



# Engineering geological applications of muon imaging

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Mission 4 “Education and Research” - Component 2: “From research to business” - Investment  
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”



# Using muons to detect density anomalies underground



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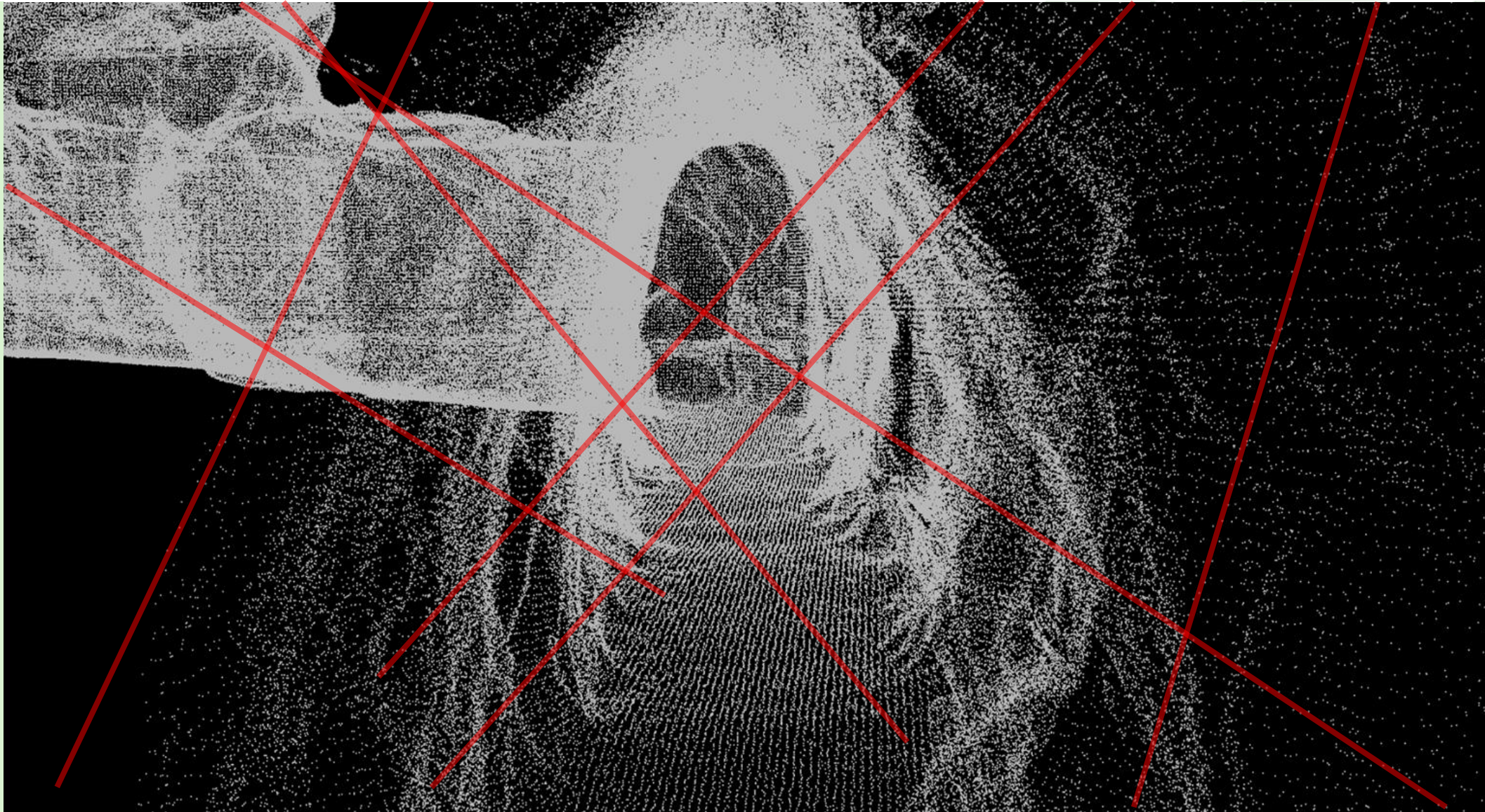
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## Summary

### 2021-2024 Three years of PhD

Department of Earth Science of the University of Florence (DST-UNIFI)

PhD thesis title: "Engineering geological applications of muon imaging"

### 2021-2023 Research fellow

National Institute for Nuclear Physics (INFN) division of Florence

### 2023 Research fellow

Department of Earth Science of the University of Florence (DST-UNIFI)

### 2023-2025 Technologist

Department of Earth Science of the University of Florence (DST-UNIFI)



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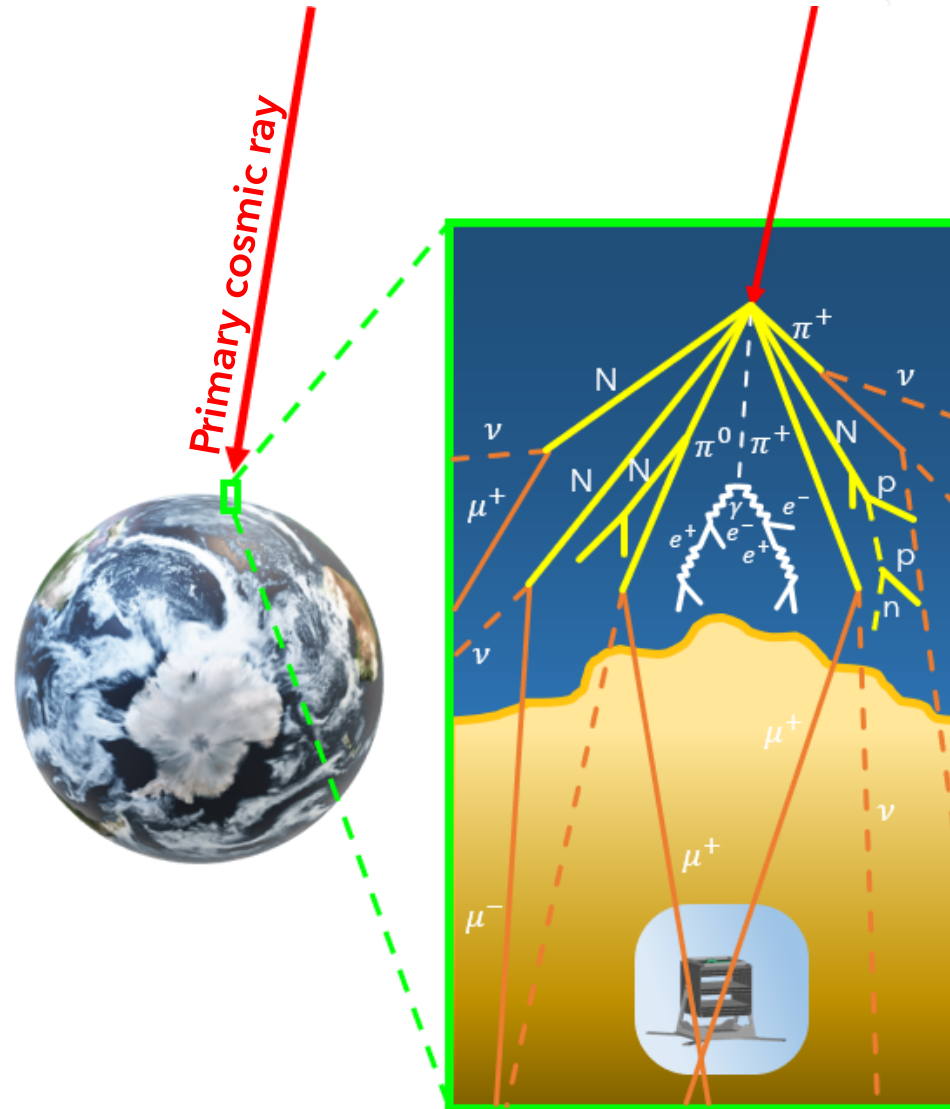
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Cosmic-rays

air shower



Muons  $\mu$

Highly penetrating charged particles

Average life-time  $\mu$ :  $\sim 2.2 \mu\text{s}$

Mass  $\mu$ :  $105.6 \text{ Mev}/c^2$  ( $\sim 200 m_{\text{electron}}$ )

Flux at sea level:  $\sim 70 \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1}$

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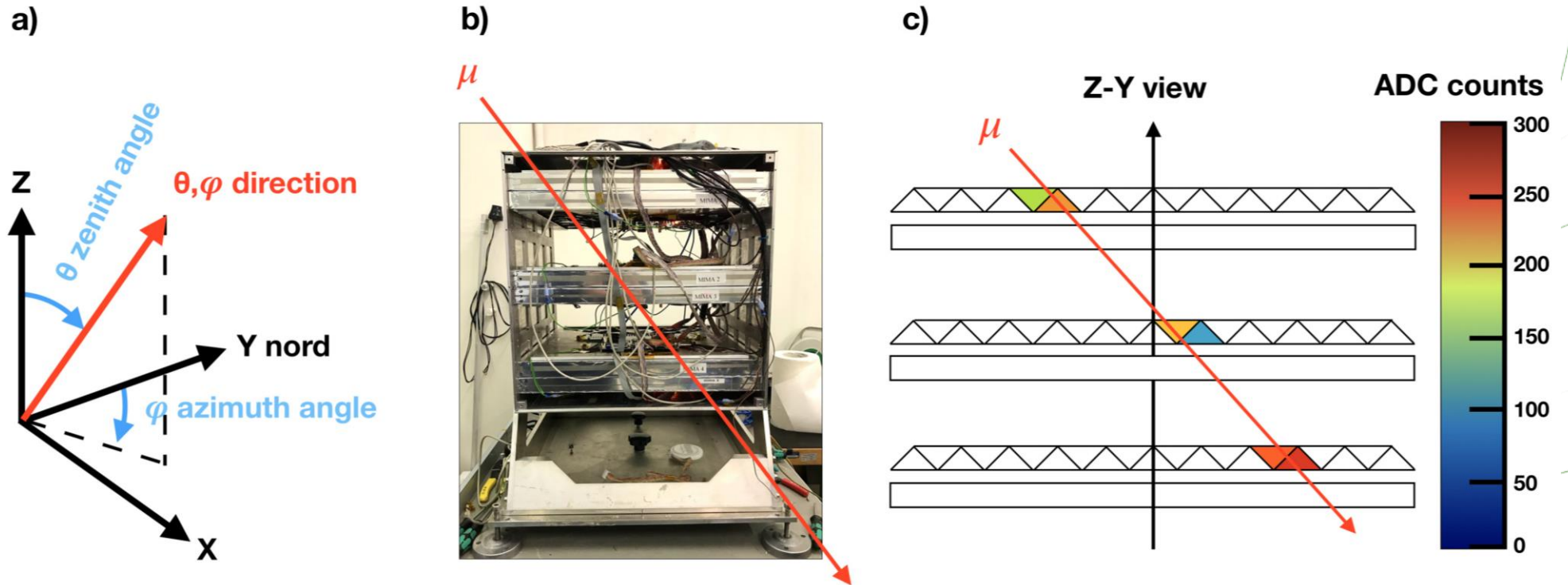
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## MIMA detector (Muon Imaging for Mining and Archaeology)



- Scintillator plastic bars
- Total consumption:  $\sim 30$  W
- Dimensions:  $50 \times 50 \times 50$  cm<sup>3</sup>

- Weight:  $\sim 60$  kg
- Angular resolution:  $\sim 7$  mrad (°??)
- Active surface:  $0.16$  m<sup>2</sup>

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# Mining applications

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## Examples:

Many published studies highlight the potential of muon radiography in the field of mining activities:

- Zhang, ZX., Enqvist, T., Holma, M. et al. **Muography and Its Potential Applications to Mining and Rock Engineering**. Rock Mech Rock Eng 53, 4893-4907 (2020). <https://doi.org/10.1007/s00603-020-02199-9>
- Schouten, D. (2019). **Muon geotomography: Selected case studies**. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377(2137), 20180061.
- Schouten, D., & Ledru, P. (2018). **Muon Tomography Applied to a Dense Uranium Deposit at the McArthur River Mine**. Journal of Geophysical Research: Solid Earth, 123(10), 8637-8652.
- Baccani, G., Bonechi, L., Bongi, M., Brocchini, D., Casagli, N., Ciaranfi, R., Cimmino, L., Ciulli, V., D'Alessandro, R., Del Ventisette, C., Dini, A., Gigli, G., Gonzi, S., Guideri, S., Lombardi, L., Melon, B., Mori, N., Nocentini, M., Noli, P., ... Viliani, L. (2019). **Muon radiography of ancient mines: The San Silvestro Archaeo-Mining Park (Campiglia Marittima, Tuscany)**. Universe, 5(1), 34.
- Kaiser, R. (2019). **Muography: Overview and future directions**. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 377(2137), 20180049.
- ...and so on

**But the reality is that most of these studies are related to simulations, with only a few real case studies!**

# Case study

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The **Temperino mine** inside the **archaeological and mining park of San Silvestro (LI)**



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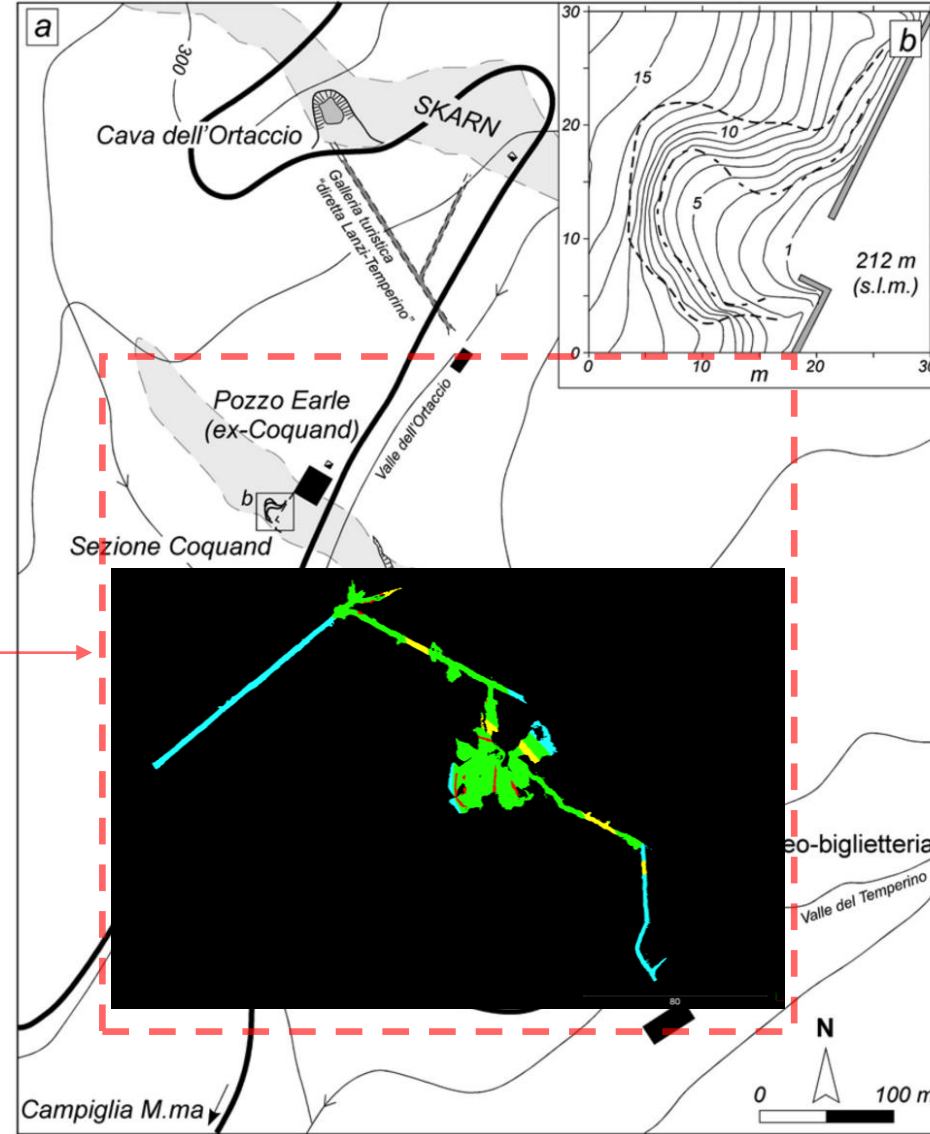
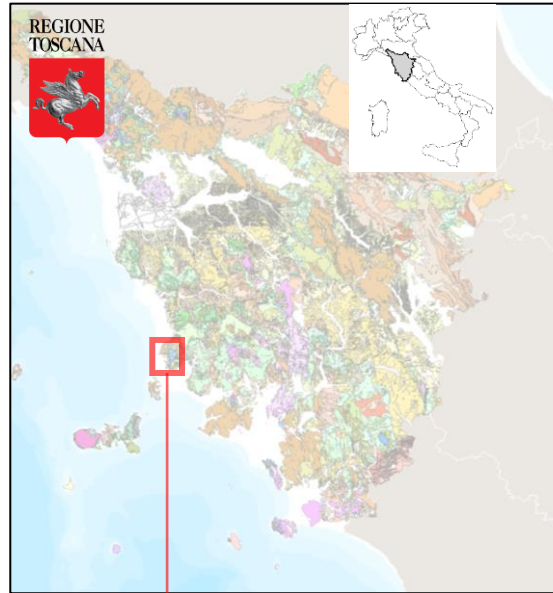
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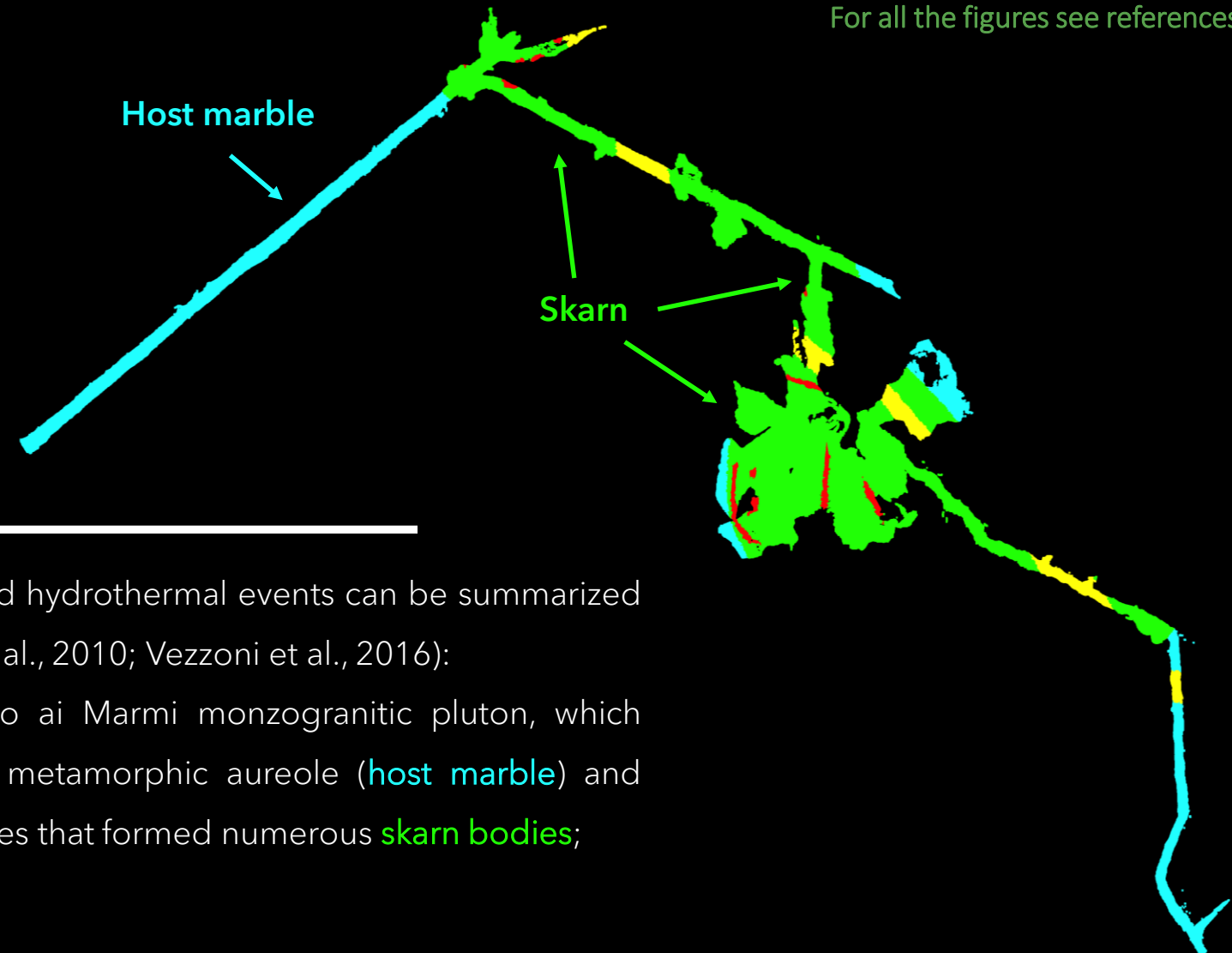
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The sequence of magmatic and hydrothermal events can be summarized in three points (Da Mommio et al., 2010; Vezzoni et al., 2016):

(1) emplacement of the Botro ai Marmi monzogranitic pluton, which created an extensive contact metamorphic aureole (**host marble**) and activated metasomatic processes that formed numerous **skarn bodies**;

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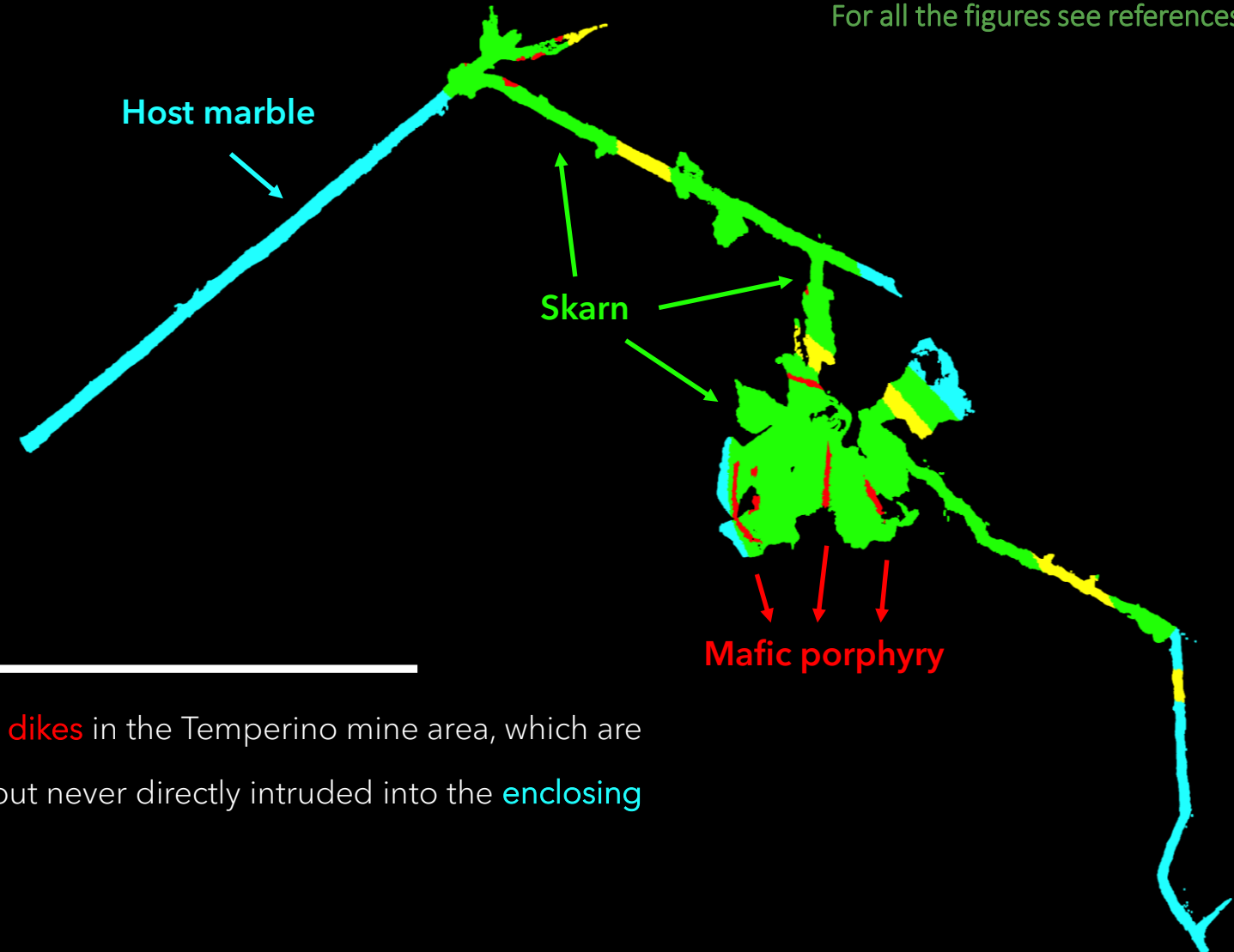
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(2) Intrusion of **mafic porphyry dikes** in the Temperino mine area, which are associated with the **skarn body** but never directly intruded into the **enclosing marble**;

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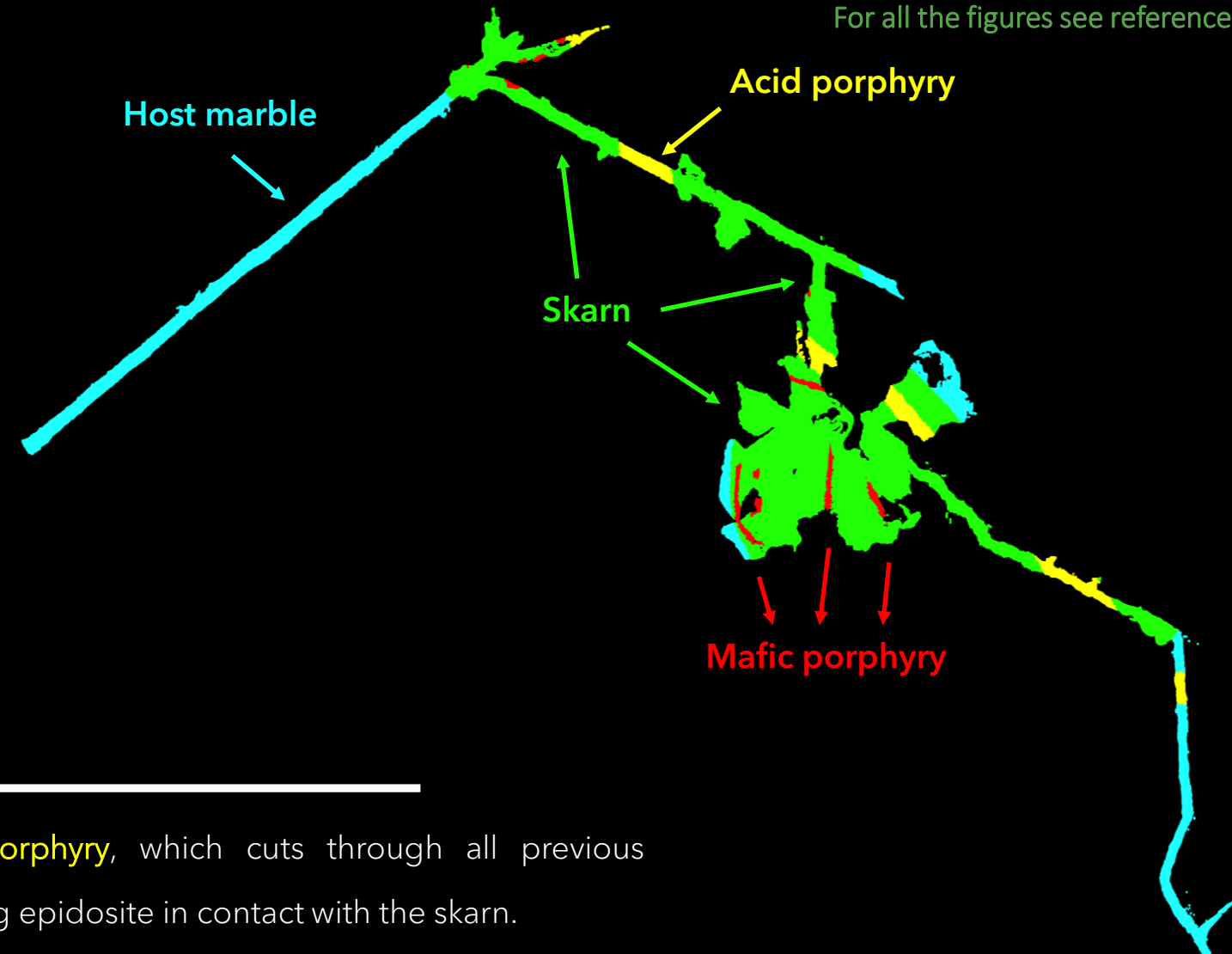
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**(3)** Intrusion of the **acid porphyry**, which cuts through all previous lithologies and contacts, forming epidosite in contact with the skarn.

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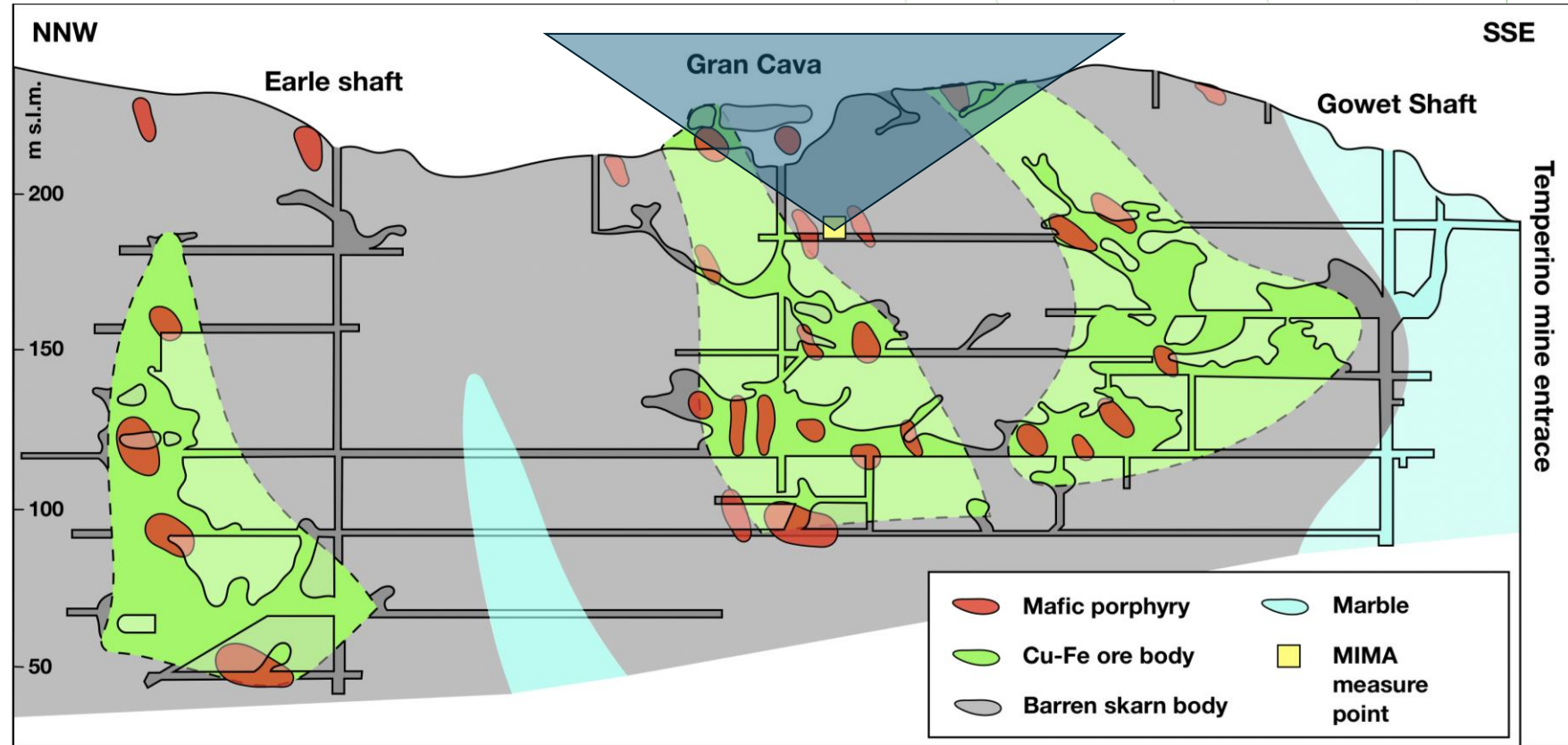
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At the Temperino mine, Cu-Fe ore type are strictly associated with the intruded mafic porphyry masses (NNW-SSE) and are composed by massive chalcopyrite-pyrrhotite-pyrite association. The Cu-Fe ores are spatially associated to mafic intrusions, which shape and location depend on the primary skarn macroporosity mainly present in the internal portions of the skarn.

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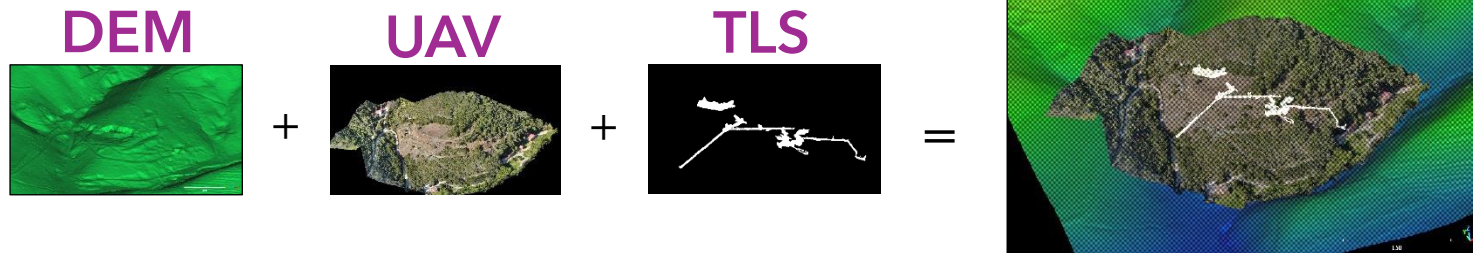
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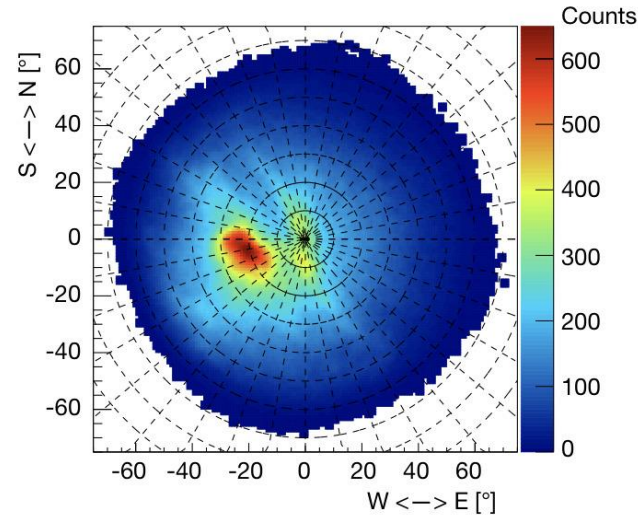
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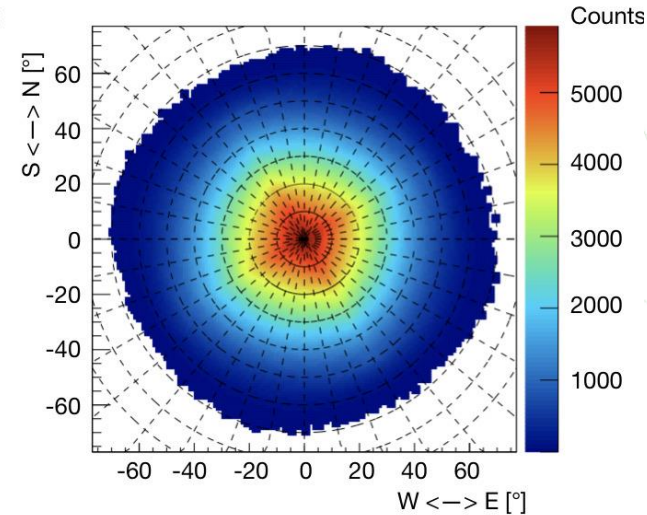
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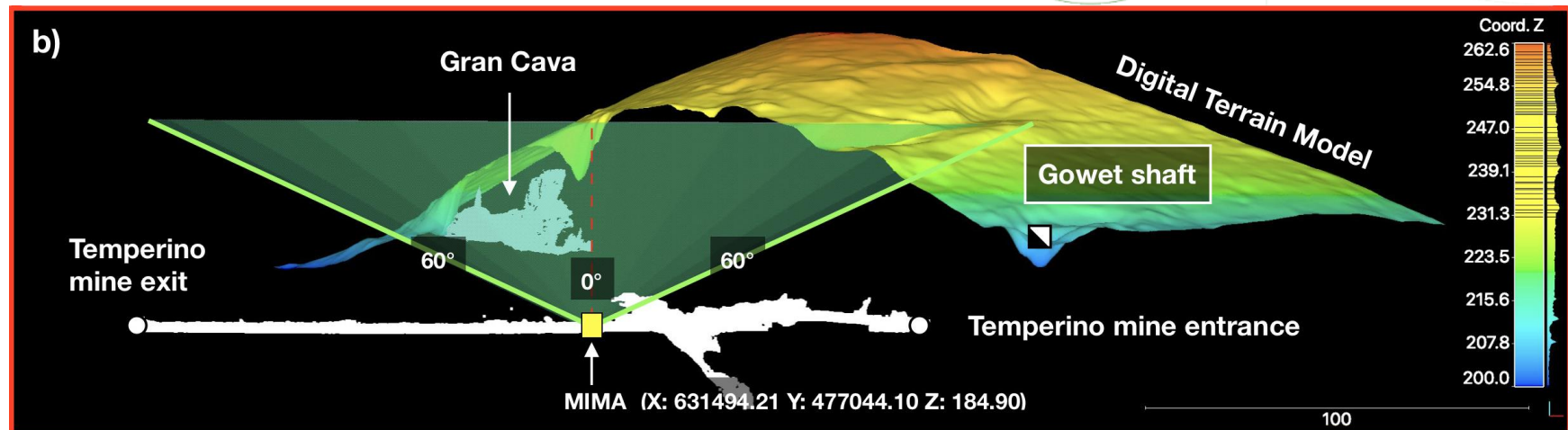
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a) Target configuration events  $N_{target}(\theta, \varphi)$



b) Free-sky configuration events  $N_{free-sky}(\theta, \varphi)$



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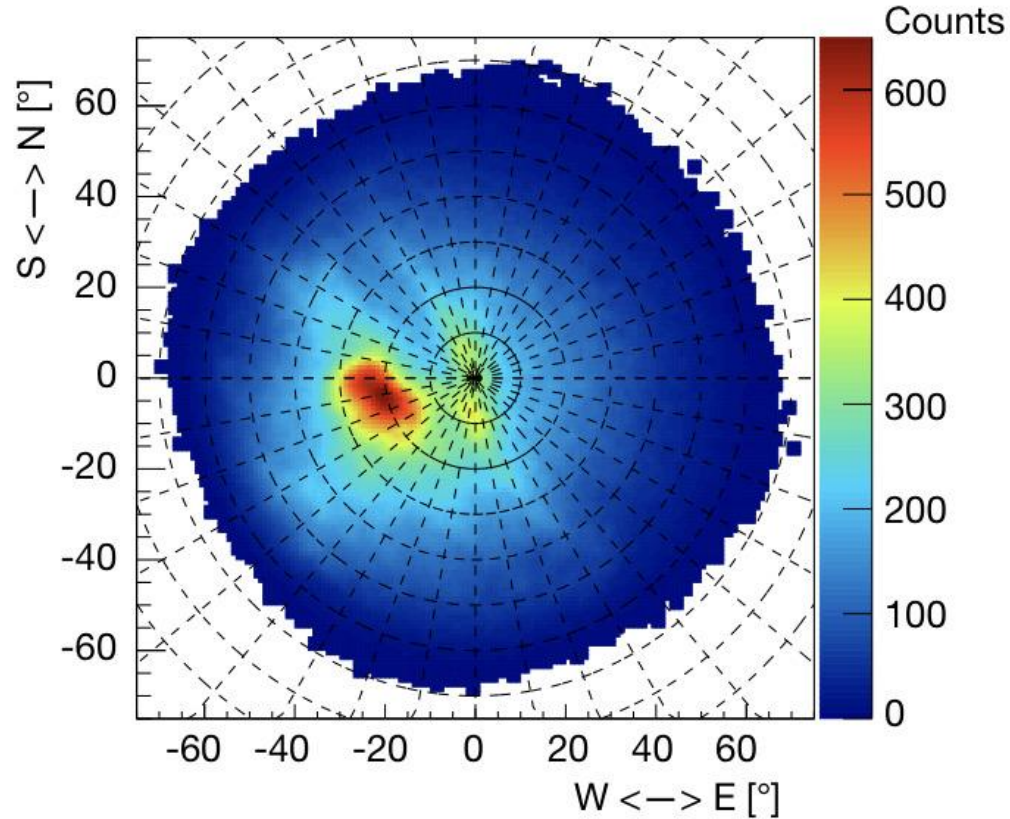
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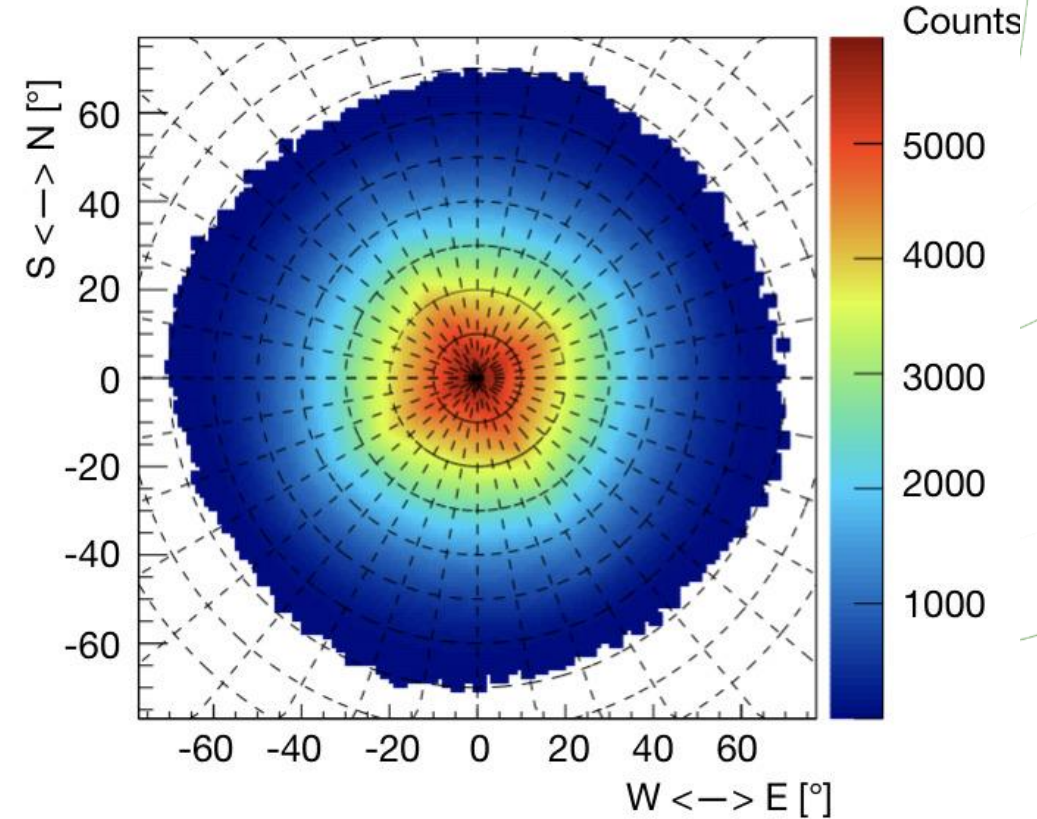
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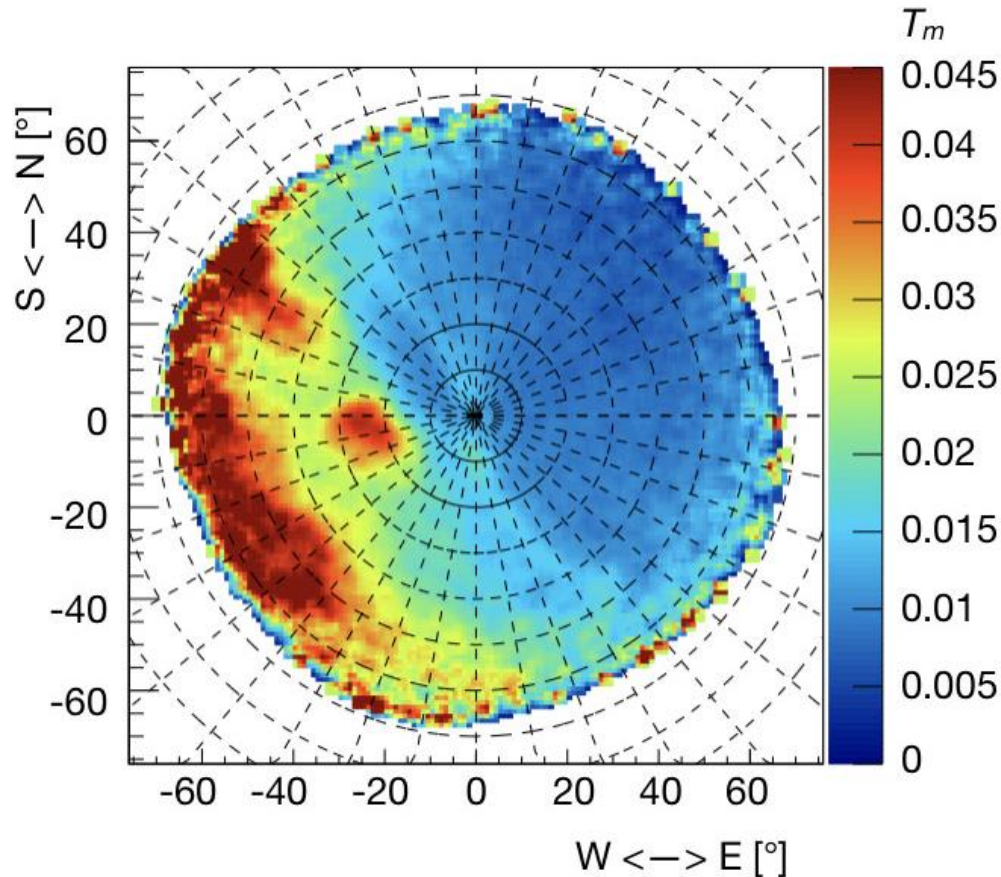
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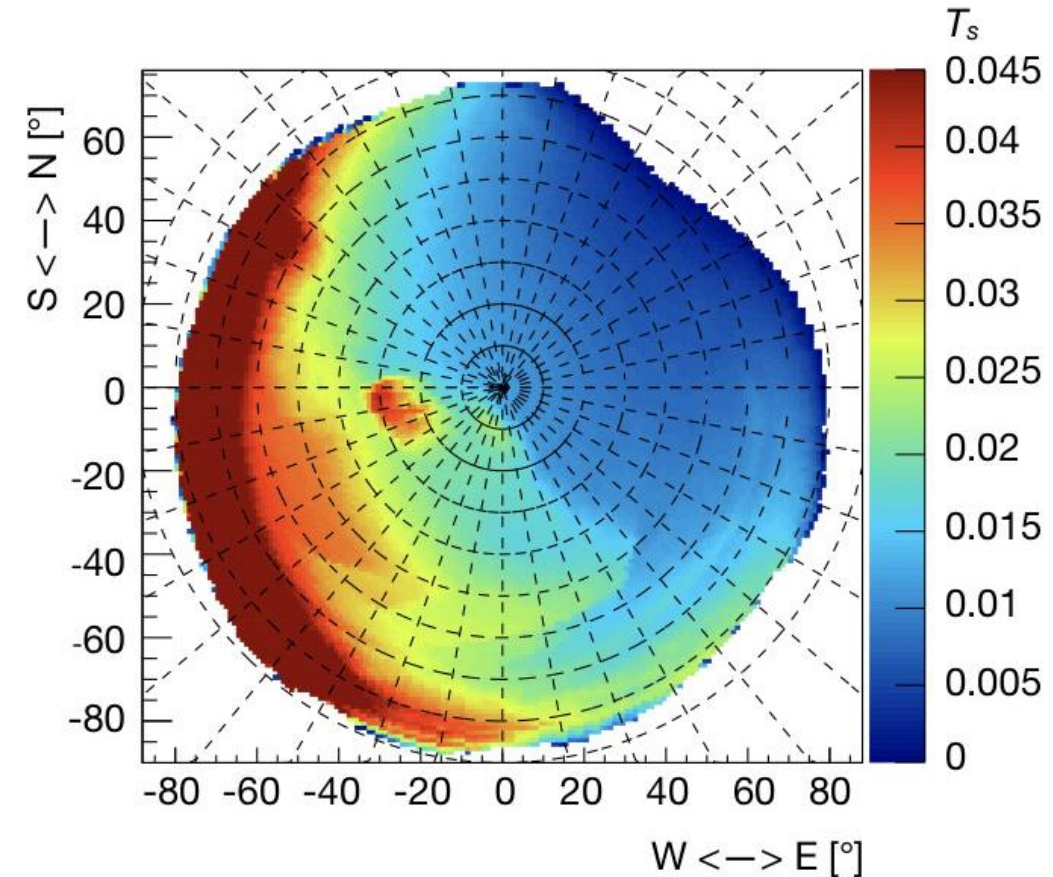
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c) Measured transmission  $T_m(\theta, \varphi)$



d) Simulated transmission  $T_s(\theta, \varphi, \bar{\rho})$

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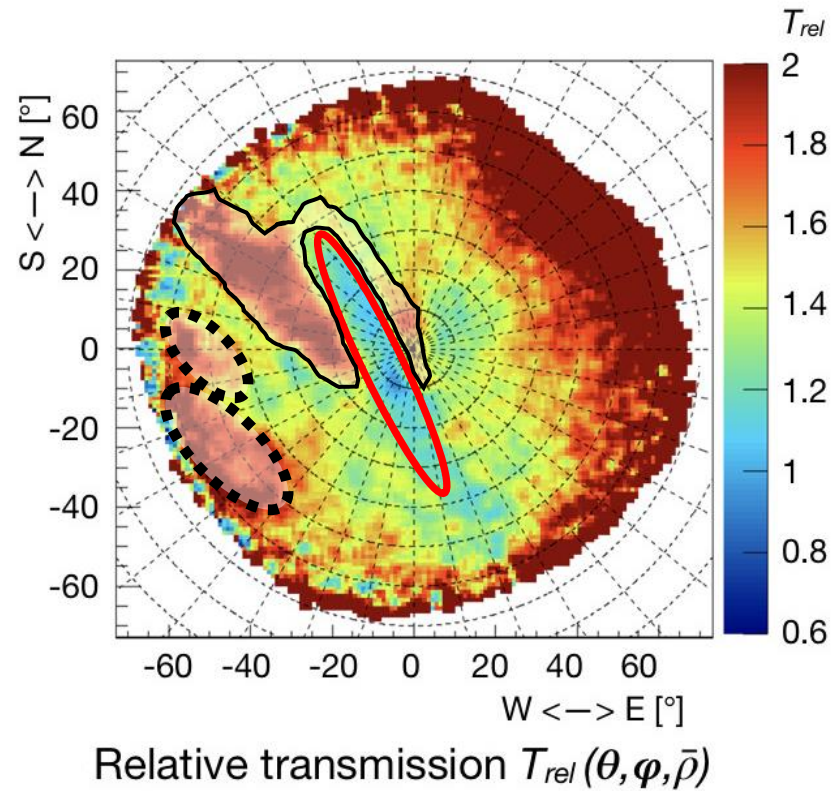
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The **measured flux** is defined as:

$$\phi_m(\theta, \varphi) = \frac{N(\theta, \varphi)}{t A_{eff}(\theta, \varphi)}$$

The **measured transmission**:

$$T_m(\theta, \varphi) = \frac{\phi_{m,target}(\theta, \varphi)}{\phi_{m,free-sky}(\theta, \varphi)}$$

The **simulated transmission**:

$$T_s(\theta, \varphi, \bar{\rho}) = \frac{\phi_{s,target}(\theta, \varphi, \bar{\rho})}{\phi_{s,free-sky}(\theta, \varphi)}$$

The **relative transmission**:

$$T_{rel}(\theta, \varphi, \bar{\rho}) = \frac{T_m(\theta, \varphi)}{T_s(\theta, \varphi, \bar{\rho})}$$

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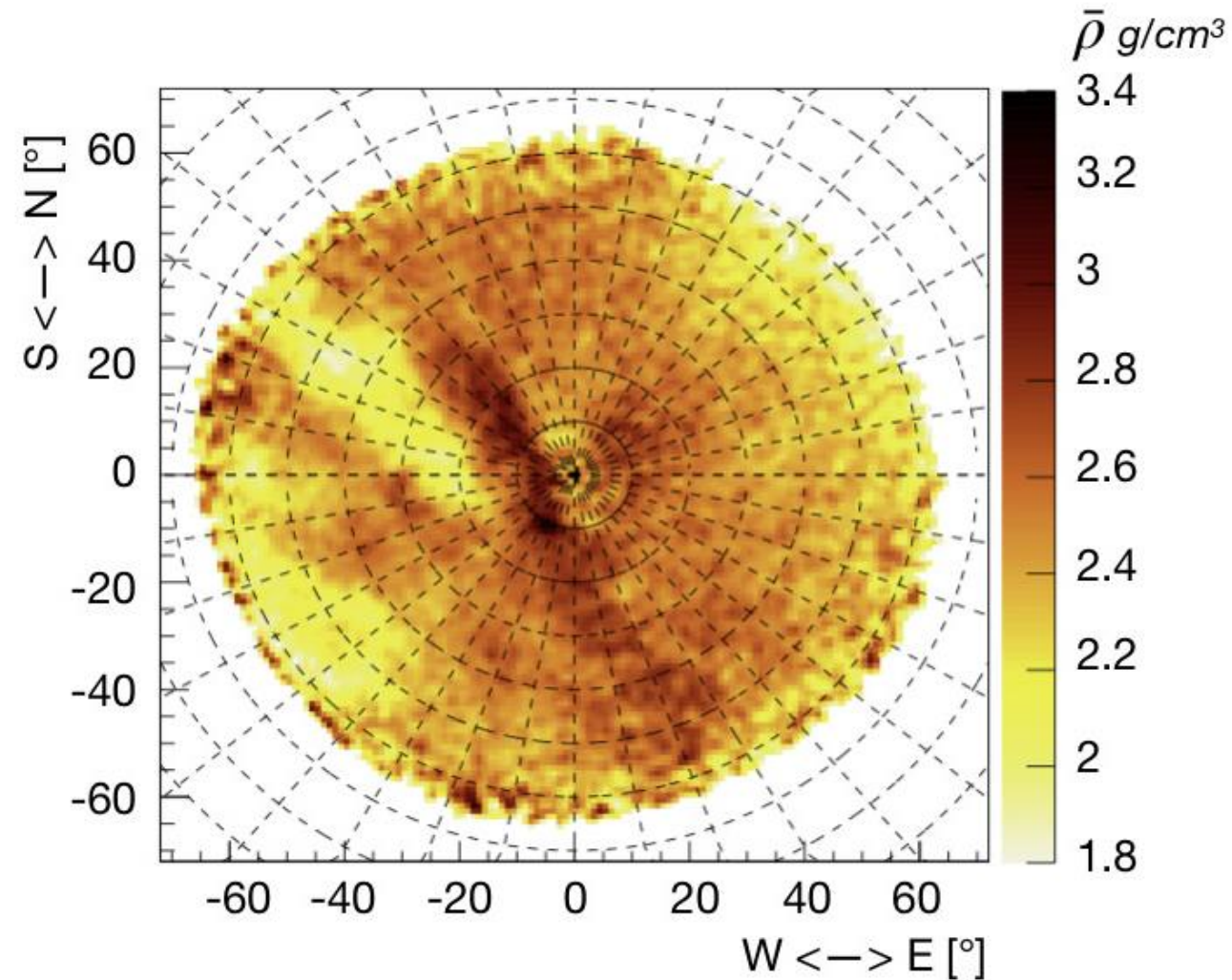
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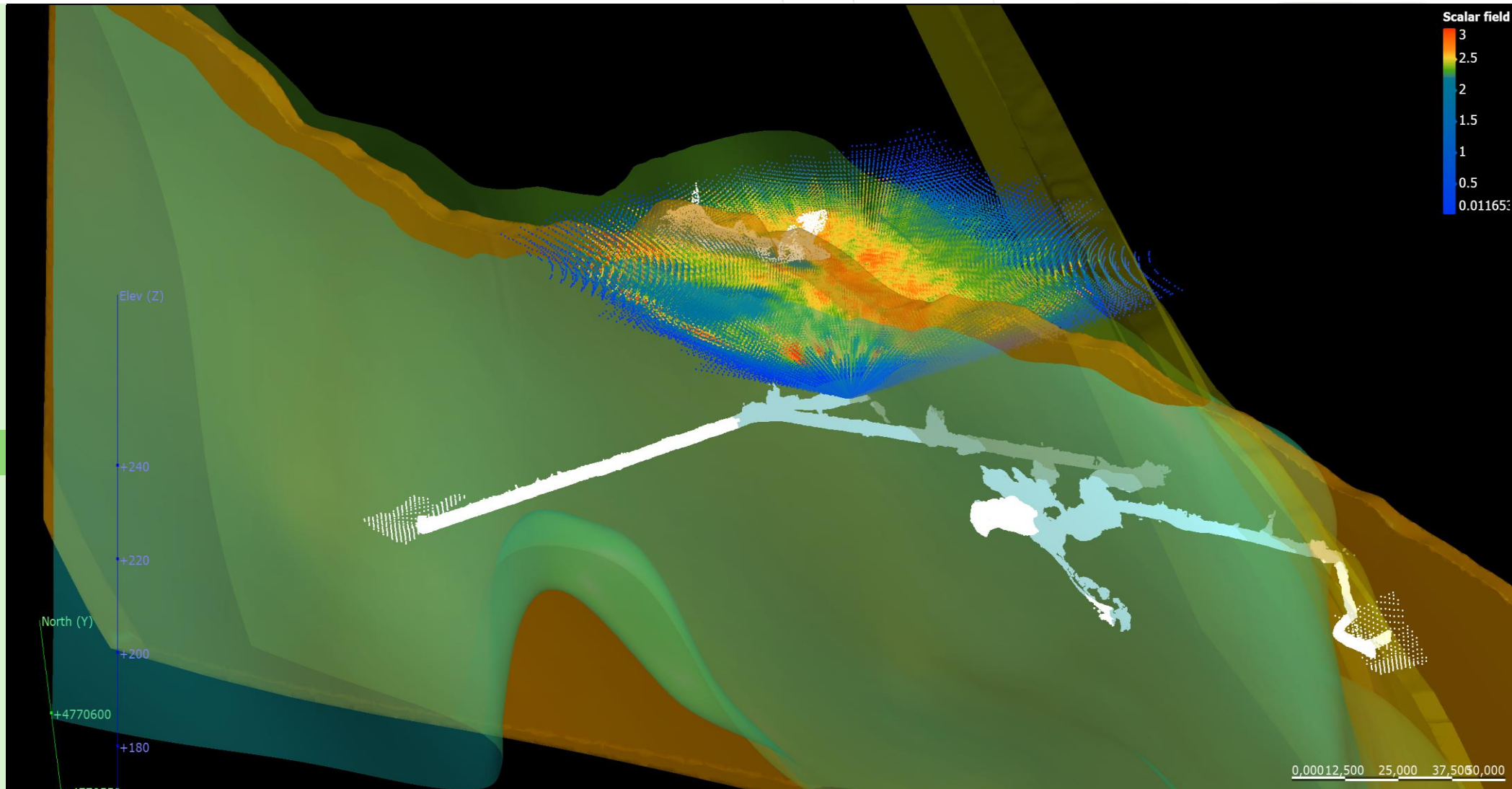
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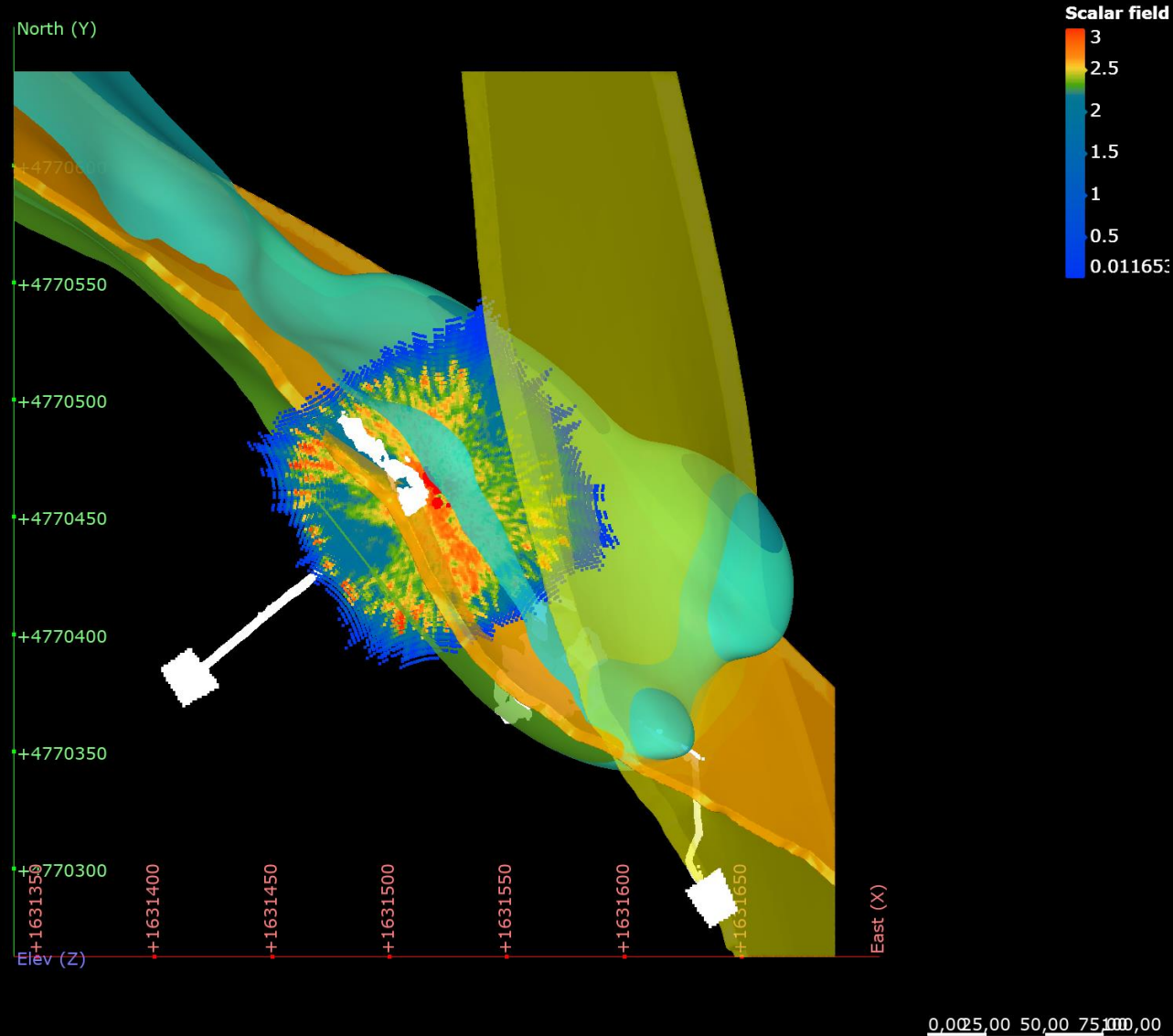
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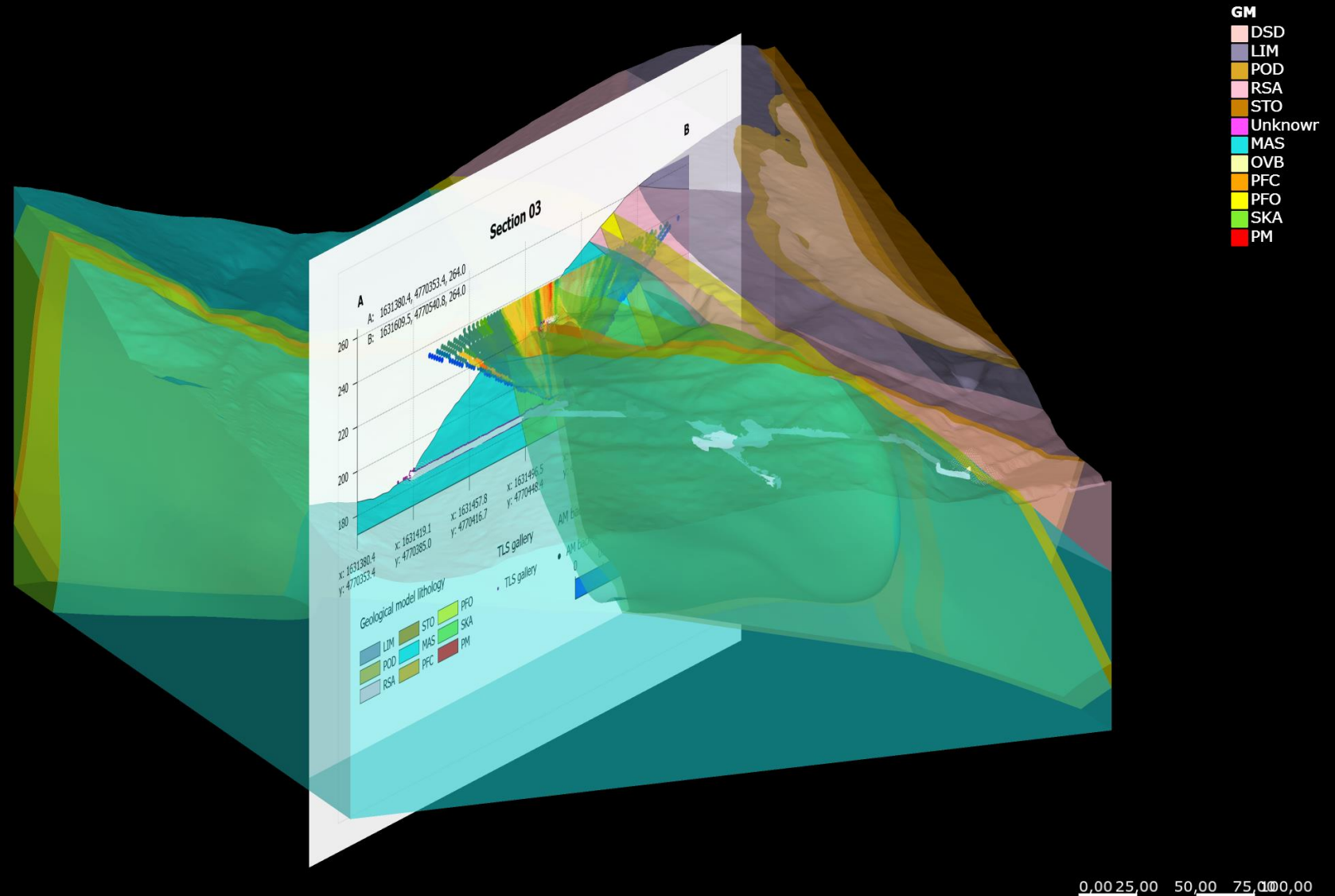
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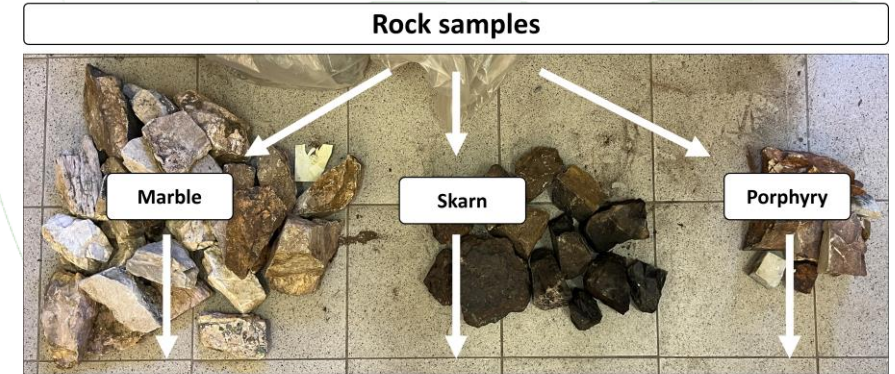
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- 1) Assess the effectiveness of transmission-based muography in identifying and characterizing the internal geometries of overlying rock formations by analyzing variations in transmission and density.
- 2) Demonstrate the potential of muography as a complementary tool to conventional mineral exploration techniques, enabling the visualization of density distributions within overlying rocks and indicating the presence of dense bodies or cavities to inform future mining planning and safety strategies.
- 3) Establish that even a single transmission-based muographic measurement can yield critical insights for subsurface operations.

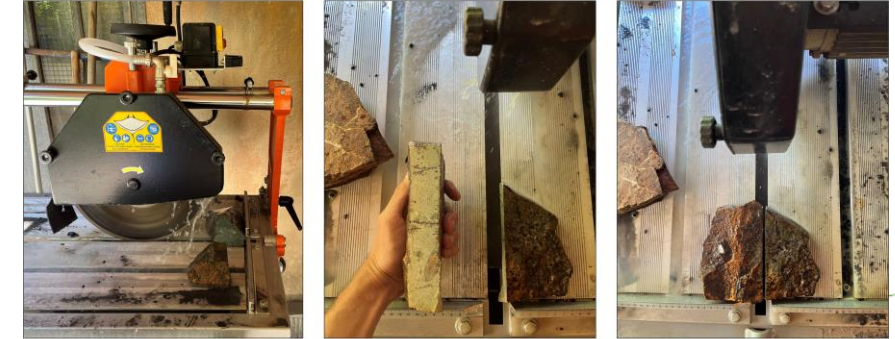
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<p><b>GEOLOGICAL STRENGTH INDEX FOR POINT-TO-POINT TESTS (see Table 2003)</b></p> <p>From the lithology, structure and surface condition of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Giving a range from 10 to 27 is more realistic than giving just a single value. Be sure that the value you give is structurally controlled. Failure planes must occur discontinuity planes are present in an unfavourable orientation with respect to the excavation face. Hence the shear strength of rock mass is reduced. If changes in moisture content will be induced, a shift to the right may be made. In wet conditions, water pressure is dealt with by effective stress analysis.</p> <p><b>SURFACE CONDITIONS</b></p> <p>VERY HIGHLY FRESH (no weathering surfaces) HIGH (highly weathered, no loose surfaces) MODERATE (moderately weathered and stable surfaces) POOR (discontinuity highly weathered surfaces with important weathering products) VERY POOR (discontinuity surfaces with soft clay coatings or fillings)</p> <p><b>STRUCTURE</b></p> <p><b>INTACT OR MASSIVE</b> - intact rock specimens or massive in situ rock with few widely spaced discontinuities</p> <p><b>BLOCKY</b> - well interlocked unfractured rock mass consisting of angular blocks formed by three intersecting discontinuity sets</p> <p><b>VERY BLOCKY</b> - interlocked, partially disintegrated mass with multi-faceted angular blocks formed by 4 or more joint sets</p> <p><b>BLOCKY WITH DISCONTINUITIES</b> - block with angular blocks formed by many intersecting discontinuity sets. Presence of bedding planes or schistosity</p> <p><b>DISINTEGRATED</b> - poorly interlocked, newly broken rock mass with mixture of angular and rounded rock pieces</p> <p><b>LAMINATED/SHEARED</b> - Lack of blockiness due to close spacing of weak schistosity or shear planes</p>	
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**Slab saw for resizing bigger samples into smaller ones**



**Samples ready for PLT**



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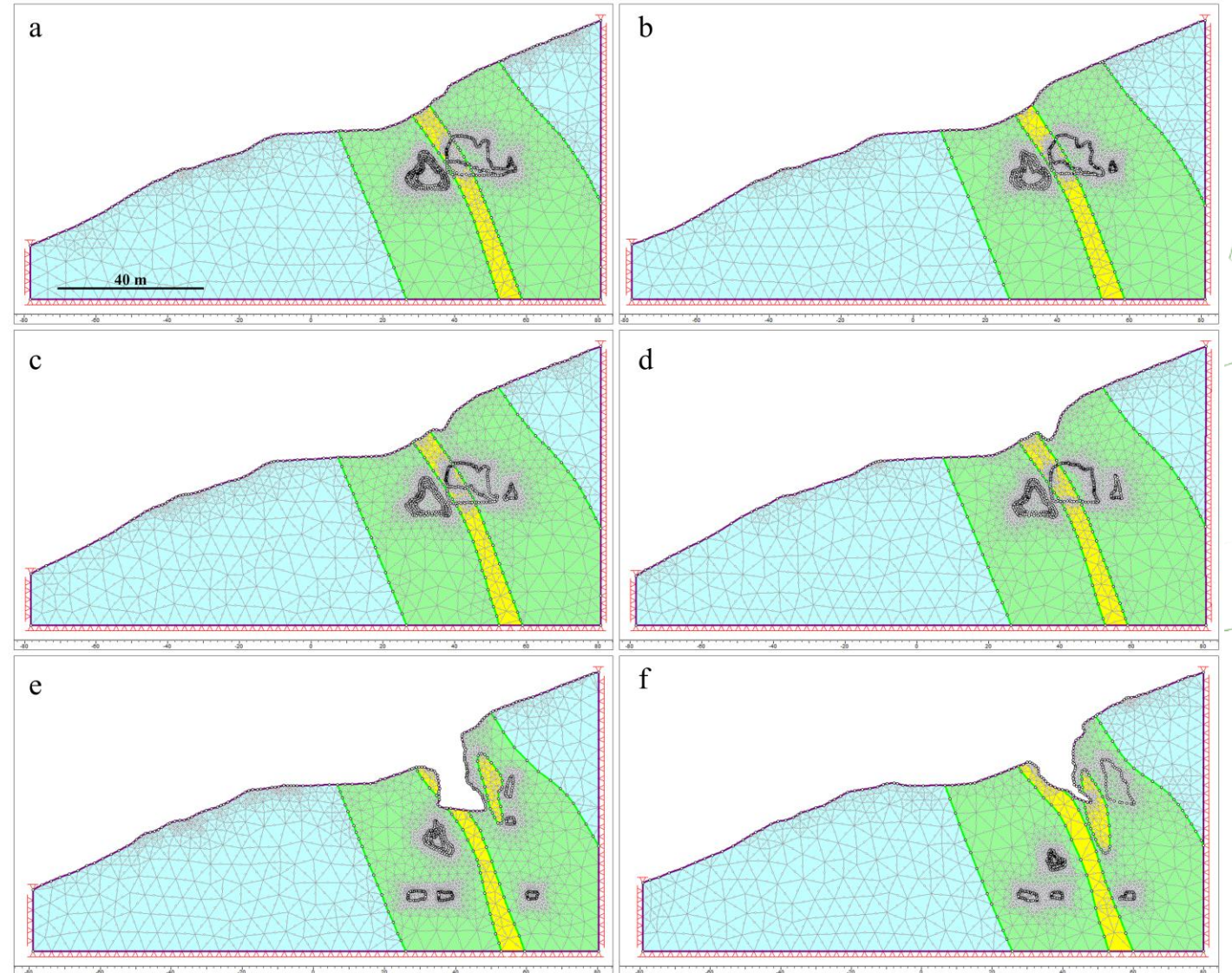
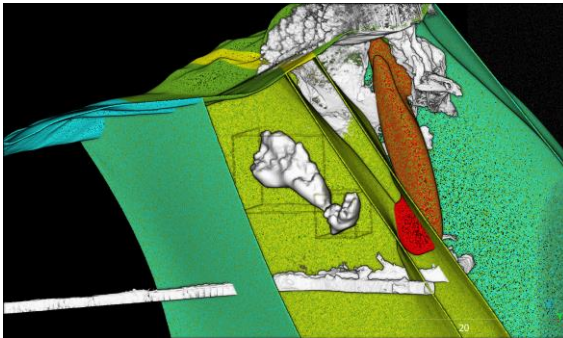
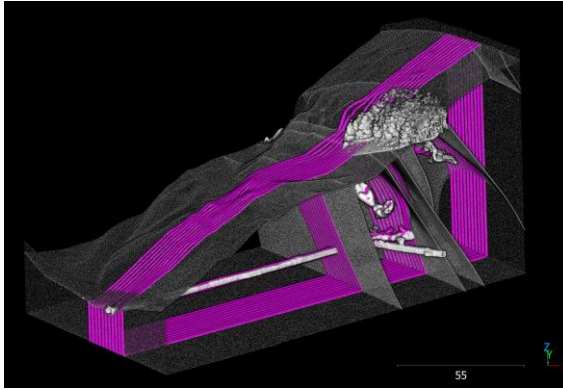
4.4 Video animation

## 5. Conclusions

5.1 Goals

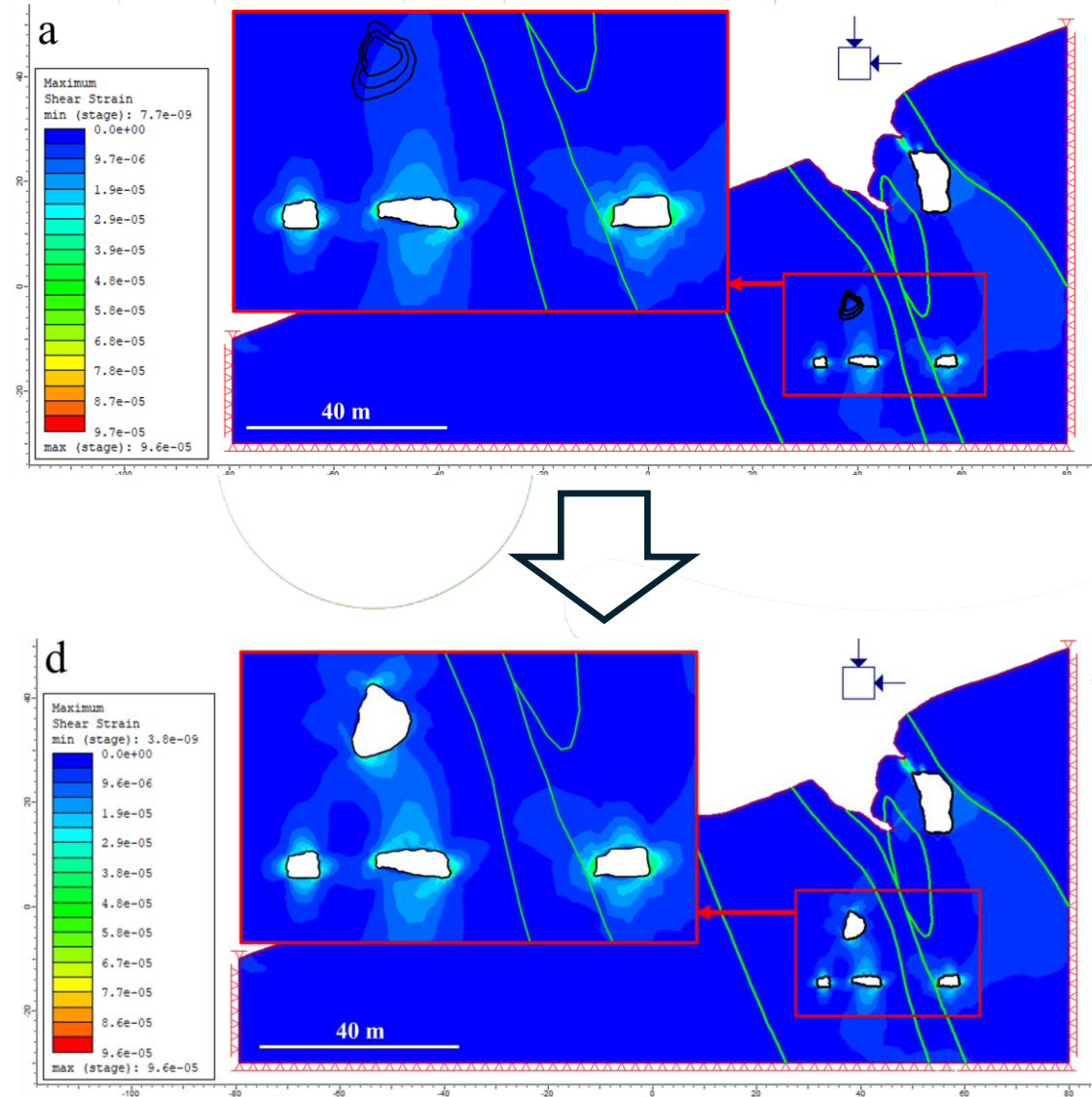
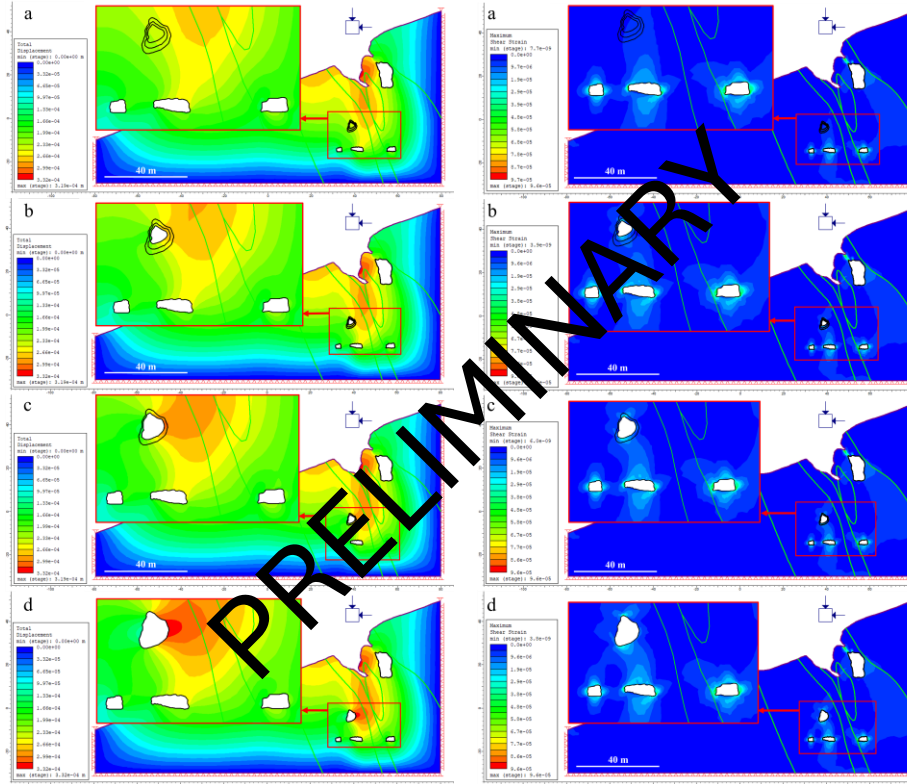
5.2 Challenges

5.3 References



# Challenges

- 1. About me
- 2. Muon imaging
  - 2.1 Mining applications
- 3. Case study
  - 3.1 Where?
  - 3.2 Geological setting
- 4. Results
  - 4.1 Transmission map
  - 4.2 Density map
  - 4.3 Interpretations
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- 5. Conclusions
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## 1. About me

## 2. Muon imaging

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## 4. Results

### 4.1 Transmission map

### 4.2 Density map

### 4.3 Interpretations

### 4.4 Video animation

## 5. Conclusions

### 5.1 Goals

### 5.2 Challenges

### 5.3 References

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3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"

