ET ITALY
Einstein Telescope

3D Geological Modeling strategies for the Italian ET candidate site. State of the art and future development

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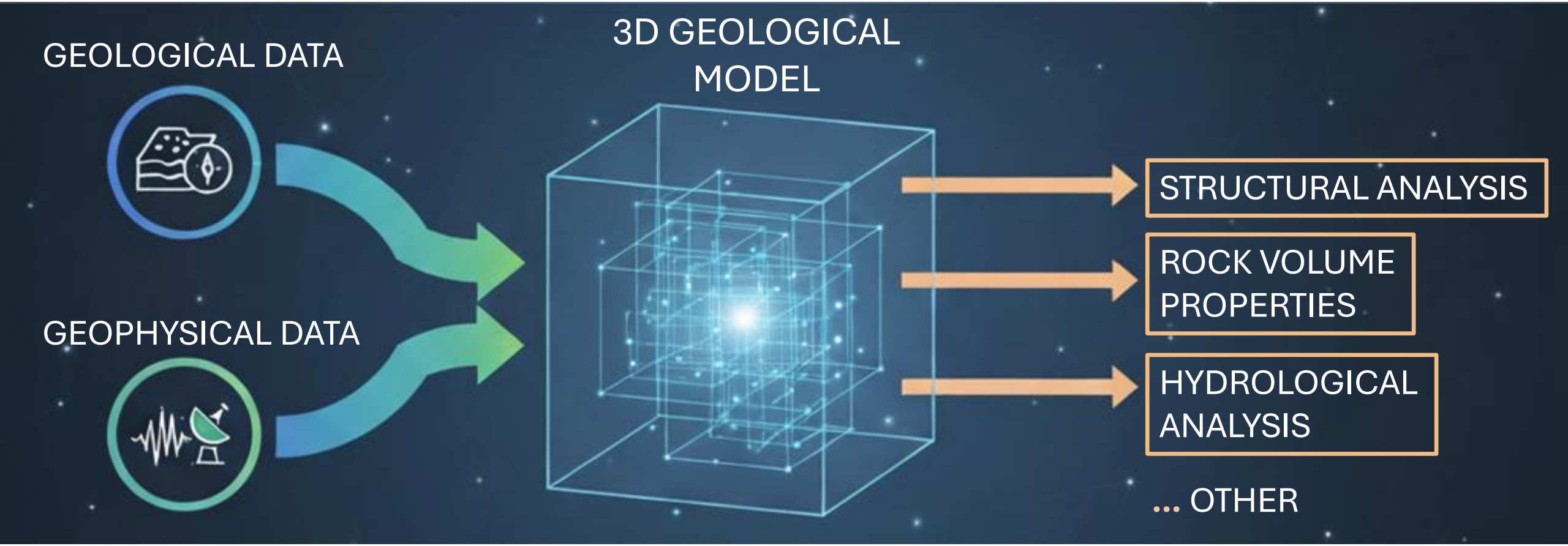
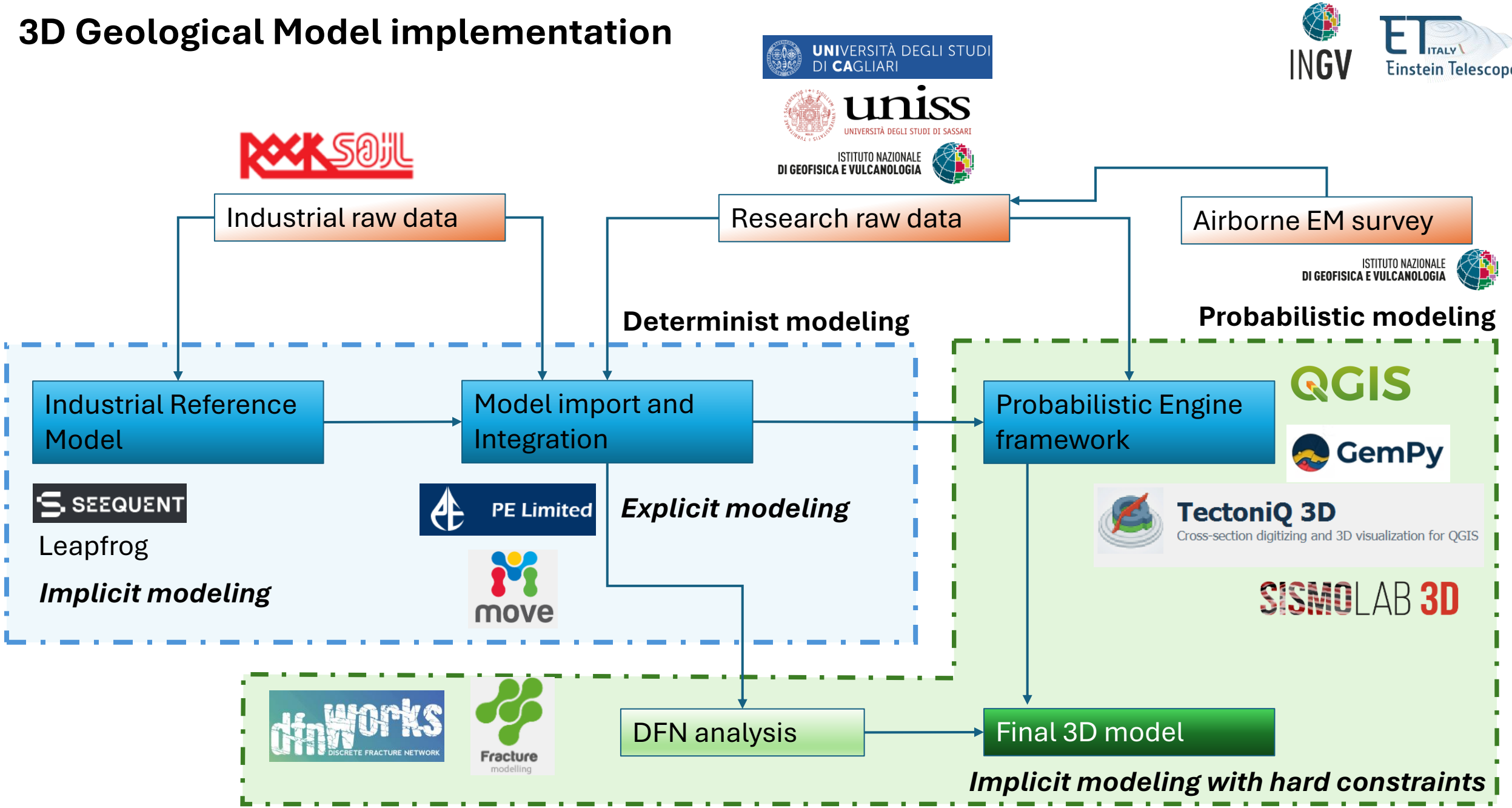
ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

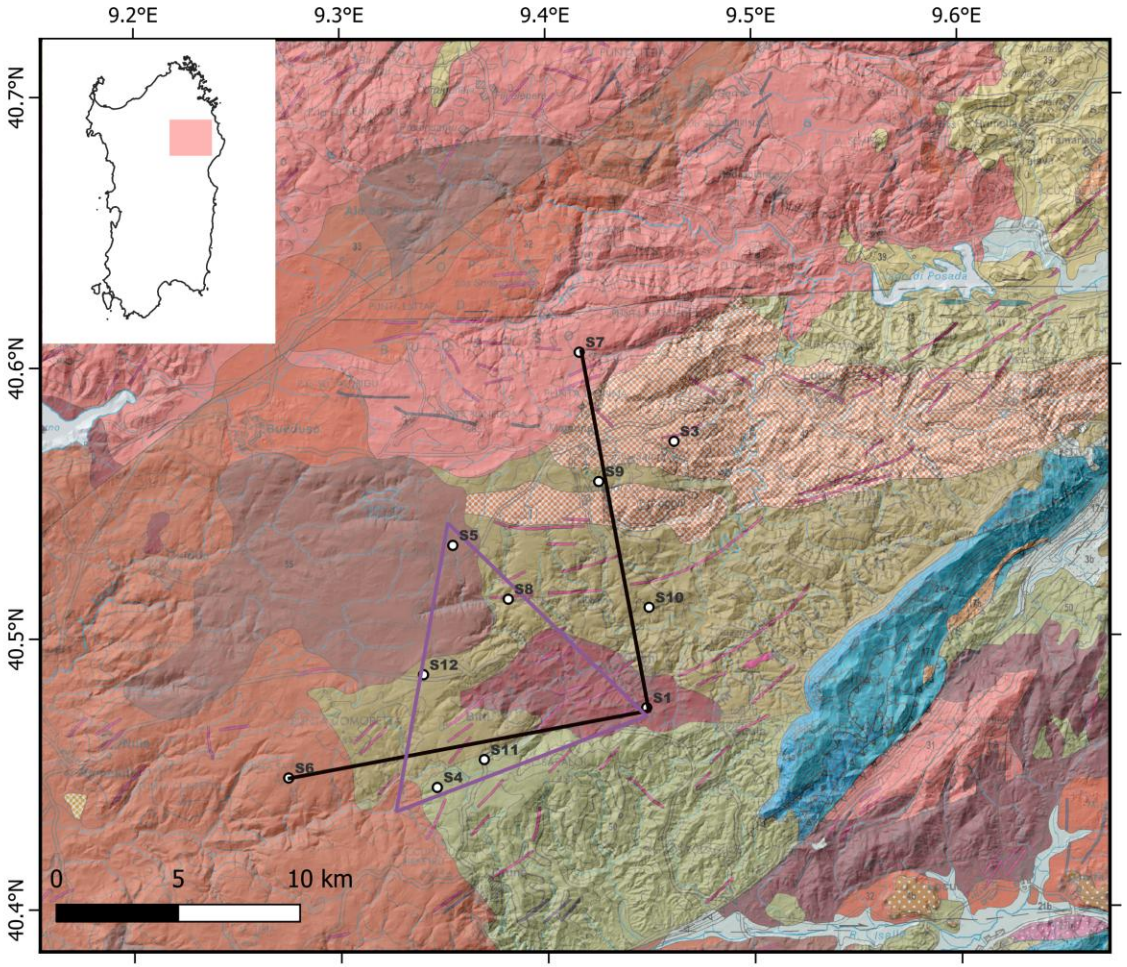
CONCEPTUAL ARCHITECTURE: 3D GEOLOGICAL MODELS



3D Geological Model implementation



Site Candidate Geological Setting



Carmignani et al. (2015) Geological Map of Sardinia

Carbonate shelf (Jurassic)

Variscan Magmatic complex (Upper Carboniferous/Permian)

Granodiorites/orthogneiss (Upper Carboniferous/Permian)

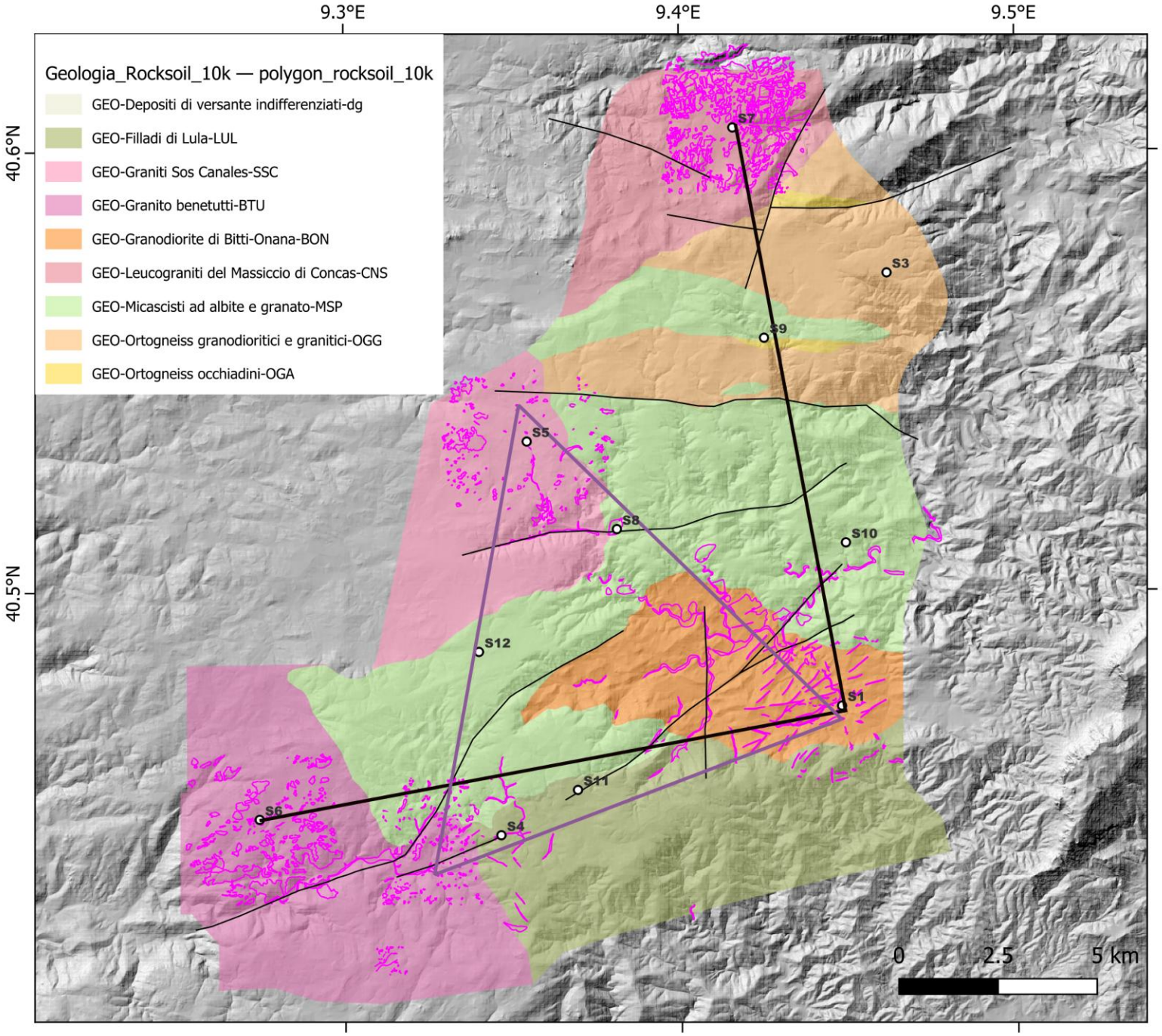
Micaschist/paragneiss (Paleozoic?)

Migmatites/paragneiss (pre-Cambrian?)

- **Setting:** Variscan crystalline basement of north-east Sardinia.
- **Lithology:** Paleozoic metasediments and orthogneisses intruded by late Variscan granitoids (310–290 Ma).
- **Key Site Attributes:** High-quality mechanical properties , long-term tectonic stability , and low seismic ambient noise.

Input data

- **Data Acquisition:** Geophysical surveys, petrographic sections, and laboratory testing.
- **Structural Analysis:** 1:10k mapping and photolineament verification.
- **Conceptual Modeling:** Definition of ductile/brittle tectonic evolution via 90+ field stations.
- **3D Integration:** 3D geometric modeling of the project area in **Leapfrog**.



Input data

Integrated Borehole Network

- **Dataset:** 13 deep boreholes (11 new + 2 pre-existing) covering the entire project area.
- **Vertical Scope:** Boreholes reaching depths between **110 and 480 meters**.
- **Geomechanical Detail:** Targeted continuous coring to investigate rock mass conditions at tunnel elevations.
- **Data Integration (Example):**
- **Structural:** High-resolution ABI imaging.
- **Hydraulic:** Lugeon and Hydrofracturing tests.
- **Mechanical:** Dilatometer and laboratory core testing.

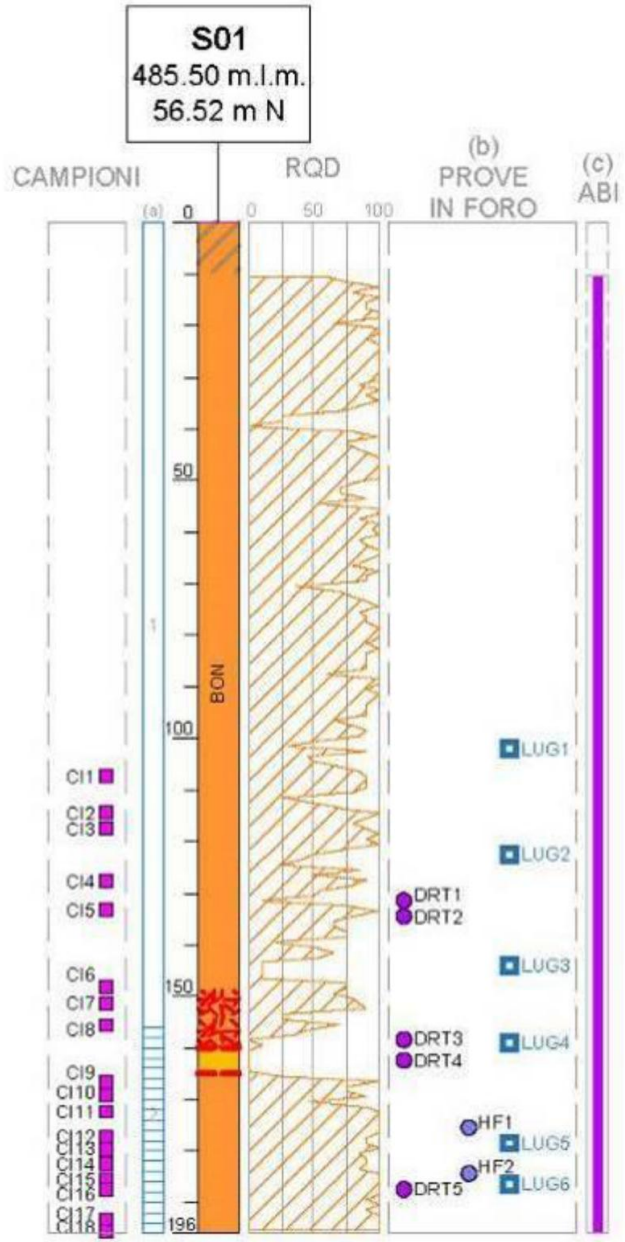


Figura 3-5 – Estratto fotografico delle carote di S01 relative agli ultimi 60 m di profondità del sondaggio.

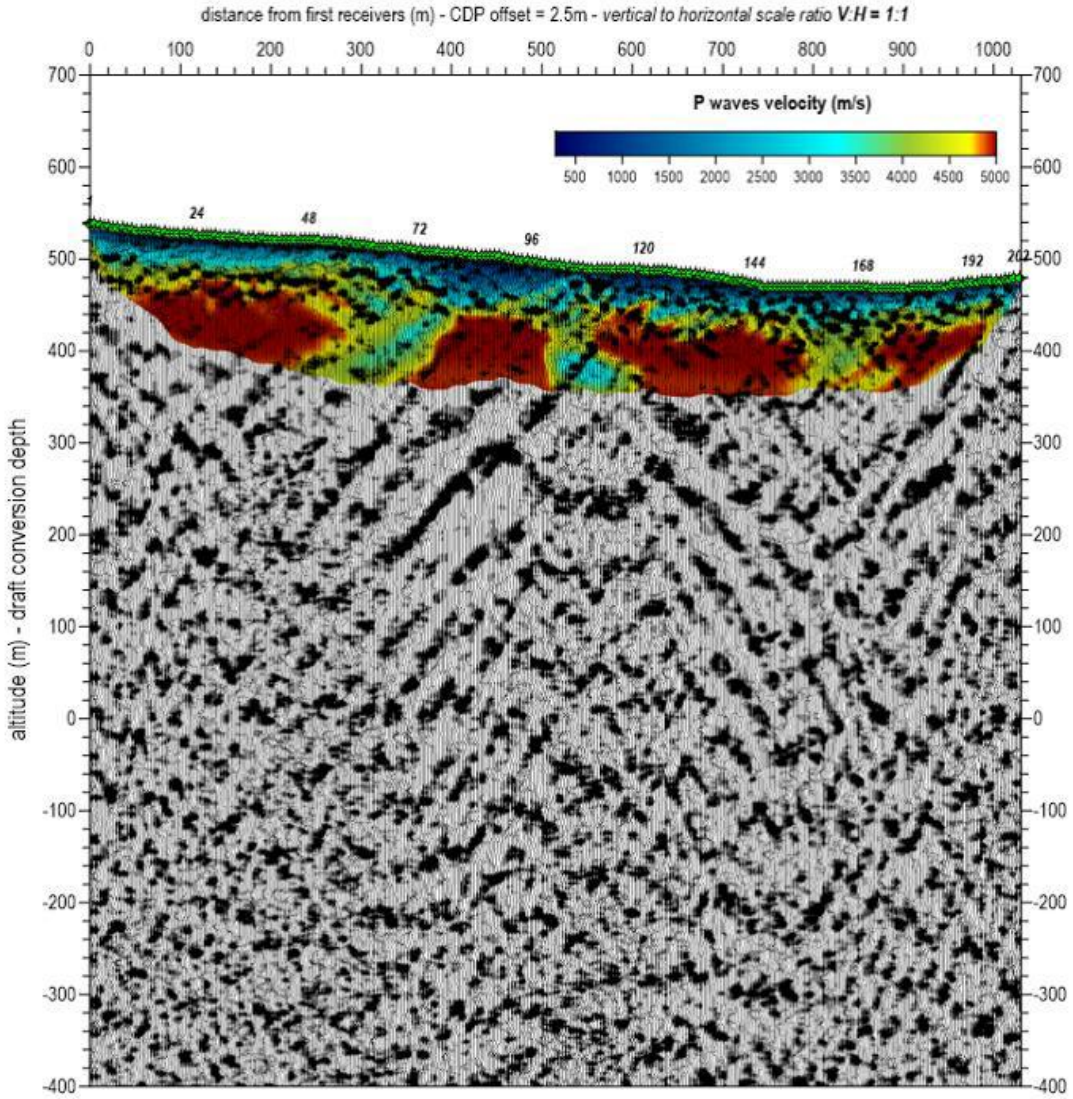
Codice sondaggio	Zona di indagine	Longitudine	Latitudine	Quota [mlm]	L totale [m]	L carot. [m]	N. prove in foro				N. campioni prelevati
							D	L	A	I	
S01	Vertice V1	537969	4480379	485,50	196	196	5	6	1	2	17
S03	Lato V1-V3-L	539089	4491301	748,05	465	300	5	5	-	-	28
S04	Vertice V2-T	529373	4477116	749,47	461,4	294,4	5	5	-	2	20
S05	Vertice V3-T	530014	4487110	767,35	481	294	2	5	-	-	22
S06	Vertice V2-L	523280	4477500	735,80	448	300	5	5	-	2	17
S07	Vertice V3-L	535205	4494945	706,12	423	254	5	5	-	2	26
S08	Lato V1-V3-T	532278	4484815	608,76	326	196	5	5	-	2	20
S09	Lato V1-V3-L	535992	4489655	762,99	480	305	5	5	-	2	17
S10	Lato V1-V3-L	539089	4491301	404,29	113	68	5	5	-	2	8
S11	Lato V1-V2-T Lato V1-V2-L	531308	4478329	741,40	454	290	5	5	1	2	28
S12	Lato V2-V3-T	528811	4481807	761,22	474,3	284,3	4	4	-	-	-

Tabella 3-1 – Sintesi delle caratteristiche dei sondaggi realizzati. Legenda della prova in foro: D - dilatometriche, L – permeabilità Lugeon, A – ABI (*Acoustic Borehole Imager*), I – idrofratturazione.

Input data

Hybrid Seismic Investigation: 5 Survey Lines (~1 km each)

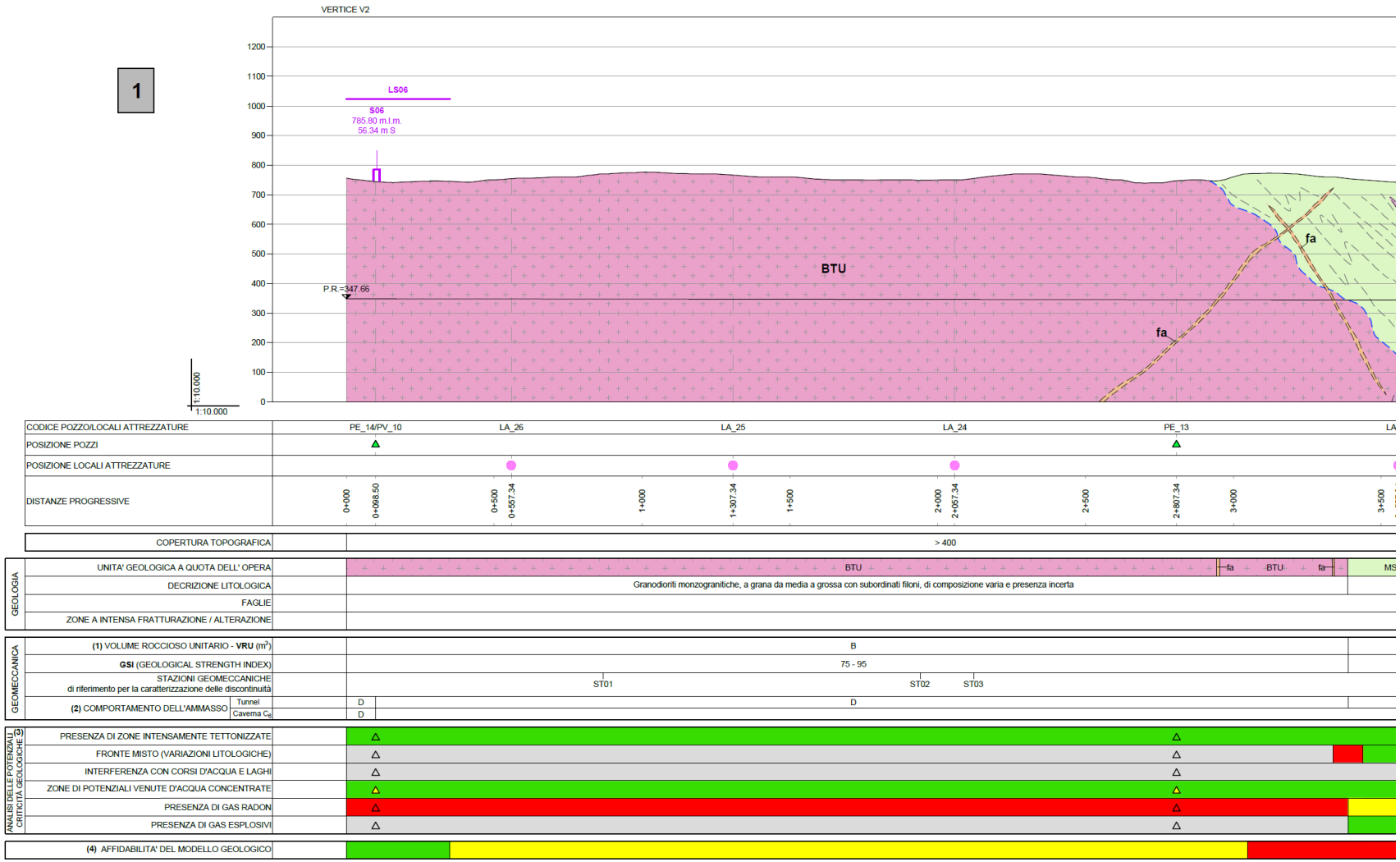
- **Strategic Layout:** Targeted lines at the **L and T vertices** to characterize critical cavern locations.
- **Integrated Methodology:** Hybrid approach combining **Refraction Tomography** (velocity mapping) and **2D Reflection** (structural geometry).
- **Seismic Stratigraphy (Sismofacies):**
  - **Facies 1 (Top 20–30m):** Weathered layer/regolith; lower velocities and high impedance contrast at the base.
  - **Facies 2 (Bedrock):** Compact, homogeneous rock mass with high seismic velocities.
- **Geomechanical Insight:** High-velocity, continuous reflections indicate a **competent and consistent rock mass**.
  - Minor differences between intact and moderately fractured rock suggest overall **excellent geomechanical properties** at project depth.



Input data

Geological & Geomechanical Profiles: L and T Configurations

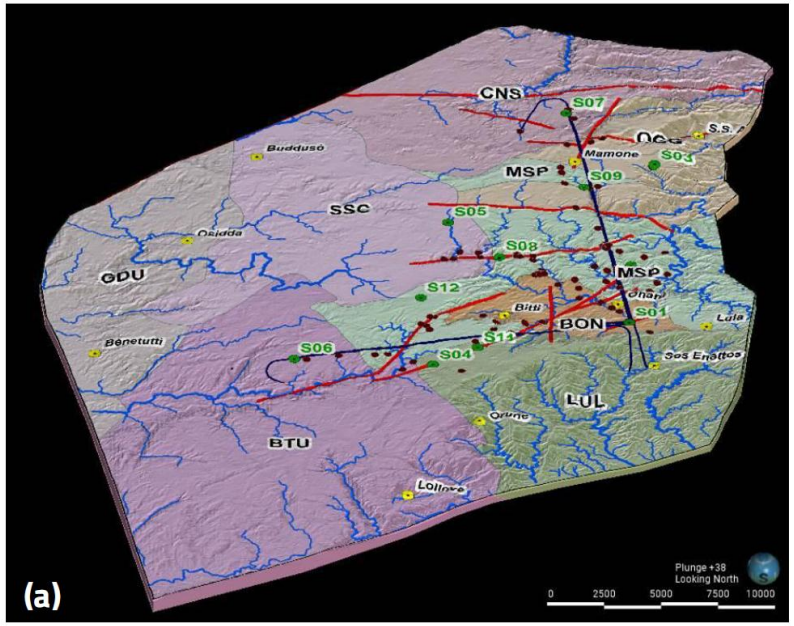
- **Integrated Sections:** Profiles extracted along the arm tunnel layouts, combining litho-structural mapping with rock mass mechanical properties.
- **Model Reliability Index:** Each profile includes a "Confidence Level" parameter, quantifying the data density and interpretive certainty.
- **Probabilistic Foundation:** This reliability index is critical for the subsequent **probabilistic processing** and the generation of the final validated model.

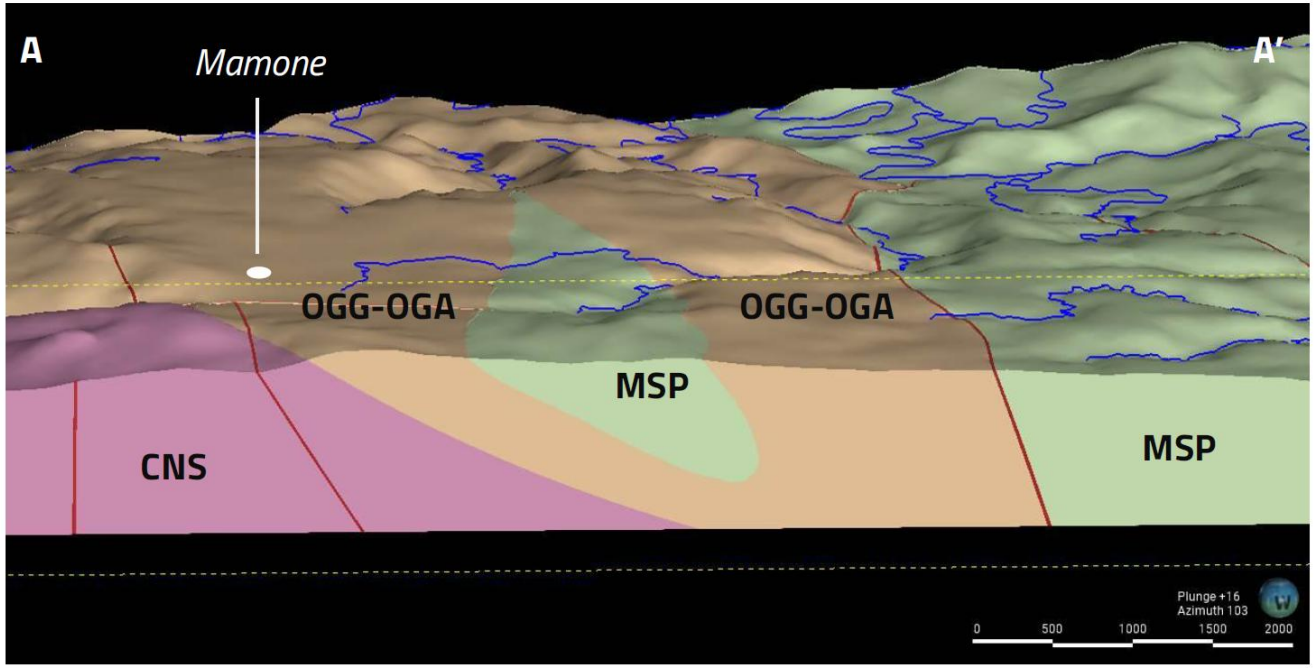


Industrial Standard Reference Model

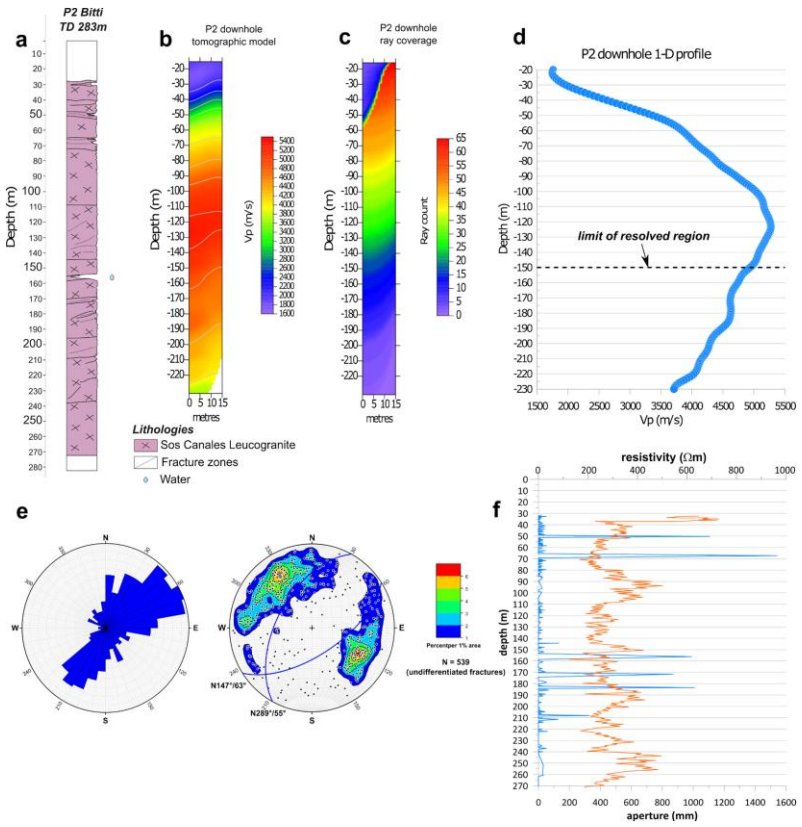
3D Geological Baseline & Profiling

- **Model Source:** 3D Deterministic Model (Leapfrog) by **RockSoil & GeoTec**; acquired by **INFN**.
- **Project Profiles:** Targeted sections along **L and T layouts** integrating geology and geomechanical properties.
- **Reliability Index:** Defined confidence levels for each sector, providing the foundation for future **probabilistic modeling**.
- **Next Steps:** Official baseline for upcoming multi-agency data integration (**INGV**) and stochastic optimization.

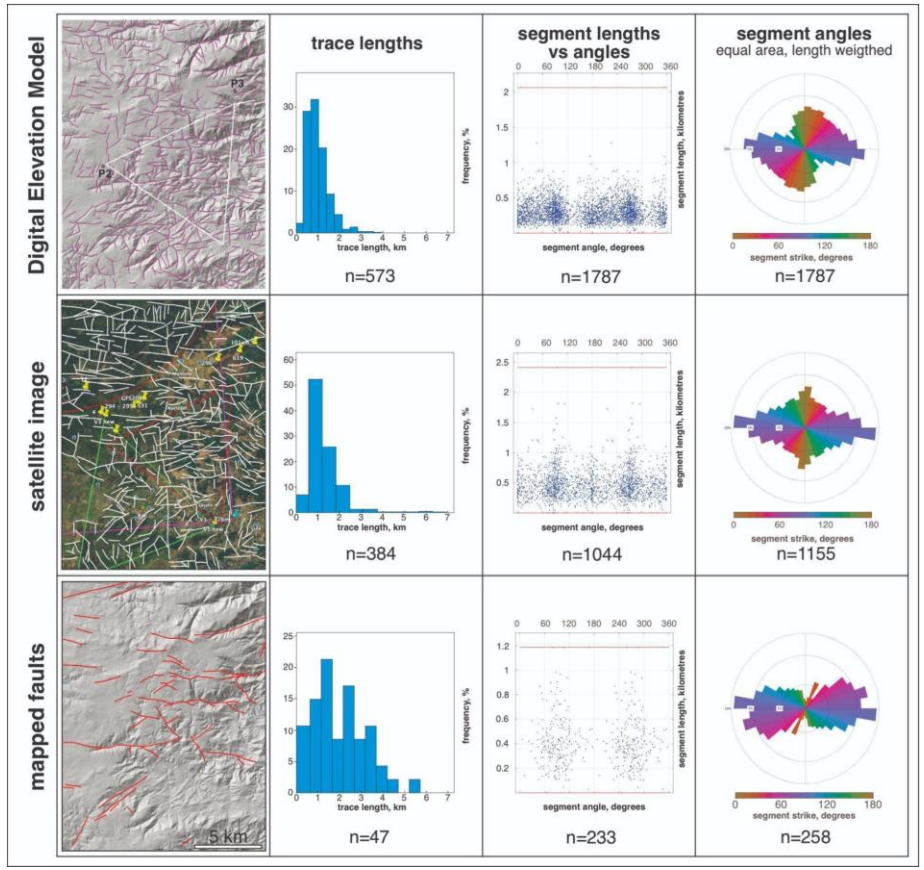




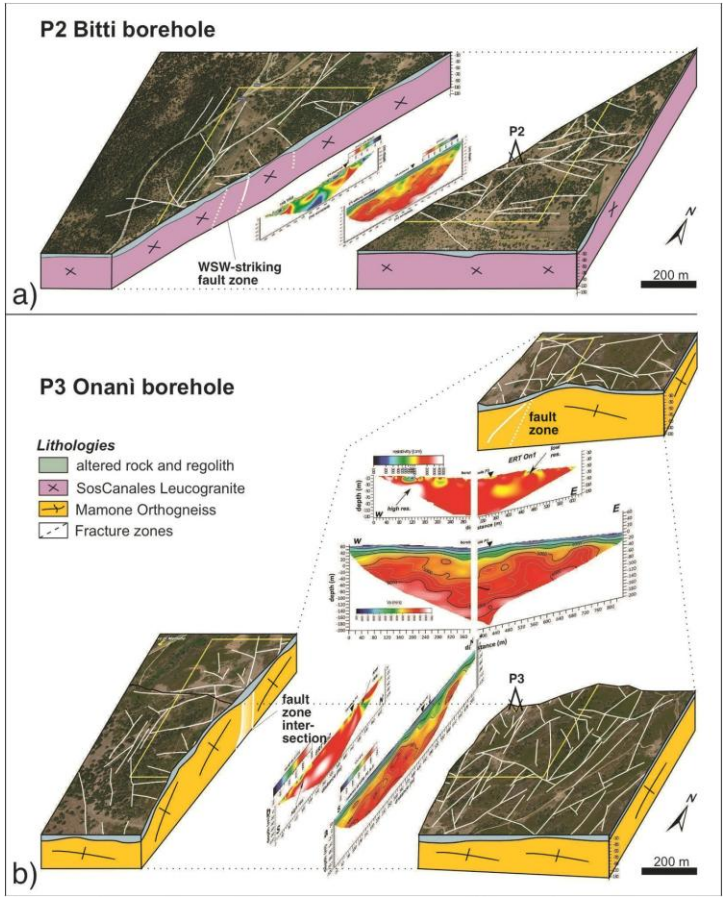
Data Integration (Villani et al., 2025)



Borehole Characterization: Combined 1D/2D seismic tomography, optical imaging (OBI), and geomechanical logs (aperture and resistivity).



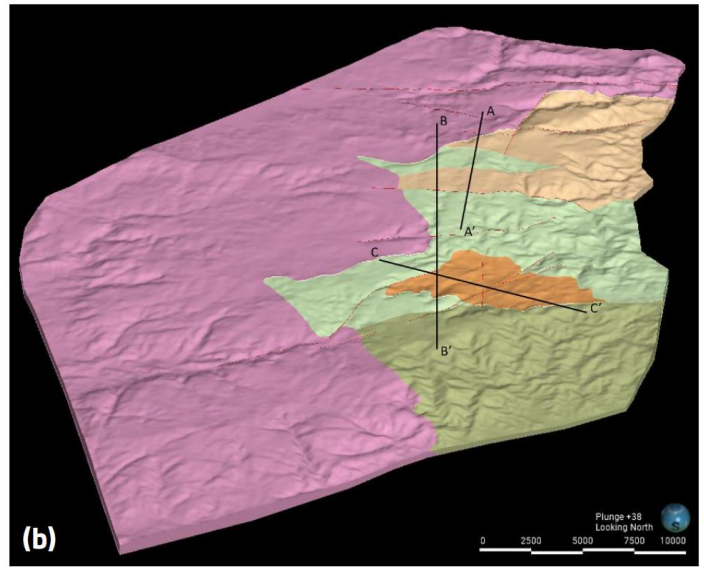
Regional Morphostructures: Multiscale lineament analysis derived from DEM and satellite imagery, focusing on trace lengths and azimuthal distributions.

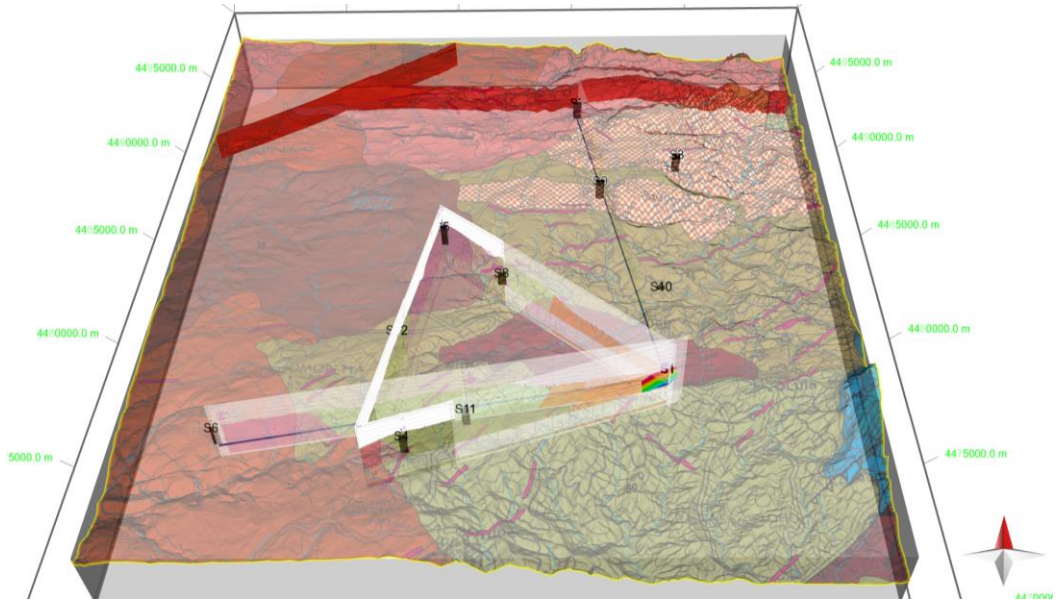


Integrated 3D Modeling: Conceptual perspective models correlating subsurface geophysical anomalies with surface-mapped structural features.

From Implicit to Explicit: Structural Model Refinement

- **Deterministic Baseline Integration**: Importing Leapfrog's implicit 3D volumes as the project's primary structural reference.
- **Explicit Modeling (Move):** Transitioning to Move software to exercise direct, vertex-level control over surface geometries and fault planes.
- **Data-Driven Optimization:** Incorporating high-resolution findings from Villani et al. (2025).
- **Structural Consistency:** Integrating surface morphostructural lineaments and fault mapping into the 3D environment to ensure kinematic integrity.
- **Geometry Consolidation:** Finalizing the reference geometry as the reference for the upcoming probabilistic and stochastic modeling phase.



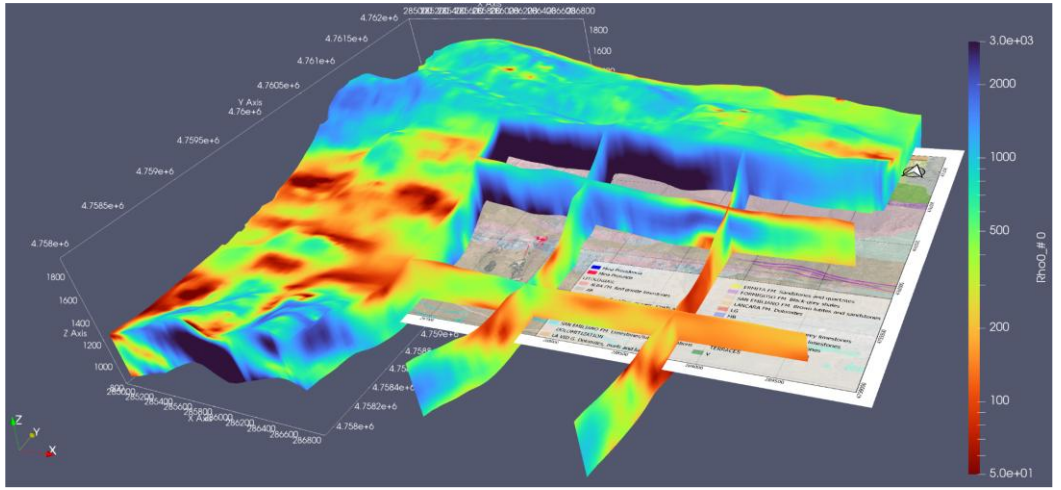


EinstAEM Telescope Project: KEY ASPECTS

To achieve the objectives set by the project, it is necessary to use an AEM system with well-defined technical characteristics:

1. dual-moment system;
2. high dipole moment (≥ 500,000 A x m^2);
3. rigid frame;
4. effective minimization of the primary field in the receiver (Rx);
5. cesium optically-pumped magnetometer (sampling at 10 Hz);

Example of output result from a deterministic modelling, in 3D



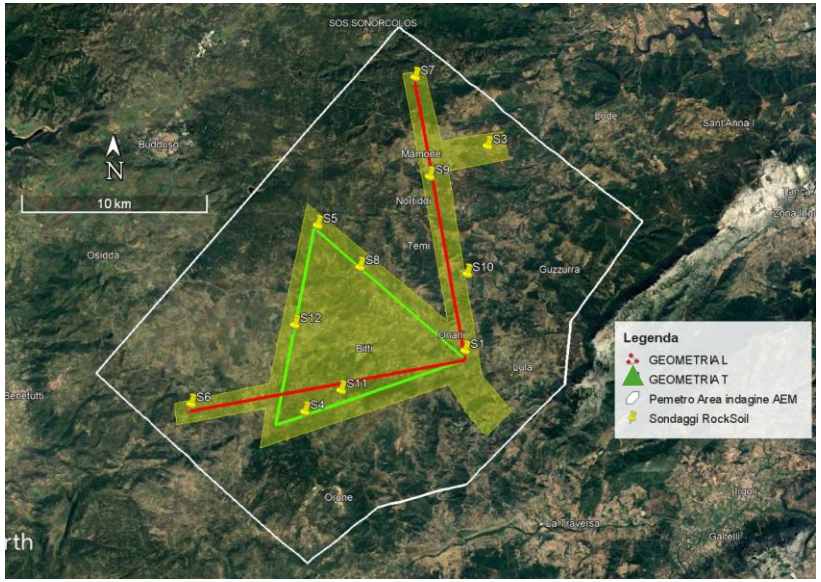
The geophysical modelling will be carried out using different approaches:

1. both “smooth” and “sharp”;
2. both modelling and ignoring induced polarization effects;
3. both deterministic and probabilistic;
4. both unconstrained and constrained (by geology, etc.);

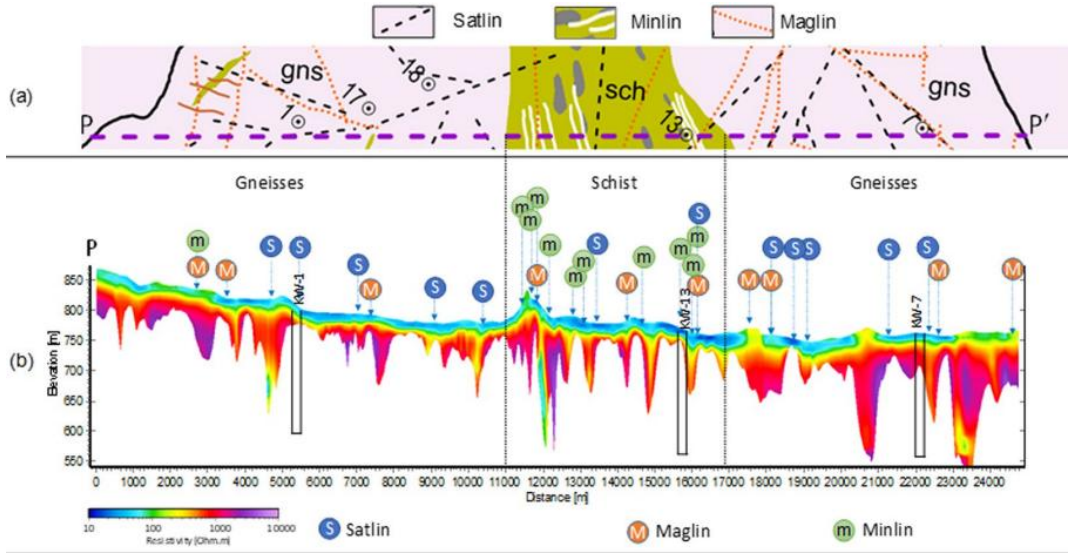
OUTPUTS:

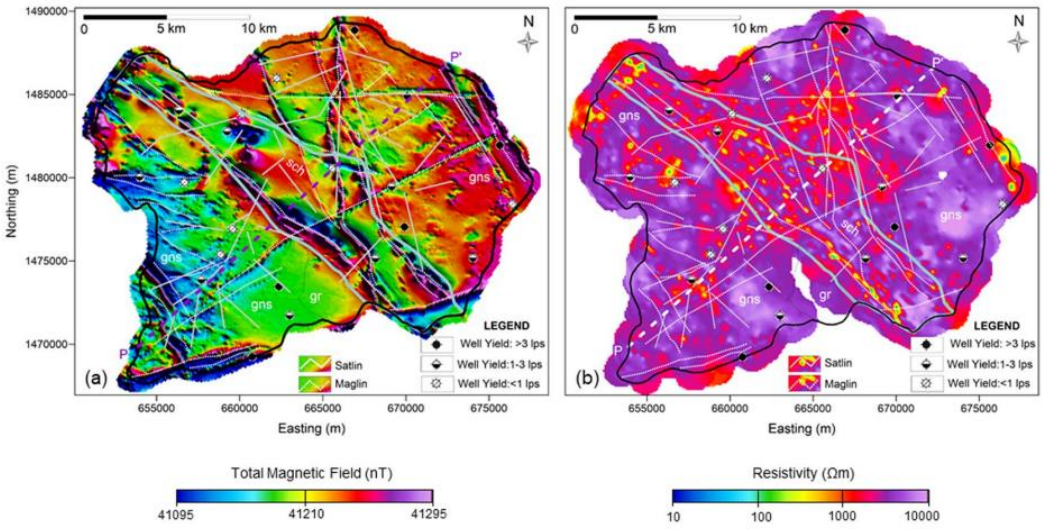
1. 3D res and IP models of the ET Area and 2D sections;
2. 3D probability models of granite fracturing levels;
3. Total Magnetic Intensity and Reduction to Pole maps;
4. Identification of areas with high-criticality;

The geophysical and fracture probability models will reach depths of “up to 500 m”, with a lateral spacing of approx 30–50 m.



AEM SENSITIVITY TO DEEPLY FRACTURED GRANITES:
Example in «similar» geological settings (i.e. gneiss and schist)





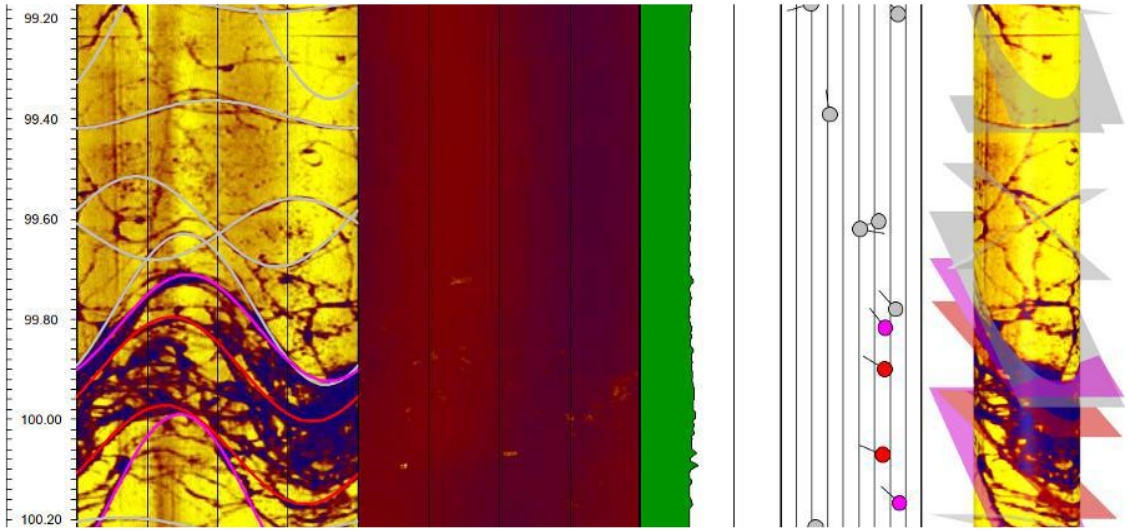
SCIENTIFIC REPORTS

OPEN

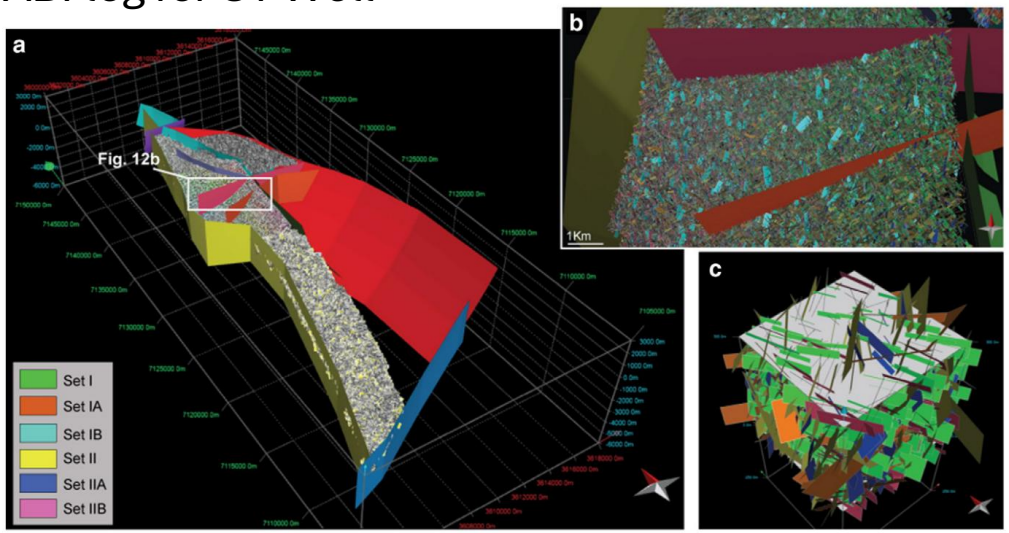
Large Scale Mapping of Fractures and Groundwater Pathways in Crystalline Hardrock By AEM

from Chandra et al 2017 – Scientific Reports

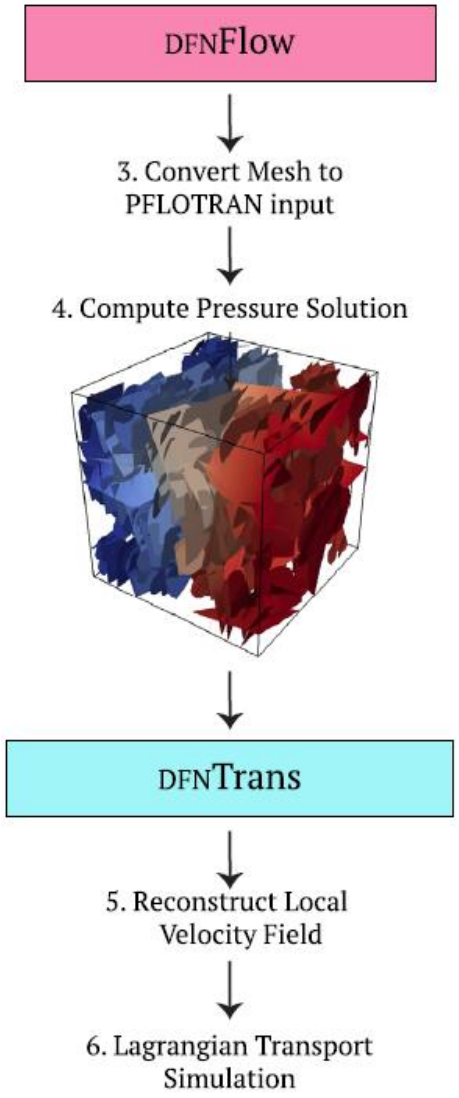
DFN Generation: Discrete Fracture Network Modeling



ABI log for S1 Well



Maffucci et al., 2015



Hyman et al., 2015

- **Input:** Extraction of high-resolution fracture orientation and aperture data from field data and ABI (Acoustic Borehole Imager) logs.
- **Structural Framework:** Definition of primary fracture sets and deterministic structural lineaments using **Move**'s explicit modeling suite.
- **Stochastic Simulation:** Utilization of the **DFNFlow workflow** for the multi-scale generation of discrete fracture networks.
- **Volumetric Population:** Integration of the DFN into the 3D model to analyze potential fluid flow pathways.
- **Probabilistic Refinement:** Incorporating discrete discontinuities to provide a robust dataset for final uncertainty quantification.

Geomechanical Parametrization & Model Population

- **Formation-Specific Data:** Comprehensive tables defining the physical and mechanical properties for the project's main lithological units.
- **Integrated Dataset:** Parameters are derived from the synthesis of borehole stratigraphy, laboratory core testing, and geophysical proxies such as P-wave velocity and electrical resistivity.
- **Volumetric Population:** These geomechanical values are used to populate the **3D deterministic model**, transforming a purely geometric framework into a physical-property model.
- **Geostatistical Foundation:** The defined parameter ranges and standard deviations provide the essential input for the **probabilistic modeling** phase and stochastic.

BON		min	max	med	freq
γ	[kN/m³]	25.3	26.8	26.4	-
σ_{ci}	[MPa]	8.6	136.4	84.4	120
$\sigma_{ci,PLT}$	[MPa]	91.2	350.4	215.5	-
E_{tan}	[GPa]	3.2	49.7	40.0	45
E_{sec}	[GPa]	8.2	48.4	37.5	-
MR	[-]	366.9	519.9	409.8	-
m_i	[-]	16			-
ν	[-]	0.25			-
V_p	[m/s]	4397	6577	6021	-
V_s	[m/s]	2318	4473	3650	-
G_0	[GPa]	13.9	54.5	36.8	-
E_0	[GPa]	36.2	116.5	86.4	-
$E_0/1.5$	[GPa]	-	-	57.6	-
GSI_{ril_sup}	[-]	60	90	75	-
GSI_{carote}	[-]	70	75	72.5	-

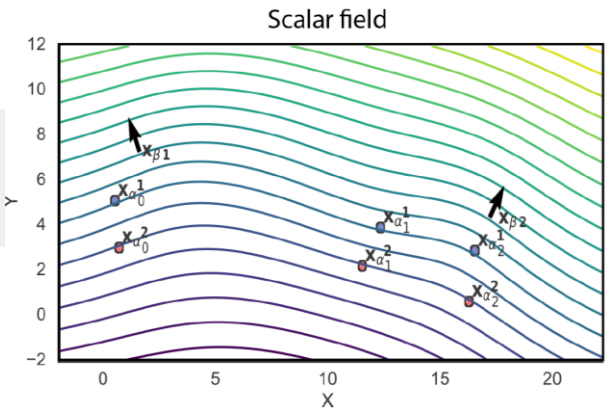
BTU		min	max	med	freq
γ	[kN/m³]	25.5	26.1	25.9	-
σ_{ci}	[MPa]	32.4	176.2	130	140
$\sigma_{ci,PLT}$	[MPa]	62.4	429.6	279.8	-
E_{tan}	[GPa]	52.9	67.8	60.4	60
E_{sec}	[GPa]	40.4	63.8	53.5	-
MR	[-]	384.7	538.8	435.9	-
m_i	[-]	14			-
ν	[-]	0.25			-
V_p	[m/s]	4692	6464	5805.2	-
V_s	[m/s]	2878	4387	3673.4	-
G_0	[GPa]	21.6	51.2	36.1	-
E_0	[GPa]	51.7	105.4	83.2	-
$E_0/1.5$	[GPa]	-	-	55.5	-
GSI_{ril_sup}	[-]	75	95	85	-
GSI_{carote}	[-]	65	80	72.5	-

TectoniQ-3D: The Synthesis Tool for Probabilistic Modeling

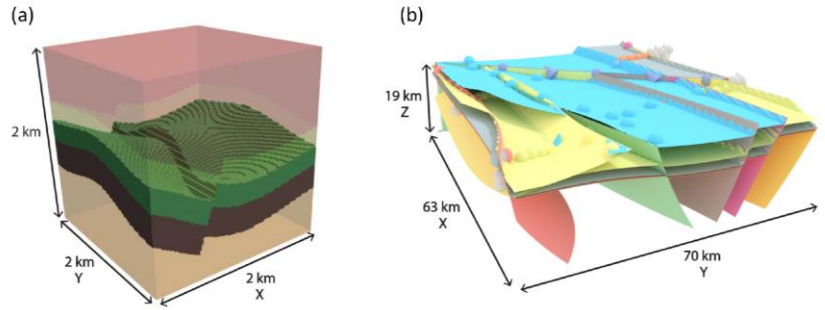
QGIS + SISMOLAB 3D

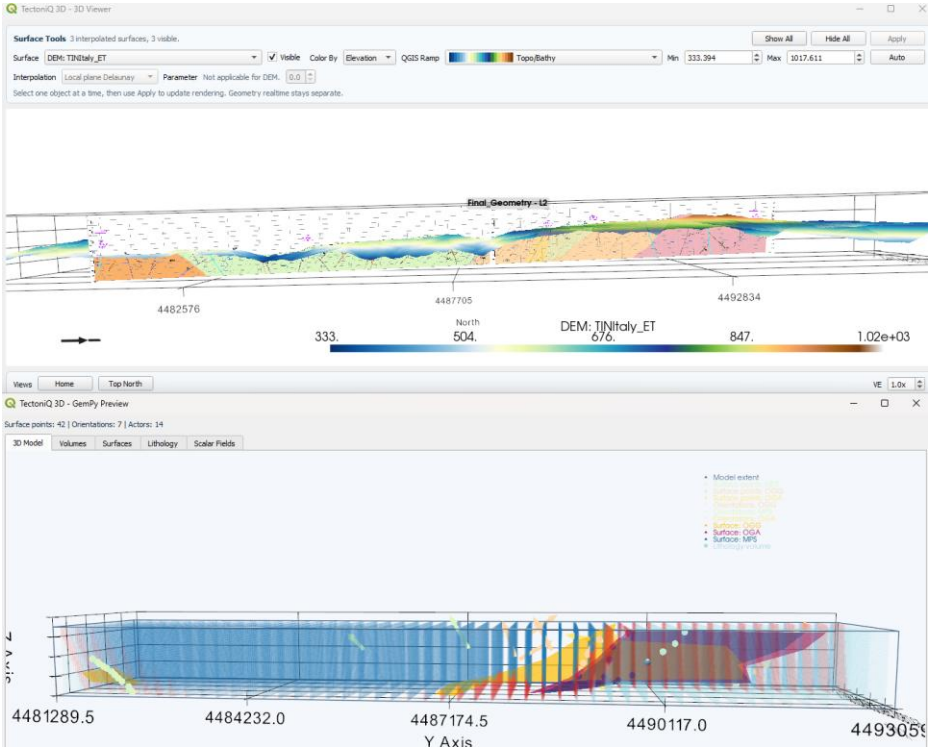
TectoniQ 3D
Cross-section digitizing and 3D visualization for QGIS

GemPy



De la Varga et al. (2019)





- **Software Synergy: TectonicQ-3D** is a dedicated **QGIS plugin** under development in the SismoLab-3D integrating advanced territorial management with **GemPy's** implicit probabilistic engines.
- **Scalar Field Modeling:** Utilizing potential fields to reconstruct complex 3D volumes from the heterogeneous datasets (boreholes, surface geology, and AEM).
- **From Deterministic to Stochastic:** Transitioning from the Leapfrog/Move baseline to the automated generation of **stochastic realizations** to quantify subsurface uncertainty.
- **Project Vision:** Providing a unified, open-source environment for the final structural and geomechanical validation of the **Einstein Telescope** infrastructure.

3D Geological Model implementation