Engineering geological applications of muon imaging

Beni Tommaso

Technologist at the Department of Earth Sciences of the University of Florence

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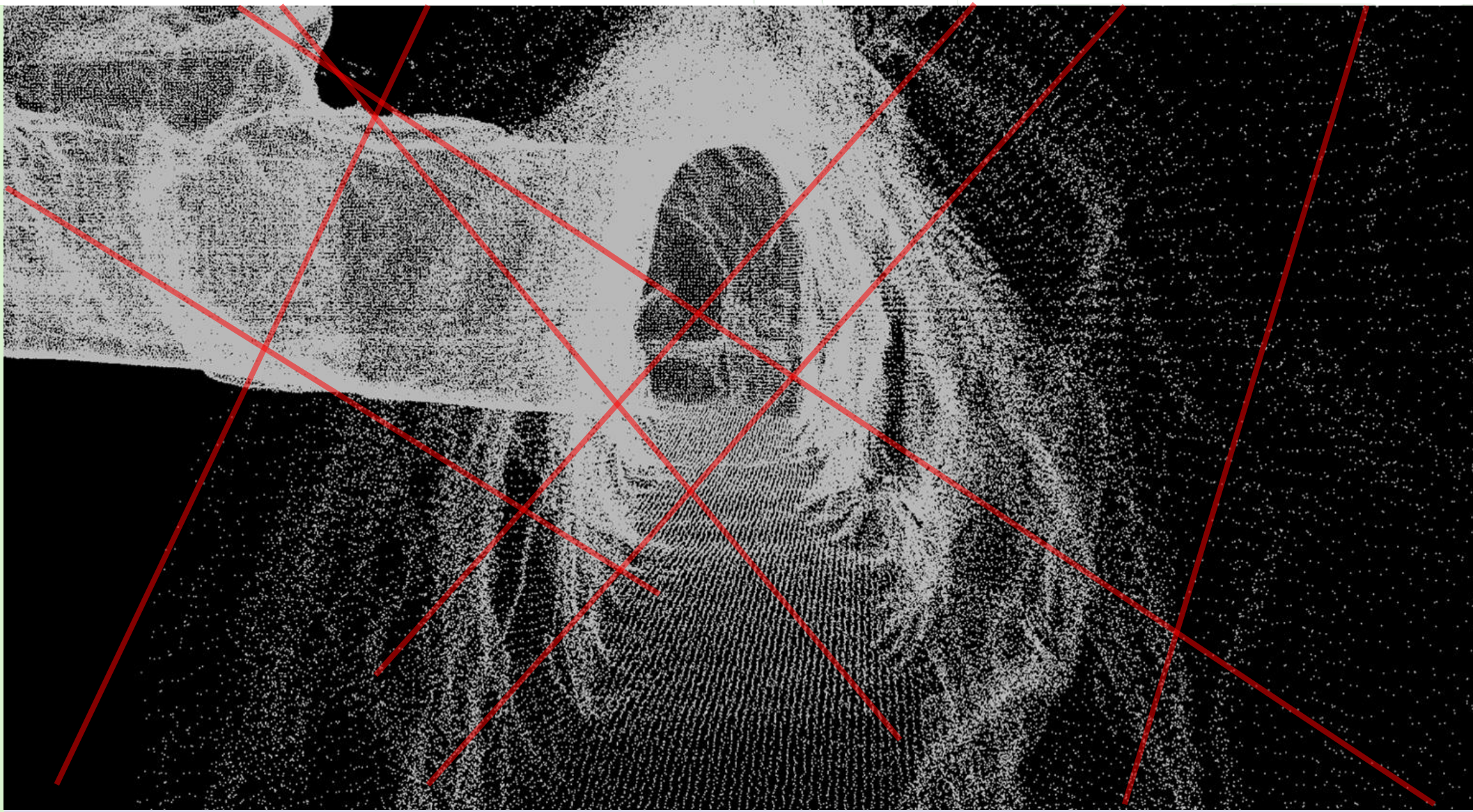
Using muons to detect density anomalies underground



About me

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

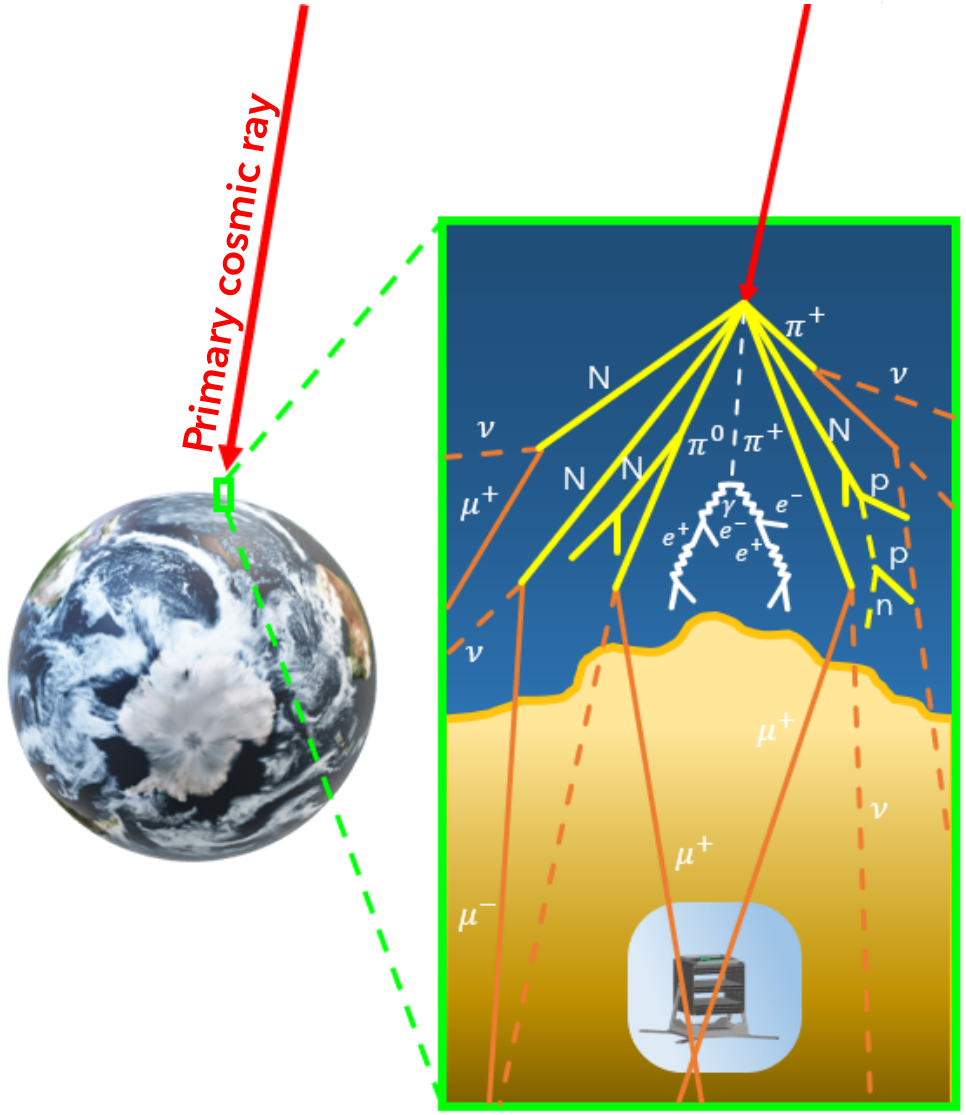
2023 Research fellow

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)

Muon imaging



Cosmic-rays

air shower

Muons μ

Highly penetrating charged particles

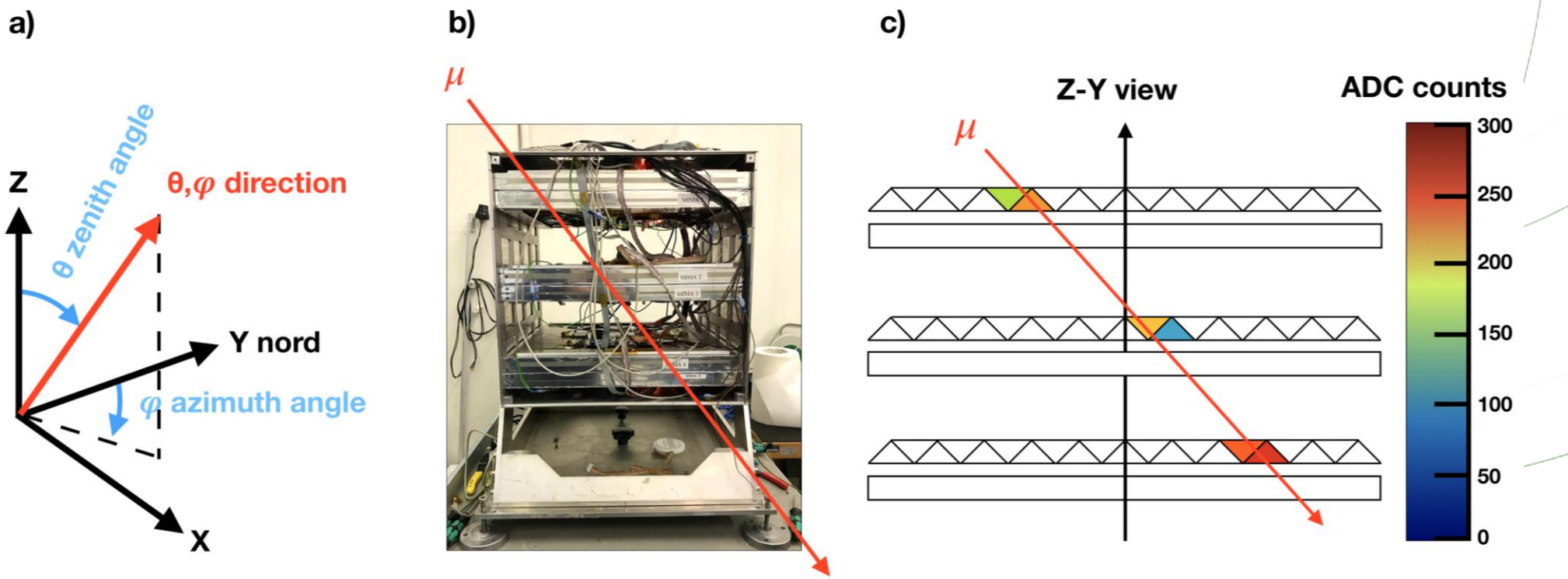
Average life-time μ: ~ 2.2 μs

Mass μ: 105.6 Mev/c^2 (~ 200 $m_{electron}$)

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

Muon imaging

MIMA detector (Muon Imaging for Mining and Archaeology)



- Scintillator plastic bars
- Total consumption: ~ 30 W
- Dimensions: 50 x 50 x 50 cm^3
- Weight: ~ 60 kg
- Angular resolution: ~ 7 mrad (°??)
- Active surface: 0.16 m^2

For all the figures see references

Mining applications

Examples:

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

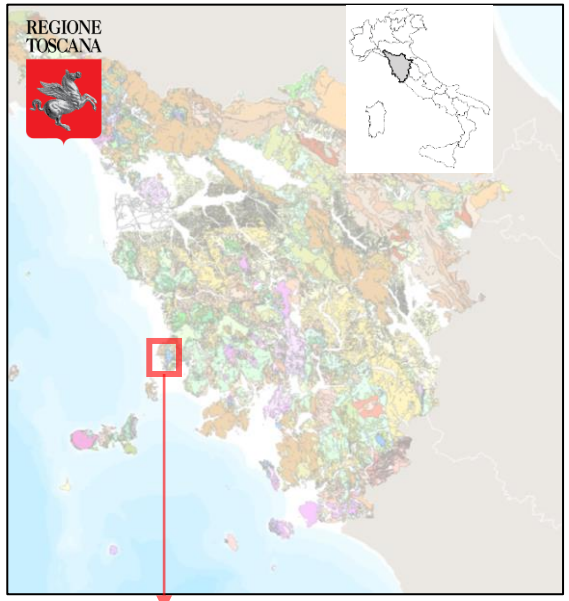
- Zhang, ZX., Enqvist, T., Holma, M. et al. **Muography and Its Potential Applications to Mining and Rock Engineering**. Rock Mech Rock Eng 53, 4893–4907 (2020). https://doi.org/10.1007/s00603-020-02199-9
- Schouten, D. (2019). **Muon geotomography: Selected case studies**. Philosophical Transactions 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

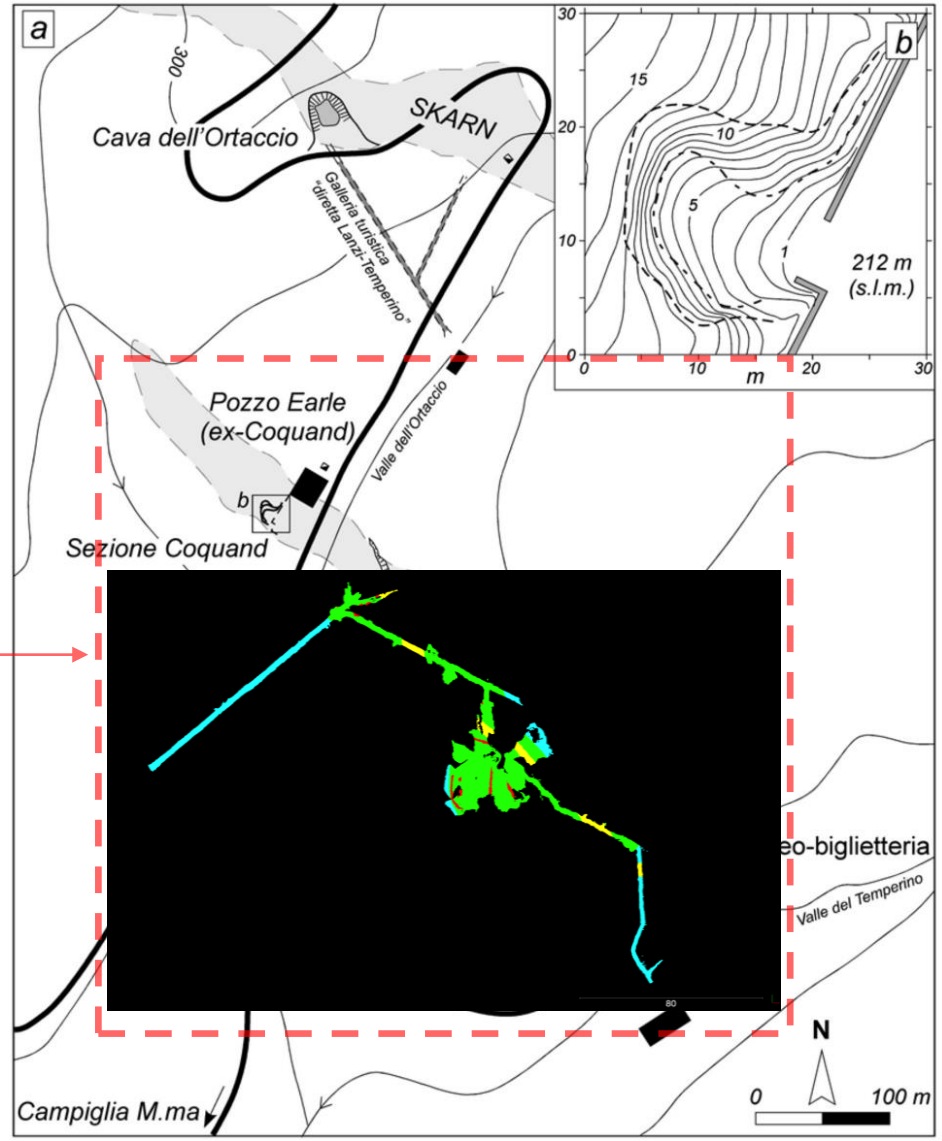
But the reality is that most of these studies are related to simulations, with only a few real case studies!

Case study

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

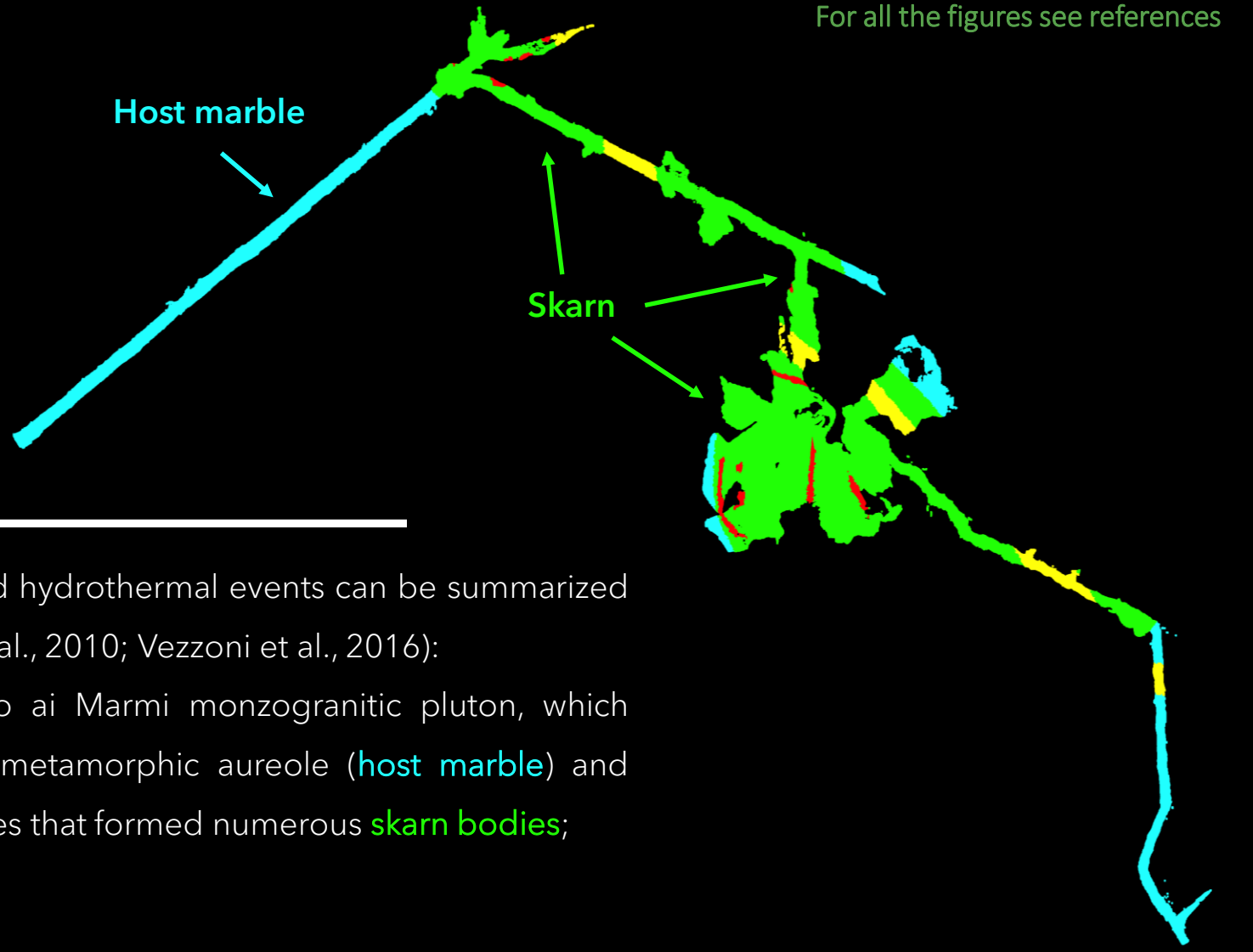
Where?





Geological setting of the mine

For all the figures see references



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;

Geological setting of the mine

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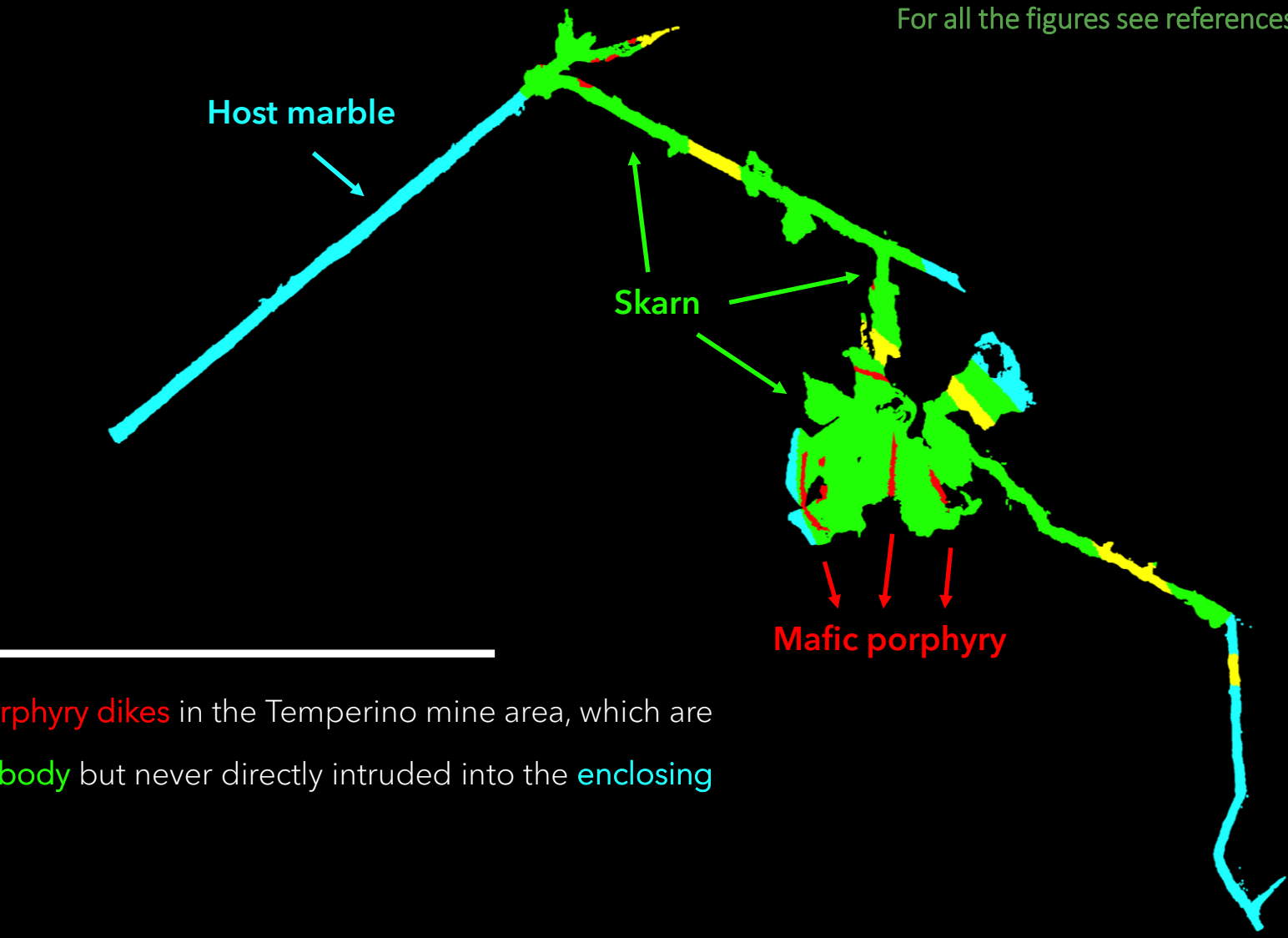

(2) Intrusion of mafic porphyry dikes in the Temperino mine area, which are associated with the skarn body but never directly intruded into the enclosing marble;

Geological setting of the mine

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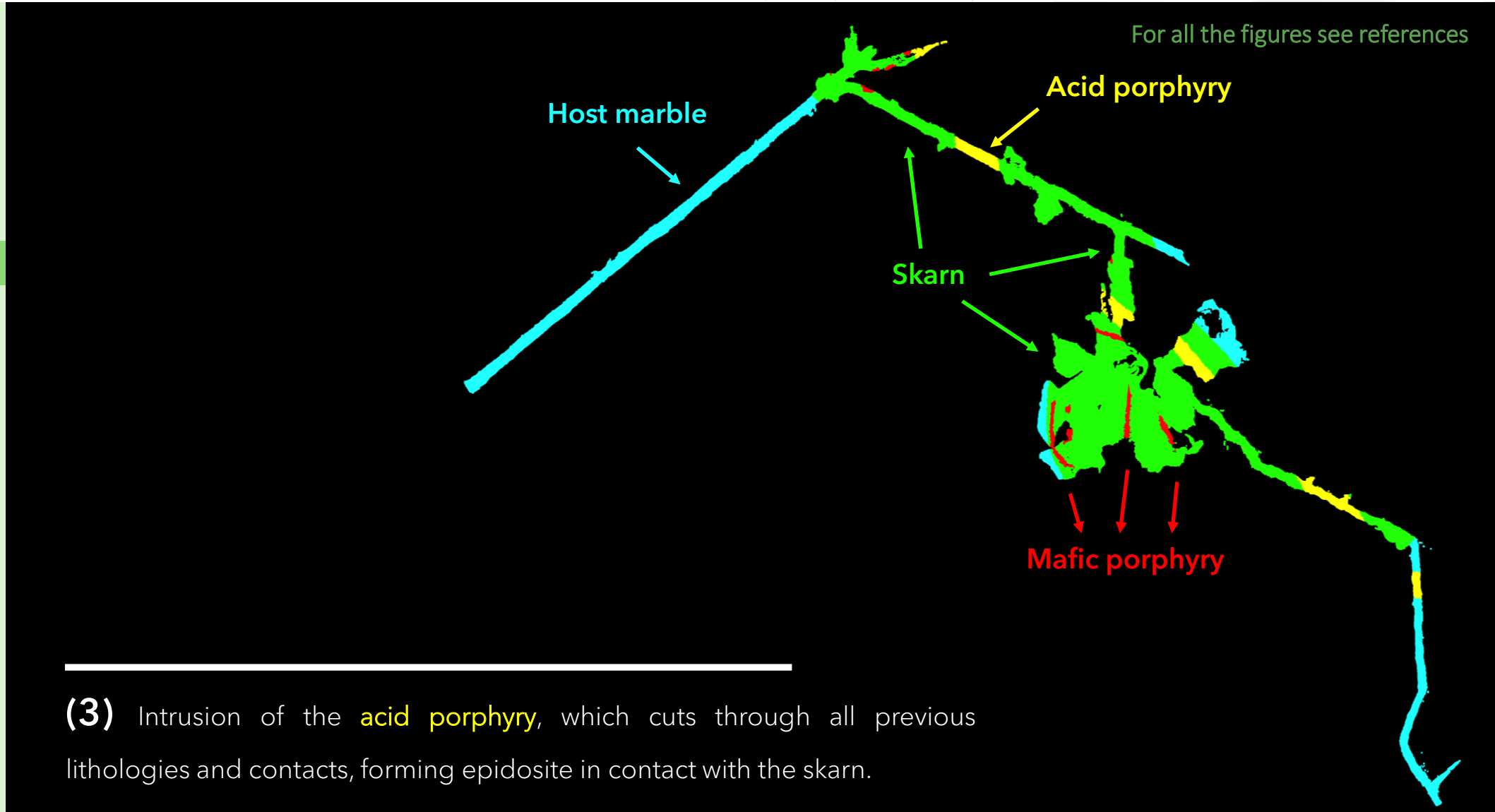
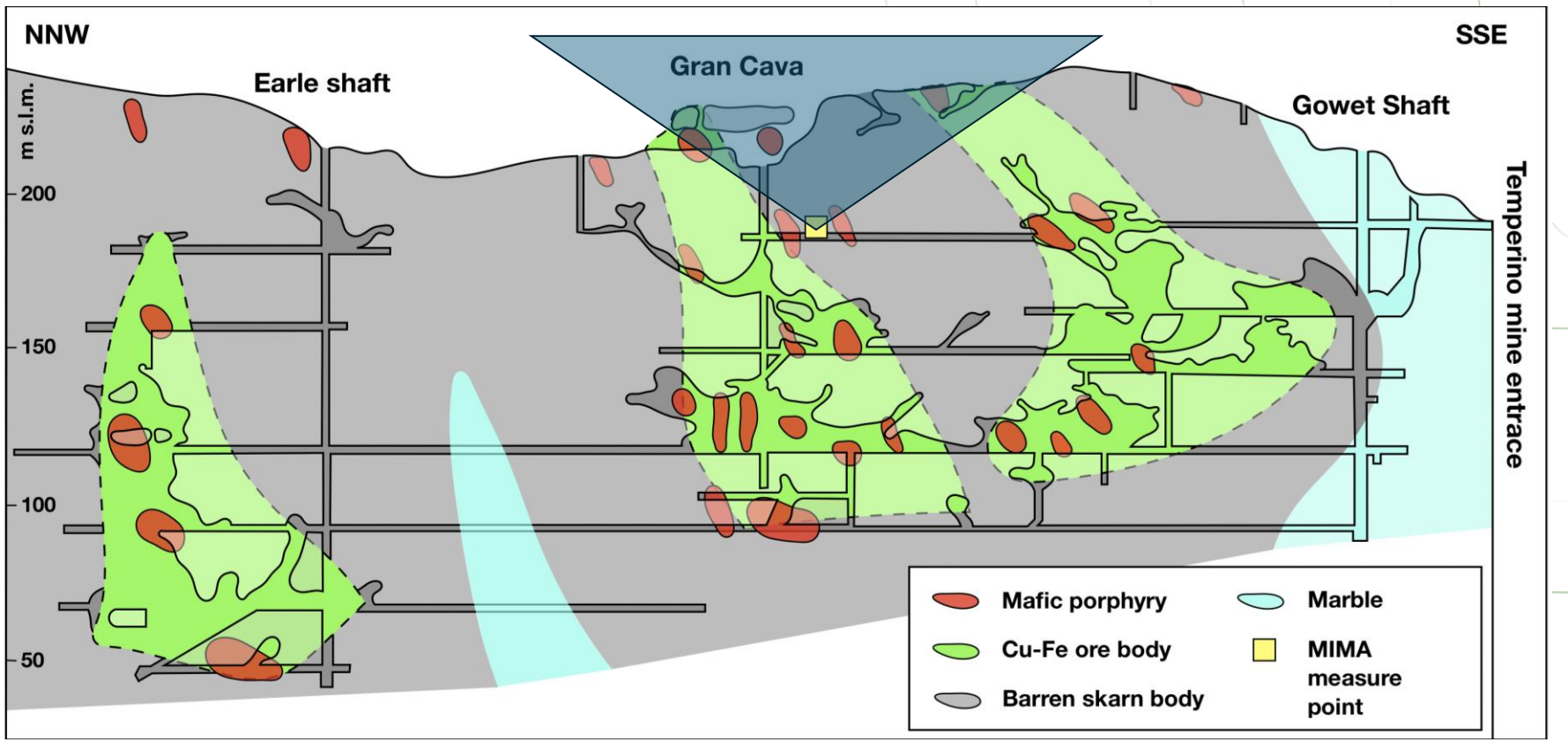


(3) Intrusion of the acid porphyry, which cuts through all previous lithologies and contacts, forming epidosite in contact with the skarn.

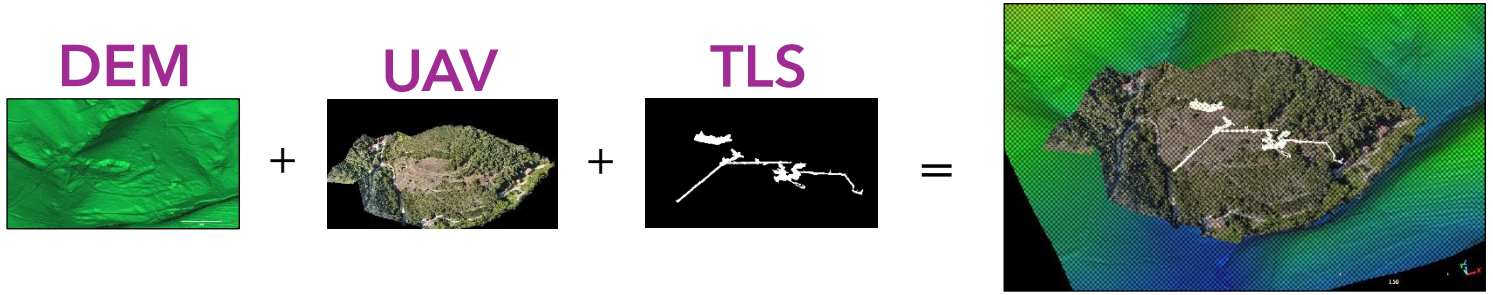
Geological setting of the mine

For all the figures see references



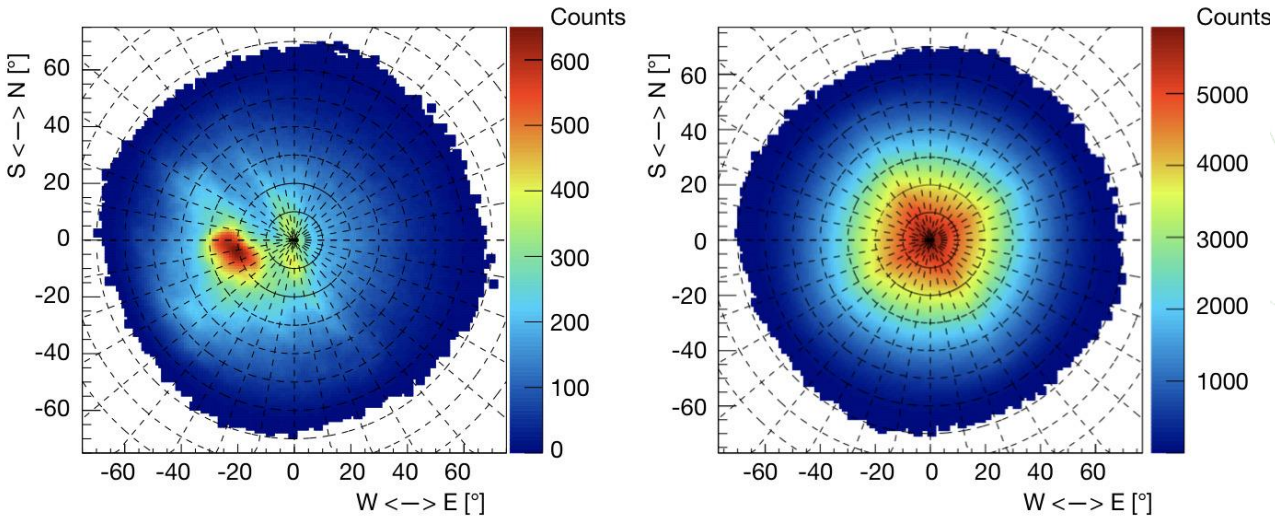
At the Temperino mine, Cu-Fe ore type are strictly associated with the intruded mafic porphyry masses (NNW-SSE) and are composed by massive chalcopyrite-pyrrhotite-pyrite association. The Cu-Fe ores are spatially associated to mafic intrusions, which shape and location depend on the primary skarn macroporosity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

Results

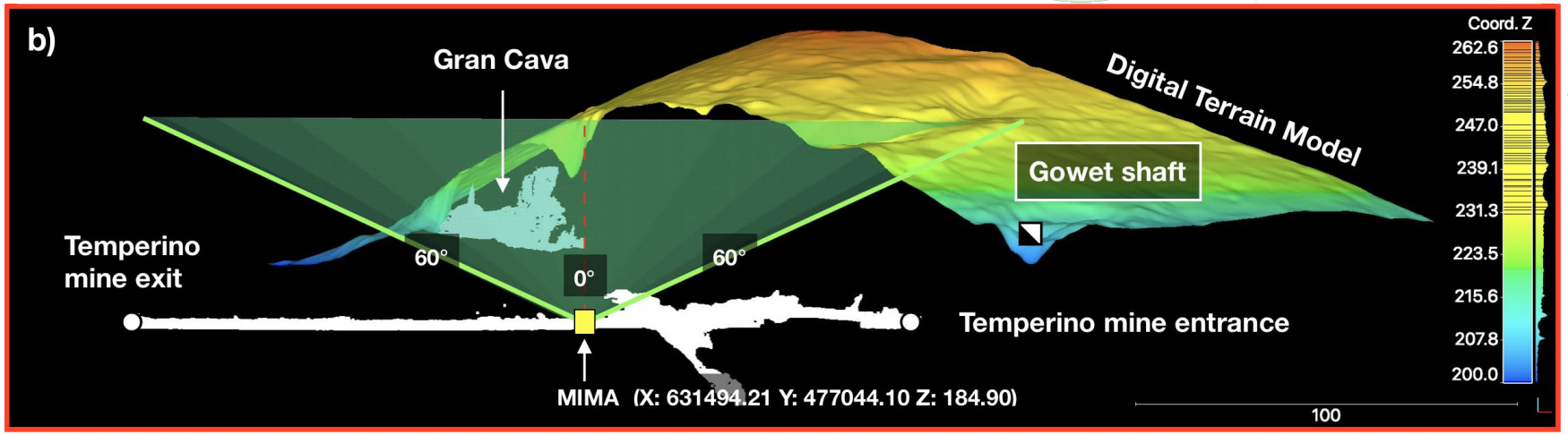


Transmission map

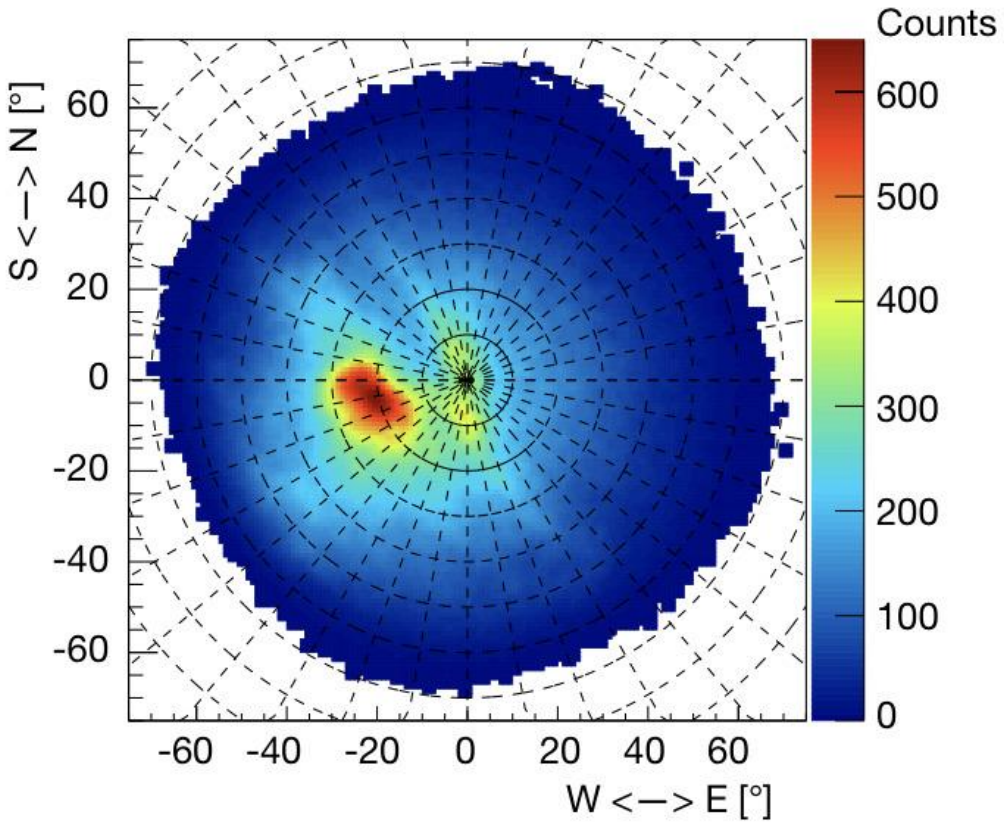
For all the figures see references



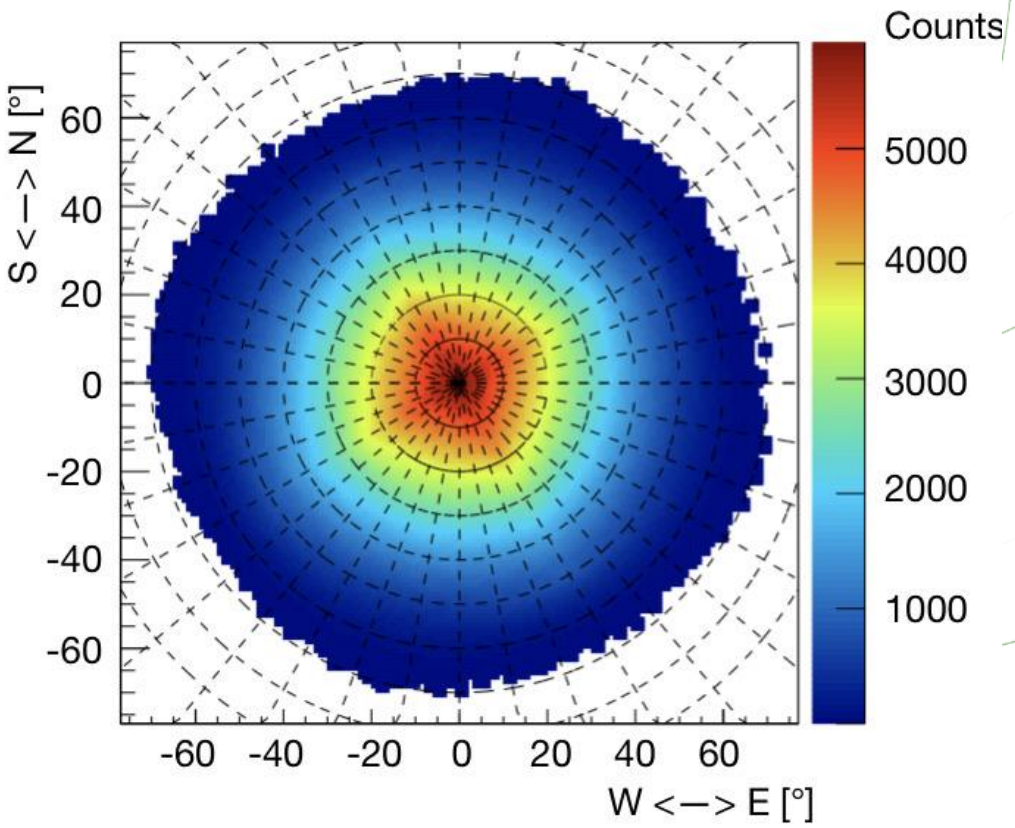
a) Target configuration events $N_{target}(\theta,\varphi)$ b) Free-sky configuration events $N_{free\text{-}sky}(\theta,\varphi)$



Transmission map



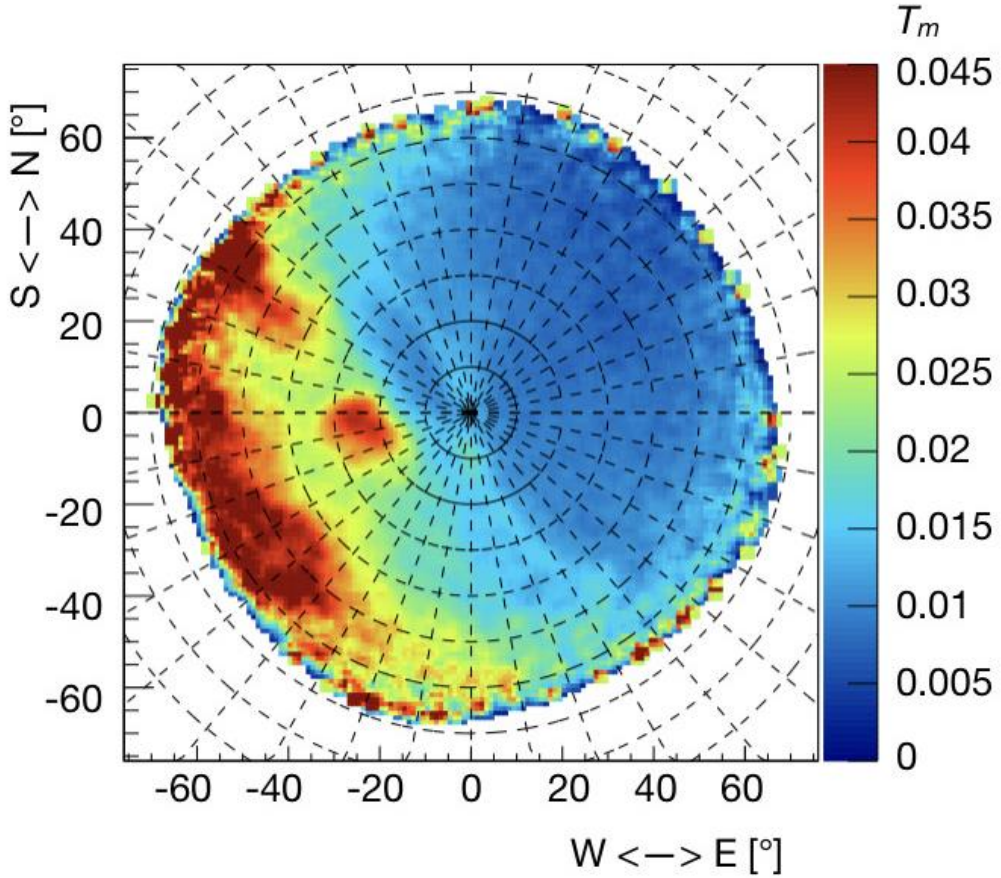
a) Target configuration events $N_{target}(\theta, \varphi)$



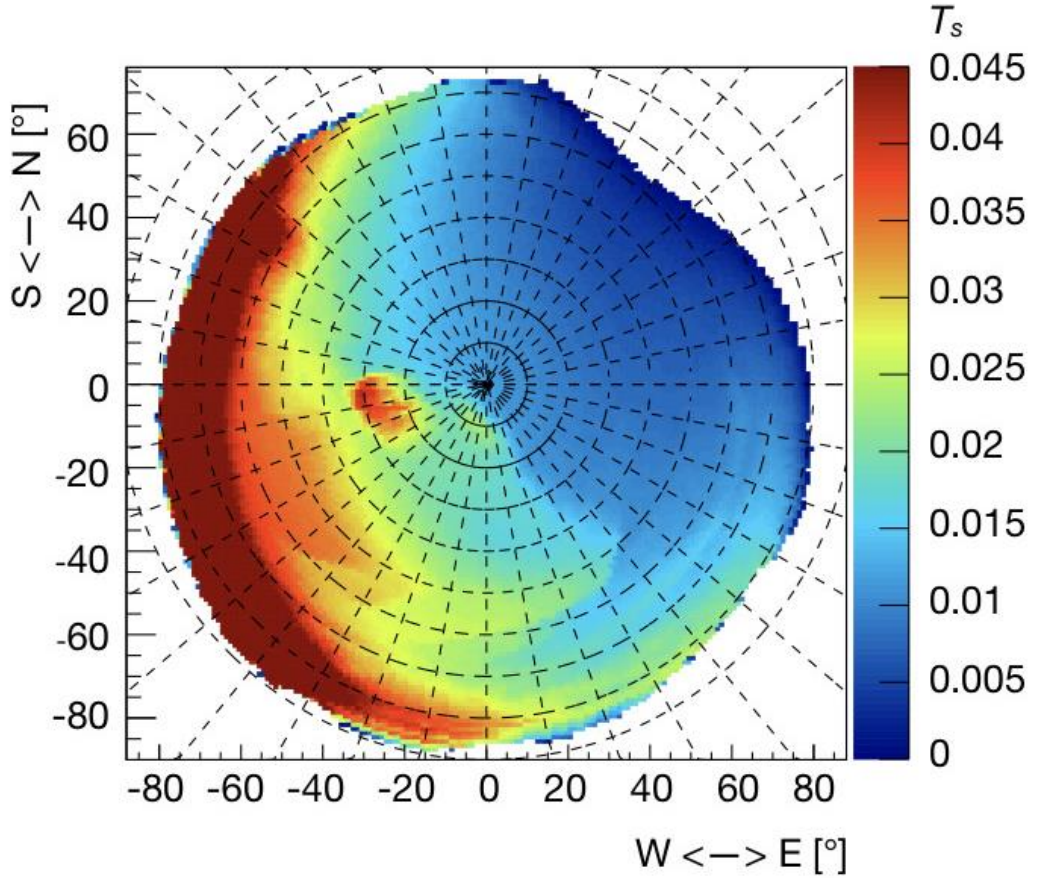
b) Free-sky configuration events $N_{free\text{-}sky}(\theta, \varphi)$

For all the figures see references

Transmission map



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



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

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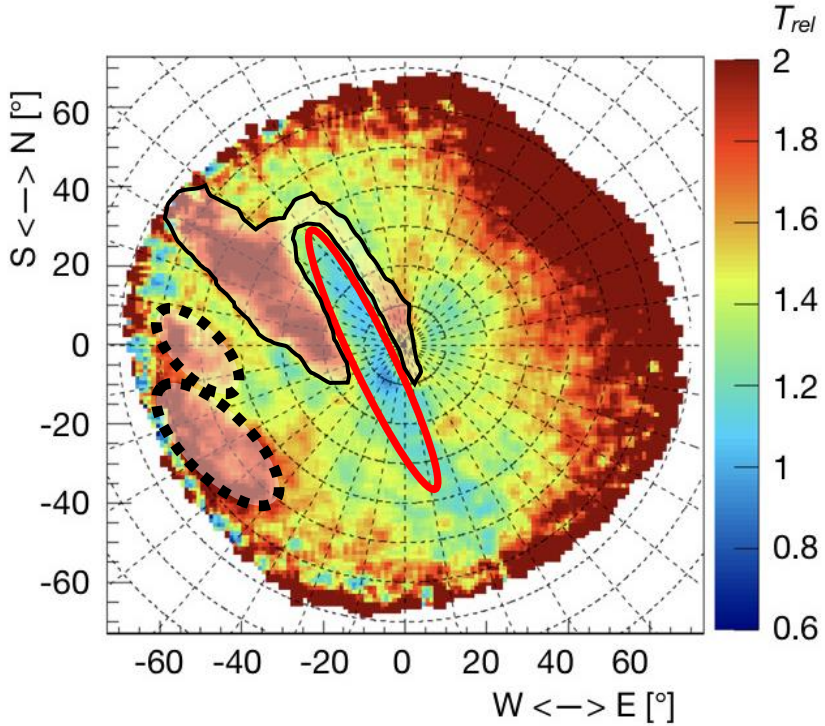
Transmission map



Relative transmission $T_{rel}(\theta, \varphi, \bar{\rho})$

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**:

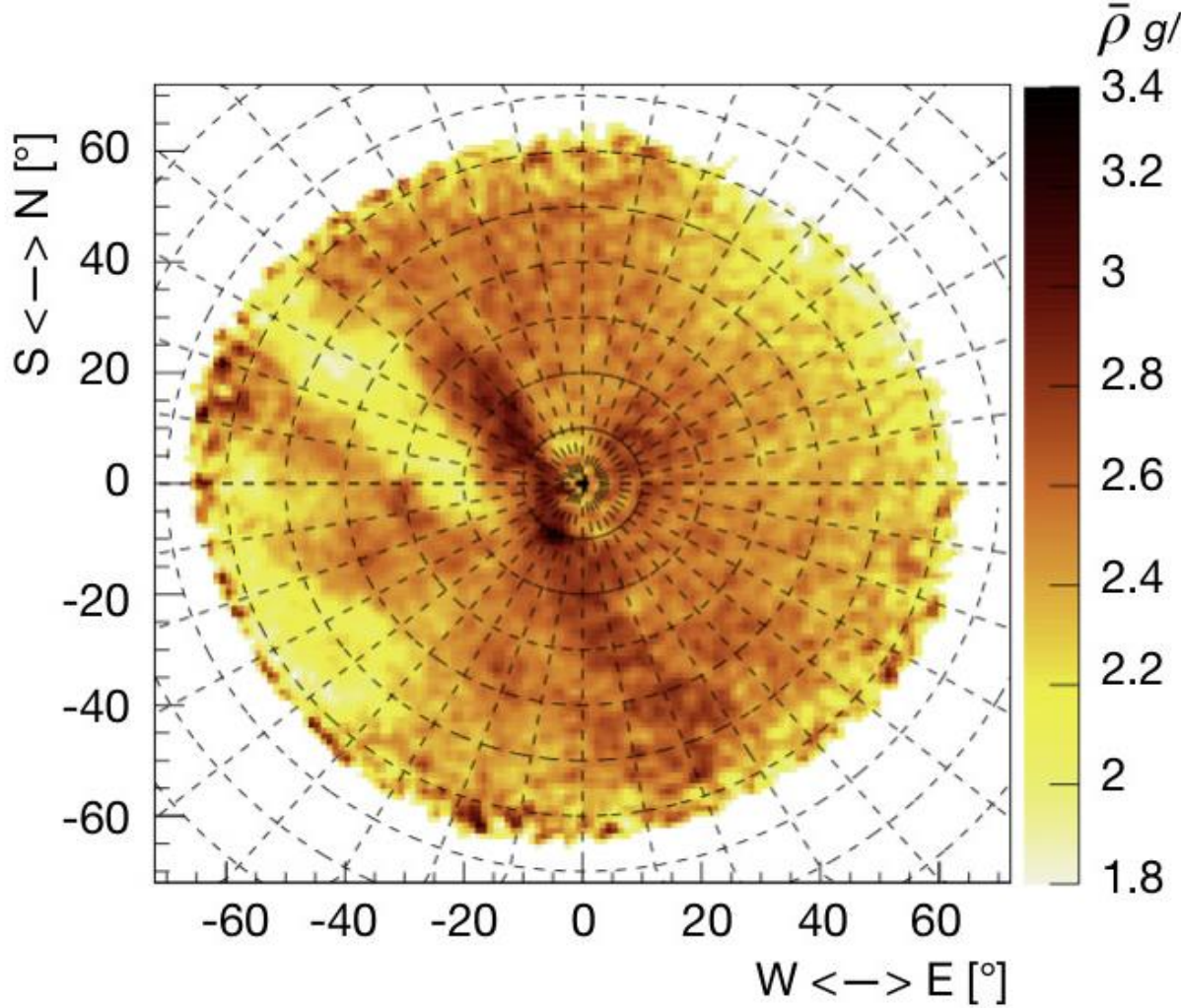
$$T_s(\theta, \varphi, \bar{\rho}) = \frac{\phi_{s,target}(\theta, \varphi, \bar{\rho})}{\phi_{s,free-sky}(\theta, \varphi)}$$

The **relative transmission**:

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

For all the figures see references

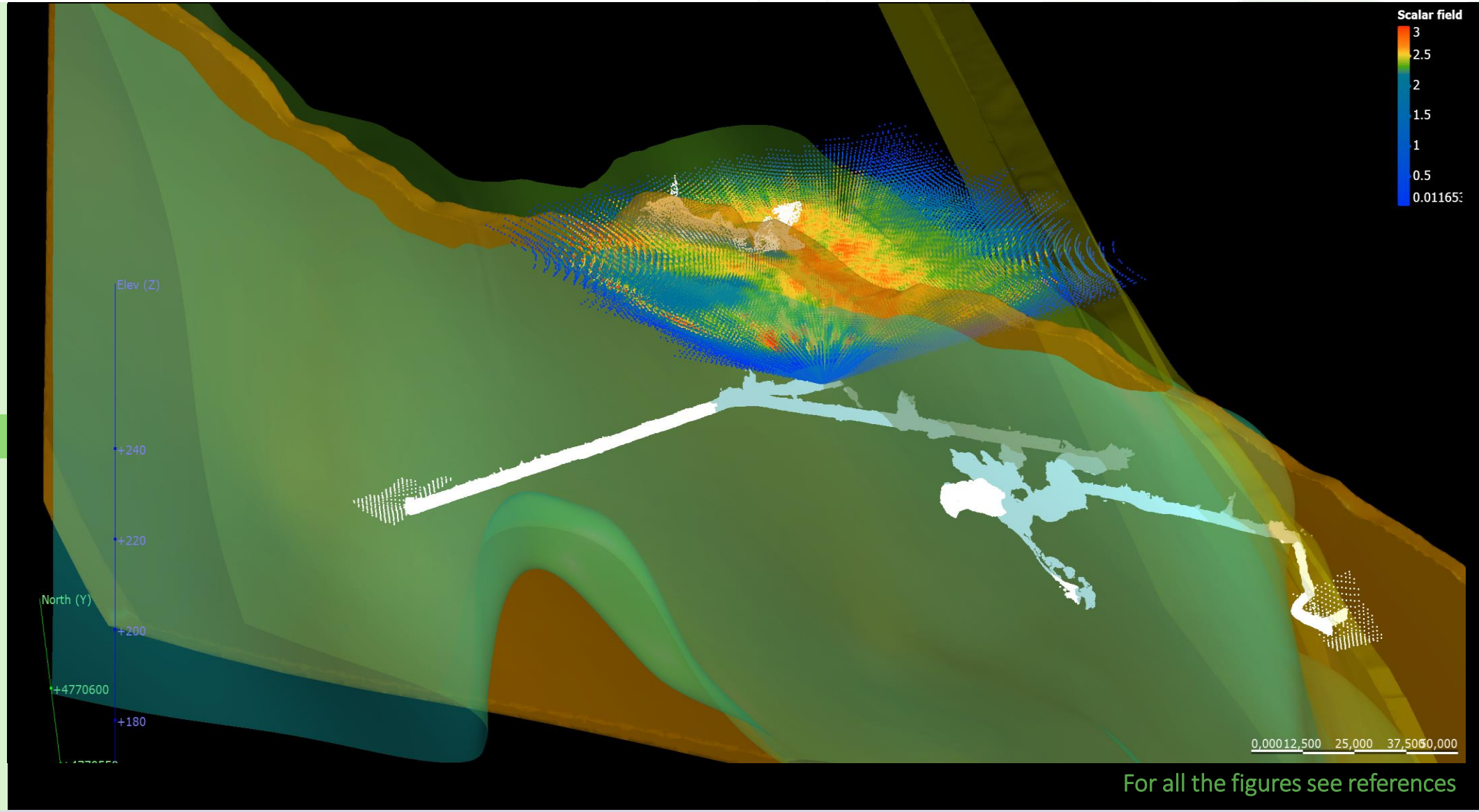
Density map



Average density $\bar{\rho}\,(\theta,\varphi)$

For all the figures see references

Interpretations



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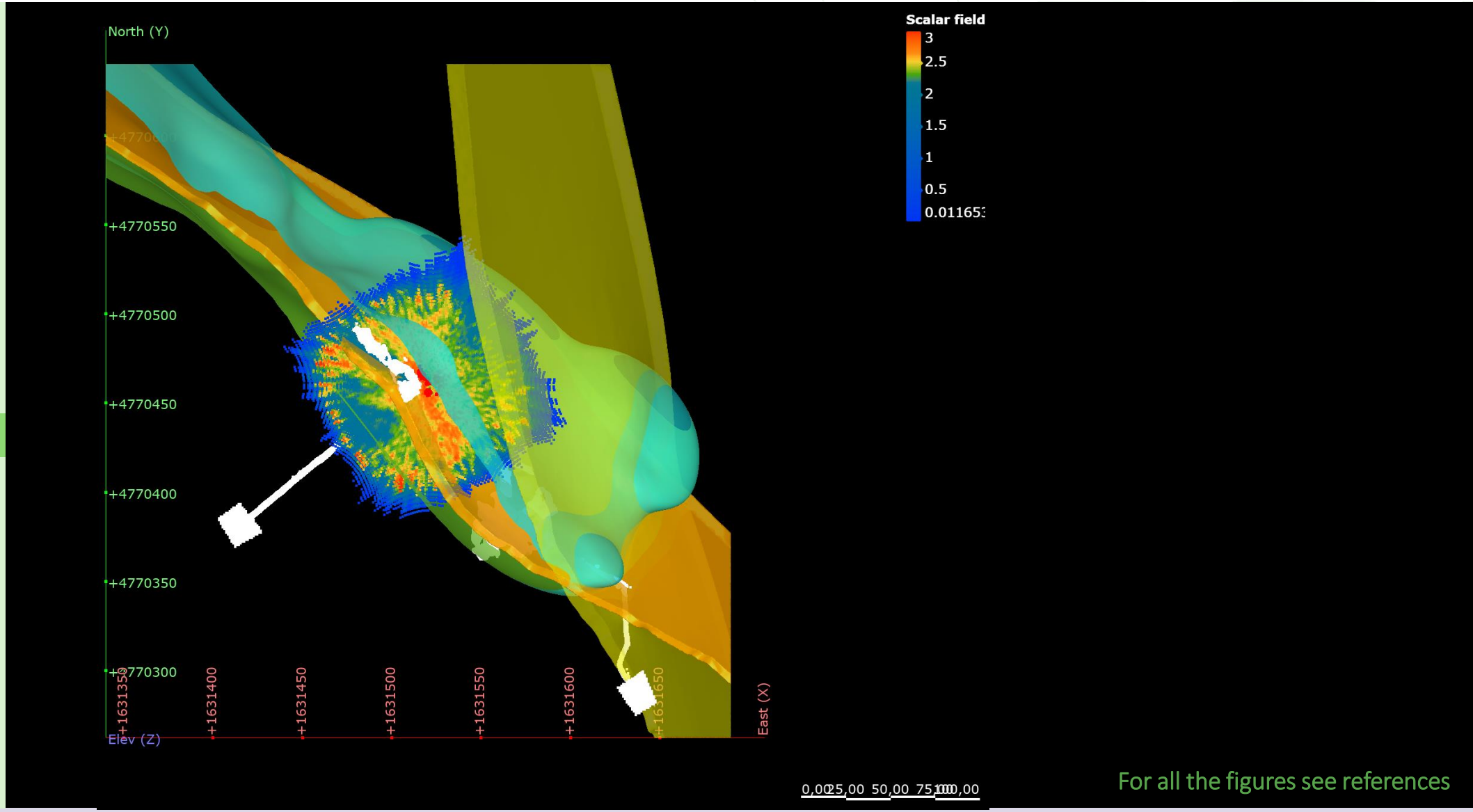

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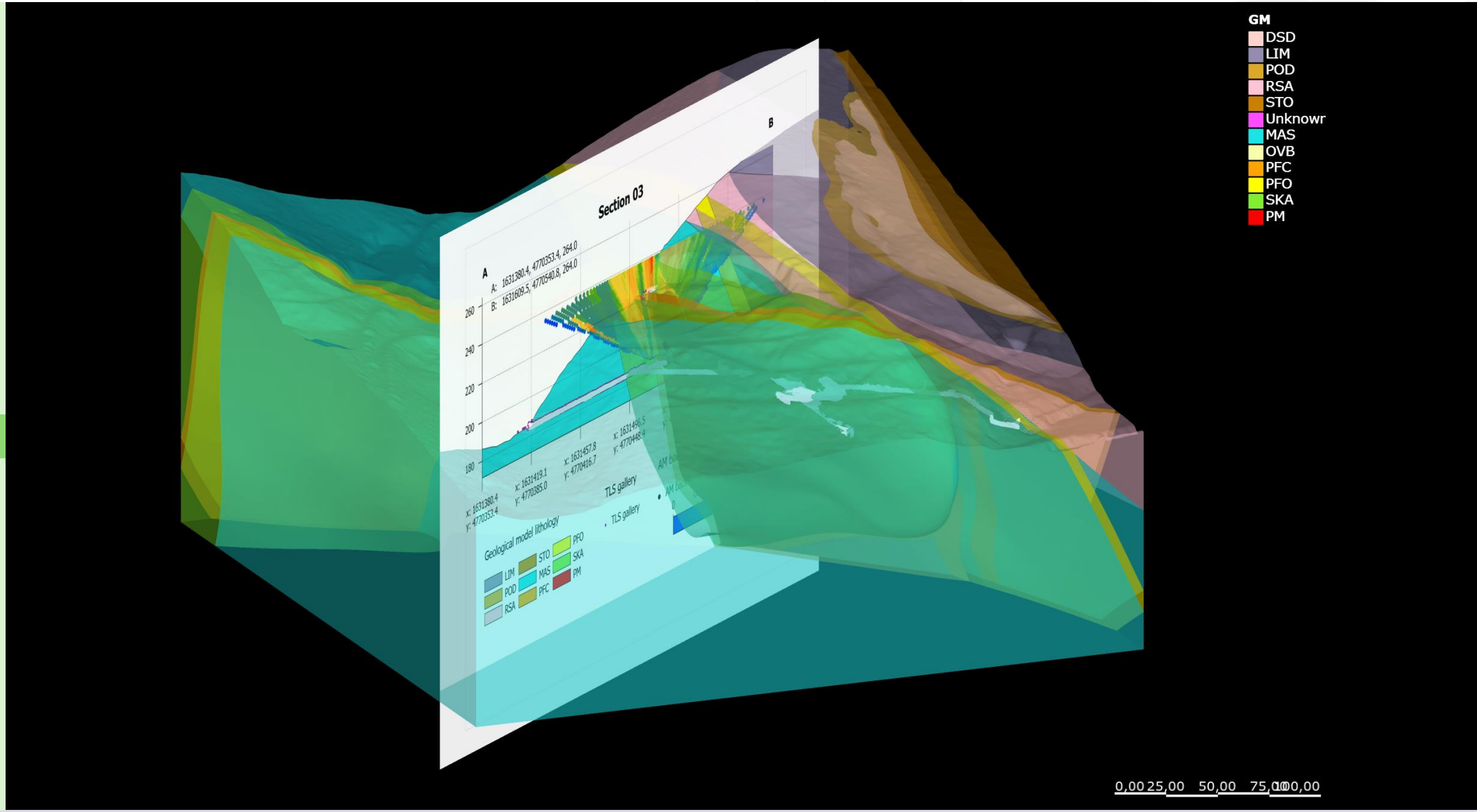
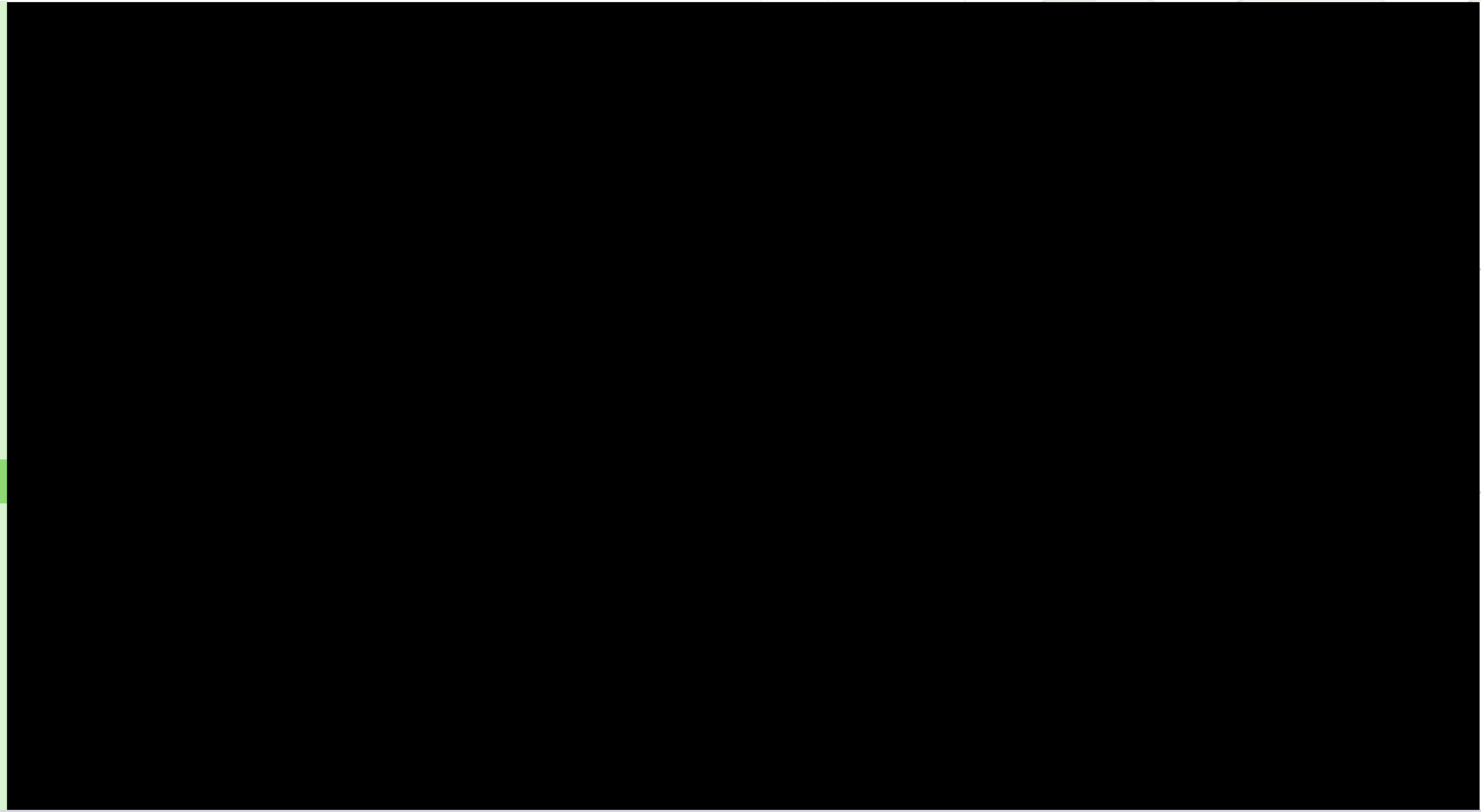


Video animation



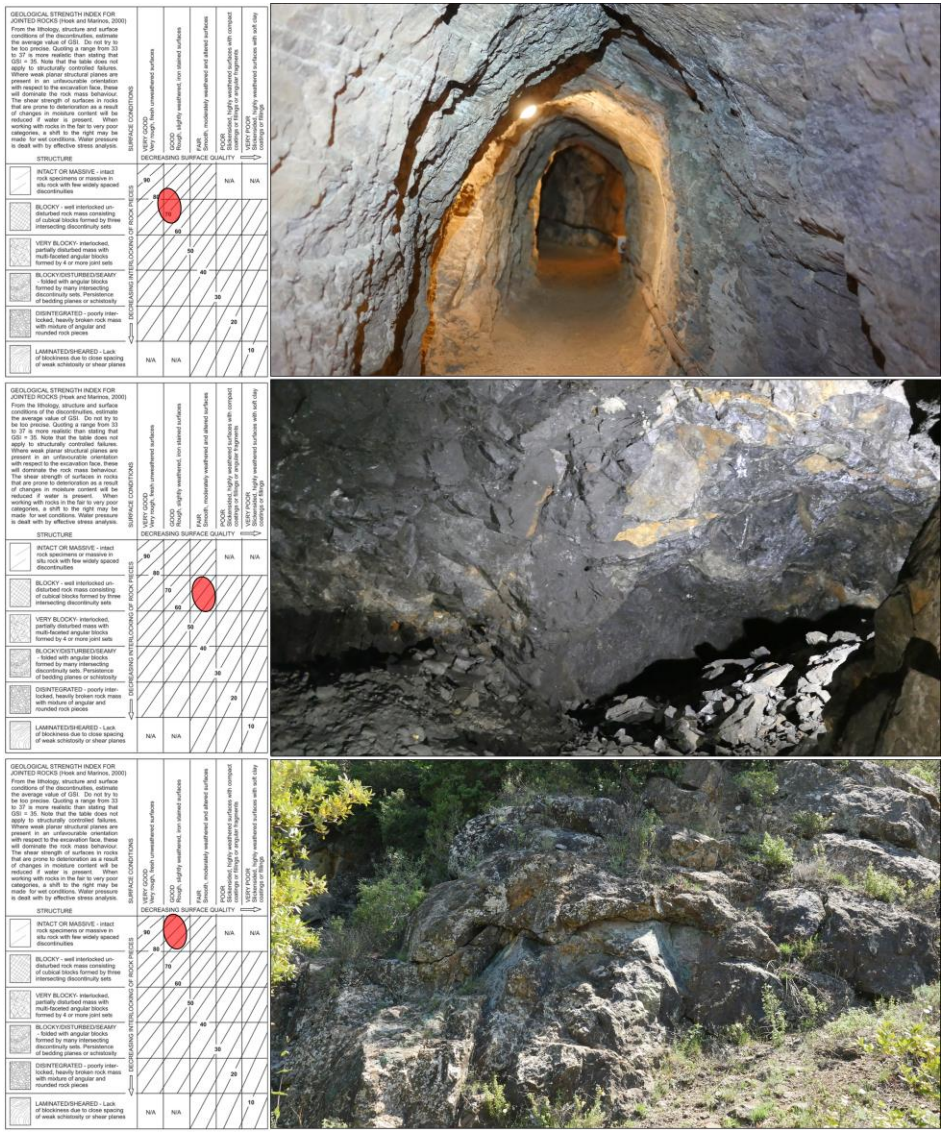
Conclusions: goals

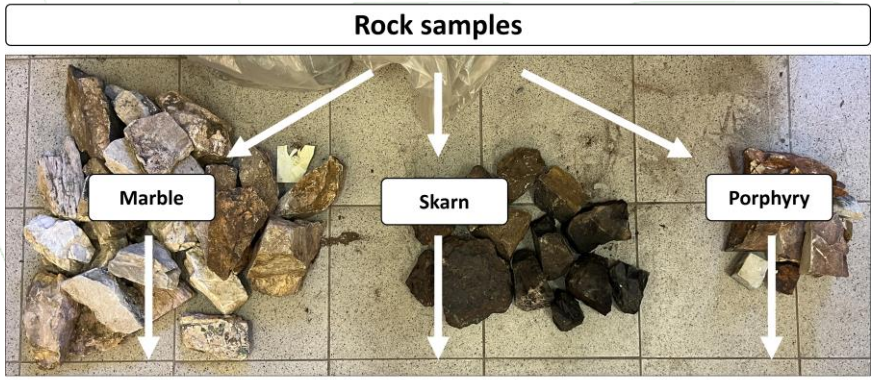
1) Assess the effectiveness of transmission-based muography in identifying and characterizing the internal geometries of overlying rock formations by analyzing variations in transmission and density.

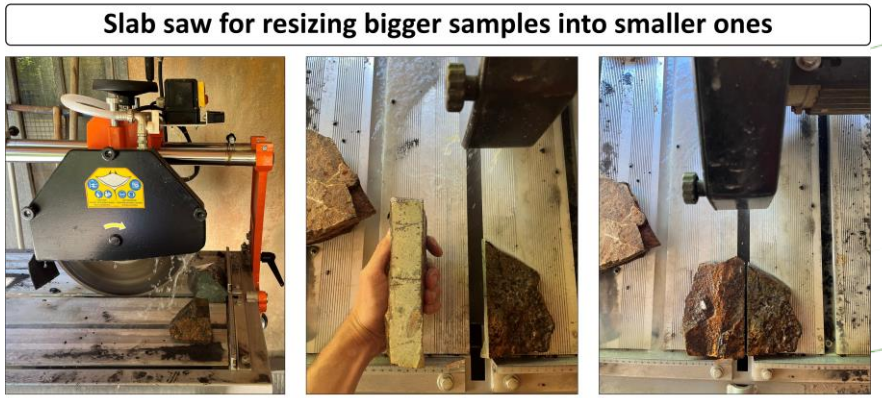
2) Demonstrate the potential of muography as a complementary tool to conventional mineral exploration techniques, enabling the visualization of density distributions within overlying rocks and indicating the presence of dense bodies or cavities to inform future mining planning and safety strategies.

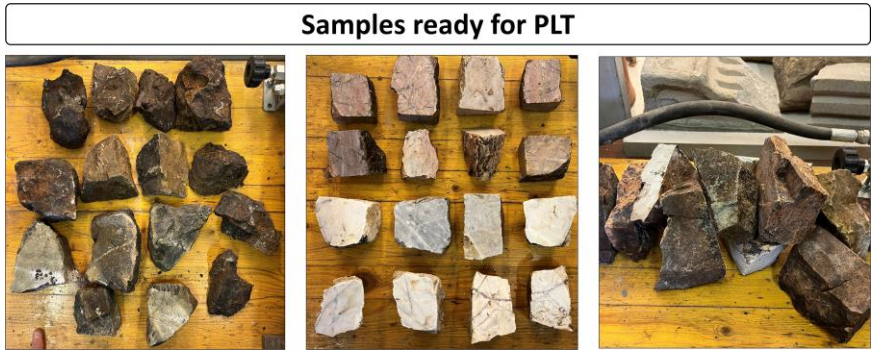
3) Establish that even a single transmission-based muographic measurement can yield critical insights for subsurface operations.

Challenges

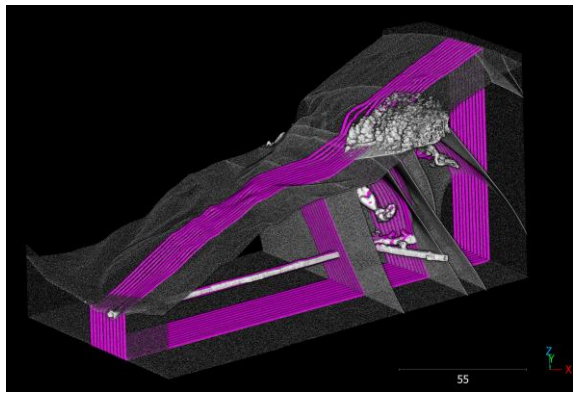


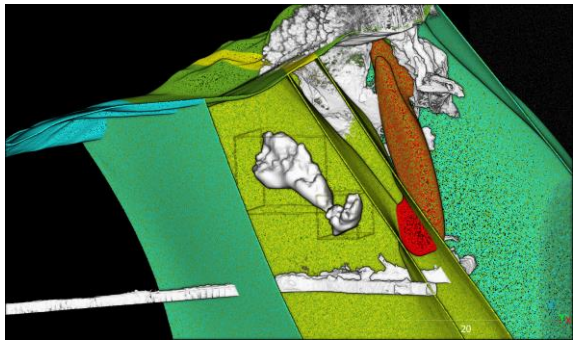


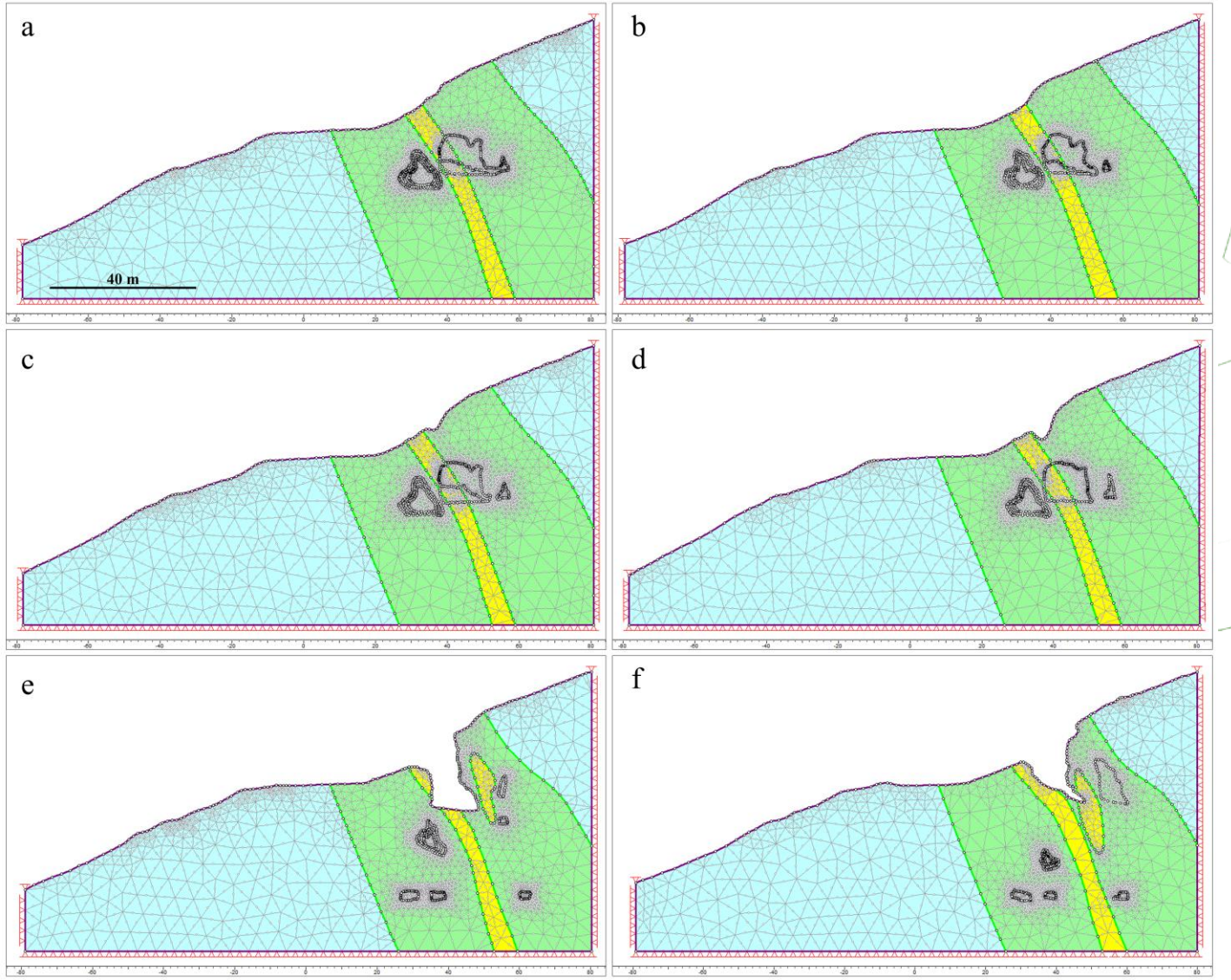




Challenges







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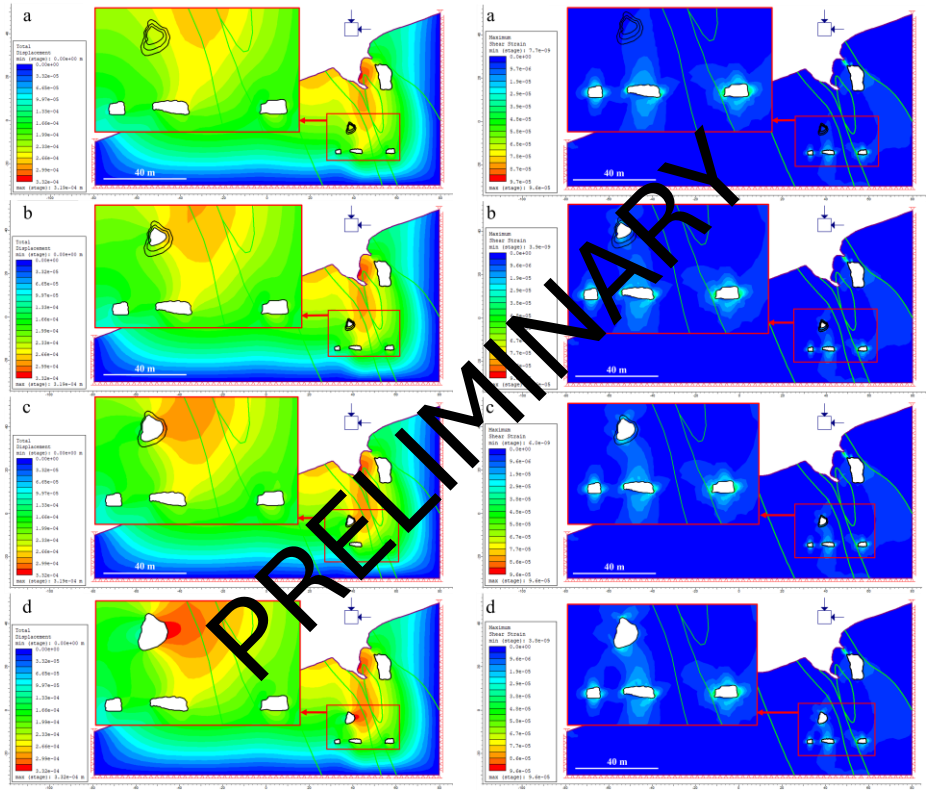

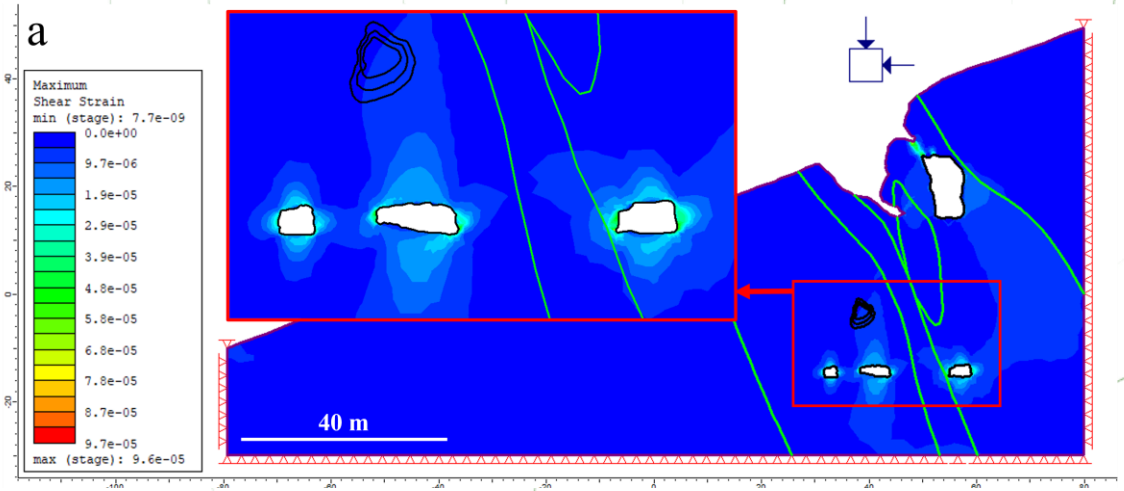

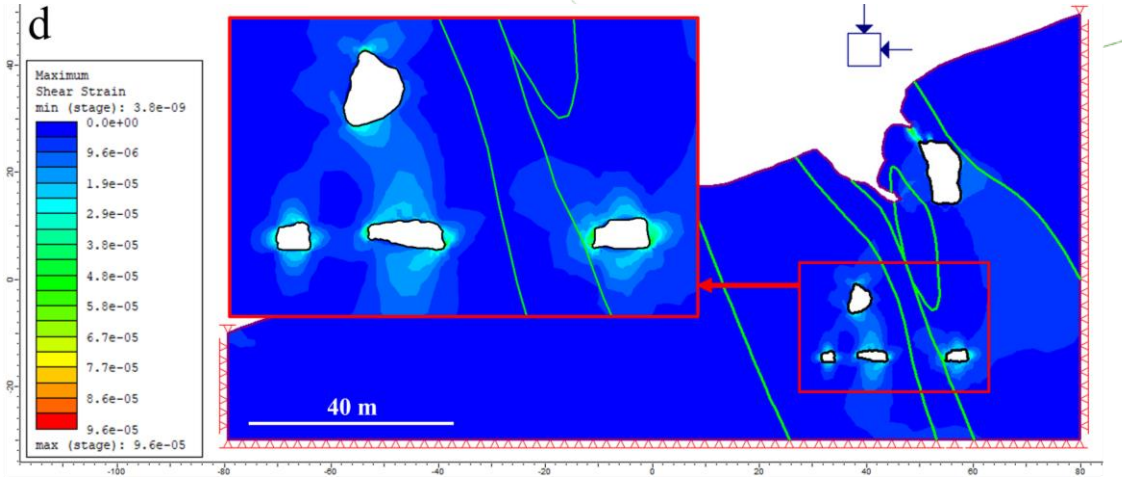

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Ministero dell'Università e della Ricerca
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