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From HEP experiments to industrial applications : a roadmap for muography

Jacques Marteau | IP2I (CNRS, UCBL) | Muographers 2026

MUOGRAPHY USE CASES

Muography = transmission/scattering imaging technique → sensitive to (scattering) density + Z/A

Geosciences

- Volcanology
- Geology
- Hydrology
- Atmosphere physics
- CR physics
- ...

Archaelogy

- Pyramids
- Tumulus
- Anthropic structures
- Ruins
- ...

Industrial controls

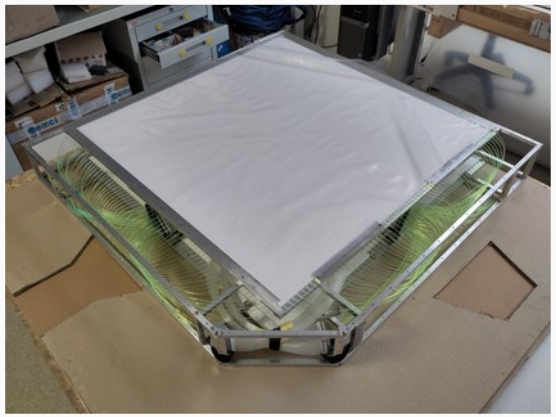
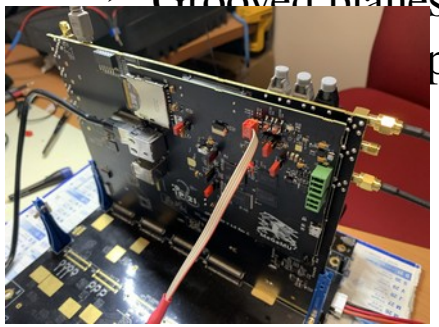
- Non invasive controls
- Nuclear cycle production
- Civil engineering
- Tunnel boring machines
- Prospection & mining
- ...

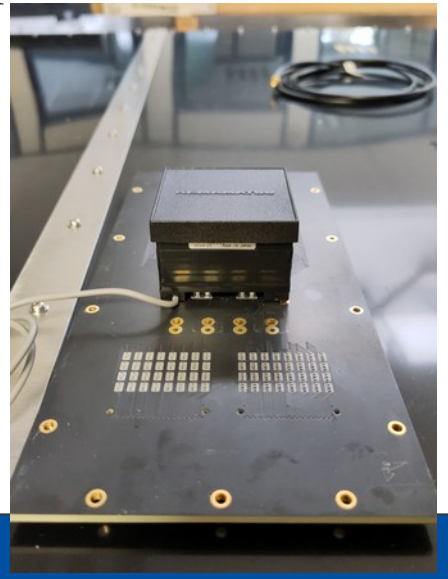
FROM HEP DETECTION TECHNIQUES TO FIELD EXPERIMENTS

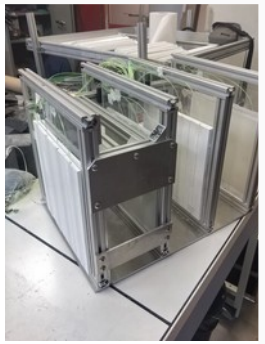
- **Muon trackers optimization :**
  - Increasing the spatial segmentation with constant channel numbers
  - Multiplexing strategy
  - Hybrid detection methods : Micro-Megas (MM) & Scintillators (SC)
  - Water Cerenkov prototype

- **R&D**
  - 3D printed scintillator matrix
  - Staggered scintillator bars
  - Grooved planes
  - pto-electronics readout chain



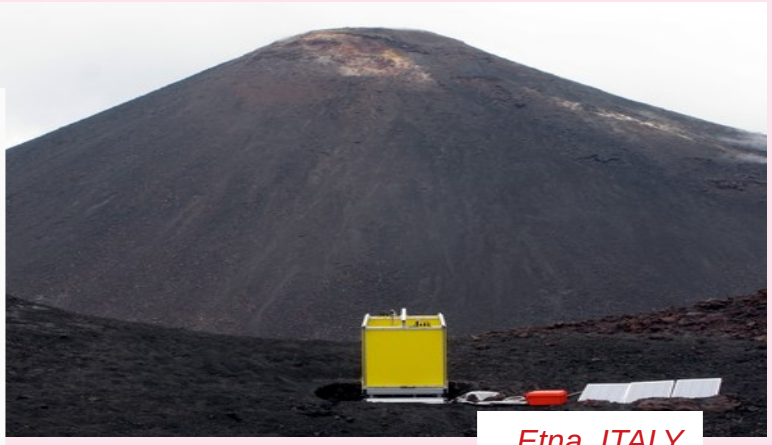





OPERA EXPERIMENT

La Soufrière de Guadeloupe, FRANC

Copahue, ARGENTINA



Etna, ITALY

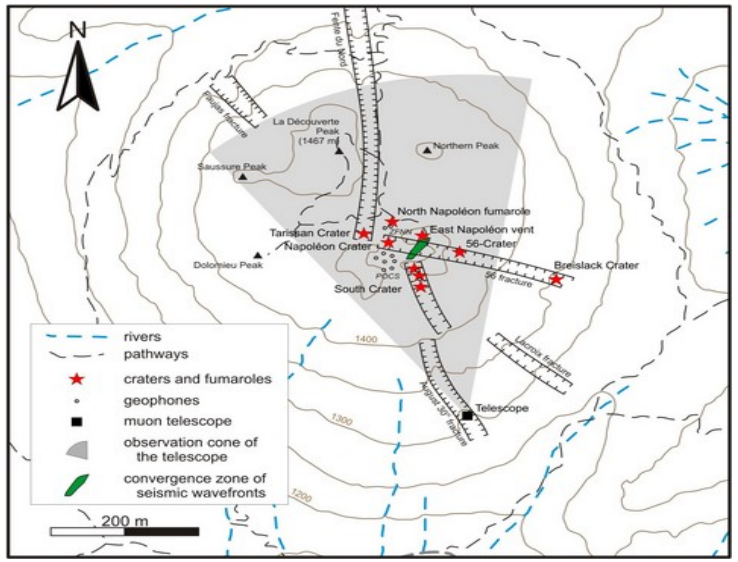
Volcanoes

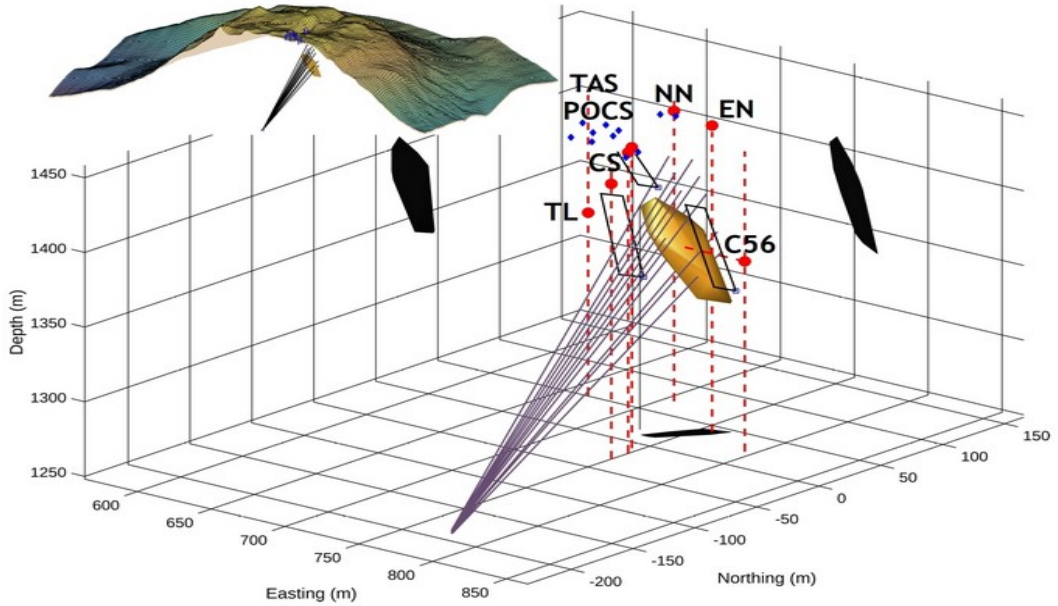
Vulcano, ITALY

Snaefellsjökull, ICELAND

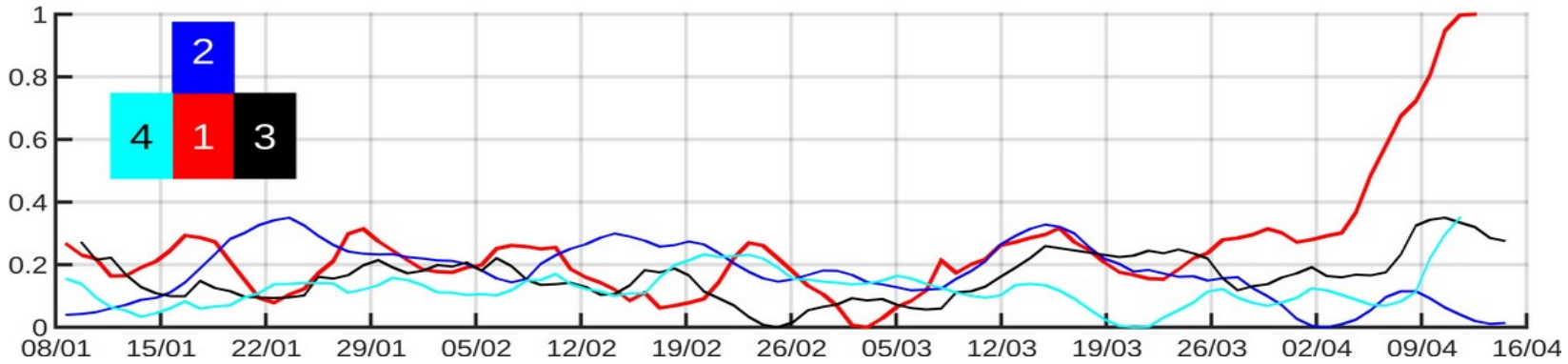
Mayon, PHILIPPINES

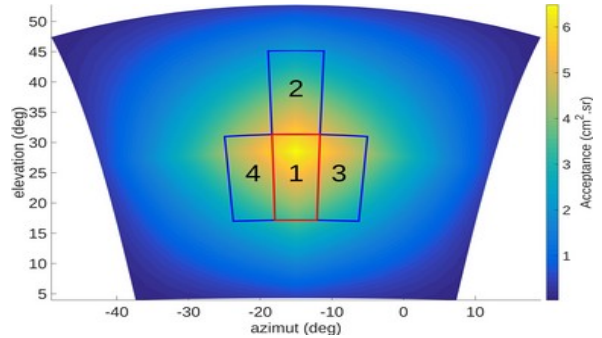
SOUFRIÈRE : SISMO-MUON JOINT MONITORING





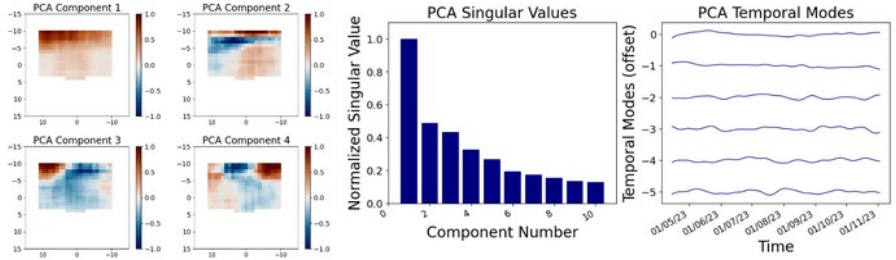
Global analysis of muon and seismic monitoring

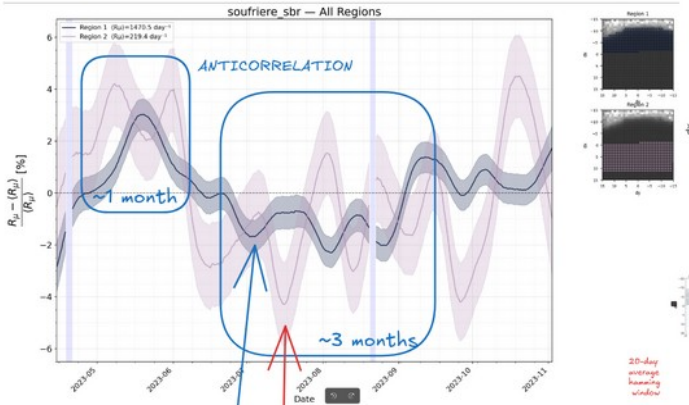


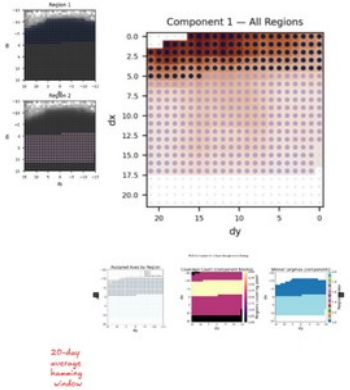


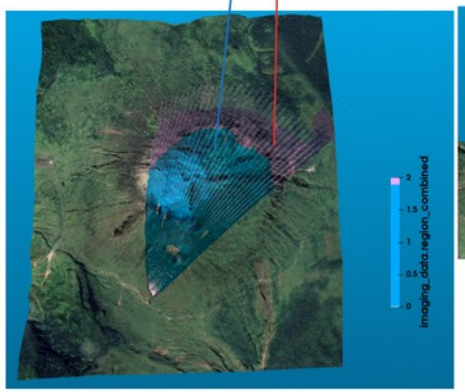
SOUFRIÈRE : PCA-BASED MONITORING

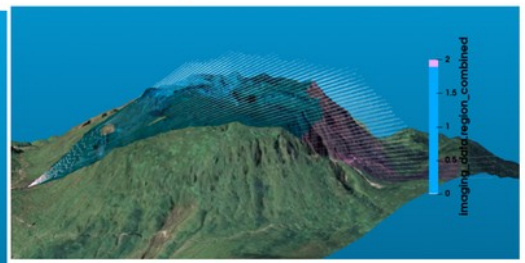
SBR



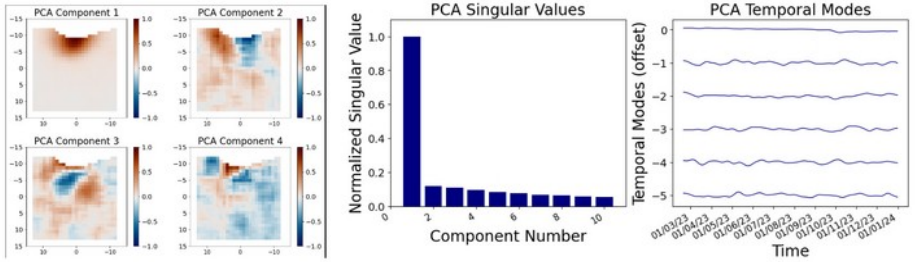


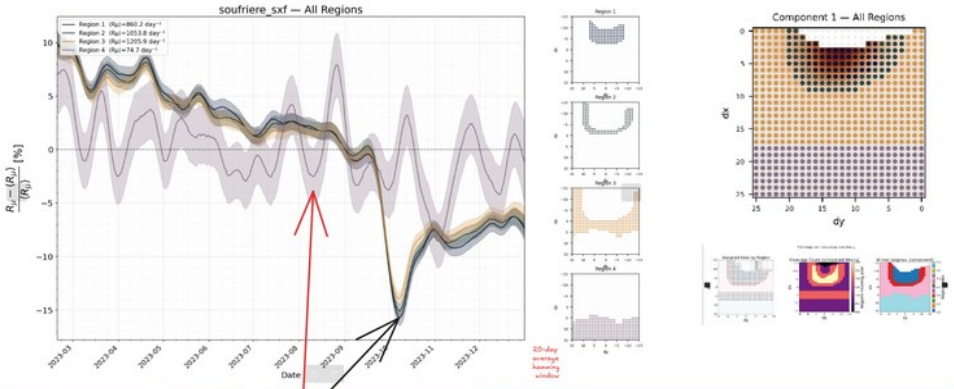


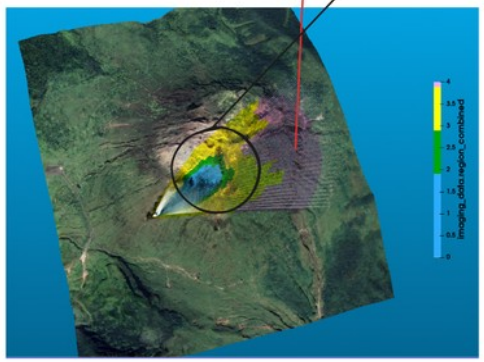


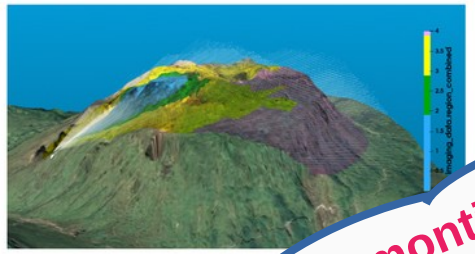


SXF



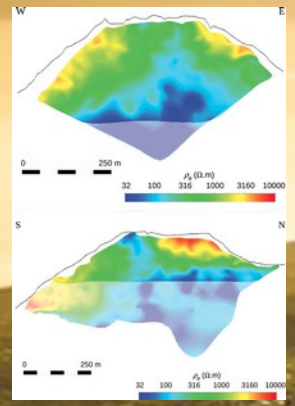




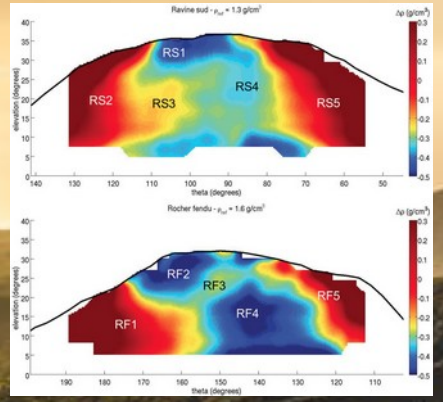


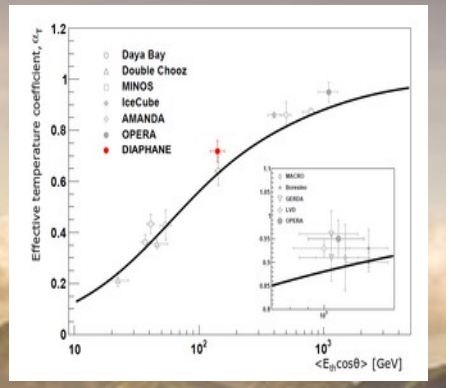
Matias Tramontini's talk (@IP2I)

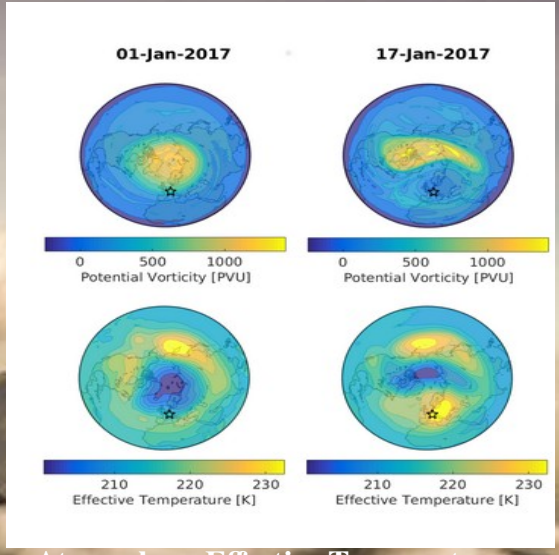
2D – ERT
(Electric Resistivity Tomography)



2D – Muography



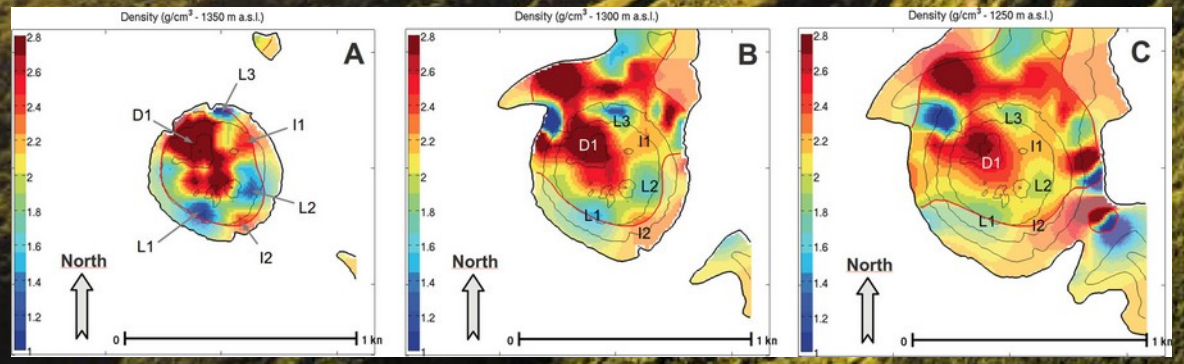




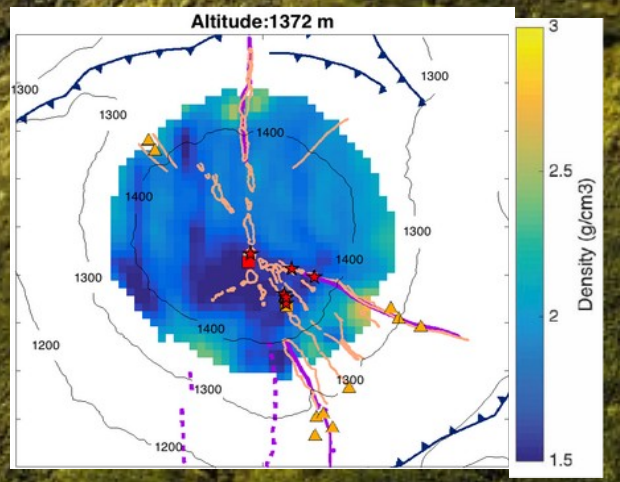
Atmosphere Effective Temperature measurement

Multimessenger Geophysics

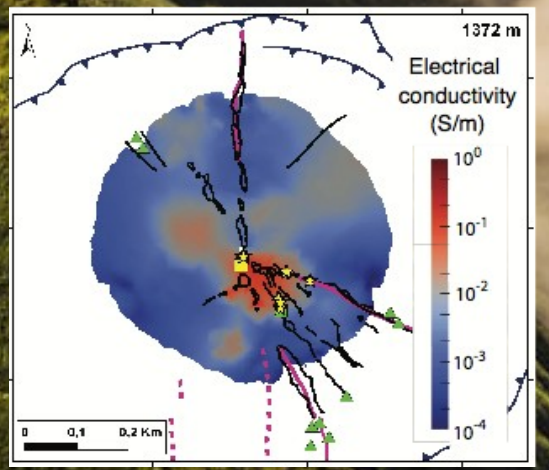
Gravimetry



3D – Muography+gravimetry



3D – ERT



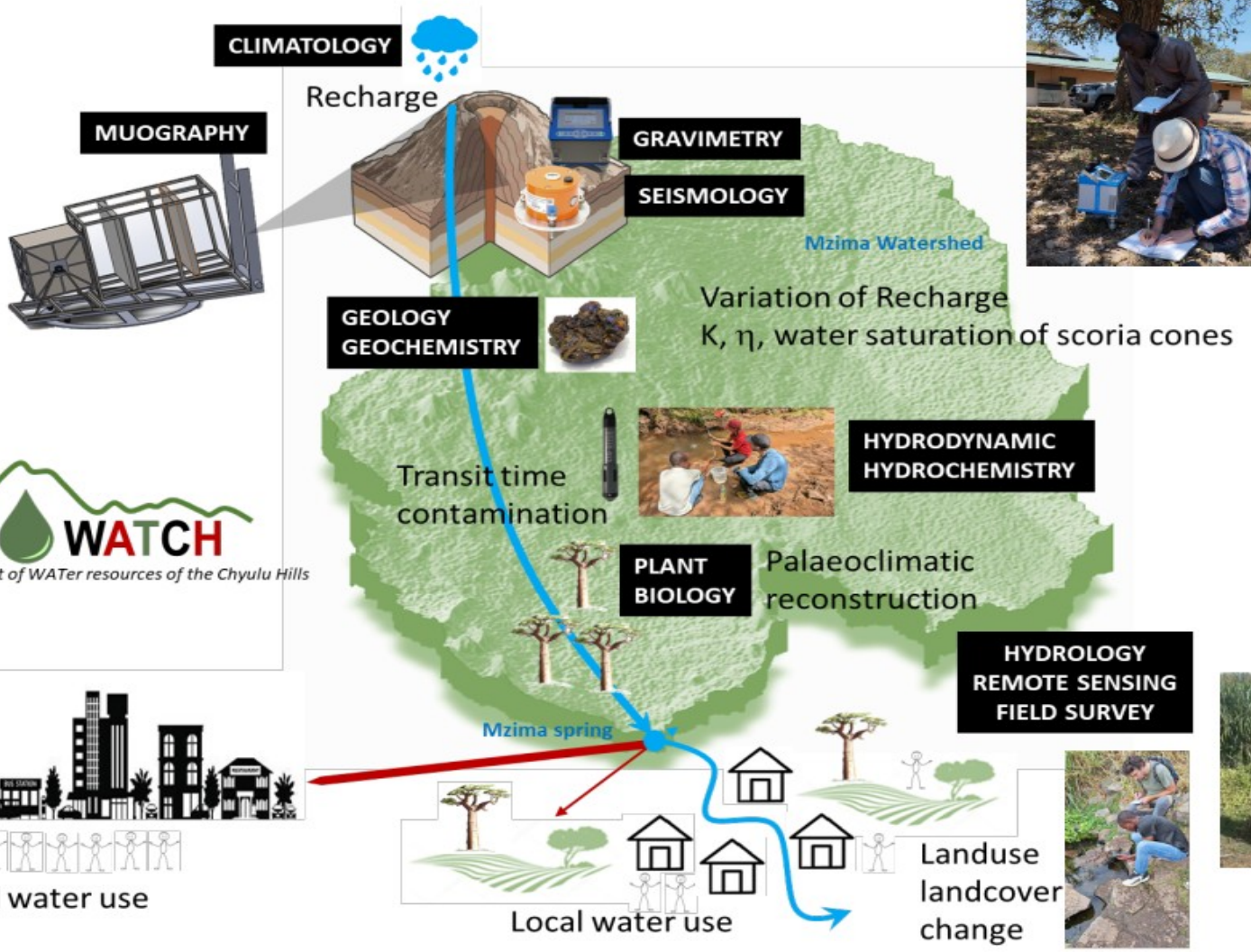
THE WATCH PROJECT

(ASSESSMENT OF WATER RESOURCES FROM MUON TOMOGRAPHY IN THE CHYULU HILLS, KENYA)

WATCH : AAP (2023-2025)

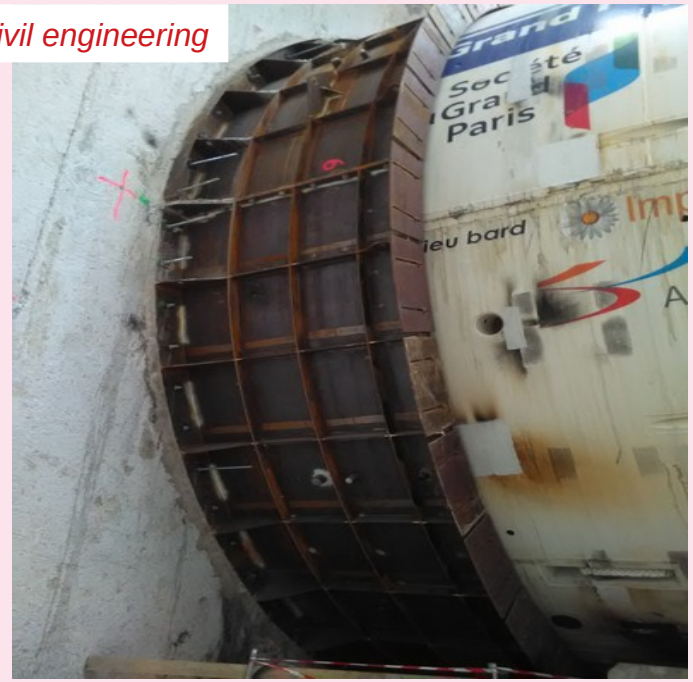
Time2Watch : PIB (2024-2026)

ERC Synergy Grant (post-2026)



Nuclear industry

Civil engineering



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Storage

Geotechnics

Blast furnace

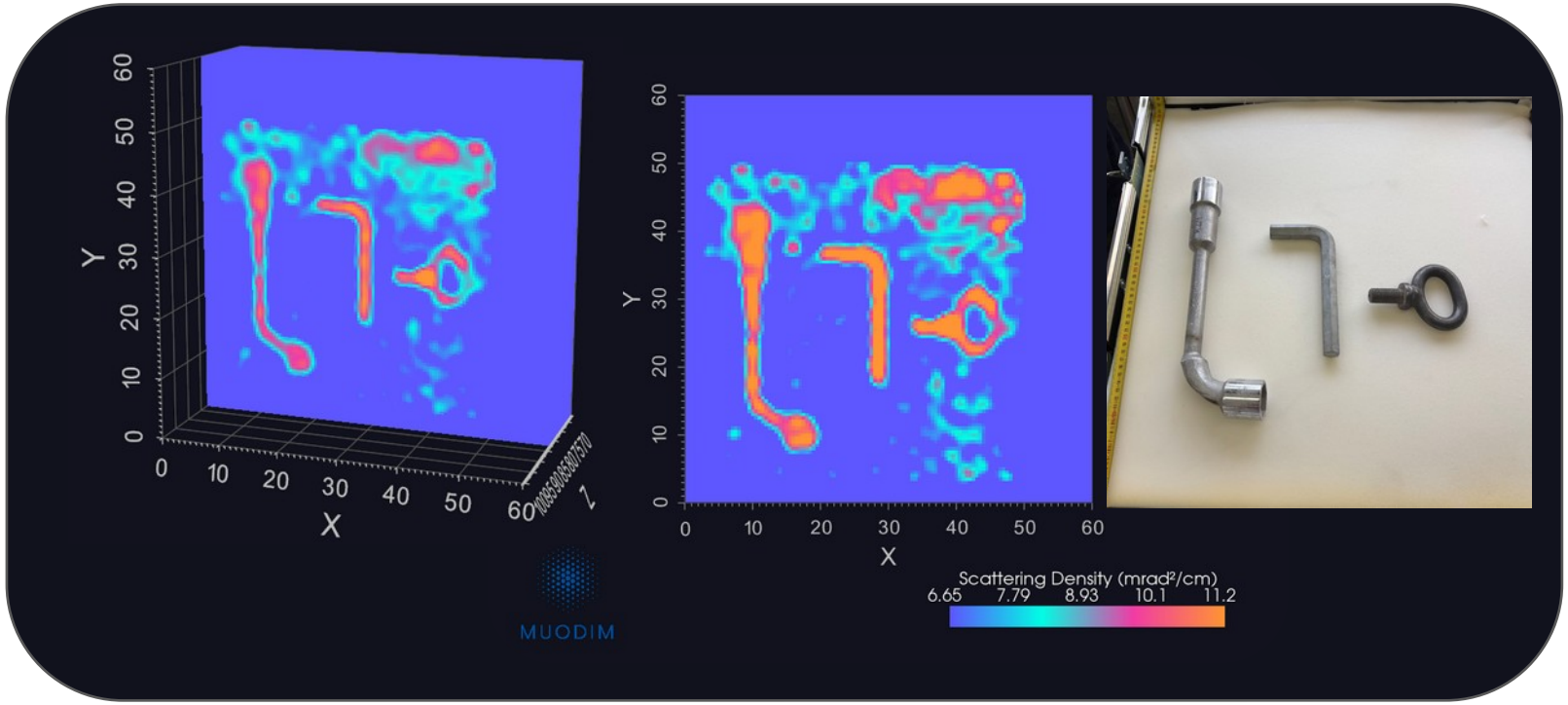
Heavy industry

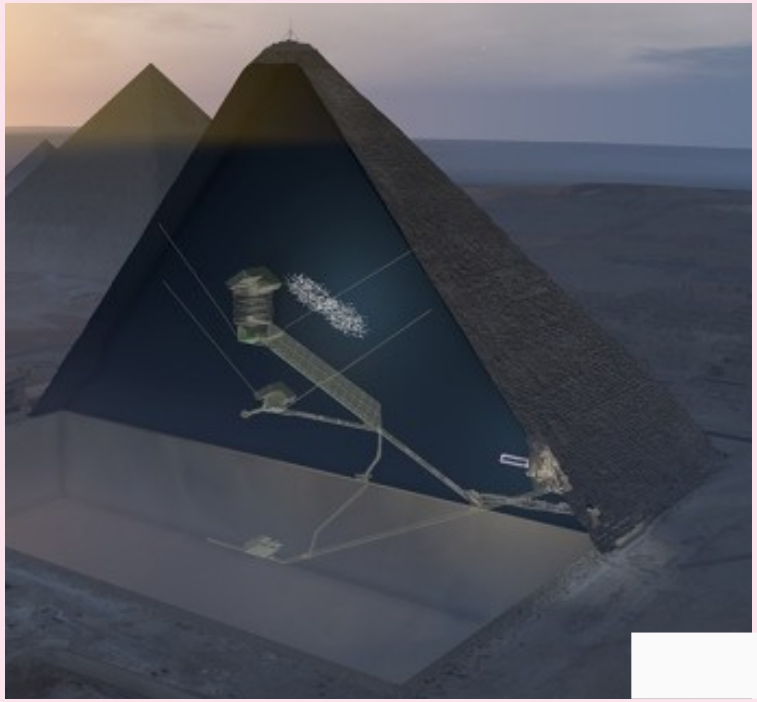
Fabio Dogliotti's talk (@MUODIM)

SCATTERING DEMONSTRATION
EXPERIMENT WITH ~CM SCALE RESOLUTION !

Experimental setup:

- Plastic scintillator bars (~1 cm).
- Detector panels are approximately 50 x 50 cm.
- Exposure period: 20 days (real time).
- Images are exploitable after about 10 days.
- Efficient data processing via in-house toolchain (in minutes). More on this later.



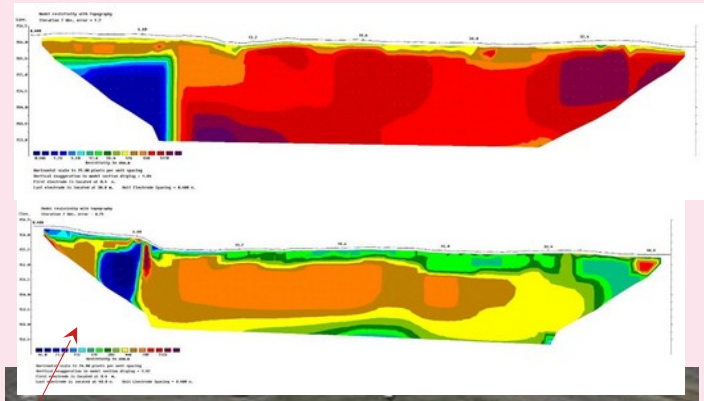


Great pyramids

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino



Palais du miroir :

- *georadar + ERT*
- *DAS (optical fiber seismology)*
- *muography*

Archaeology

Apollonia

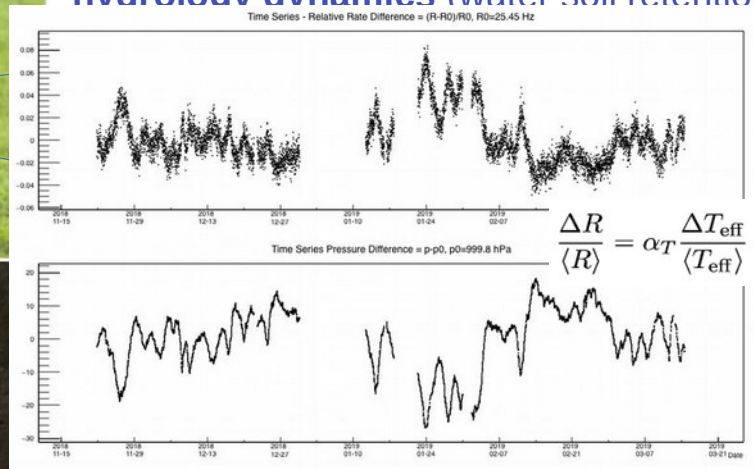
Palais du miroir

Joined analysis of an archaeological site with Innovative investigation techniques :

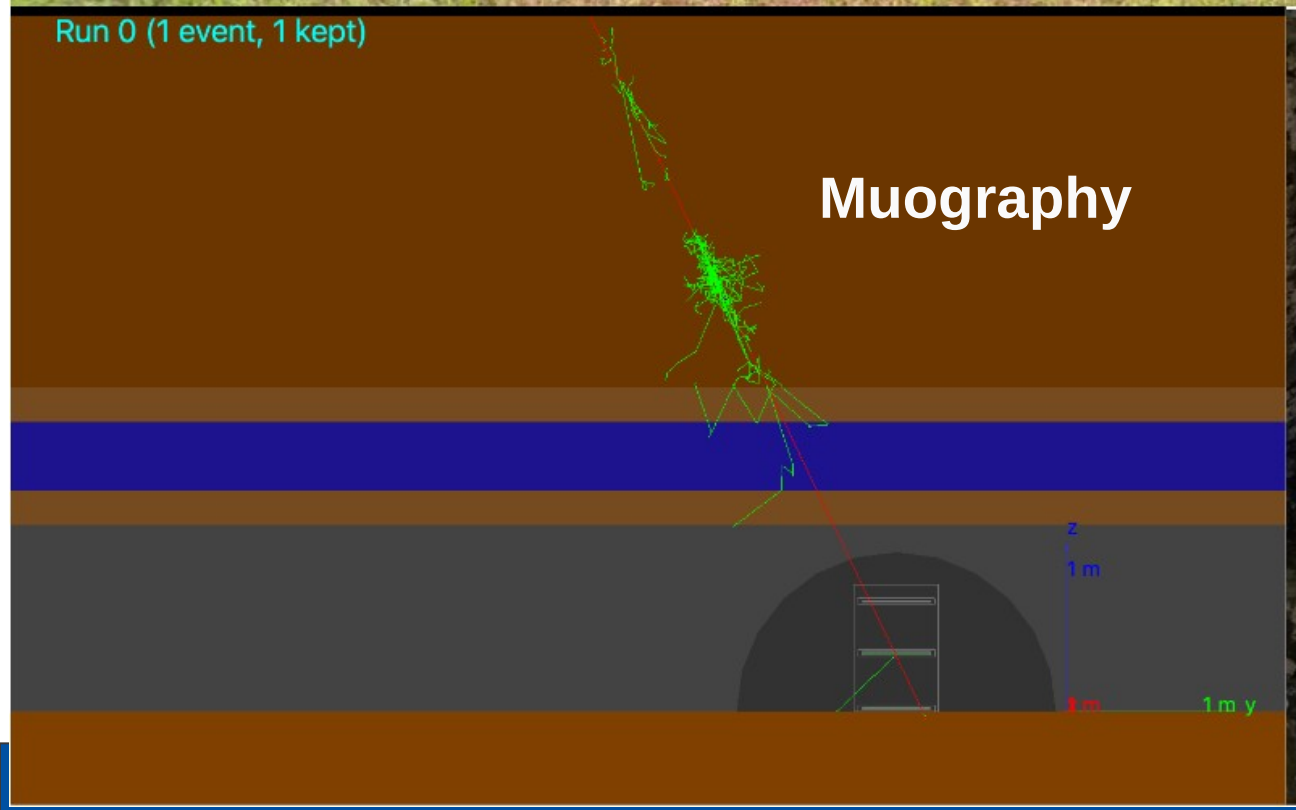
- **Distributed Acoustic Sensing (DAS)**
- **Muography**

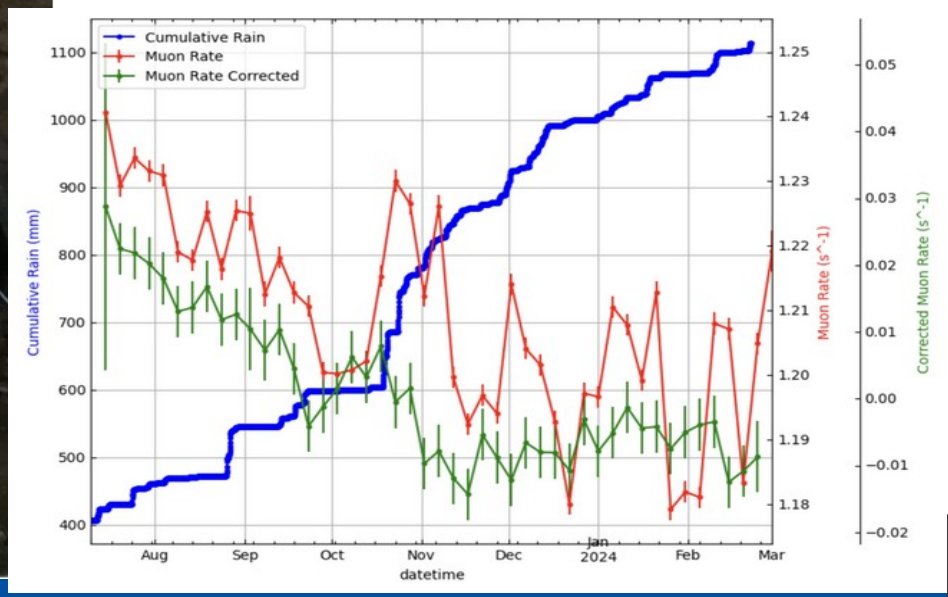
Characterization of the near surface zone :

- **archaeological structures**
- **hydrology dynamics** (water soil retention)



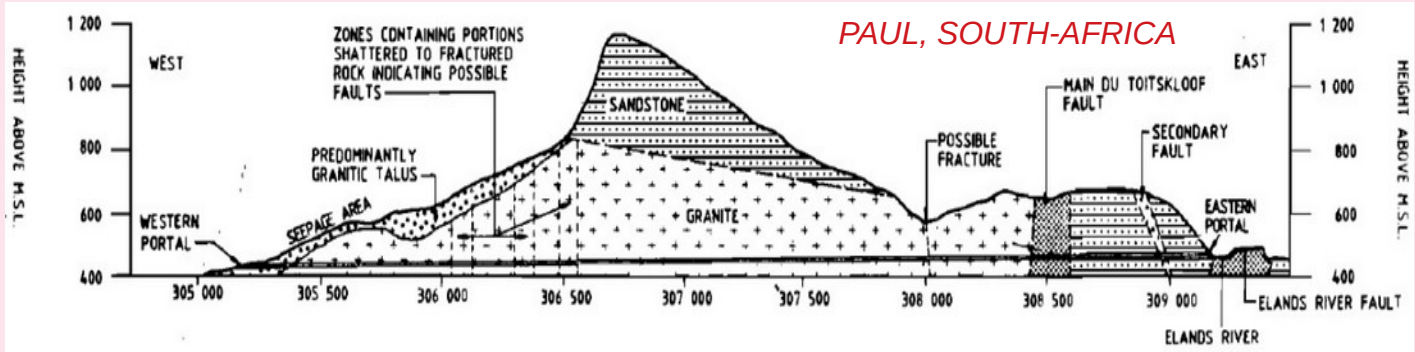
$$\frac{\Delta R}{\langle R \rangle} = \alpha_T \frac{\Delta T_{\text{eff}}}{\langle T_{\text{eff}} \rangle} + \beta_P (p - \langle p \rangle)$$

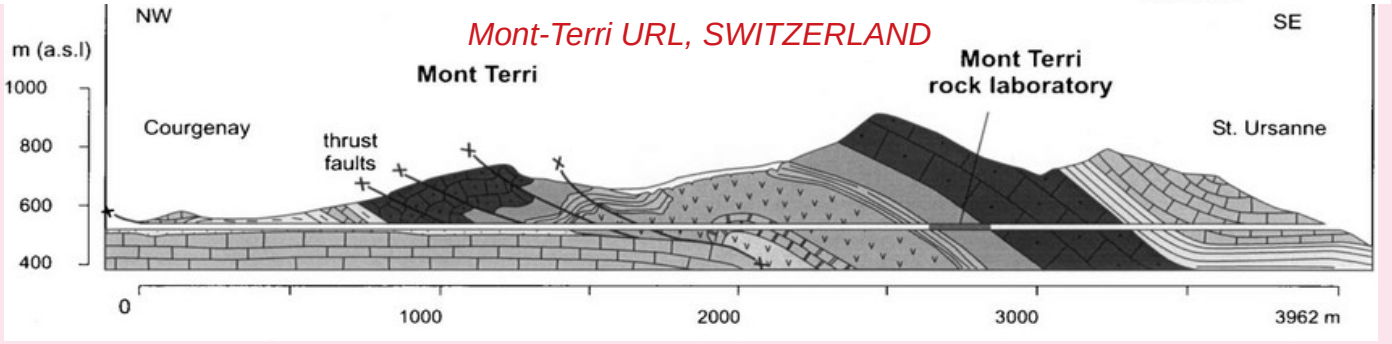




UNDERGROUND SITES

LSBB facility, FRANCE





Paarl Underground Laboratory (PAUL)

Terri URL

Sos Enattos (Sardainia, ITALY)

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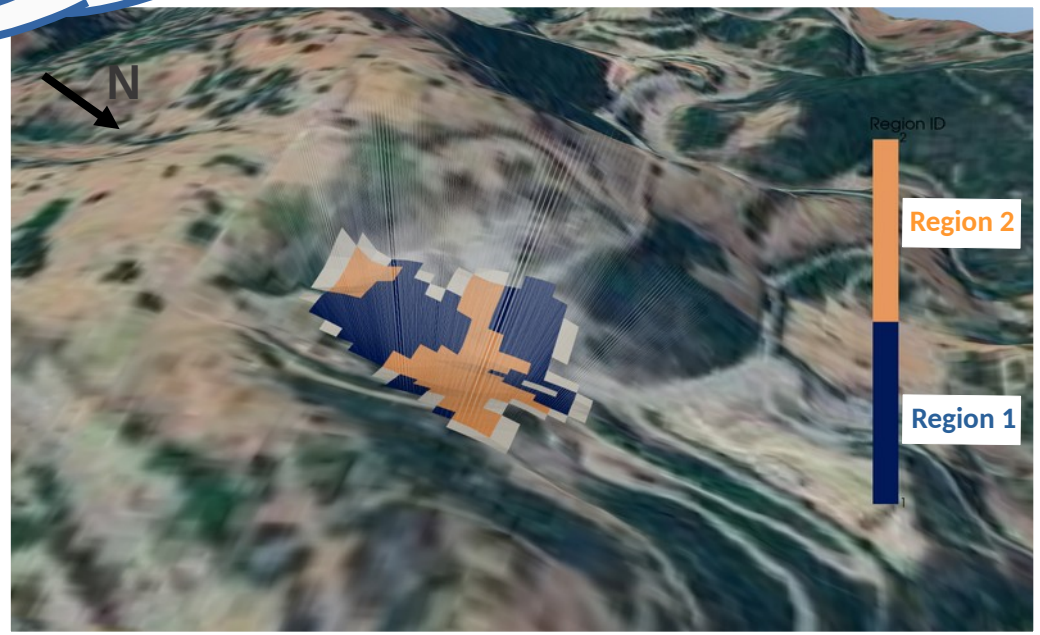
Matias Tramontini's talk (@IP2I)

Sos Enattos PCA

Spatial modes



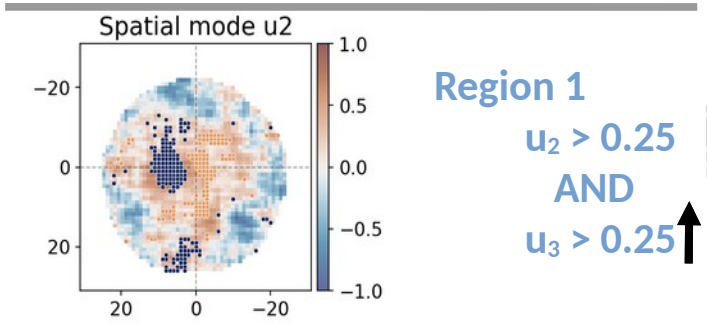
Regions mapped at the surface. Lines of sight in gray lines.

Mean rock thickness

Region 1: (165 ± 10) m

Region 2: (160 ± 15) m

Spatial modes to lines of sight mapping

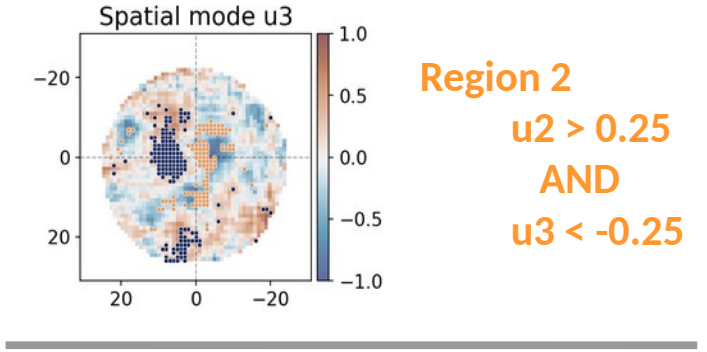


Region 1

u_2 > 0.25

AND

u_3 > 0.25

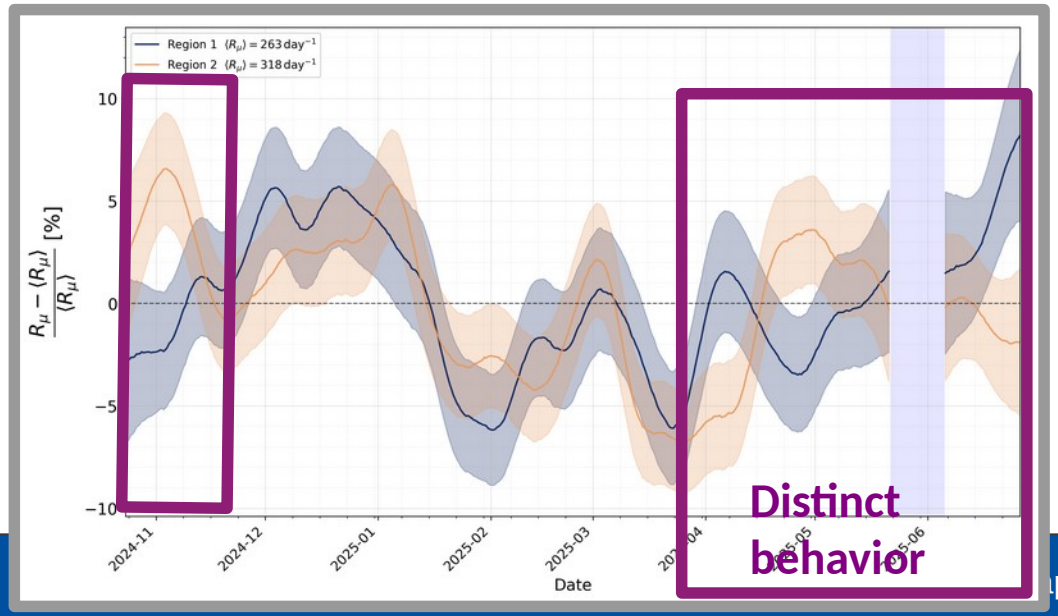


Region 2

u2 > 0.25

AND

u3 < -0.25



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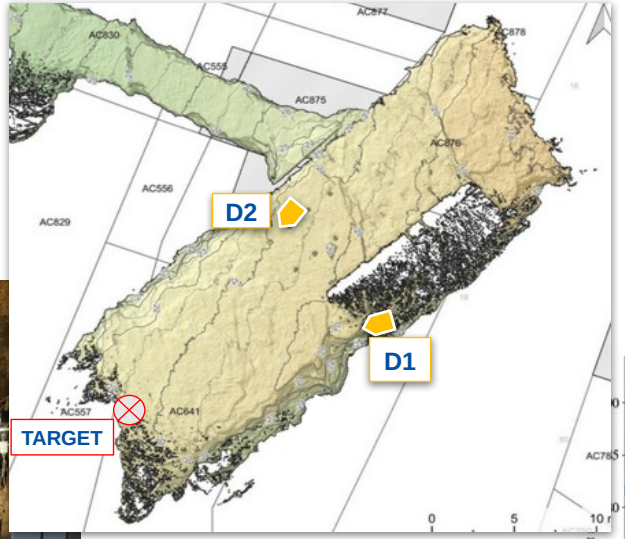
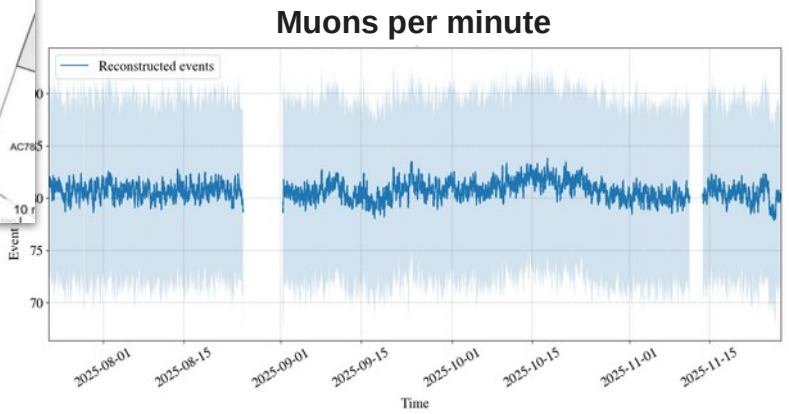
Alistair Boyce's talk (@MUODIM)

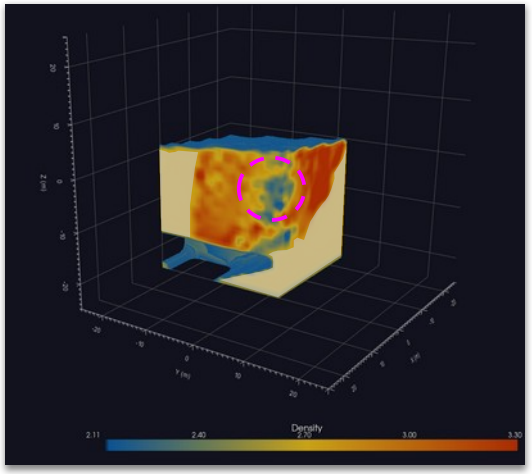
THIL SITE : JOINED MM + SC EXPERIMENT

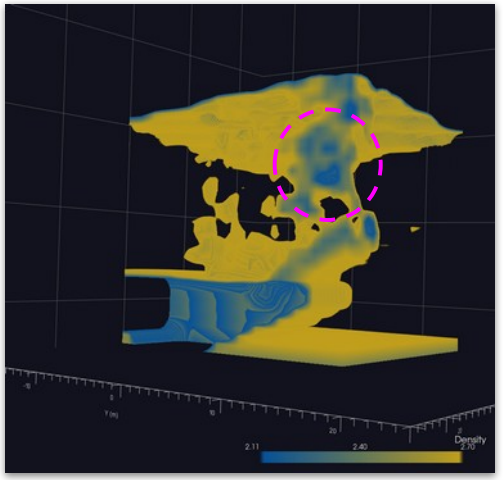




Rear view - D1 - MicroMegas - "MM"

Rear view - D2 - Scintillator - "SC"



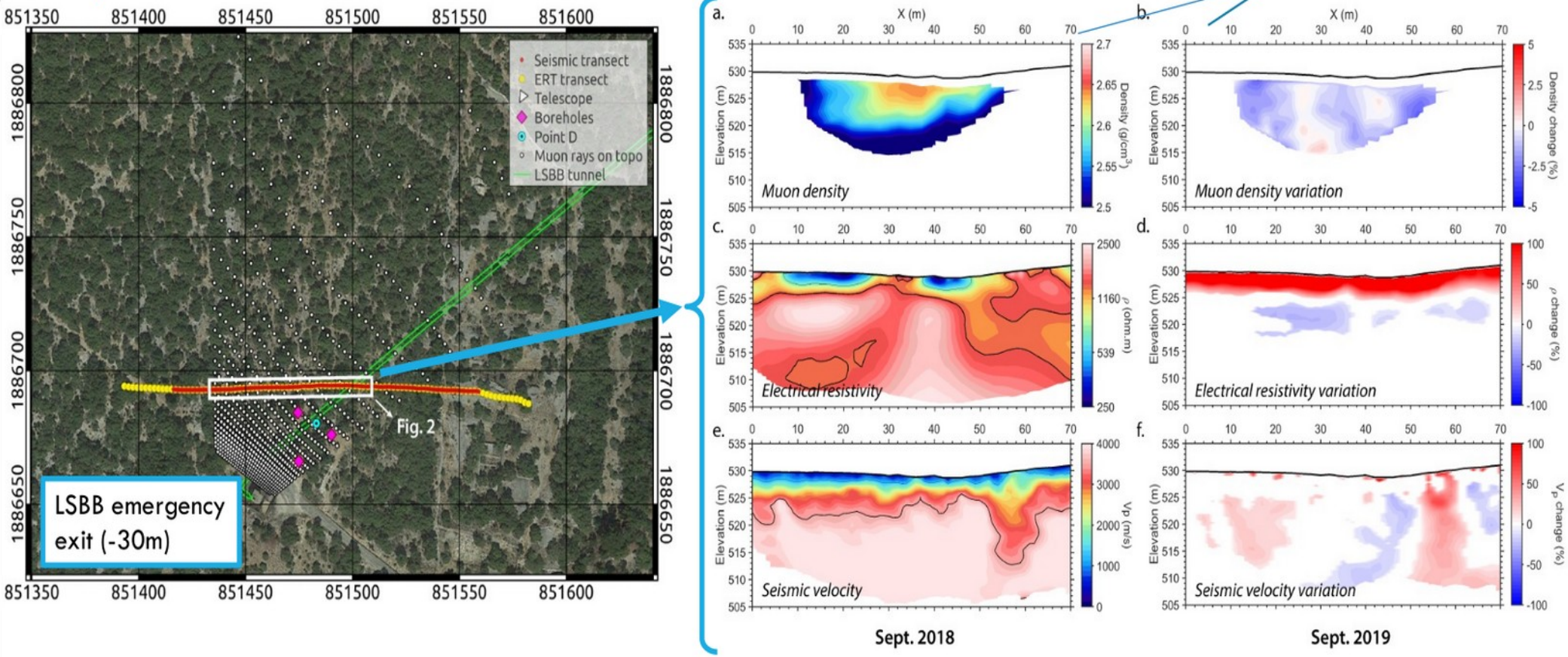


- First successful simultaneous use of gas and plastic detectors
- The muon flux remained very stable for over three months (for SC) – no significant changes were detected in the rock.
- The 2D and 3D density images indicate variations in density, notably significantly reduced densities (-0.6 g/cm^3) covering a volume of 7 x 9 x 9 m, which may be concentrated at a depth of approximately 10 m below the surface at the end of the gallery.

: JOINED MEASUREMENTS MUONS+ERT+SEISMIC VELOCITY

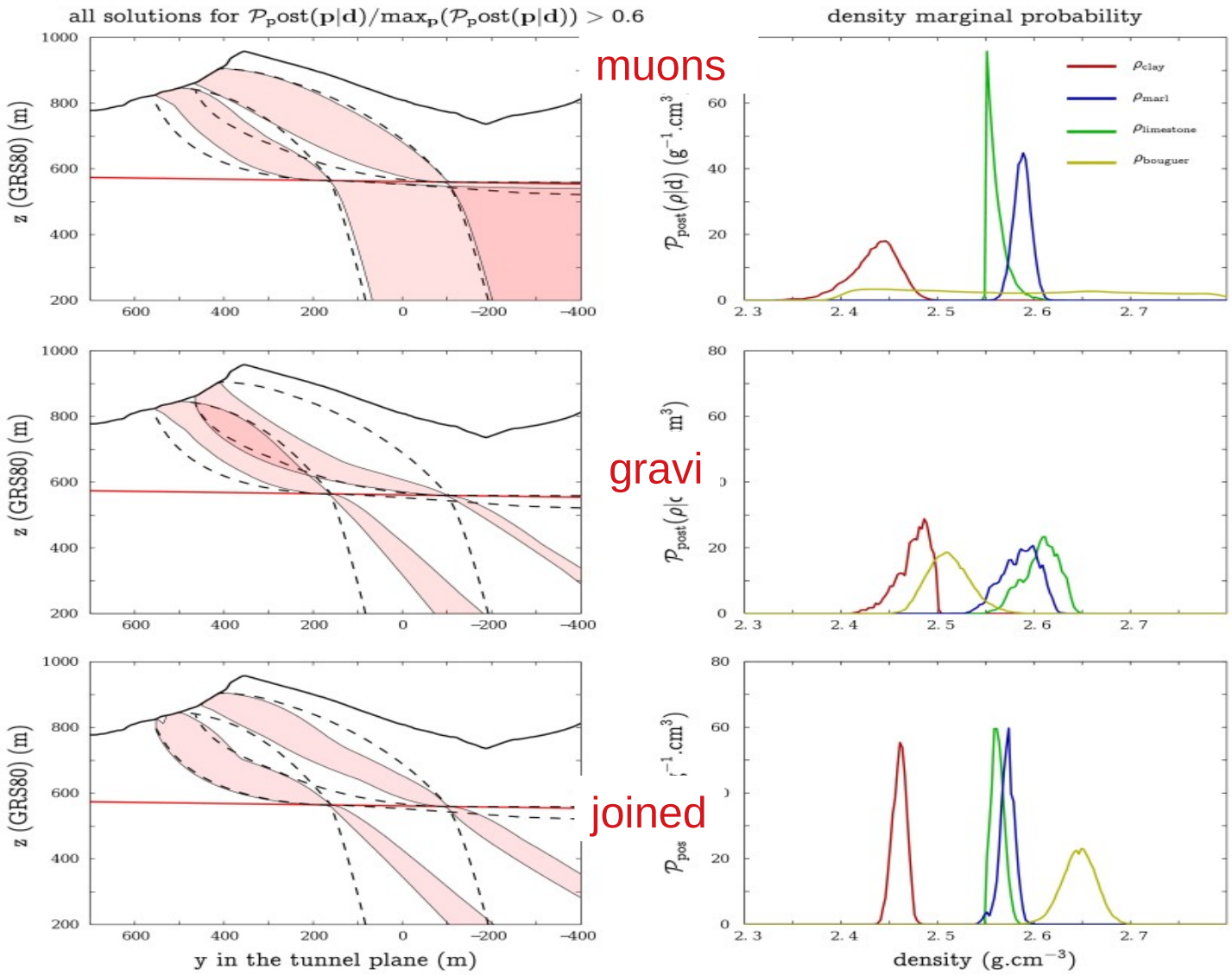
SC muon detector

A GOOD EXAMPLE: THE BUISSONIÈRE EXPERIMENT

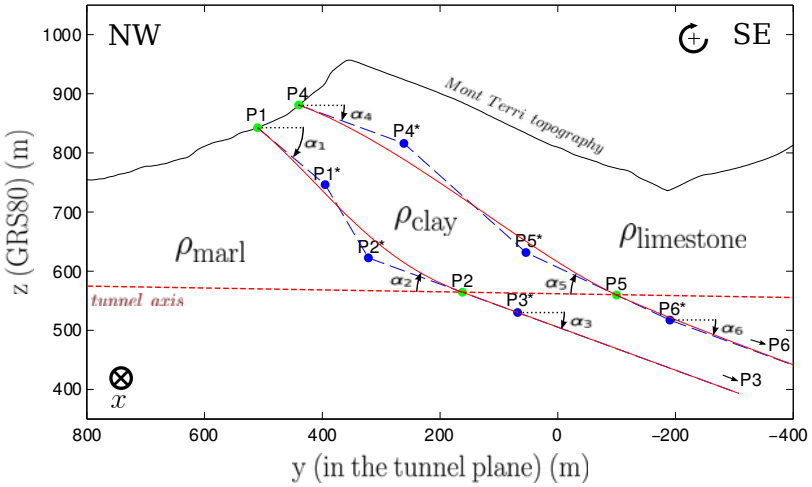


Ref: Lázaro Roche, I.; Pasquet, S.; Chalikakis, K.; Mazzilli, N.; Rosas-Carbajal, M.; Decitre, J.B.; Batiot-Guilhe, C.; Emblanch, C.; Marteau, J.; et al.
Water resource management: The multi-technique approach of the Low Background Noise Underground Research Laboratory of Rustrel, France, and its muon detection projects.
In Muography: Exploring Earth's Subsurface with Elementary Particles. **2021**, Geophysical Monograph Series; Oláh, L., Tanaka, H., Varga, D., Eds. American Geophysical Union , USA. DOI:10.1002/9781119722748.ch10

MONT-TERRI : JOINED ANALYSIS MUON-GRAVI FOR OVERBURDEN CHARACTERIZATION



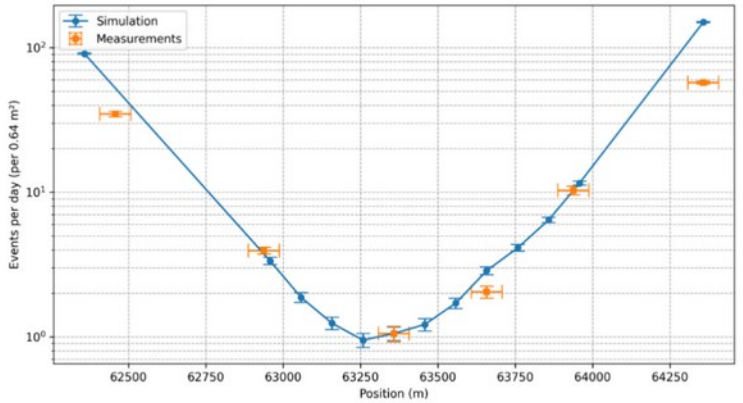
Opalinus layer parametrization



: DIRECT OVERBURDEN CHARACTERIZATION

Data comparison

Measured data compared to Simulated data



Science | EyeNzululwazi ngezeNdalo | Natuurwetenskappe

https://arxiv.org/abs/2306.12083

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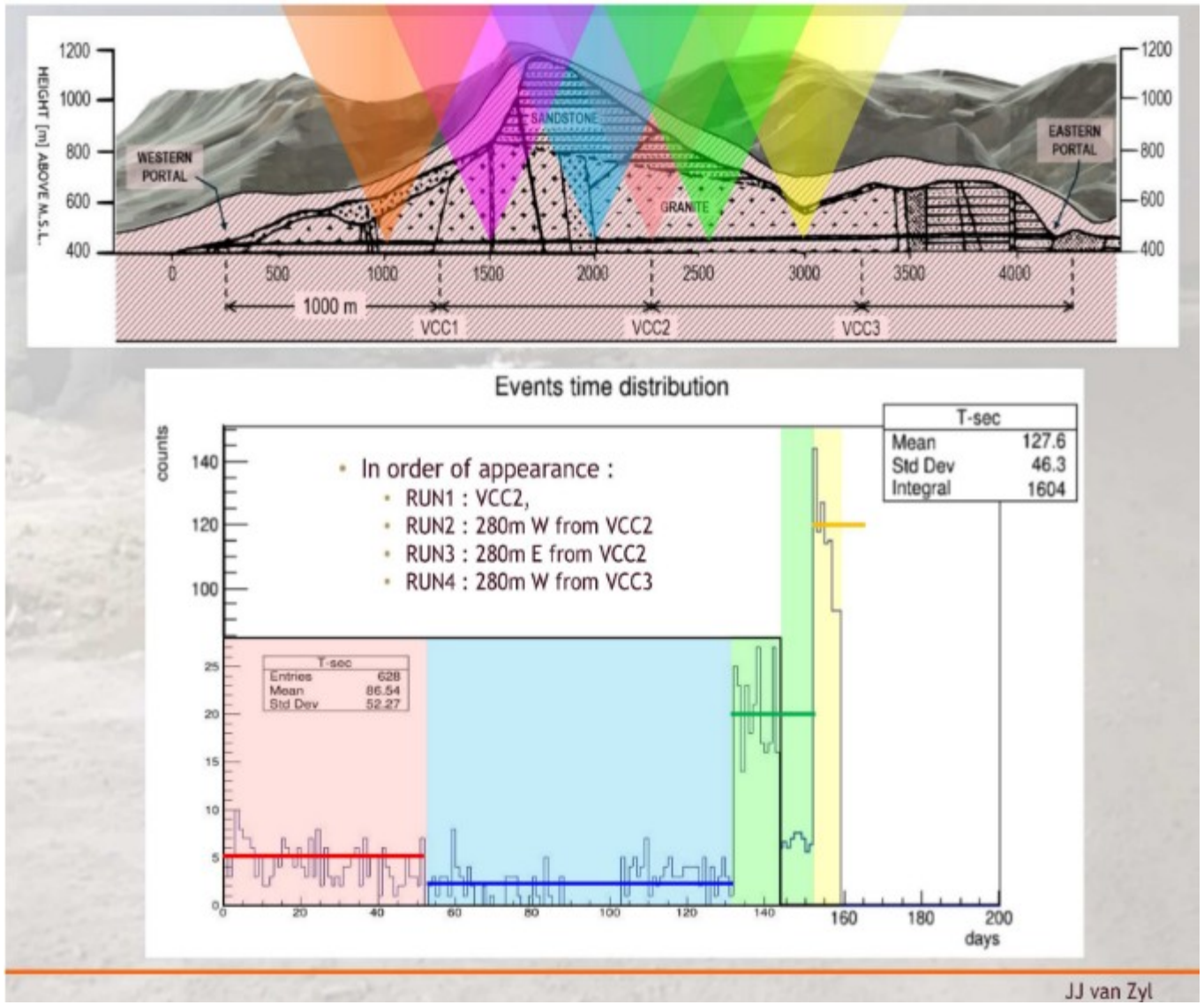

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