Geophysical Research via Cosmic-ray Muon Tracking

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5 March 2024

東京大学 THE UNIVERSITY OF TOKYO

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Muographix

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MUOGRAFIA

HUN-REN Magyar Kutatási Hálózat

WIGNER

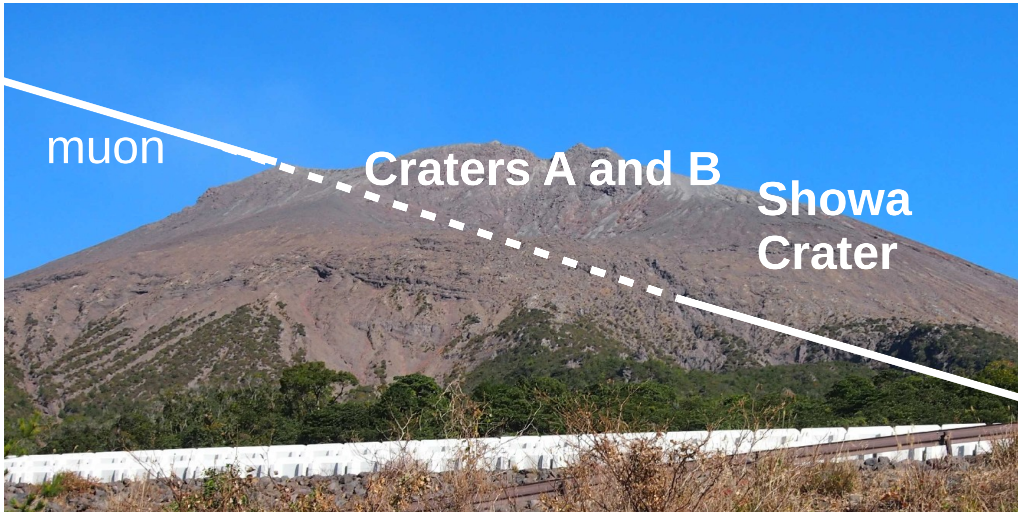
Outline

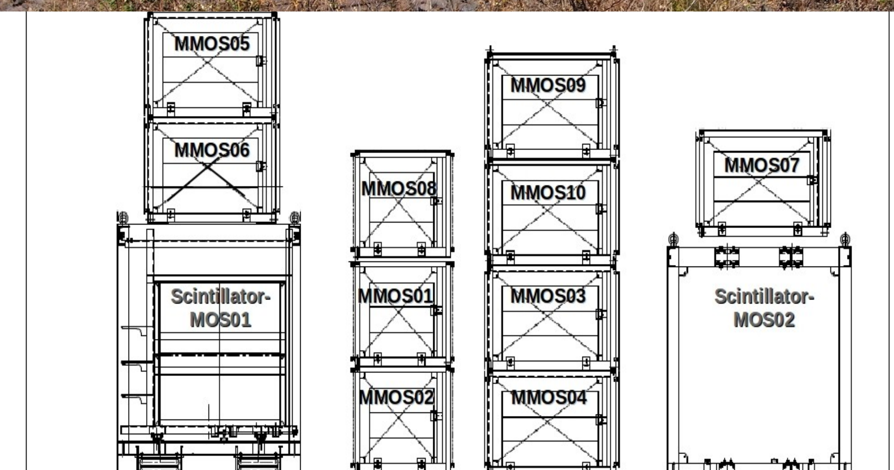
I. Research Infrastructures and Instrumentation

Vesztergombi High Energy Physics Laboratory (VLAB)
of HUN-REN Wigner RCP
→ Application oriented R&D of gaseous tracking detectors

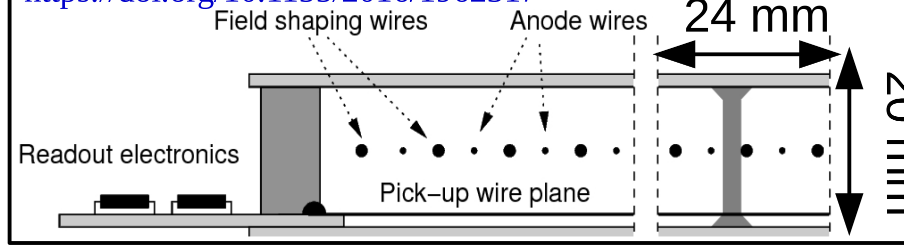
International Virtual Muography Institute (VMI)
→ framework for data storage, monitoring and simulation

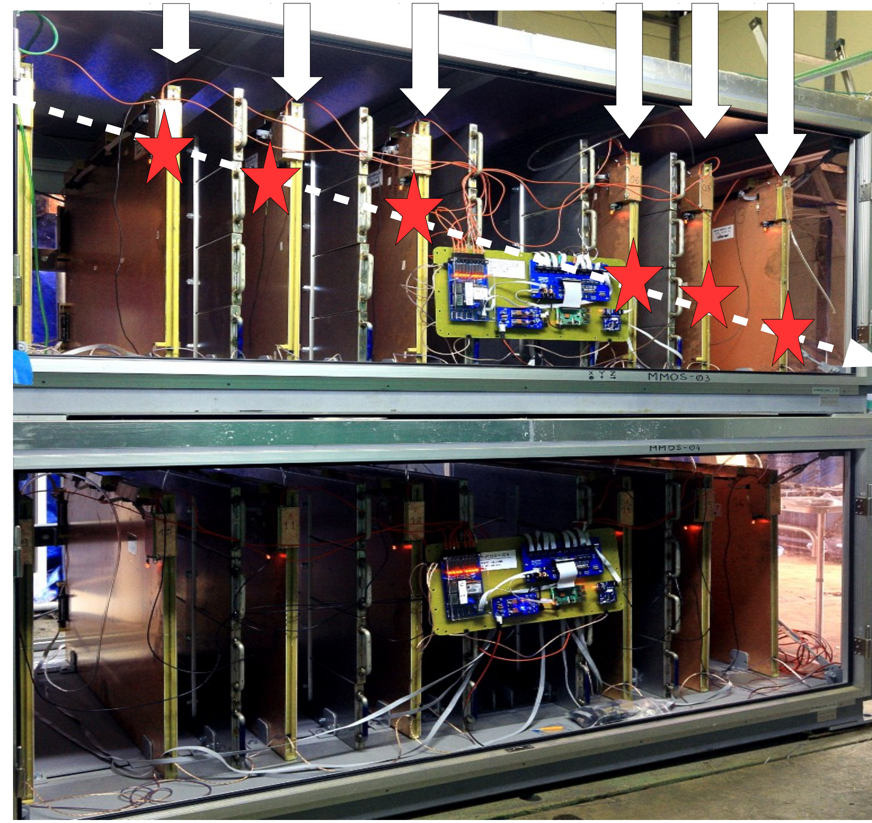
Muographic Observation Instrument (MOI)





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





- 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)

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

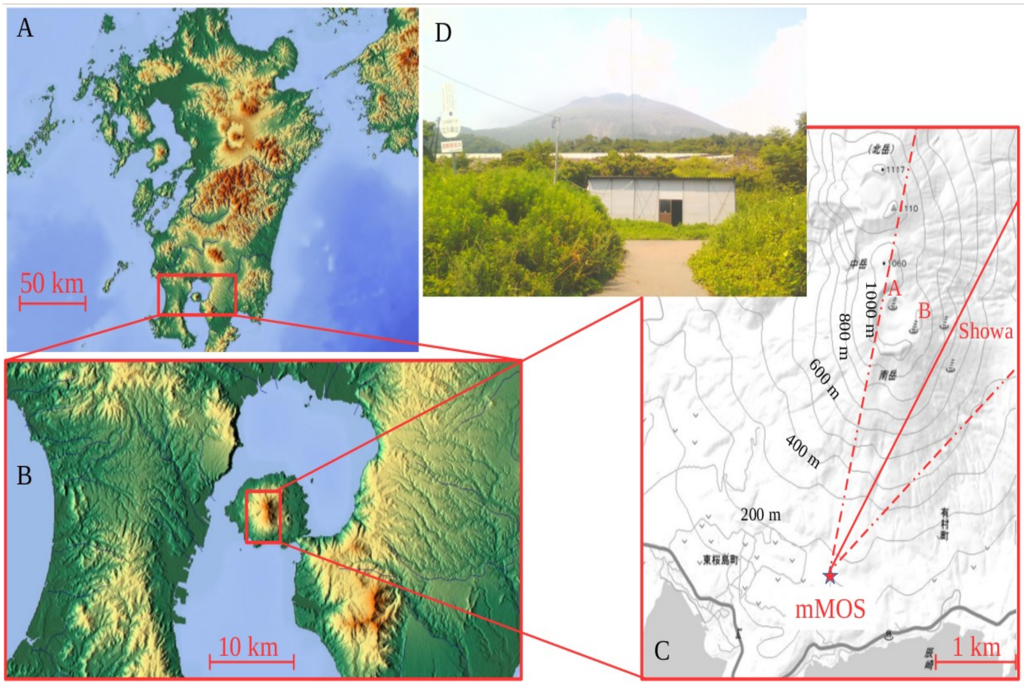
Muograpic Observation Instrument WO2017187308
https://patentscope2.wipo.int/search/en/detail.jsf?docId=WO2017187308

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

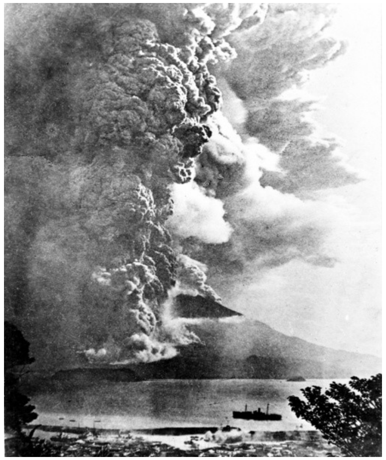
II. Volcanological Studies

Muography of Sakurajima volcano

- **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



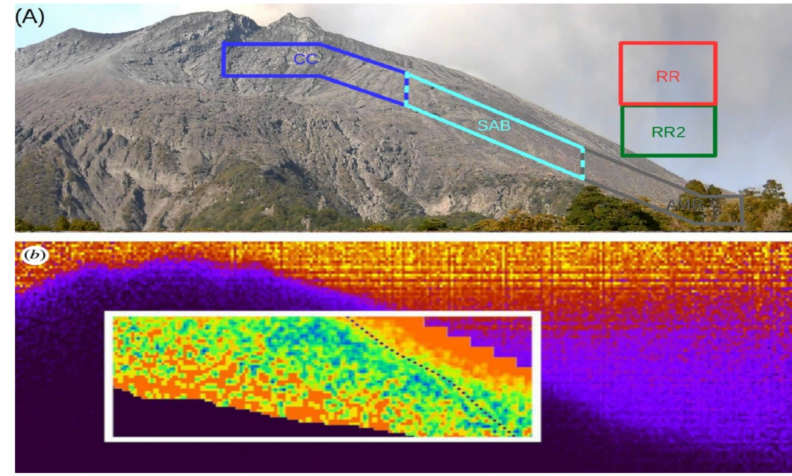
Source: Wikipedia

Source: Kimon Berlin, CC BY-SA 2.0

The First Observations:
Plug Formation, Tephra Deposition and Erosion

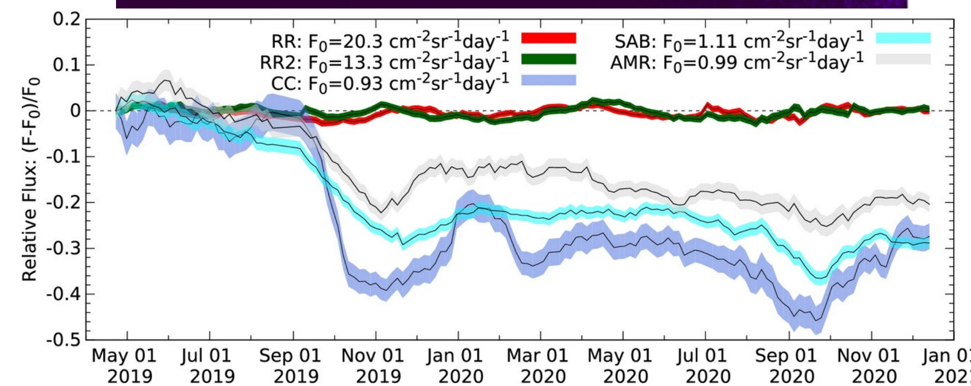
- Resolving the internal structure of the volcano with a spatial resolution of below 10 metres that is challenging to other techniques

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



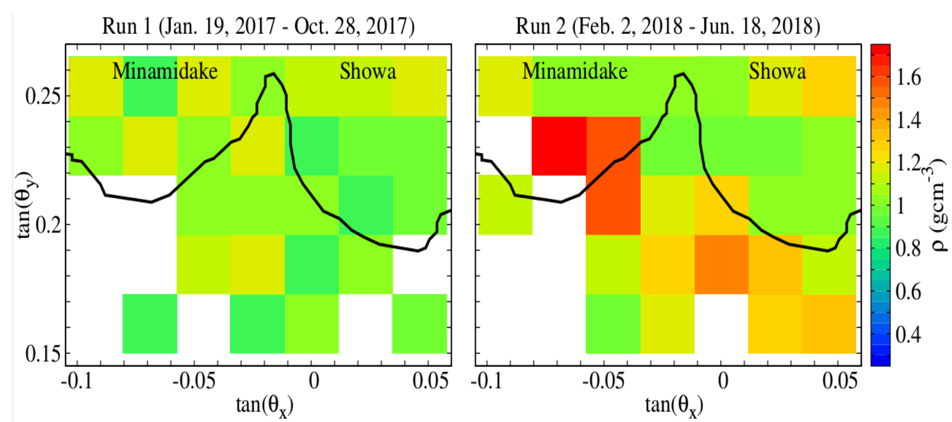
- Monitoring changes in the amount of materials on the volcanic edifice due to volcanic ejecta deposition, erosion and mudflows (lahars)

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

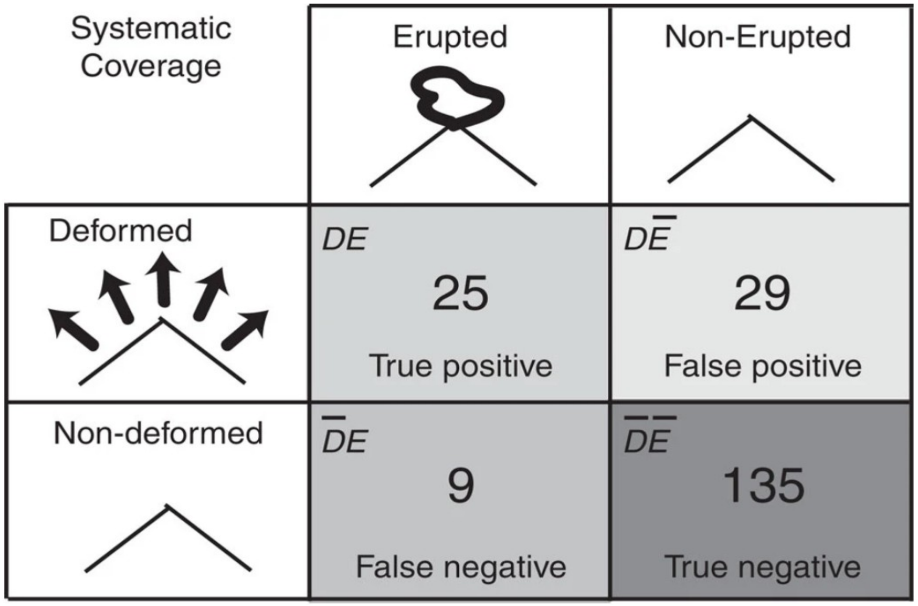
L. Oláh et al. Geophys. Res. Lett. 46, 10417, 2019, https://doi.org/10.1029/2019GL084784



Link between ground deformation and eruptions

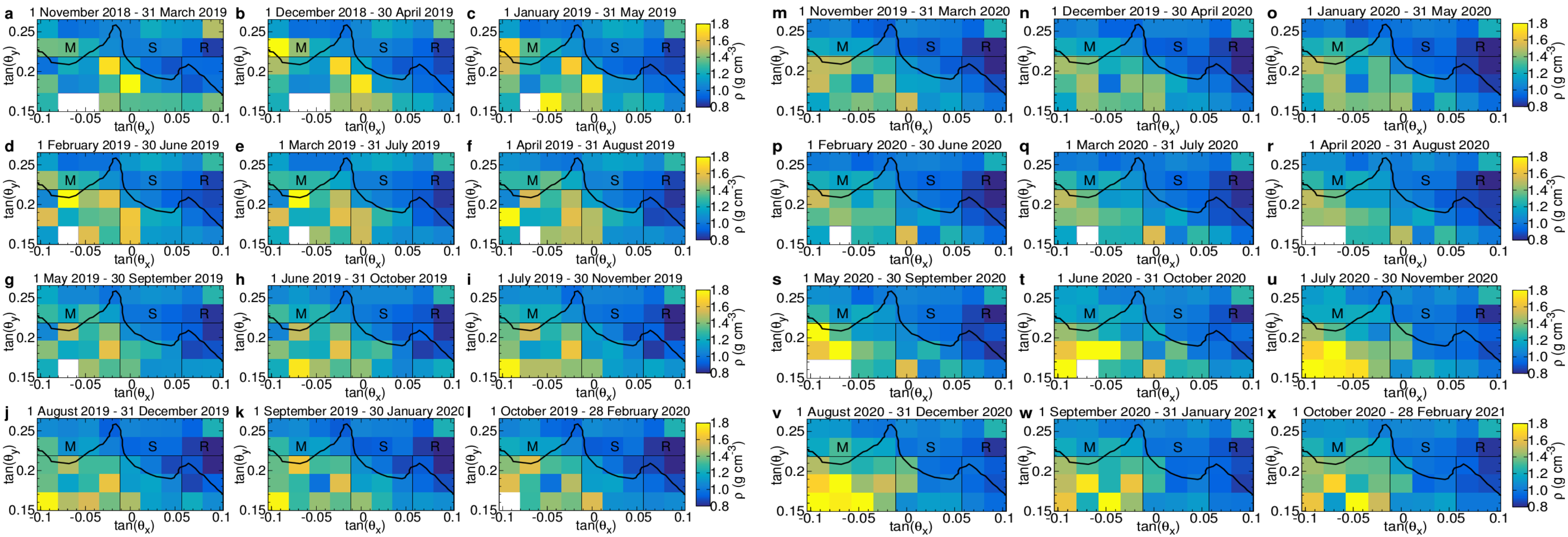
- **Active volcanism** is driven by the subsurface evolution and movement of magmatic materials, which **may induce seismicity, ground deformation, gas emission, and fumarolic activity**
- Monitoring of the signals induced by these phenomena is indirect and interpretation of the origin of the signals 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

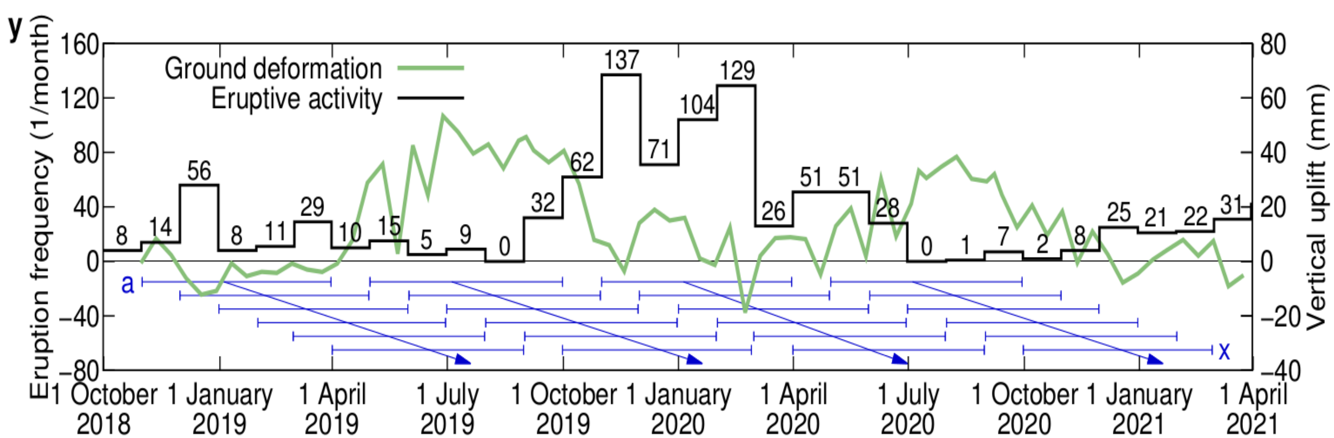


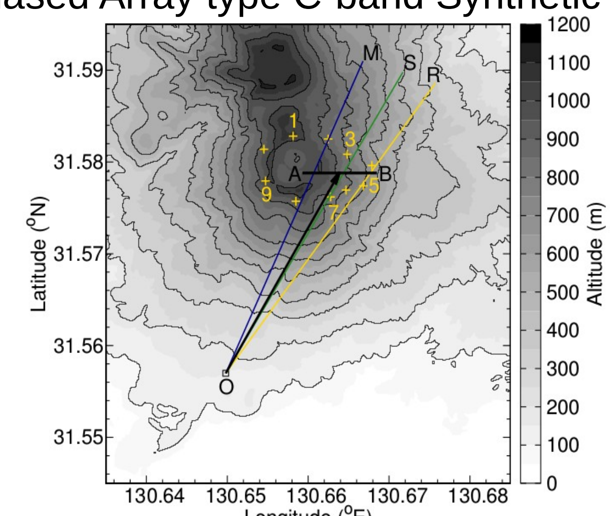
Muography and InSAR Observations of Sakurajima

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.



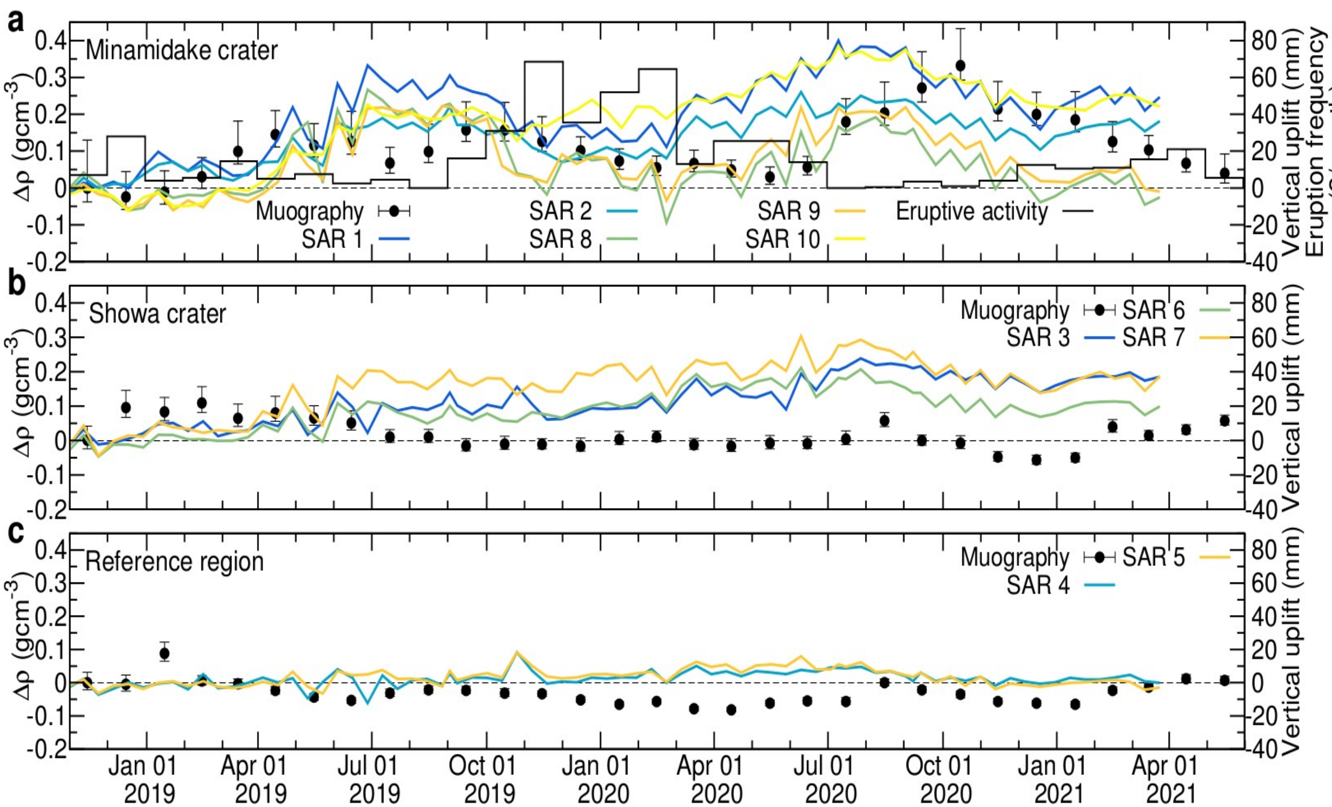
Vertical displacement around the active crater of Sakurajima was determined relative to the ground level measured on 31 October 2018 at ten locations (yellow-coloured crosses) by NEC using the Phased Array type C-band Synthetic Aperture Radar images acquired by Sentinel-1 with a periodic time of 12 days.

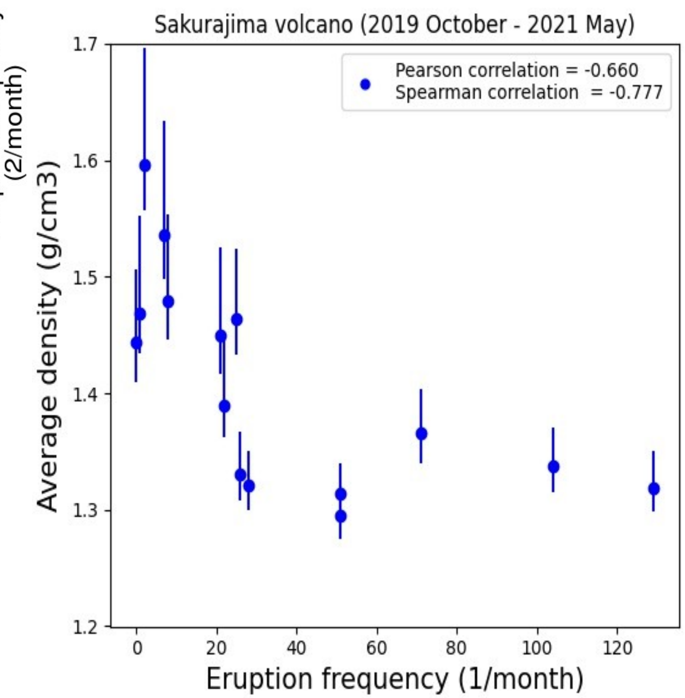




Volcanological Implications

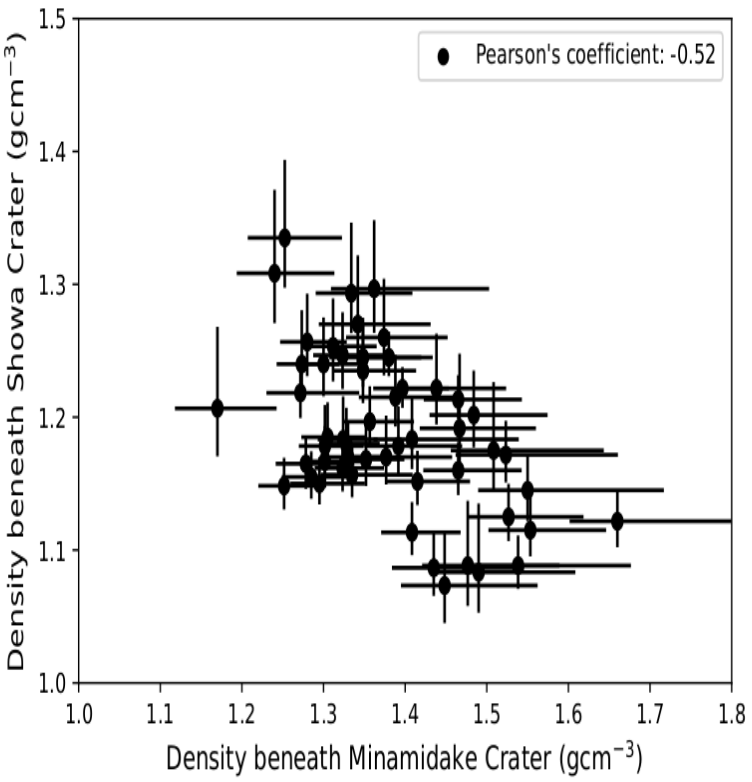
- Mass density increased during inflation, when eruption frequency was low, and decreased during deflation, when eruption frequency was high.
- Periods of low eruption frequency are associated with the formation of a dense plug in the conduit, which we infer caused inflation of the edifice by trapping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





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

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

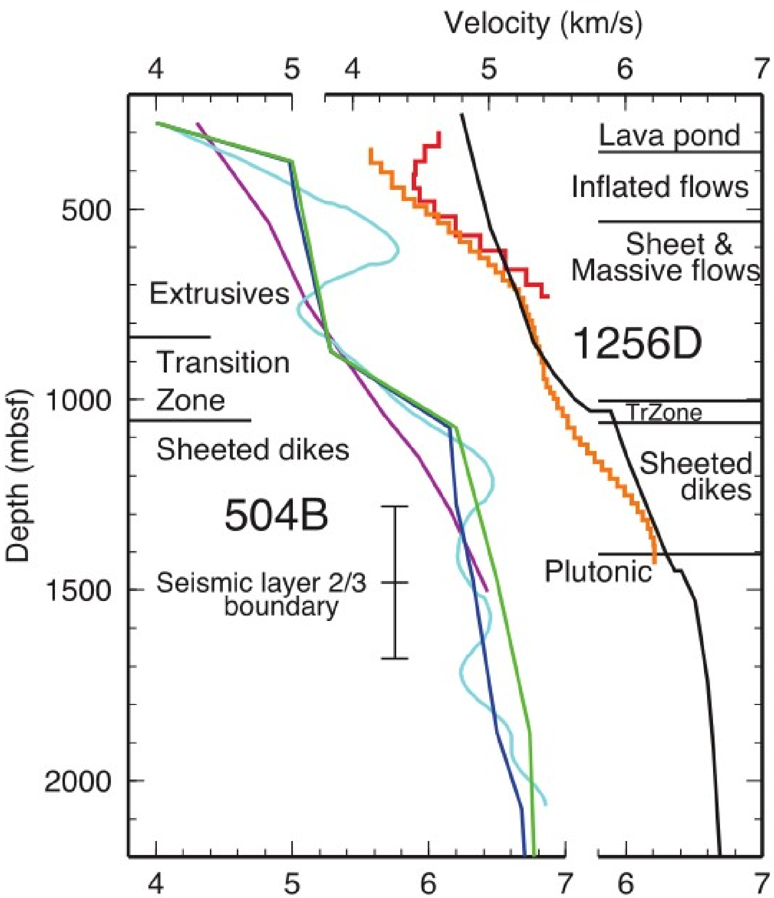
  → **a branched connection between the conduits of the two active craters**

III. Studying Oceanic Lithosphere via Muography of Ophiolites

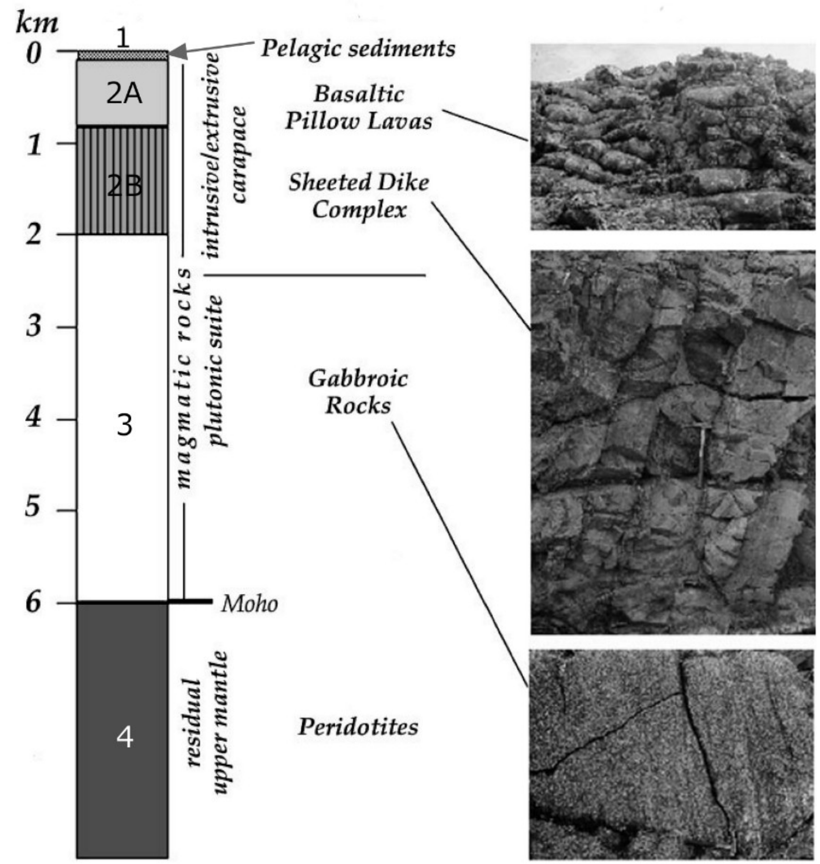
Oceanic litosphere in Ophiolites

- **Oceanic litosphere (crust and upper solid mantle) cycle (1. formation, 2. evolution and 3. desctruction) → cycle of matter and energy**
- Only one vertical seismic profile reached seismic layer 2/3 boundary and **Moho has not yet been reached by oceanic drilling** → geological nature is not yet well understood
- Different seismic layers (layer 2/3 boundary and Moho) are exposed above ground in ophiolites

→ **Ophiolites help to understand the correlation between oceanic structure and geology**



Swift, et al. 2008. Velocity structure of upper ocean crust at Ocean Drilling Program Site 1256. Geochim. Geophys. Geosys., 9, Q10O13, DOI:10.1029/2008GC002188

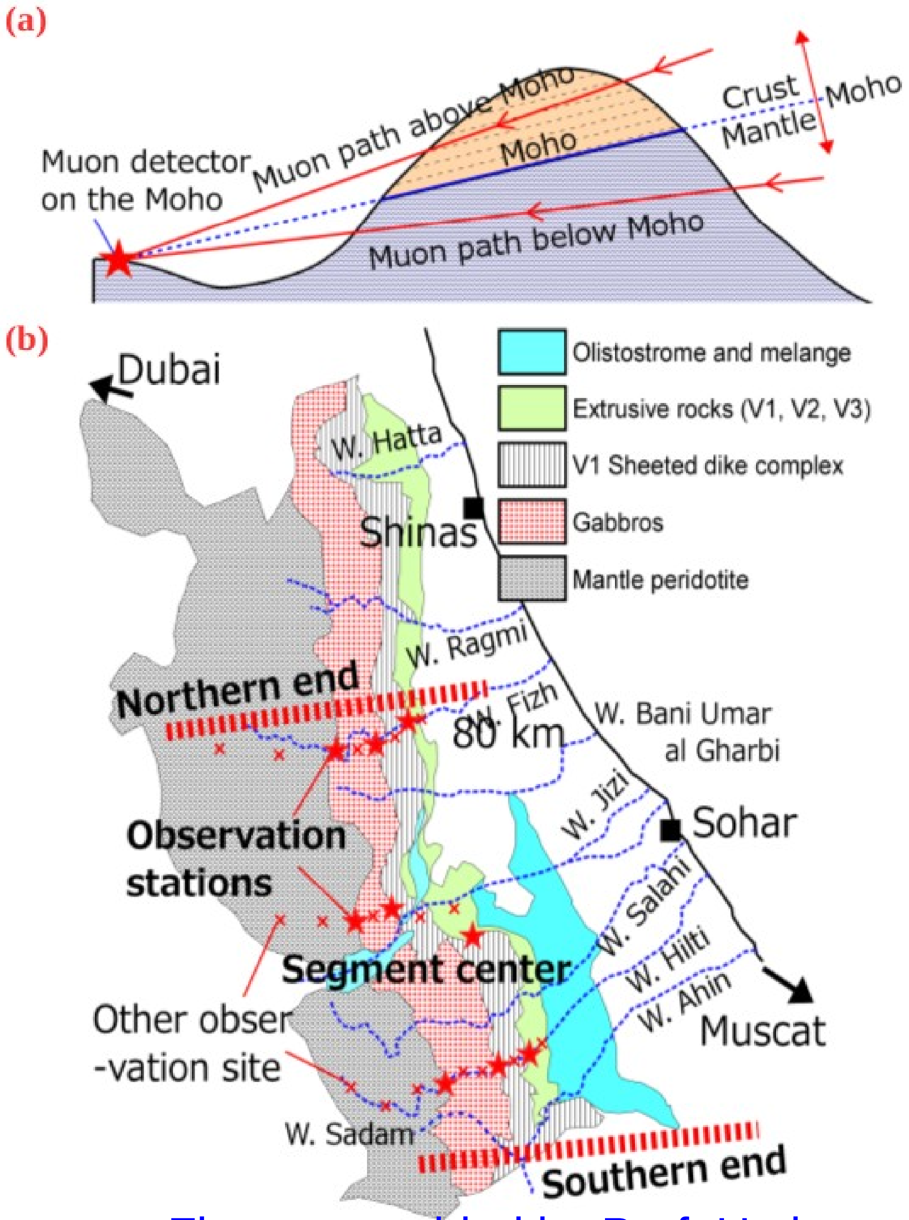


Karson, J.A., Geological structure of the uppermost oceanic crust created at fast- to intermediate-rate spreading centers. *Annu. Rev. Earth Planet. Sci.* **2002**, 30, 347. DOI: 10.1146/annurev.earth.30.091201.141132.

Muography of the Samail Ophiolite

- Sampling is available but sampling density is low
  → seismic velocities are different
- **Objective: better understand the geologic nature of the crust/mantle (Moho) and upper/lower crustal boundaries of the Oman Ophiolites**
- Muographic images of the bulk density structure can be compared to the
  seismic data of the ocean floor
- The Oman ophiolite is the largest and best preserved fragment of oceanic lithosphere in the world, extending 80 km × 500 km
- **Oman ophiolites oceanic crustal structure is similar to the structure of East Pacific Rise**

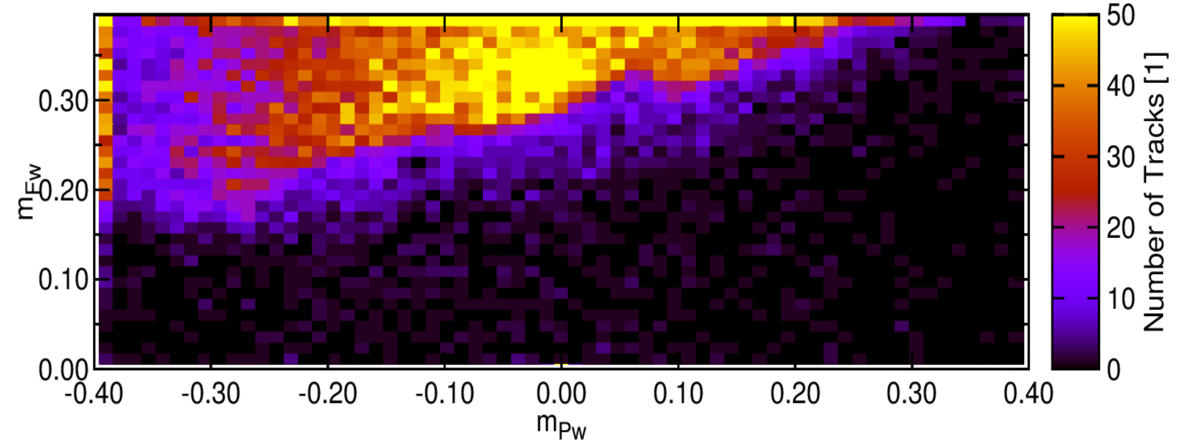
  → data can be compared with the structure of the Pacific Plate, the target of the
  IODP-805 MoHole to Mantle (M2M) Proposal



Figures provided by Prof. Umino

Data collection started a few days ago...

- Moho tranzition zone at Wadi Fizh, Oman



IV. Muography of Tropical Cyclones

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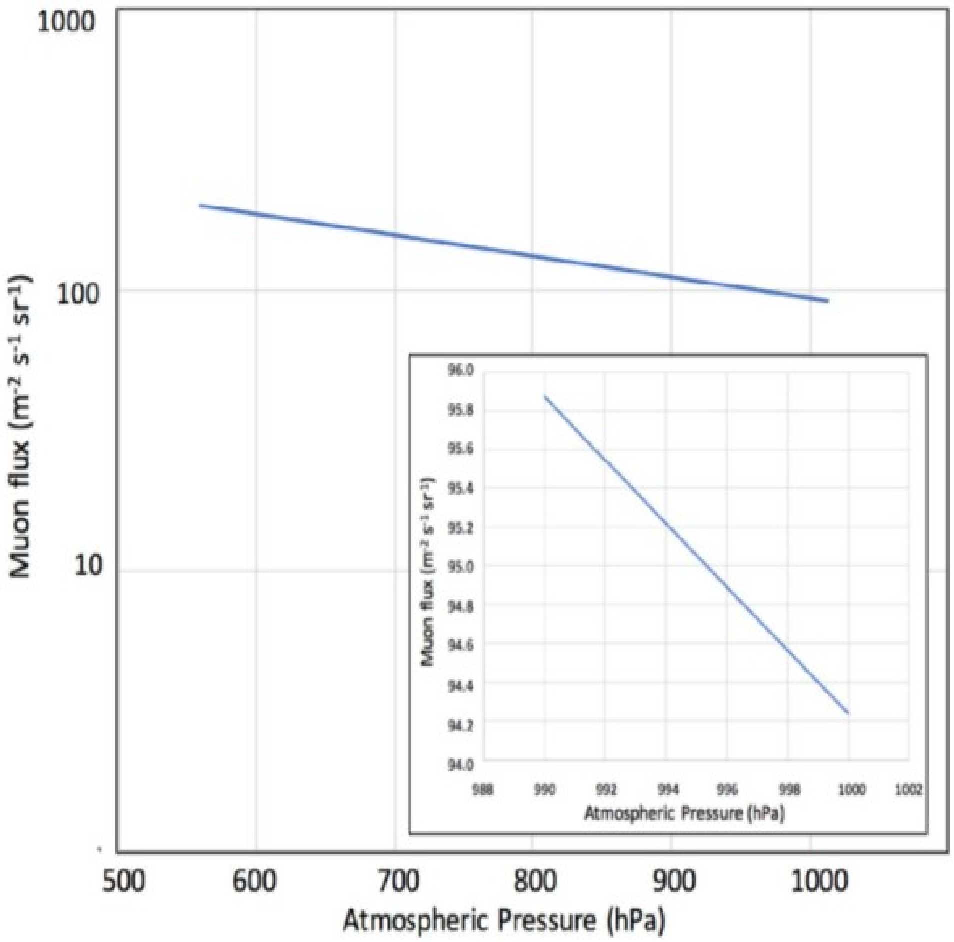
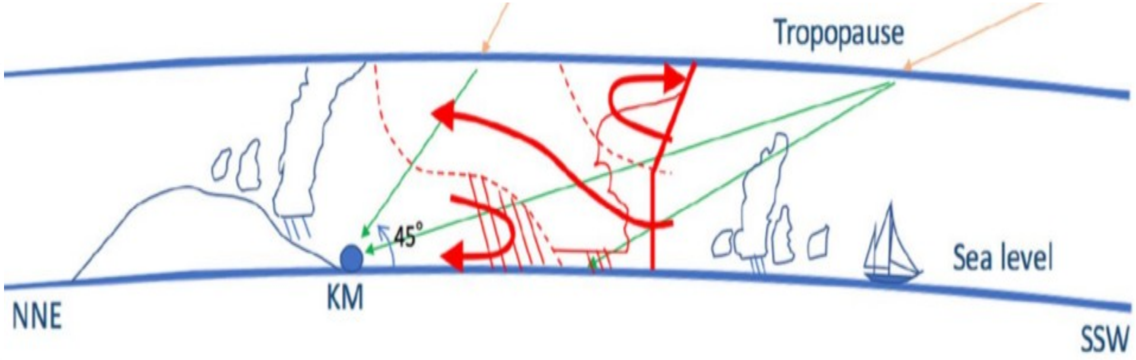
Tanaka et al. (2022) Sci. Rep. 12, 16710 https://doi.org/10.1038/s41598-022-20039-4





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

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

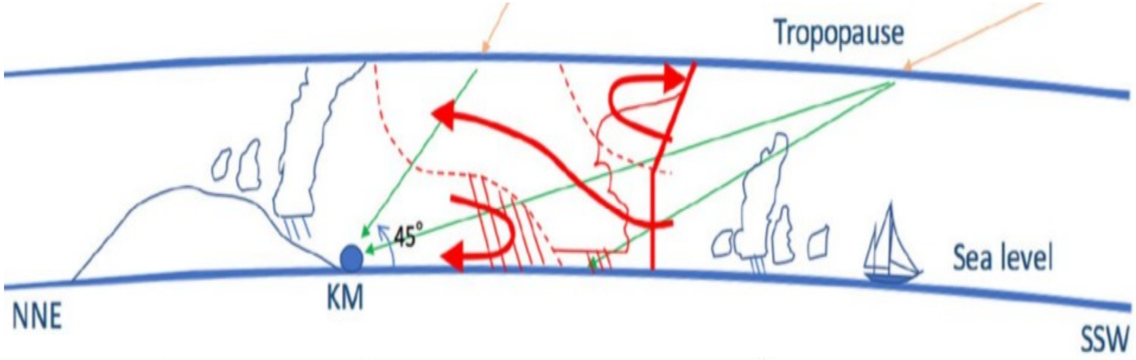
  (e.g., 1 % pressure drop result in 2 % flux increase)

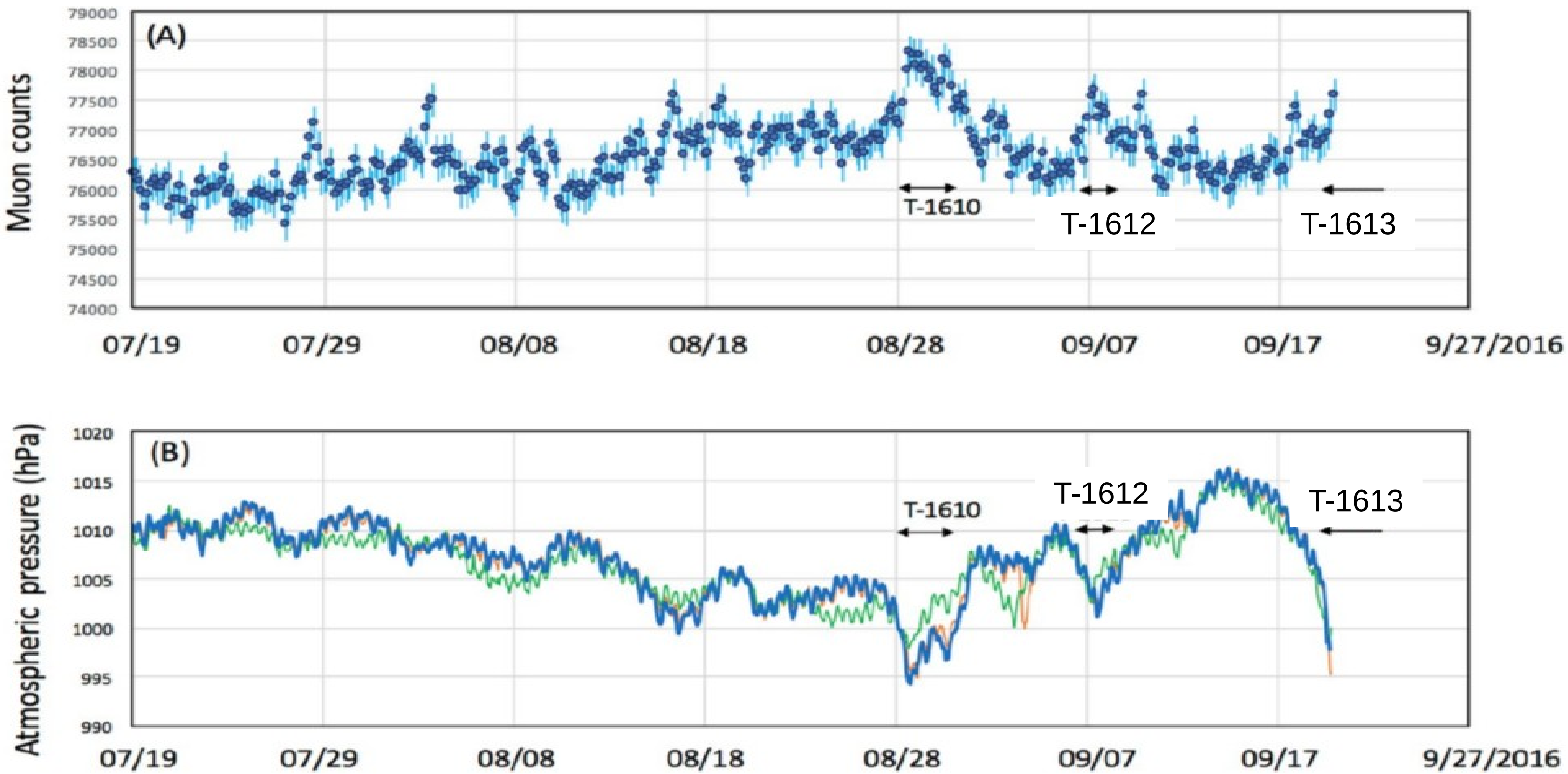
- **Muography allows to resolve the vertical pressure profile of TCs**

IV. Muography of Typhoons

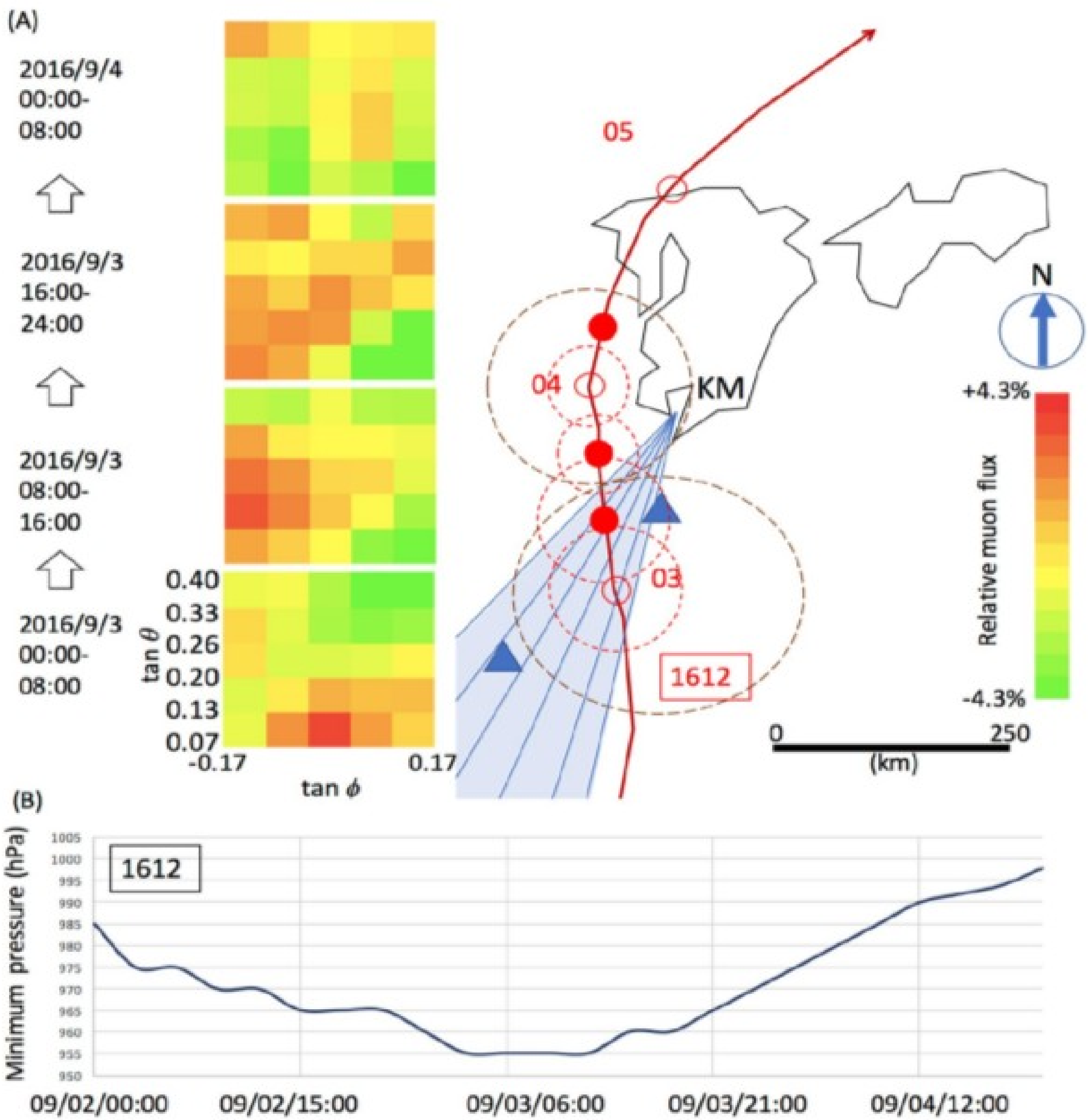
Tanaka et al. (2022) Sci. Rep. 12, 16710 https://doi.org/10.1038/s41598-022-20039-4

- 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

Possible applications of cosmic-ray muon muography in Earth Sciences:

- Volcanology

- Researching the geology of oceanic lithosphere

- Studying and monitoring of tropical cyclones

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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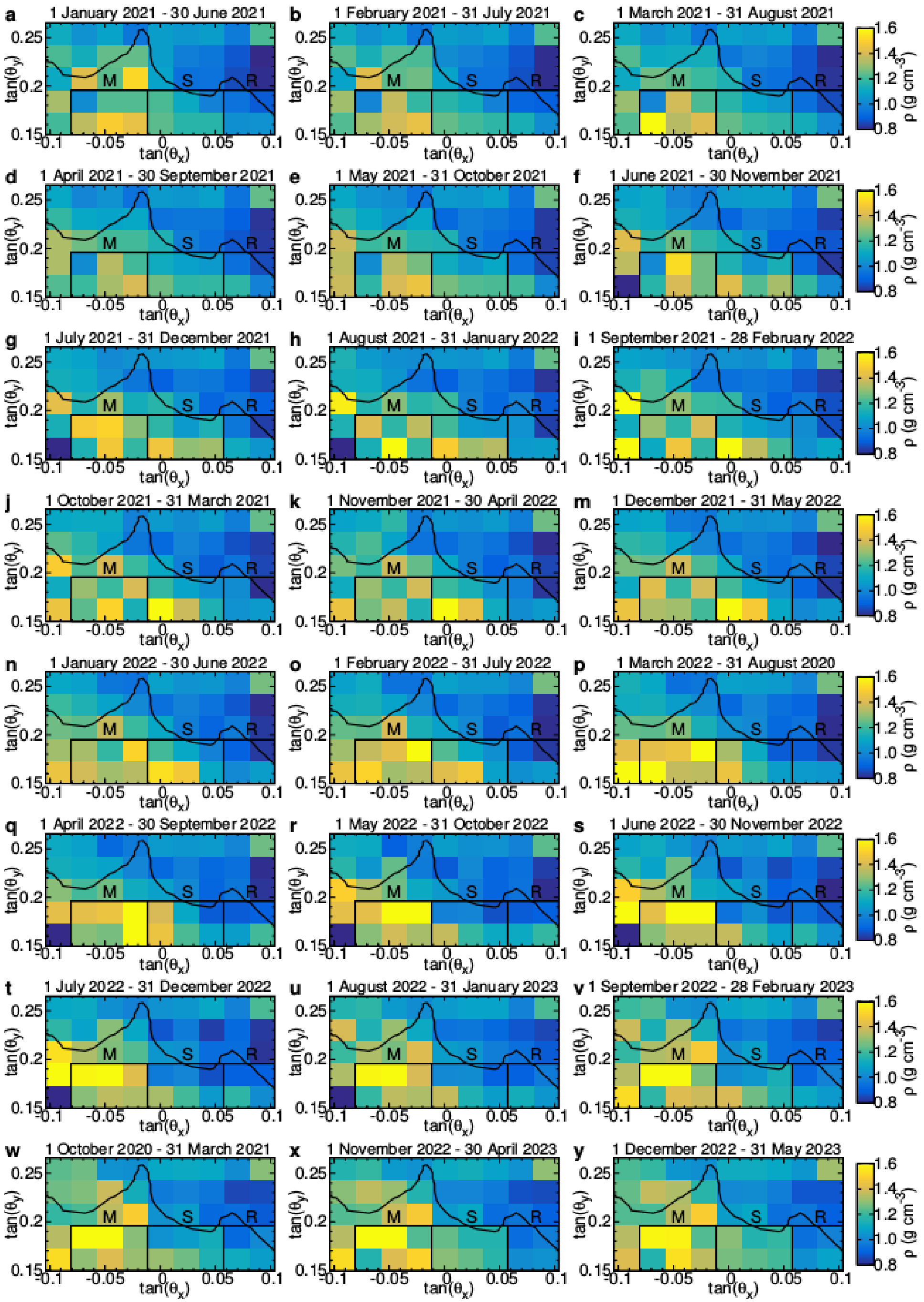
https://wigner.hu/s/high-energy-geophysics/index_eng.html

Back up slides

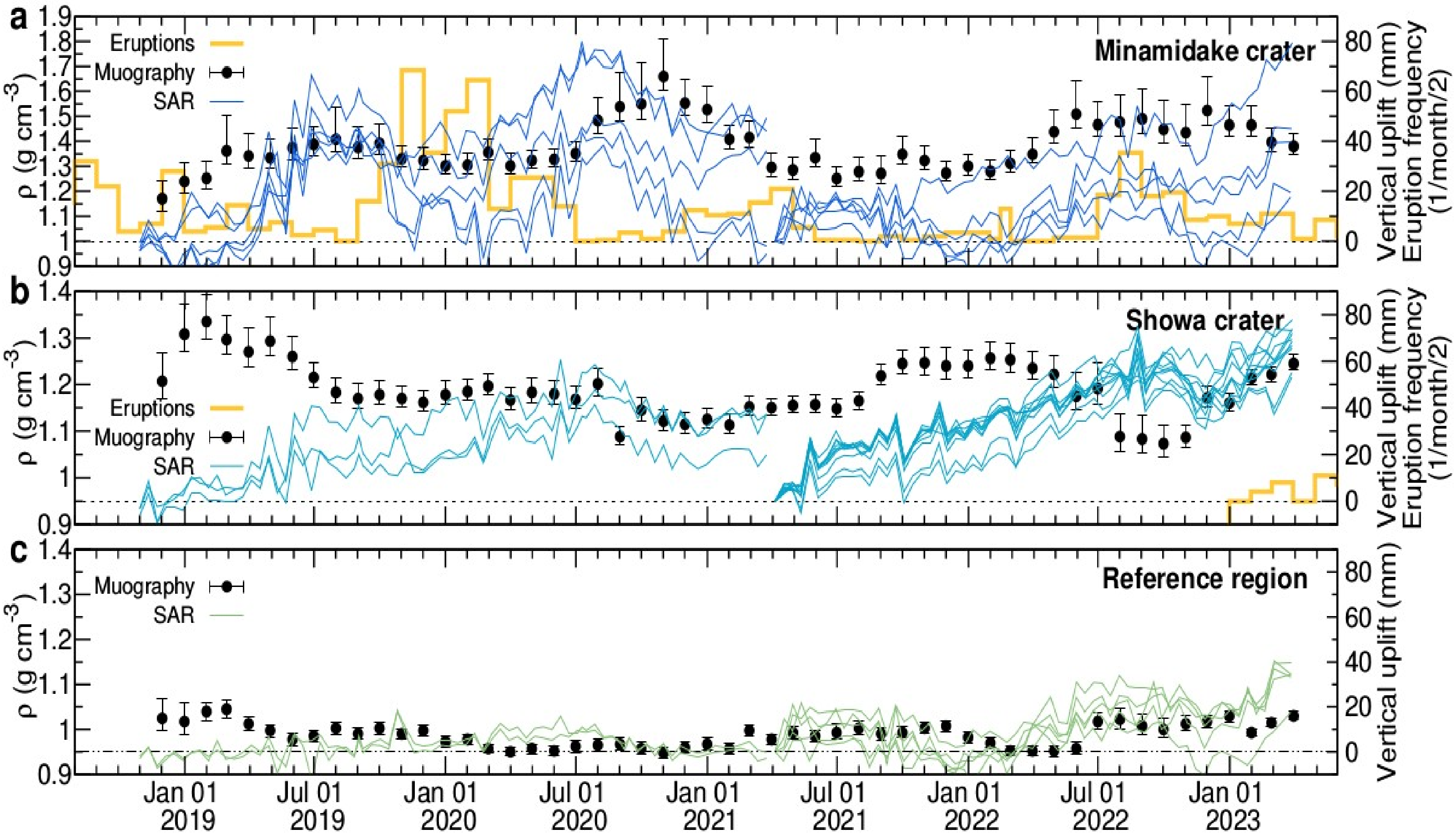
A Unified Region Beneath the Active Craters



- The muographic images shows that the density increased beneath the Minamidake crater and decreased beneath the Showa crater after January 2022.
- Figures 5o-y shows that the **conduits are unified beneath the eastern part of Minamidake crater and Showa crater and this unified volume might be slanted towards east.**
- The **seismic epicenters distributed beneath both craters** at shallow depths from September to December 2020 and June to December 2021 (Japan Meteorological Agency, 2021) when densities increased across the region M and S, respectively.
- **Infrared thermal imaging revealed simultaneous presence of geothermal areas** in the eastern part of Minamidake crater and Showa crater in October 2021 (Japan Meteorological Agency, 2021), in February and October 2022 (Japan Meteorological Agency, 2022). The eruptive activity has switched from Minamidake crater to Showa crater in June 2023 (Japan Meteorological Agency, 2023).

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.
- **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 data** support our current picture. The magma has recurrently risen and the plug was recurrently generated underneath both of the craters. However, at Minamidake crater, sufficient gas was provided and as a result, the gas pressure has risen. Consequently, the ground surface was significantly upheaved in the Minamidake crater region. On the other hand, at Showa crater, sufficient gas was not provided after the plug formation underneath Showa crater, thus the ground surface was not significantly upheaved. On the contrary, in February 2023, from the InSAR data, there was an indication that the pressure underneath the generated magmatic plug increased underneath Showa crater, inducing a significant uplift of the ground surface in the Showa crater region. Consequently eruption occurred at Showa crater.

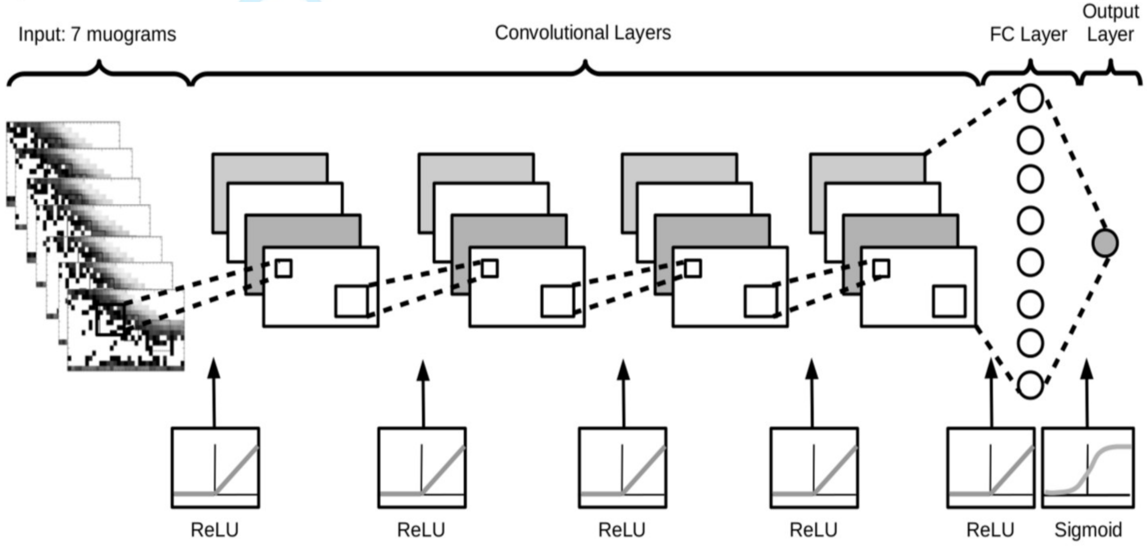


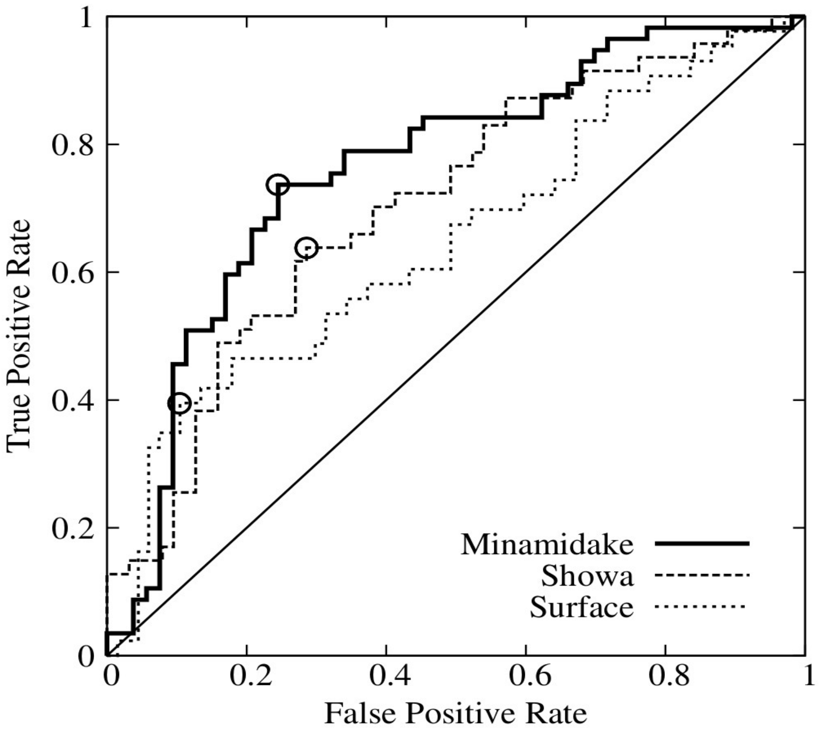
VI. Towards Short-term Eruption Forecasting via Machine Learning of Muon Images

- 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

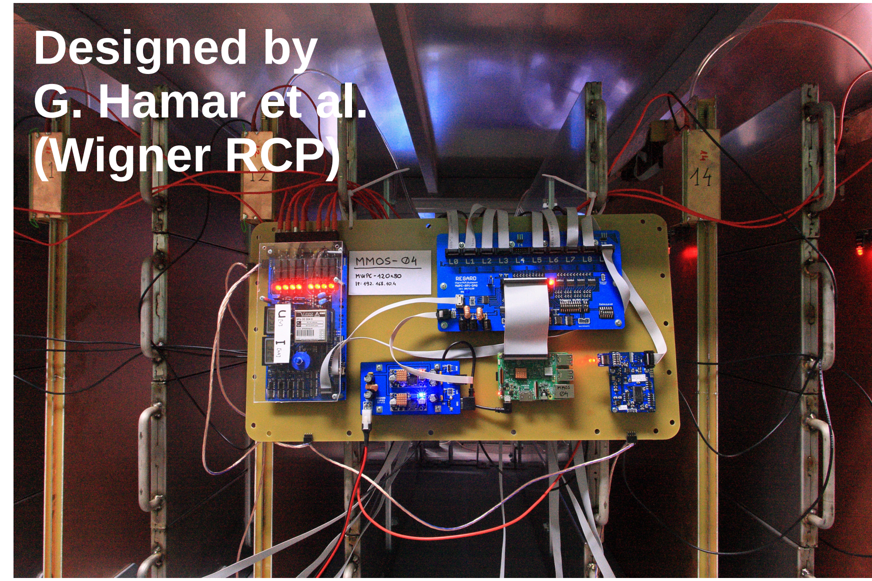
	Minamidake	Showa	Surface
Area Under the Curve	0.761	0.704	0.644
Sensitivity	0.737	0.638	0.395
Specificity	0.755	0.714	0.896

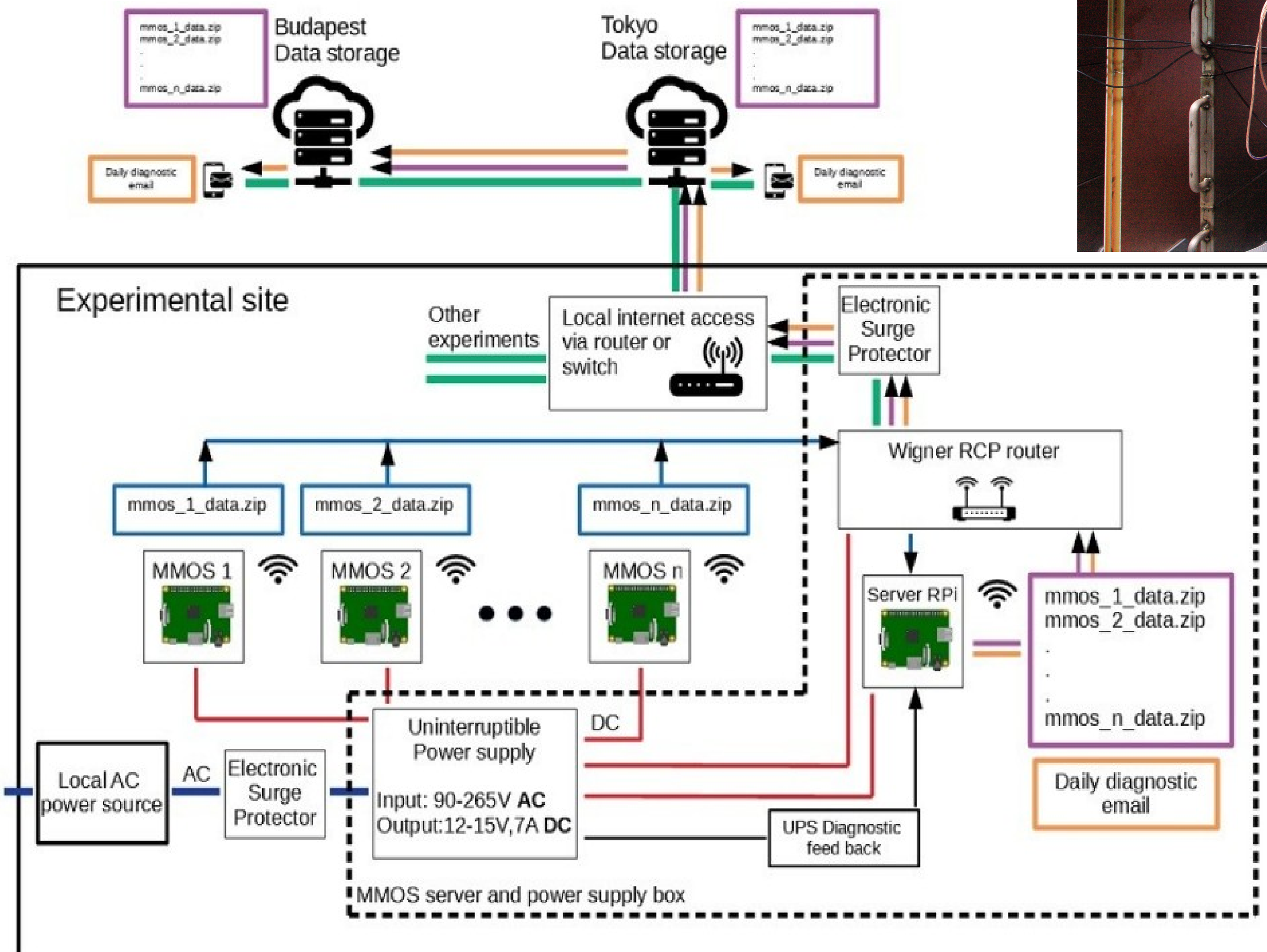




System Plan of SMO

D. Varga et al.: Nucl. Instrum. and Meth. A
https://doi.org/10.1016/j.nima.2019.05.077

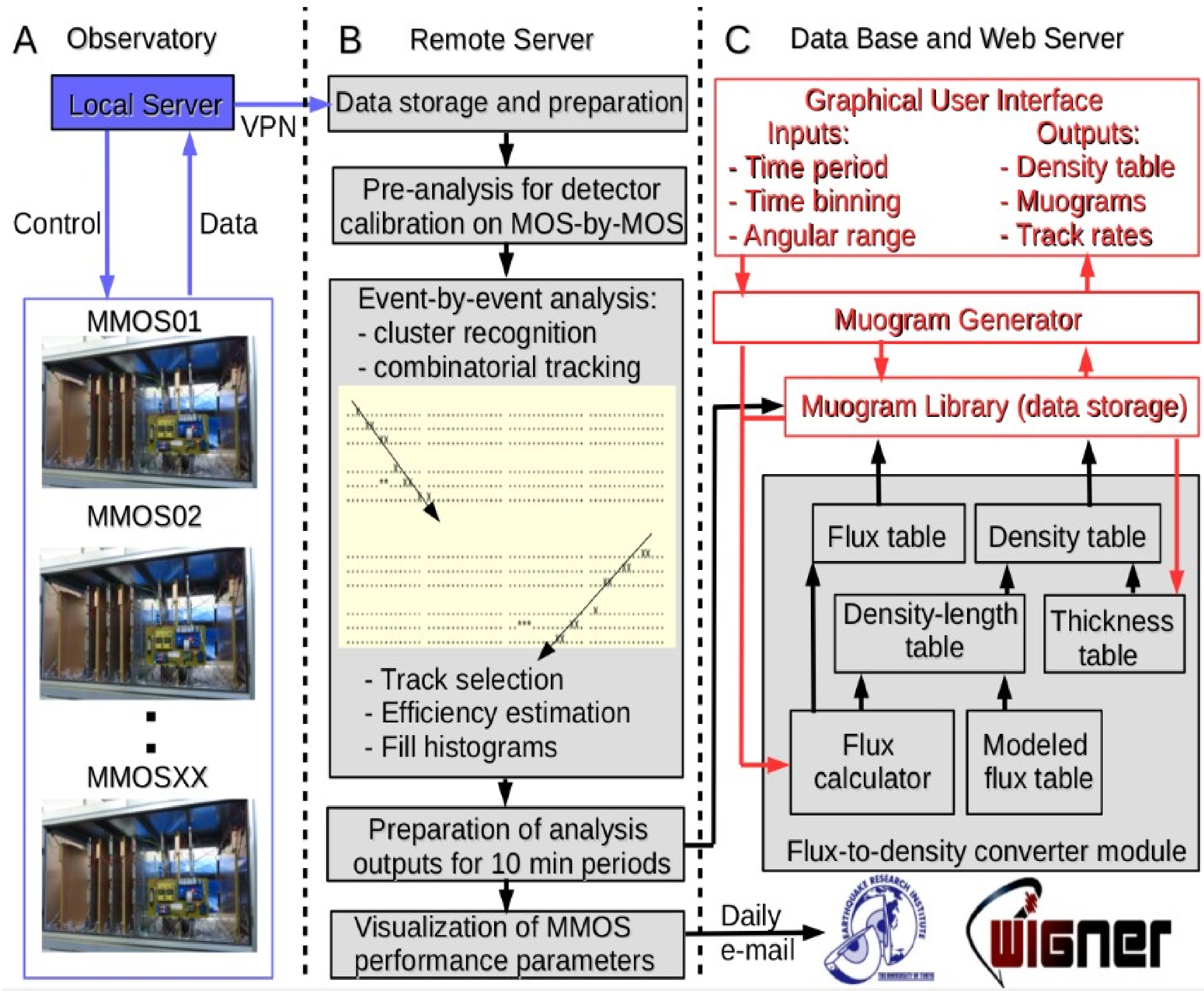


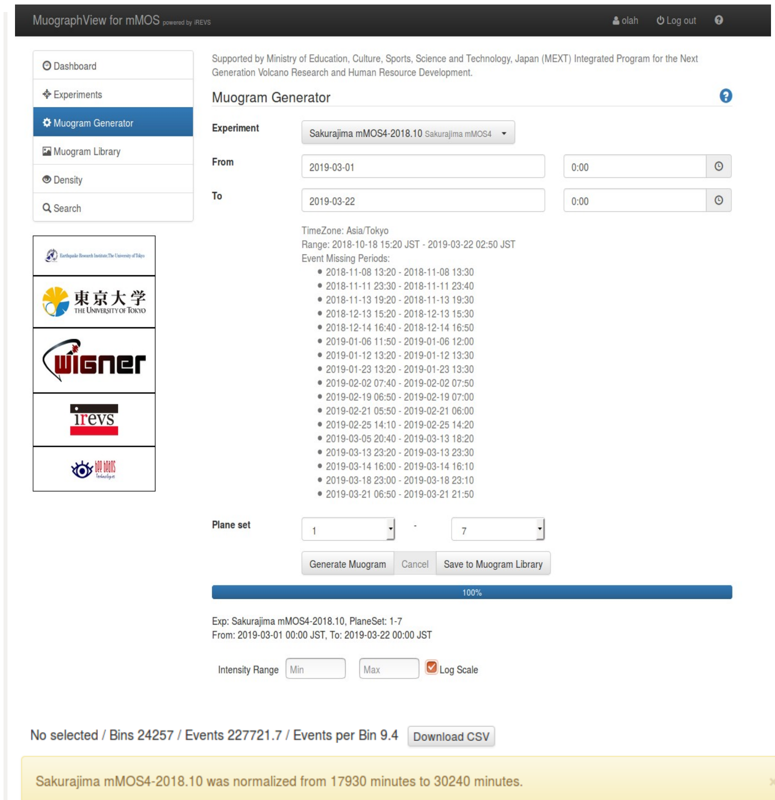


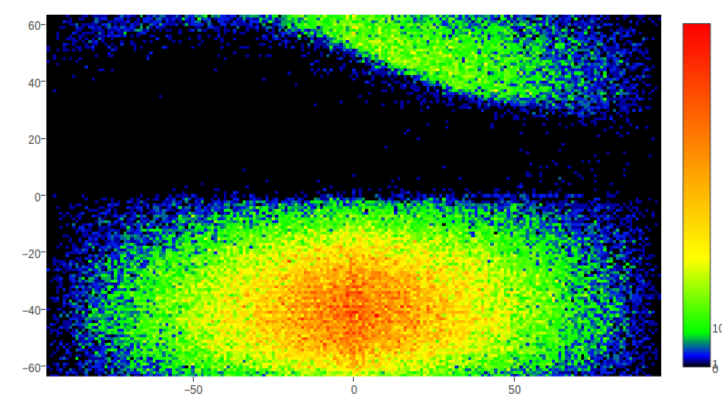
Source of this figure: Szabolcs József Balogh

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

II. Data Processing







https://mmos.muographers.org

Density Imaging

- Density values are extracted for each angular bin („pixel”) via comparing the modeled flux to the measured flux
- Numerical integration of zenith-angle and energy depedent spectra from minimal energies that required for muons the penetrate the volcanic edifice