GHENT 24-26 NOV. Muographers 2021

Muography of the active Sakurajima volcano: recent results and future perspectives of hazard assessment

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24th November 2021

Outline

I. Motivation

II. Sakurajima Muography Observatory

III. Muographic Monitoring of Tephra Deposition and Erosion

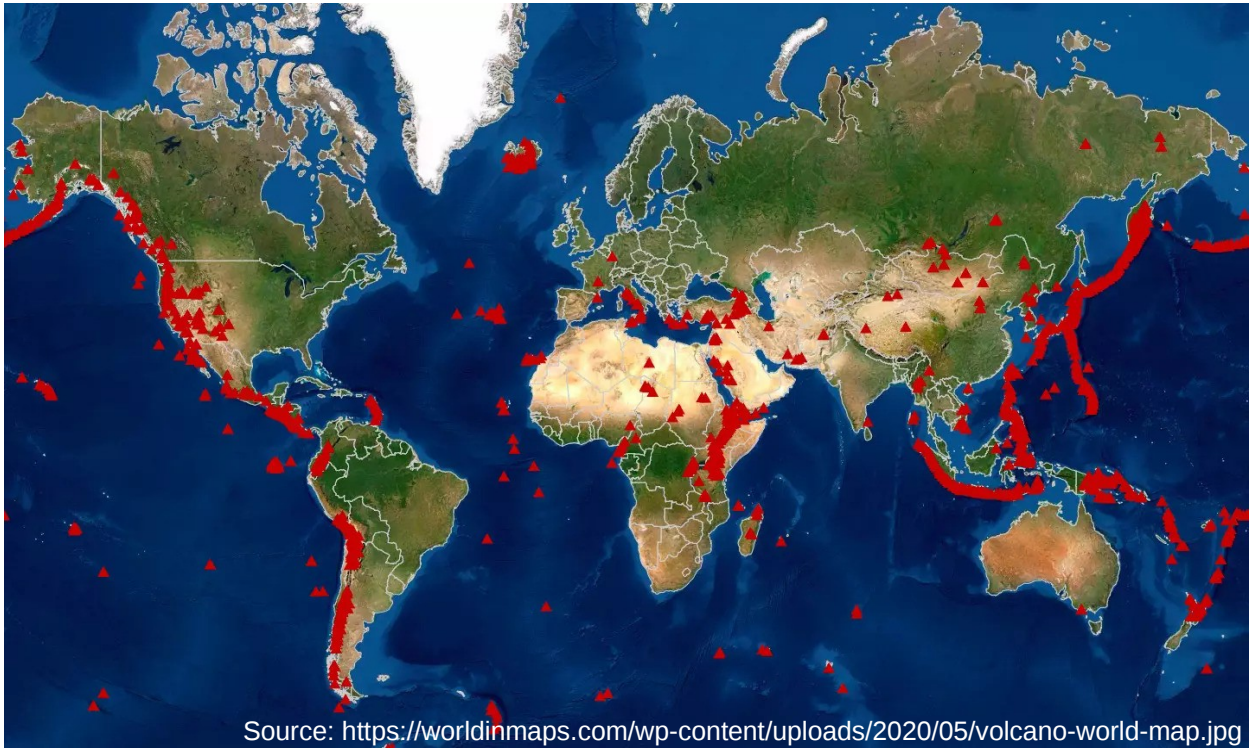
IV. Muography of Magmatic Plug Formation

V. Eruption Forecasting by Machine Learning of Muographic Data

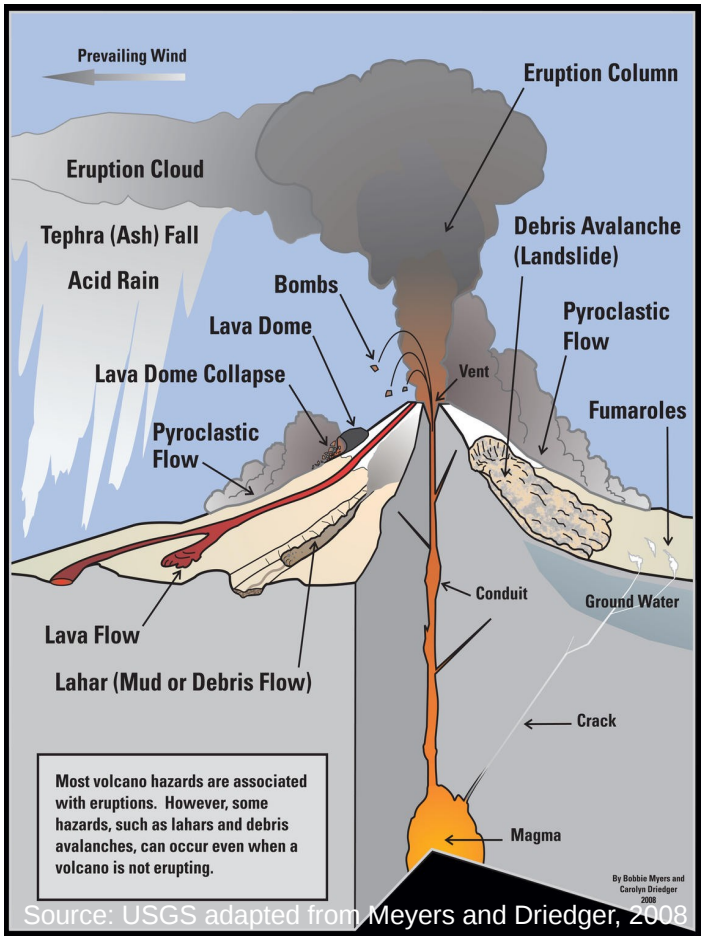
VI. Summary

I. Motivation: Volcanic Hazards

- More than 500 volcanoes confirmed historical eruptions (69 volcanoes erupted in 2021)
- 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



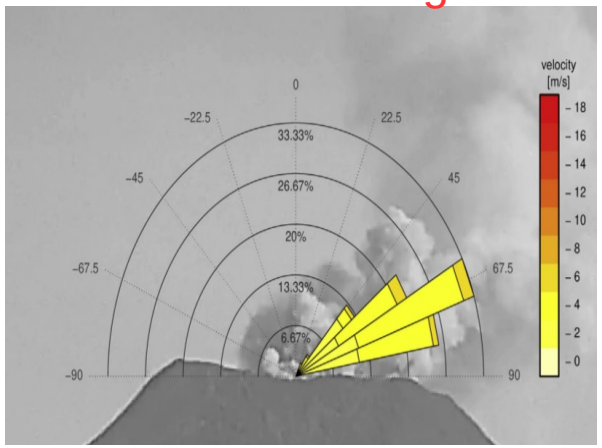
Source: https://worldinmaps.com/wp-content/uploads/2020/05/volcano-world-map.jpg



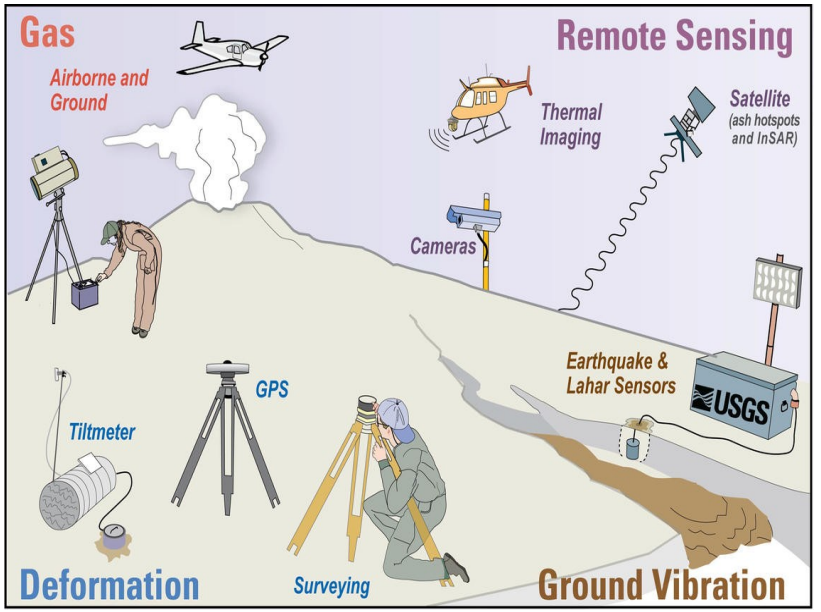
Source: USGS adapted from Meyers and Driedger, 2008

Volcano Monitoring

Video recording

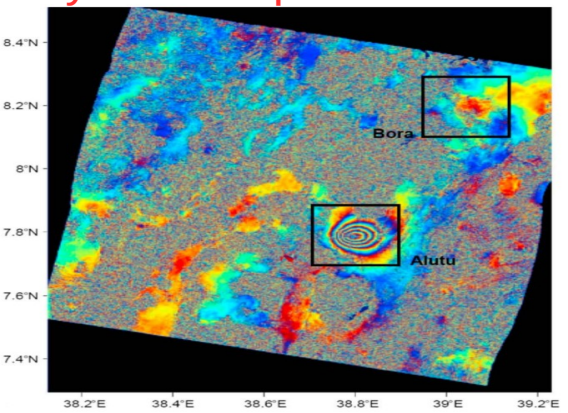


Source: https://doi.org/10.1016/j.gsf.2020.01.016



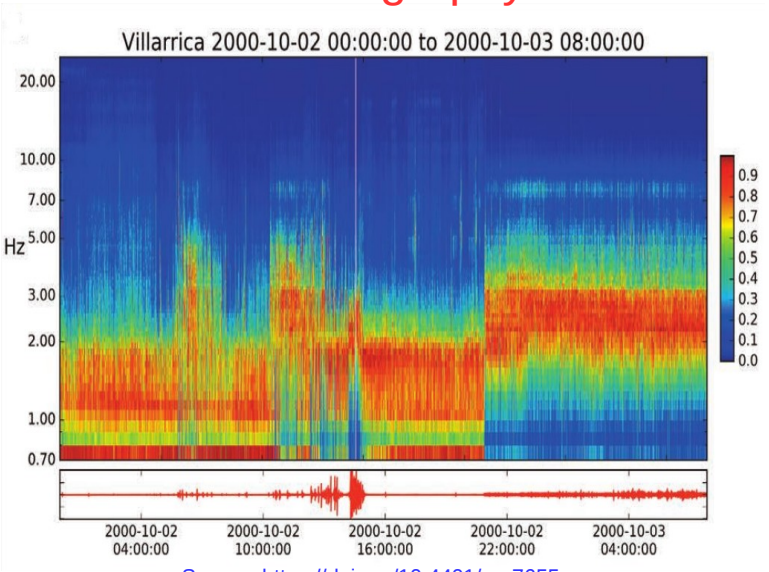
Source: USGS from Faust, Lisa

Synthetic Aperture Radar



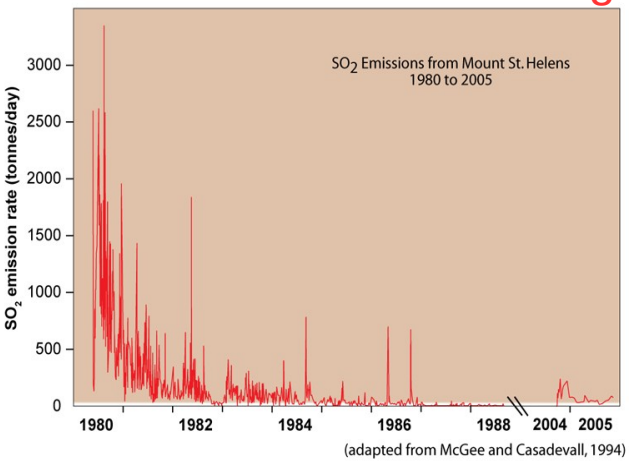
Source: https://doi.org/10.1029/2018JB015911

Seismography



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

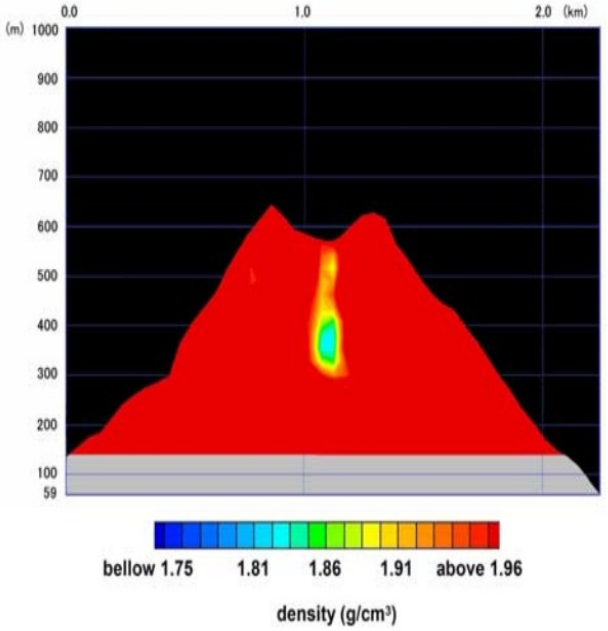
Gas Emission Monitoring



Source: USGS

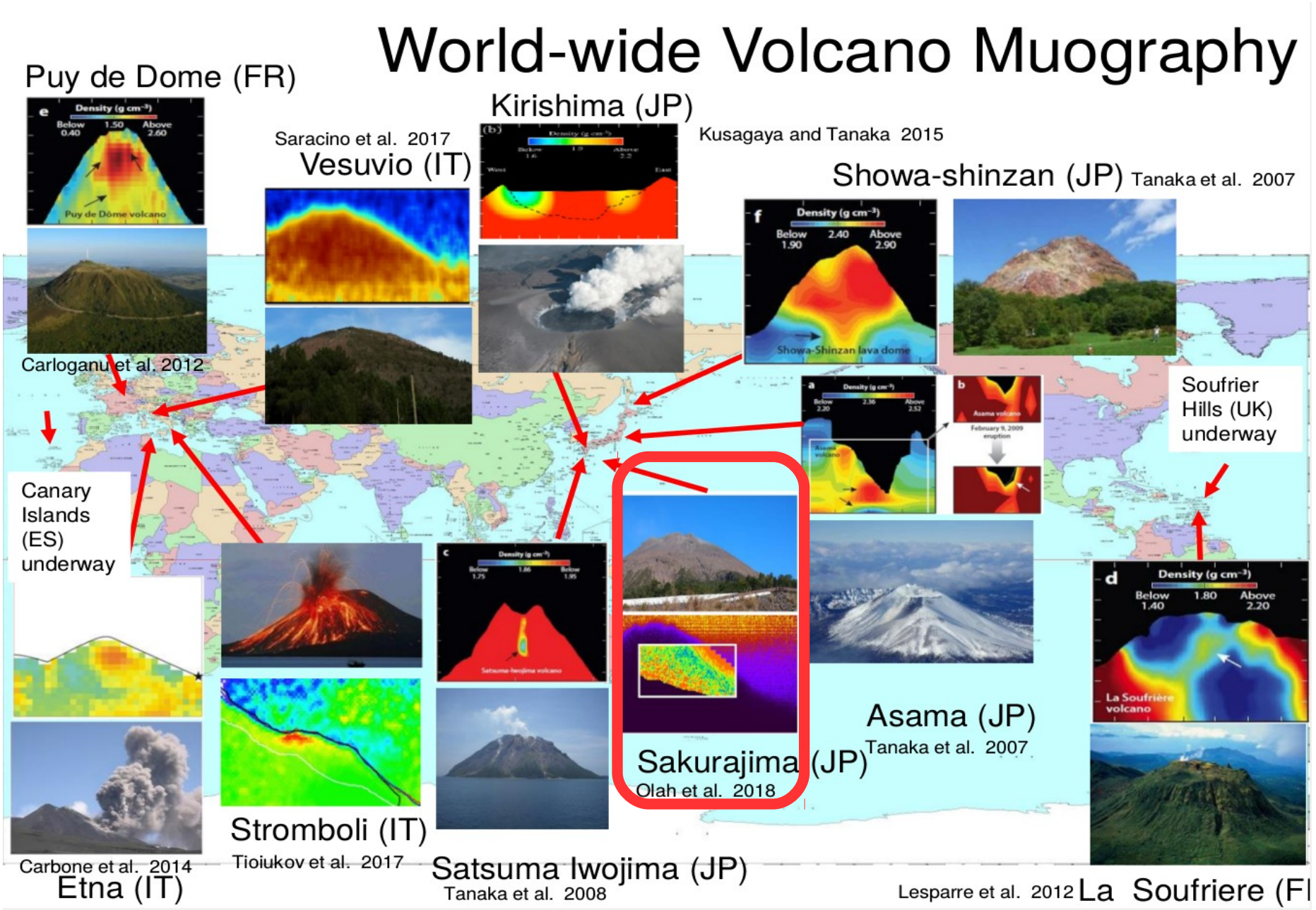
Oláh Muographers2021

Cosmic-ray Muography



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

World-wide Volcano Muography

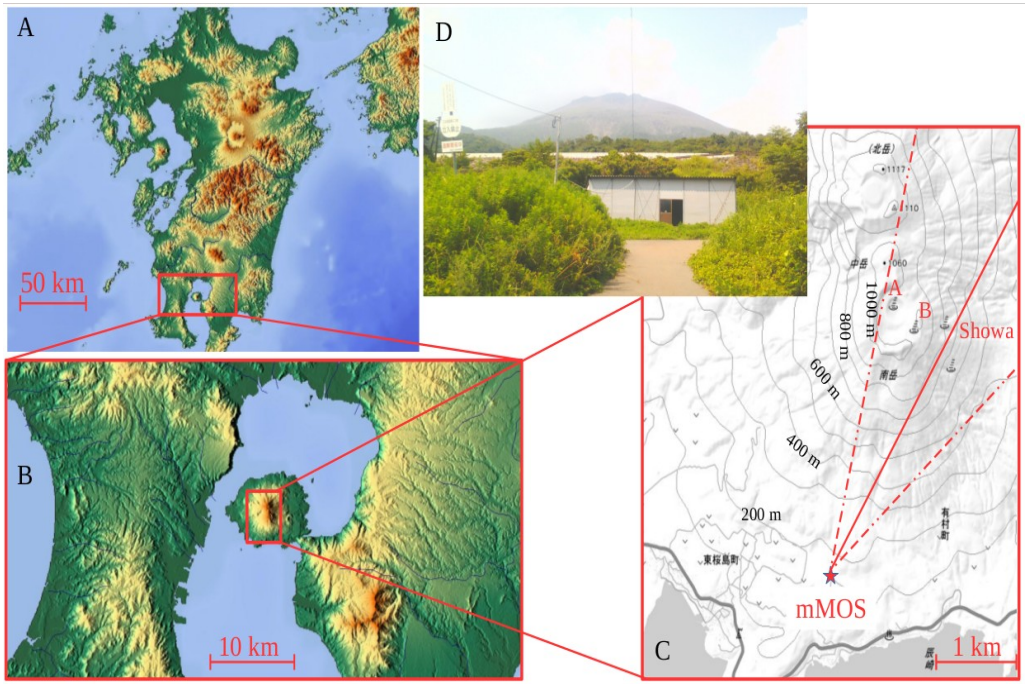


Source: H. K. M. Tanaka

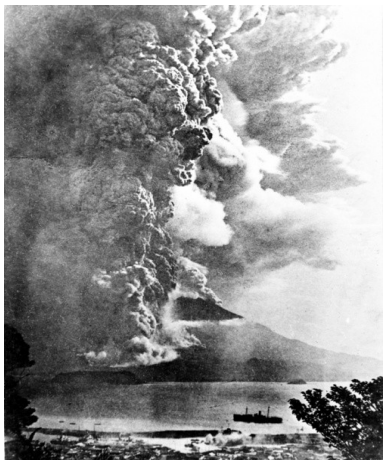
See more in talks by
Jesus Peña Rodriguez (MuTe),
Mariaelena D'Errico and Marwa Al Moussawi (MURAVES),
Raphael Bajou (DIAPHANE).

The Sakurajima Volcano, Kyushu, Japan

- 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
- **Protection of tourists motivates the forecasting of short-term eruptions of the Sakurajima volcano**



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



Source: Wikipedia

Source: Kimon Berlin, CC BY-SA 2.0

II. Sakurajima Muography Observatory

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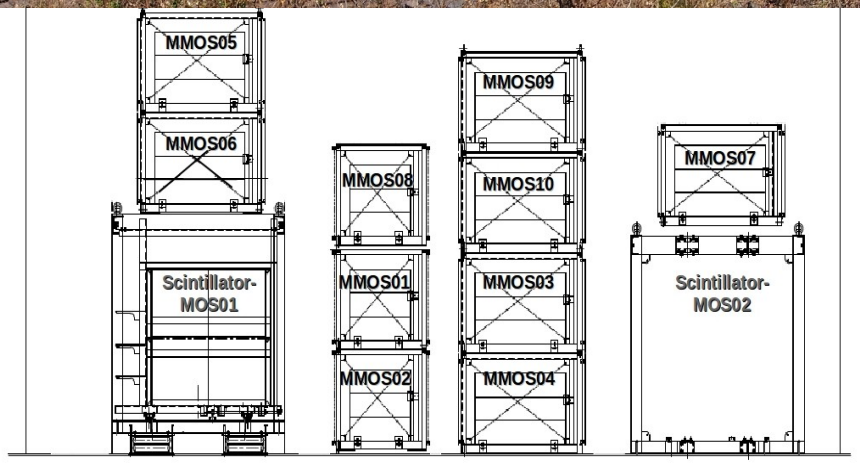
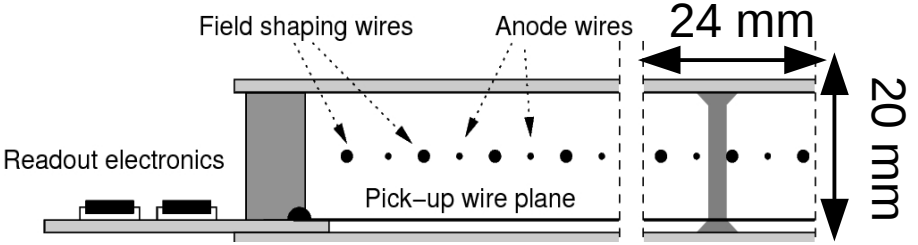
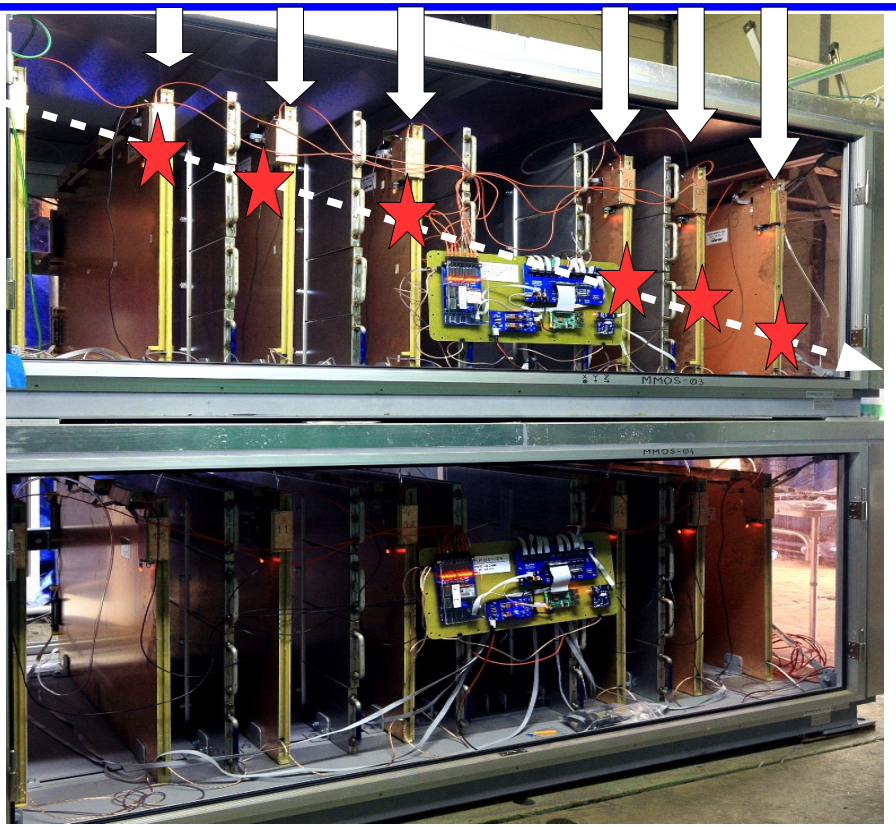
Multi-Wire Proportional Chamber (MWPC)-based Muography Observation System (MMOS)

See more in the talk by Dezső Varga



2-dimensional muon localization by gaseous detectors
https://doi.org/10.1155/2016/1962317





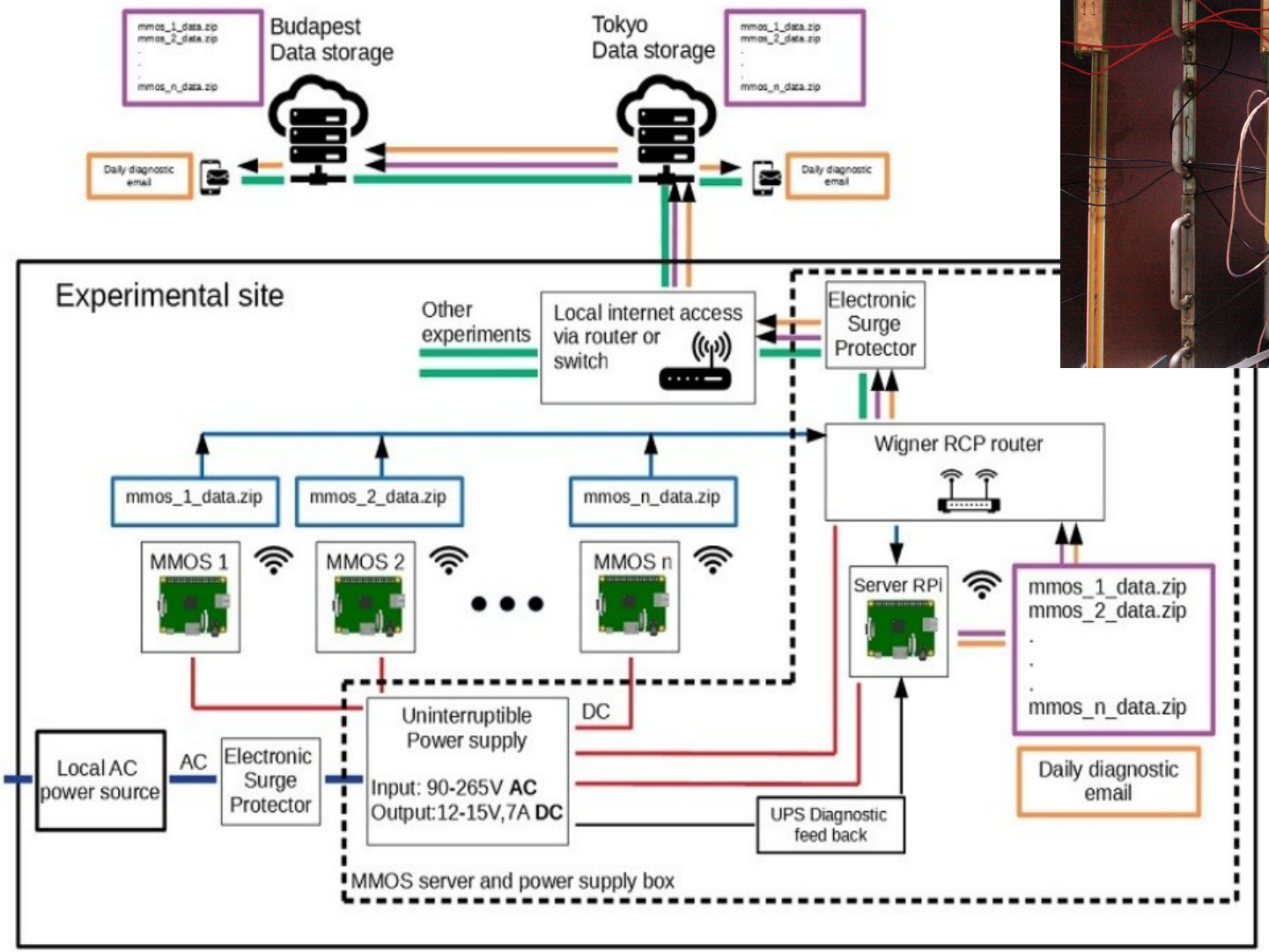
2017: 0.6 m² **2018: 3.6 m²** **2021: 8.7 m²** T

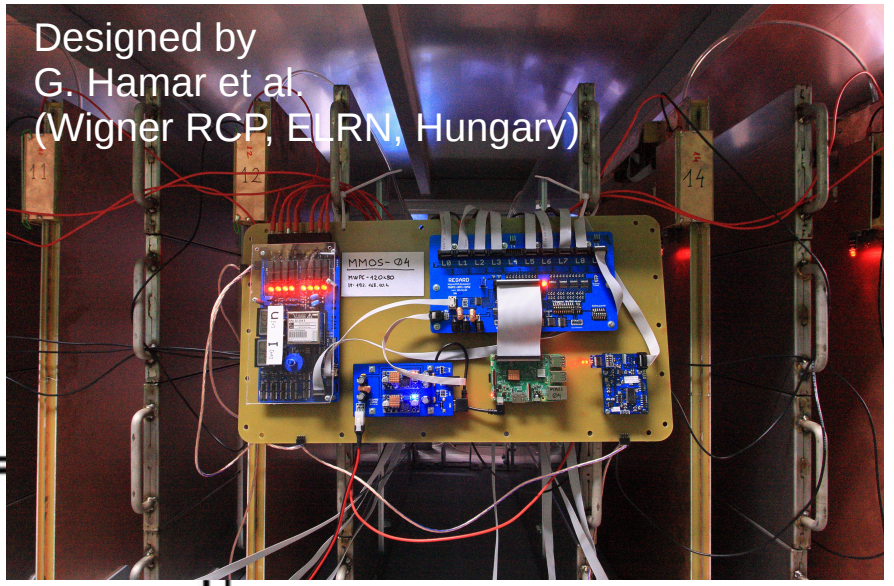
Patent: Muographic Observation Instrument (WO 2017/187308 A1)

Publications:

https://doi.org/10.1038/s41598-018-21423-9
https://doi.org/10.1029/2019GL084784
https://doi.org/10.1016/j.nima.2019.05.077

System Plan: Data Acquisiton





- Custom-designed electronics
- Power consumption:
  ~ 6 W per MMOS
- **Micro-computer controlled**
  → real-time DAQ & analysis
- Data transferred and stored on remote computers

Source: Szabolcs József Balogh (Wigner RCP, ELRN, Hungary)
See more in Varga et al.
https://doi.org/10.1016/j.nima.2019.05.077

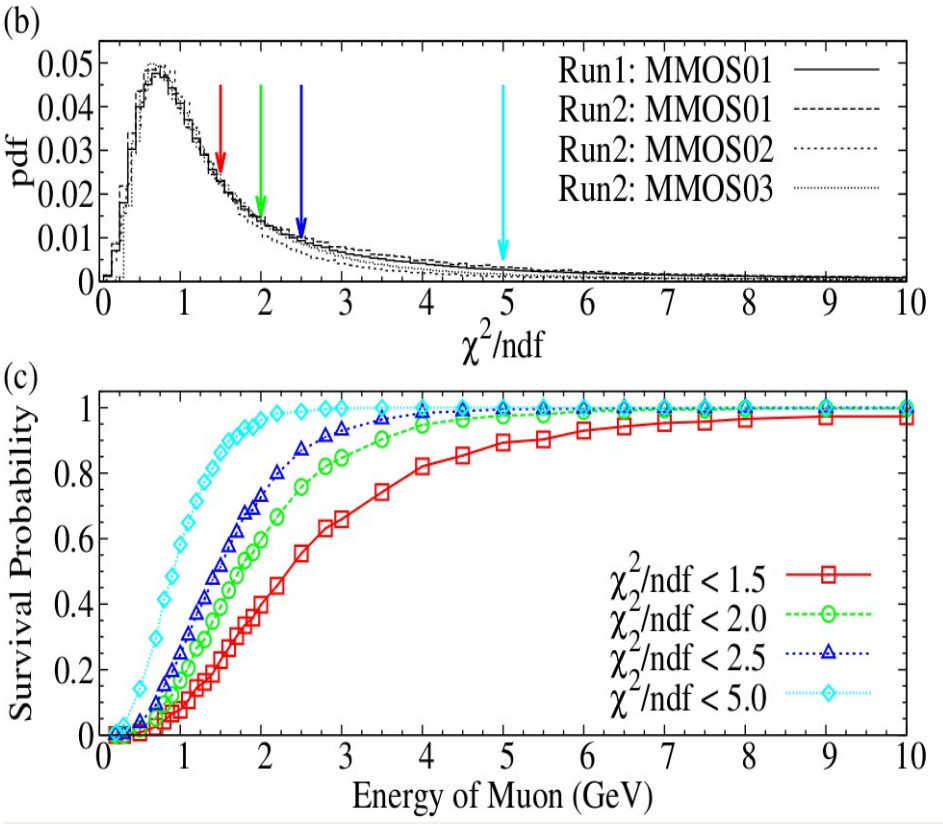
Track Reconstruction and Analysis Methods

- Event-by-event offline track reconstruction (slopes in 1+1 dim and χ^2/n.d.f.) was applied independently for each MMOS module
- Pre-analysis was applied for alignment of detector layers and exclusion of noisy or malfunctioned electronics channels
- Track selection was based on χ^2/n.d.f.

See more at https://doi.org/10.1038/s41598-018-21423-9

- GEANT4-based detector simulations were applied to set energy cuts of muons to approx. 1 GeV that corresponded to χ^2/n.d.f. < 1.5
- Directions of different MMOS modules were oriented to the reference direction that was 30.25° from North and horizontal
- Muon fluxes were weighted with the inverse of their relative errors, and thereafter averaged

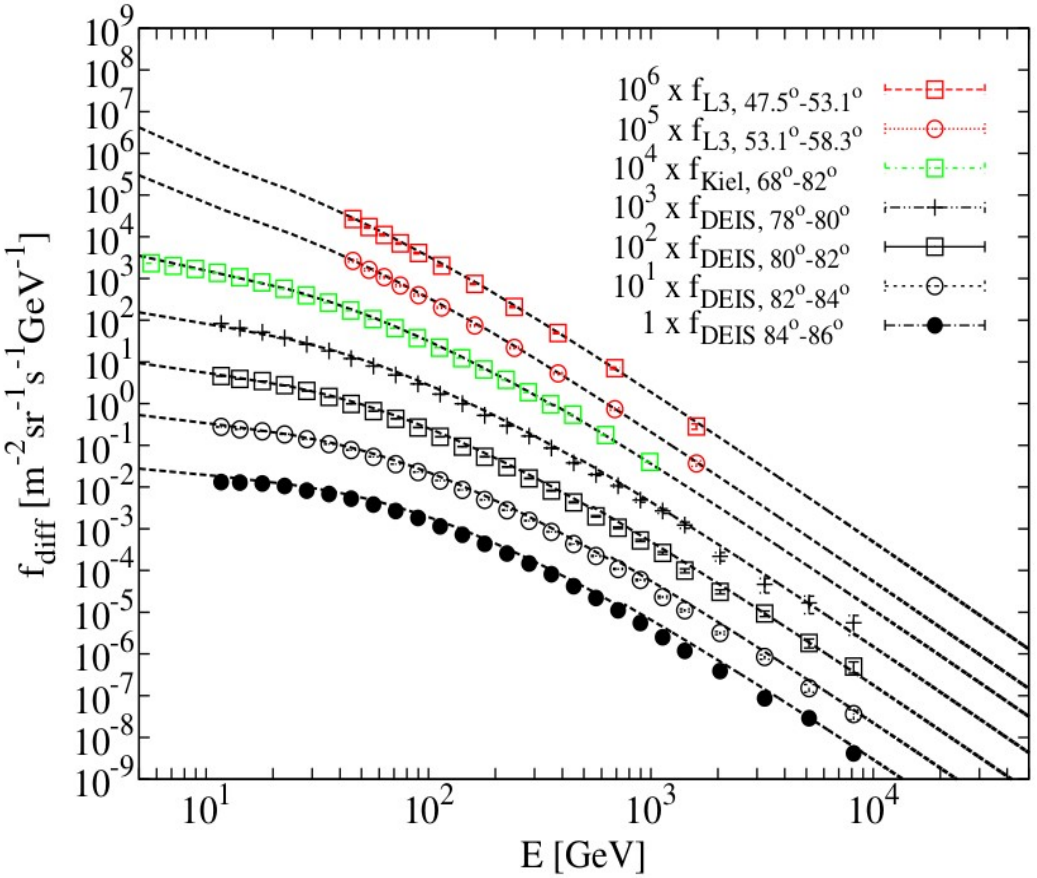
See more at https://doi.org/10.1029/2019GL084784



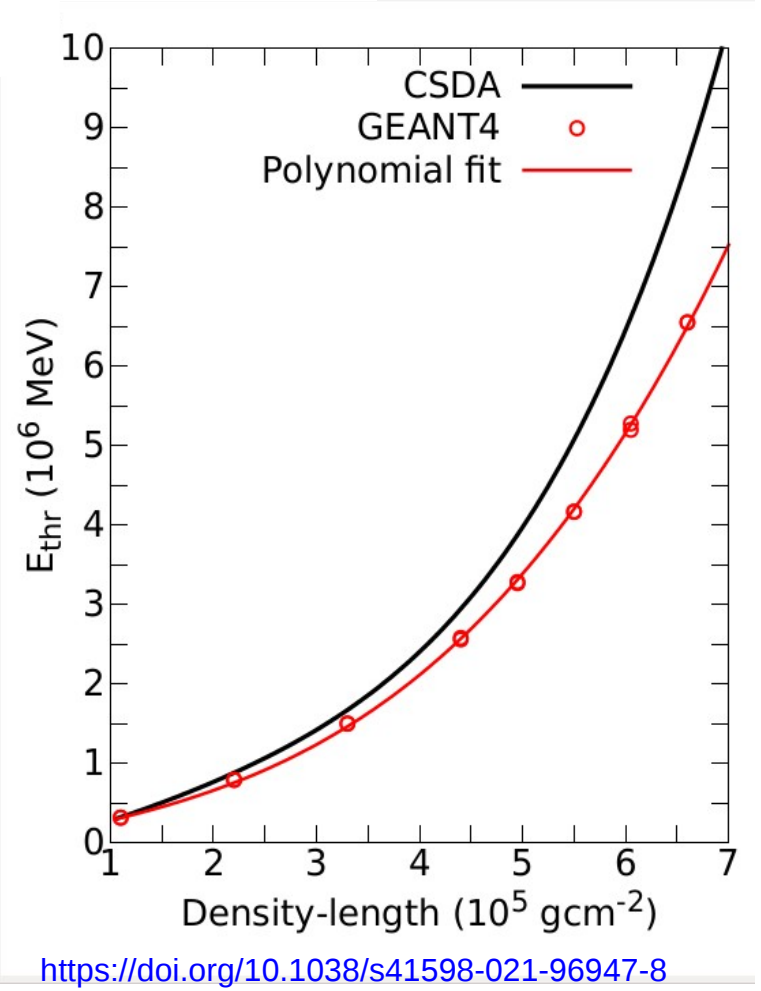
Numerical and Simulation Methods

Density-length is determined by means of comparison of calculated fluxes to the measured values:

$$F_{calc}(90^\circ - \theta_y, L) = \int_{\mathrm{E_{thr}}(L)}^{\infty} f_{diff}(E, 90^\circ - \theta_y)\mathrm{d}E$$



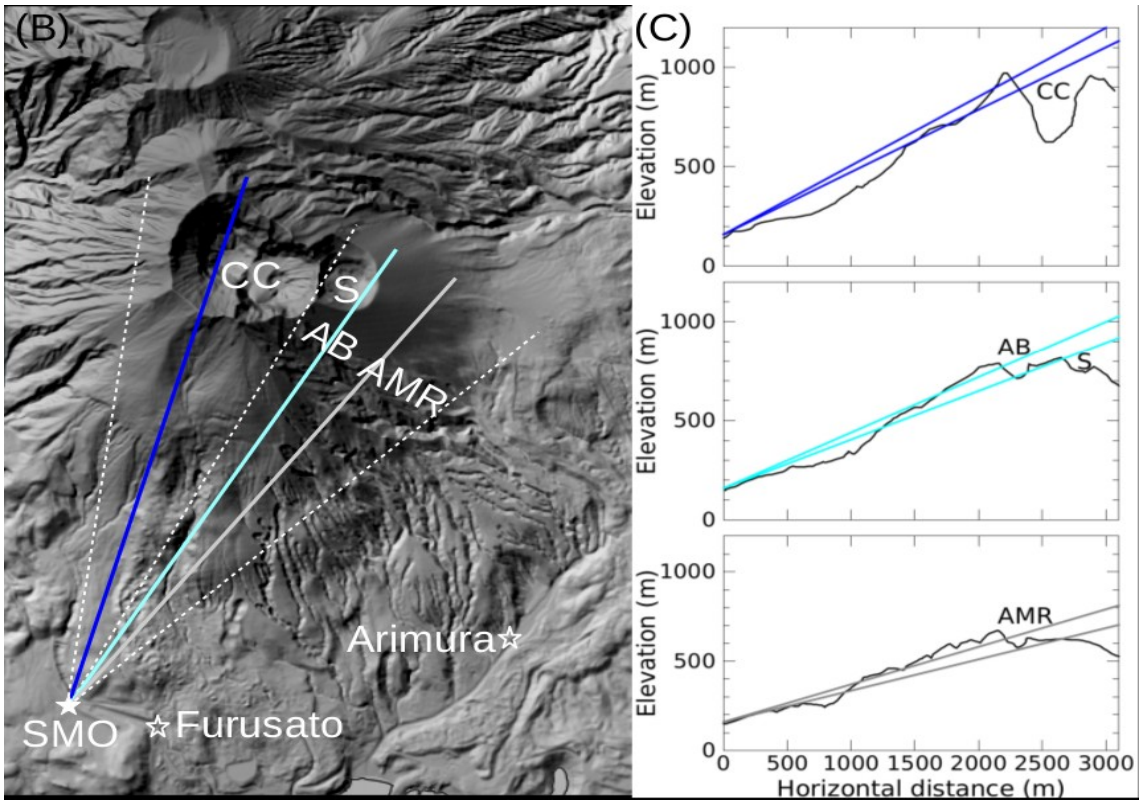
https://doi.org/10.1038/s41598-018-21423-9



https://doi.org/10.1038/s41598-021-96947-8

III. Muographic Monitoring of Tephra Deposition and Erosion

Indirect Volcanic Hazards



Lahars are fast-moving gravity-driven flows of mixture of volcanic rocks and water occurred either during eruptions or when the volcano is dormant.

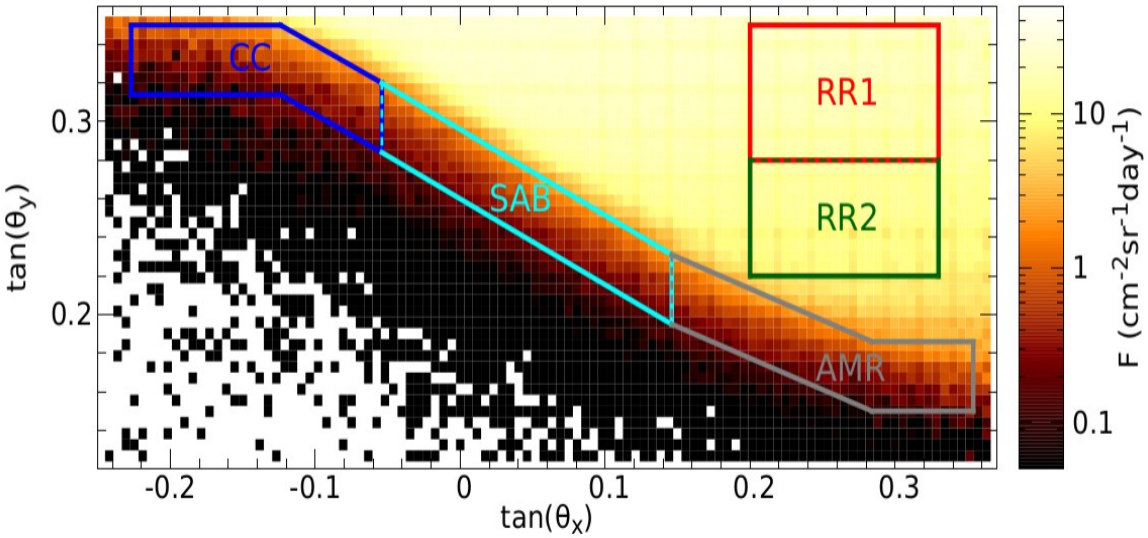
Wind and water driven erosion processes can destabilize and mobilize the tephra deposition before they become fully incorporated into the soil.

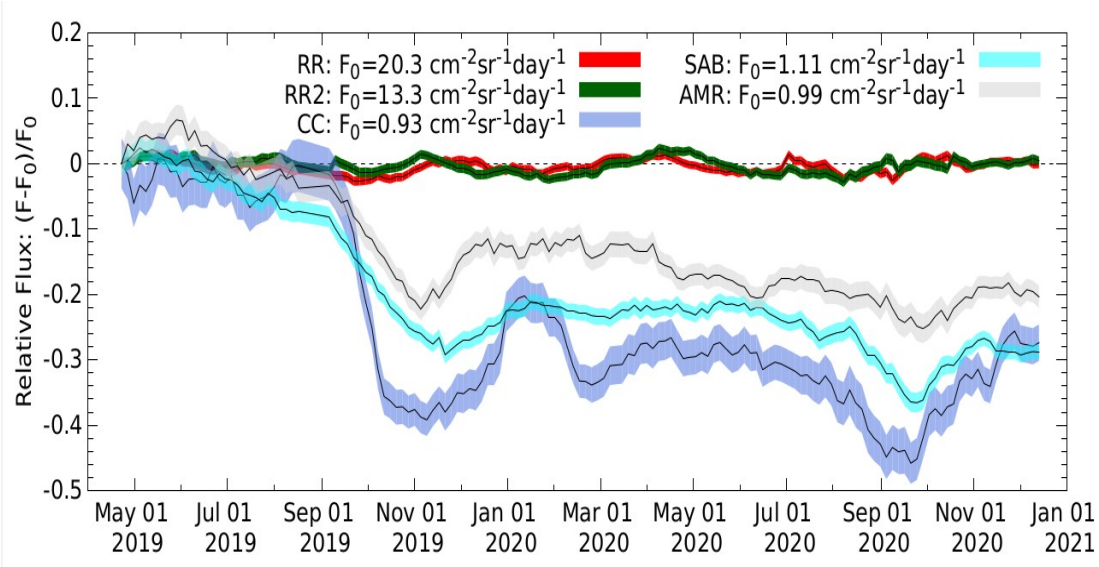
The generation and dynamics of lahars are controlled by the following factors:
(i) local topography,
(ii) volcanic activity,
(iii) amount and composition of tephra,
(iv) intensity and duration of rainfall.

Muography has potential to measure the amount (mass and thickness) of tephra deposition and topographical changes that controlling the onset of post-eruptive lahars.

https://doi.org/10.1038/s41598-021-96947-8

Muographic Observation of Tephra Deposition





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

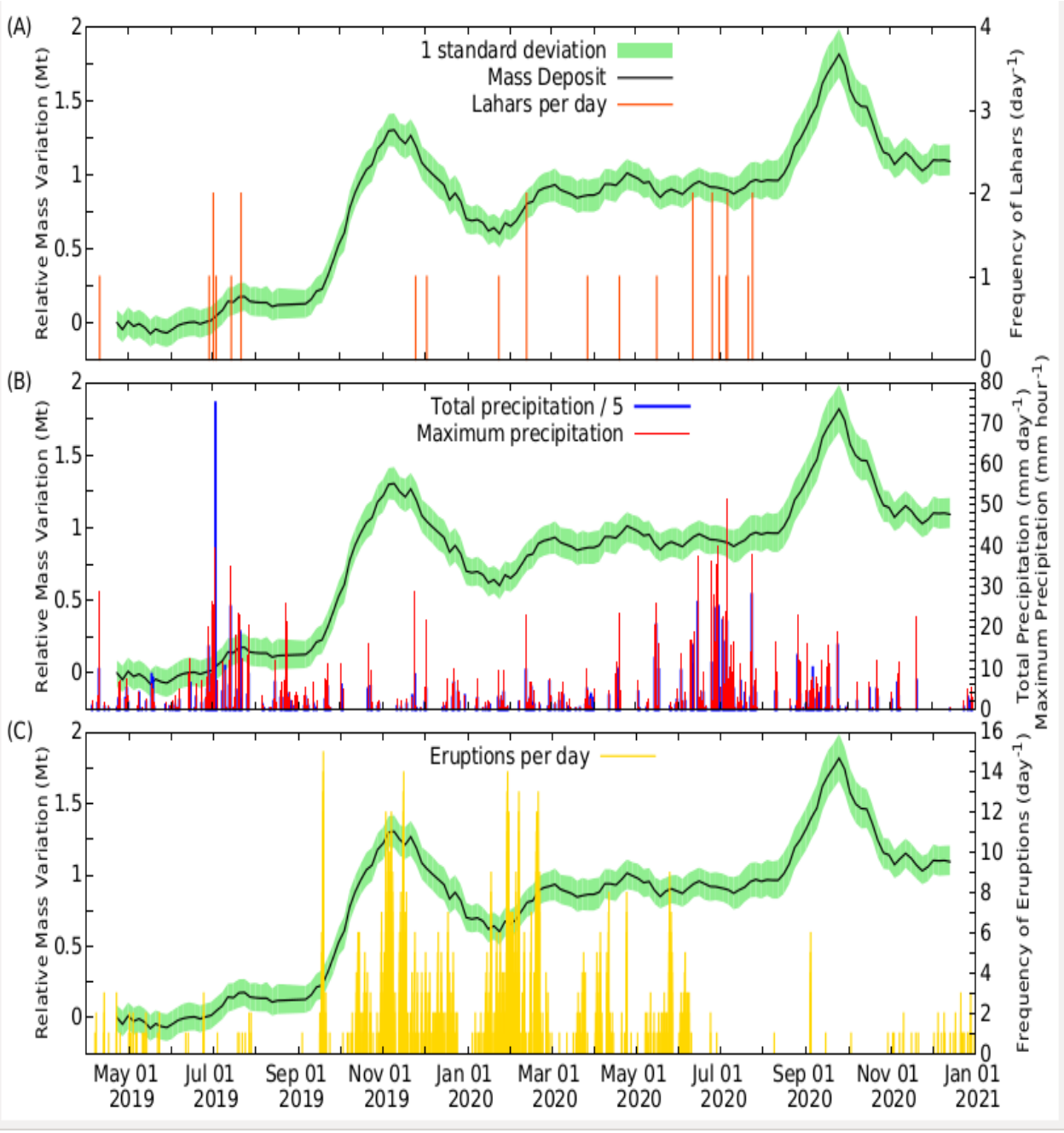
- **The fluxes were averaged** in each angular region for time-intervals of 4 days, and the averaged fluxes were smoothed by applying a moving average calculated from the previous ten consecutive time-intervals, i.e. **over a period of 40 days.**

- **After September 2019, the relative averaged fluxes (measured relatively the flux of the first time sequence, F0) 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

https://doi.org/10.1038/s41598-021-96947-8

Muographic Observation of Erosion



- The total mass (volcanic edifice and tephra) was measured to M0 = (7.54 ± 0.05) Mt during the 1st time-interval → **Relative mass variation (M – M0) was quantified**

- **Mass deposit showed significantly decreasing trends** through various periods, e.g. from November 2019 to January 2020, during March 2020 and October 2020:

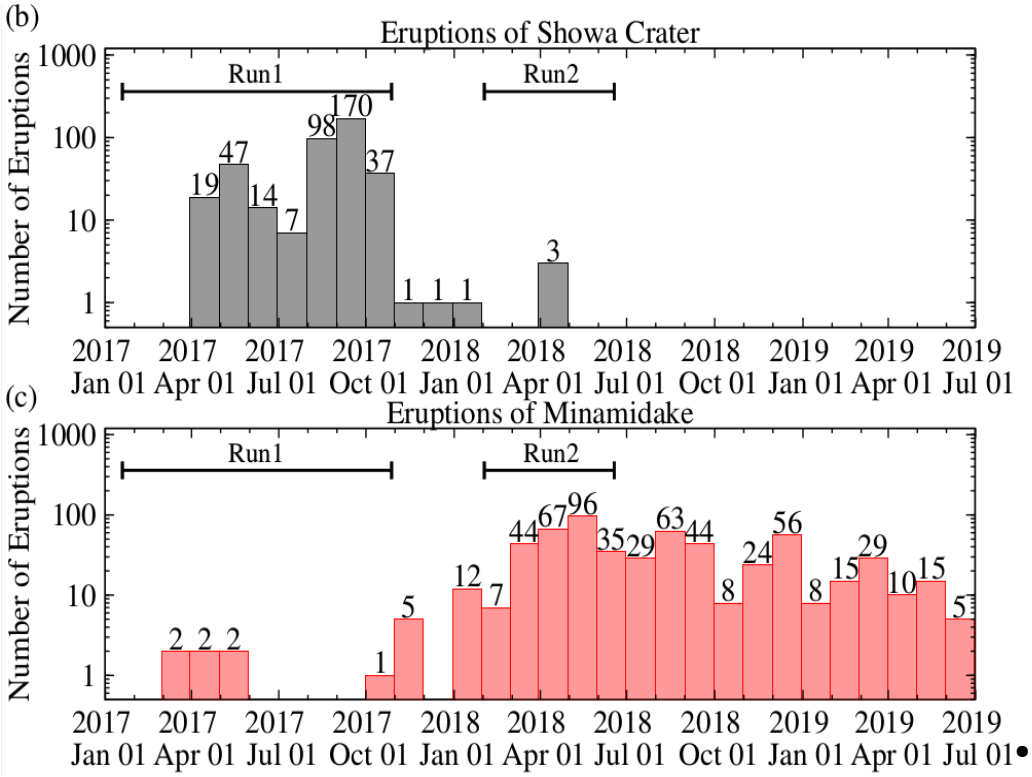
  - (i) The volcanic sediments were transported from the selected peak regions to downstream regions of the volcano **by the onset of rain-triggered lahar events.**

  - (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**.

https://doi.org/10.1038/s41598-021-96947-8

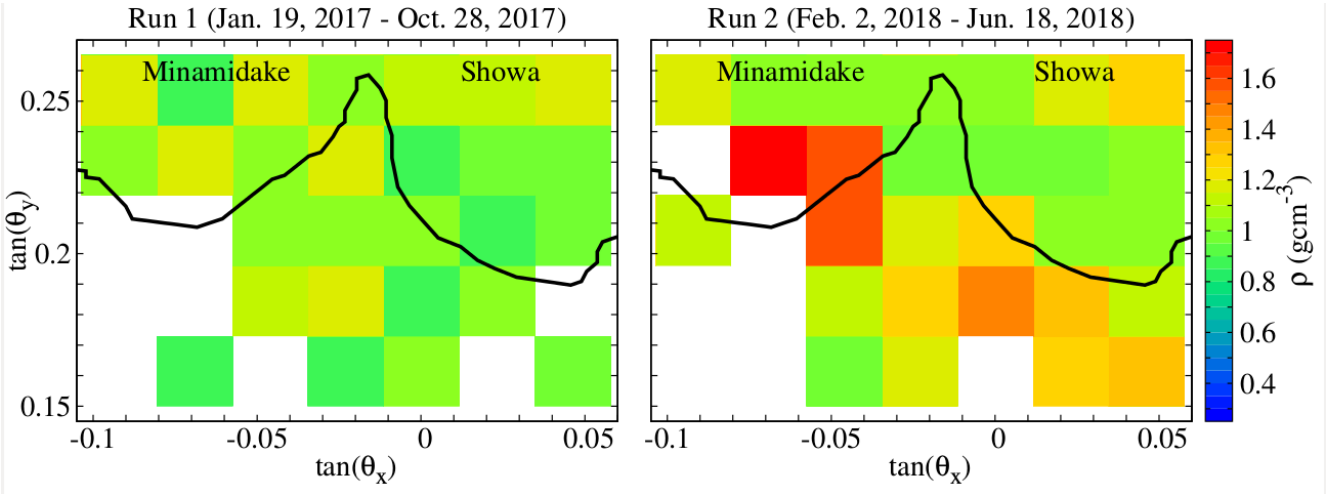
IV. Muography of Magmatic Plug Formation

Deactivation of Showa Crater



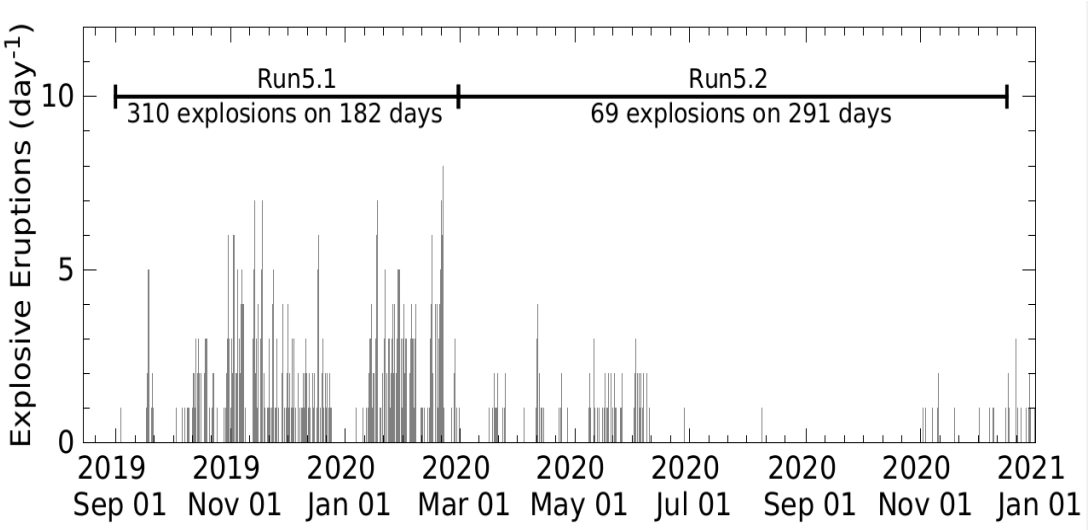
- **What is the cause of the shift of eruption sequence from Showa to Minamidake?**
- Two data sets were analysed:
  Run 1: January - November 2017;
  Run 2: February - June 2018.
- Systematics effects on muon flux: < 5 %

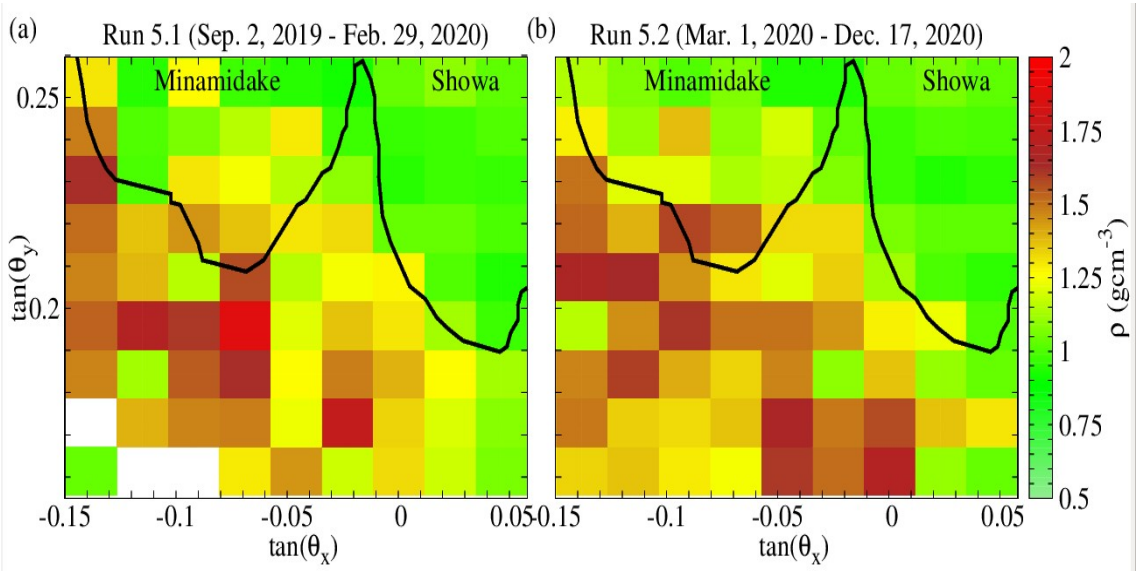
See more in https://doi.org/10.1029/2019GL084784



- Significant density increase from 2σ-4σ was observed bin-by-bin across Minamidake and beneath Showa crater (~7 Mt)

Decreased Activity of Minamidake Crater





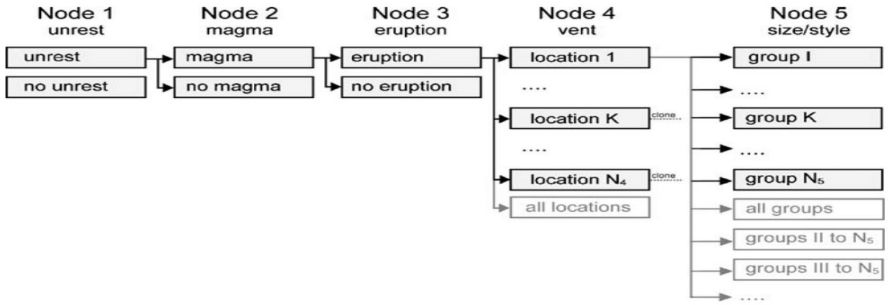
- We assume the existence of a low-density, debris-filled volume under the two craters that acts as a magma reservoir. The lateral extension of this volume is estimated to be approx. 300 m at depth of 100-200 m.
- Liquid magma fills the inter-grain spaces in this volume a few tens of minutes before the onset of eruption.
- After the eruption, the liquid magma is drained back to the conduit.
- Thereafter, the solidification of this volume creates a magmatic plug under the crater. The decreasing of the permeability of this volume explains the deactivation of the Showa crater in April 2018 and the latest dormant periods of Minamidake crater from March to December 2020.

https://doi.org/10.1002/9781119722748.ch08

V. Eruption Forecasting by Machine Learning of Muographic Data

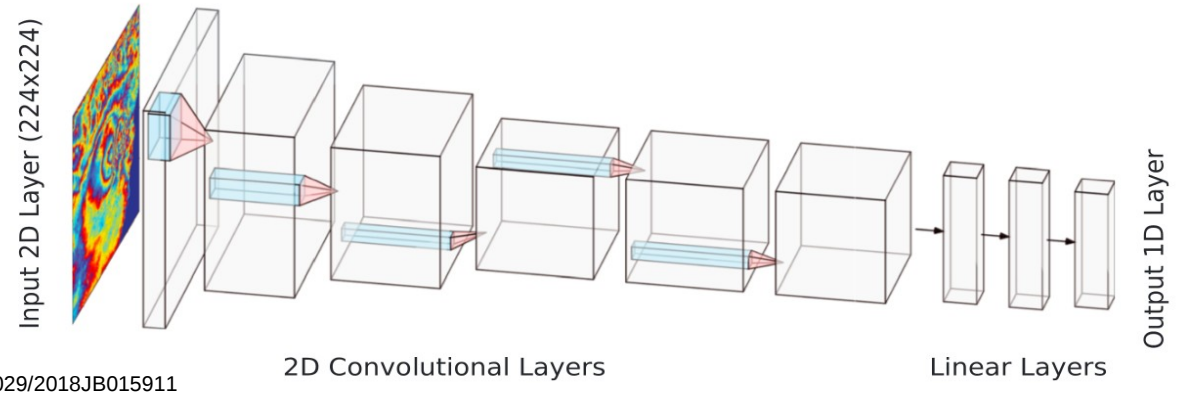
Eruption Forecasting

- Bayesian Event Trees for **long-term eruption forecasting**



Source: https://doi.org/10.1007/s00445-009-0311-9

- Convolutional Neural Networks for classification of volcanic deformation and **short term eruption forecasting**

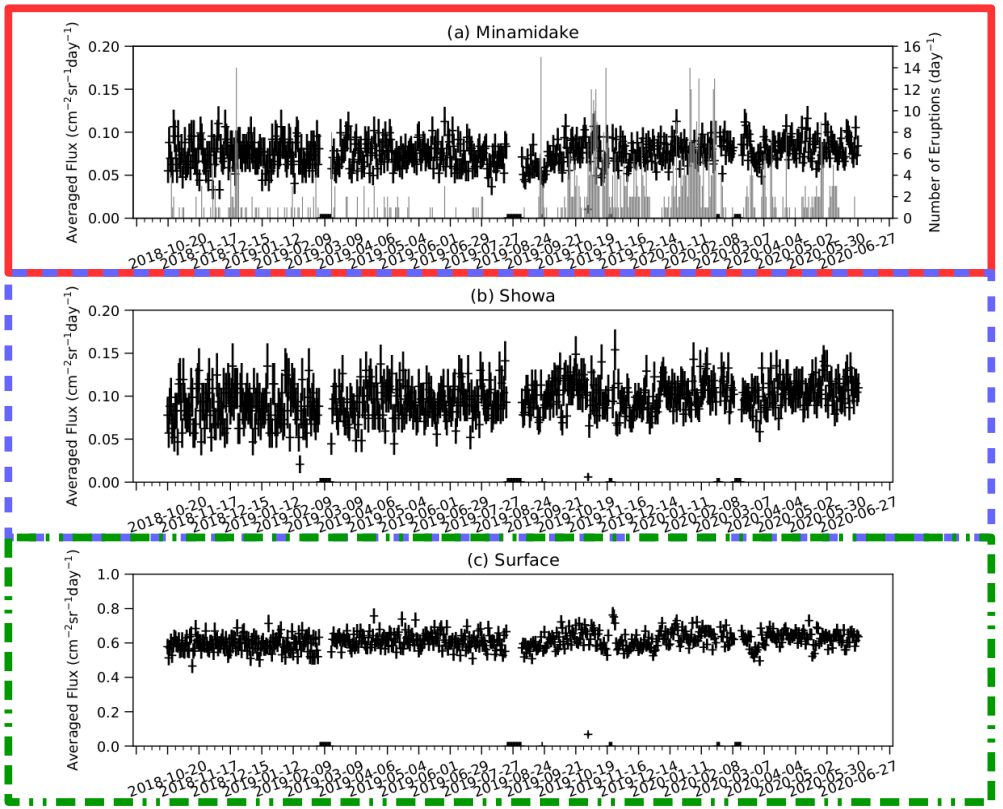


Source: https://doi.org/10.1029/2018JB015911

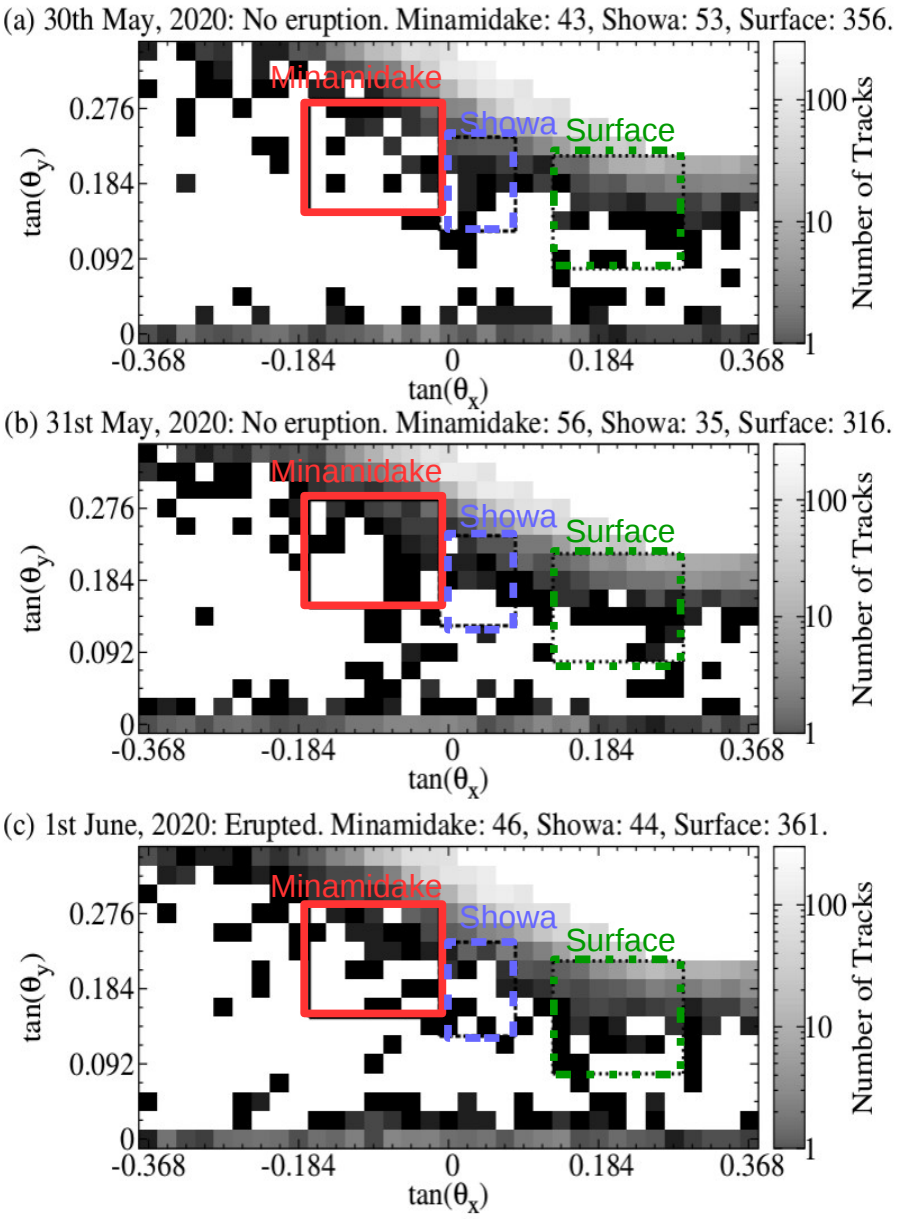
- **Goal:** real-time eruption forecasting by machine learning of muographic data

Preparation of Data to Supervised Machine Learning

- Daily muograms were determined for period from October 2018 to June 2020
- **Average flux values and sub-images** were extracted from three selected regions:
  - Active Minamidake crater,
  - Dormant Showa crater,
  - Surface region.
- **Eruption labels** were also derived to all days
  Eruption → 1, No eruption → 0

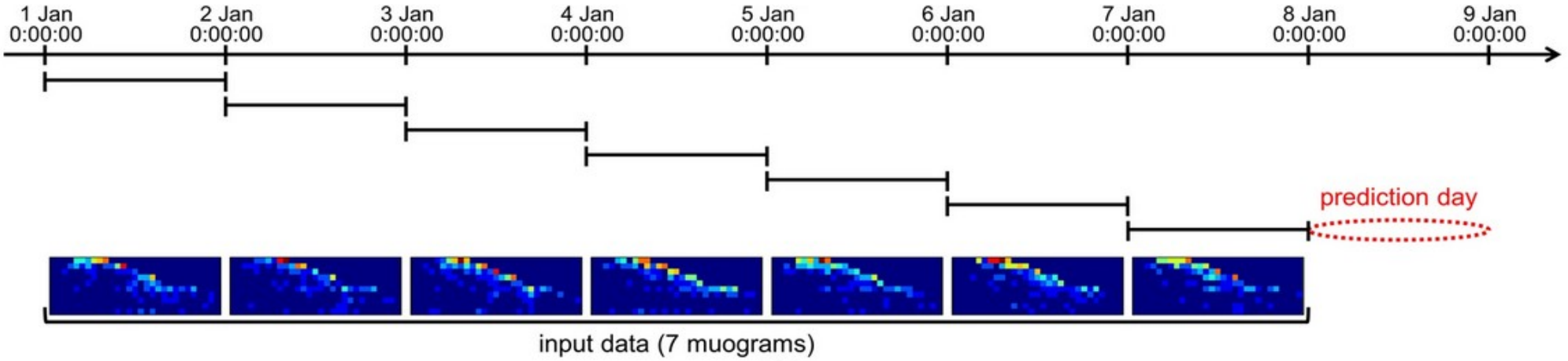


Muographic image resolution:
23 mrad x 23 mrad → 60 m x 60 m



Cocept of the Study

This study applied the concept that was developed by Nomura et al. for forecasing of the eruptions of Showa crater and achieved a ROC AUC of 0.726 (https://doi.org/10.1038/s41598-020-62342-y) using the data collected with two scintillator-based tracking systems (https://www.nature.com/articles/s41598-020-71902-1) between 2014 and 2016.



The data collected by the MWPC-based tracking system for forecasting the eruptions of Minamidake crater were organized as follows.

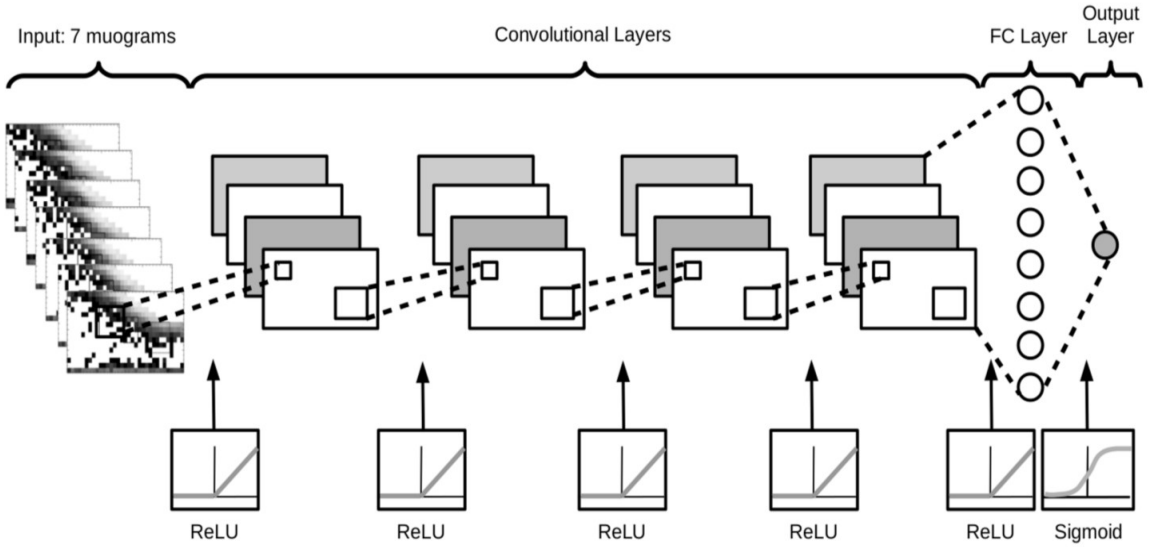
Training data: 394 days with 146 eruption days (only Minamidake erupted)
Validation data: 110 days with 48 eruption days (only Minamidake erupted)
Test data: 109 days with 56 eruption days (only Minamidake erupted)

Applied Software: scikit-learn version 0.22.1, Keras version 2.4.3 and Tensorflow version 2.3.0

Receiver Operating Characteristic (ROC) analysis was applied to determine eruption forecasting performances

Learning of Muographic Images with Convolutional Neural Network

- Application of a series of convolutional layers allows to reveal the hidden features of images on layer-by-layer basis, and fully-connected neurons can process the extracted features to predict the eruptions.
  A fix filter size of 3x3 was used in this analysis.
- CNN was trained using Adam method.
- The hyperparameters of the CNN model were tuned with Bayesian optimization and selected by ROC analysis.
  The Number of epochs was found to be 100 and number of early patience was found to be 10.



Region	Minamidake	Showa	Surface
Convolutional Layers	2	2	3
Filters on 1st Conv. Layer	16	64	8
Filters on 2nd Conv. Layer	64	32	8
Filters on 3rd Conv. Layer	-	-	4
Neurons on FC Layer	32	128	32
Dropout	0.215	0.313	0.332
Batch Size	16	8	32
Learning Rate	0.000448	0.002749	0.00002
Decay Rate	0.926	0.969	0.981

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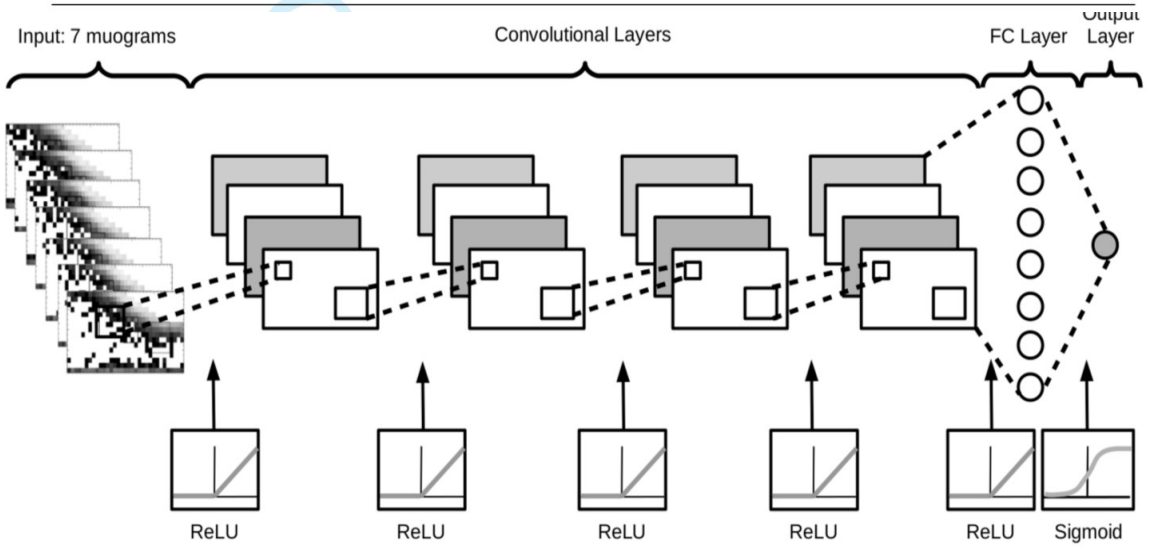
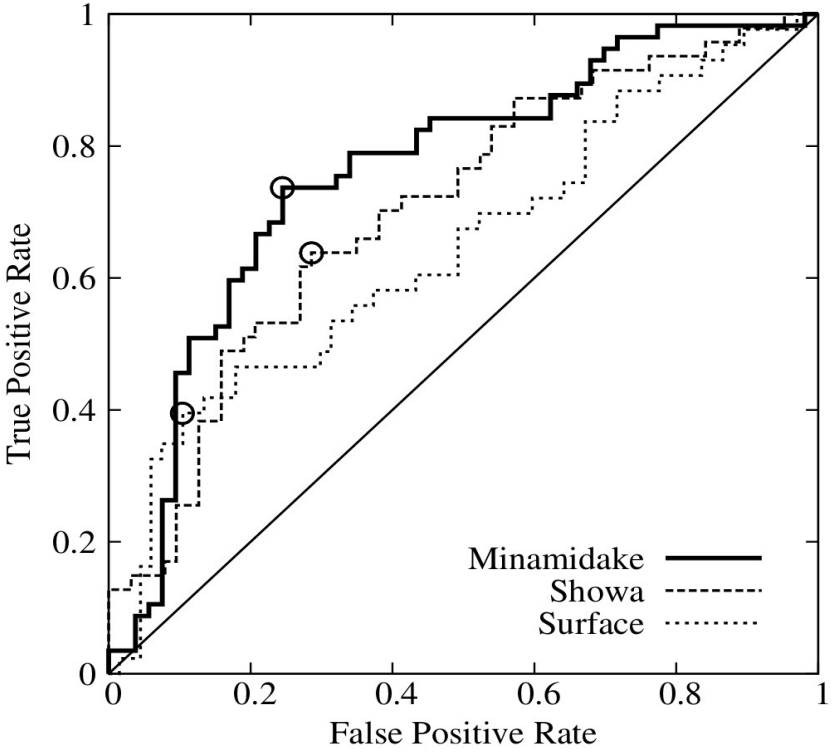
  A fix filter size of 3x3 was used in this analysis.
- CNN was trained using Adam method.
- The hyperparameters of the CNN model were tuned with Bayesian optimization and selected by ROC analysis. The optimal number of epochs was found to be 100 and number of early patience was found to be 10.
- Results of ROC analysis showed that CNN achieved a fair AUC of 0.761 in Minamidake from the eruptions occurred

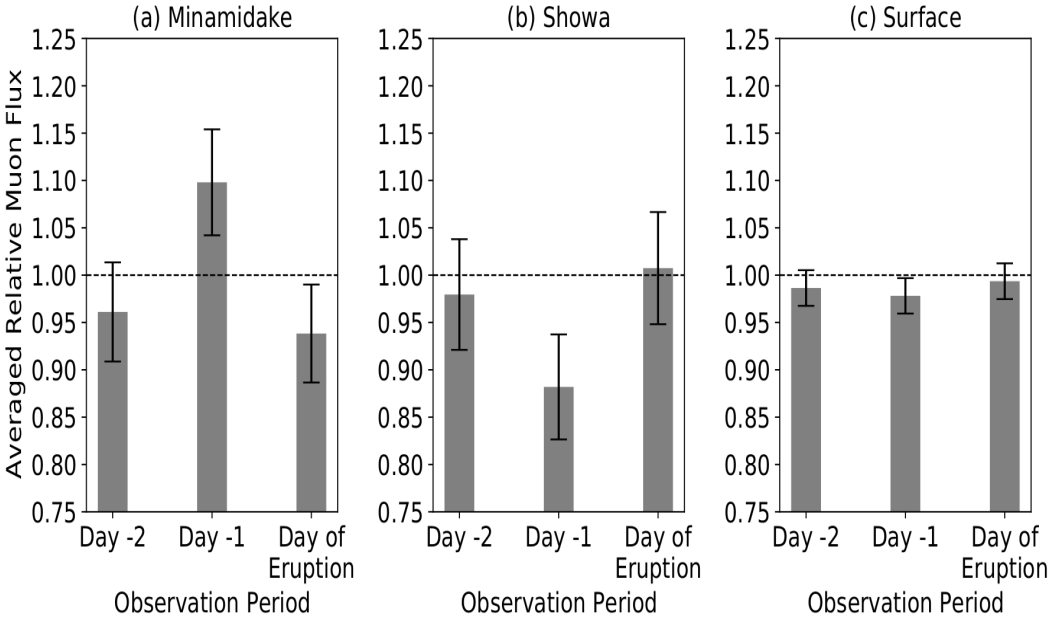
	Minamidake	Showa	Surface
Area Under the Curve	0.761	0.704	0.644
Sensitivity	0.737	0.638	0.395
Specificity	0.755	0.714	0.896





Discussion and Future perspectives

- **Comparison to the results of Nomura et al. (forecasting of Showa's eruptions with ROC AUC of 0.726) and this work (forecasting of Mindamidake's eruptions with ROC AUC of 0.761):** Despite the application of upgraded muography obsrevation system with enlarged (5 sqm → 8 sqm) sensitive surface area and higher angular resolution (33 mrad → 23 mrad), the forecasting performance was not drastically improved probably due to the following reasons:
  - smaller number of eruptions occurred in Minamidake (832) than in Showa (1432) that resulted in smaller amount of training data,
  - smaller amount of mass was transportated beneath the Minamidake than Showa that resulted in smaller variations in muographic images,
  - the geometrical difference between the two craters is also assumed to be an influencing factor.

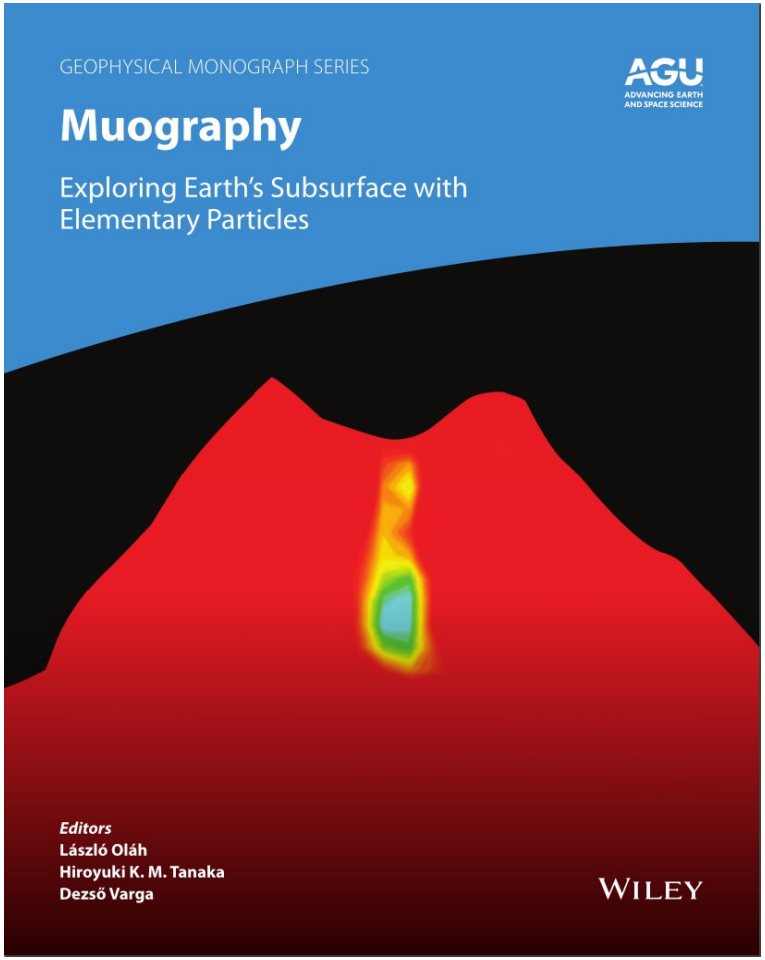


- **Future Perspectives:**
  - The upgrade of the MMOS is planned to collect more data → MAGMA
  - Recurrent Neural Network with Long-Short Term Memory is expected to improve forecasting
  - Integration of muographic data with other remote sensing data
  - CNN works as a black box function → Interpretable machine learning

VI. Summary

- MWPC-based Muography Obsevation System (MMOS) of Sakurajima Muography Observatory (SMO) is being under development in international collaboration since 2017
  https://doi.org/10.1038/s41598-018-21423-9

- **Volcanological applications with the MMOS:**
  - Monitoring of tephra deposition and erosion of volcanic edifice
    https://doi.org/10.1038/s41598-021-96947-8
  - Muographic imaging of plug formation beneath deactivated craters
    https://doi.org/10.1002/9781119722748.ch08
    https://doi.org/10.1029/2019GL084784
  - Machine learning of muographic data for volcano eruption forecasting
    https://doi.org/10.1002/9781119722748.ch04



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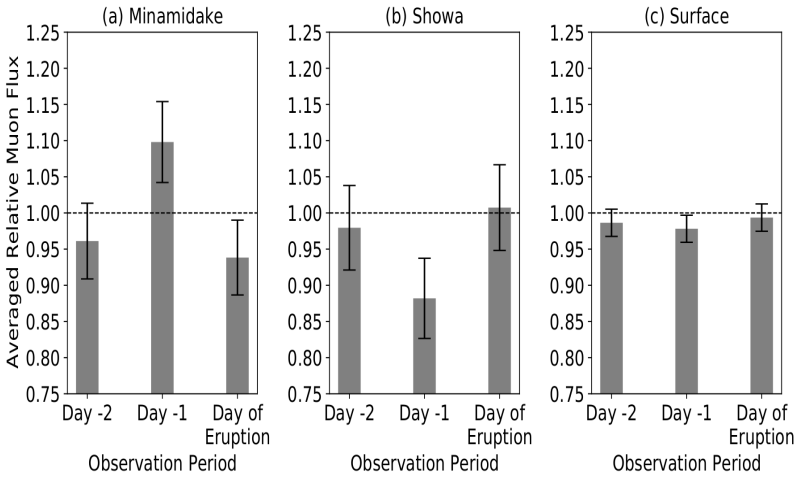
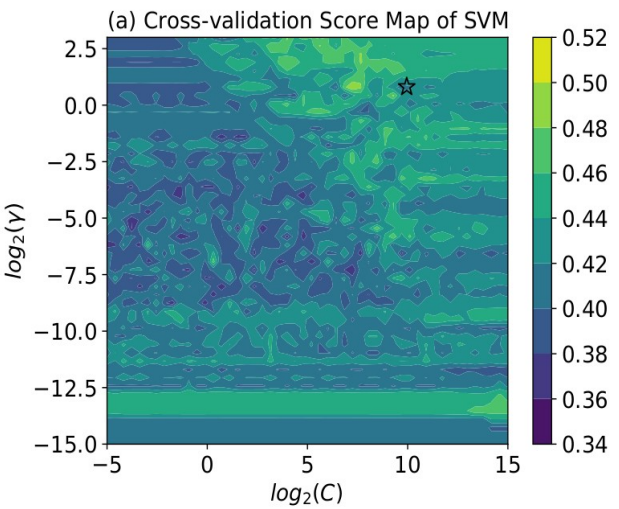
Thank you for your attention!

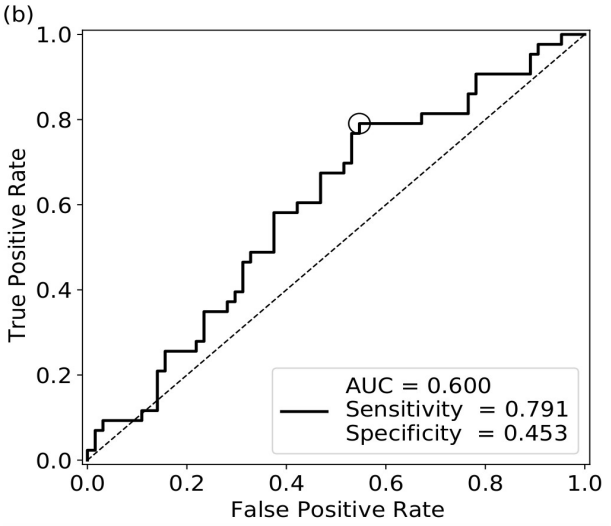
Backup Slides

Learning of Average Flux Values with Support Vector Machine

- Relative flux values were averaged for 16 turns: an increase above 2.5 sigma was observed 1 day before eruption hints the explosion of volcanic plug beneath Minamidake before eruption
- Support Vector machine with radial basis kernel (C and γ parameters) was trained with the average flux values and eruption labels from training data set
- Parameters were selected based on their cross-validation score: C=925.827 and γ=1.74564
- Results of Reciever Operating Characteristic (ROC) analysis using test data set:
  Moderate accurracy of 0.6 → SVM (and other ML models, e.g. ANN) can not capture the patterns created by uprision magma or plug explosion before the occurrence of volcano eruption

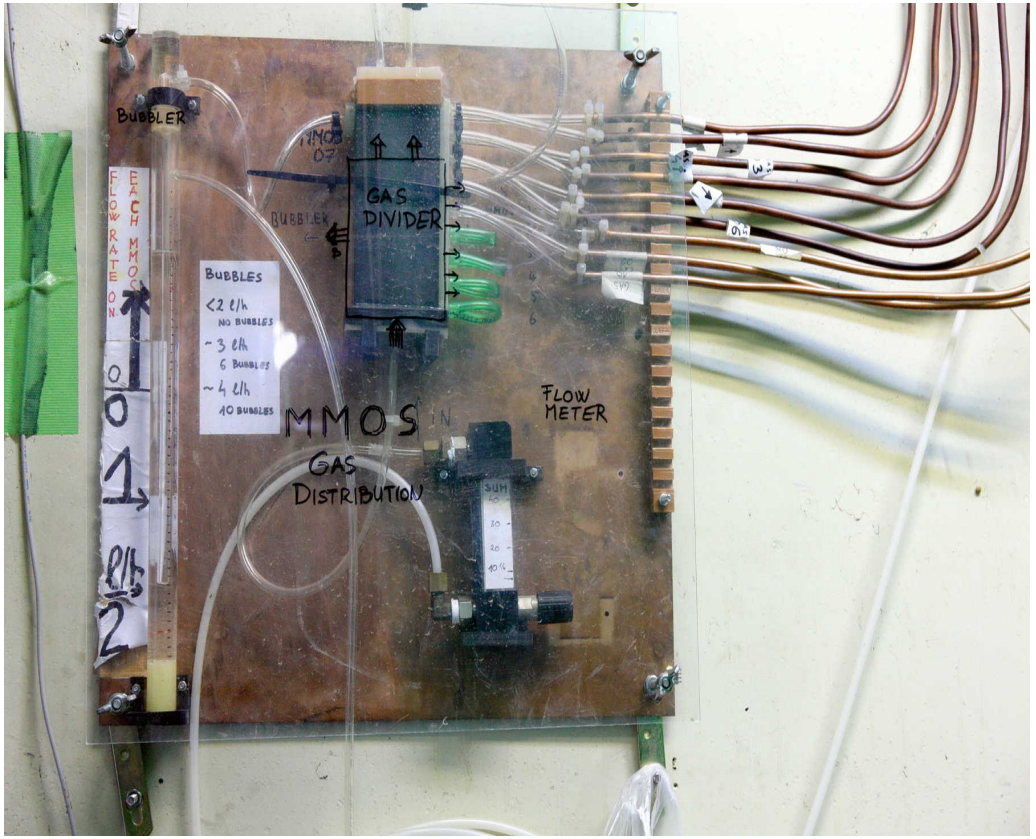






Gas System of MMOS

- Detector operation is provided by continuous flow of non-flammable, non-toxic Ar-CO_2 gas mixture with a flow of 2 Liters/hour
- 3-5 months continuous operation by a cluster of gas bottles (a volume of 40 Liters at a pressure of 140 bars each)



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https://doi.org/10.1016/j.nima.2019.05.077

III. Automated Muographic Visualization Framework