7.54 \pm 0.05)$ Mt during the 1st time-interval → Relative mass variation ($M - M_0$) was quantified
- Mass deposit showed significantly decreasing trends through various periods, e.g. from November 2019 to January 2020, during September 2020 and October 2020:
 - (i) The volcanic sediments were transported from the selected peak regions to downstream regions of the volcano by the onset of rain-triggered lahar events.
 - (ii) Further mass decreases were observed without the occurrence of lahar events, e.g. after mid-September 2020. This observation suggests the water driven erosion of the peak region of Sakurajima volcano.

III. Structural Characterization of Mount Unzen

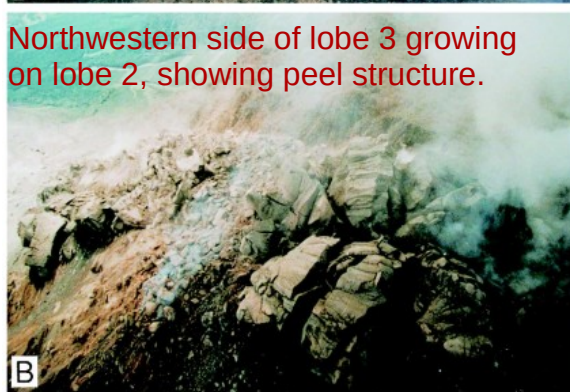
Petals of lava are growing within a large scar left by the 3 June 1991 pyroclastic-flow event.



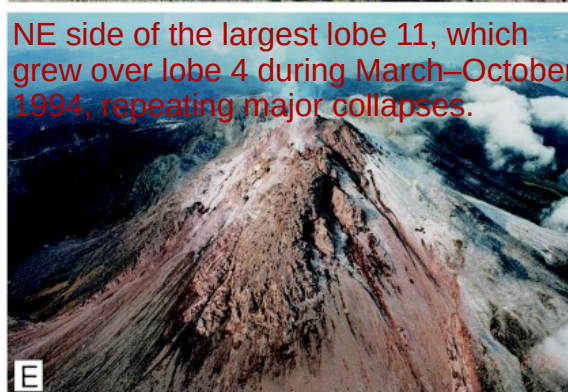
SW side of lobe 10 growing on the dome (top) above the Jigokuato Crater.



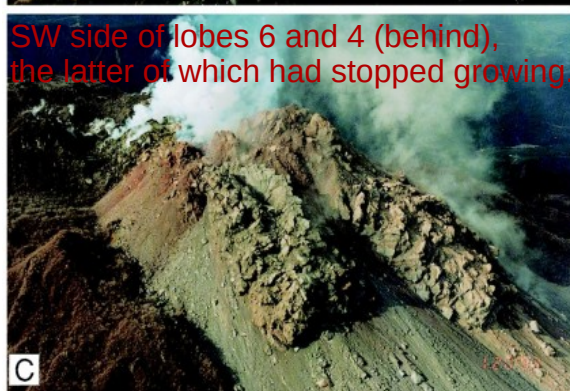
Northwestern side of lobe 3 growing on lobe 2, showing peel structure.



NE side of the largest lobe 11, which grew over lobe 4 during March–October 1994, repeating major collapses.



SW side of lobes 6 and 4 (behind), the latter of which had stopped growing.



Southern side of lava spine extruded at the top of the endogenous dome in the final stage.

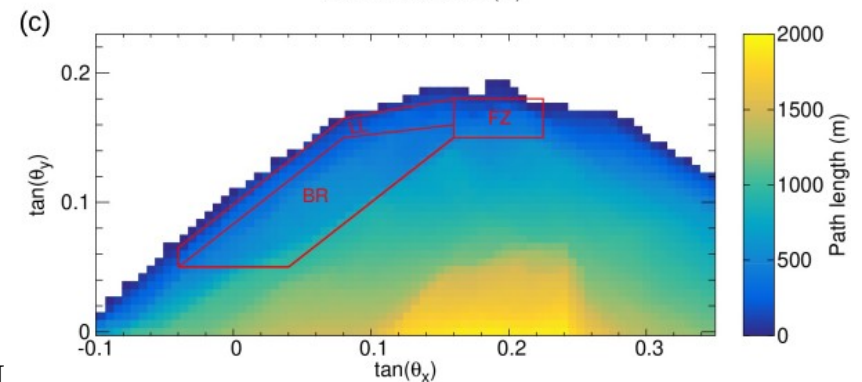
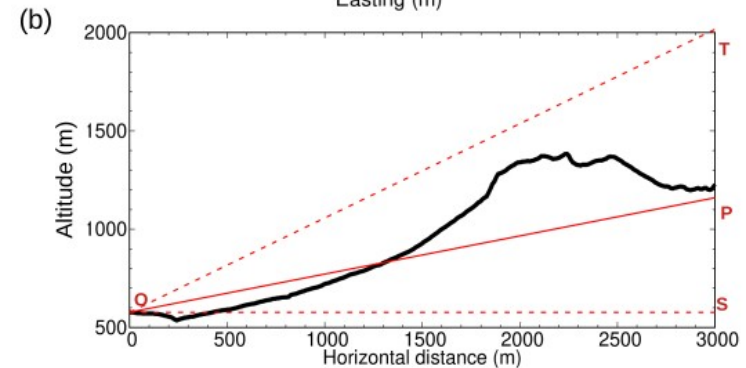
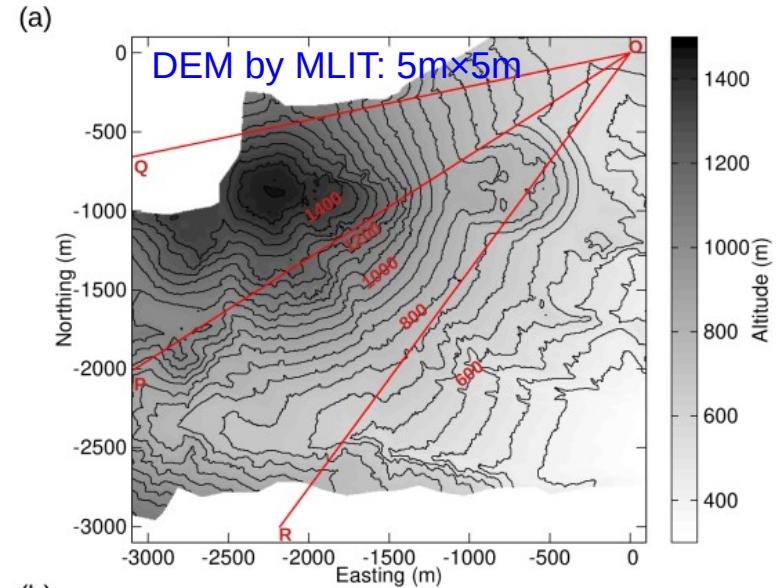
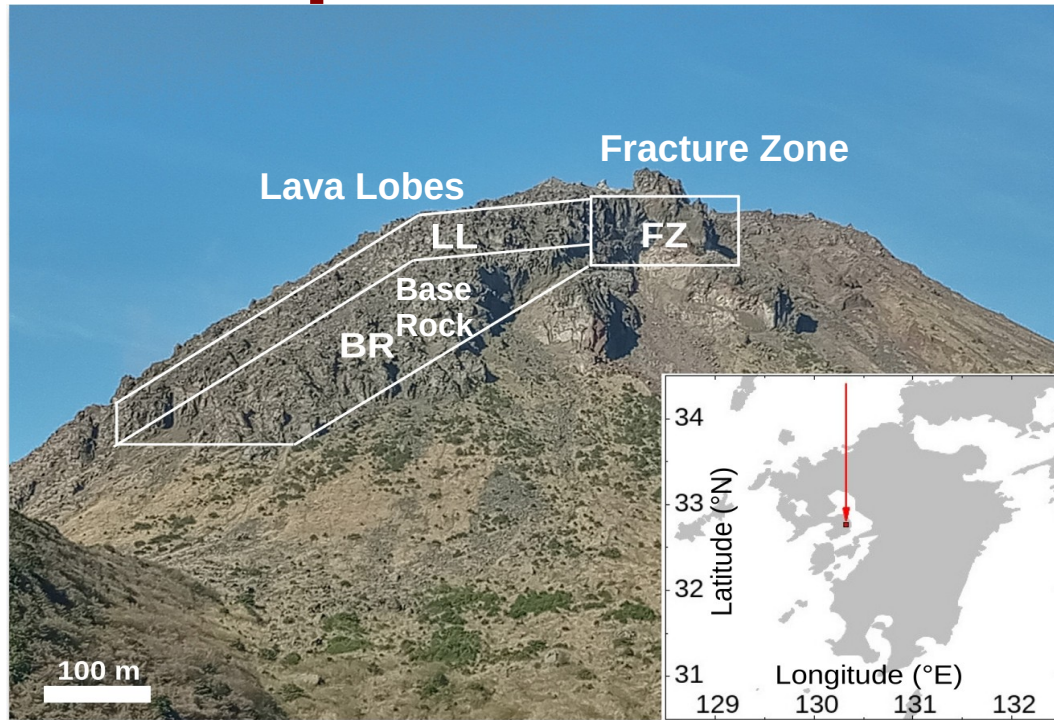


- Lava lobes deposited on the summit of Mount Unzen during the eruption of 1990-1995.

Nakada, S., Shimizu, H. & Ohta, K., 1999. Overview of the 1990-1995 eruption at Unzen Volcano, *J. Volc. Geotherm. Res.*, 89, 1–22
[https://doi.org/10.1016/S0377-0273\(98\)00118-8](https://doi.org/10.1016/S0377-0273(98)00118-8)

- Destabilization of lava lobes can generate debris avalanches with catastrophic impacts on their environment.
- Muography has potential to characterize and monitor the structure of lava lobes by means of density monitoring and contribute to hazard assessment.

Experimental Setting at Mount Unzen



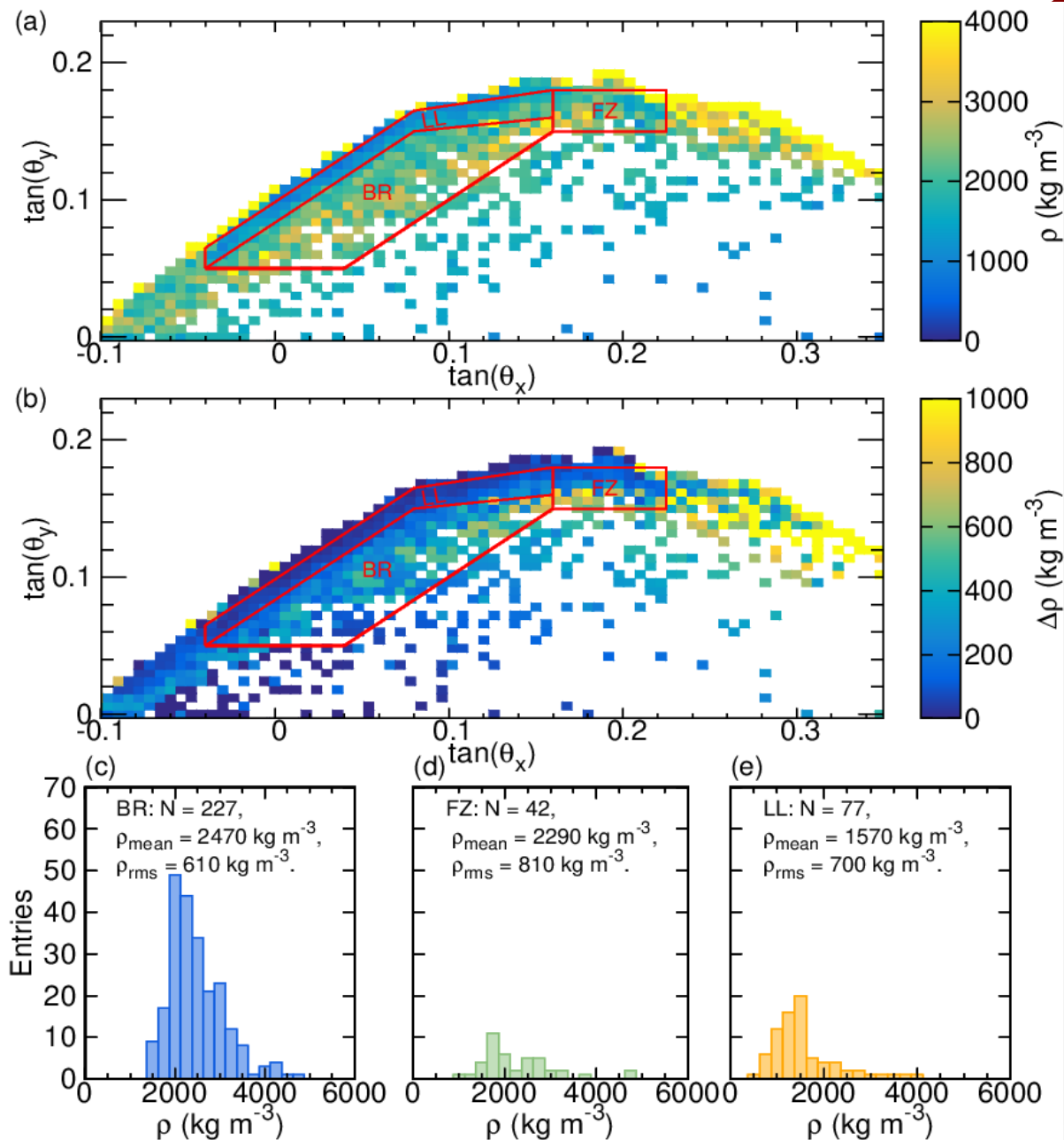
MOS was installed at a longitude of 130.322515 E° and a latitude of 32.769151 N° at an altitude of 576 m above sea level at a distance of about 2000 m in a northeast direction from the Fugendake peak.

The MOS was oriented to the azimuthal direction of 236.5° from north and tilted up 11.5° from the horizontal direction.

The data collection was performed for **203 d between 2024 March 28 and December 14.**

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Long-term Weakening of Lava Lobes Inferred from Density Reduction



- The obtained high-resolution muographic image shows the internal **density structure** with a **spatial resolution of 12 meters**.
- Mean densities were respectively measured as 2470 and 2290 kg m^{-3} for the **base rock (BR)** and a **fracture zone (FZ)**, and **both were consistent with the results of prior drilling and sampling experiments**.

Ikeda, R., Kajiwar, T., Omura, K. & Hickman, S., 2008. *J. Volc. Geotherm. Res.*, 175, 13-19. <https://doi.org/10.1016/j.jvolgeores.2008.03.036>

- The mean density of **lava lobes (LL)** was measured significantly lower value of 1570 kg m^{-3} , **indicating post-eruptive structural weakening**.

Nakada, S., Shimizu, H. & Ohta, K., 1999. *J. Volc. Geotherm. Res.*, 89, 1-22. [https://doi.org/10.1016/S0377-0273\(98\)00118-8](https://doi.org/10.1016/S0377-0273(98)00118-8)

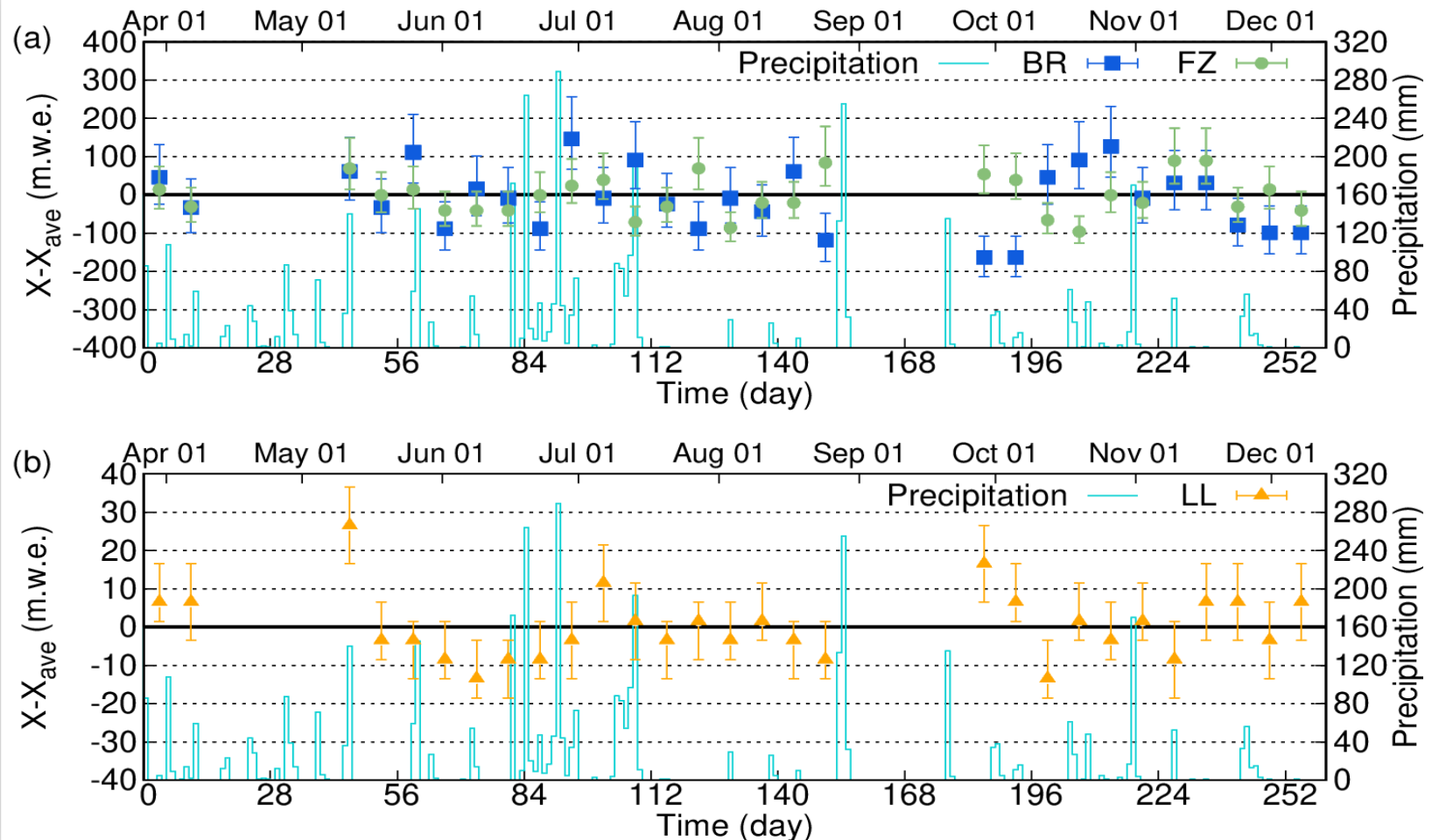
- Alteration of lava lobes may caused by hydrothermal circulation occurred beneath the lava lobes**

Hashimoto, T. & Tanaka, Y., 1995. *Geophys. Res. Lett.*, 22, 191-194. <https://doi.org/10.1029/94GL03077>

Saibi, H., Gottsmann, J. & Ehara, S., 2010. *J. Volc. Geotherm. Res.*, 191, 137-147. <https://doi.org/10.1016/j.jvolgeores.2010.01.007> 10

Muon Monitoring of Heavy Rainfall Induced Mass Gains in the Lava Lobes

- A comparison between the time-series of muographically measured density-lengths (mean values for period of 7 days) and daily precipitation records suggest that **rainfall-induced gravitational destabilization did not occur during the observational period.**
- When the density-lengths reached their local maxima, those started to decrease within a few days because highly fractured rocks are highly permeable for water. Therefore, the short-term density-length increases had no impact on the stability of the lava lobes during the measurement period.



IV. Discussion, Conclusion

- Muography is sensitive to mass/density changes occurred in volcanic slopes → Monitoring of tephra deposition and removal, ground/rain water inflows, localization of structural weakening, etc.
- Muography can cover a large surface area with spatial resolution of a few metres → complementing of the sampling and drilling experiments
- Muography provides complementary data for intermediate-term (from a few days to a few months) assessment of post-eruptive hazards.