Muographers Workshop 2024, Santa Fe, New Mexico

Studying Volcanoes and Oceanic Lithosphere with Muography

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Ministry of Energy and Minerals
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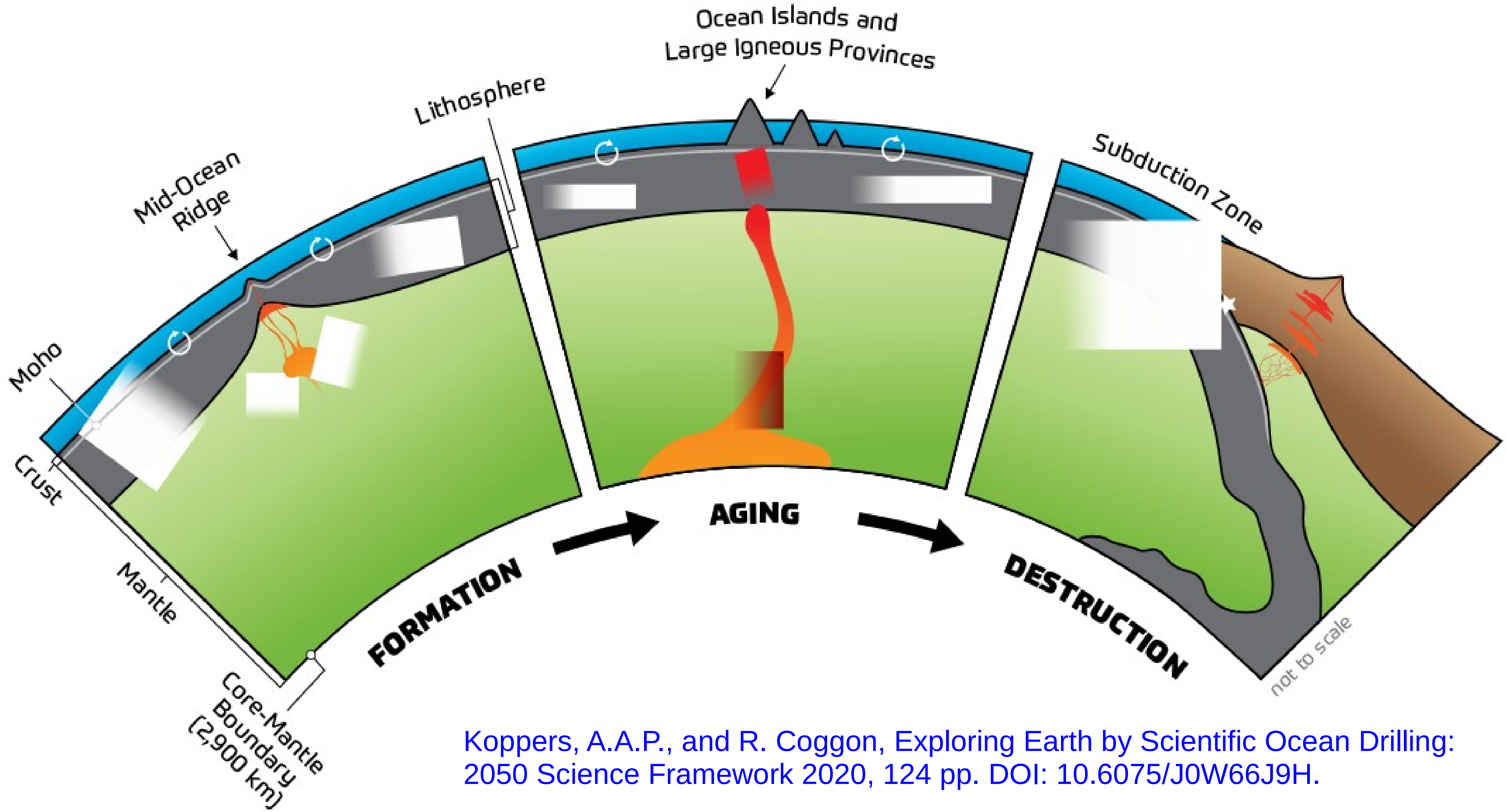
Outline

I. Scientific Background and Objectives

Oceanic Lithosphere

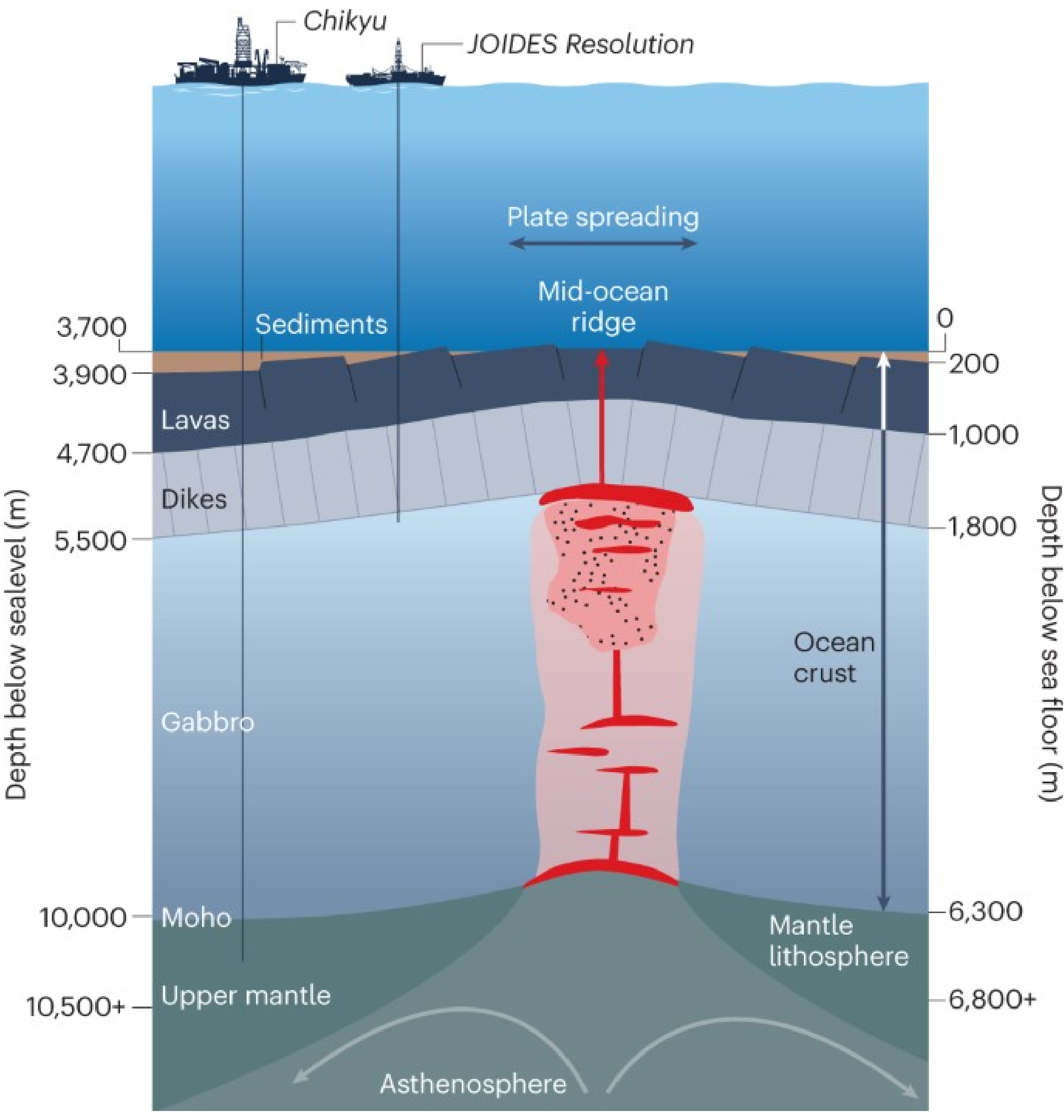
- **Lithosphere is built up from crust and upper solid mantle.**
- Crust has upper and lower layers with a tranzition zone.
  Mohorovičić (Moho) tranzition zone is situated betwen crust and mantle.
- **Oceanic lithosphere cycling:**
  (1) formation, (2) evolution, (3) desctruction occurs over a few tens to hundreds of million years.
- **Cycle of matter and energy**
  produces critical resources to economy,
  governs the occurrence various natural hazards from earthquakes to volcanic eruptions and
  regulates Earth's climate system.



Koppers, A.A.P., and R. Coggon, Exploring Earth by Scientific Ocean Drilling: 2050 Science Framework 2020, 124 pp. DOI: 10.6075/J0W66J9H.

Scientific Ocean Drilling: Mohole 2 Mantle (M2M)

- Combining the geophysical surveying of ocean basins and petrological studies via in situ sampling of the segments of oceanic lithosphere in different tectonic environments is expected to advance the understanding of the nature of oceanic lithosphere
- Scientific ocean drilling aims to collect fundamental data on the plate tectonic cycle since 1960s
- Oceanic drilling has already revealed critical pieces of evidences about plate tectonics, break up of continents, etc.
- Recently, Integrated Ocean Discovery Program's (IODP) MoHole to Mantle (M2M) drilling proposal aims to reach the Moho and the underlying mantle at three candidate sites including the Hawaiian arch and on the Cocos Plate



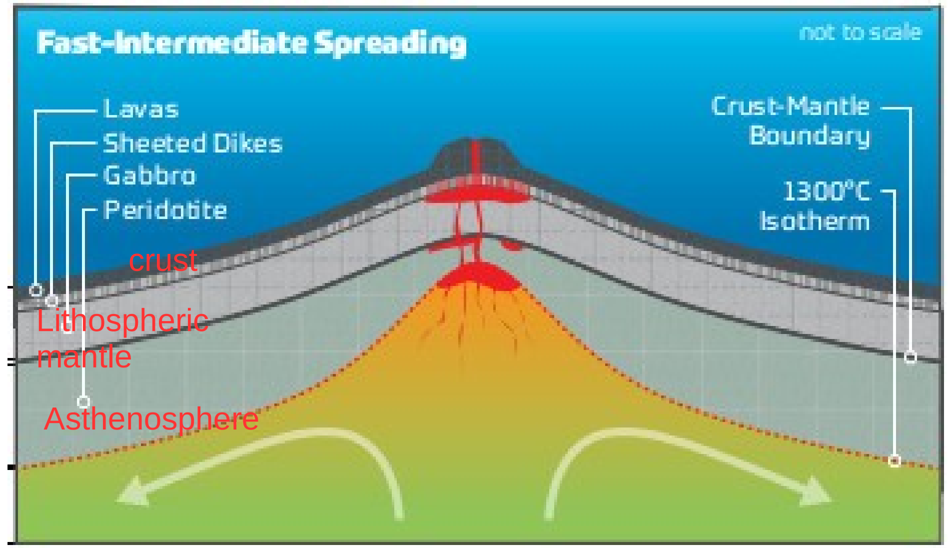
Teagle, D.A.H. Re-energizing the quest of drilling to the mantle. Nat Rev Earth Environ 4, 207–208 (2023). https://doi.org/10.1038/s43017-023-00413-0

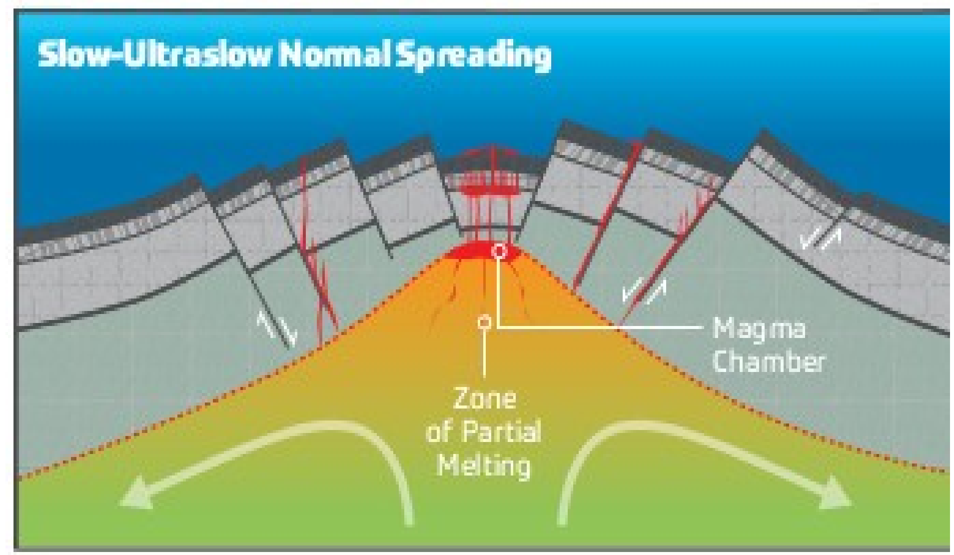
Actual Knowledge and Scientific Questions

- **Volume, composition and architecture of crust depends on the seafloor spreading rate and the nature of underlying mantle (1967)**
  - fast spreading →
    tectonic extension dominates that is leading to heterogenous crust
  - Ultra slow spreading →
    low angle detachment faulting that result in exposure of mantle rocks (periodites, pyroxenites)
- Magma chamber depth negatively correlated with fast spreading rate → shallower magma chamber has higher magma supply rate

  (see Prof. Umino's talk at Muographers 2022 GA)

- **Questions:**
  - **Why and how does the crustal structure depend on spreding rate?**
  - **What is the geological nature of Moho?**



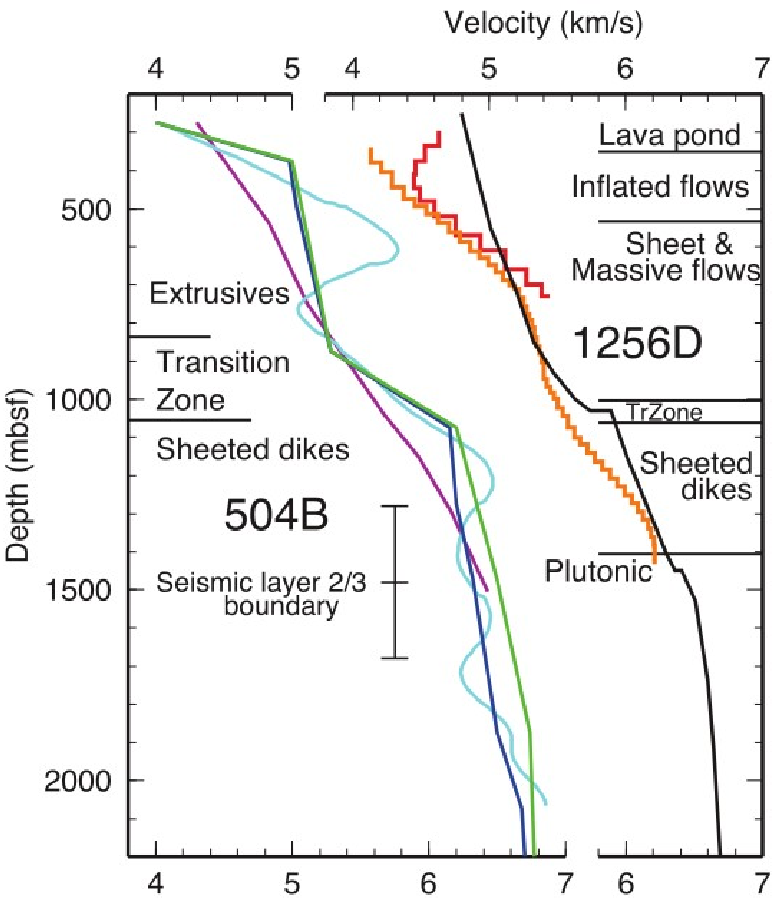


Koppers, A.A.P., and R. Coggon, Exploring Earth by Scientific Ocean Drilling: 2050 Science Framework 2020, 124 pp. DOI: 10.6075/J0W66J9H.

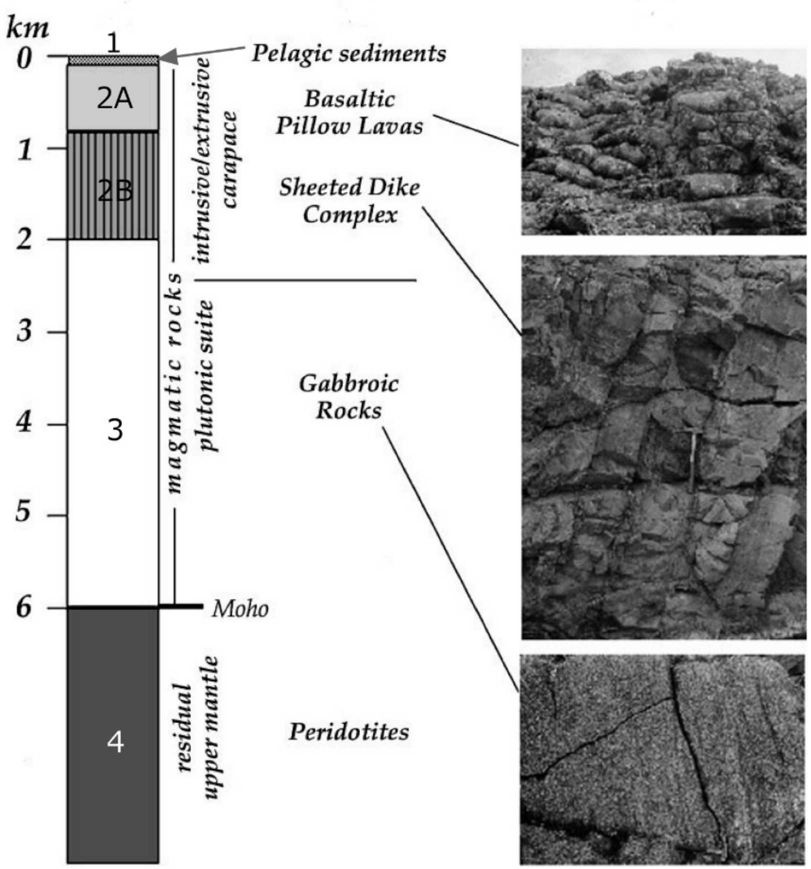
Oceanic lithosphere in Ophiolites

- Only one vertical seismic profile reached seismic layer 2/3 boundary and **Moho has not yet been reached** → geological nature is not yet well understood
- Sampling is available but sampling density is low → seismic velocities are different
- **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

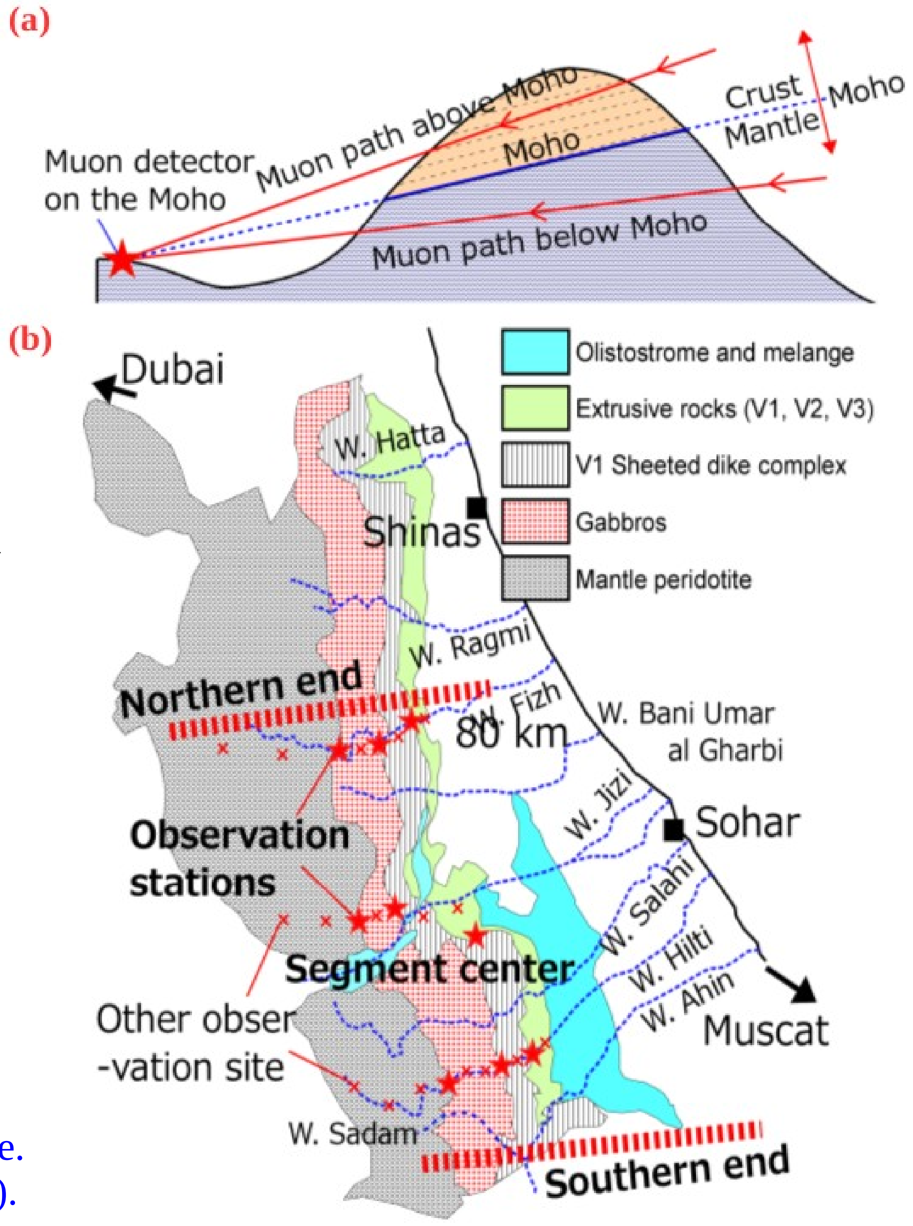


Karson, J.A., Geological structure of the uppermost oceanic crust created at fast- to intermediate-rate spreading centers. *Annu. Rev. Earth Planet. Sci.* **2002**, 30, 347. DOI: 10.1146/annurev.earth.30.091201.141132.

Objective 1: Muography of Samail Ophiolite

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

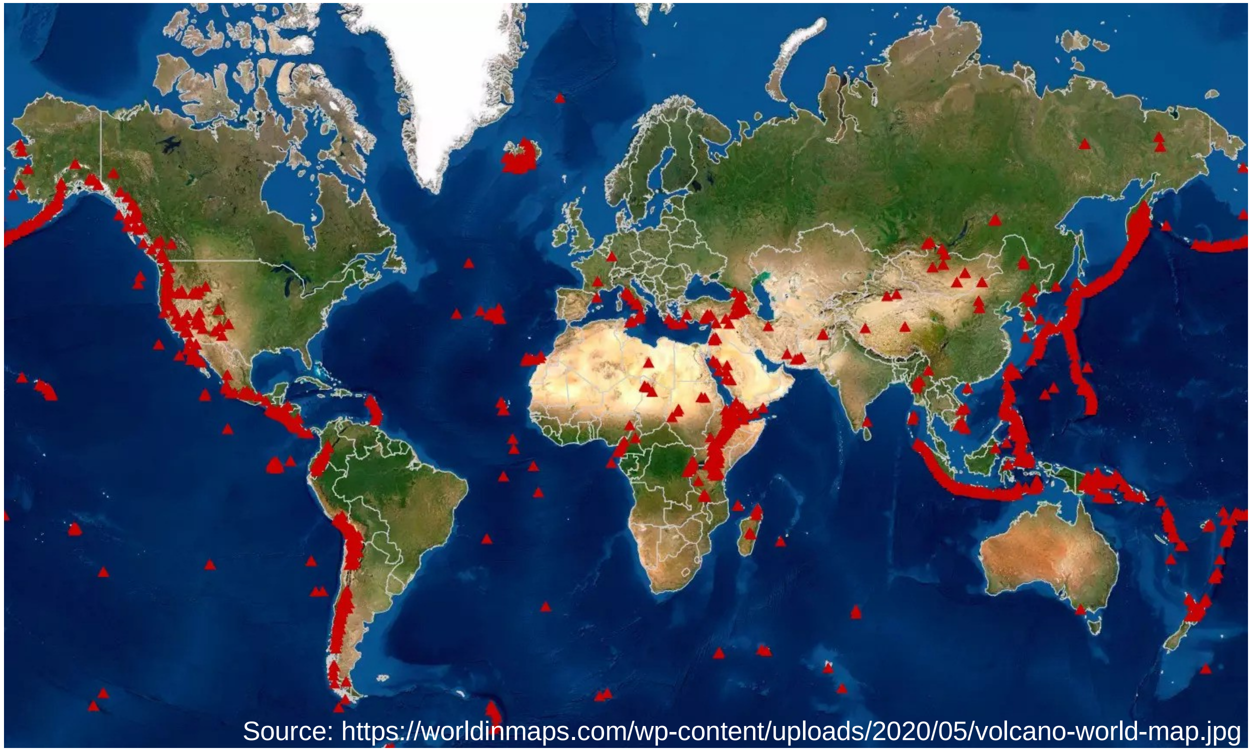
  → data can be compared with the structure of the Pacific Plate, the target of the IODP-805 MoHole to Mantle (M2M) Proposal

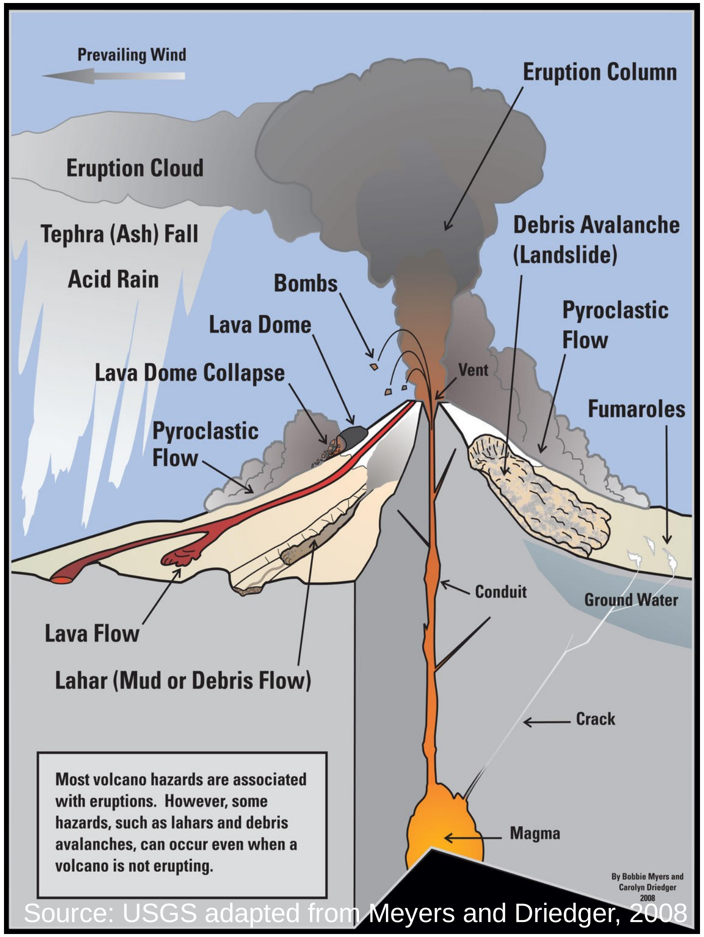


Oláh, L., Umino, S. et al. Plans for Muography of Samail Ophiolite. Journal of Advanced Instrumentation in Science, JAIS-499, (2024). DOI: 10.31526/JAIS.2024.499

Active Volcanoes and Volcanic Hazards

- Plate tectonics resulted in formation of volcanoes around plate boundaries (Ring of Fire)
- More than 500 volcanoes confirmed historical eruptions (62 volcanoes erupted in 2024)
- Approx. 10 % of Earth's population live around volcanoes
- Volcanic hazards can cause serious socioeconomic loss:
  - syn-eruptive hazards: bombs, tephra fall, pyroclastic flows, etc
  - post-eruptive hazards: lahars, debris avalanche, etc

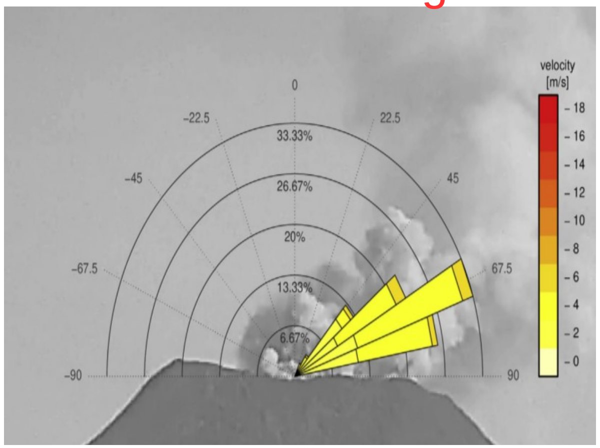

Source: https://worldinmaps.com/wp-content/uploads/2020/05/volcano-world-map.jpg



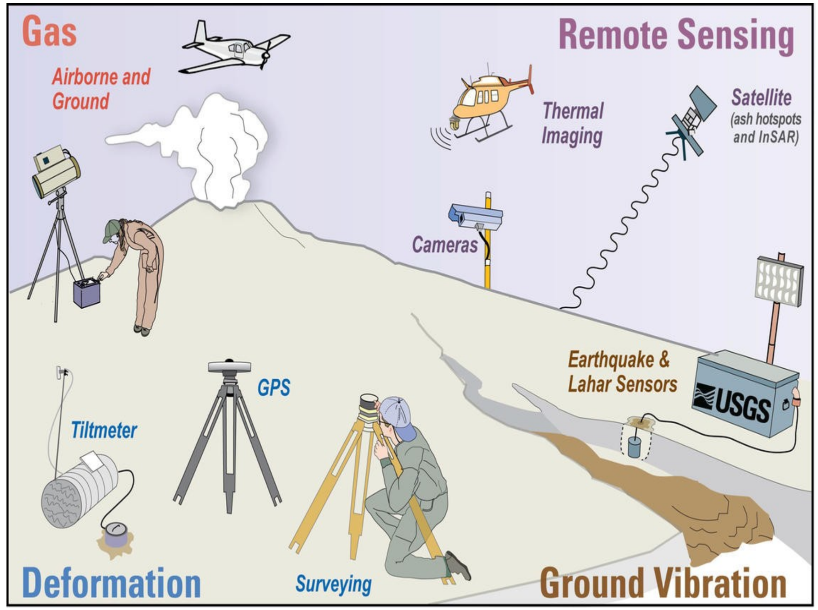
Source: USGS adapted from Meyers and Driedger, 2008

Volcano Monitoring

Video recording

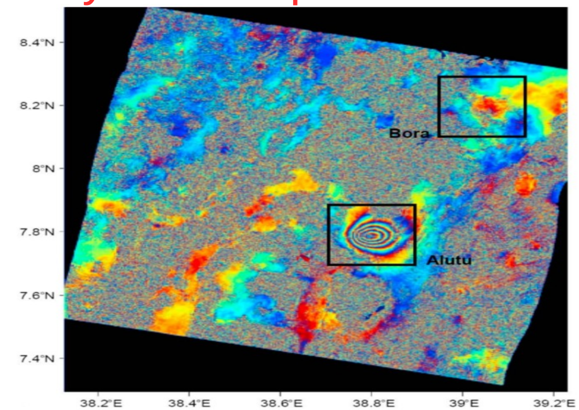


Source: https://doi.org/10.1016/j.gsf.2020.01.016



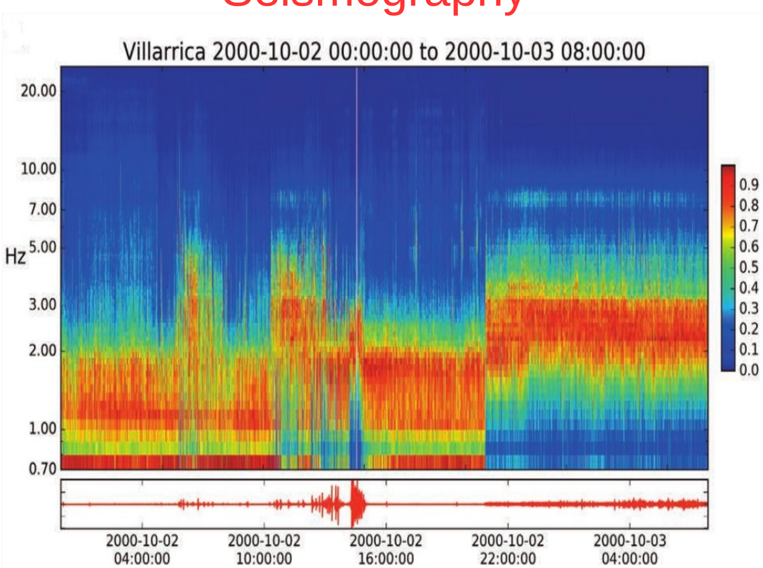
Source: USGS from Faust, Lisa

Synthetic Aperture Radar



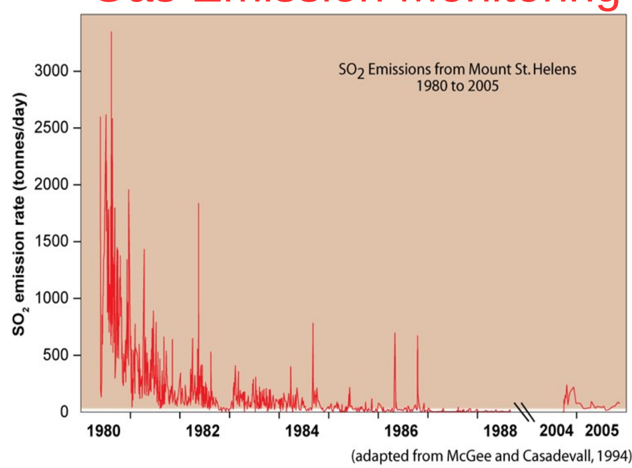
Source: https://doi.org/10.1029/2018JB015911

Seismography



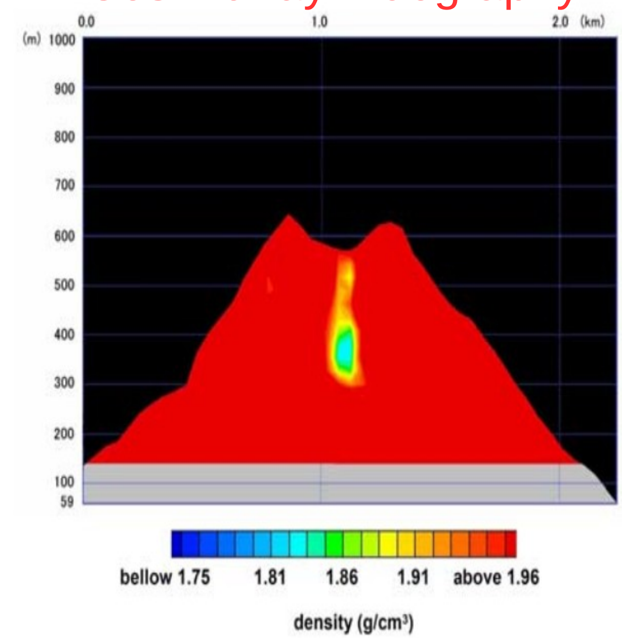
Source: https://doi.org/10.4401/ag-7655

Gas Emission Monitoring



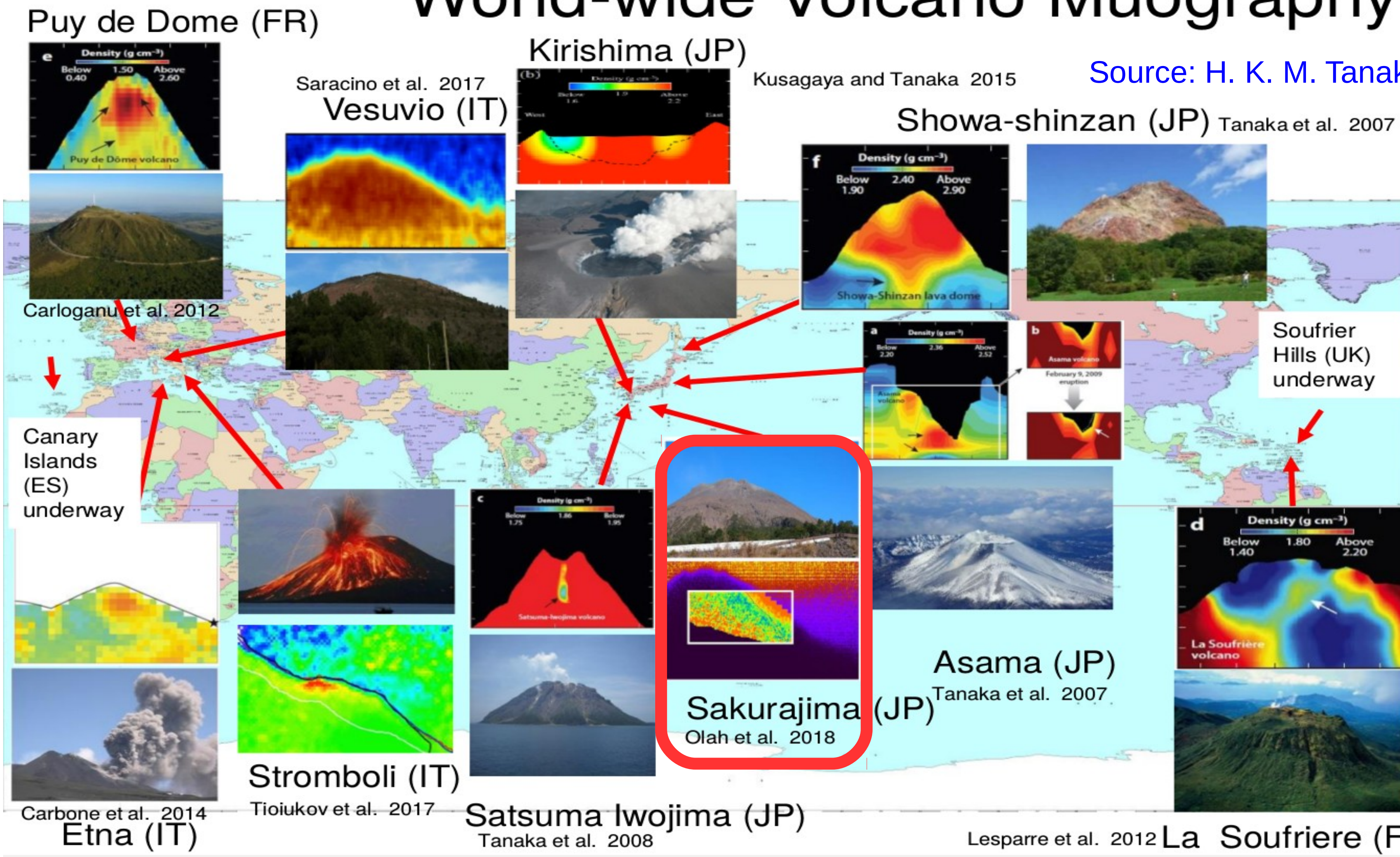
Source: USGS

Cosmic-ray Muography



Source: https://doi.org/10.1029/2008GL036451

World-wide Volcano Muography



Contributions of Muography to Volcanology:

(1) Studying formation and stability of lava domes (Showa-Shinzan, La Soufrière de Guadeloupe),

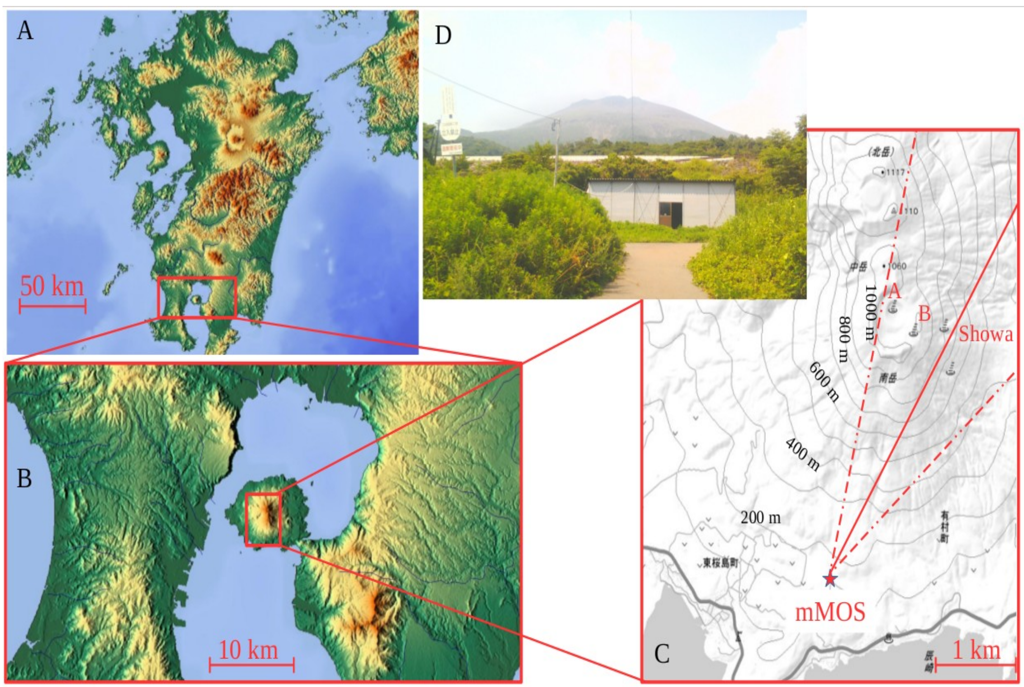
(2) Exploring conduit structure for eruption modelling (Stromboli),

(3) Monitoring magma evolution and movement (Asama, Sakurajima).

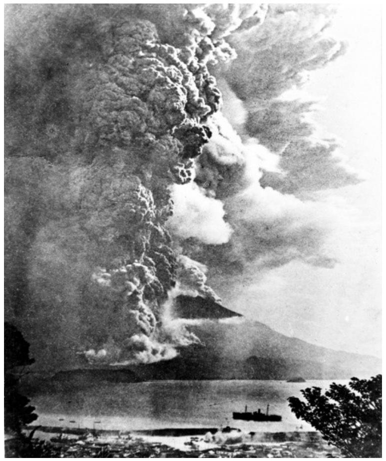
See more information in talks by C. Carloganu (TOMUVOL) and Y. Hong (MURAVES).

Objective 2: 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 HUN-REN Wigner RCP conduct muography of Sakurajima 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

II. Research Infrastructures and Instrumentation

Research Infrastructures and Instrumentation

Vesztergombi High Energy Physics Laboratory (VLAB) of HUN-REN Wigner RCP
involves clean rooms, construction labs, underground labs, etc.
→ Application oriented R&D of gaseous tracking detectors
for HEP Experiments (ALICE, CMS, NA61, etc.) and applications
See more details in talk by D. Varga.

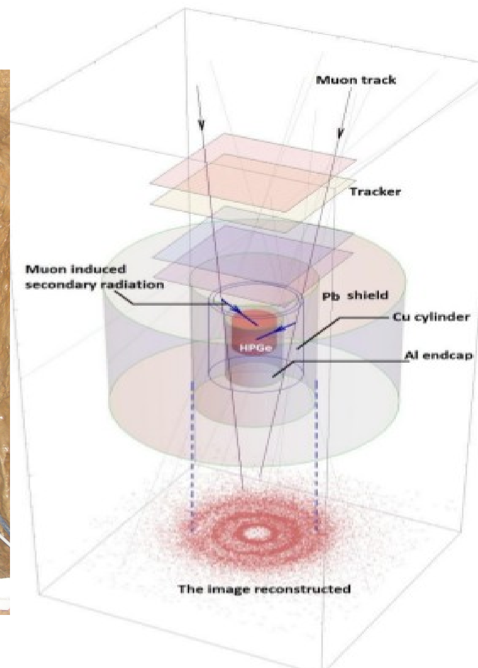
International Virtual Muography Institute (VMI)

→ Joint laboratories and muography observatories in Japan, Italy, Oman, etc.
→ Common frameworks for data storage, monitoring and simulation
Tanaka, H.K.M. & Oláh, L. Overview of Muographers. PRSTA 377 20180143 (2019). https://doi.org/10.1098/rsta.2018.0143

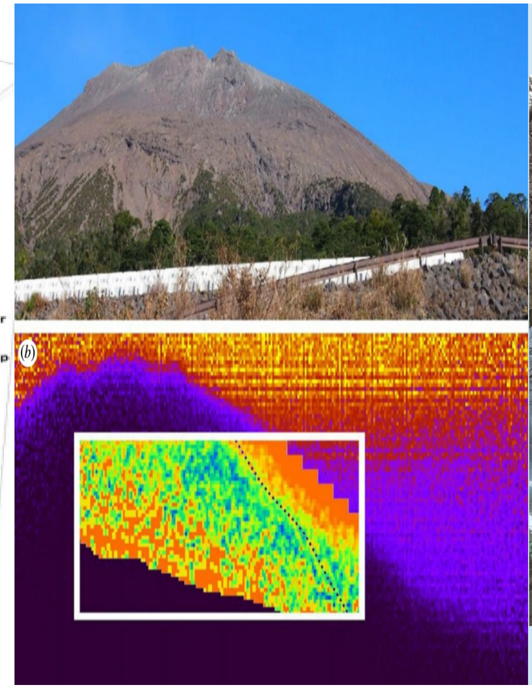
Muography Project Portfolio in Wigner RCP

Application oriented R&D of Instrumentation

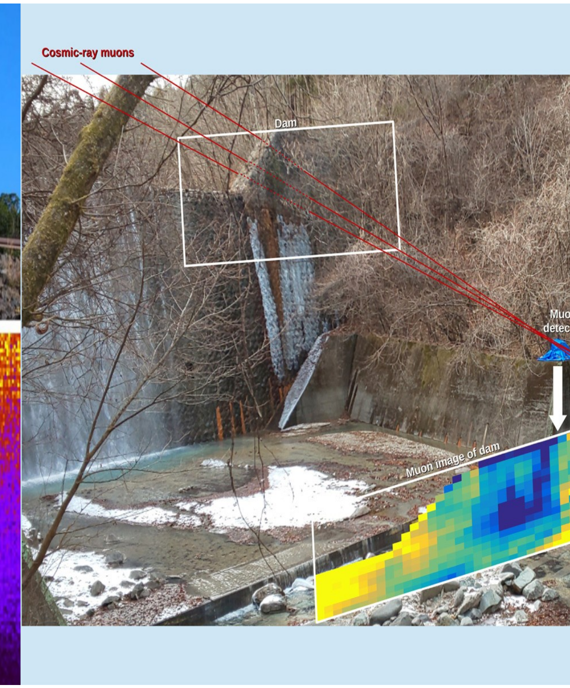
Development of novel imaging techniques



Geophysical Applications: volcanology, geology



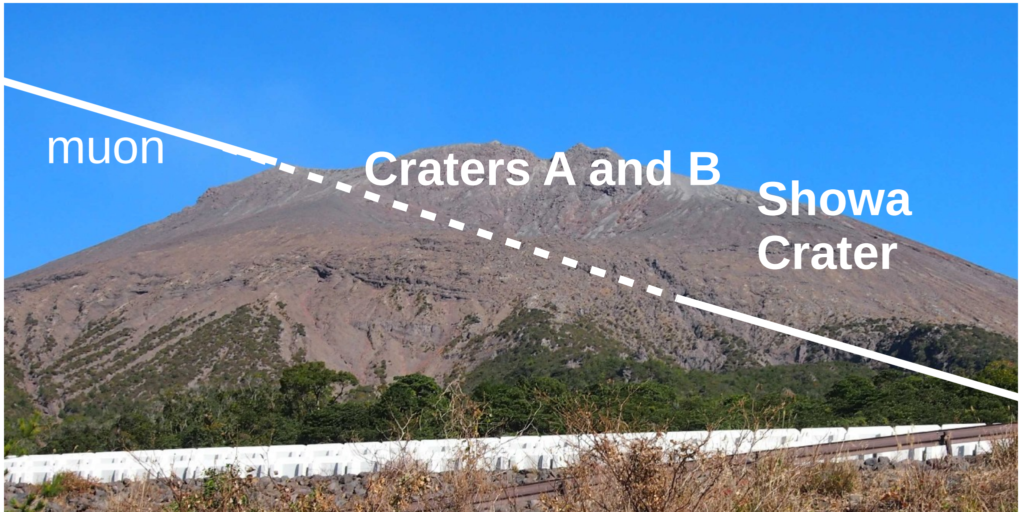
Geotechnics and civil engineering

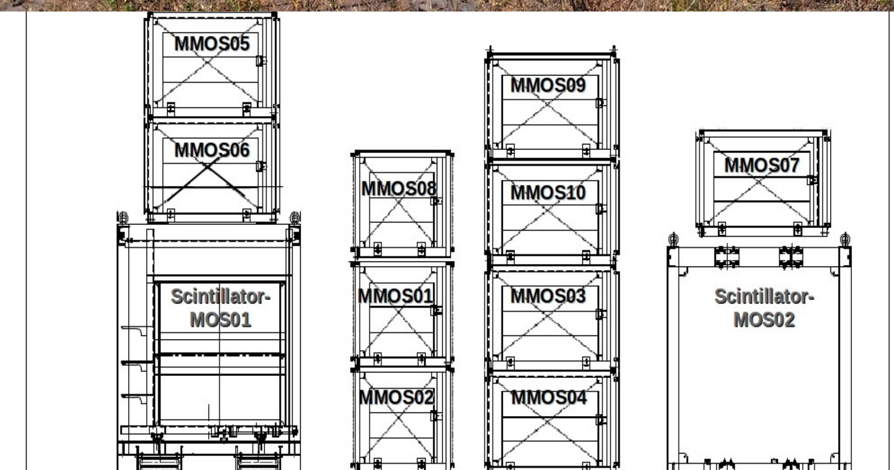


- R&D for Muography has been launched in HUN-REN Wigner RCP 15 years ago
- **Innovative Detector R&D Momentum Research Group** (https://regard.wigner.hu/ 2013-)
- **High-Energy Geophysics Research Group** (https://wigner.hu/s/high-energy-geophysics/ 2024-)
- International and intersectoral collaborations in Europe and Asia

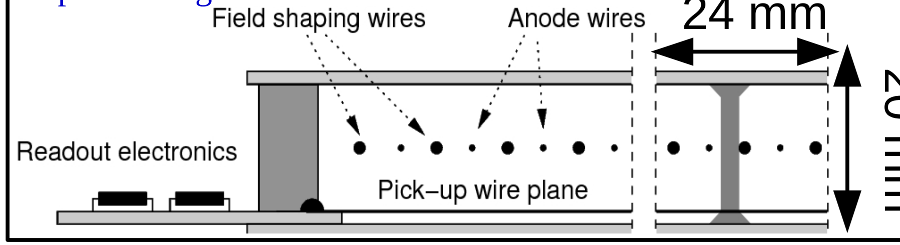
See more details in talks
by G. Surányi and D. Varga.

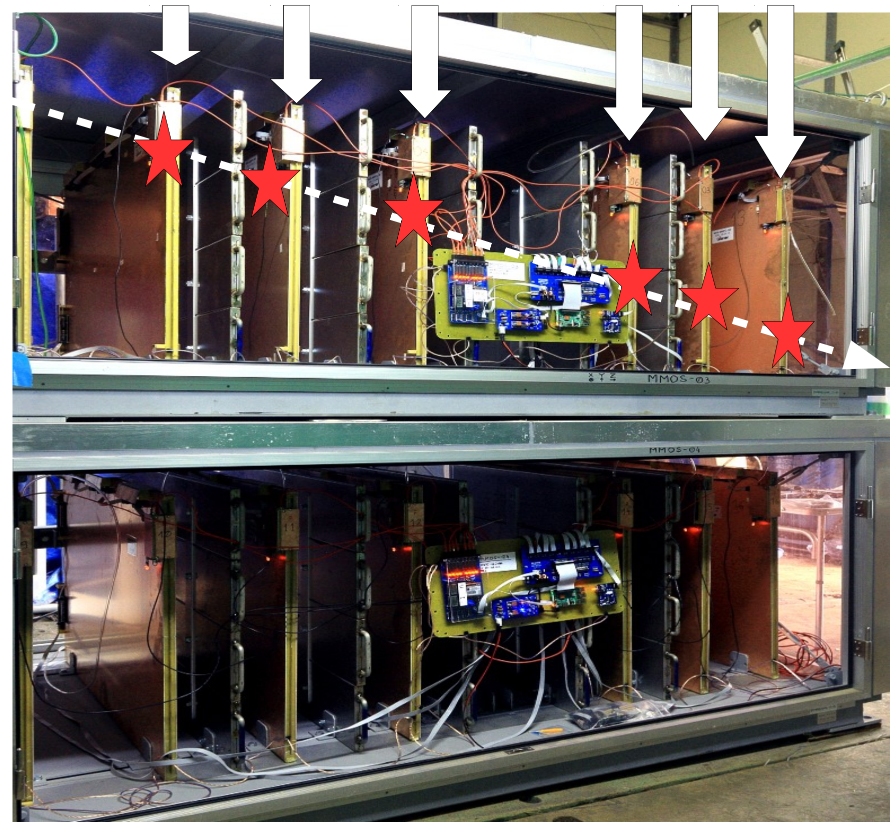
Muographic Observation Instrument (MOI)





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)

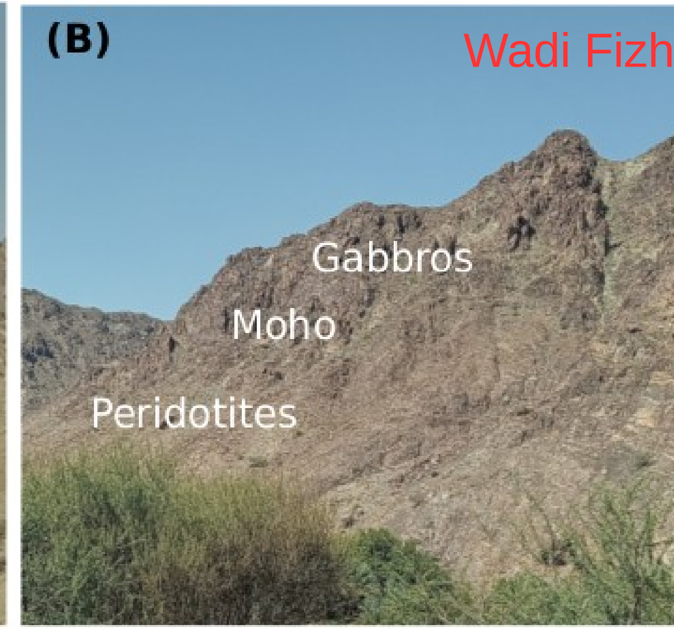
Muograpic Observation Instrument WO2017187308
https://patentscope2.wipo.int/search/en/detail.jsf?docId=WO2017187308

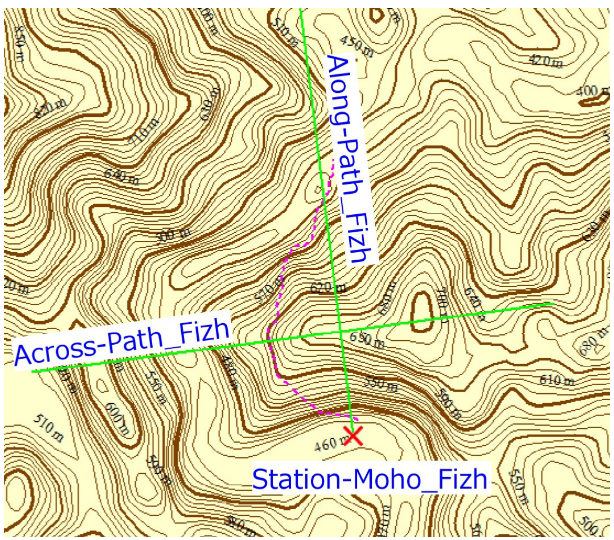
L. Oláh et al. Scientific Reports, 8, 3207, 2018,
https://doi.org/10.1038/s41598-018-21423-9

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

IV. Muography of Samail Ophiolite

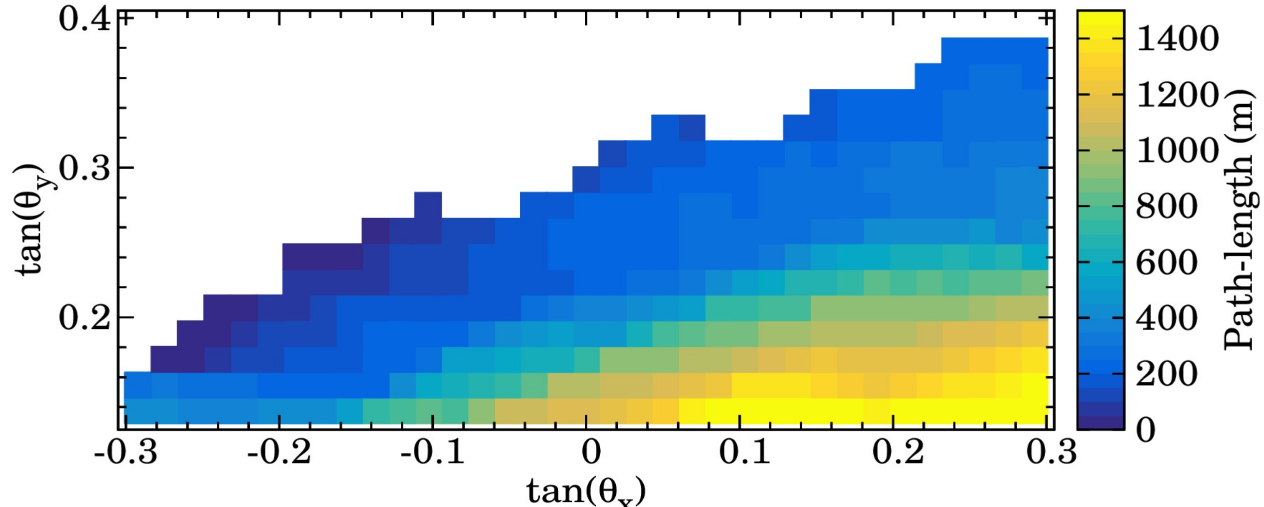
The first Run at a Moho at Wadi Fizh

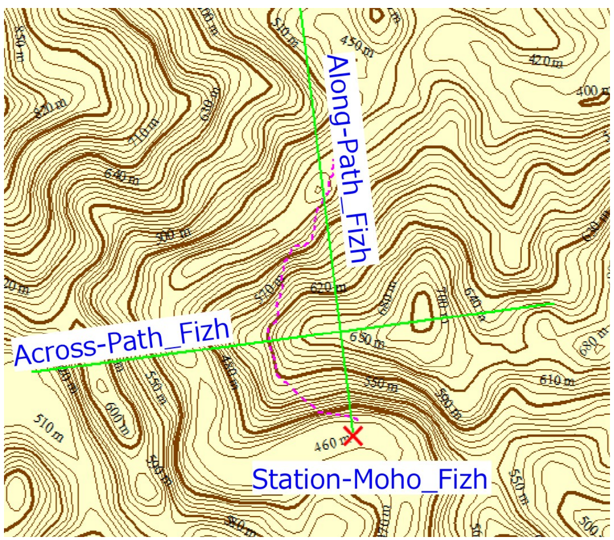




Observation location & orientation:
Lattitude: 24.45655 deg
Longitude: 56.29703 deg
298 deg from north

The first Run at a Moho at Wadi Fizh





Observation location & orientation:

Lattitude: 24.45655 deg

Longitude: 56.29703 deg

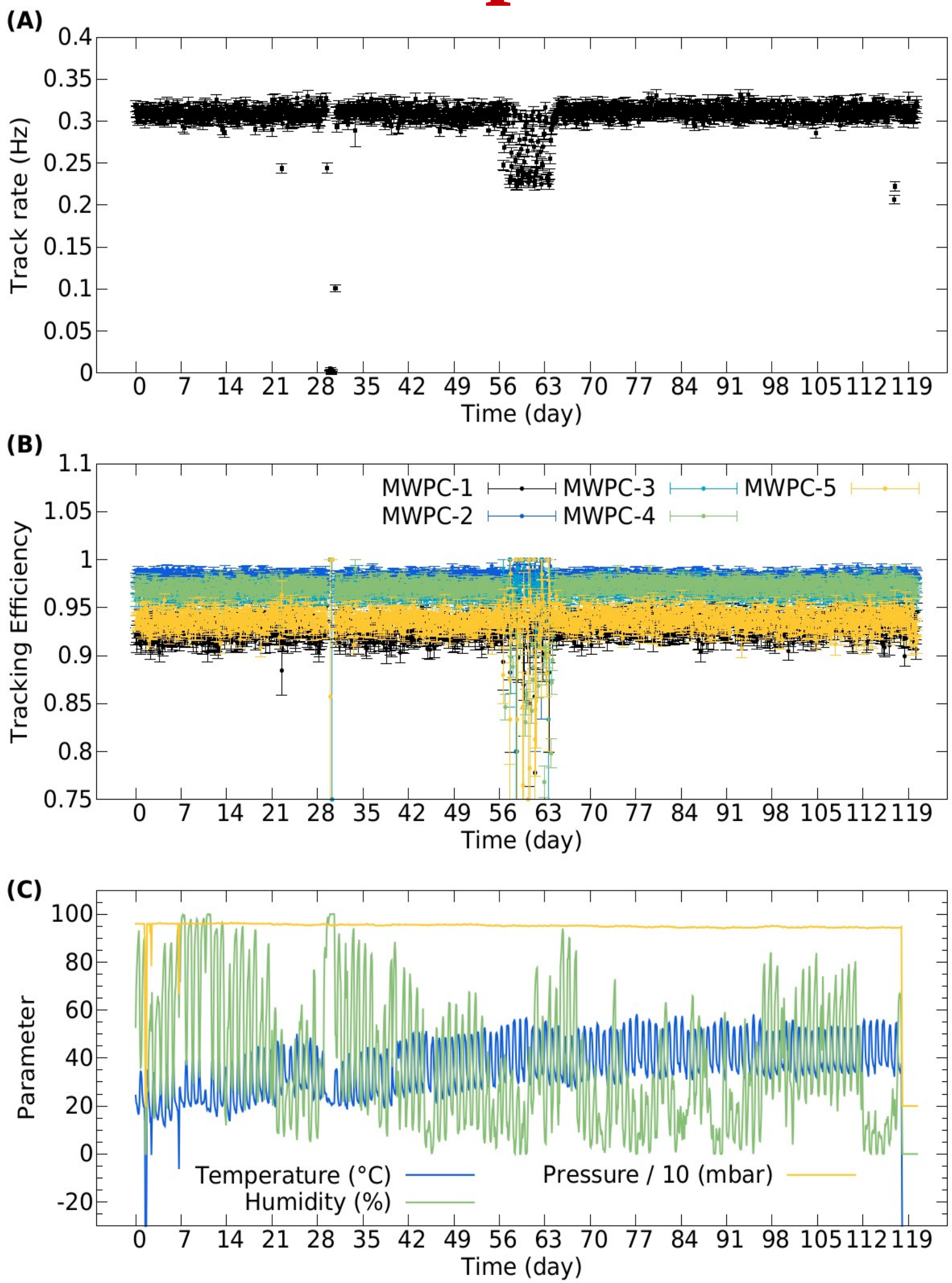
298 deg from north

Muography Instrumentation

- **MWPC-based Muography Observation System (MMOS):**
  - Seven 80 cm by 80 cm sized Multi-Wire Proportional Chambers each with a spatial resolution of 4 mm, >95% trigger and >98% tracking efficiency,
  - Rasperry PI controlled DAQ with a deadtime of 100 microsec,
  - Total power consumption of about 6 W.
  - Power supply: 110 V (60 Hz) AC (+ 100 W solar panel)
  - Gas supply: Ar + CO2 (80:20), flow of 1-2 L/h

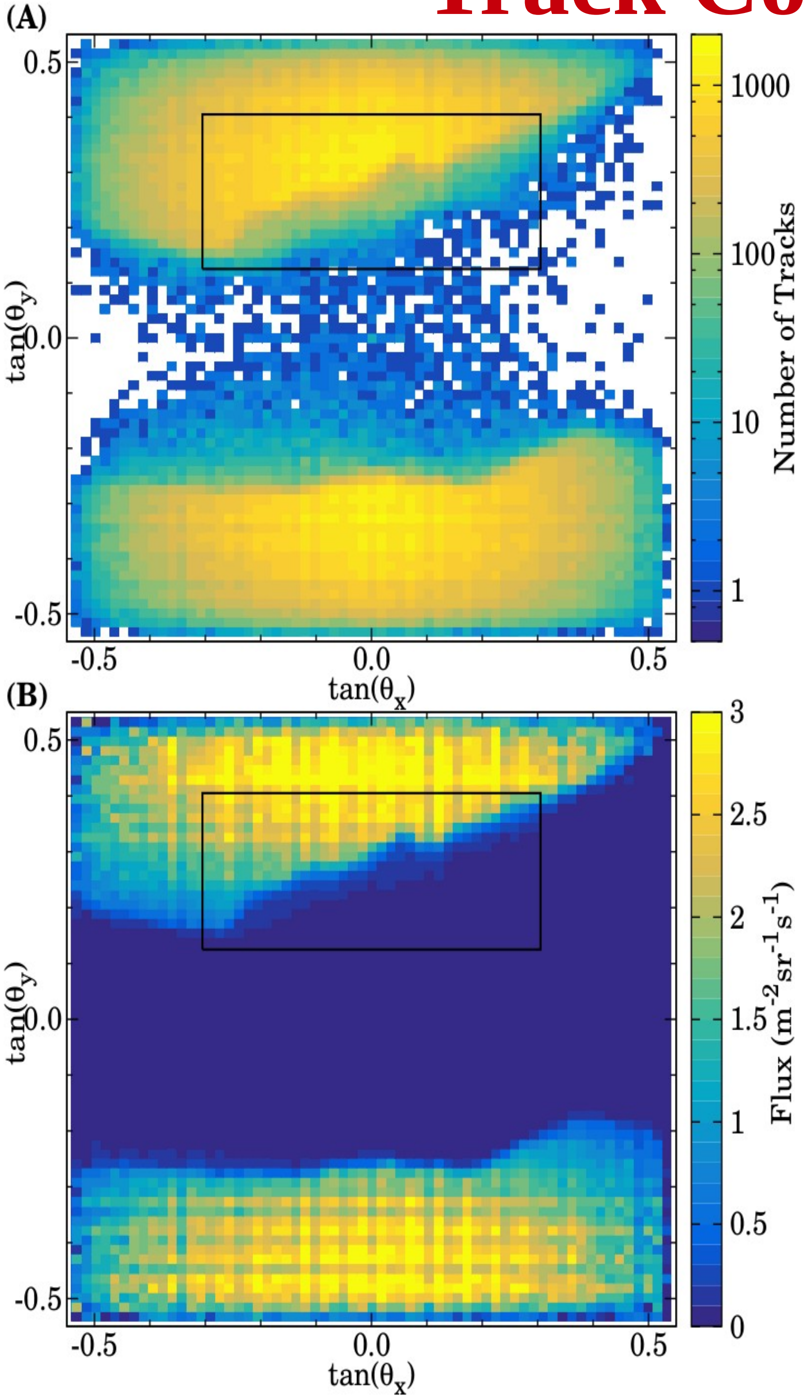
D. Varga, L. Oláh, G. Hamar, H. K. M. Tanaka, T. Kusagaya:
Muographic Observation Instrument, WO2017187308A1
https://patents.google.com/patent/WO2017187308A1/en
D. Varga et al. Advances in High Energy Physics, 2016, 1962317 https://doi.org/10.1155/2016/1962317
L. Oláh et al. Scientific Reports, 8, 3207, 2018 https://doi.org/10.1038/s41598-018-21423-9

Operational Performance



- Track rate is measured around 0.3 Hz
- Trigger and tracking efficiencies are respectively measured above 93 % and 94 % for each MWPC
- Daily variations of temperature and humidity are significant

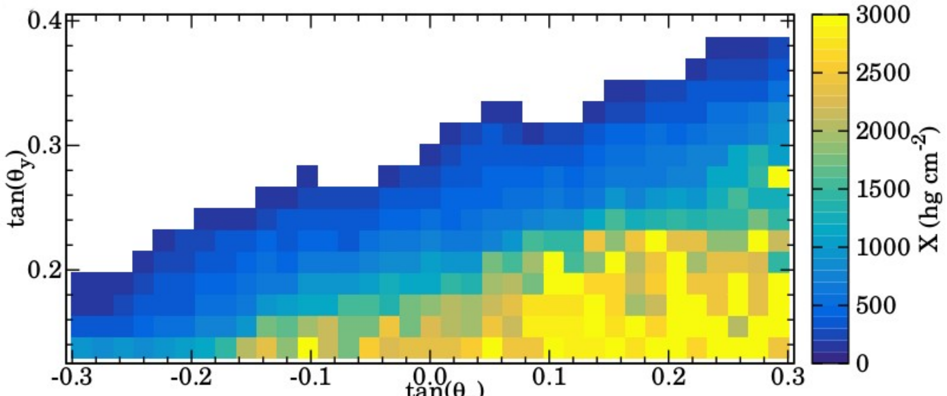
Track Count and Muon Flux

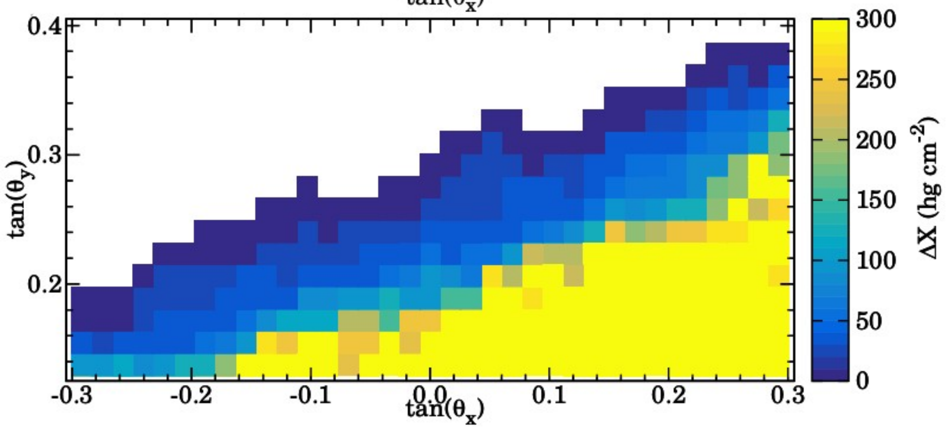


- Cluster reconstruction on each MWPC and combinatorial track reconstruction
- Track selection: ADC > 200, Chi2/ndf < 1
- Tracks visualize the ridge of the ophiolite with a slope binning of 15 mrad that corresponnds to 5 m spatial resolution from a distance of 300 m

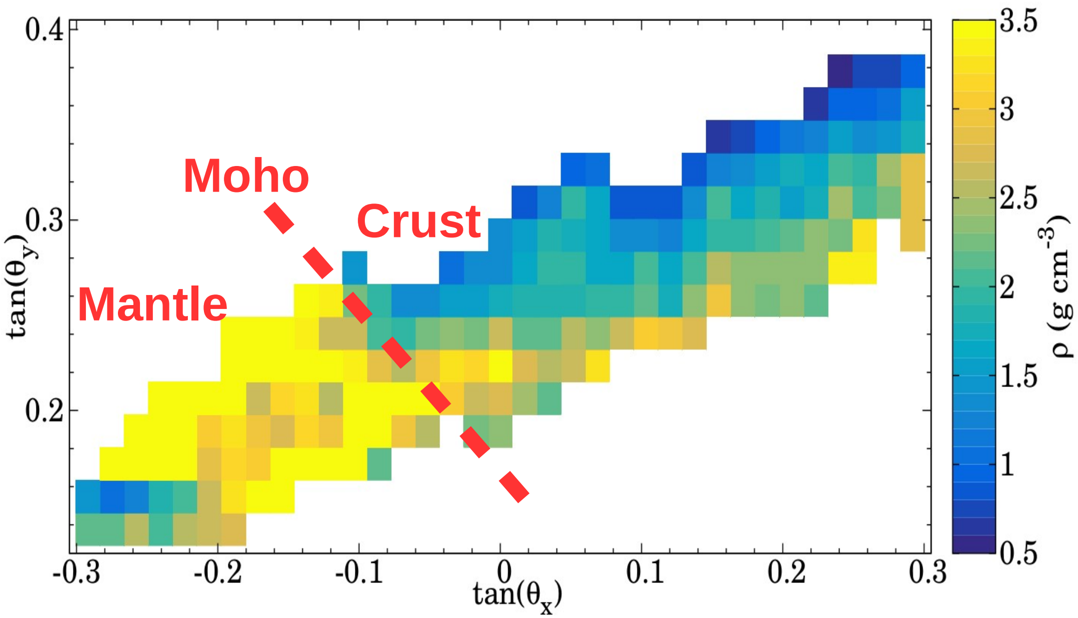
Density-length and Density

- Density-length (X) and its error (ΔX) are determined by comparing the measured and modelled (based on Modified-Gaisser model) muon fluxes





- Density = density-length / path-length
- Two regions can be distuinguished that may corresponds to mantle and crust
- The Moho has not yet been explored
- First Run is planned until February 2025

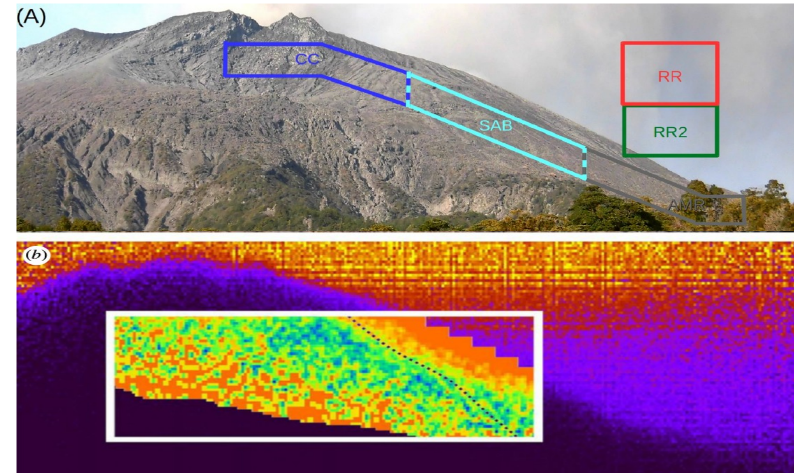


IV. Muography of Sakurajima Volcano

The First Observations: Plug Formation, Tephra Deposition and Erosion

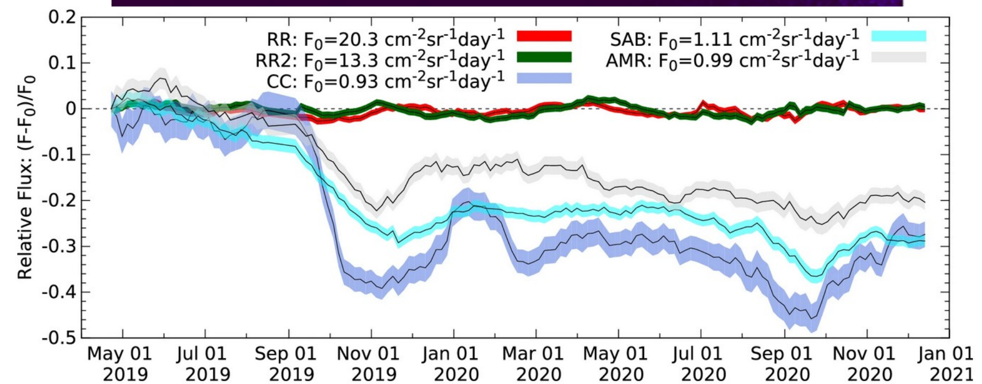
- Resolving the internal structure of the volcano with a spatial resolution of below 10 metres that is challenging to other techniques

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



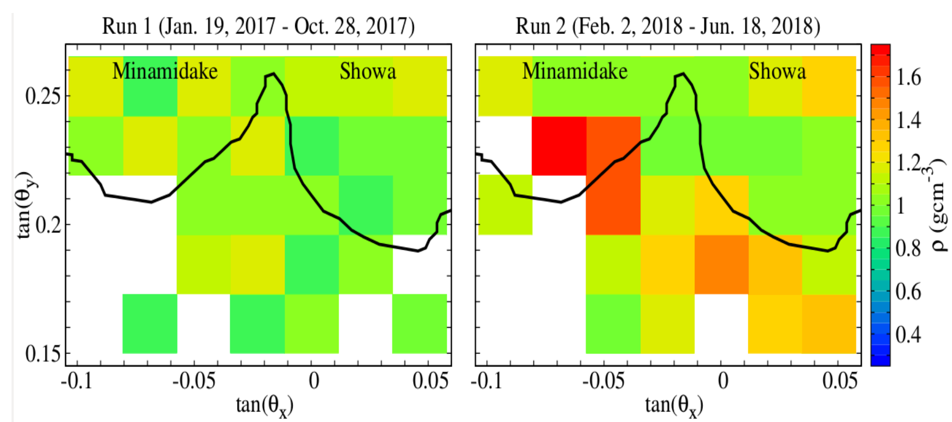
- Monitoring changes in the amount of materials on the volcanic edifice due to volcanic ejecta deposition, erosion and mudflows (lahars)

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

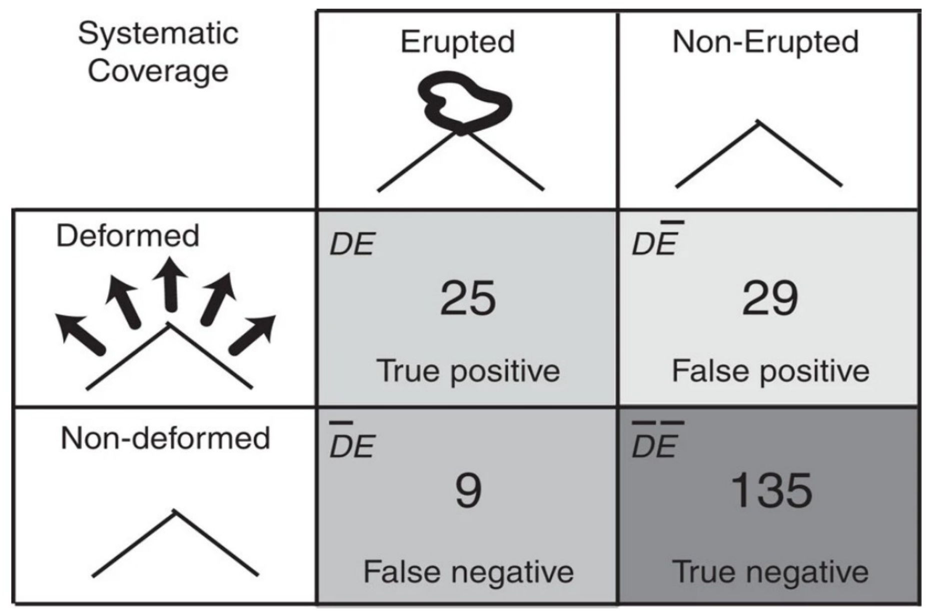
L. Oláh et al. Geophys. Res. Lett. 46, 10417, 2019, https://doi.org/10.1029/2019GL084784



Link between ground deformation and eruptions

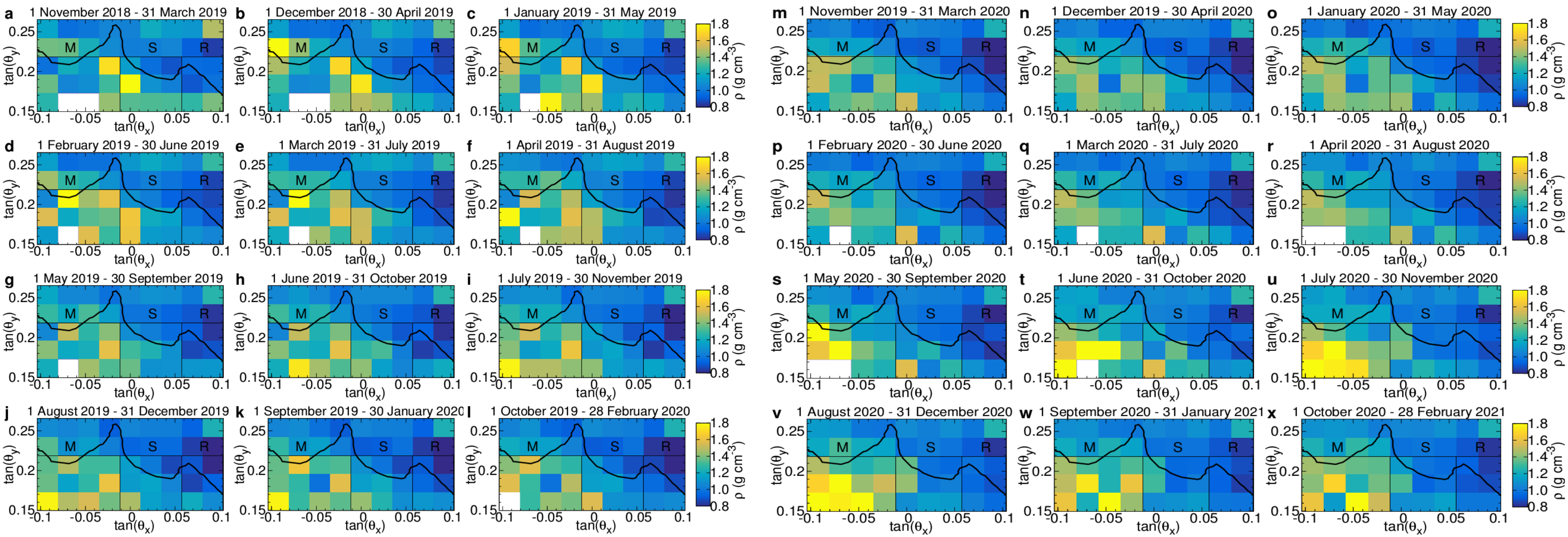
- **Active volcanism** is driven by the subsurface evolution and movement of magmatic materials, which **may induce seismicity, ground deformation, gas emission, and fumarolic activity**
- Monitoring of the signals induced by these phenomena is indirect and interpretation of the origin of the signals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

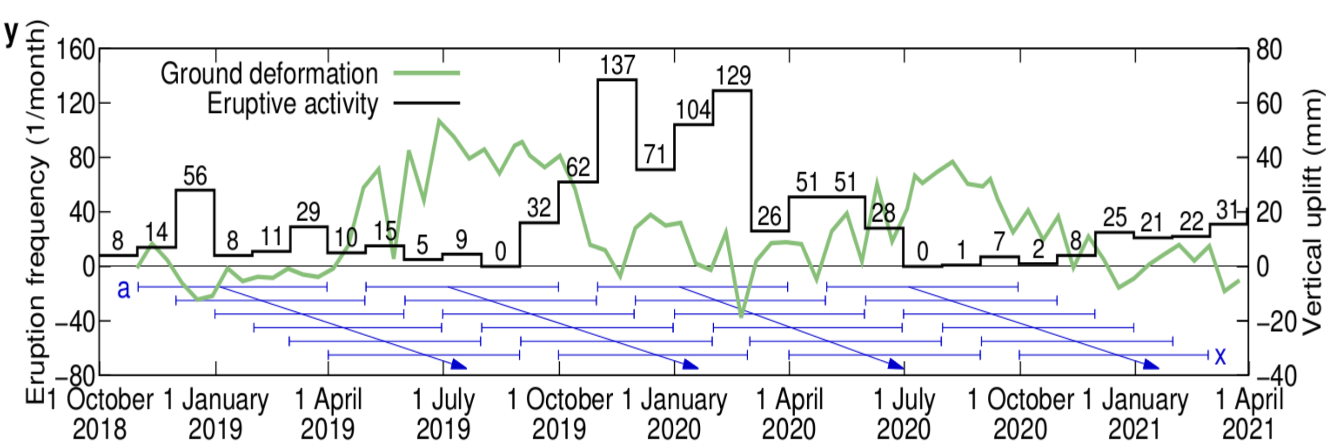


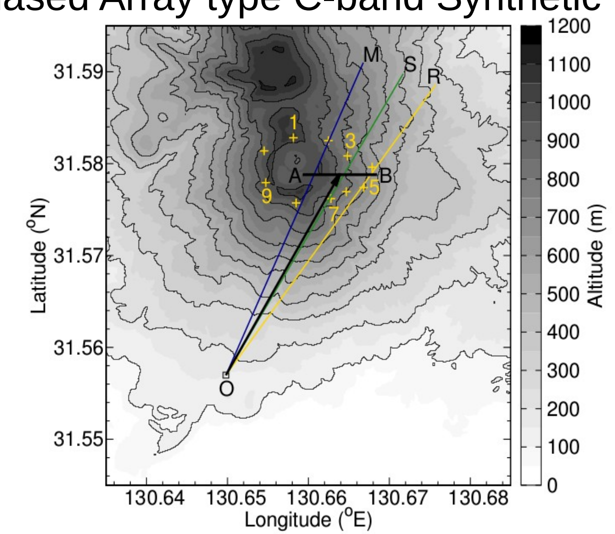
Muography and InSAR Observations of Sakurajima

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.

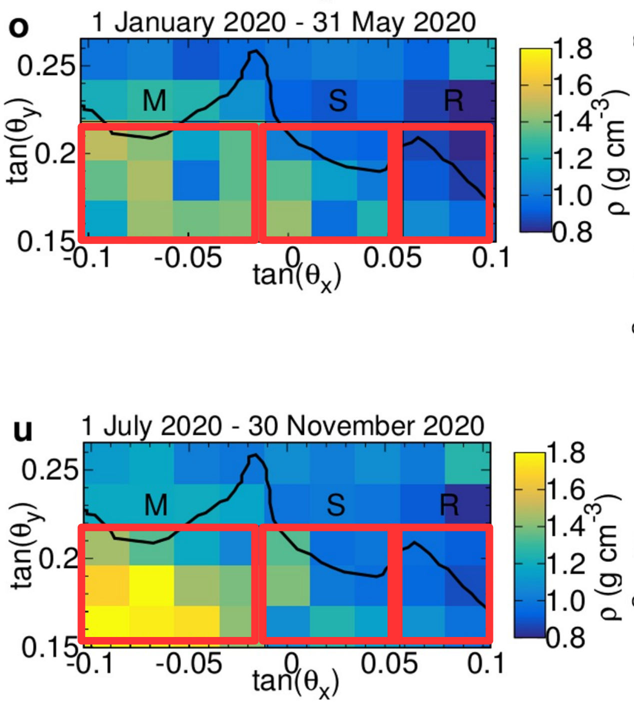




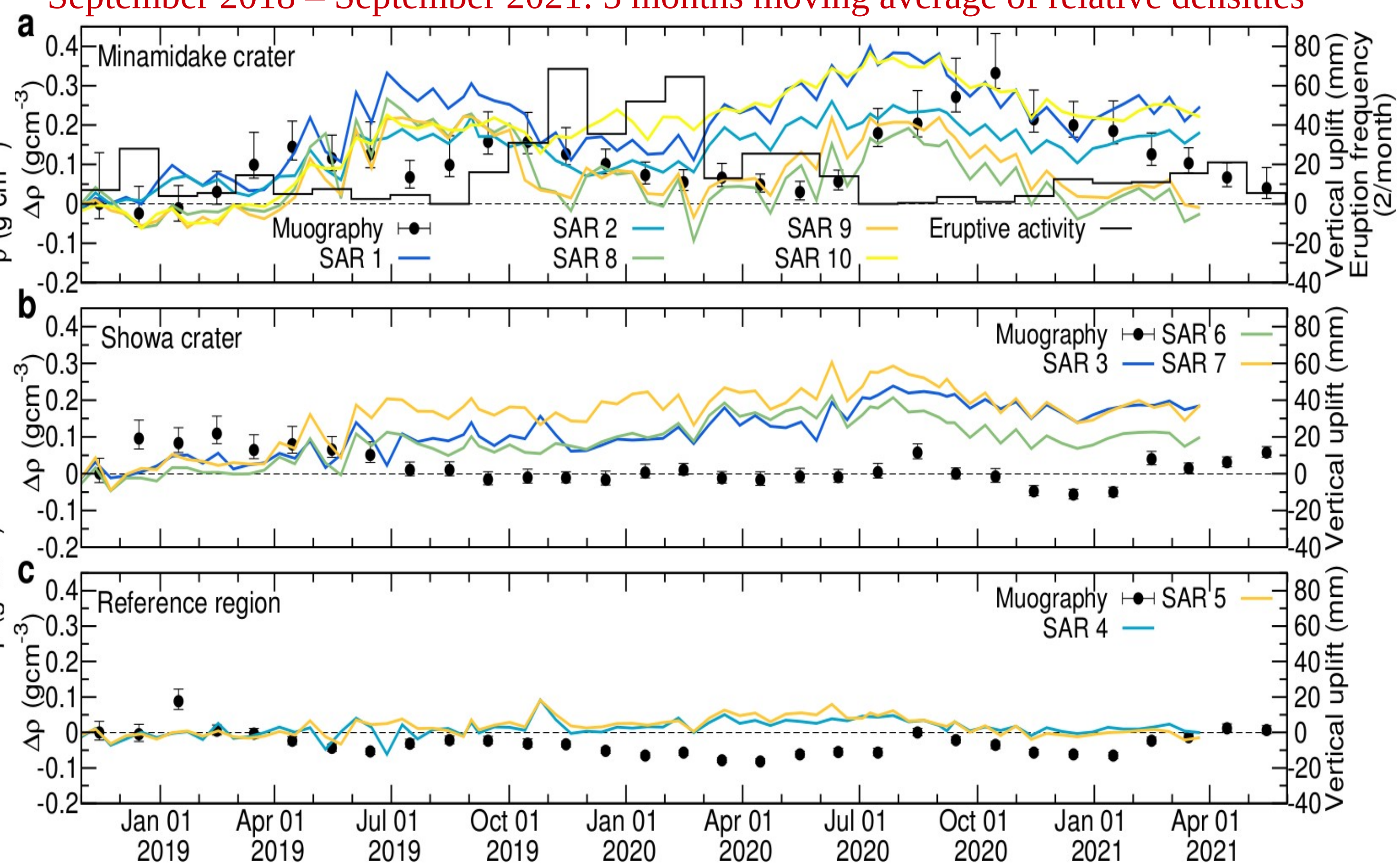
Muography explains link between eruption frequency and ground deformation

- 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

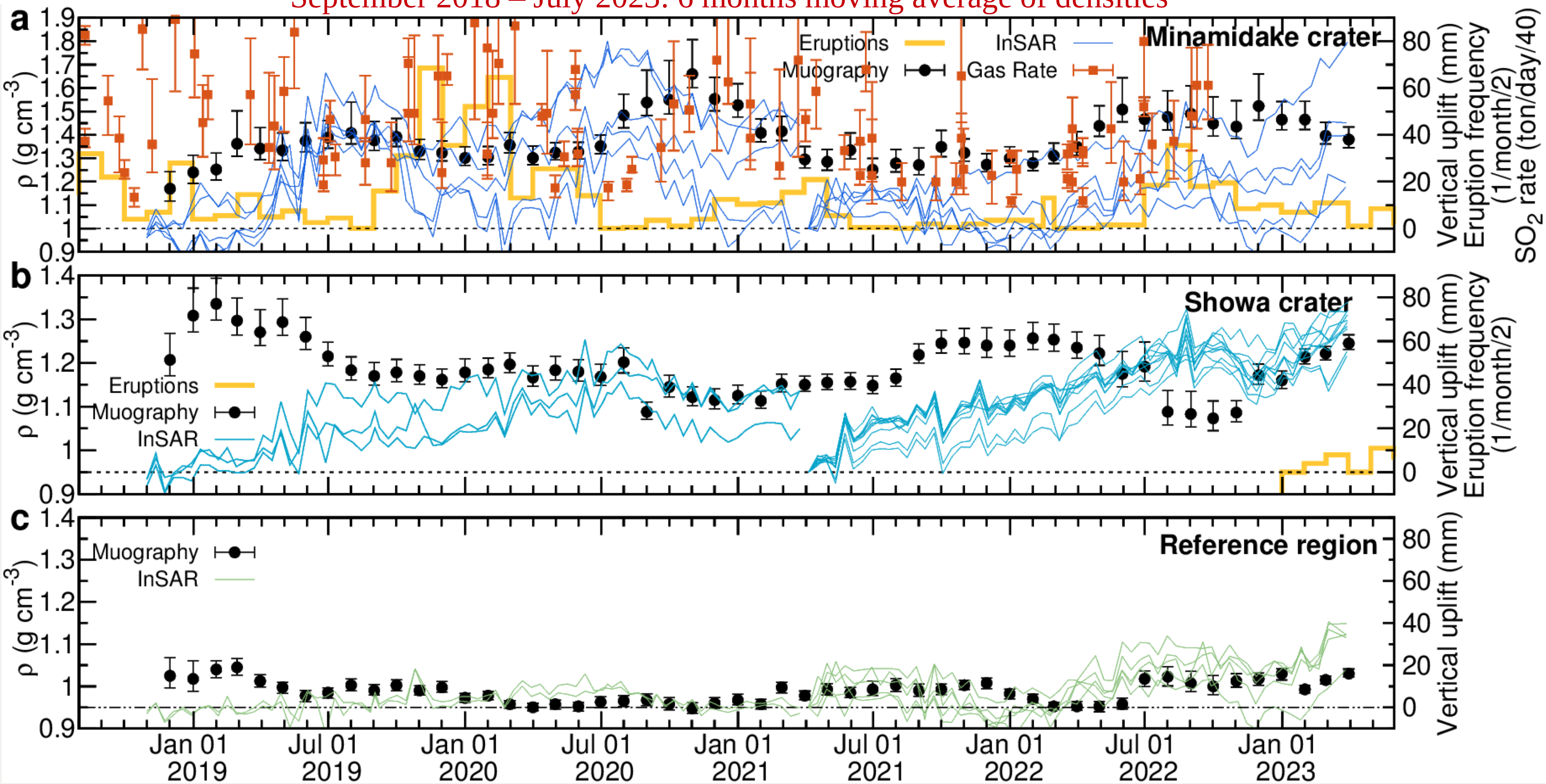
Plug Formation and Magma Drain-back Process

- **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.

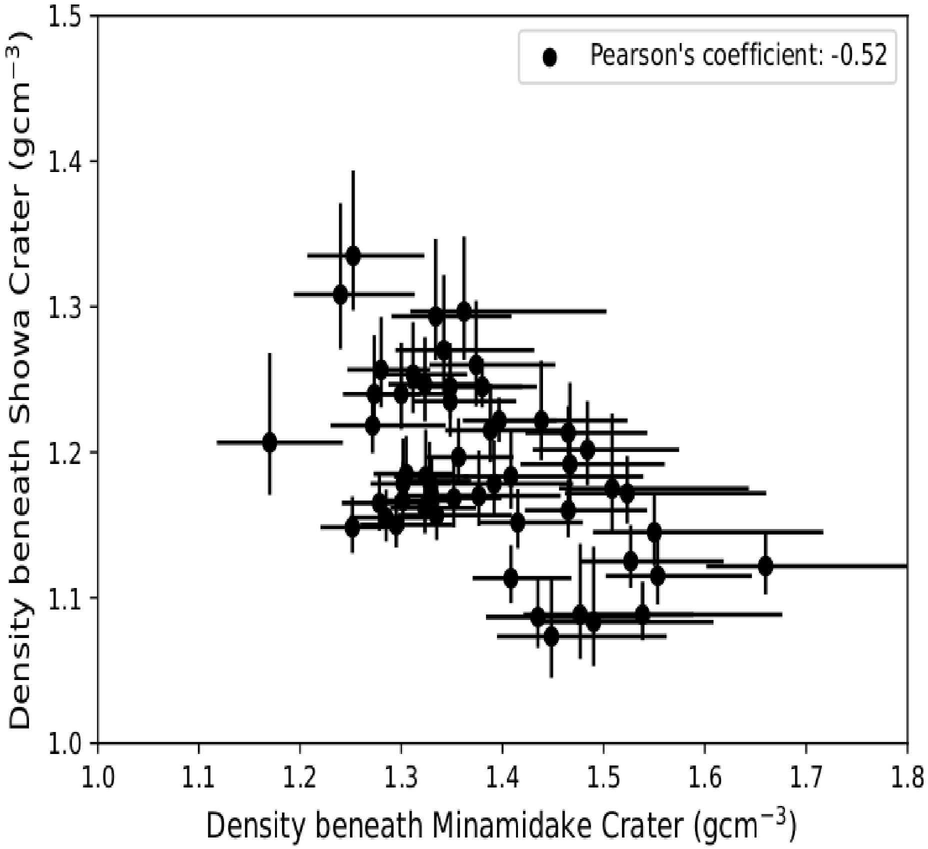
- **Showa crater:** eruptions did not follow the density increase observed beneath Showa crater in January 2019 and in August 2021; however, later the mass density decreased. It was interpreted that the uprising magma generated the plug underneath Showa crater. However, the gas pressure mightn't be enough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

V. Summary

Two applications of cosmic-ray muography in Earth sciences:

- Researching the geology of oceanic lithosphere

- Studying active volcanism

Thank you for your attention!

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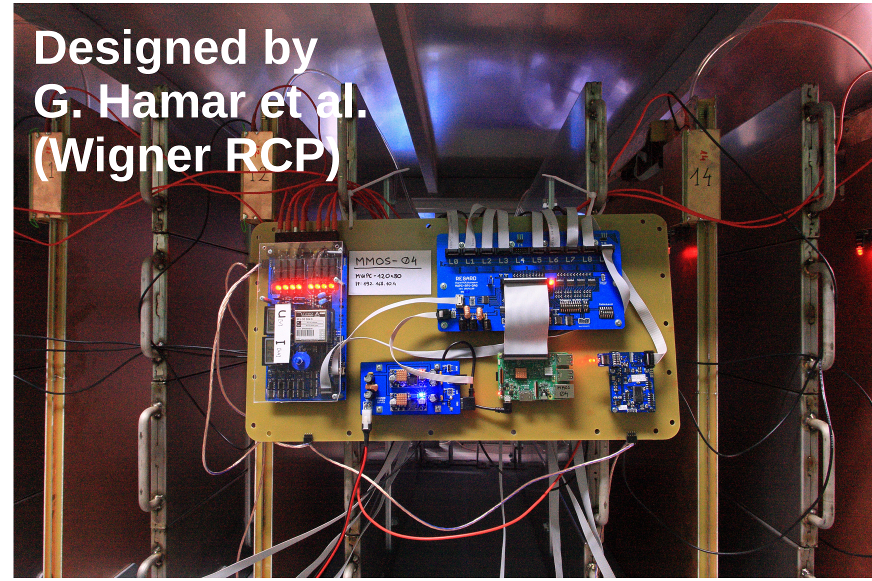
Supporters:

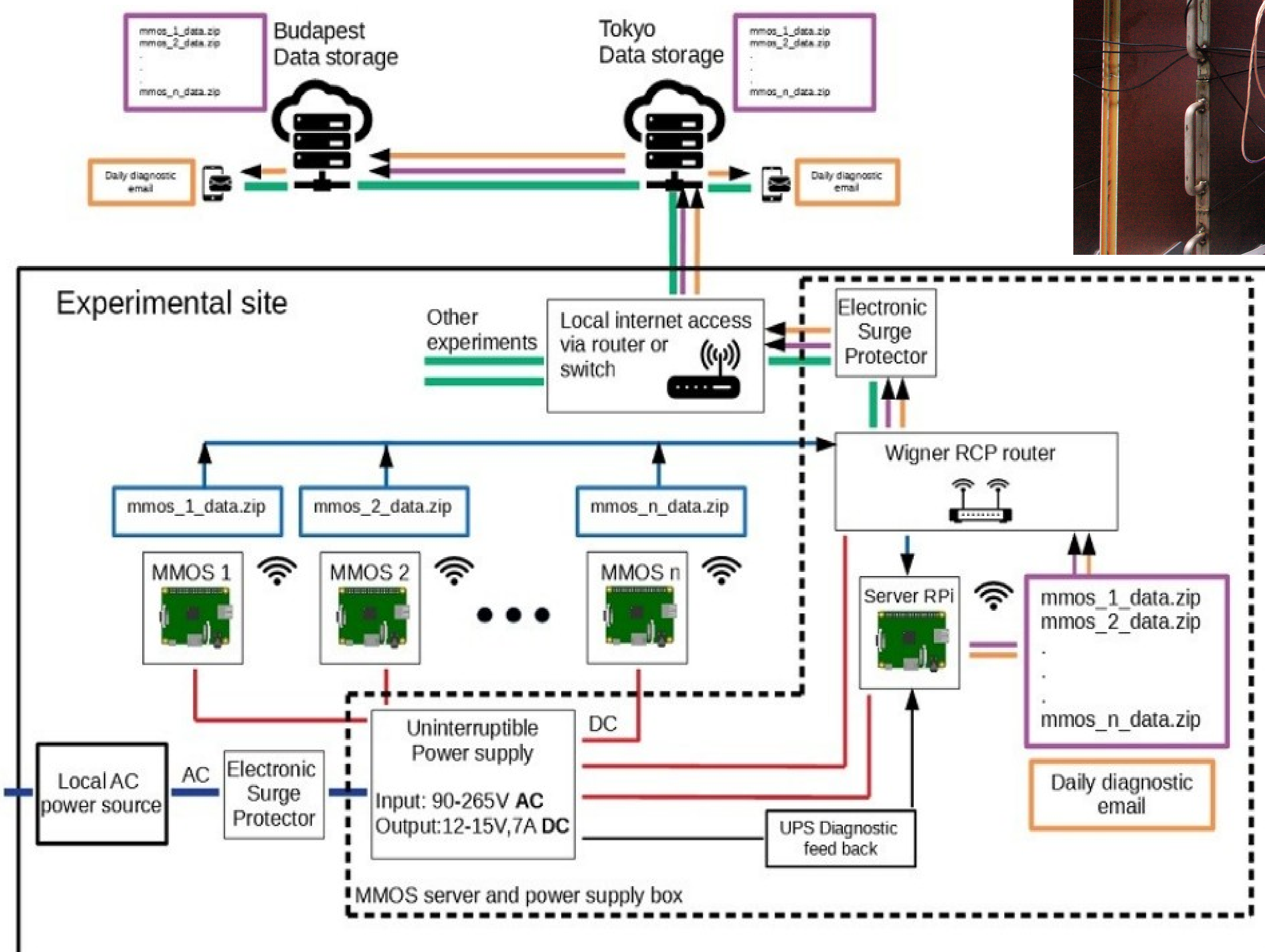
- **Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT)**
  Integrated Program for the Next Generation Volcano Research
  https://kazan-pj.bosai.go.jp/next-generation-volcano-pj-2019-jun
- **Joint Usage Research Project (JURP) from the ERI, University of Tokyo**
  https://www.eri.u-tokyo.ac.jp/en/joint-usage-top/
- **”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**

Back up slides

System Plan of SMO

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

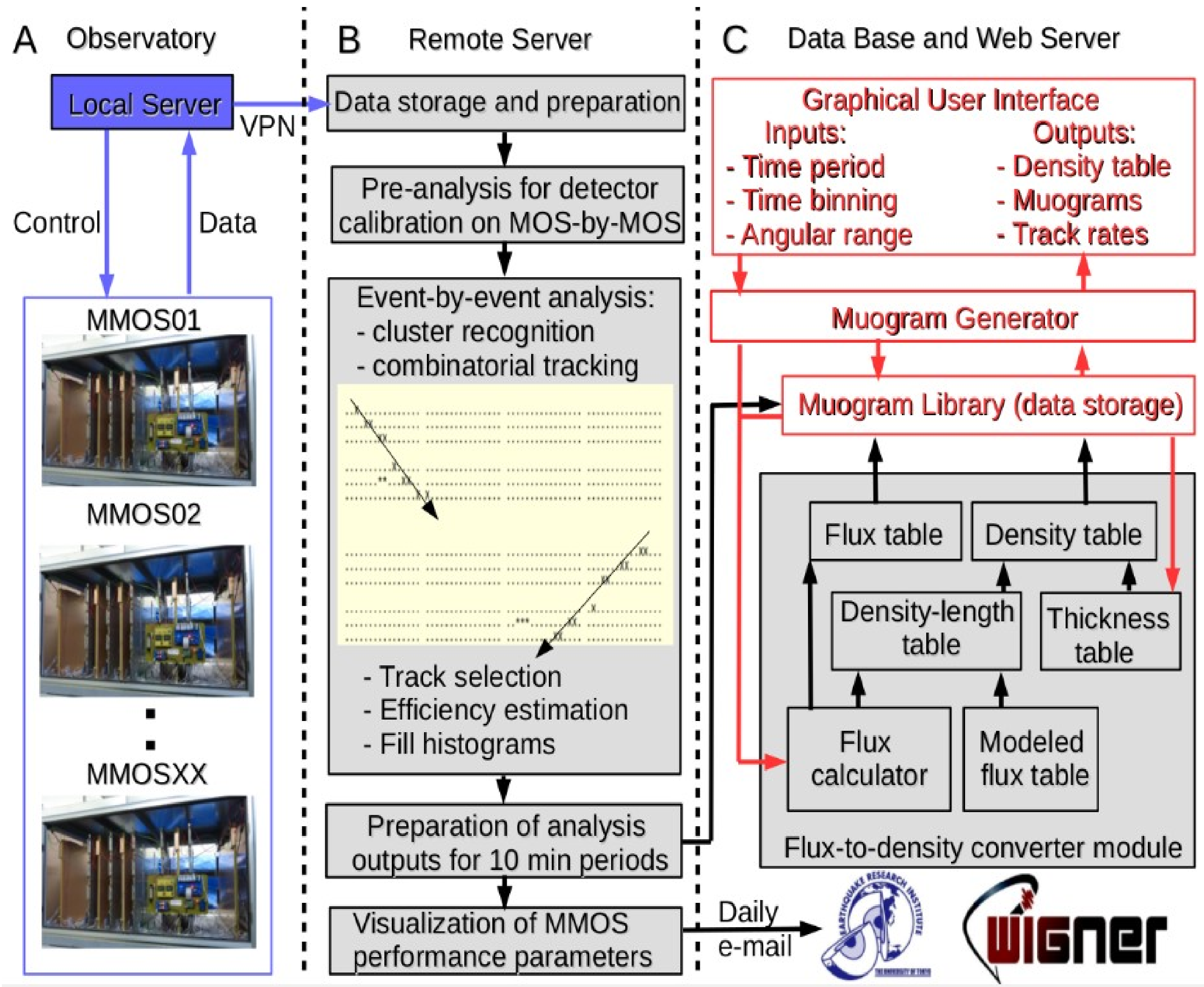


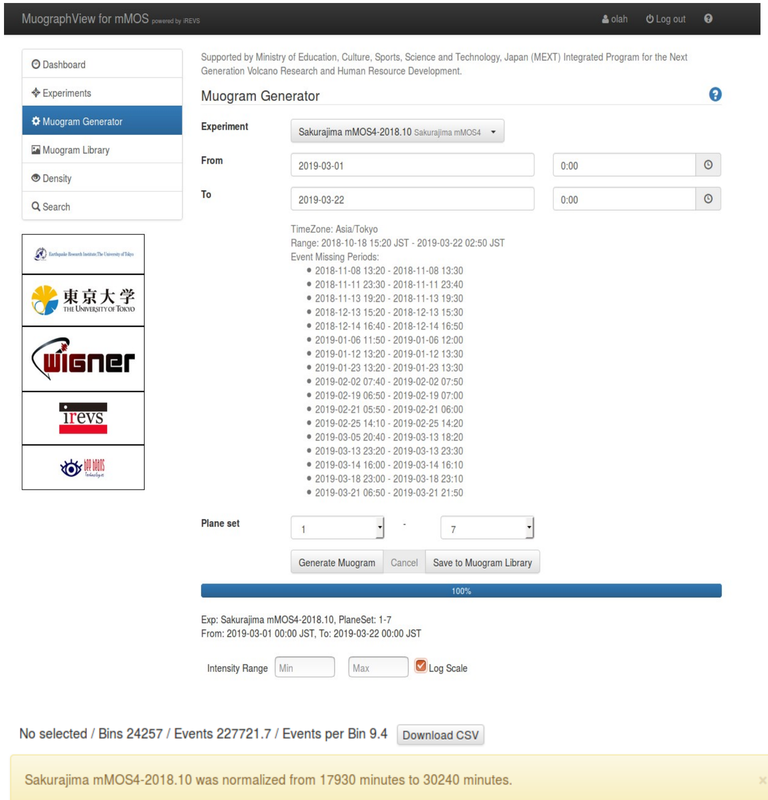


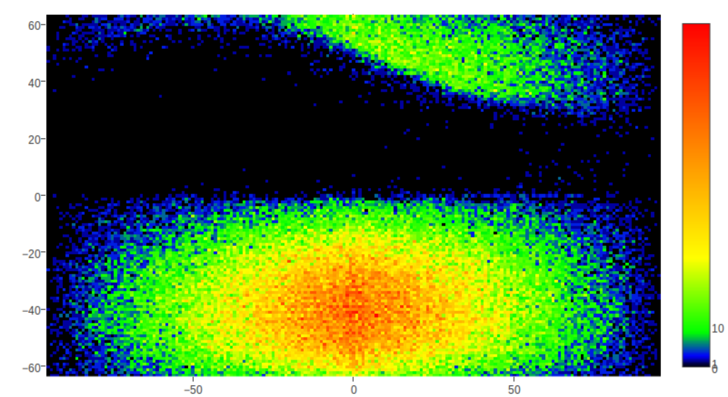
Source of this figure: Szabolcs József Balogh

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

Data Processing





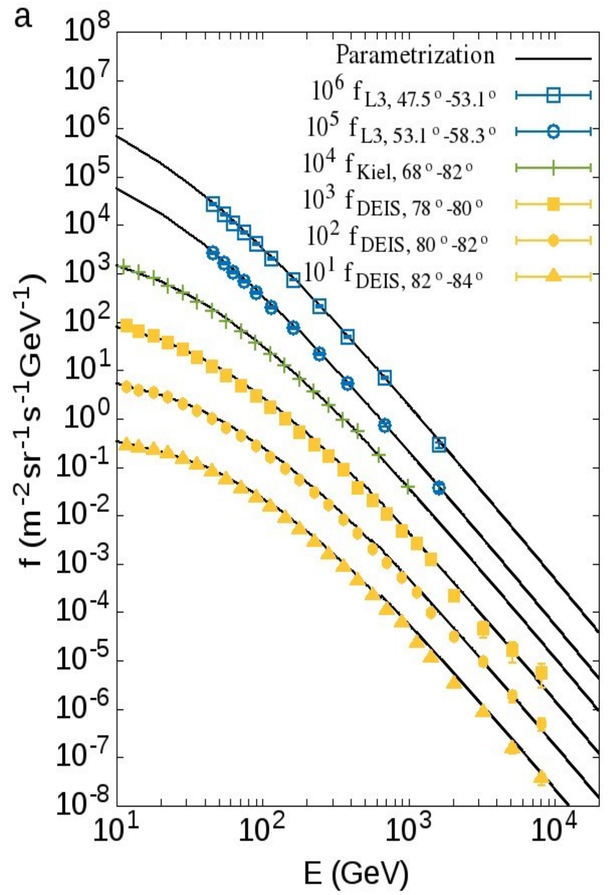


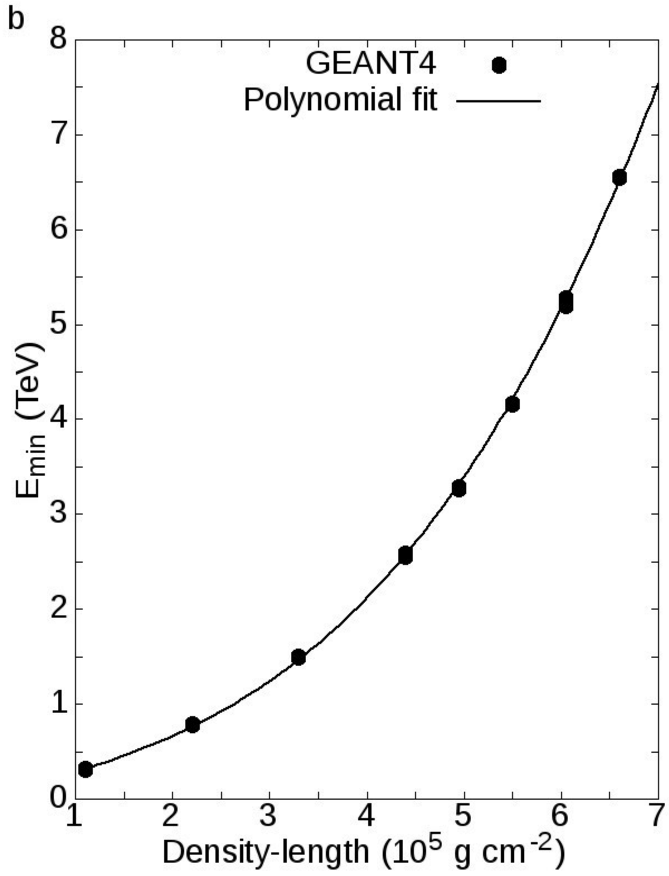
https://mmos.muographers.org

Oláh Muon WS 2024

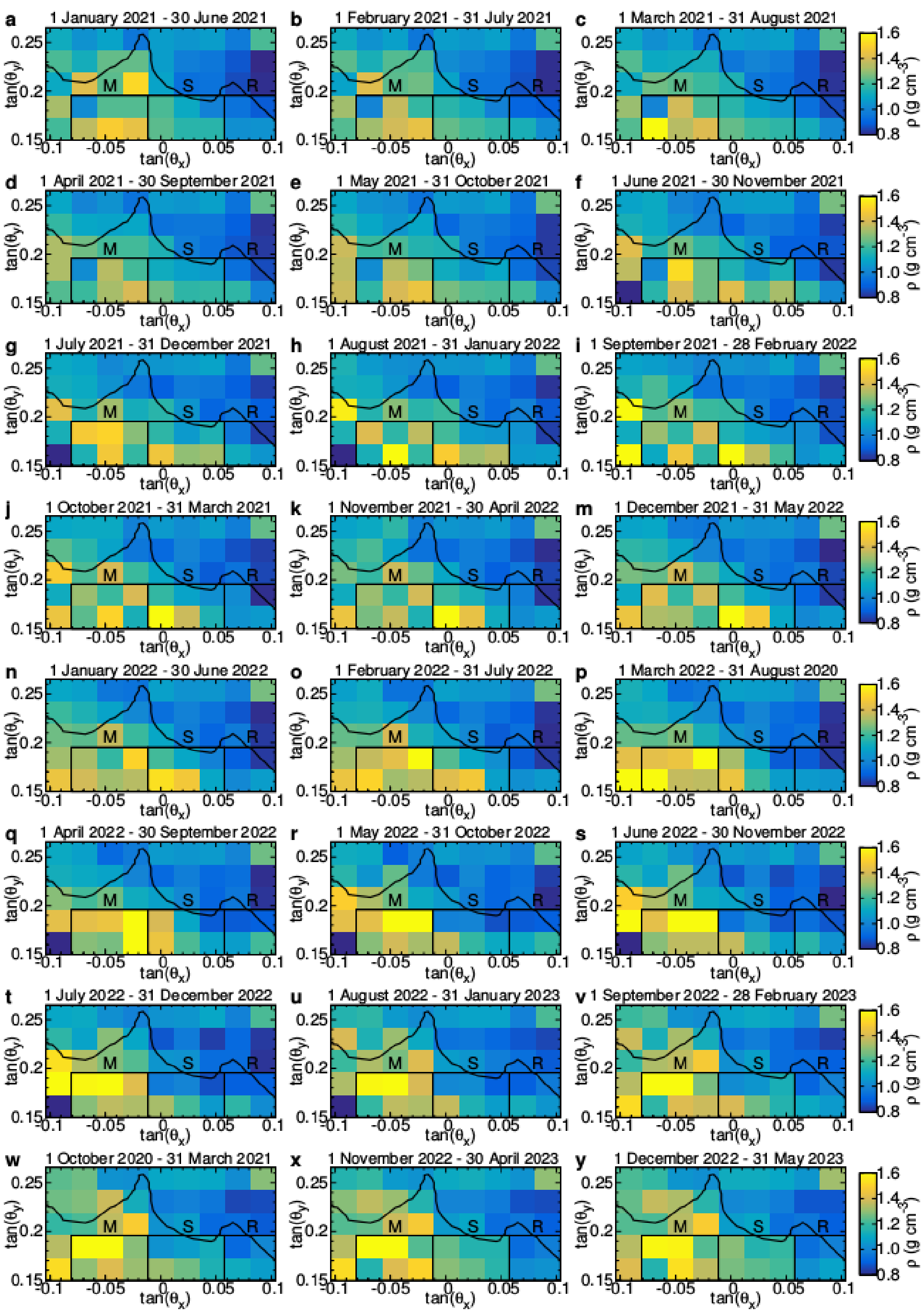
Density Imaging

- 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





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).

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