Muography of Volcanic and Atmospheric Hazards at Sakurajima Volcano, Japan

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III. Towards Short-term Eruption Forecasting via Machine Learning of Muon Images

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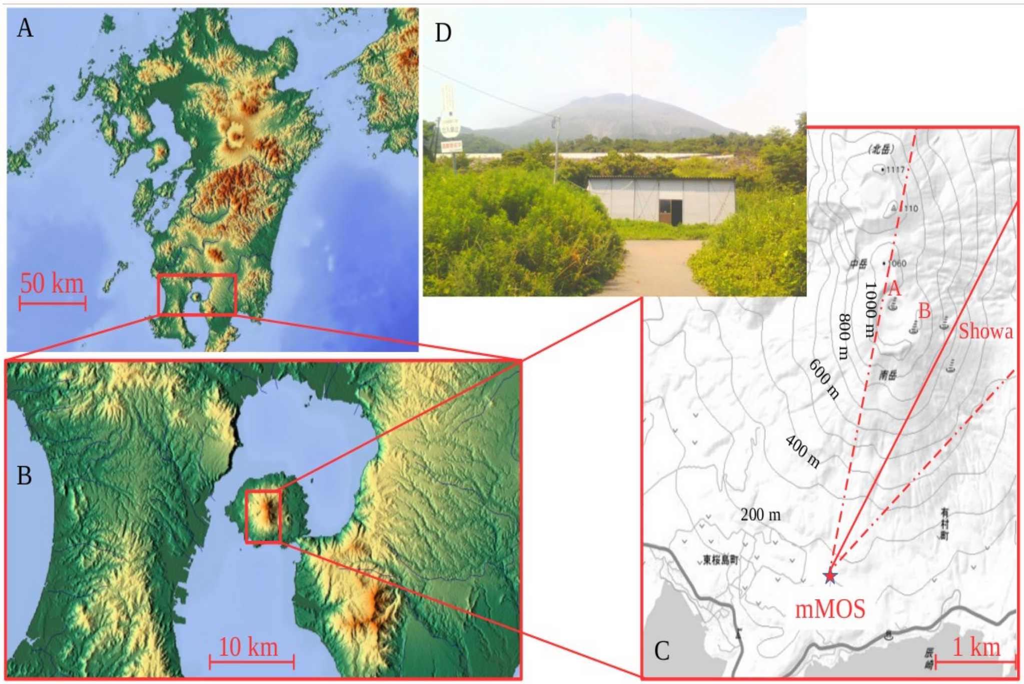
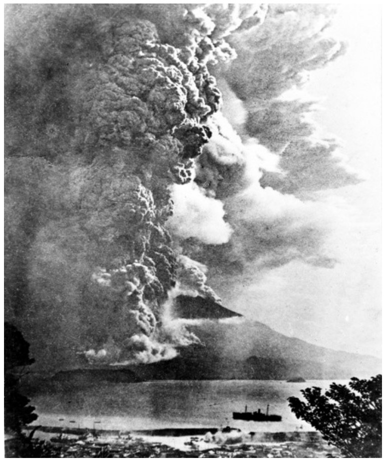
V. Summary

I. Sakurajima Muography Observatory

- **Sakurajima volcano is an active stratovolcano** on the "Ring of fire" within the Aira caldera in Kagoshima Bay
- Latest plinian eruption occurred in 1914 → Next plinian eruption is expected in 25 years https://doi.org/10.1038/srep32691
- **Two craters of the southern peak** (the connected Vents A and B, as well as Showa crater) erupted consecutively in the recent years
  → **A few hundreds of (explosive) short-term 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 Wigner RCP conduct muography of Sakurajima volcano since January 2017**



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



Source: Wikipedia

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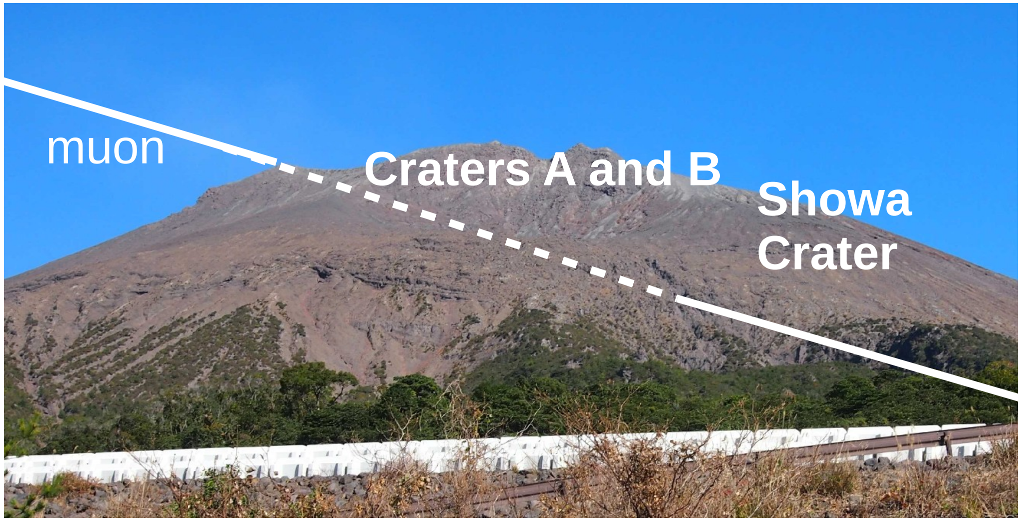
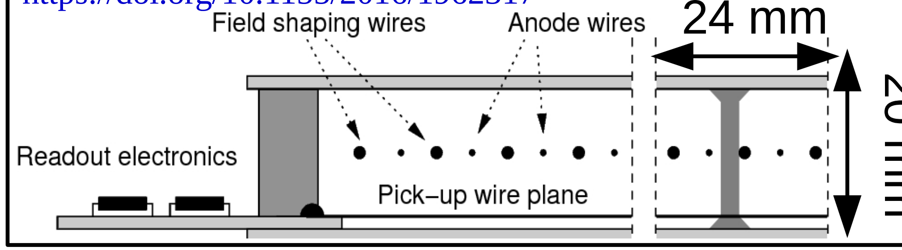
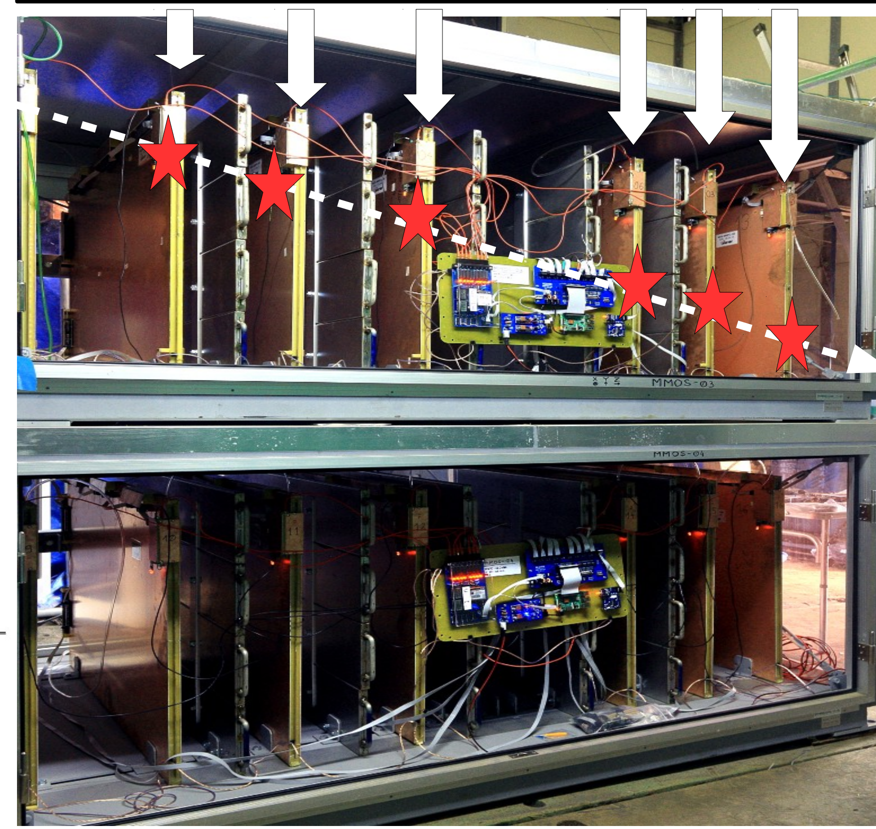
Muographic Observation Instrument (See more in the presentation by D. Varga)

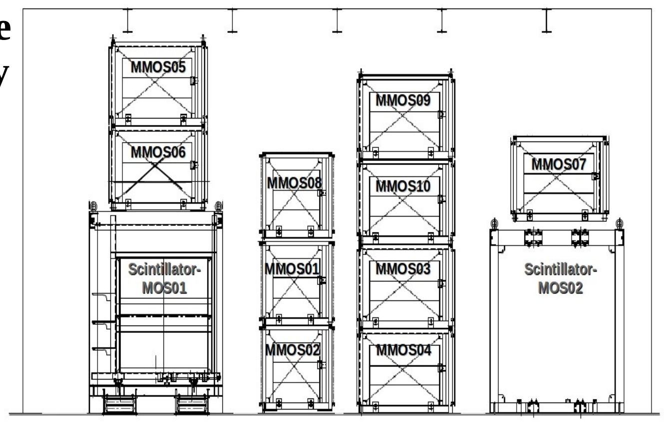


D. Varga et al. Advances in High Energy Physics, 2016, 1962317
https://doi.org/10.1155/2016/1962317





- **Modular infrastructure for volcano muography** (12 MWPC-based tracking systems cover 10 sqm surface area)



- Micro-computer controlled DAQ → real-time monitoring
- Track data transferred to remote computers

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

Highlights from Earlier Results

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

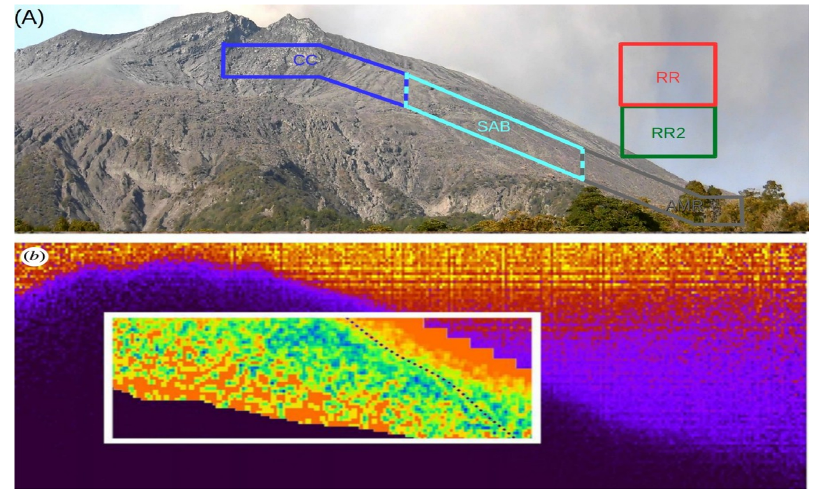
  L. Oláh et al. Scientific Reports, 8, 3207, 2018, https://doi.org/10.1038/s41598-018-21423-9

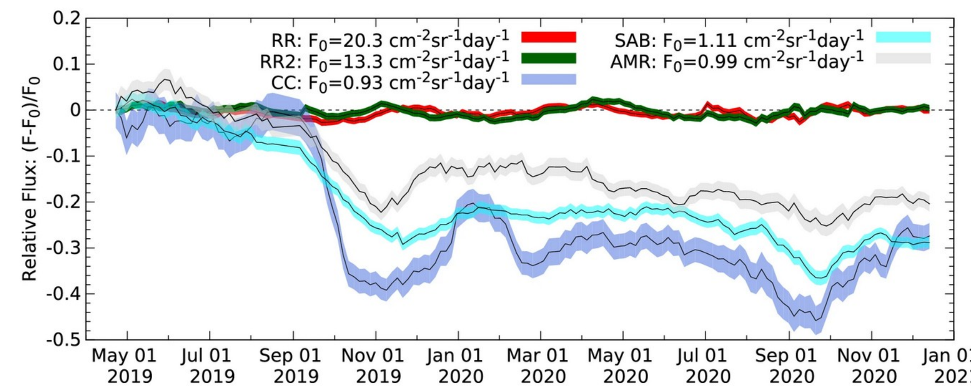
- Monitoring changes in the amount of materials on the volcanic edifice due to volcanic ejecta deposition, erosion and mudflows (lahars)

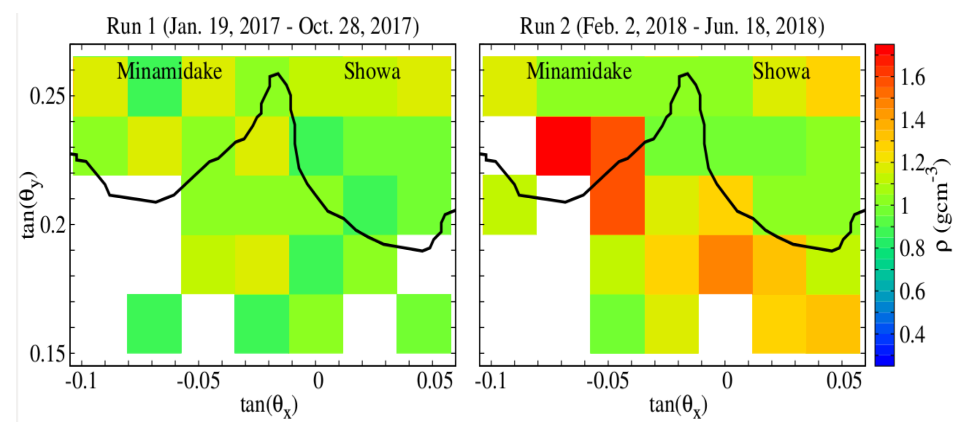
  L. Oláh et al. Scientific Reports 11, 17729, 2021, https://doi.org/10.1038/s41598-021-96947-8

- 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







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

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

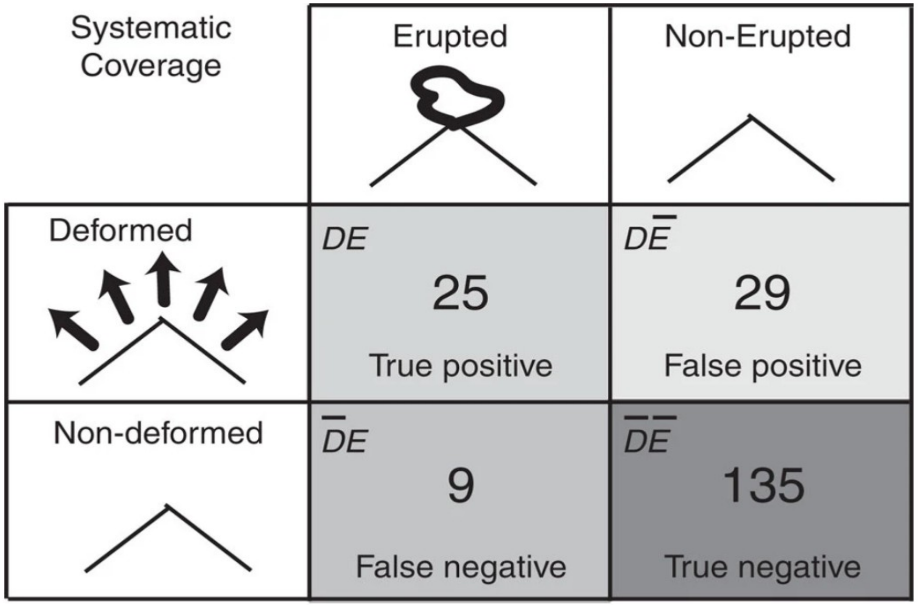
- Monitoring of the signals induced by these phenomena is indirect and interpretation of the origin of the signals is challenging because a wide variety of factors influence the behaviour of magma and host rock in the run-up towards eruption

- 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**

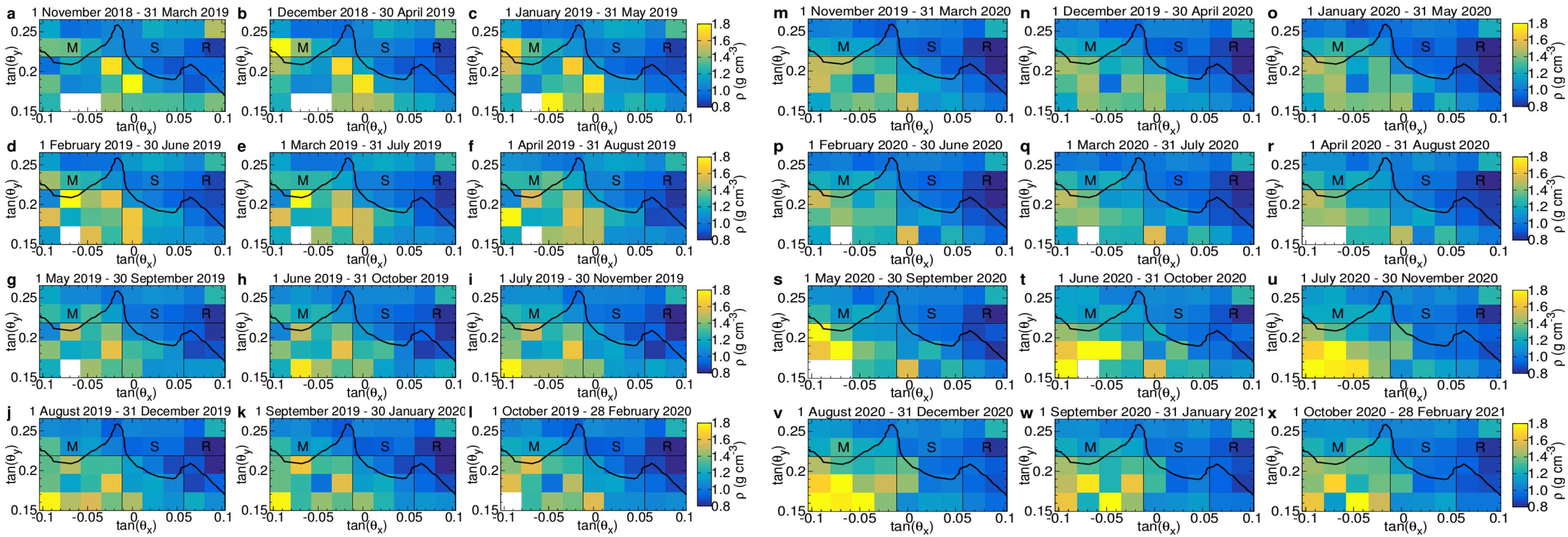
- **Aim: Revealing the causal physical mechanism of ground deformations (changing in the state of magma) via density monitoring with muography**

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

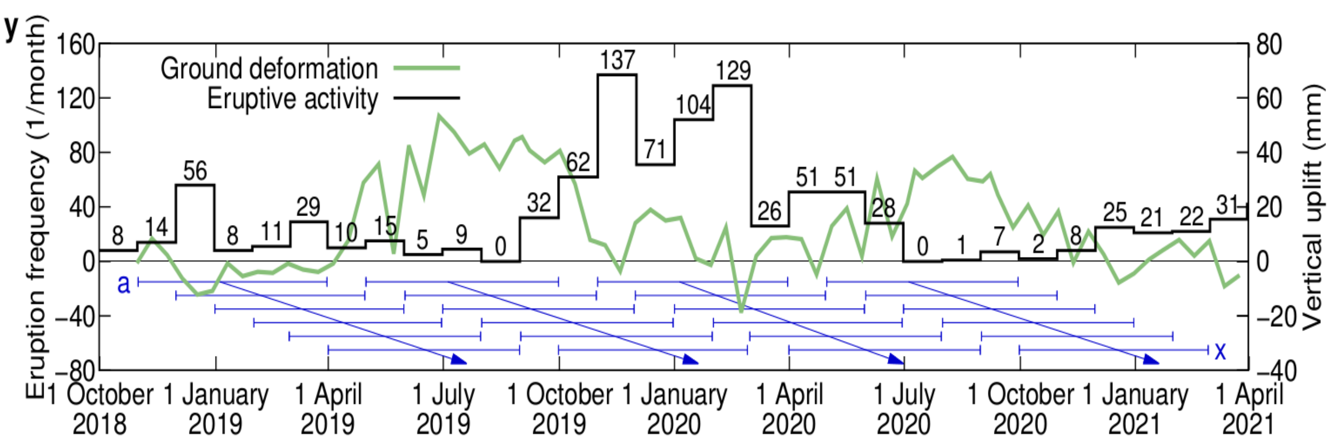


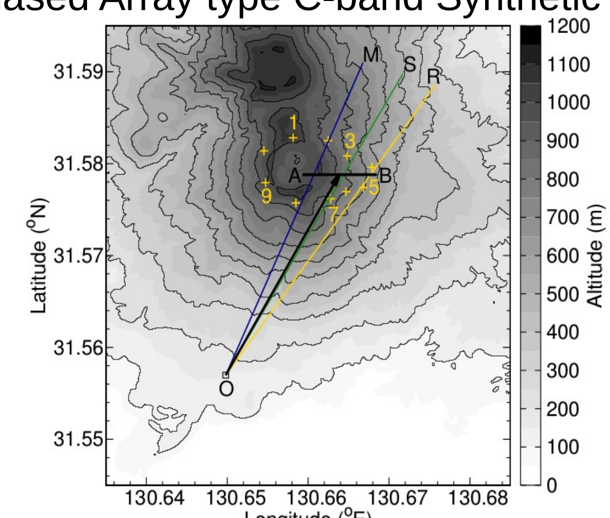
Muography and InSAR observations of Sakurajima

Muographic images were captured for the crater region with 9 × 5 angular bins for time sequences of 5 months between November 2018 and March 2021.



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

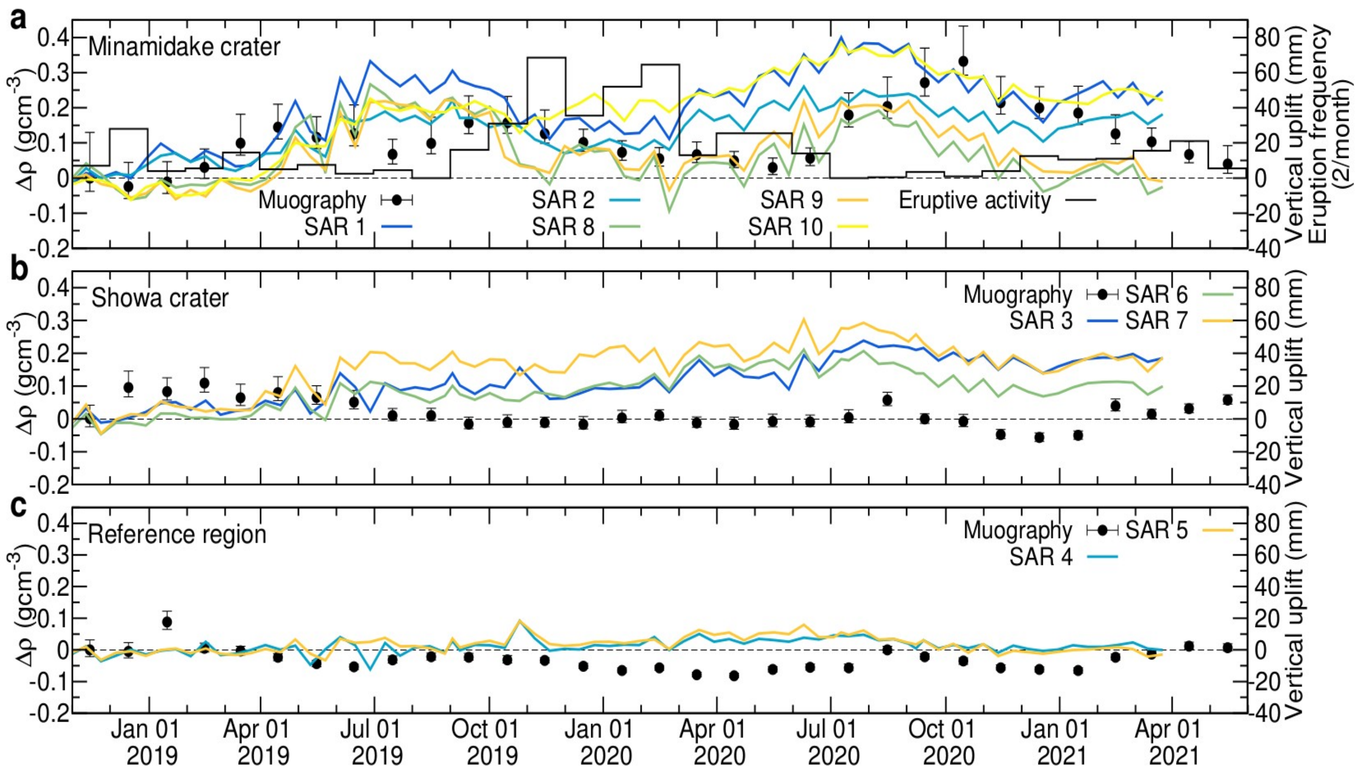


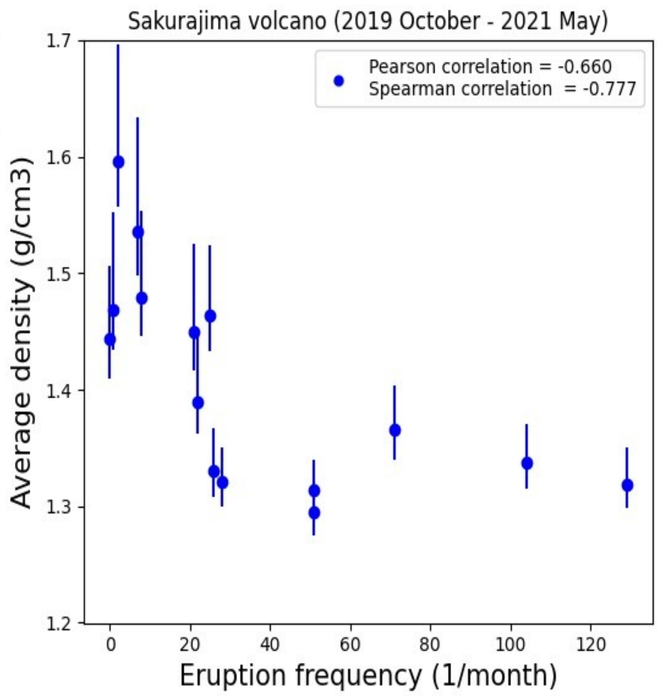


Volcanological Implications

- 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.**

L. Oláh, G. Gallo, G. Hamar, O. Kamoshida, G. Leone, E. W. Llewellin, D. Lo Presti, G. Nyitrai, T. Ohminato, S. Ohno, H.K.M. Tanaka, D. Varga. (2023) Geophys. Res. Lett. 50, e2022GL101170 https://doi.org/10.1029/2022GL101170

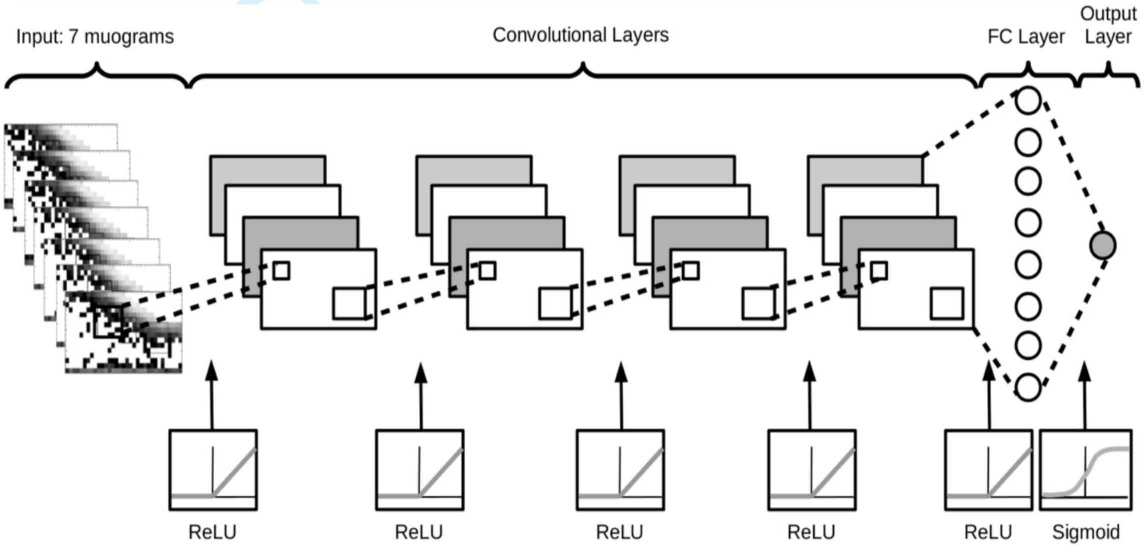


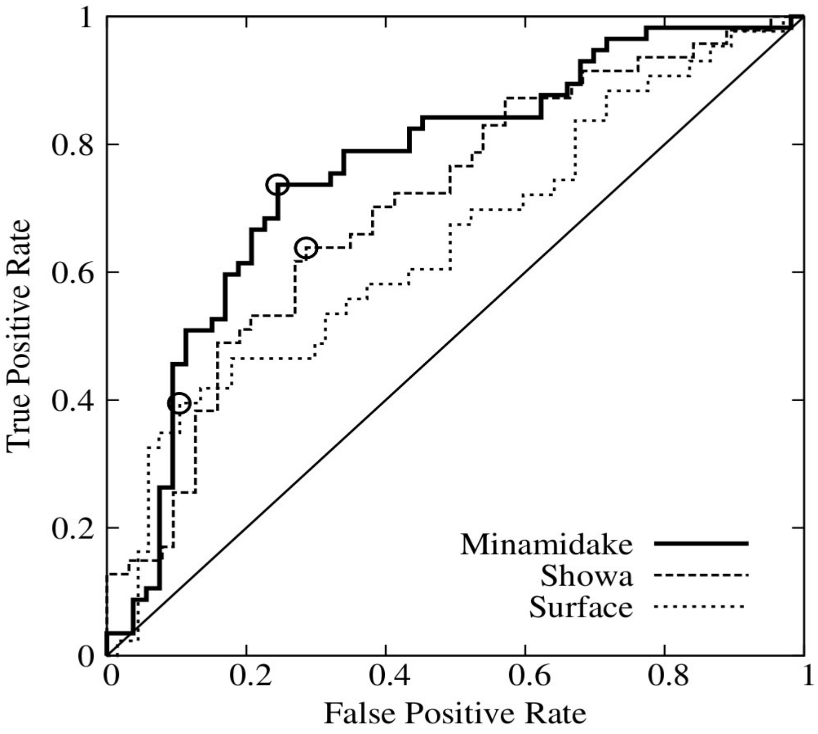


III. Towards Short-term Eruption Forecasting via Machine Learning of Muon Images

- 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





IV. Muography of Tropical Cyclones

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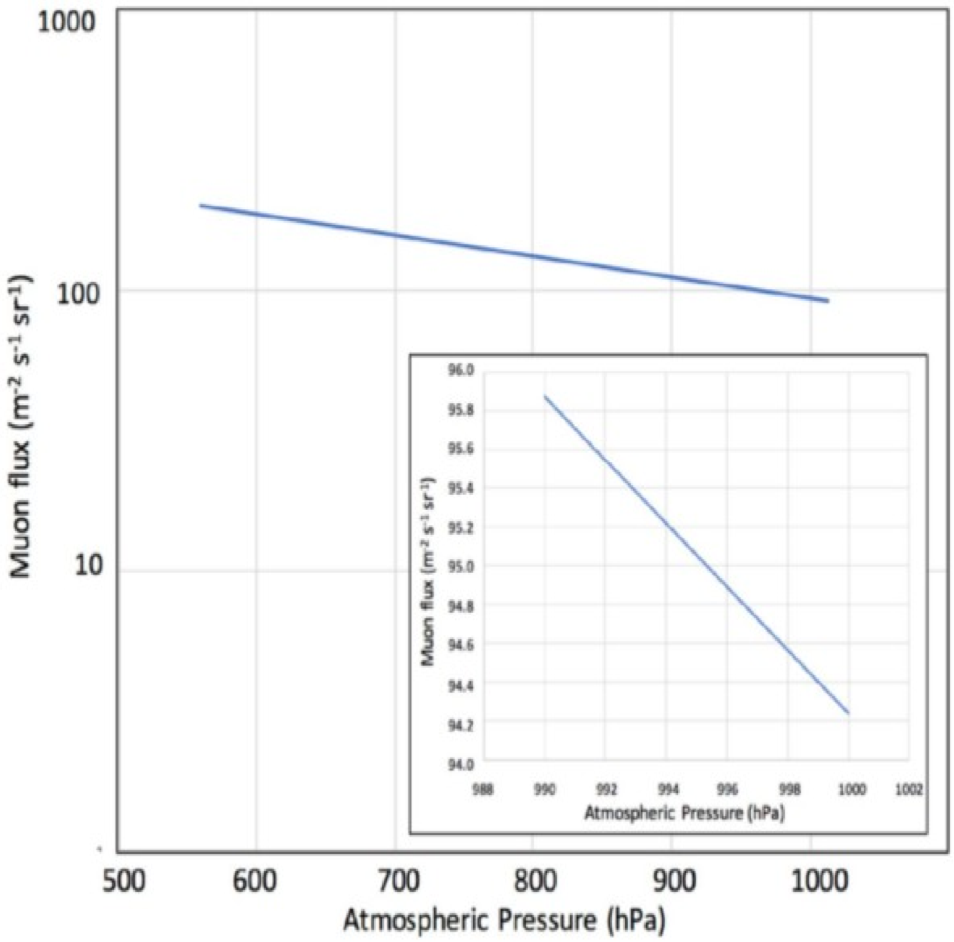
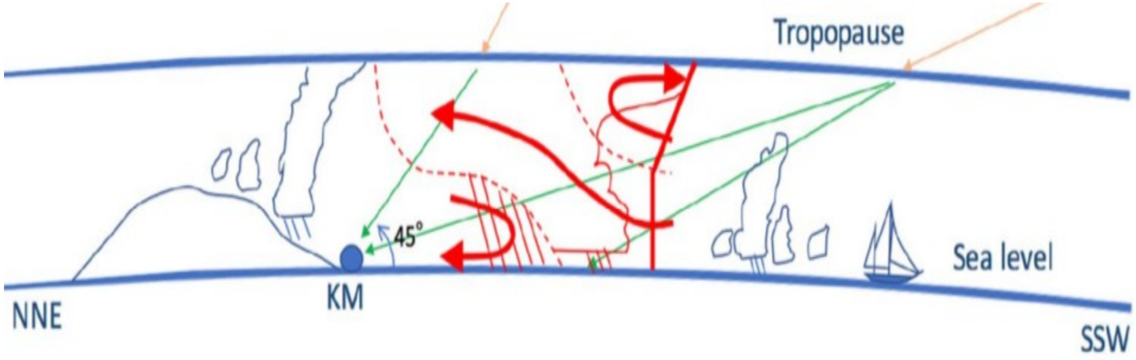
Tanaka et al. (2022) Sci. Rep. 12, 16710 https://doi.org/10.1038/s41598-022-20039-4





- Increase in atmospheric pressure increase the probability of muon decay and interaction

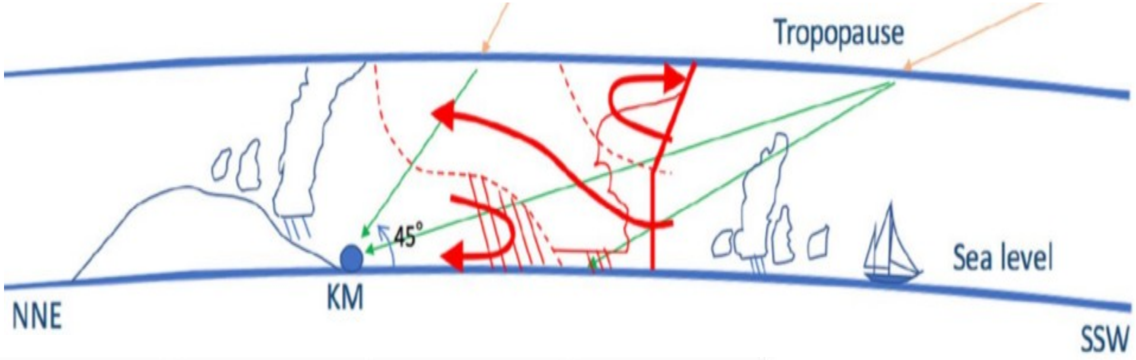
  → **muon flux is inversely correlated with atmospheric pressure**

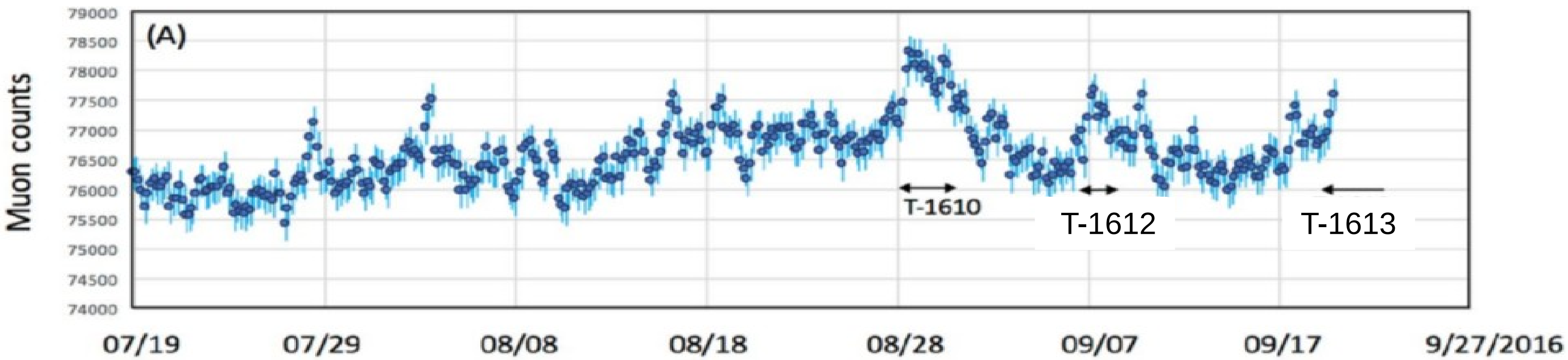
  (e.g., 1 % pressure drop result in
  2 % flux increase)

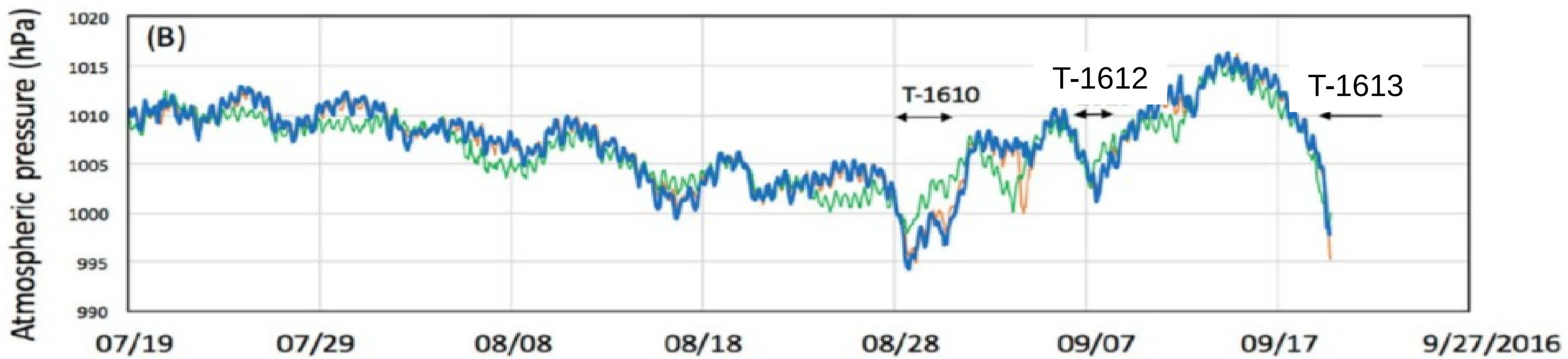
IV. Muography of Typhoons

Tanaka et al. (2022) Sci. Rep. 12, 16710 https://doi.org/10.1038/s41598-022-20039-4

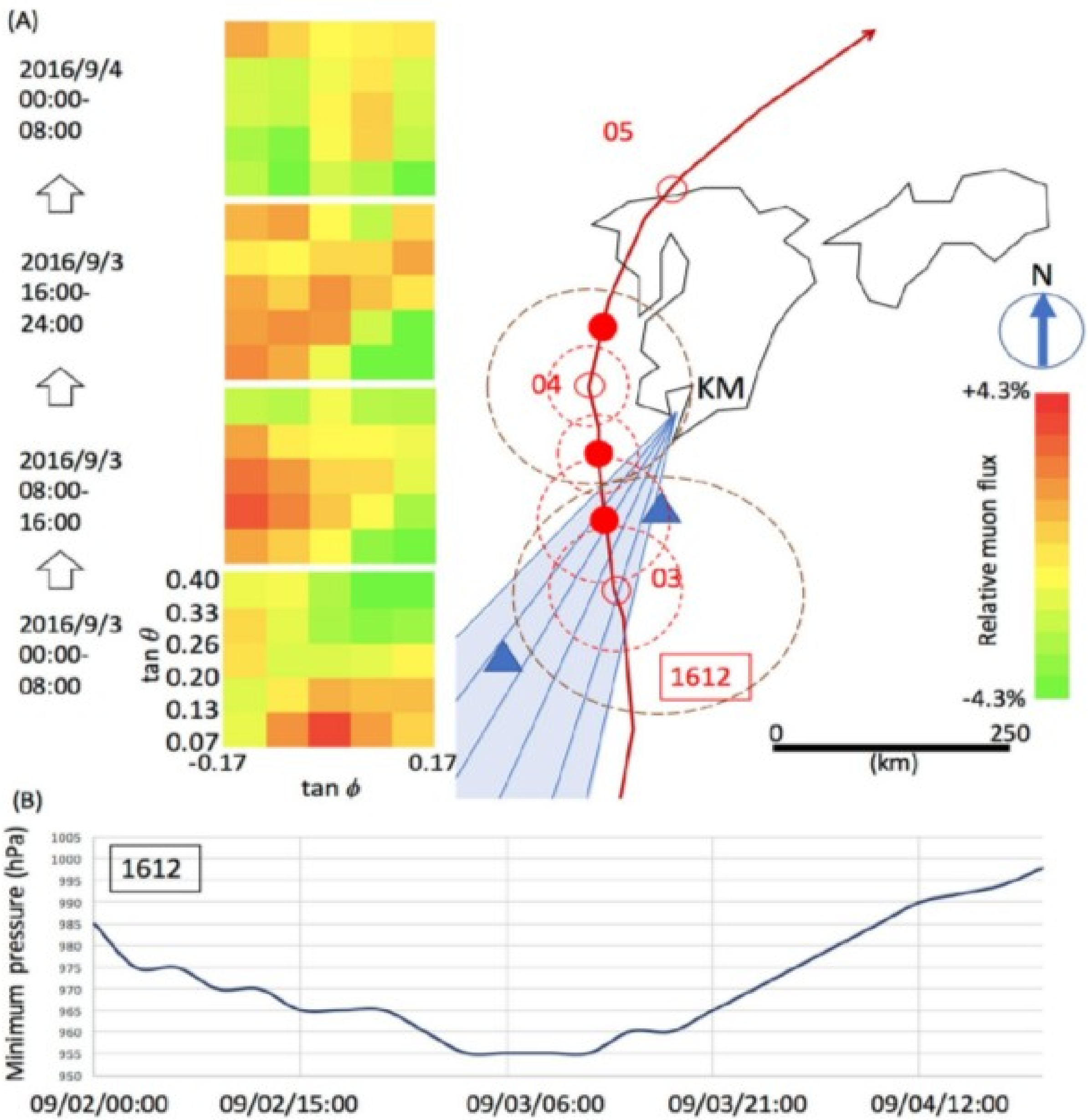
- Scintillator-based MMOS of SMO was applied to measure the muon flux between zenith angles 45 deg and 90 deg
- Muon counts increased during typhoons







Time-sequential Muographic Images



- T-1612 passed across the LOS of SMO from South to North on 2016/09/03 – 2016/09/04
- Angular dependent relative muon flux increased consistently with the passage of typhoon
- **High-resolutional Dynamic Muography:**
  - **Studying the genesis and maintenance of tropical cyclones**
- 2 solid angle is planned to be covered with MWPC-based tracking systems

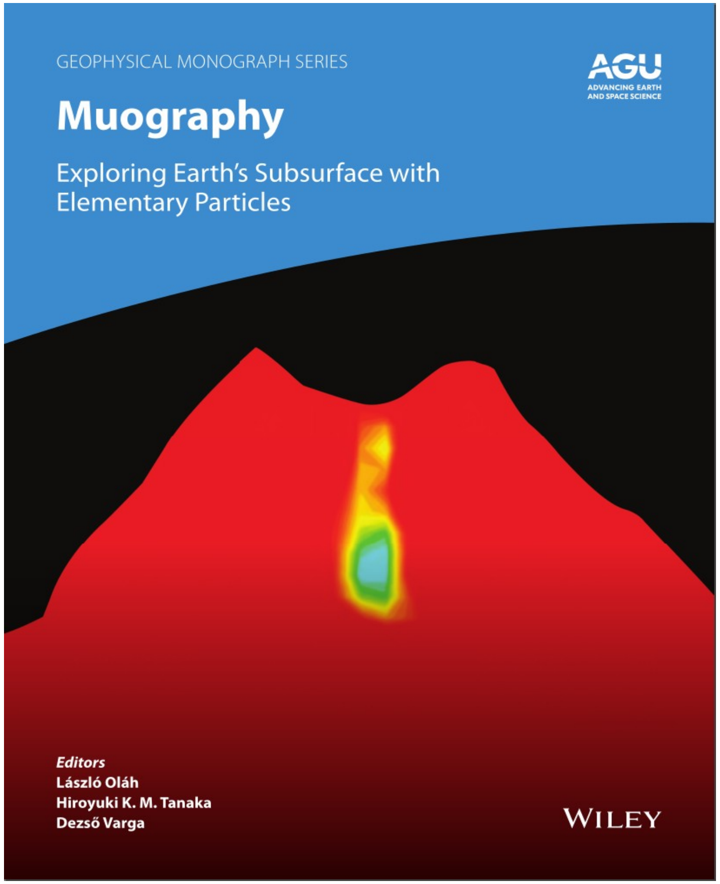
V. Summary

- Sakurajima Muography Observatory is monitoring both internal and surface mass-density changes
- A link between ground deformation and eruption frequency was revealed via time-sequential muography of Sakurajima

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

- Convolutional Neural Networks captured hidden features of muographic images and achieved a fair AUC score of 0.761 for eruption prediction
- Muography of tropical cyclones has been demonstrated

Tanaka et al. (2022) Sci. Rep. 12, 16710
https://doi.org/10.1038/s41598-022-20039-4



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

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