Applications of HEP innovations of HUN-REN Wigner RCP for Earth Sciences and Geotechnics

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2 International Virtual Muography Institute, Global
3 The University of Tokyo, Japan
4 Muon Solutions Oy, Finland

30 May 2024

Outline

I. Motivation, Research Infrastructures and Instrumentation

II. Results of Volcano Monitoring

III. Geotechnics by Cosmic Muon Tracking

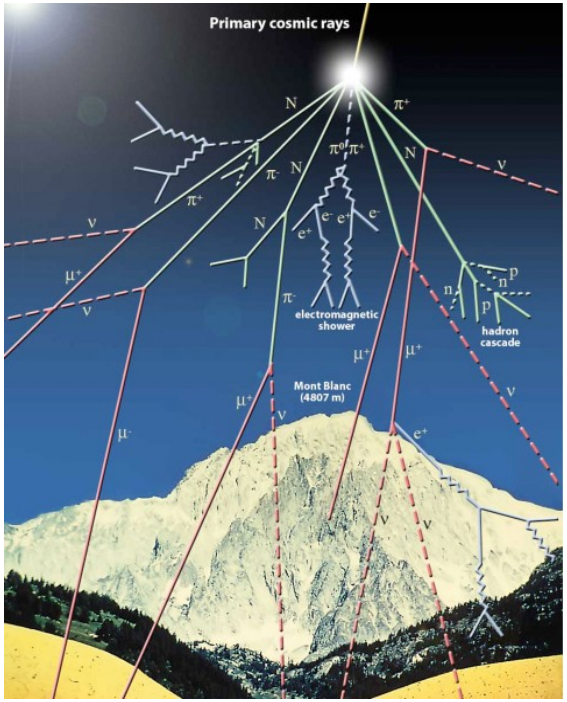
IV. Undersea Muography

V. Atmospheric Muography

VI. Summary and Future Perspectives

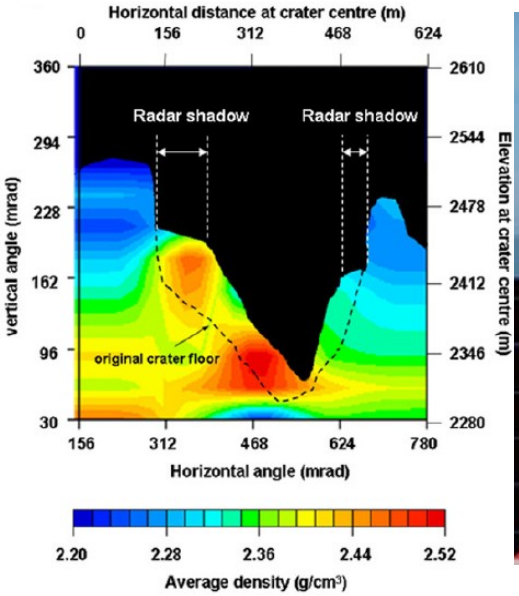
I. Motivation: Cosmic-ray Muon Imaging

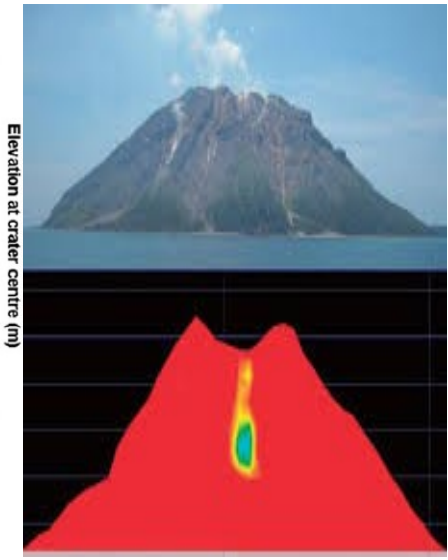
- **Cosmic-ray muons** continuously produced in the atmosphere and observed everywhere on Earth
- Muons are **highly penetrative particles** which reach down even a few km into Earth's subsurface.
- **Muography**: ”X-raying” of large structures (mountains, volcanoes, pyramids, nuclear reactors, etc.) via tracking of cosmic-ray muons → **non-destructive, non-invasive, passive imaging technique**
- Methodology of muography has been developed before mid 1960s (E.P. George, L.W. Alvarez et al.) but the imaging of large structures was achieved just in mid 2000s thanks to the development of detector technologies



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

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



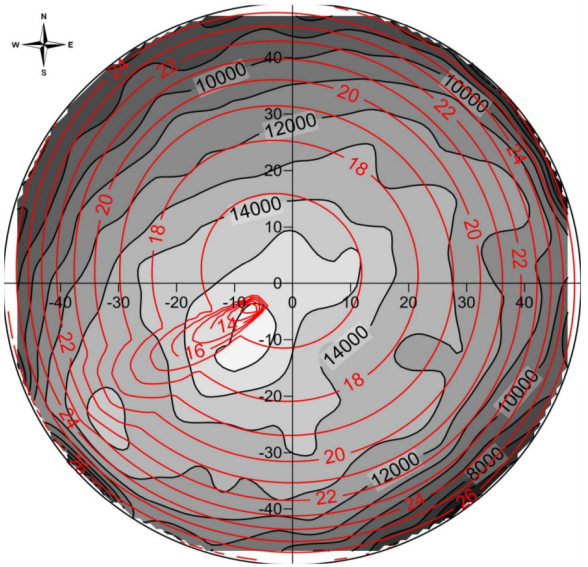


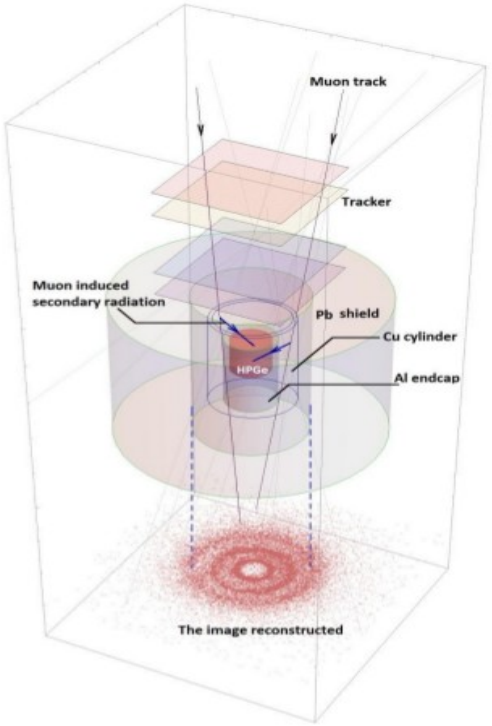
From HEP to Application Oriented Detector R&D

- **REGARD:** R&D of particle physics instruments for CERN experiments and muon tracking in HUN-REN Wigner RCP
- **The first applications of the portable muon trackers developed by Wigner RCP (2010-2017):**
  - Development of portable muon detectors for **cave search, tunnel inspection**, etc
  - **Measurement of cosmic background** in an underground astrophysical laboratory in Dresden, Germany
  - Development of a novel non destructive technique for **imaging of low-density materials** in collaboration with the University of Novi Sad, Serbia
- The **Momentum Grant of the Hungarian Academy of Sciences (PI: Dezső Varga)** supported our work since 2013

L. Oláh et al.:
Geosci. Instrum. Method. Data Syst., 1, 229-234, 2012, https://doi.org/10.5194/gi-1-229-2012
Advances in High Energy Physics, 2013, 560192, 2013, https://doi.org/10.1155/2013/560192
CERN-THESIS-2017-085 https://cds.cern.ch/record/2273649?ln=en
Astroparticle Physics 93, 17-27, 2017, https://doi.org/10.1016/j.astropartphys.2017.06.002

I. Bikit, D. Mrdja, K. Bikit, J. Slivka, N. Jovancevic, L. Oláh, G. Hamar, D. Varga:
Europhys. Lett., 113, 58001, 2016, https://doi.org/10.1209/0295-5075/113/58001
Europhys. Lett., 116, 48003, 2016, https://doi.org/10.1209/0295-5075/116/48003





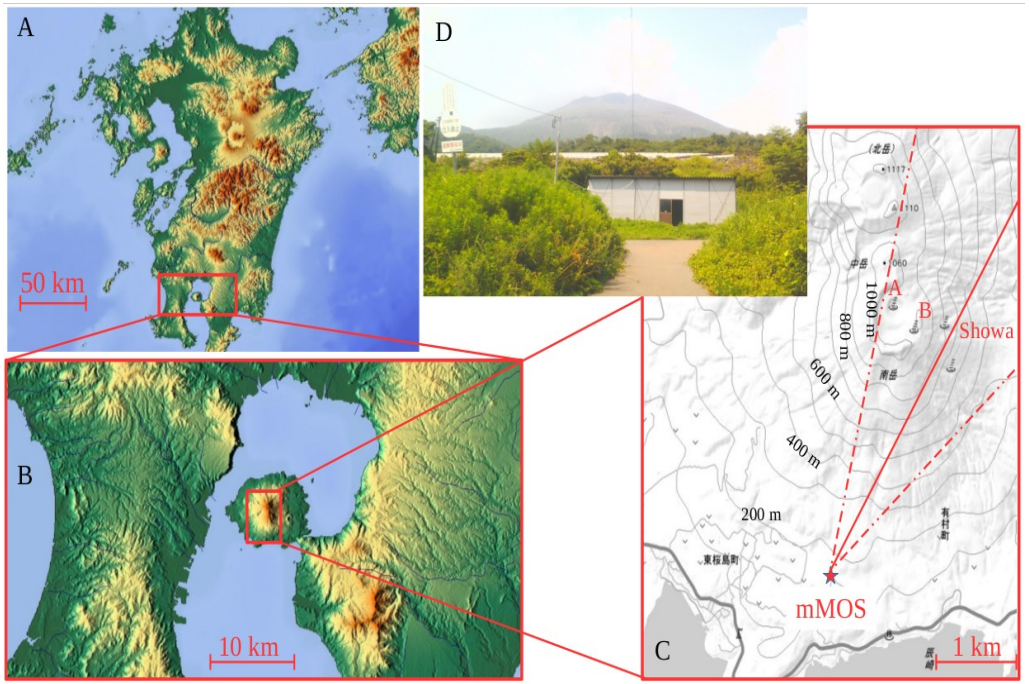
Research Infrastructures and Instrumentation

Vesztergombi High Energy Physics Laboratory (VLAB)
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

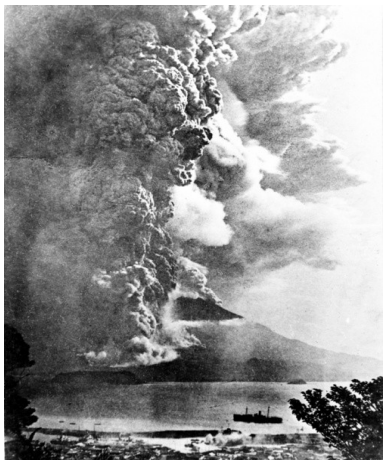
International Virtual Muography Institute (VMI)
→ framework for data storage, monitoring and simulation

I. Sakurajima Muography Observatory

- **Sakurajima is an active stratovolcano** on the "Ring of fire" within the Aira caldera in Kagoshima Bay, Kyushu, Japan
- Latest plinian eruption occurred in 1914 → Next large eruption is expected in 25 year 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**
- 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**



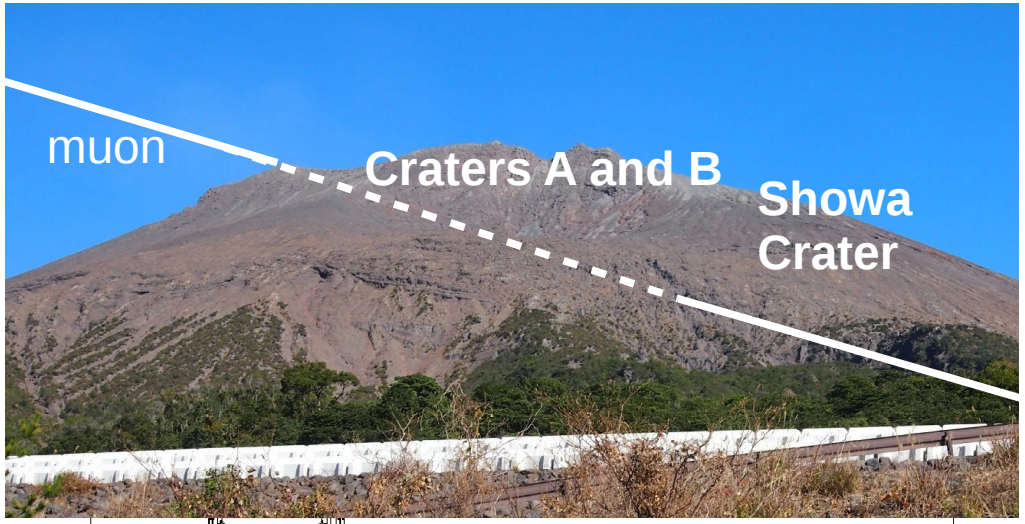
Source: https://doi.org/10.1038/s41598-018-21423-9

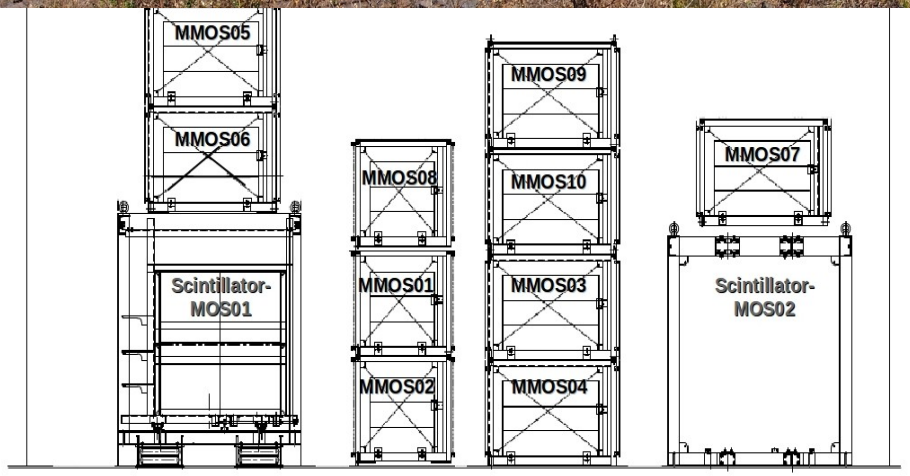


Source: Wikipedia

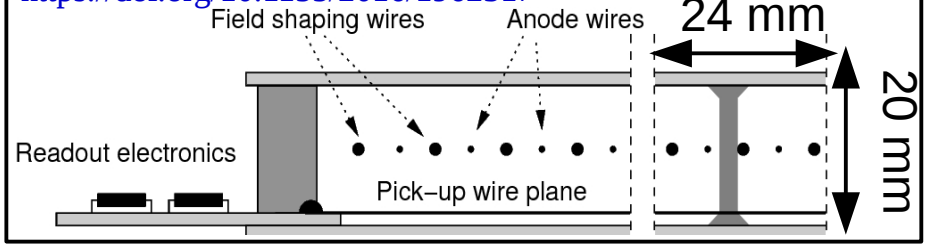
Source: Kimon Berlin, CC BY-SA 2.0

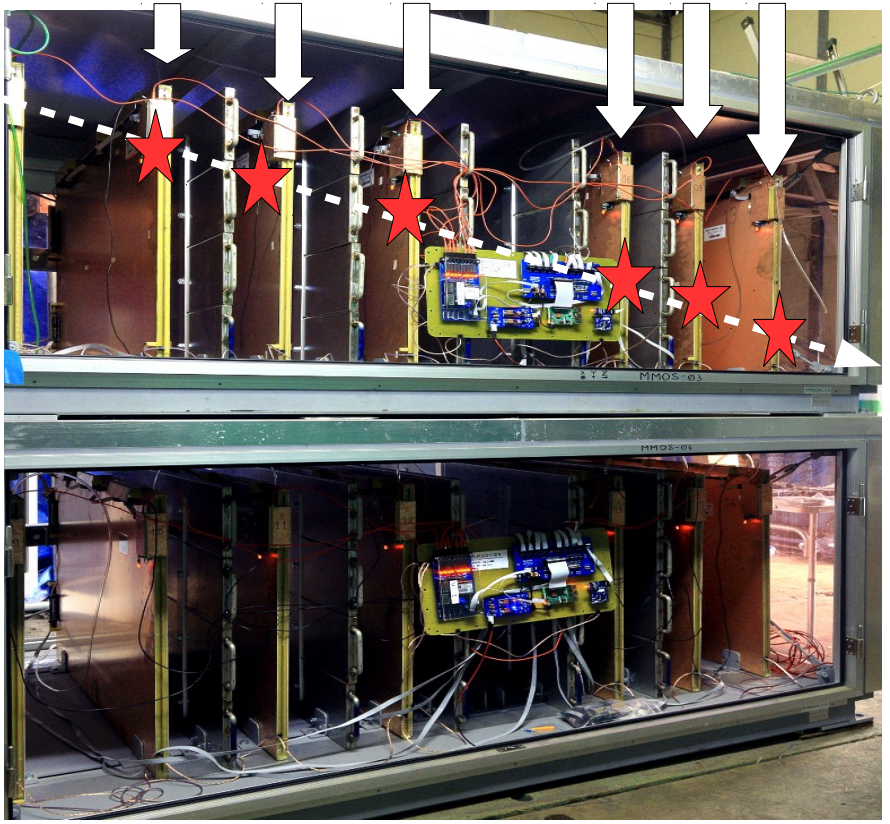
Muographic Observation Instrument (MOI)





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

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

Muograpic Observation Instrument WO2017187308
(patent is licenced by NEC and Muon Solutions)
https://patentscope2.wipo.int/search/en/detail.jsf?docId=WO2017187308

II. Results of Volcano Monitoring

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

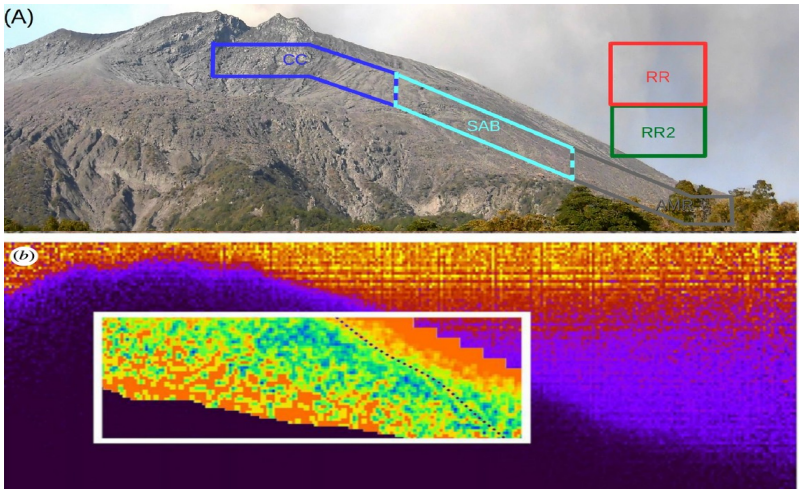
  L. Oláh et al. Scientific Reports, 8, 3207, 2018, https://doi.org/10.1038/s41598-018-21423-9

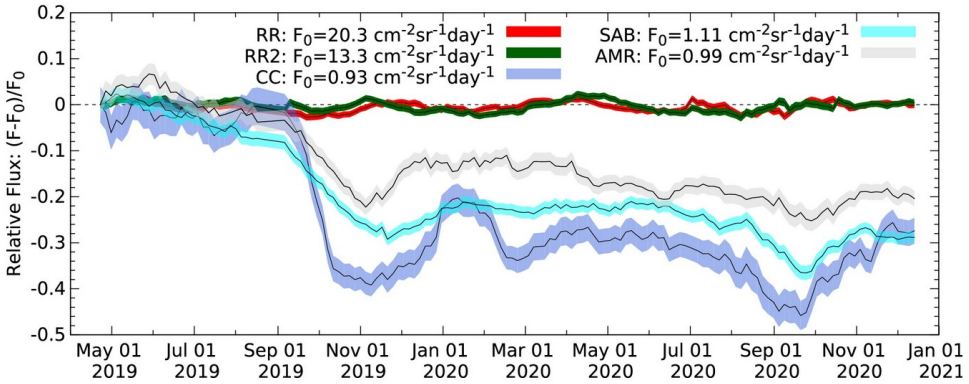
- Monitoring changes in the amount of materials on the volcanic edifice due to volcanic ejecta deposition, erosion and mudflows (lahars)

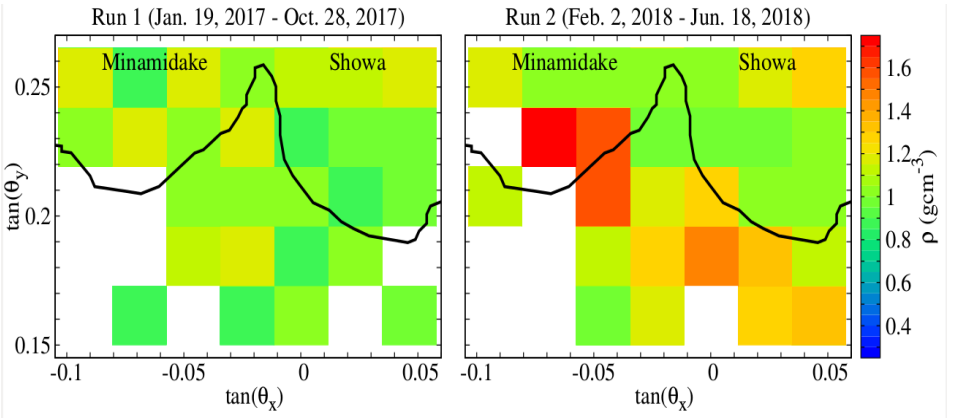
  L. Oláh et al. Scientific Reports 11, 17729, 2021, https://doi.org/10.1038/s41598-021-96947-8

- 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







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**

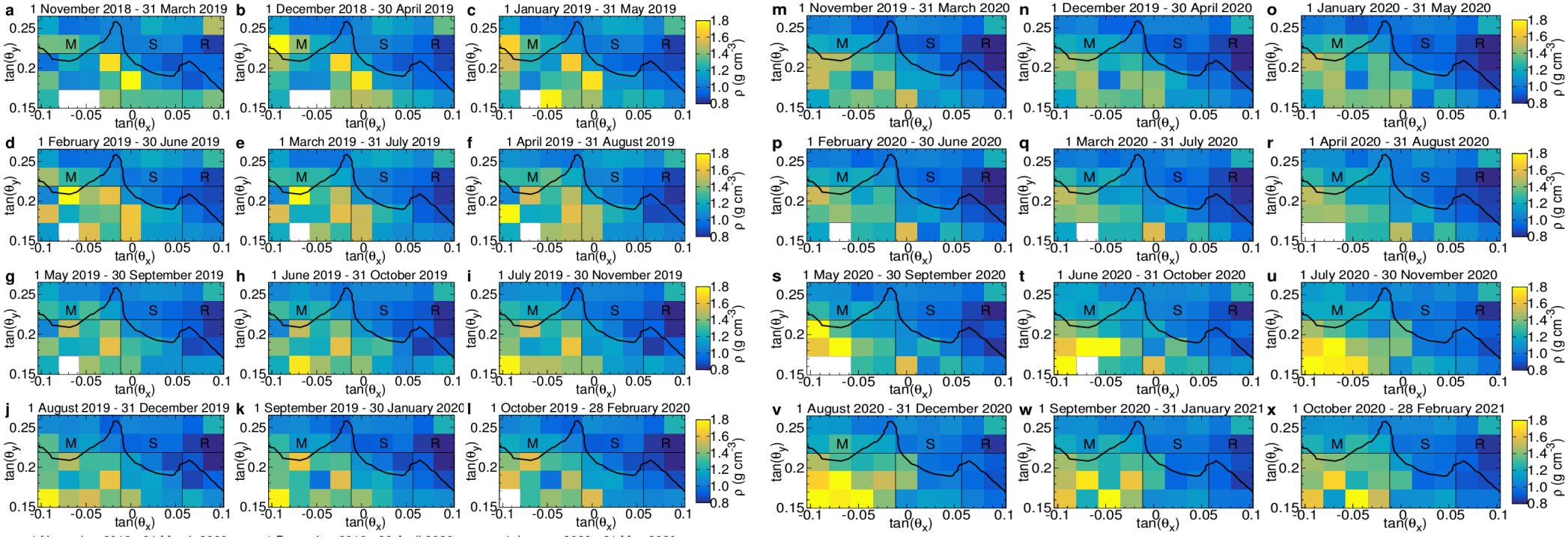
- **Aim: Revealing the causal physical mechanism of ground deformations (changing in the state of magma) via density monitoring with muography**

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

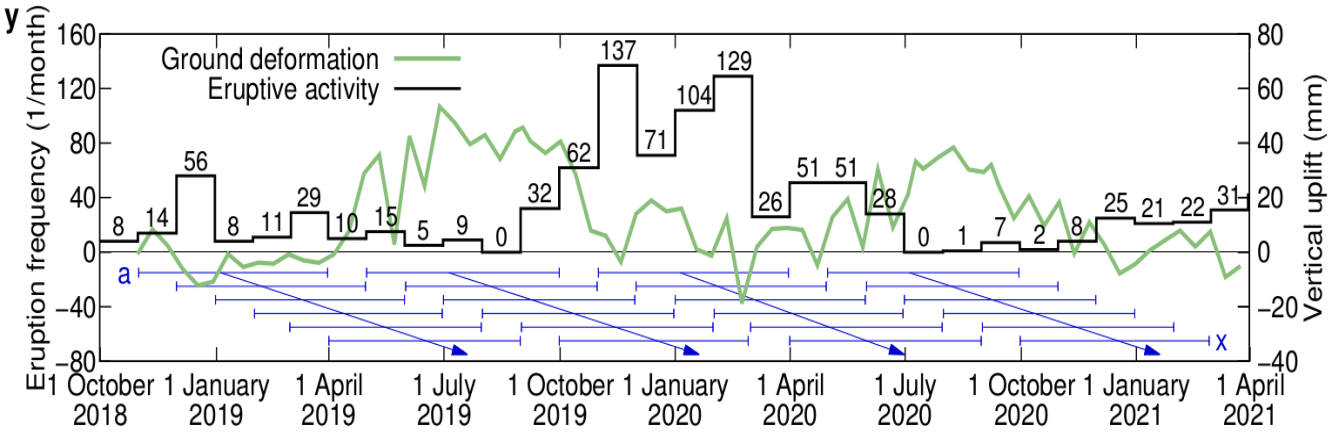
Systematic Coverage	Erupted	Non-Erupted
Deformed	DE 25 True positive	$D\bar{E}$ 29 False positive
Non-deformed	$\bar{D}E$ 9 False negative	$\bar{D}\bar{E}$ 135 True negative

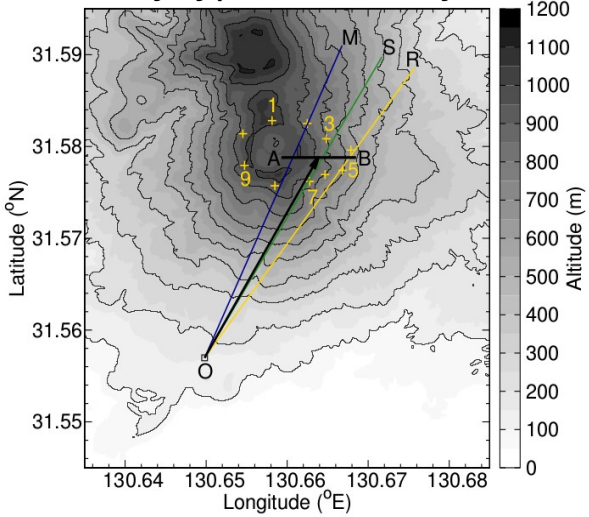
Muography and InSAR observations of Sakurajima

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.

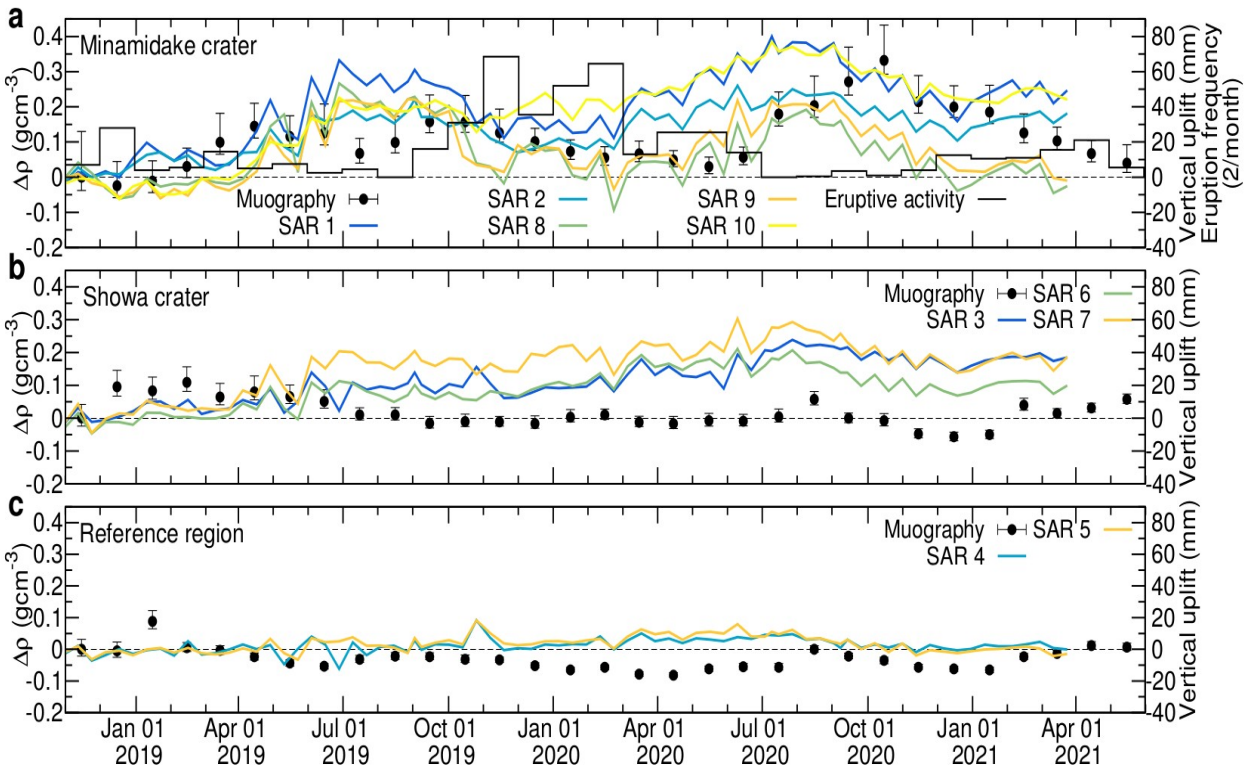




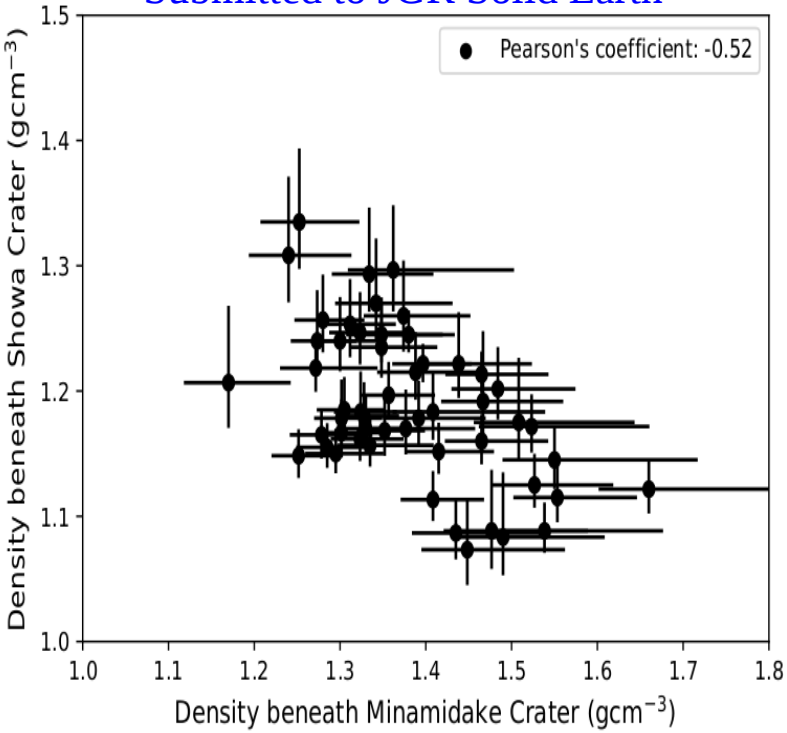
Volcanological Implications

- 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.**
- **An anti-correlation was found between the densities beneath Minamidake and Showa craters**
- **Eruptive activity and density changes suggest a branched connection between the conduits of the two active craters**

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



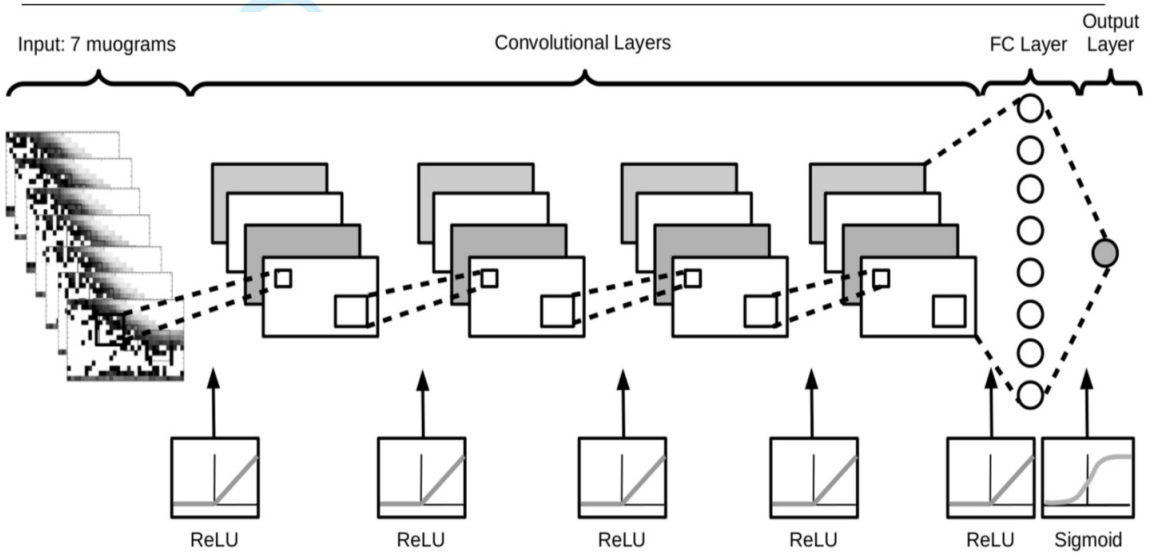
Submitted to JGR Solid Earth

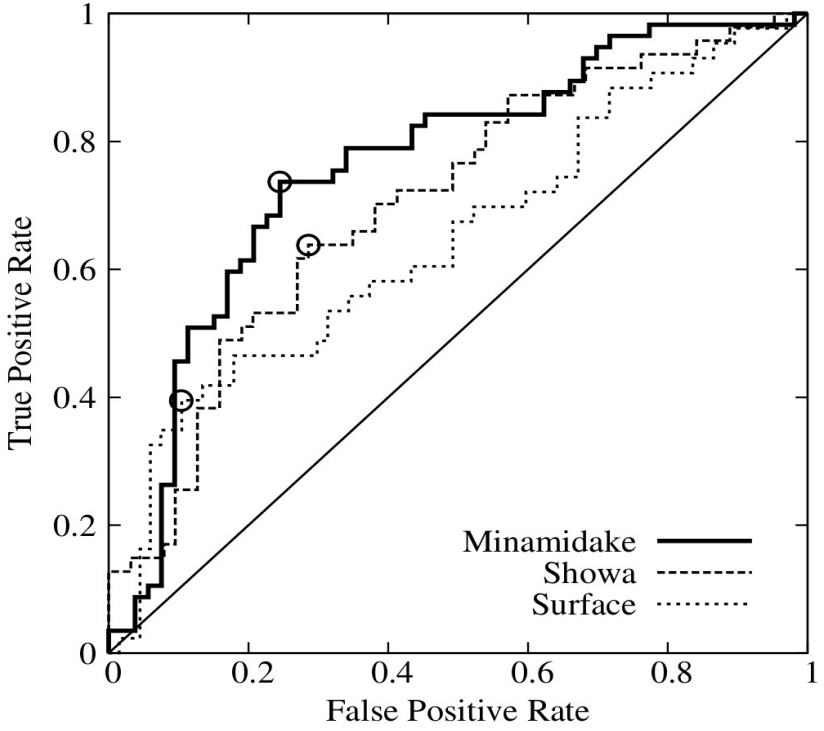


Towards Short-term Eruption Forecasting via Machine Learning of Muon Images

- 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

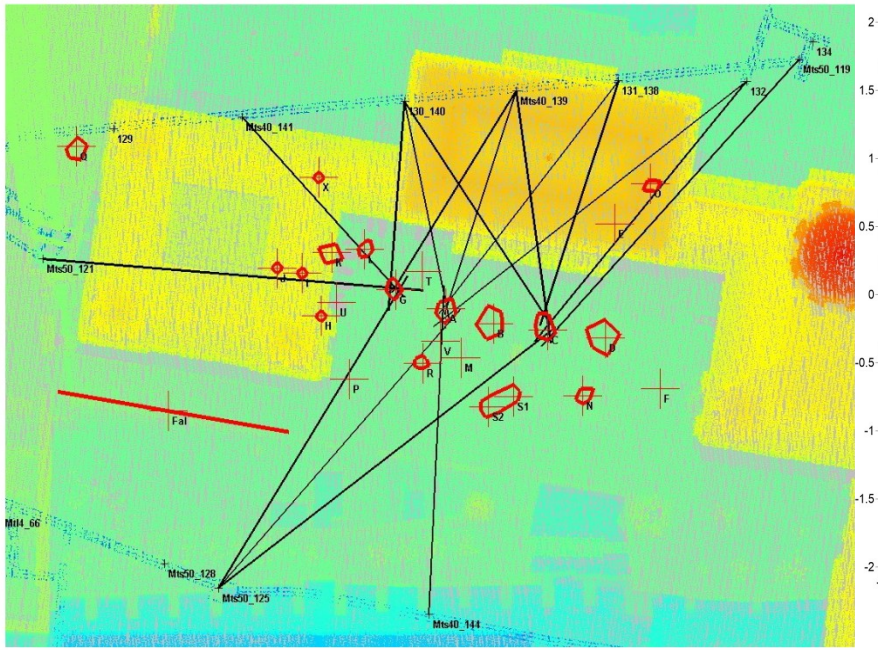




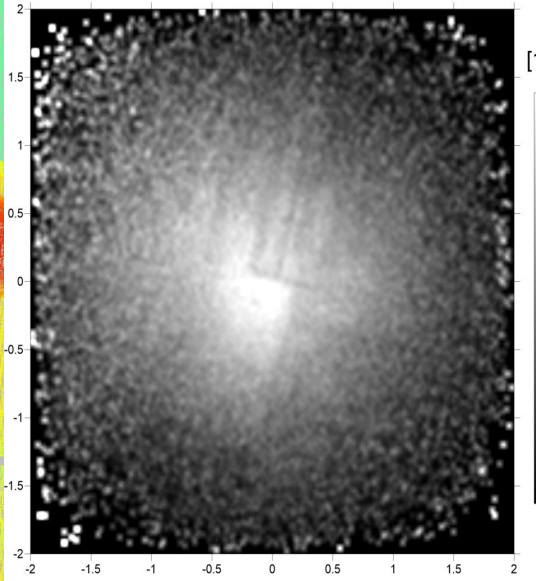
III. Geotechnics by Cosmic Muon Tracking

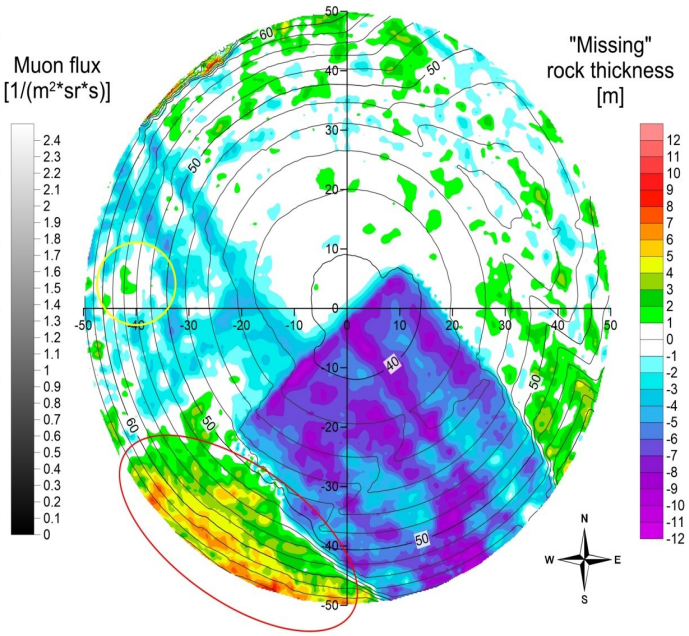
Civil engineering (Slide from D. Varga)

Searching for subsurface rock density anomalies at Buda Royal Palace, Budapest, Hungary by G. Surányi et al.



Detector coordinate system

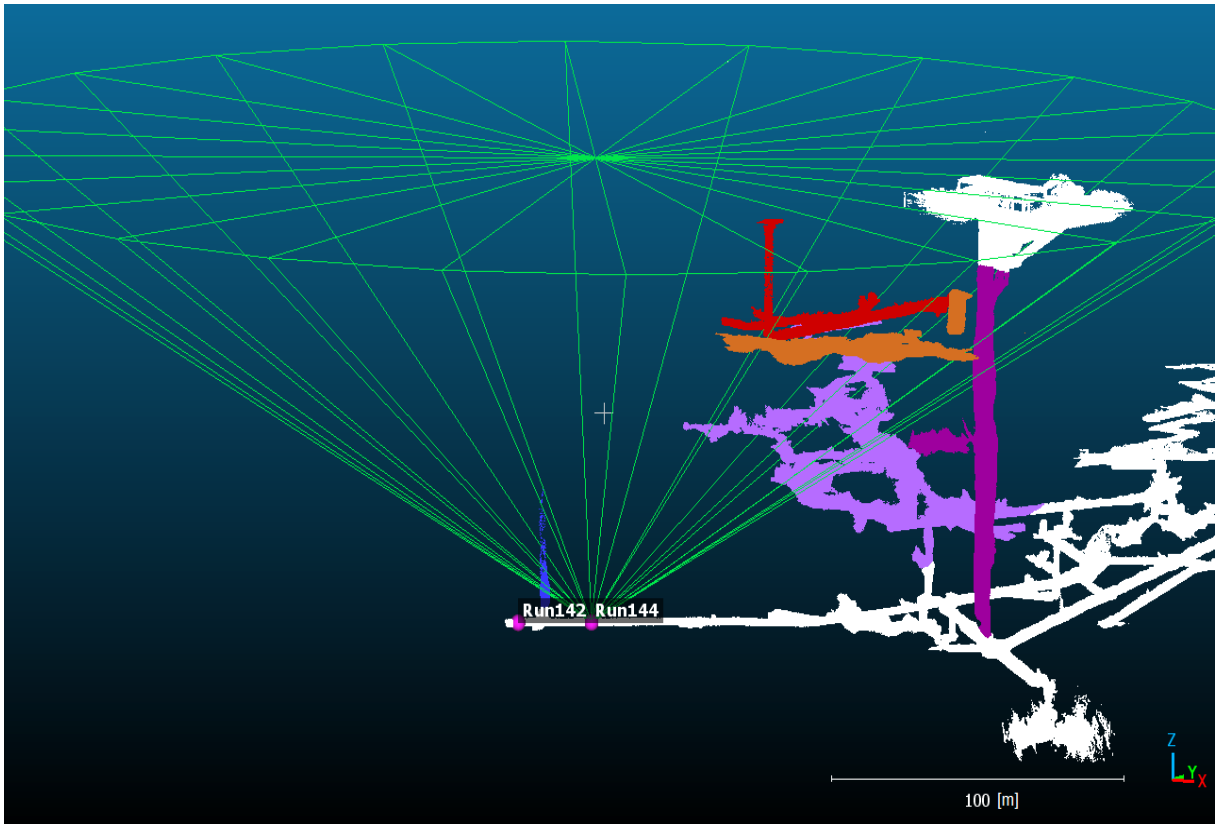


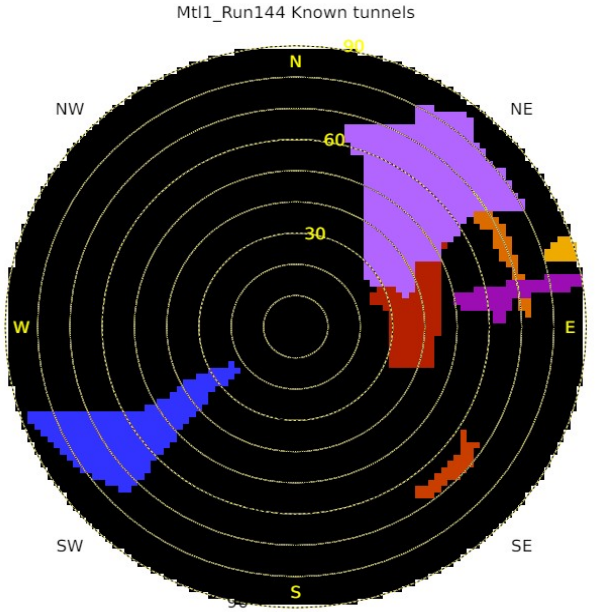


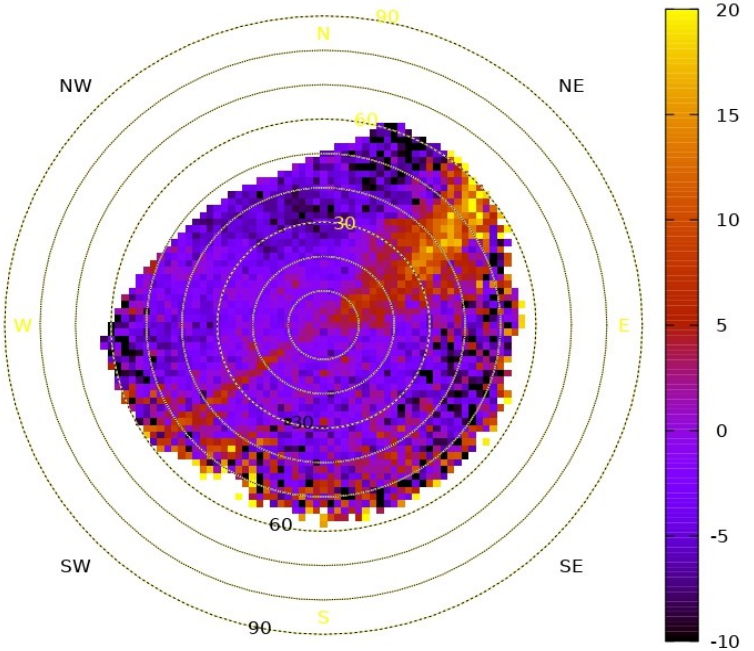
Geographical polar coordinate system

Contributions to Mining Industry (Slide from D. Varga)

- “Esztramos”: abandoned iron / limestone mine in north-eastern Hungary
- Non-collapsed, suspected tunnel
  → mine recultivation, unknown structures





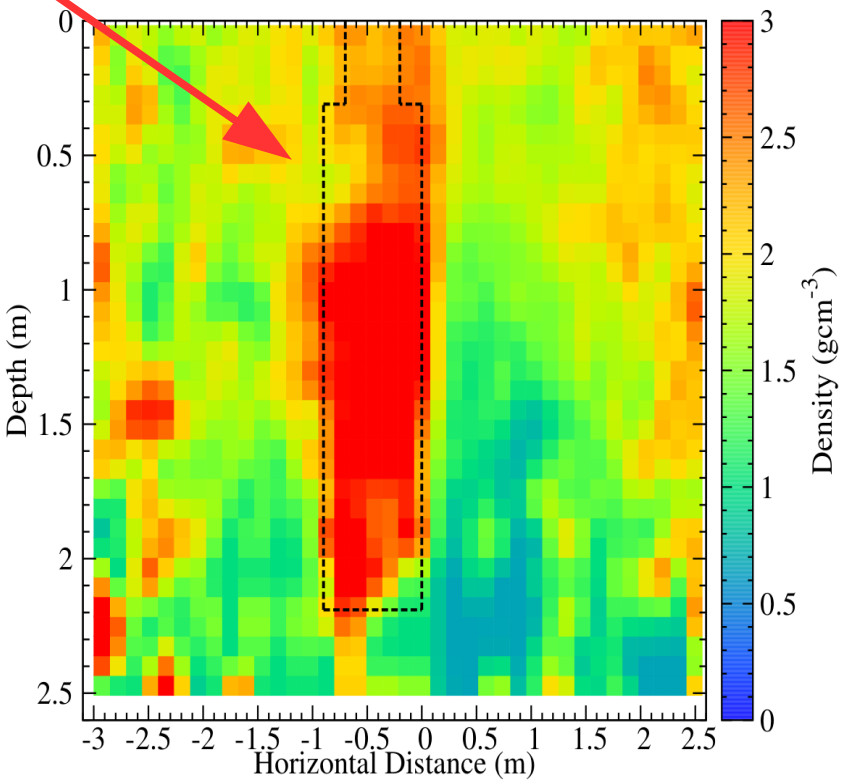


Muography of a buried concrete railway pillar by NEC, University of Tokyo and HUN-REN Wigner RCP

- Blind test of a buried railway pillar
- Few days of data collection from Drilling holes or shafts
- Muography revealed the location of the bottom of the pillar with a precision of 10 cm

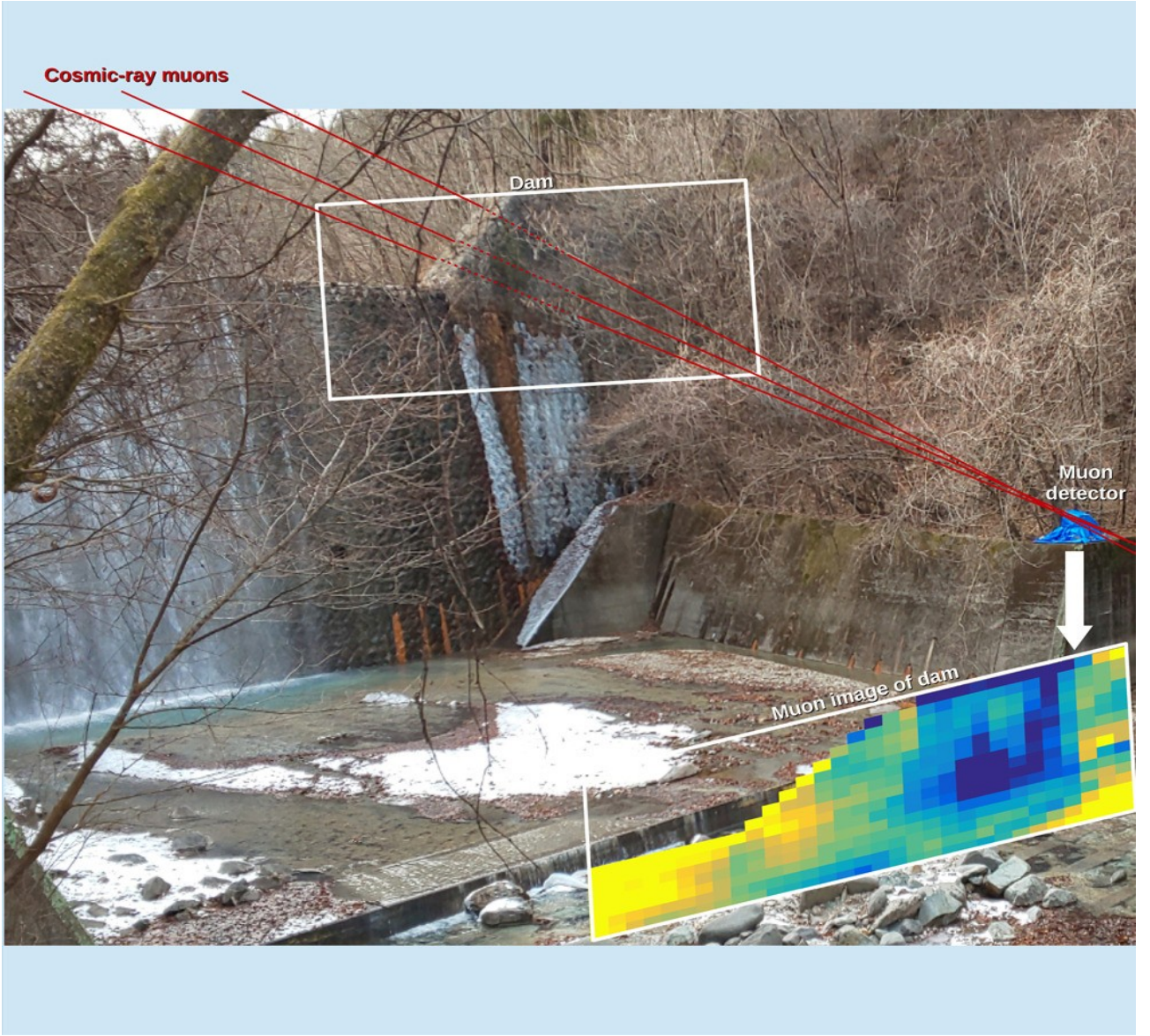
Undeground state observation device JP2020085732A
https://patents.google.com/patent/JP7269595B2/en

Oláh et al.: Geophysical Exploration 71, 161-168
https://doi.org/10.3124/segj.71.161



Muography of Sabo Check Dams by Sabo FF, University of Tokyo and HUN-REN Wigner RCP

- **Role of dams: stabilization, sediment retention, transport regulation**
- **Motivation of Sabo FF: inspecting dam structures for deciding about renovation or reconstruction**
- A Sabo Check dam was selected in the Karasu river, Gunma Prefecture, Japan.
  Detector location
- Data collection: **24th December 2020 – 2nd February 2021**, maintenance after 3 weeks for replacement of batteries and gas bottle
- **Significant density reduction was observed across the dam body where cement released out**

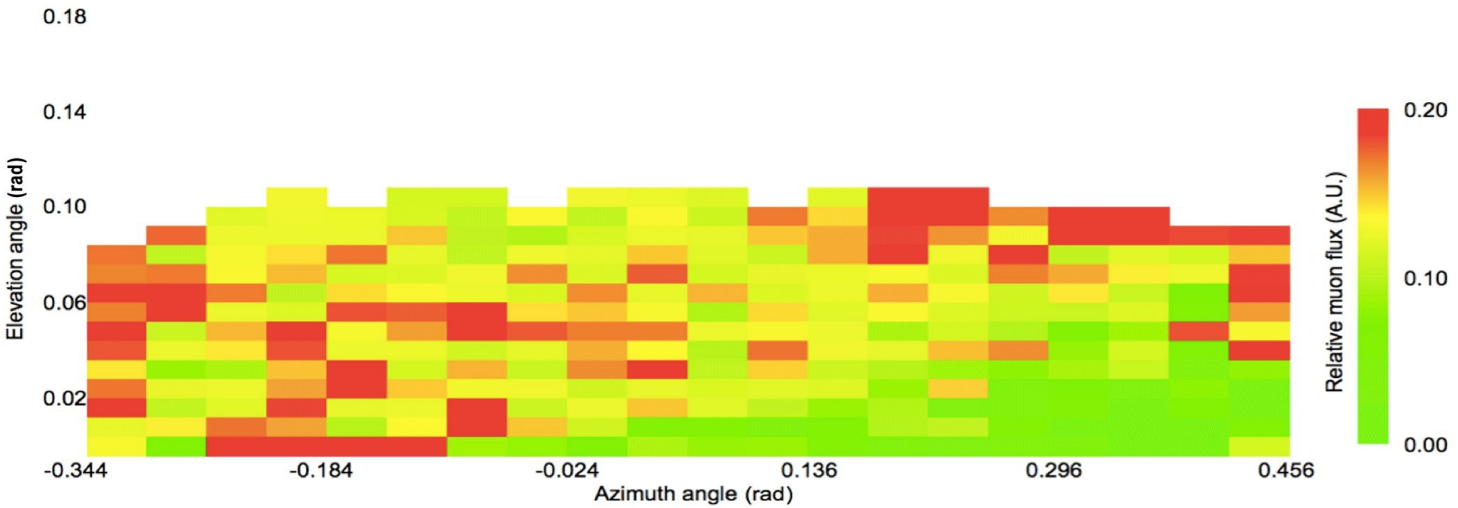


L. Oláh et al. (2023) iScience 26, 108019. https://doi.org/10.1016/j.isci.2023.108019

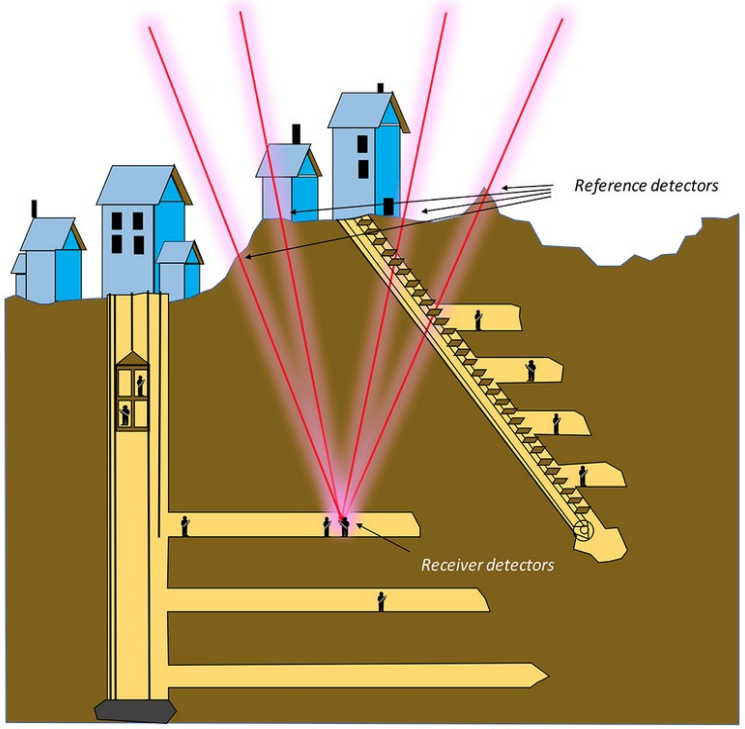
Searcing for Cracks in Burial Mounds

- Imaging the internal structure of Imashirozuka Kofun and investigating the how the 1596 Fushimi earthquake affected it

Tanaka, Sumiya és Oláh:
https://gi.copernicus.org/articles/9/357/2020/



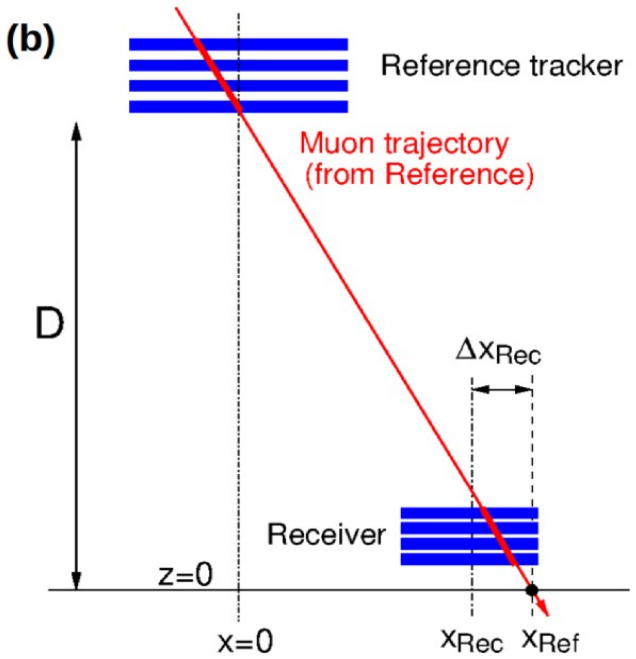
Muometric positioning

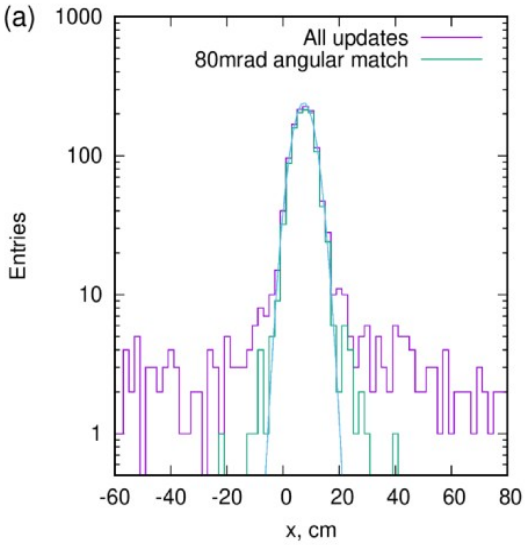


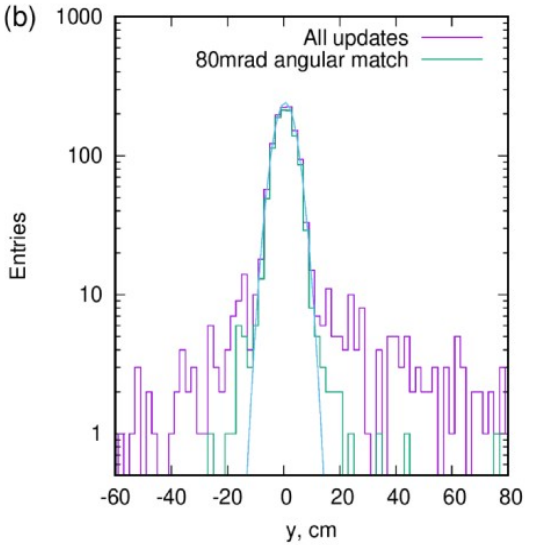
Navigation with muons in underground, underwater environments.

Unlike radio waves, acoustic signals, or laser beams, muometric positioning accuracy is not influenced by obstacles in its surrounding environment

- 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
- Tanaka, H.K.M. Muometric positioning system (muPS) utilizing direction vectors of cosmic-ray muons for wireless indoor navigation at a centimeter-level accuracy. Sci Rep 13, 15272 (2023). https://doi.org/10.1038/s41598-023-41910-y
- 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
- Submitted patent by Tanaka, Varga et al.

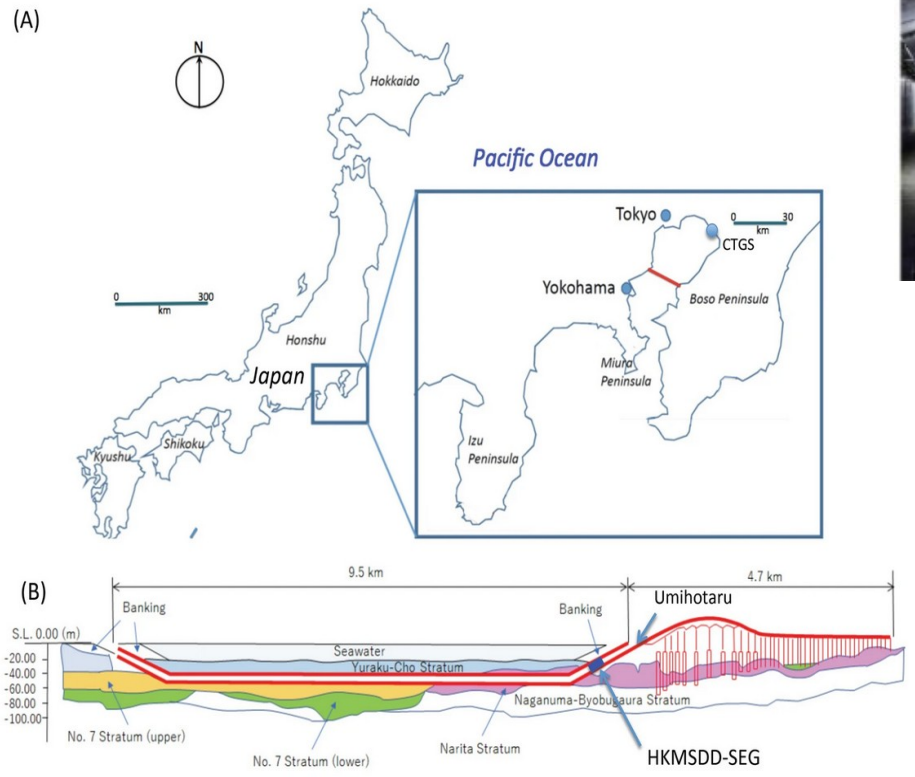


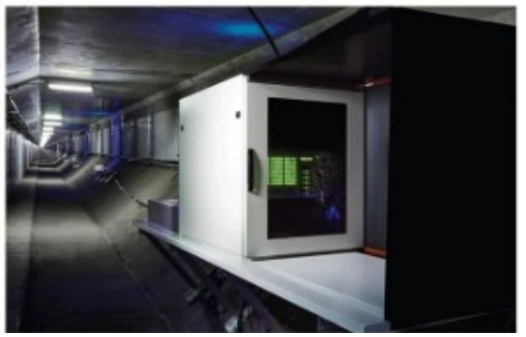


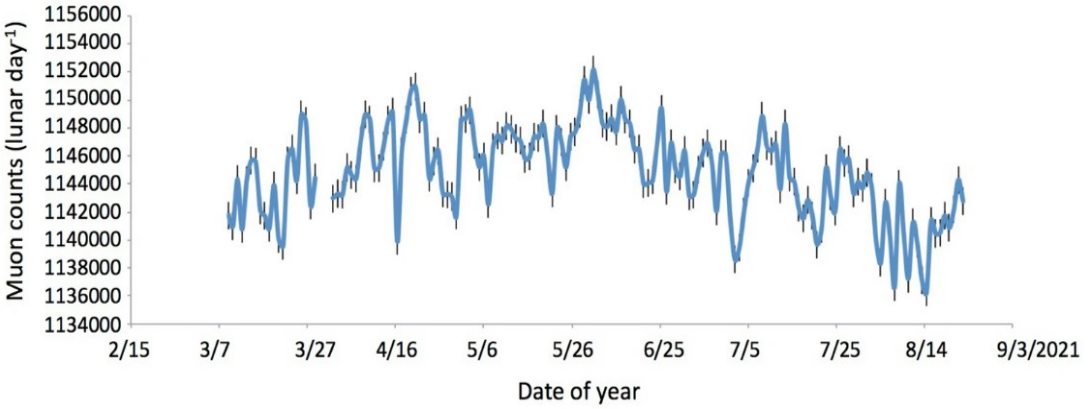


IV. Undersea Muography (HKMSDD)

Tanaka, Oláh, Varga, et al. Scientific Reports
https://www.nature.com/articles/s41598-021-98559-8
https://www.nature.com/articles/s41598-022-10078-2



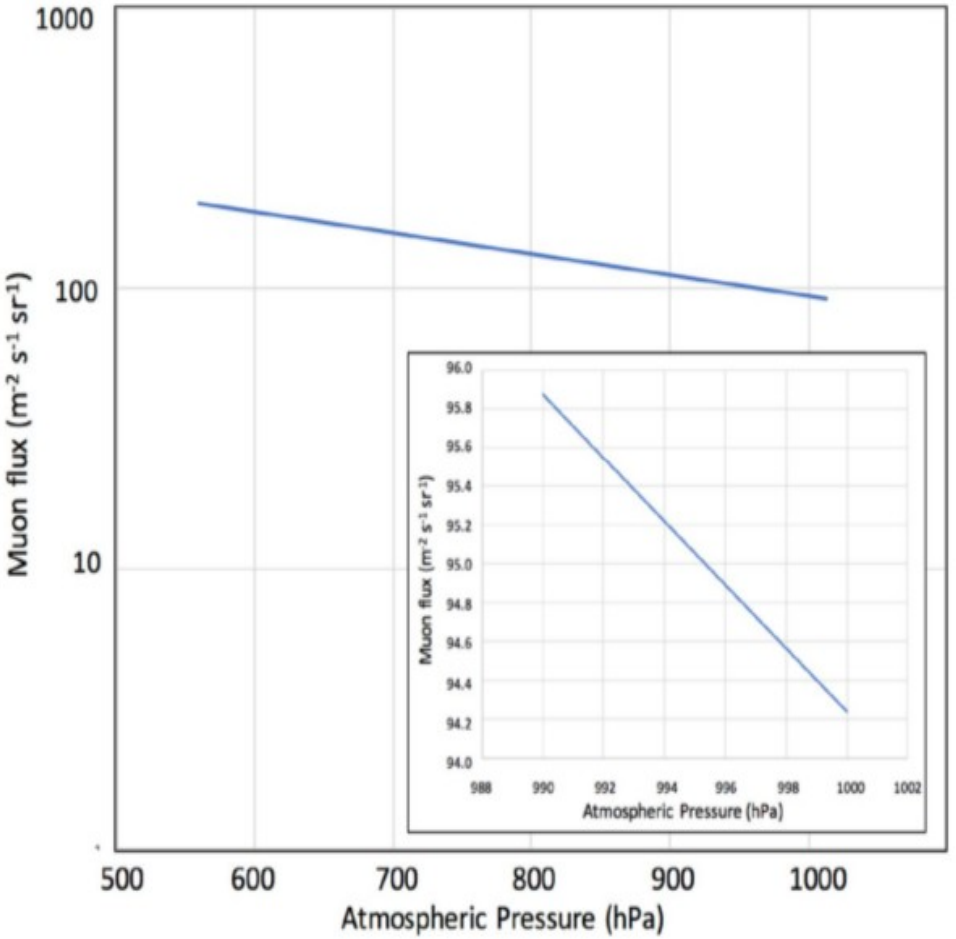


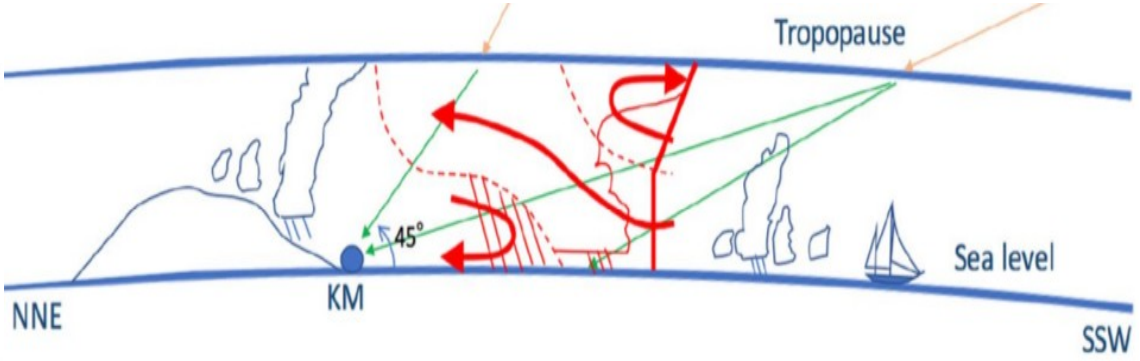


Detector system operated under the Tokyo Bay (HKMSDD):
- water level changes due to periodic effects, typhoons, etc.
- Application: protection of coastal areas with muographic alarm system

V. Atmospheric Muography

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

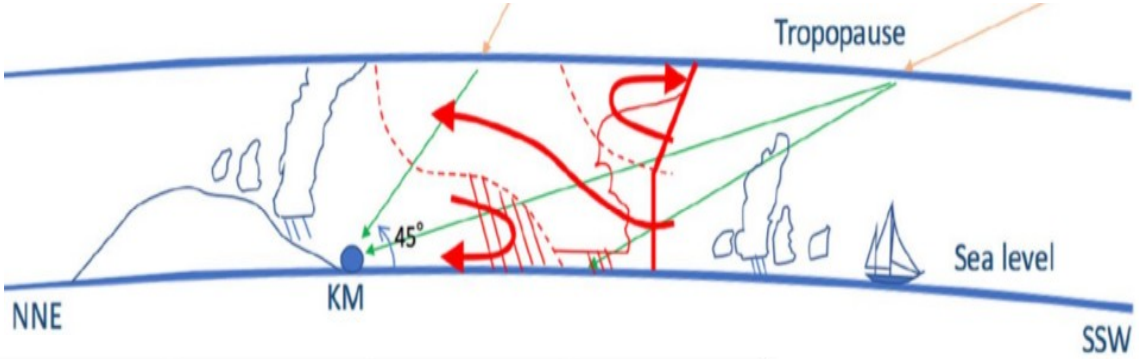
  → **muon flux is inversely correlated with atmospheric pressure**

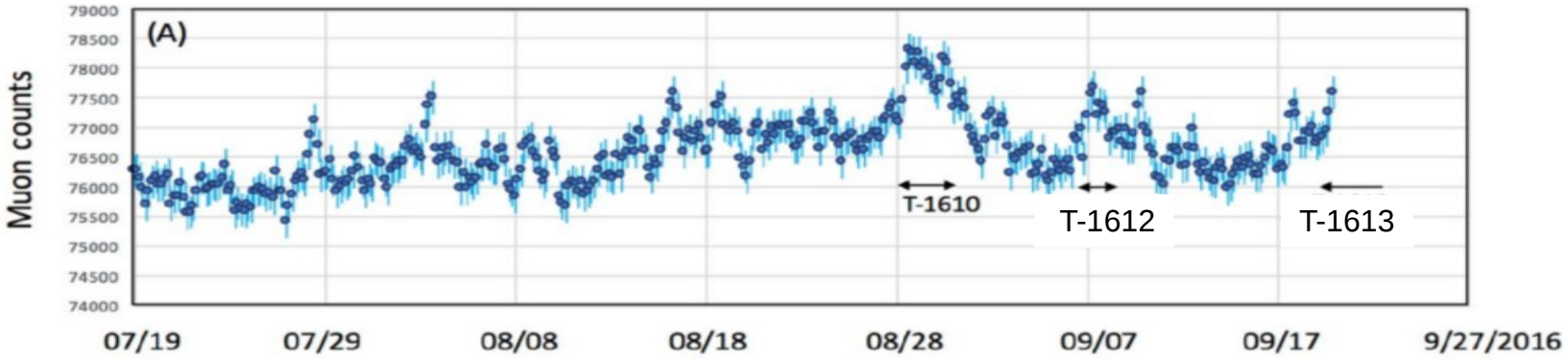
  (e.g., 1 % pressure drop result in 2 % flux increase)

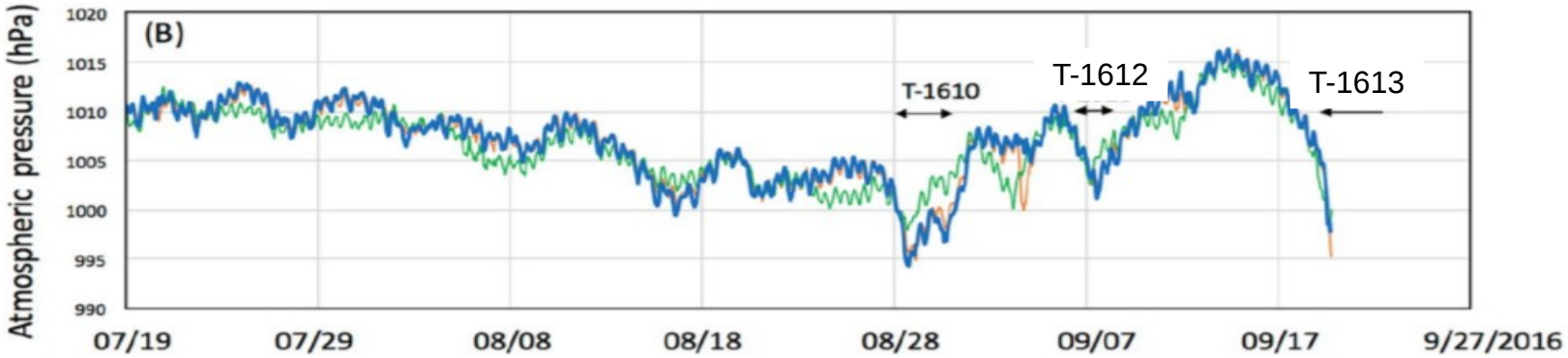
Muography of Typhoons

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

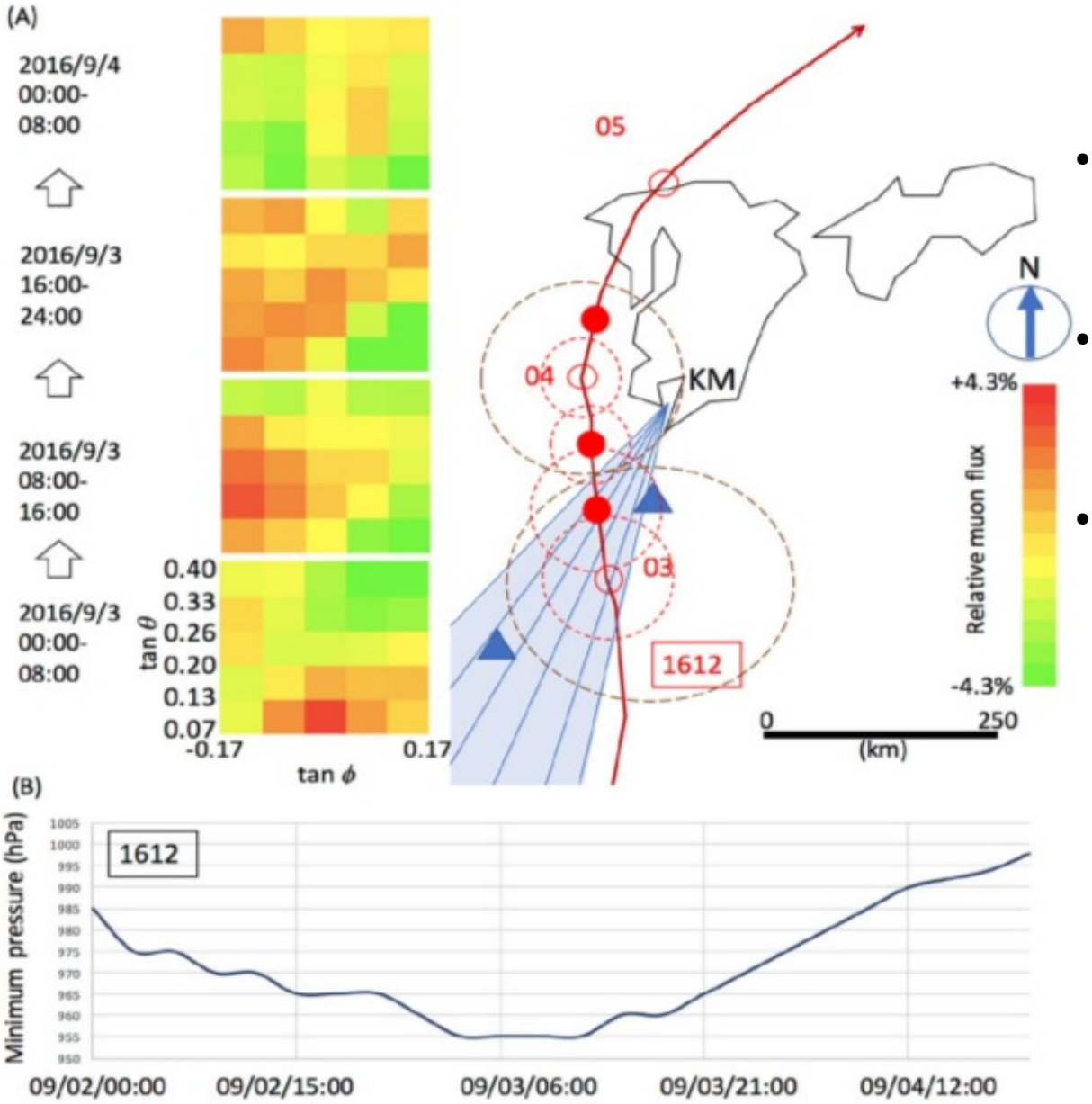
- Scintillator-based MMOS of SMO was applied to measure the muon flux between zenith angles 45 deg and 90 deg
- Muon counts increased during typhoons







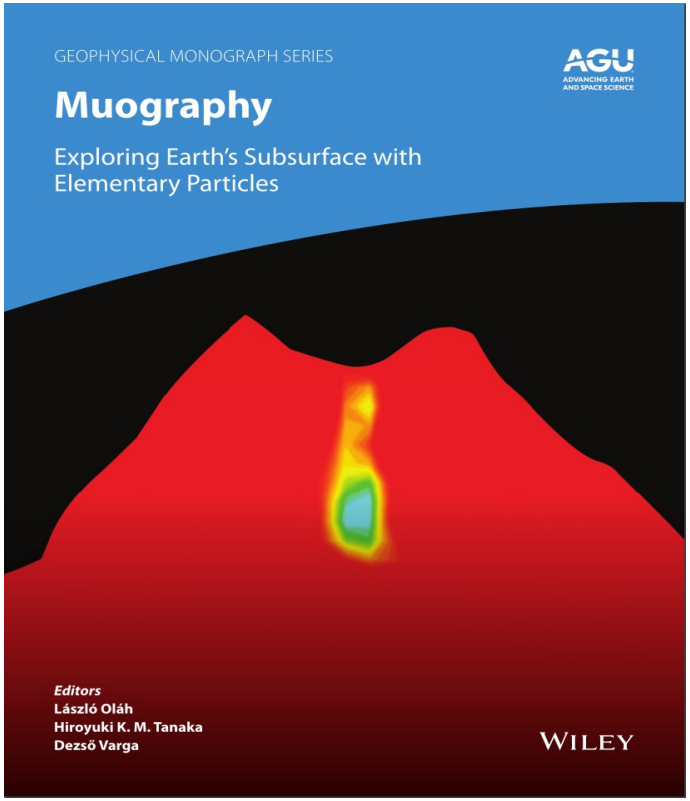
Time-sequential Muographic Images



- 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**

VI. Summary and Future Perspectives

- Muography is a non-destructive passive imaging technique that allows "X-raying" of large structures
- Progress in technological development in intersectoral collaborations can contribute to achieve resilient cities (volcano and infrastructure monitoring, muometric positioning) and sustainable resource exploration (underground muography).
- **Future perspectives:** expanding muography from large-scale solid structures to aqeous (sea, lake, etc.) and atmospheric (tropical cyclone) bodies



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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Thank you for your attention!