Japan Geoscience Union Meeting 2025
MAY 25 - 30, 2025
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On-site: MAKUHARI MESSE, Chiba, Japan
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Studying Active Volcanism with Joint Muon and Ground Surface Deformation Monitoring at Sakurajima Volcano

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26 May 2025

National Research, Development and Innovation Office Hungary
PROGRAM FINANCED FROM THE NRDI FUND

東京大学 The University of Tokyo
Muographix
Earthquake Research Institute, The University of Tokyo
HUN-REN Magyar Kutatási Hálózat
MEXT Ministry of Education, Culture, Sports, Science and Technology-Japan
Kagoshima KOSEN
Wigner

Outline

I. Introduction

II. Data Collection and Processing

III. Results

IV. Monitoring of Underground Position at Active volcanoes with muPS

V. Summary

I. Introduction

- **Active volcanism** is driven by the subsurface evolution and movement of magmatic materials, which **may induce seismicity, ground deformation, gas emission, and fumarolic activity**

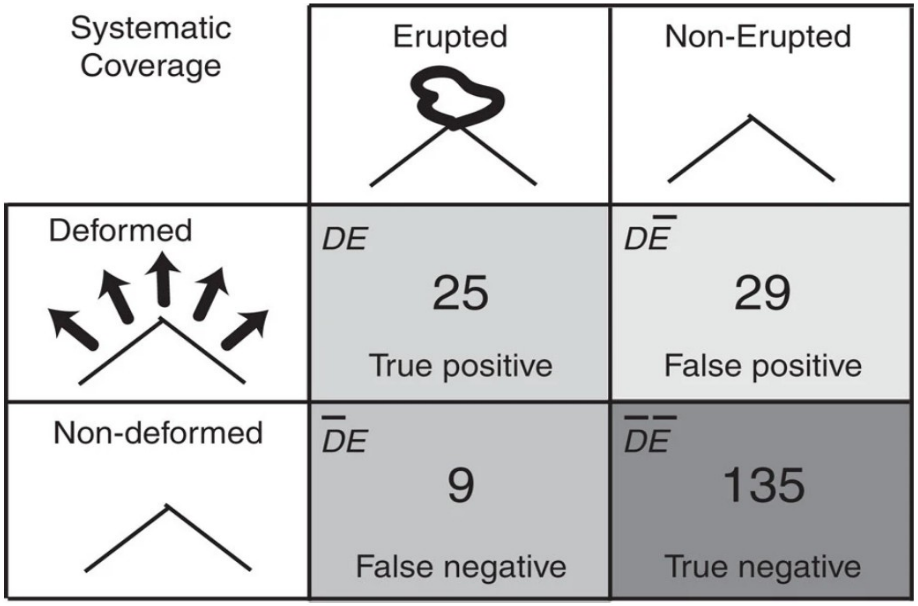
- Monitoring of the signals induced by these phenomena is indirect and interpretation of the origin of the signals is challenging because a wide variety of factors influence the behaviour of magma and host rock in the run-up towards eruption

- 198 volcanoes with a full 18-year observation history showed that **46 % of deformed volcanoes erupted**

- **Understanding the causal physical mechanism by which ground deformation and volcanic activity are linked is required for robust forecasting**

- **Aim: Revealing the causal physical mechanism of ground deformations (changing in the state of magma) via density monitoring with muography**

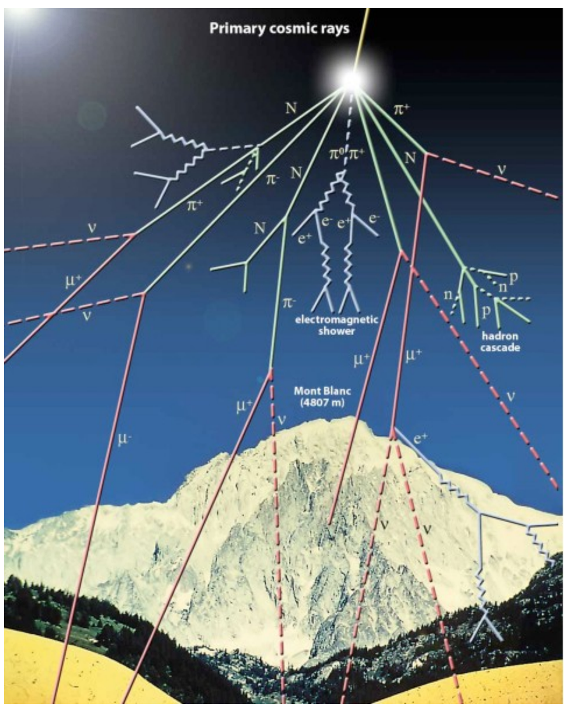
J. Biggs et al. Global link between deformation and volcanic eruption quantified by satellite imagery. Nat Commun 5, 3471 (2014).https://doi.org/10.1038/ncomms4471



Muography

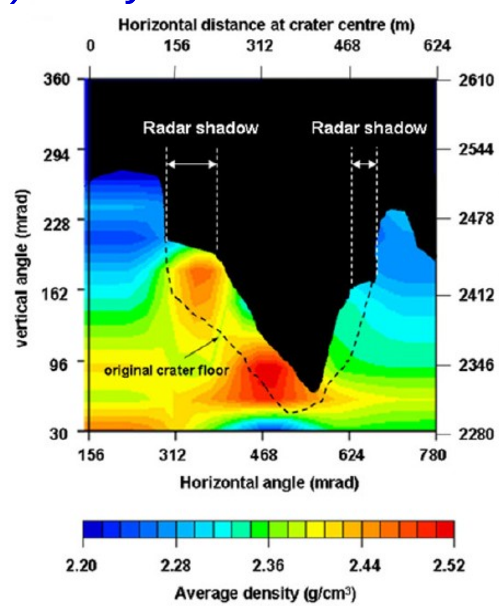
- **Cosmic-ray muons** continuously produced in the atmosphere and observed everywhere on Earth
- Muons are **highly penetrative particles** which reach down even a few km into Earth's subsurface.
- **Muography**: ”X-raying” of large structures via tracking of cosmic-ray muons
  → **non-destructive, passive, remote imaging technique**
- **Contributions of Muography to Volcanology:**
  (1) Studying formation and stability of lava domes (Showa-Shinzan, La Soufrière de Guadeloupe),
  (2) Exploring conduit structure for eruption modelling (Stromboli, Etna),
  (3) Monitoring magma evolution and movement (Asama, Sakurajima, Vesuvius).

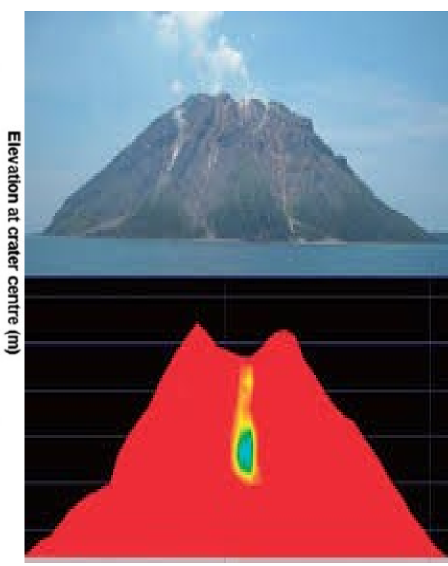
  Muography: Exploring Earth’s Subsurface with Elementary Particles, Geophys. Mon. Ser. 270
  https://agupubs.onlinelibrary.wiley.com/doi/book/10.1002/9781119722748



First medical X-ray image
by F. C. Röntgen (1895)

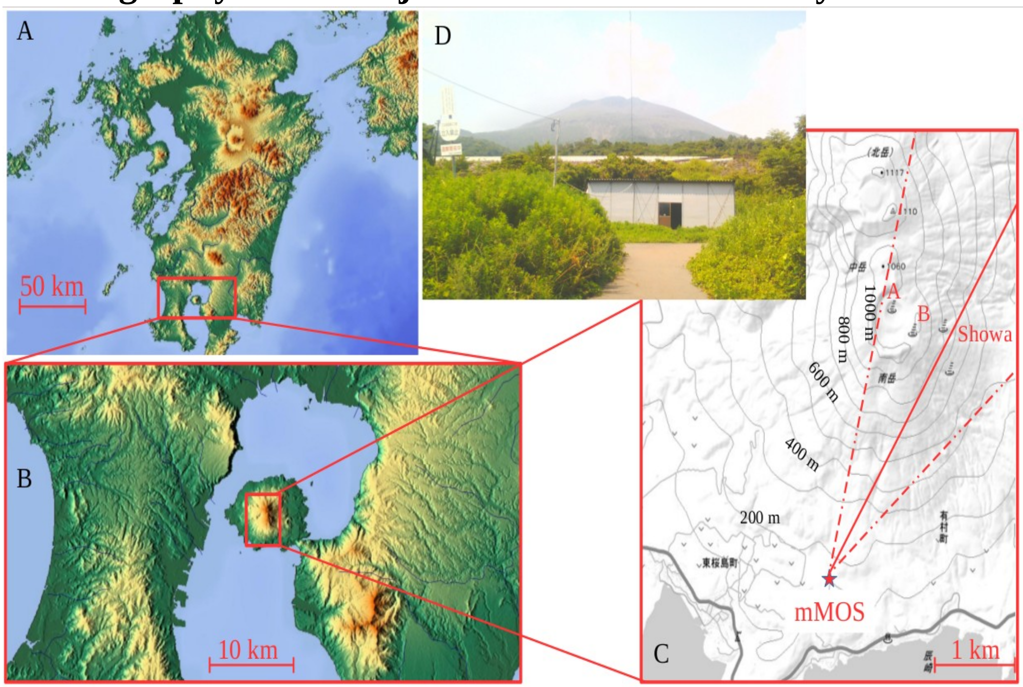
First muon images of volcanoes
by H. K. M. Tanaka et al. (mid 2000s)



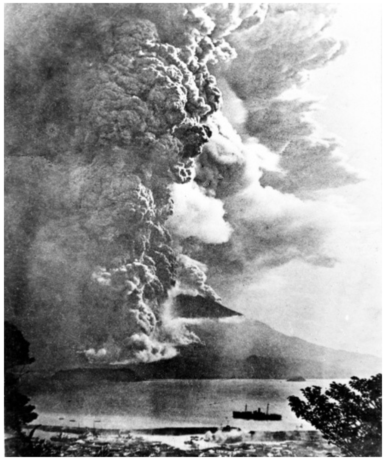


II. Data Collection and Processing

- **Sakurajima volcano is active stratovolcano** on the "Ring of fire" within the Aira caldera in Kagoshima Bay
- **Two craters of the southern peak** (the connected Vents A and B, as well as Showa crater) erupted consecutively in the recent years → **From a few tens to a few hundreds of (explosive) eruptions per year**
- Short-term eruptions eject aerosols and gas with a bulk volume of below 10^7 m^3 to a height of 1000–5000 meter above the crater rims, throwing fragments of volcanic plug and lava bombs usually within approx. 3000 m radius
→ **Sakurajima pose continuously hazard to the surrounding areas**
- MEXT launched Integrated Program for Next Generation Volcano Research and Human Resource Development https://kazan-pj.bosai.go.jp/next-generation-volcano-pj-2019-jun
- The University of Tokyo and HUN-REN Wigner RCP conduct
muography of Sakurajima volcano since January 2017 to study active volcanism



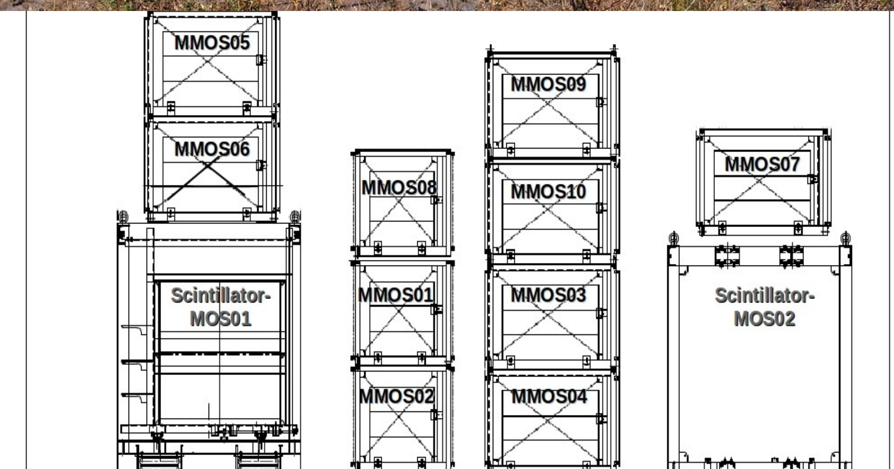
Source: https://doi.org/10.1038/s41598-018-21423-9



Source: Wikipedia

Source: Kimon Berlin, CC BY-SA 2.0

Muographic Observation Instrument (MOI)

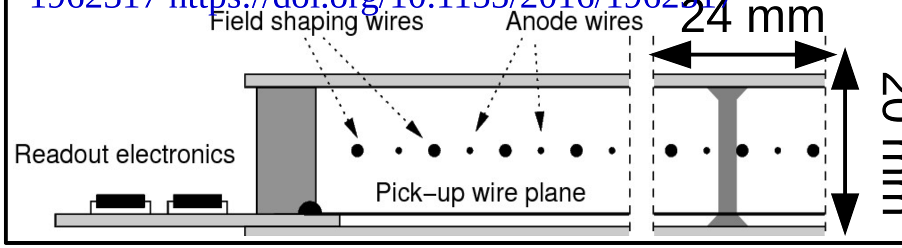


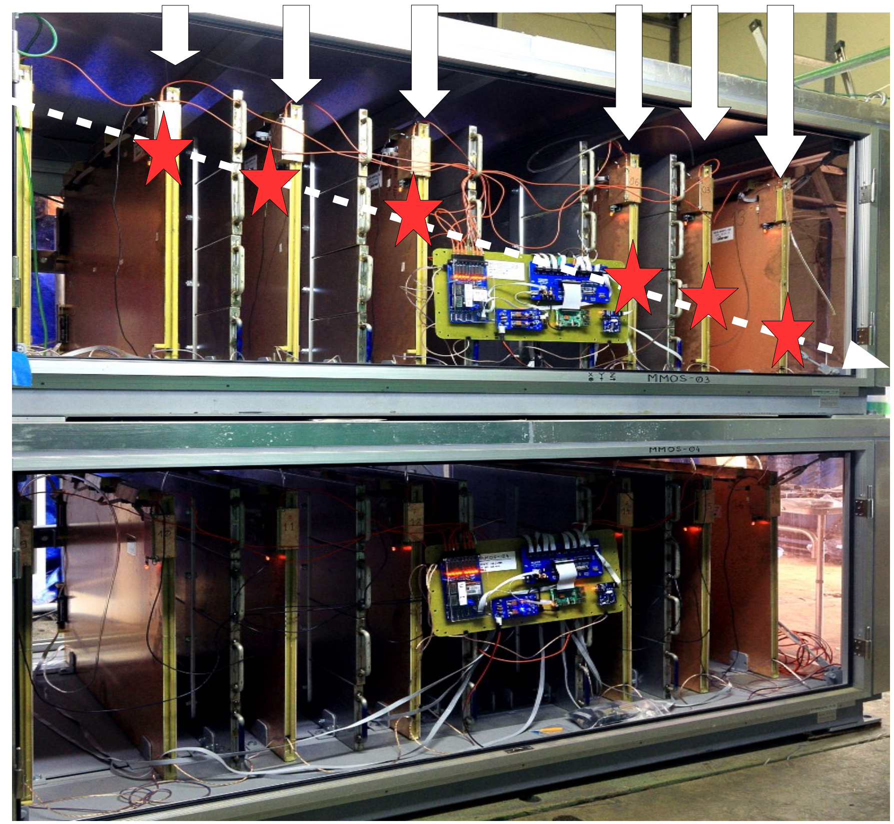
- Custom-designed electronics
- Micro-computer controlled
  → real-time DAQ & analysis
- Power consumption:
  ~ 6 W per MMOS

- **Modular infrastructure for volcano muography**
  (11 MWPC-based trackers cover10 sqm surface area)

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

D. Varga et al. Advances in High Energy Physics, 2016, 1962317 https://doi.org/10.1155/2016/1962317



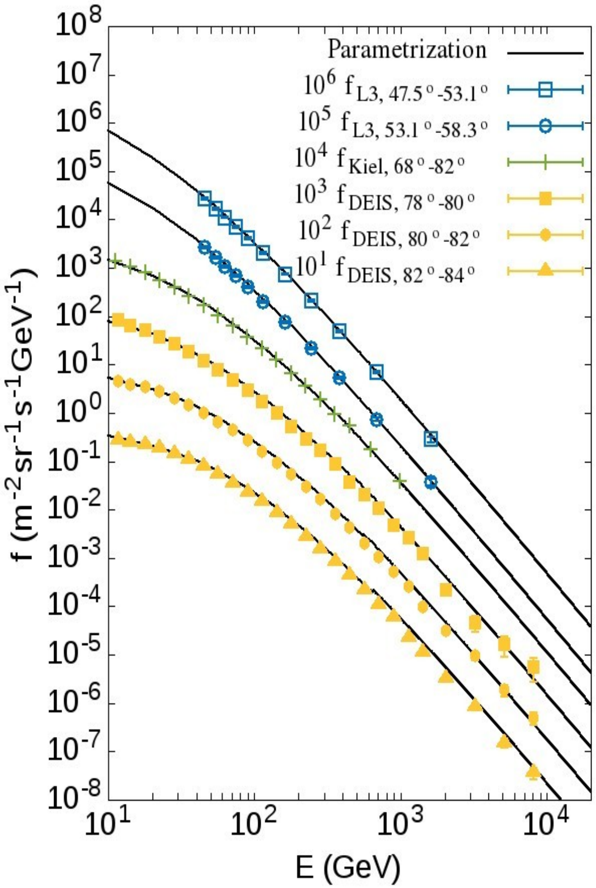


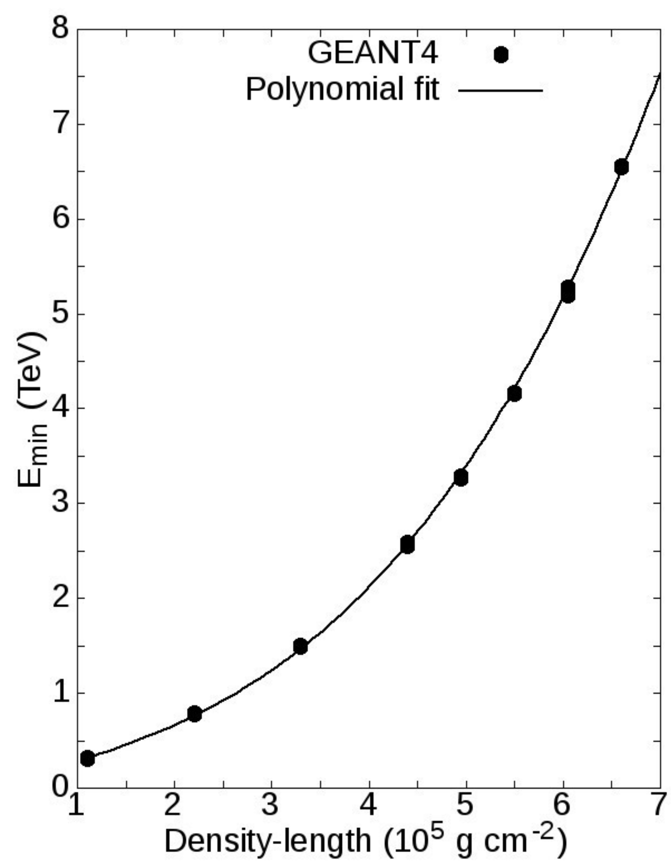
L. Oláh et al. Scientific Reports, 8, 3207, 2018,
https://doi.org/10.1038/s41598-018-21423-9

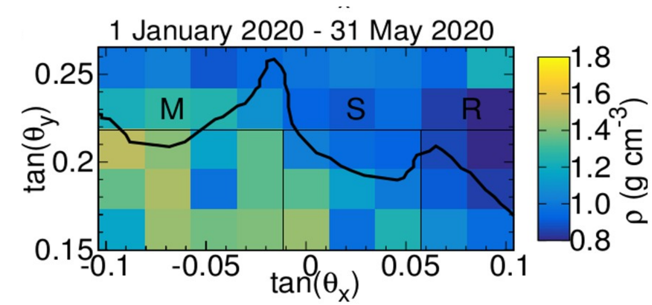
D. Varga et al. Nucl. Instrum. Meth. A 958, 162236, 2020
https://doi.org/10.1016/j.nima.2019.05.077

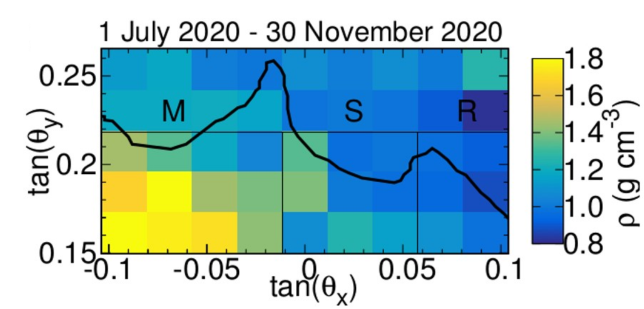
Muographic Mass Density Imaging

- Density-length values are quantified for each angular bin („pixel”) via comparing the measured flux to the modeled fluxes determined for different density-lengths. Density is density-length divided by path-length.
- The modeled fluxes are given by numerical integration of zenith-angle and energy depedent spectra from minimal energies that required for muons to penetrate the volcanic edifice
- **Density images** were determined for the crater region with 9 × 5 angular bins **for time sequences of 5-6 months**
- **Mass values** were also determined by the following expression: $\mathbf{m = \sum_i \rho_i \times T_i \times D^2 \times \Delta\tan(\theta_x) \times \Delta\tan(\theta_y)}$, where ρi is the density for the ith bin, Ti is the path-lenth for ith bin and D is the volcano-observatory distance.



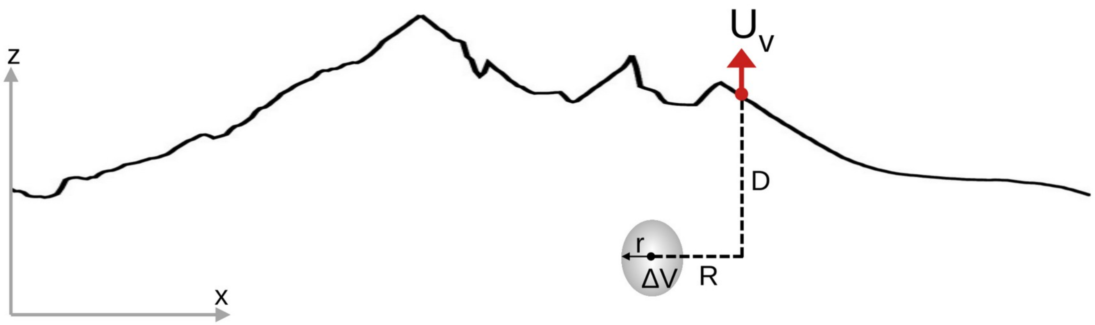


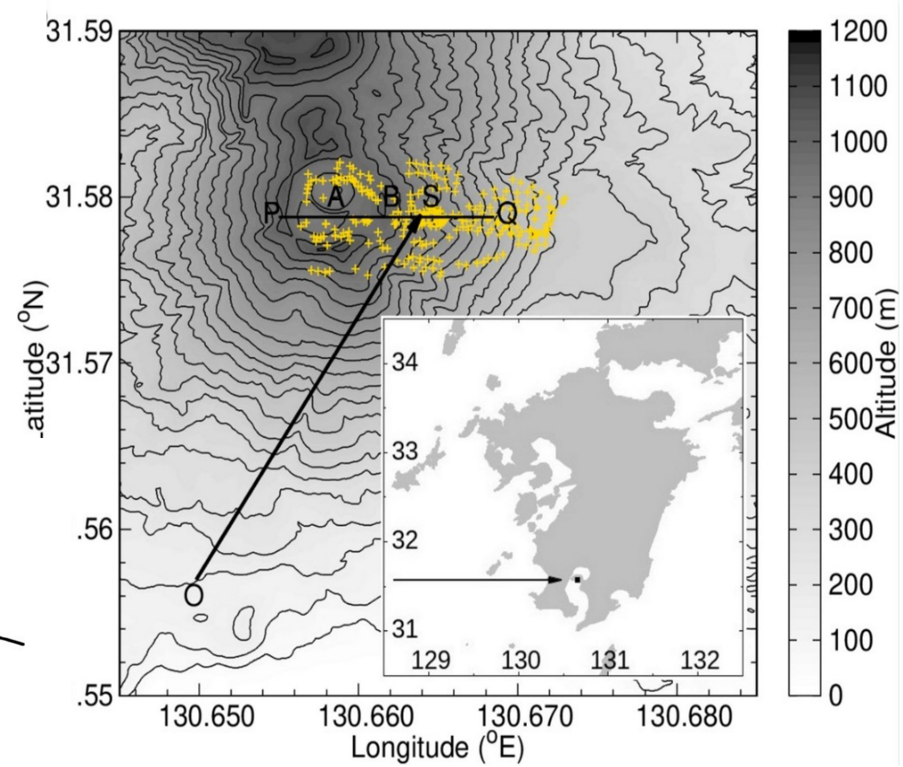


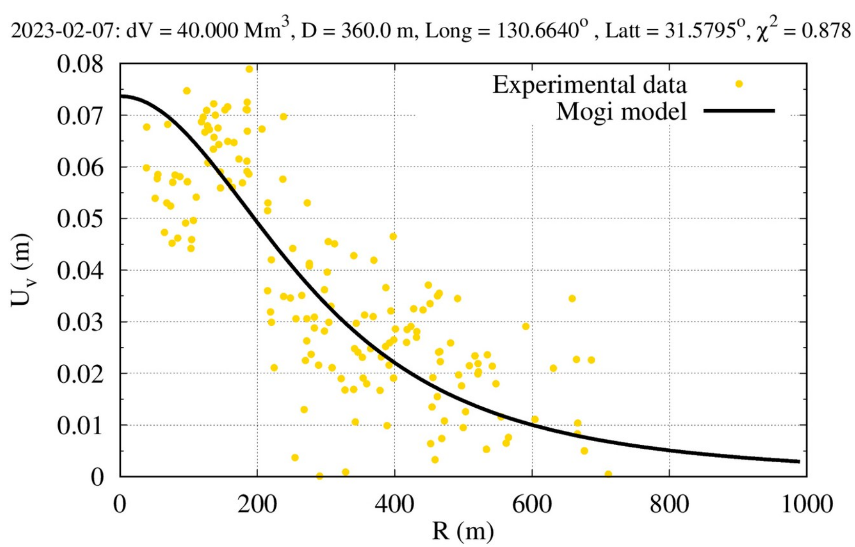


Mogi Modeling of Ground Surface Deformations Measured by InSAR

Vertical displacement around the active crater of Sakurajima (yellow-coloured crosses) was determined relative to the ground level measured on 31 October 2018 by NEC using the Phased Array type C-band Synthetic Aperture Radar images acquired by Sentinel-1 **with a periodic time of 12 days.**







- **Mogi modeling** assumes a spherical source beneath the surface. D»R.
- Comparison of Mogi modeled and measured vertical uplifts enables us to determine **volume change and spatial coordinates** of pressure source

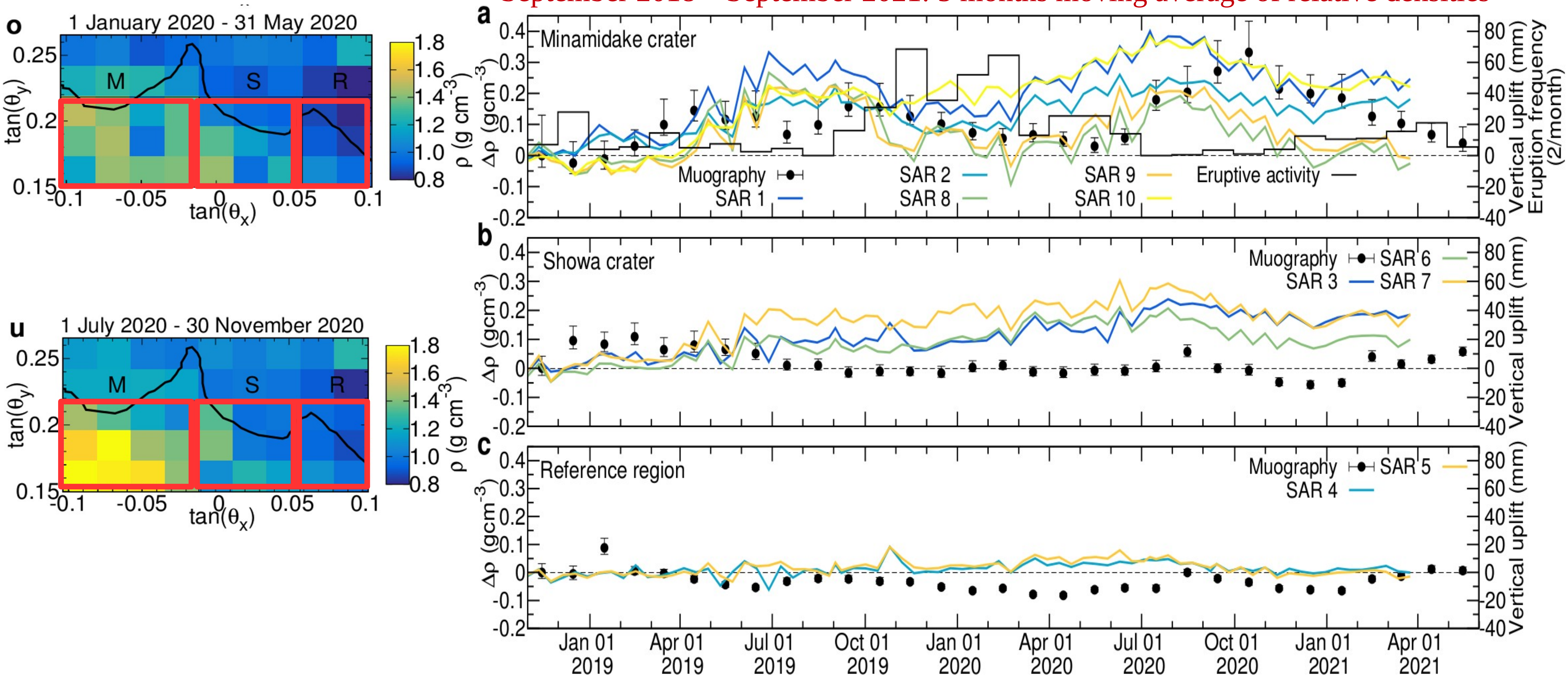
$$U_v = 3\,\Delta V\,D \;/\; [\,4\pi\,(\,R^2 + D^2\,)^{3/2}\,]$$

III. Results

- Mass density increased during inflation, when eruption frequency was low, and decreased during deflation, when eruption frequency was high.
- Periods of low eruption frequency are associated with the formation of a dense plug in the conduit, which we infer caused inflation of the edifice by trapping pressurized magmatic gas.
- **Muography reveals the in-conduit physical mechanism for the observed correlation.**

Minamidake Showa Reference

September 2018 – September 2021: 5 months moving average of relative densities



L. Oláh, et al. (2023) Geophys. Res. Lett. 50, e2022GL101170 https://doi.org/10.1029/2022GL101170

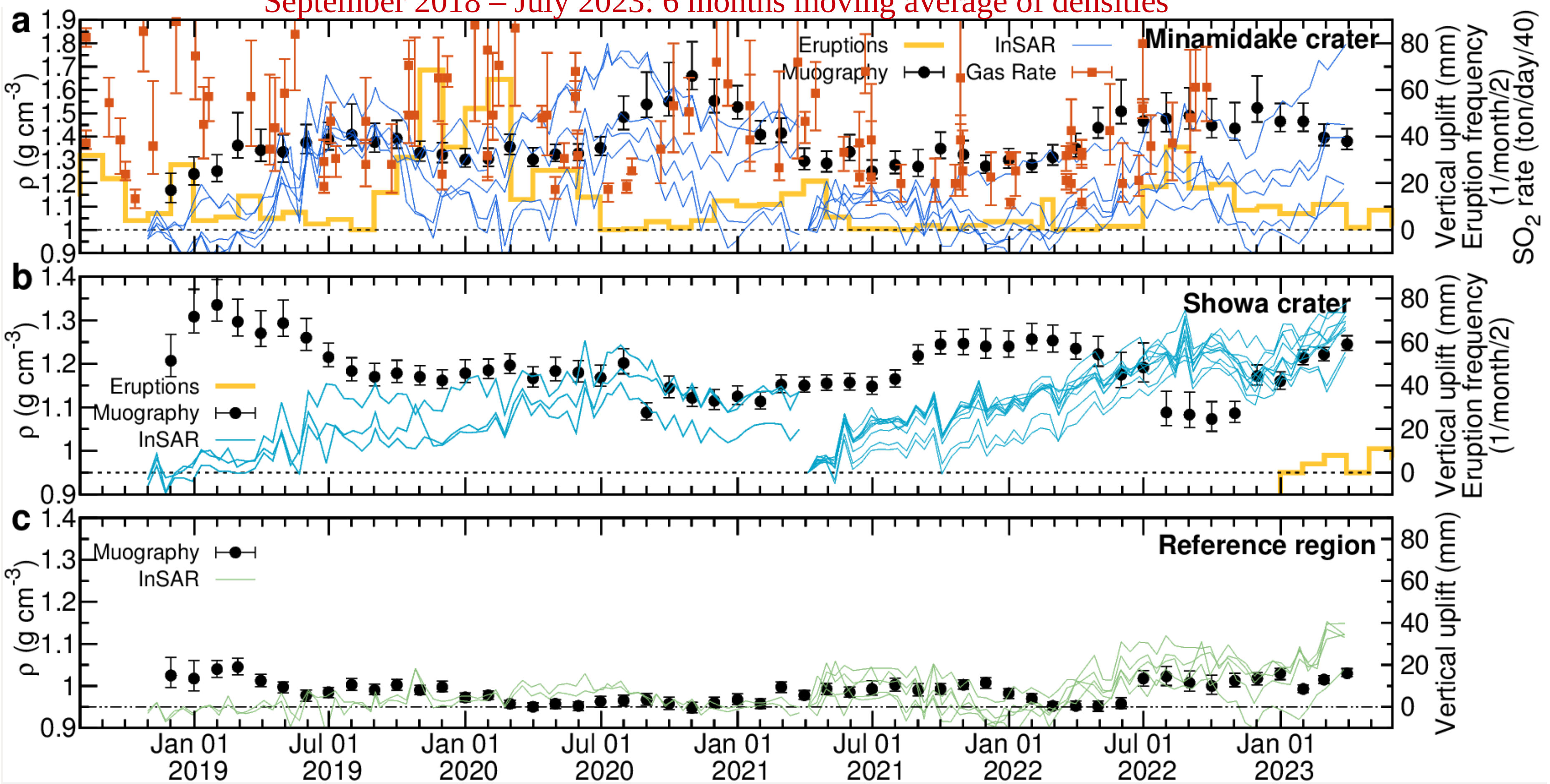
Plug Formation and Magma Drain-back Process

- **Minamidake crater:** The increasing trend in density is interpreted as plug formation due to magma rising. The decreasing trend is interpreted as plug reduction due to recurrent eruptions. (See also in Geophys. Res. Lett. 46, 10417, 2019, https://doi.org/10.1029/2019GL084784)

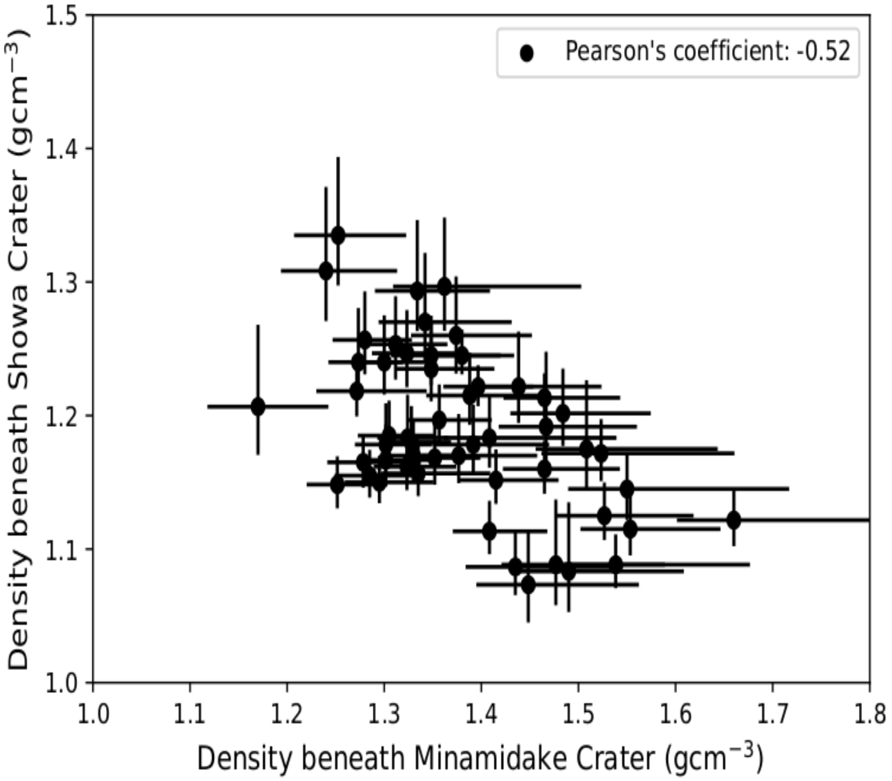
- **Showa crater:** eruptions did not follow the density increase observed beneath Showa crater in January 2019 and in August 2021; however, later the mass density decreased. It was interpreted that the uprising magma generated the plug underneath Showa crater. However, the gas pressure mightn't be enough to trigger eruptions and non-solidified part of the plug drained-back

- **The InSAR and sulfur dioxide emission rate data** support our current picture.

September 2018 – July 2023: 6 months moving average of densities



Branched Conduit Structure Inferred From Muography

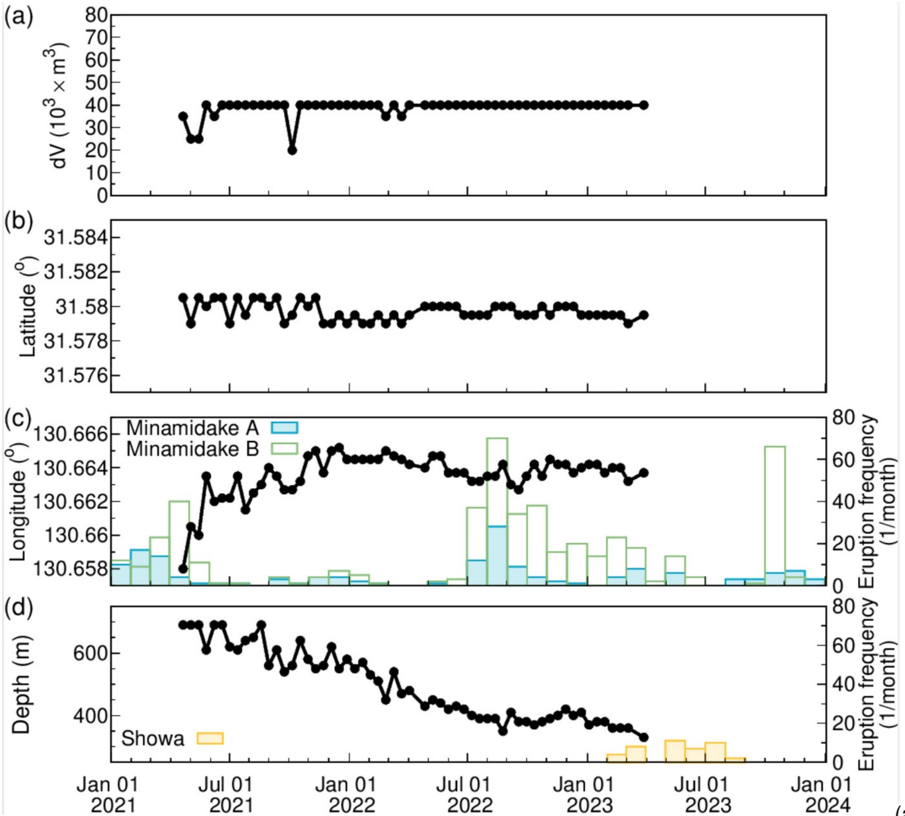


- An anti-correlation was found between the densities beneath Minamidake and Showa craters: The Pearson's coefficient was quantified to -0.52 for these mass density values.
- Infrasonic monitoring data showed a similar anti-correlation between the regions beneath the adjacent craters of Mount Etna. Marchetti et al (2009) observed the switching of infrasonic source locations (that correlated with gas pressure) and change of activity between the and Bocca Nouva and the South East Crater (SEC). A branched conduit structure was inferred.
- Inverse correlation between mass densities observed for the entire period, suggesting that magma degassing occurs either in Minamidake crater and in Showa crater, acting as a similar preferential pathway to the one observed in Etna

→ **a branched connection between the conduits of the two active craters**

Oláh, L., Hamar, G., Ohminato, T., Tanaka, H. K. M., & Varga, D. (2024).
Branched conduit structure beneath the active craters of Sakurajima volcano inferred from muography.
Journal of Geophysical Research: Solid Earth, 129, e2023JB028514.
https://doi.org/10.1029/2023JB028514

Magma migration beneath the active craters of Sakurajima volcano before the 2023 eruption of Showa crater

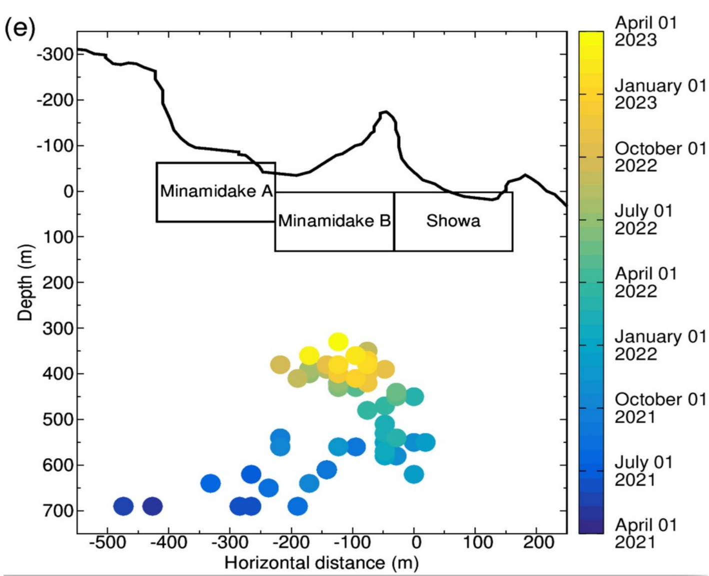


2021:
Mogi modeling: Lateral movement of ground deformation source was observed to east beneath the active craters around sea level,
Muography: mass decreased beneath Mindamidake A,B and increased beneath Showa,
Eruption frequency: Shift from Minamidake A to B crater.

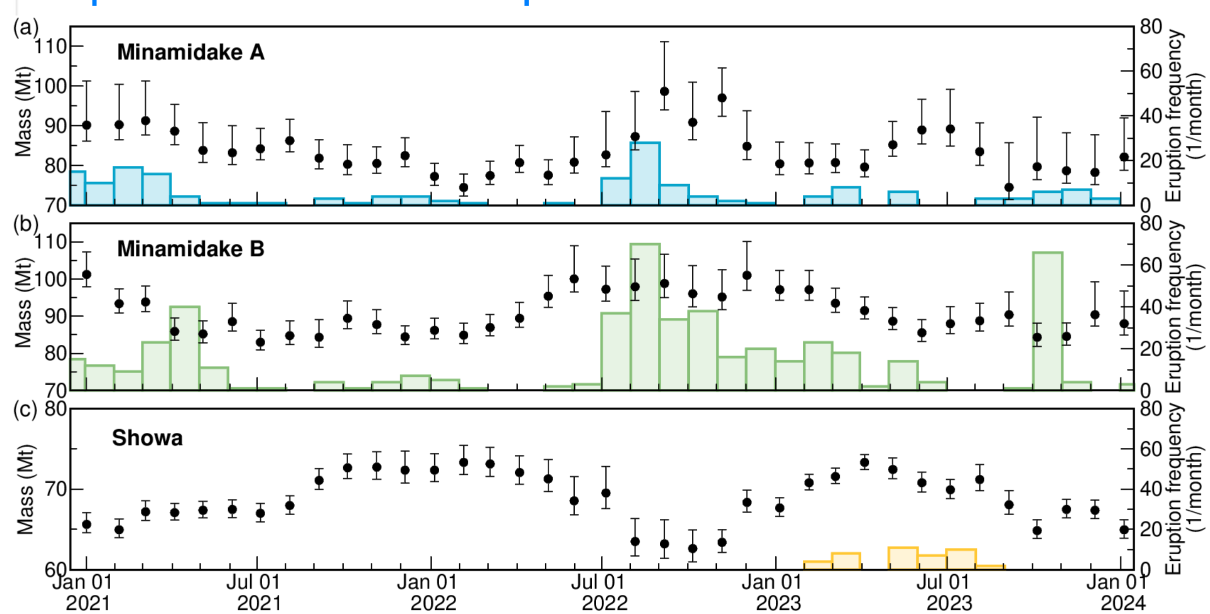
→ **(1) Deep magma channel around sea level that feeds the Minamidake craters**

2022:
Mogi modeling: source uplifted at 350 m depth,
Muography: mass increased beneath Showa crater,
Eruption frequency: Showa crater started to erupt.

→ **(2) Shallow magma chamber feeds all craters.**



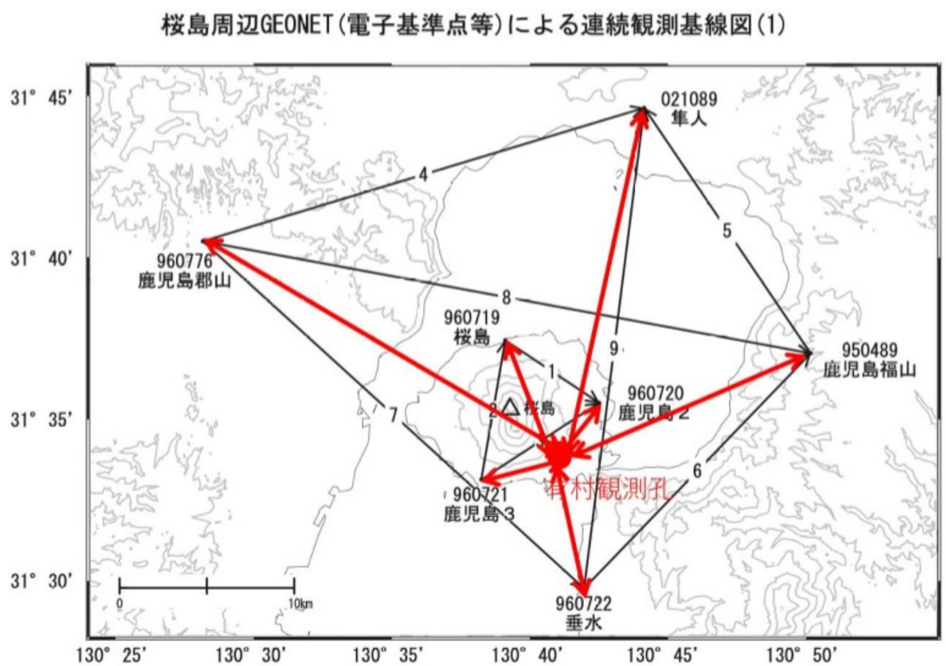
https://www.researchsquare.com/article/rs-6573242/v1

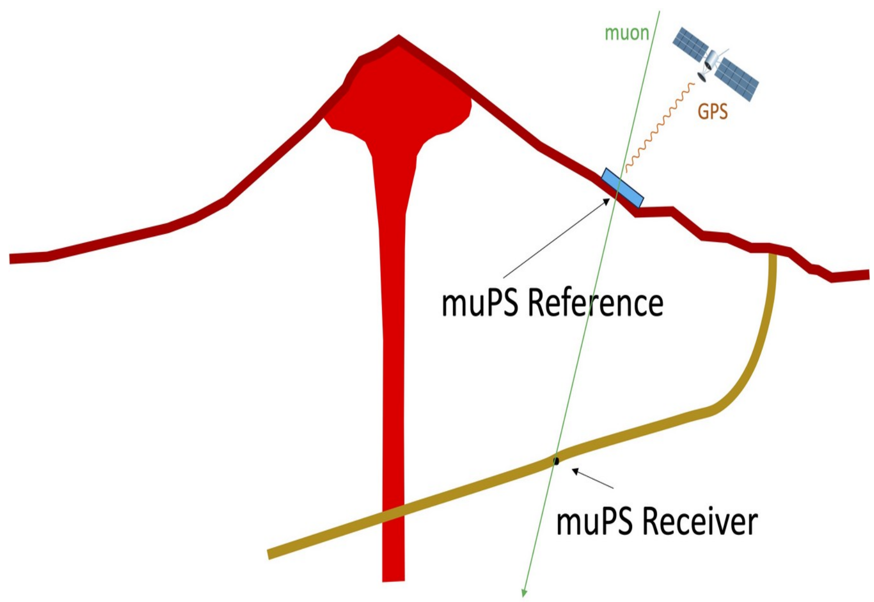


IV. Monitoring of Underground Position at Active Volcanoes with muPS

Goal: defining the underground coordinate within the national coordinate that means precise measurements of the baseline between far distant GPS station (more than 10 km away) and the muPS station at a sub cm level

Benefits of using cosmic-ray muons for positioning:
(0) Accuracy is not influenced by obstacles in its surrounding environment,
(1) Capability of monitoring,
(2) Applicability in deep bent boreholes, where triangulation is not possible,
(3) Capability of defining coordinate in global (national) coordinate system.
→ **Long-term goal:** measuring the deformation near the conduit in boreholes, similarly to Campi Flegrei and Krafla Magma Testbed





Source: https://www.jma.go.jp/jma/press/2307/12a/yochiren230712_3.pdf

Source of figure: H.K.M. Tanaka

Tanaka et al. First navigation with wireless muometric navigation system (MuWNS) in indoor and underground environments. Iscience, 26, 107000 https://doi.org/10.1016/j.isci.2023.107000

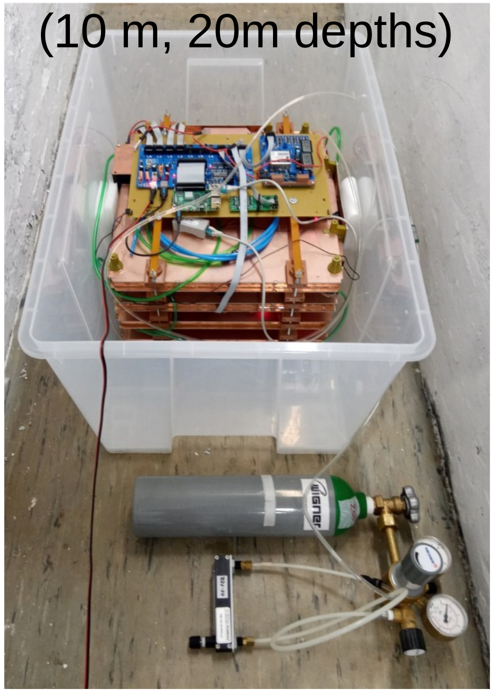
First Tests of muPS in Underground Tunnels in HUN-REN Wigner RCP, Hungary

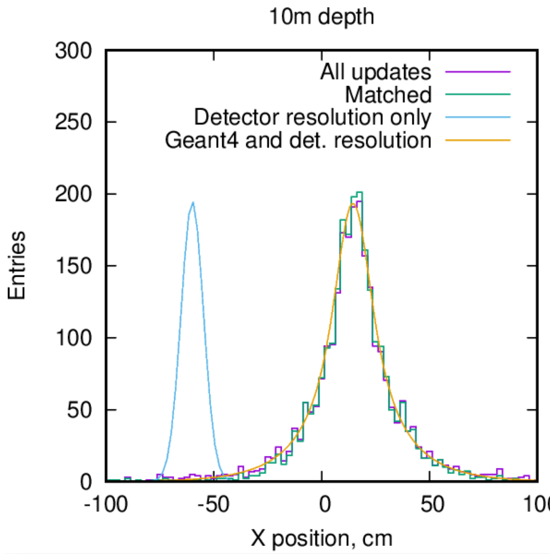
Reference at ground level

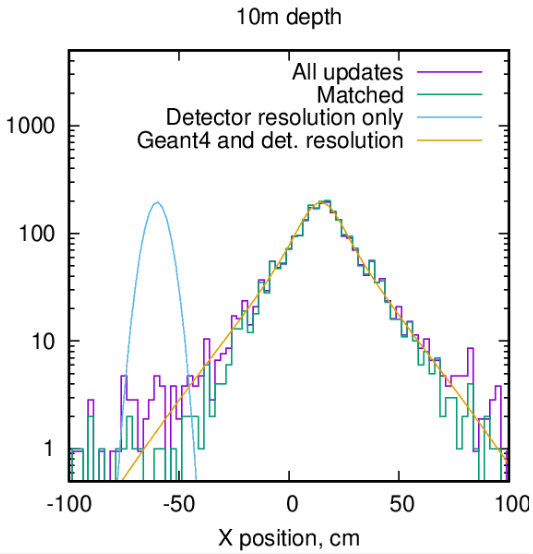
- Update rate of Receiver detector at 10m (20m) depth: 15mHz (2mHz)
- Internal clocks: temperature compensated 10MHz oscillator IQXT-200-49, nominal precision 0.05ppm
- Reference angular resolution chosen to be sufficiently good, 5 mrad to measure the effects of muon scattering.
- Experimental data are consistent with Geant4 simulations: tails due to low energy muons. Furthermore, little background is available.
- FWHM is approx. 30 cm at 10 m depth.

Source: D. Varga's talk at Muographers 2024 WS (Santa Fe)

Receiver in tunnels (10 m, 20m depths)







Varga, D., Tanaka, H.K.M. Developments of a centimeter-level precise muometric wireless navigation system (MuWNS-V) and its first demonstration using directional information from tracking detectors. Sci Rep 14, 7605 (2024). https://doi.org/10.1038/s41598-024-57857-7

V. Summary

Joint muon and ground deformation monitoring allowed to

(1) Oberve magma evolution (plug formation, drain-back process),
Geophys. Res. Lett. 46, 10417, 2019, https://doi.org/10.1029/2019GL084784

(2) Explain the link between ground deformation and eruption frequency,
Geophys. Res. Lett. 50, e2022GL101170 https://doi.org/10.1029/2022GL101170

(3) Infer to the conduit structure from magma dynamics among two craters,
Journal of Geophysical Research: Solid Earth, 129, e2023JB028514. https://doi.org/10.1029/2023JB028514

(4) Infer to shallow magma supply channels and chamber
Manuscript submitted to Earth, Planets and Space. https://www.researchsquare.com/article/rs-6573242/v1

(5) Monitoring of underground position with muometric positioning has been proposed: optimization is ongoing via underground measurements.

Thank you for your attention!

Supporters:

- **Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) Integrated Program for the Next Generation Volcano Research**
  https://kazan-pj.bosai.go.jp/next-generation-volcano-pj-2019-jun
- **Joint Usage Research Project (JURP) from the ERI, University of Tokyo**
  https://www.eri.u-tokyo.ac.jp/en/joint-usage-top/
- **”INTENSE” H2020 MSCA RISE, GA No. 822185 in Horizon 2020 from European Comission** https://cordis.europa.eu/project/id/822185
- **TKP2021-NKTA-10 and othe grants for instrument development from National Research, Development and Innovation Office, Hungary**
  https://nkfih.gov.hu/english-nkfih
- **HUN-REN Welcome Home and Foreign Researcher Recruitment Programme KSZF-144/2023**

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Backup Slides

- Resolving the internal structure of the volcano with a spatial resolution of below 10 metres that is challenging to other techniques

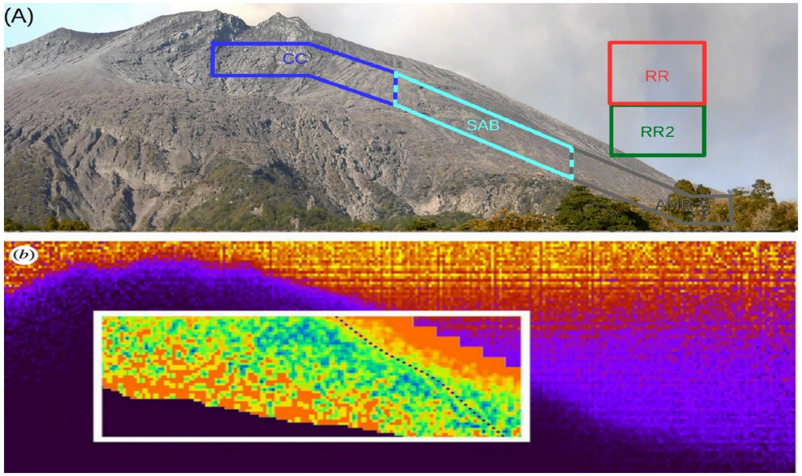
  L. Oláh et al. Scientific Reports, 8, 3207, 2018
  https://doi.org/10.1038/s41598-018-21423-9

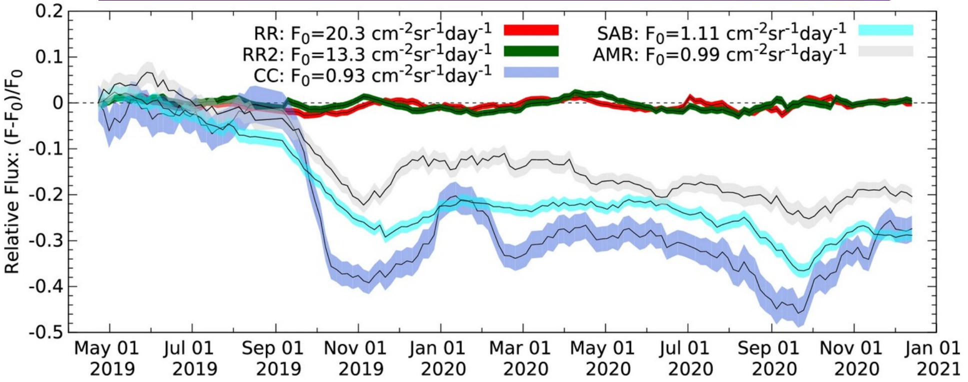
- Monitoring changes in the amount of materials on the volcanic edifice due to volcanic ejecta deposition, erosion and mudflows (lahars)

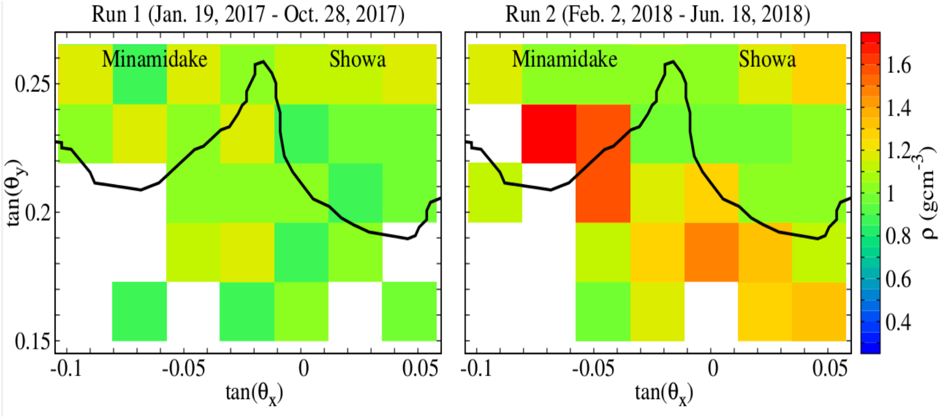
  L. Oláh et al. Scientific Reports 11, 17729, 2021,
  https://doi.org/10.1038/s41598-021-96947-8

- Imaging of a magmatic plug beneath Showa crater with the cease of eruptions

  L. Oláh et al. Geophys. Res. Lett. 46, 10417, 2019,
  https://doi.org/10.1029/2019GL084784







Eruption Forecasting via Machine Learning of Muon Images

- Machine learning of consecutive daily muon images for predicting eruption on the next day
  Y. Nomura et al. Scientific reports, 10, 5272, 2020, https://doi.org/10.1038/s41598-020-62342-y
- Convolutional neural networks can learn the hidden patterns
  (originated from mass changes occurred beneath the crater) in the muon images
- Receiver Operating Characteristic (ROC) analysis to characterize forecasting performance
- Results of ROC analysis showed that CNN achieved a fair forecasting performance, e.g. Area Under the Curve (AUC) of 0.761, for the erupting Minamidake crater

L. Oláh & H.K.M. Tanaka: Geophys. Mon. Ser., 270, 43-54, 2022, https://doi.org/10.1002/9781119722748.ch4

	Minamidake	Showa	Surface
Area Under the Curve	0.761	0.704	0.644
Sensitivity	0.737	0.638	0.395
Specificity	0.755	0.714	0.896