Geological and geoelectrical survey of the metamorphic and intrusive rocks on the Einstein Telescope site (Sardinia, Italy)

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AIM & APPROACH

AIM

We aim at structurally characterizing the Sardinia ET candidate site to help predicting **lithologies** and **fault** distribution associated with preferred **fluid circulation path-ways**.

APPROACH

We make it by means of Geological Survey, Field structural analysis, structural geomorphology studies, and Geoelectrics.

TALK'S STRUCTURE

RECAP ON:

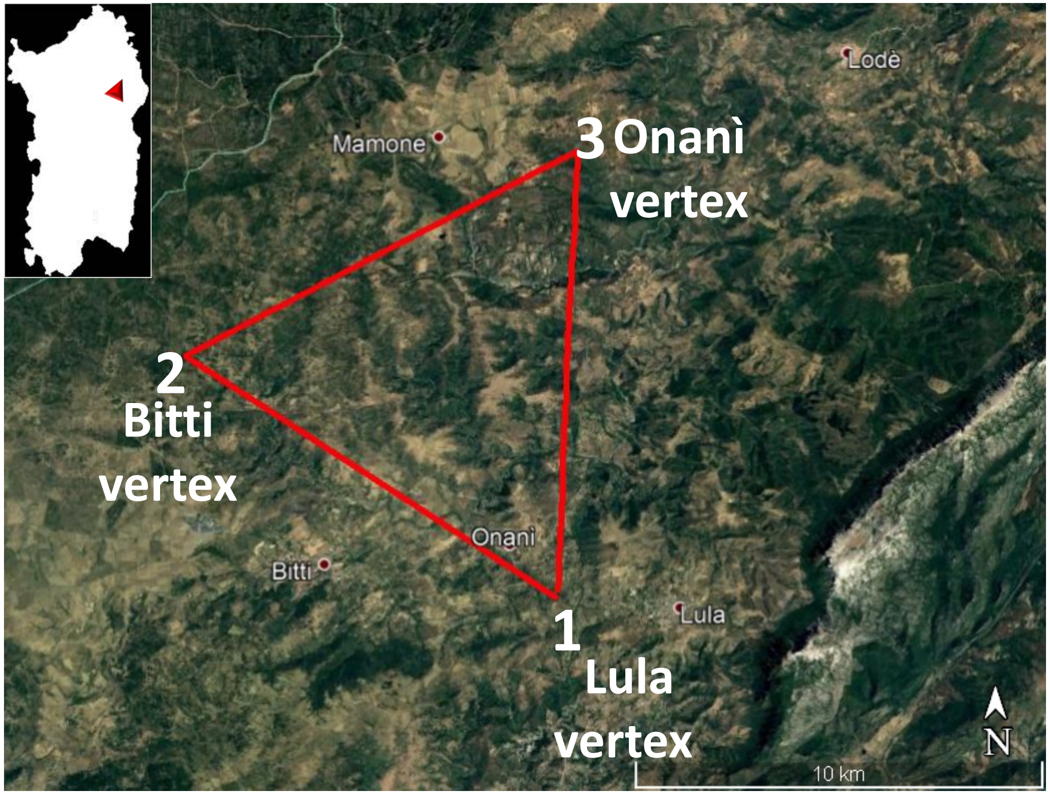
- ❖ SARDINIA GEOLOGY AND REASONS WHY THE ET INFRASTRUCTURE SHOULD BE HERE
- ❖ PREVIOUS WORK OF SASSARI UNIVERSITY ON THE PROJECT

OUR NEW RESULTS:

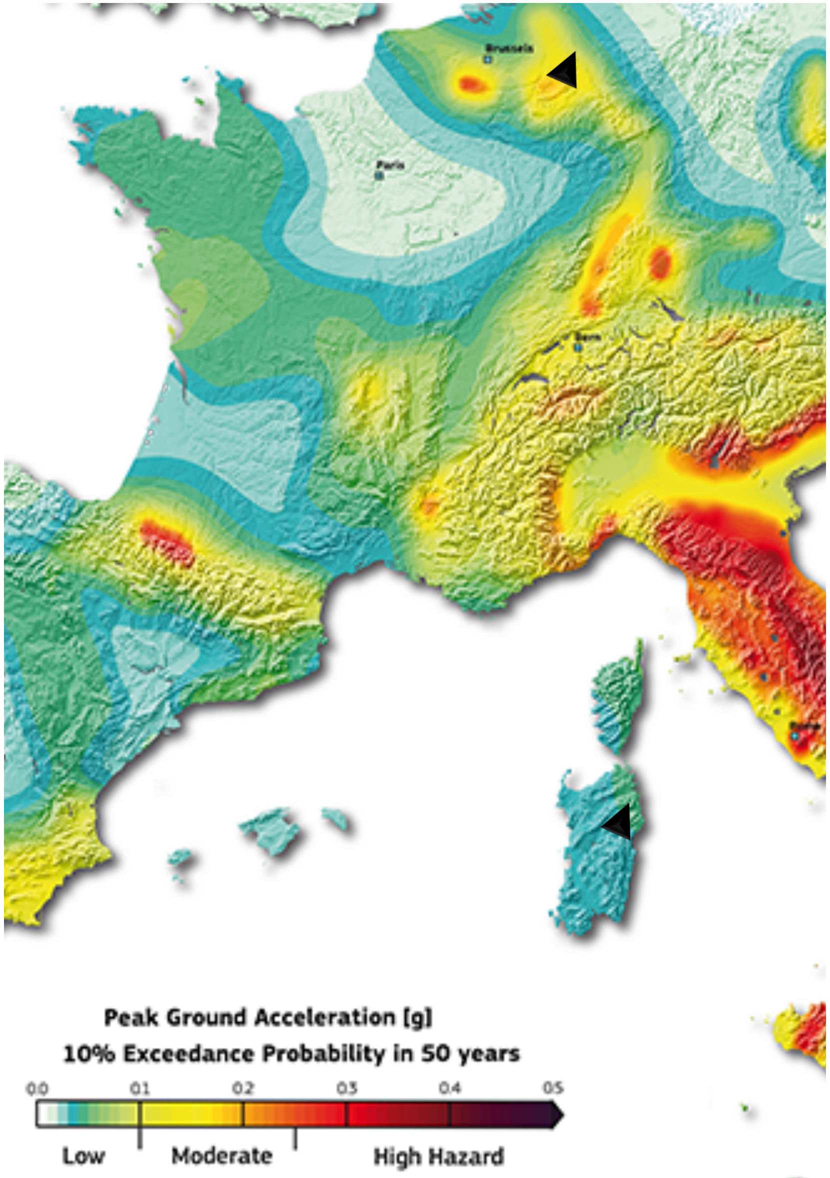
- ❖ STRUCTURAL MAP ADVANCES
- ❖ FAULT CHARACTERIZATION
- ❖ MULTISCALE GEOLOGICAL CHARACTERIZATION OF BOREHOLE SURROUNDINGS BY MEANS OF:
  - STRUCTURAL GEOLOGY
  - STRUCTURAL GEOMORPHOLOGY
  - GEOELECTRICS

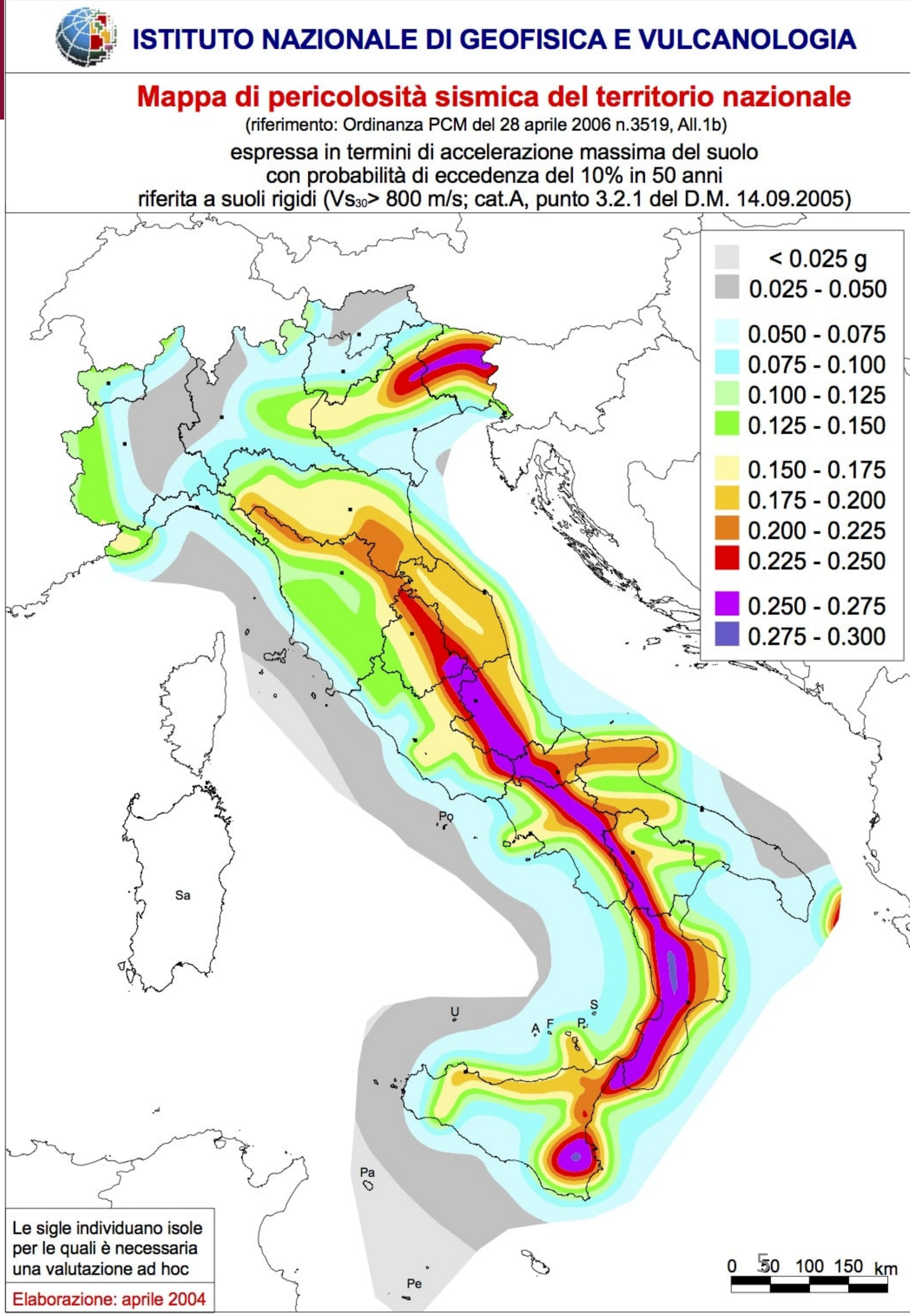
COMMON GROUND

The geological characterization preceding the construction of a large-scale underground structure, such as the Einstein Telescope (ET), is a mandatory step of civil engineering studies.



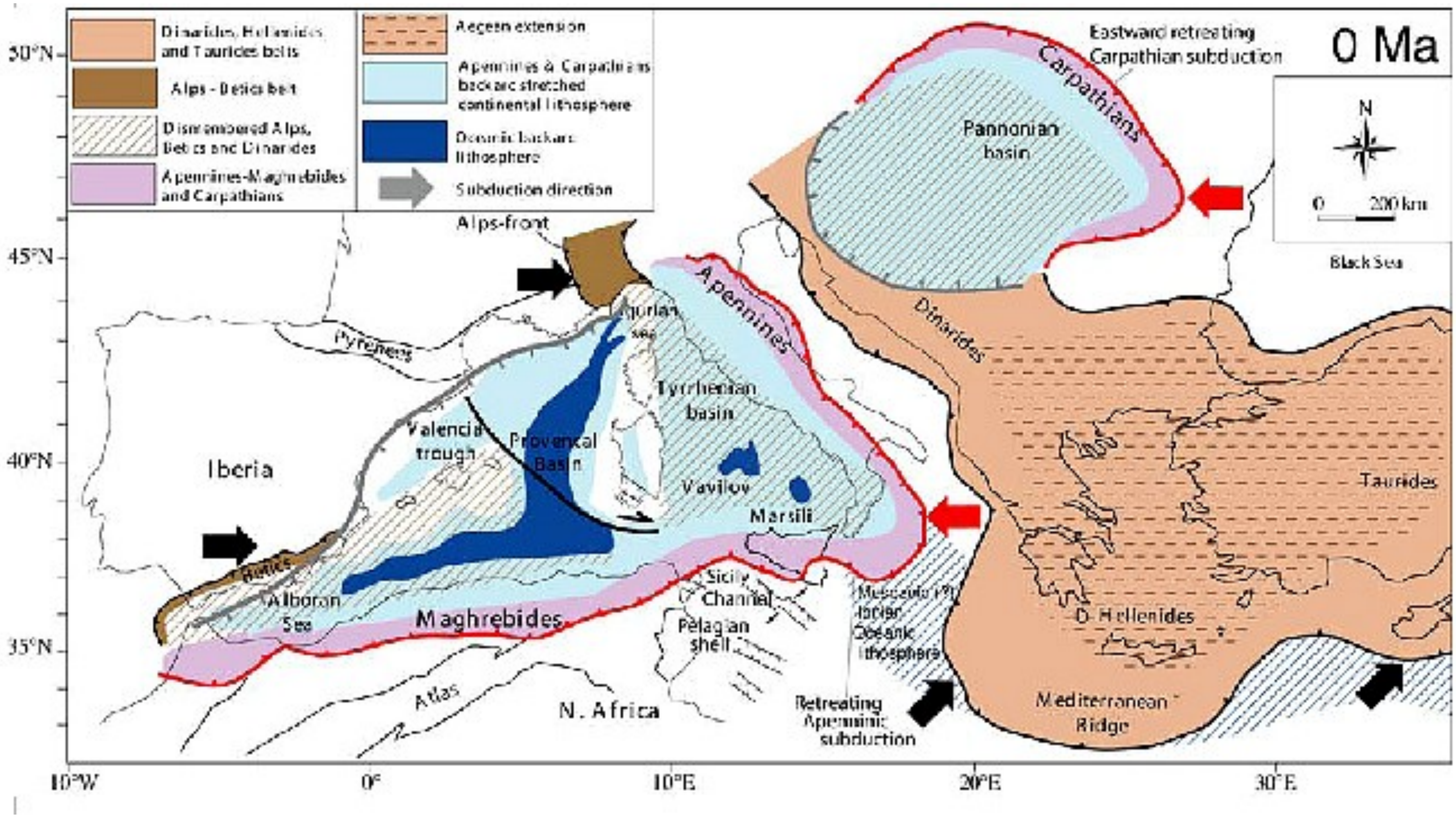
EARTHQUAKES AND VERY LOW SEISMICITY





THE GEODYNAMIC PRESENT-DAY OF SARDINIA

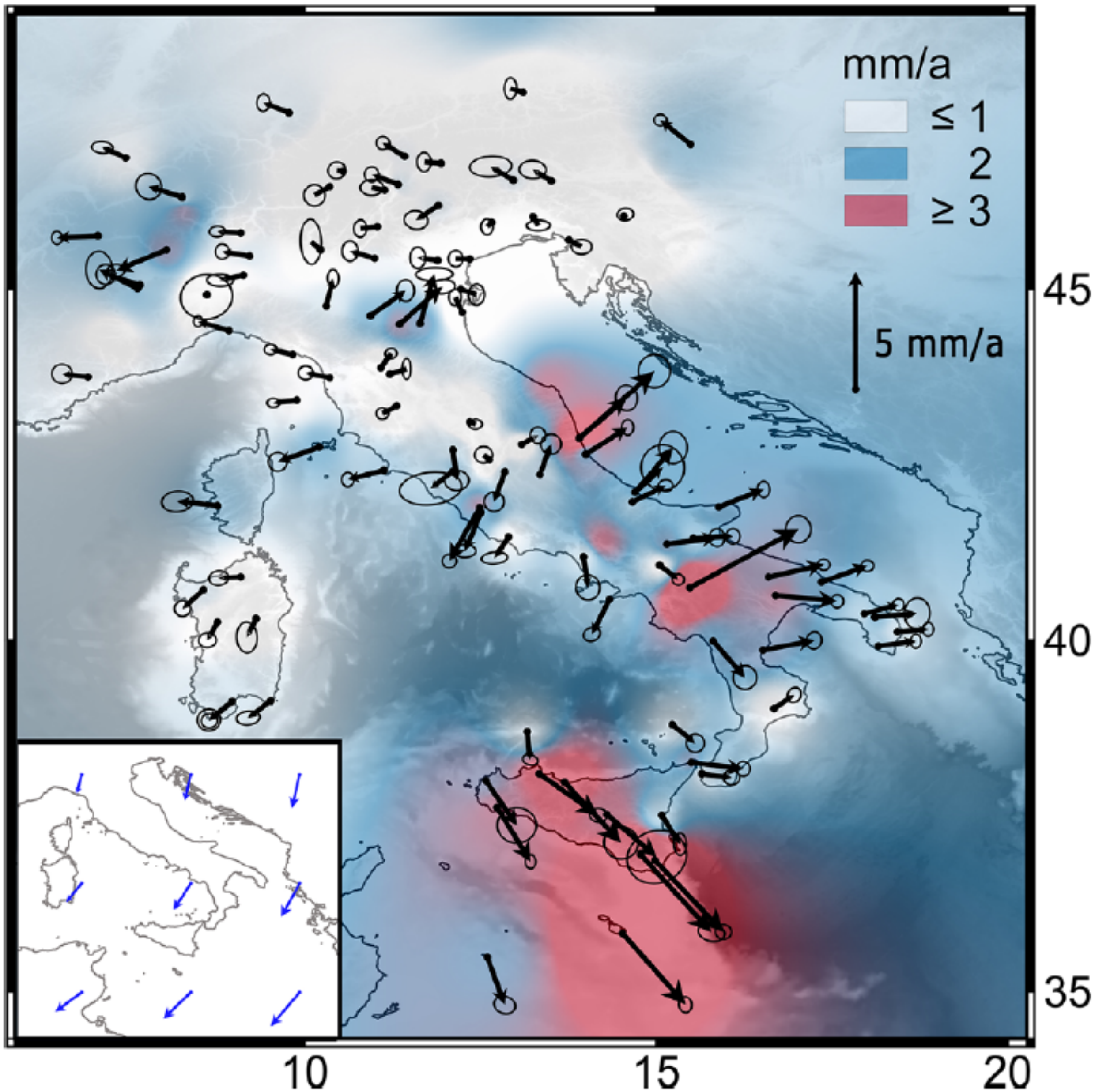
In the last million years, the Sardo-Corsican block is rather stable and quite unaffected by significative seismic activity.
This is due to localization of active geodynamics towards the East of Italy.



THE PRESENT-DAY GEODYNAMIC QUITENESS

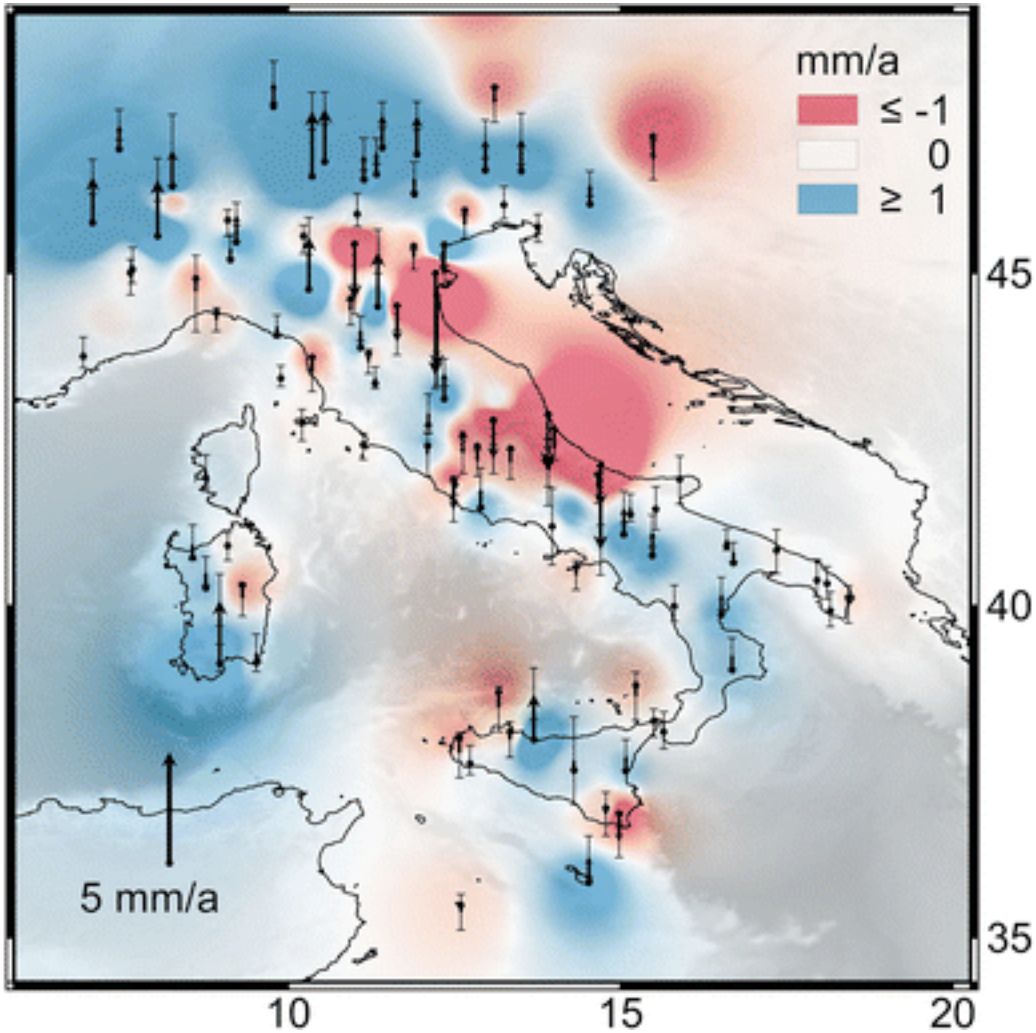
In Sardinia, Intra-plate horizontal velocities are very low.

Have a look at the interpolated results of the velocity field in the local reference frame from global navigation satellite system (GNSS).



Farolfi et al. 2016

SARDINIA VERTICAL MOVEMENTS ?



Vertical velocities and error bars with 95 % confidence level. The interpolated vertical velocity field is displayed by a graduated color scale. White represents stable area, blue is for uplift ≥1.0 mm/a and red subsidence ≤−1.0 mm/a

2019-2020 CHARACTERIZATION

Performed by the Geologist PhD Stefano Cuccuru

- Mechanical characterization of rock types collected in the field
- Radioactive mapping of the area
- Structural characterization of Sos Enattos mines

Performed by Vittorio Longo and Valeria Testone

- Geoelectrical profile of Rio Mannu (Onanì) to constrain the depth of the deposits infilling the valley.

BASICS OF SARDINIA GEOLOGY

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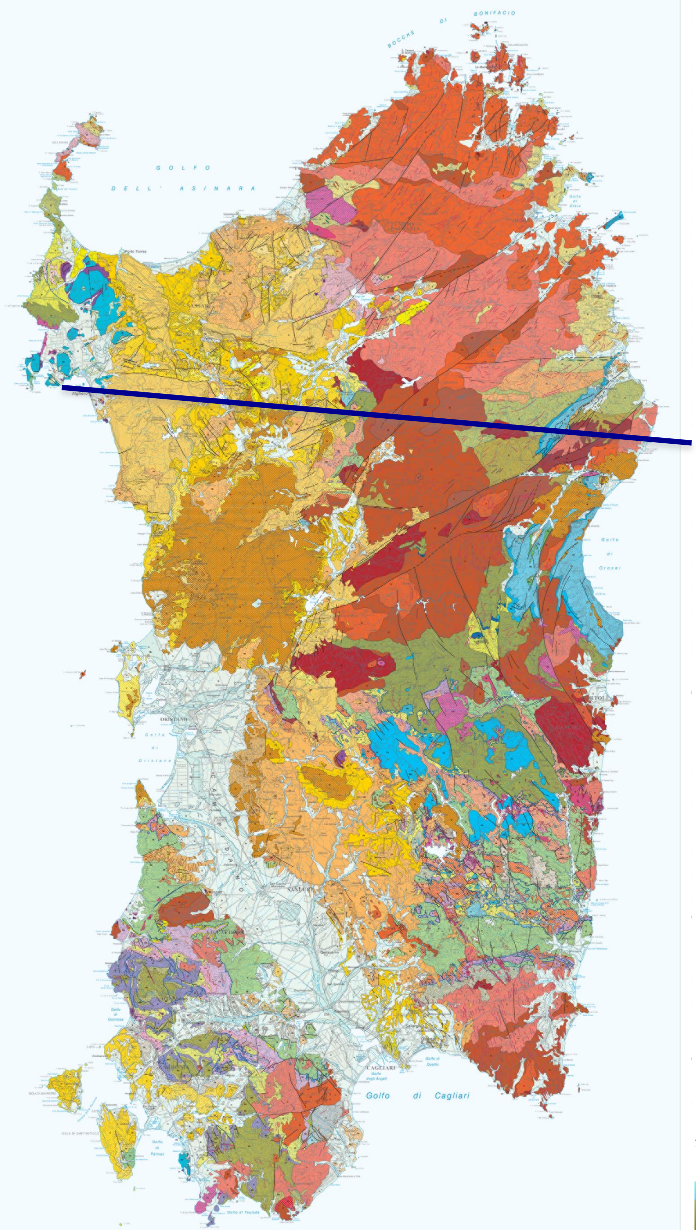
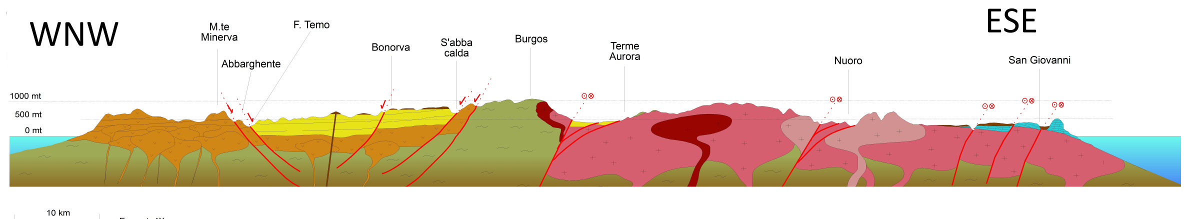


SARDINIA IS MADE OF:

- Quaternary alluvial deposits and minor intra-plate volcanism
- Tertiary sedimentary basins with volcanic units
- Deeply eroded Mesozoic sedimentary rocks
- Metamorphic basement widely intruded by Carboniferous-Permian Granitoids (Variscan orogenesis; 360-290 Ma)

The ET Italian candidate site is located in the Variscan basement of Sardinia because of its geodynamic quietness, very low seismicity and anthropogenic seismic noise.



2019-2020 CHARACTERIZATION

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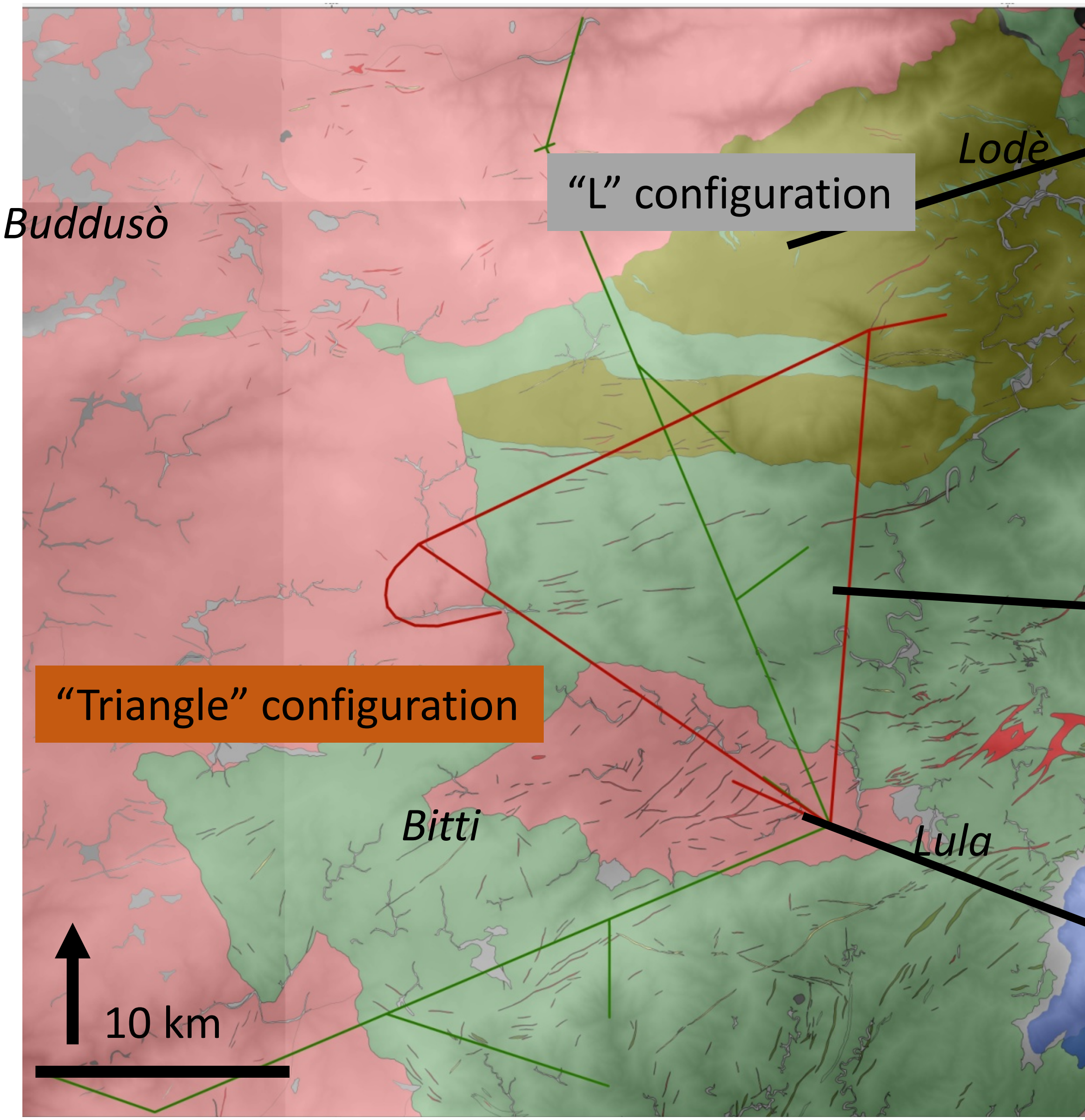

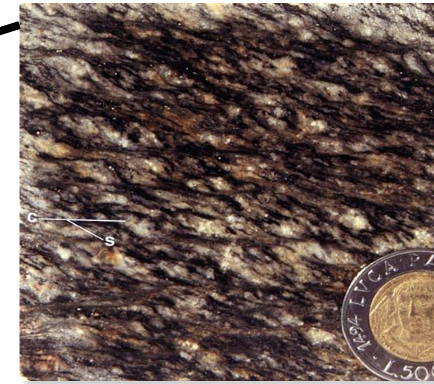

Orthogneiss
"Lodè type"
UCS: 92.6 / 60.8 Mpa

Micaschist/
paragneiss/quartzite
UCS: 9.9/8.8 Mpa

Granodiorite
"Bitti type"
UCS: 72.1 Mpa

OPEN QUESTIONS

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Geological questions:

- What is the distribution of lithologies in the area?
- What are the contacts among those?
- Is it possible to establish at least to establish a relative chronology of deformation events in the area?
- How fractures are related to the circulation of fluids?

ERT targets:

- Can we establish the thickness of altered zones above the bedrock?
- Can we identify superficial and suspended aquifers?
- Can we reconstruct the geometry of fault and fracture system at depth?

SASSARI TASKS 2020-2021

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T4 Activities

INFN
Istituto Nazionale di Fisica Nucleare

Geological mapping

Milestones	Date
Rocks and structures identification along the tunnel track	2021.09.30
Structural maps of rocks along the detector path	2021.12.31

Deliverables	Date
Structural maps of rocks along the detector path	2021.12.31

Geological stability and rock quality

Milestones	Date
Vertical displacement measurements by means of SAR observation	2021.06.30

Deliverables	Date
Faults accommodating vertical movements	2021.12.31

Hydrogeology

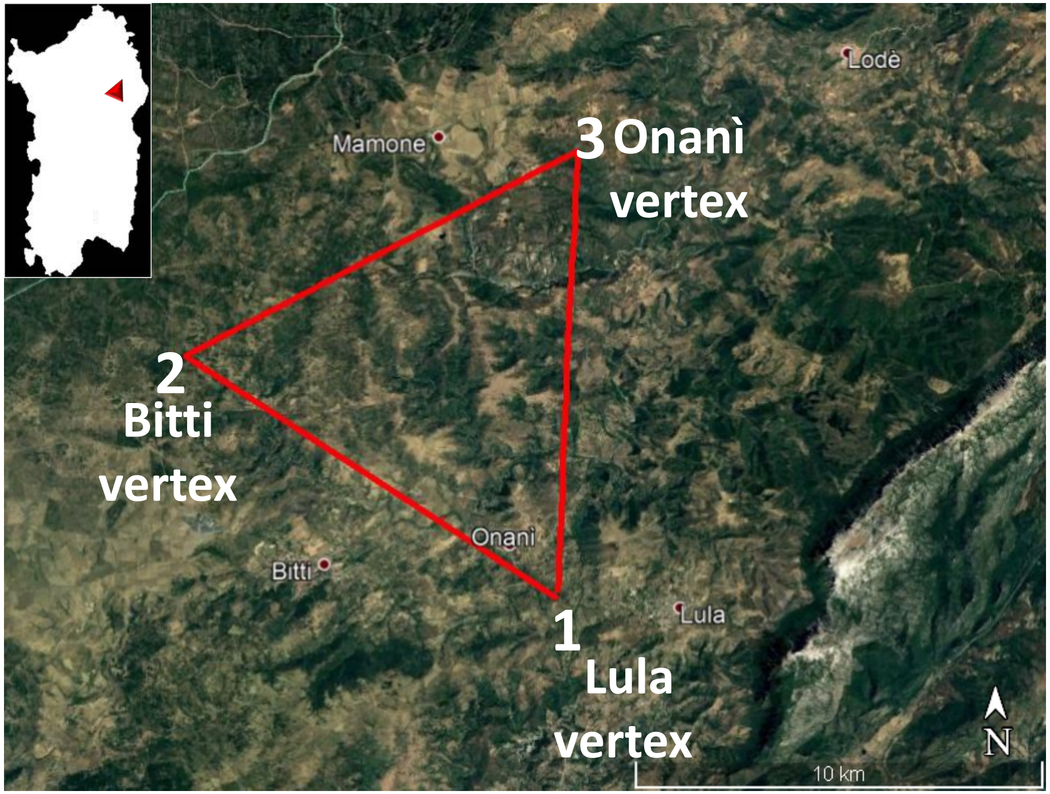
Milestones	Date
Census of well and spring along the path	2021.06.30
Chemical analysis of rocks	2021.12.31
In-situ test to estimate the average hydraulic conductivity in rock mass.	2022.06.30

Deliverables	Date
Chemical and Ionic composition of water	2021.12.31
Model describing possible paths for groundwater and numerical model including direction and velocity of water at depth	2022.06.30

THE TRIANGLE INFRASTRUCTURE

WE ARE CHARACTERIZING

The ET layout here under study is as an underground triangular infrastructure (10 km long sides), whose vertices are located between the villages of Lula, Bitti and Onanì, and is confined within an area not crossed by main regional faults.



OUR PRODUCTS

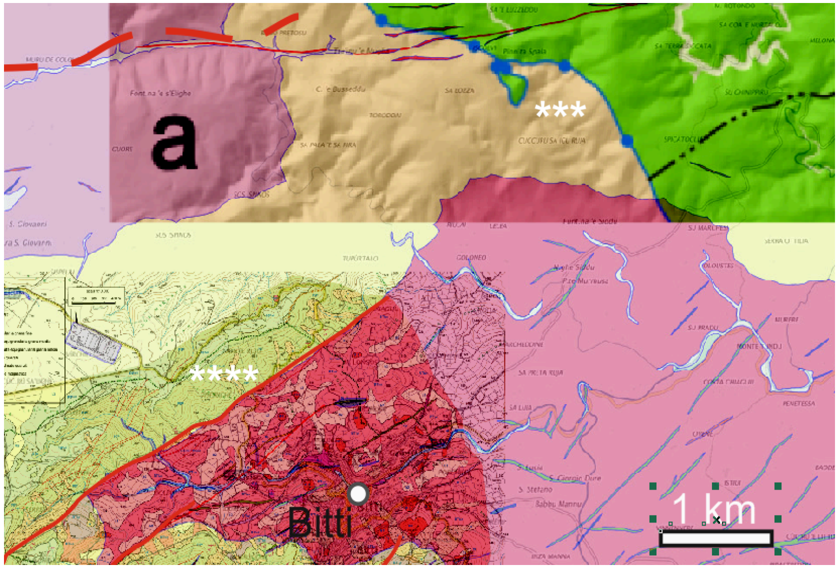
02/07/2021 "Progetto Einstein Telescope SARDEGNA" - Analisi geologico strutturale preliminare.

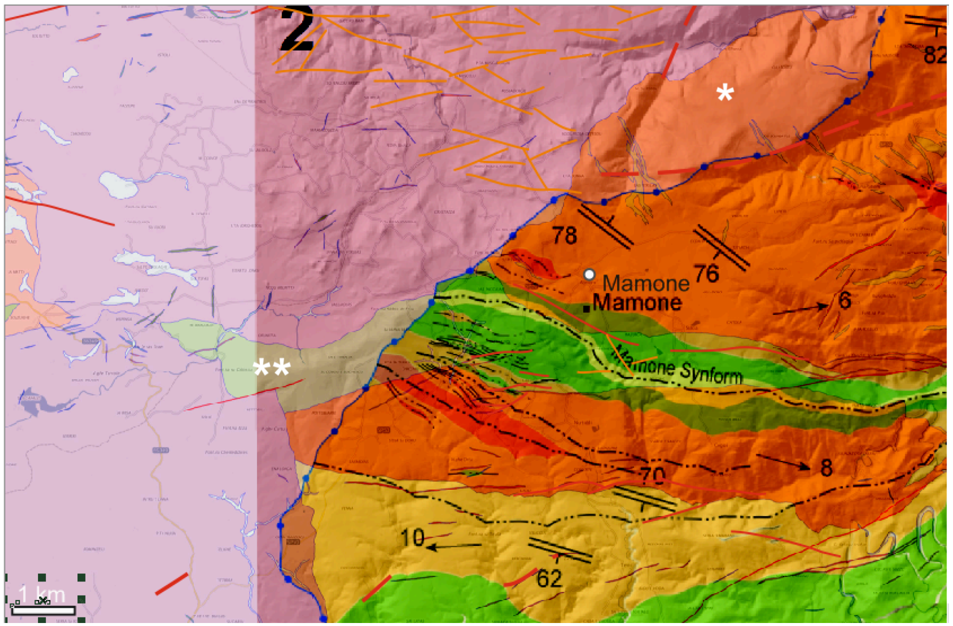
- Geological map review
- Lithological and structural characterization from new geological survey along the tunnel trace between P2 and P3 and between Bitti village and P2 borehole
- Morpho-structural and structural preliminary results

28/09/2021 "Relazione Geofisica – Prospezioni geoelettriche nel sito sardo candidato ad ospitare l'Einstein Telescope.

- ERT survey on P2 and P3 boreholes surroundings.
- Structural interpretation of tomographic lines

Beside that vulgarization at Lula


a
***
****
Bitti
1 km


2
*
82
78
76
Mamone
Mamone
6
Mamone Synform
**
70
8
10
62
1 km

MAP REVIEW

OLDER AND SIMPLIER MAP

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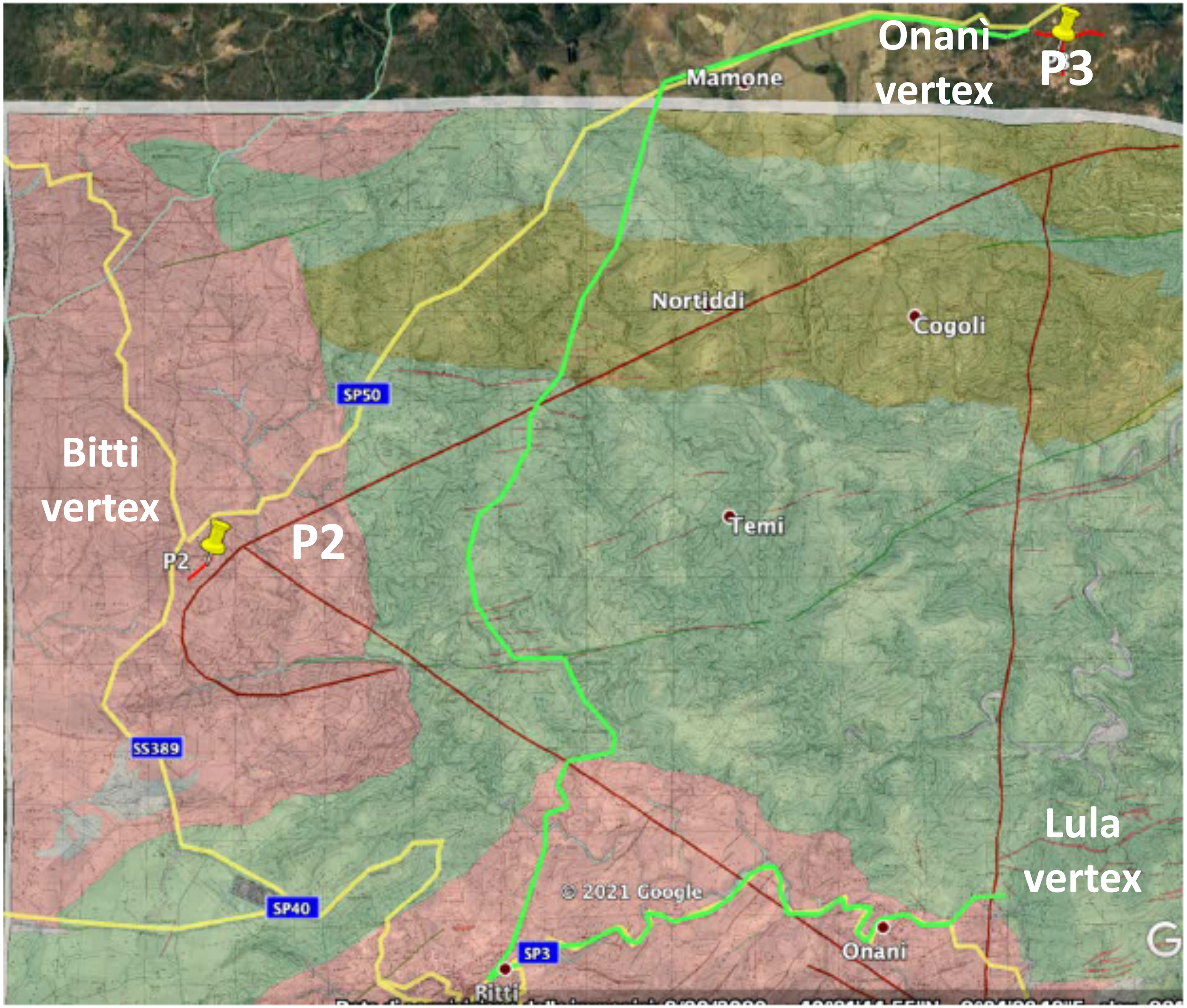


Lithologies: Orthogneiss (dark green). Micaschists (light green). Intrusive units (rose). The red trianle represents the hypthetic underground trace of ET laboratories. P2 and P3 are on the borehole location.

MAIN GEOLOGICAL FEATURES

The geological features of the Paleozoic metamorphic rocks are the result of ductile deformation with folds and related planar and linear anisotropies.

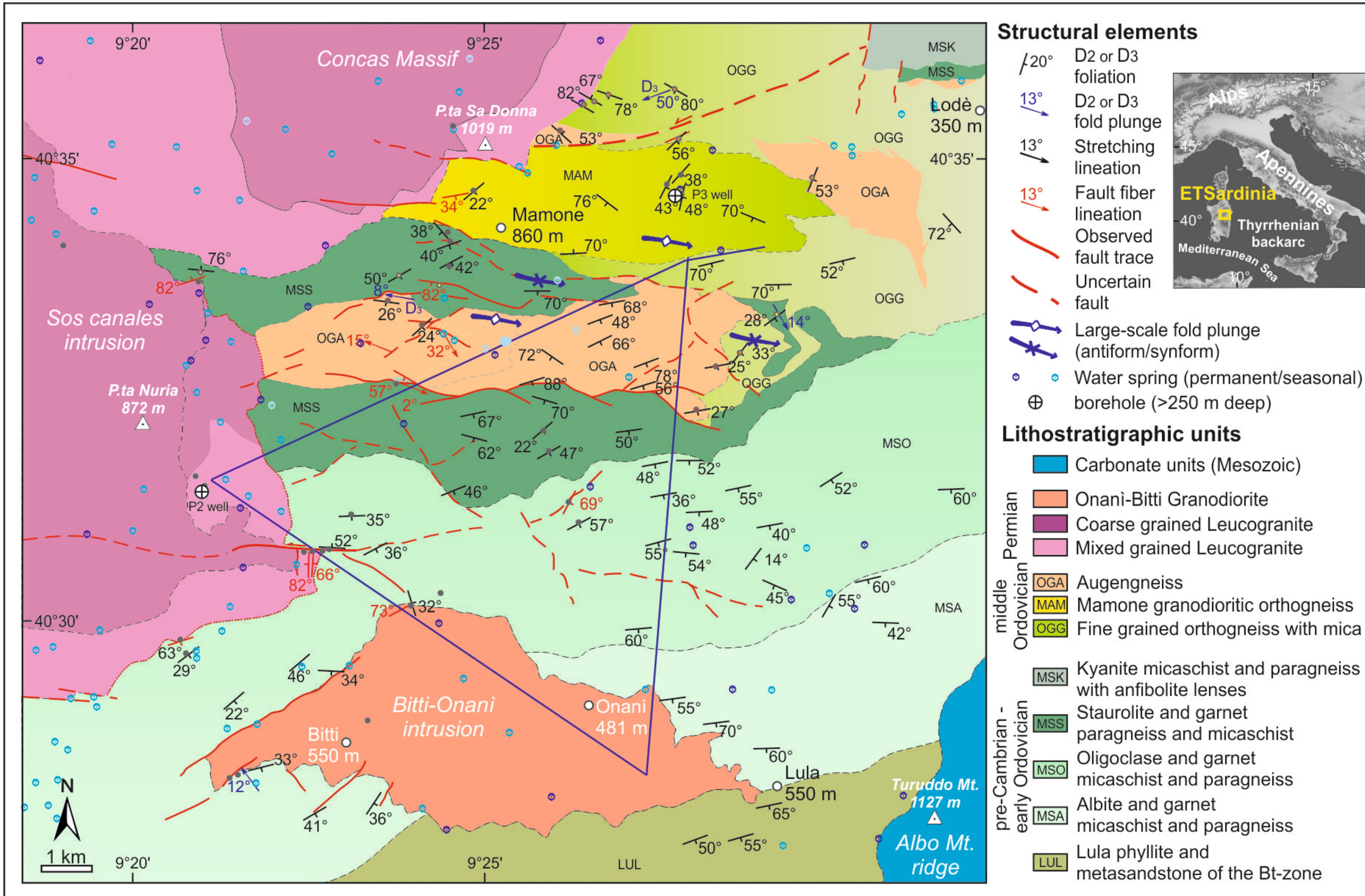
This poly-deformed metamorphic basement was intruded by several granitic bodies and by mafic to acidic dykes, mostly of early Permian age.

A brittle to ductile fault network affects the metamorphic-plutonic ensemble providing a complex aquifer.

Within such a structural frame it is difficult to accurately predict lithologies at depth by means of the geological survey alone.

GEOLOGICAL SURVEY

A NEW STRUCTURAL MAP



We have merged the lithologic information from published maps (also by comparing satellite images) and added new data collected in the field.

NEW HINTS ON THE MAP

The map provides a **higher quality definition of lithologies** involved and their distribution.

Tectonic contacts are also better mapped, thus allowing to predict the distribution of structures at depth.

Faults were mapped by using crossed field and satellite evidence.

A first attempt of location and distinction of **permanent and seasonal water springs** was also performed on the map by means of initial field checks.

Springs (preferentially permanent) are located near larger faults and intrusive contacts

LITHOLOGIES: BITTI-ONANI’ GRANODIORITE

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Lithostratigraphic units

- Carbonate units (Mesozoic)

Permian
- Onanì-Bitti Granodiorite
- Coarse grained Leucogranite
- Mixed grained Leucogranite

middle Ordovician
- OGA Augengneiss
- MAM Mamone granodioritic orthogneiss
- OGG Fine grained orthogneiss with mica

pre-Cambrian - early Ordovician
- MSK Kyanite micaschist and paragneiss with anfibolite lenses
- MSS Staurolite and garnet paragneiss and micaschist
- MSO Oligoclase and garnet micaschist and paragneiss
- MSA Albite and garnet micaschist and paragneiss
- LUL Lula phyllite and metasandstone of the Bt-zone

Top of the intrusive unit of Bitti-Onanì near Bitti on the trace of the triangle. It consists of a granodiorite with mafic xenoliths crossed by veins with low pressure epidote (green)
40°30'12''N; 9°24'6'' E

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The Concas Massif Leucogranite on the country road near Punta Sa Donna.

40°32'17" 9°28'02"

AGEN GNEISS

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Augen Gneiss (Gneiss occhiadino) on the P1-P3 tunnel trace between Onanì and Mamone 40°33'11''N; 9°24'7'' E.

LITHOLOGIES: THE MAMONE ORTHOGNEISS

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Lithostratigraphic units

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Permian
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- MSA Albite and garnet micaschist and paragneiss
- LUL Lula phyllite and metasandstone of the Bt-zone

Mamone Orthogneiss (40°34''45'' N 9°27''39'' E). Oblique view

BOREHOLE COMPOSITION AND STRUCTURE

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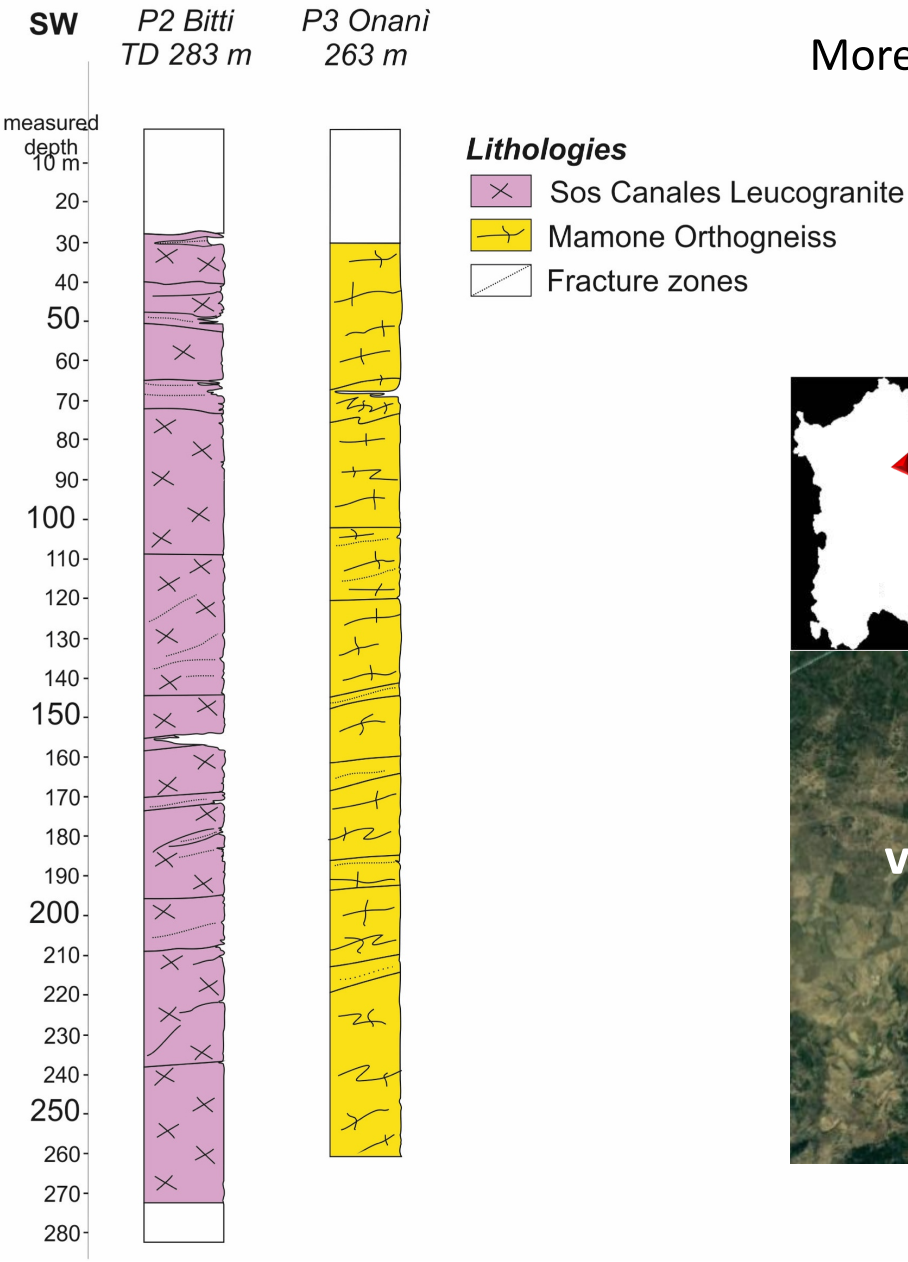
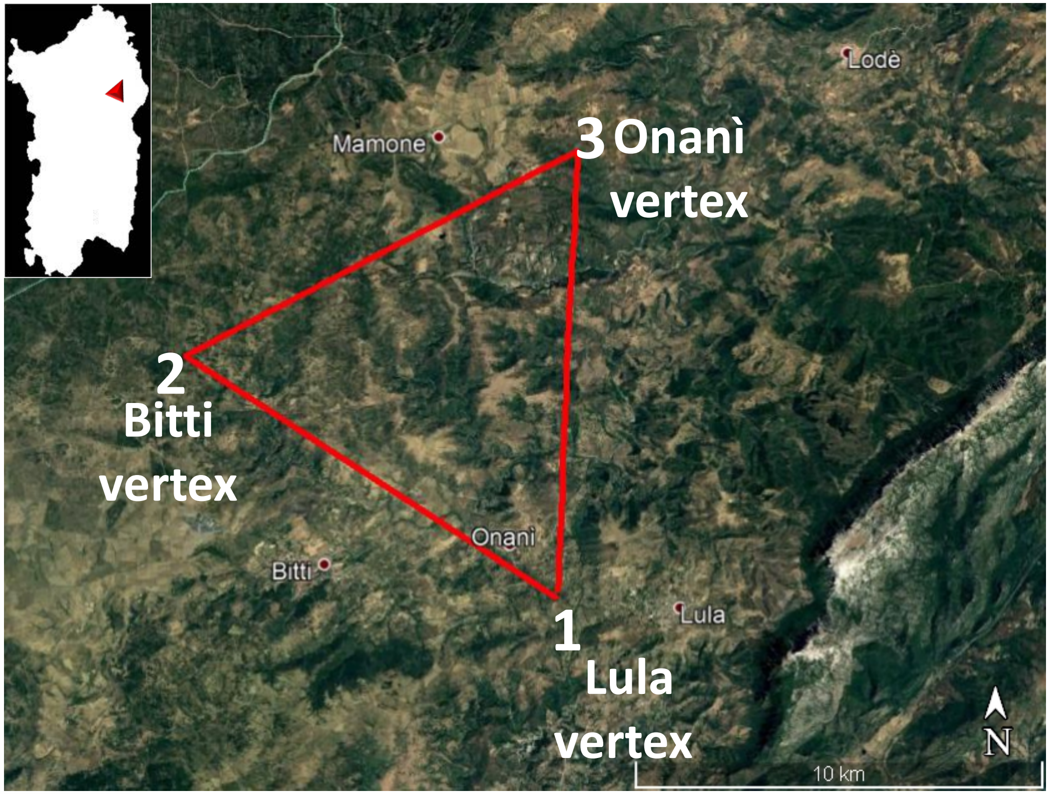
More data and insights in the Luca Naticchioni's talk





LITHOLOGIES: MICASCHISTS

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Lithostratigraphic units

- Carbonate units (Mesozoic)

Permian
- Onanì-Bitti Granodiorite
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Foliated Micaschists. Mamone south 40°33'56''N 9°24'31'' E

LITHOLOGIES: METAPELITIC ROCKS

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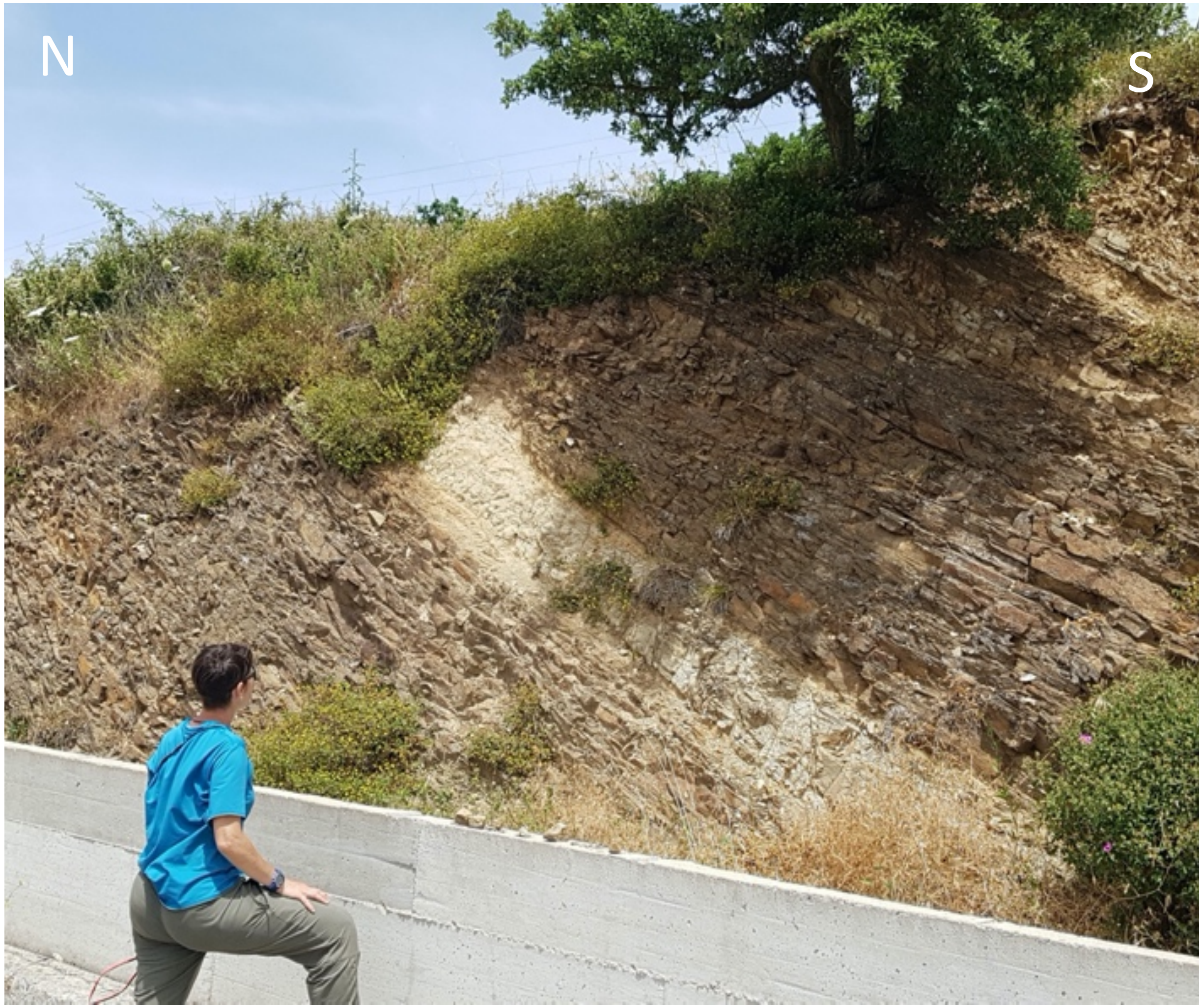

meta-ash and meta-arenite rocks on the road between Mamone and Bitti 40°31'9''N; 9°23'6’’E

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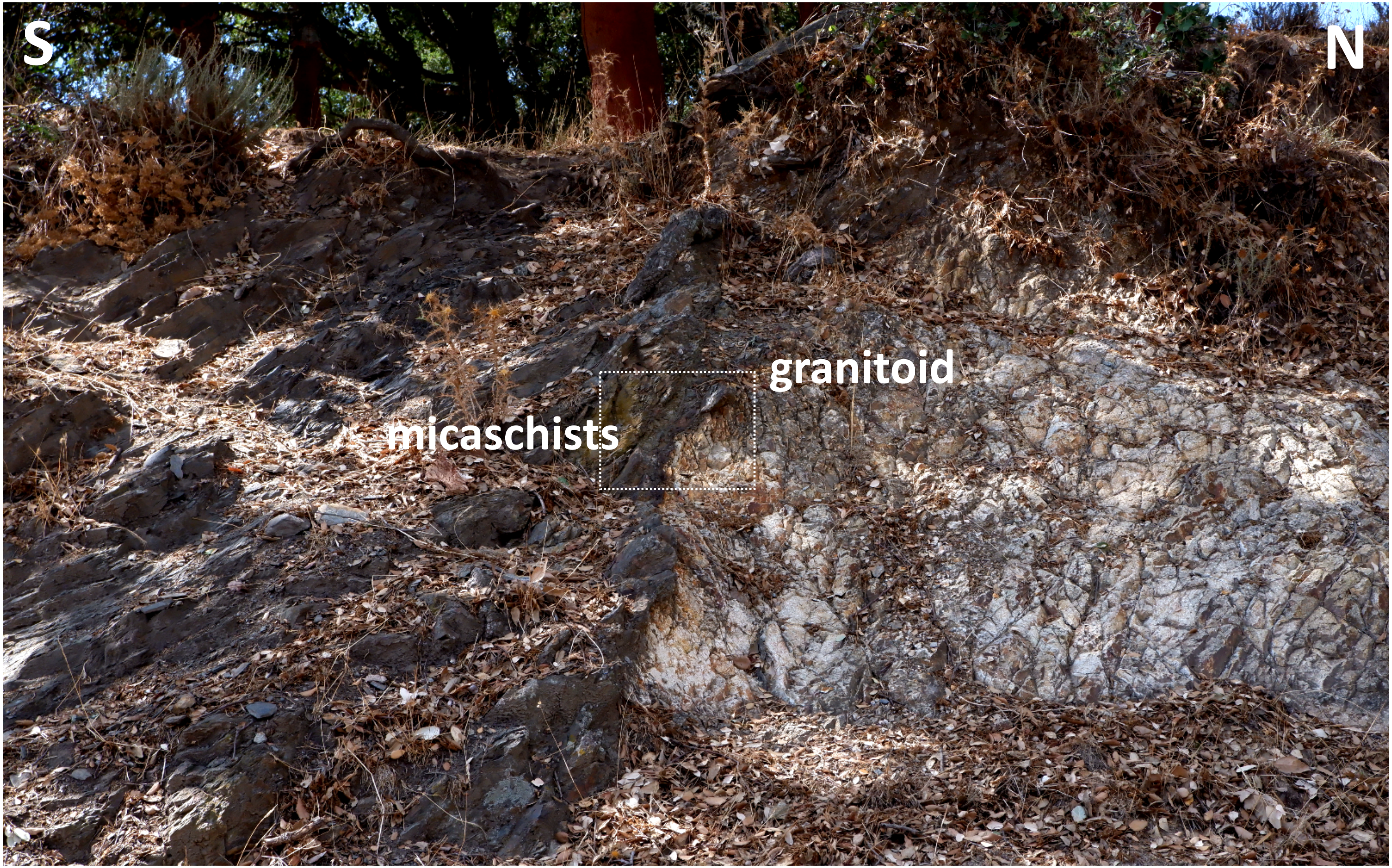
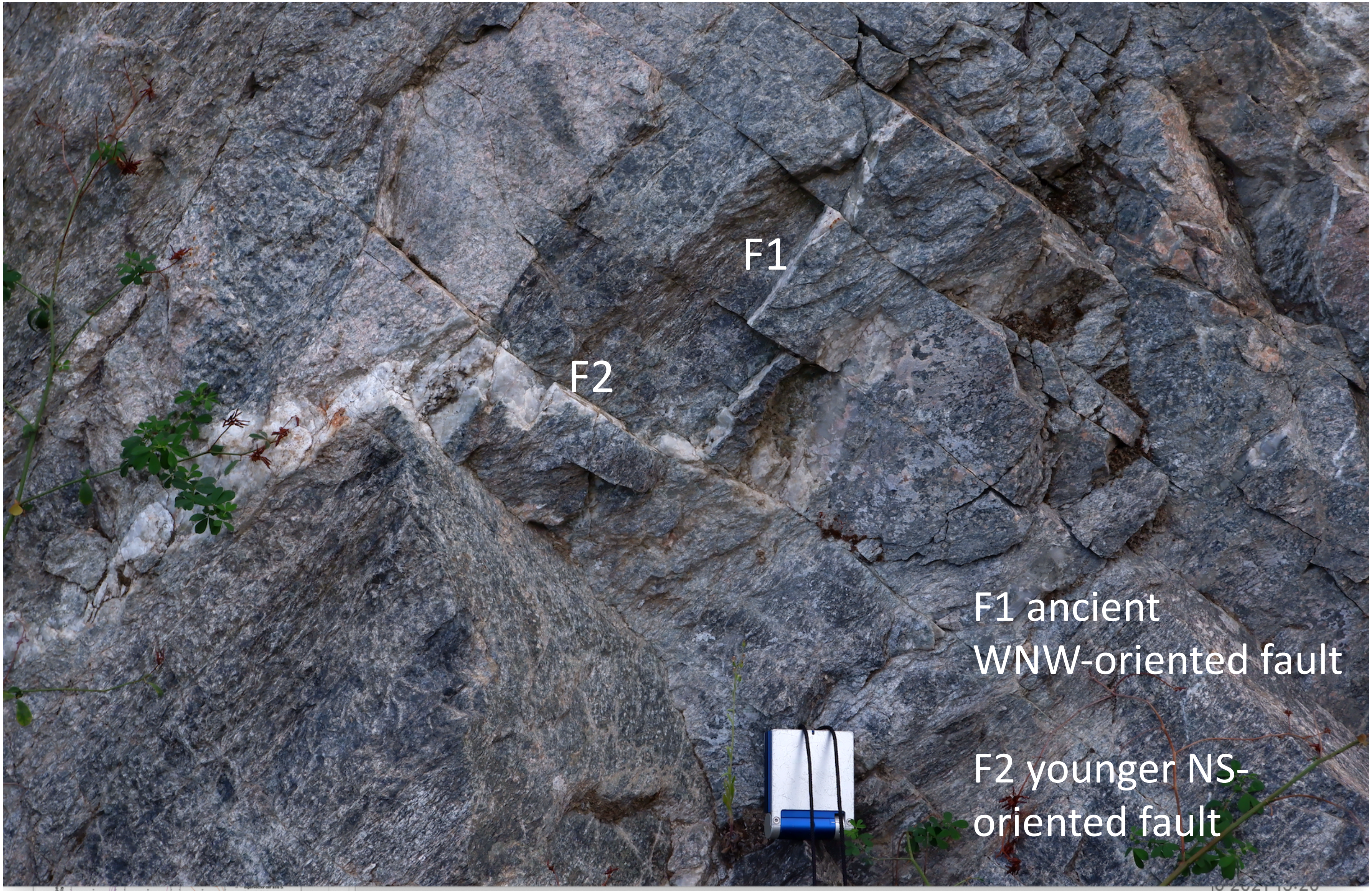
STRUCTURAL GEOLOGY

LITHOLOGIES: GRANITOID DYKES



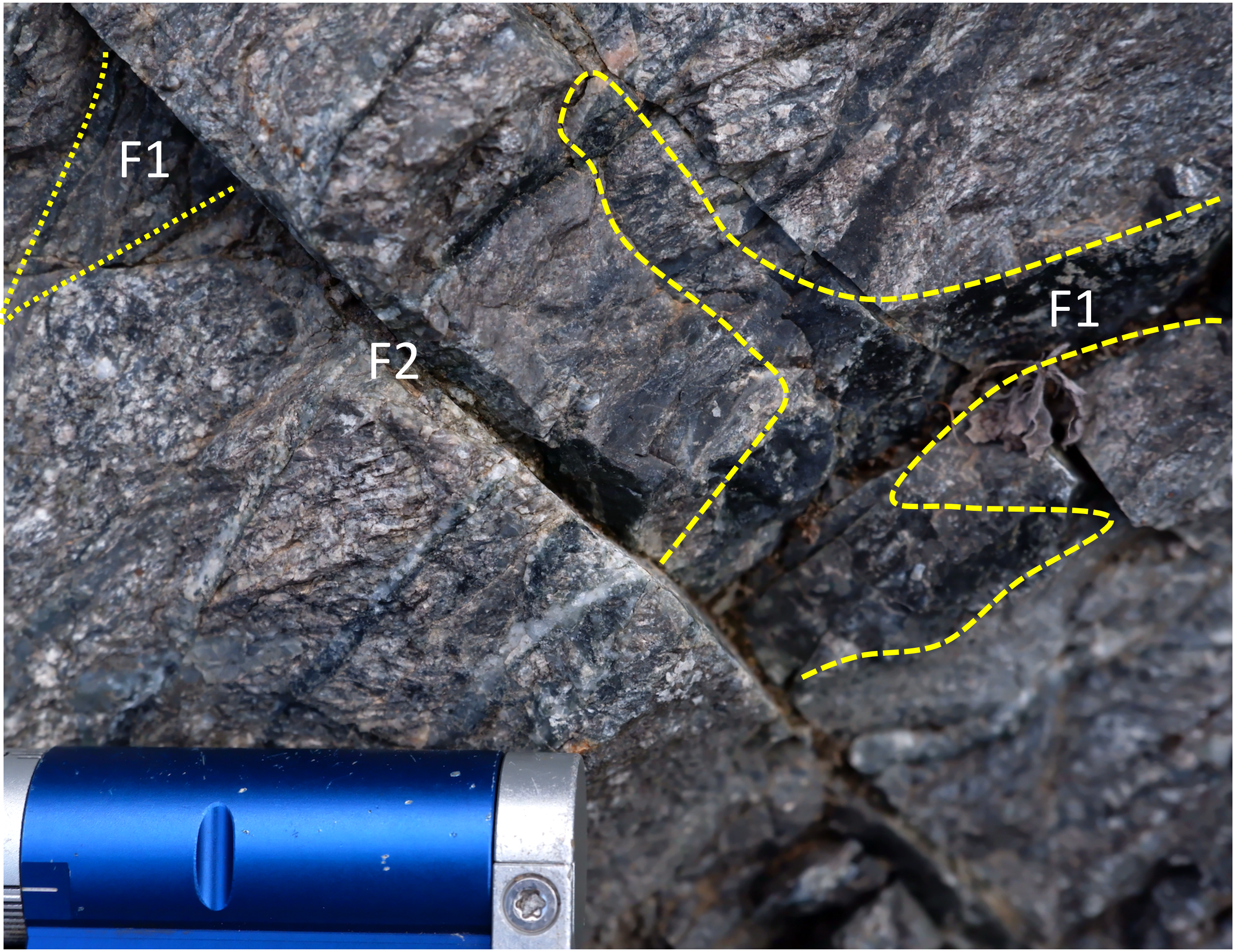
dicchi alterati intrusi in micascisti piegati in fase D2+D3 (scistosità in viola) ritagliati da faglie normali tardive immergenti verso SSE (In rosso). 40°34'7'' N; 9°24'30'' E

RELATIVE AGE OF FAULTS



Follow the fault-and-vein geometry, which is dissected by small scale discrete F2 faults

RELATIVE AGE OF FAULTS



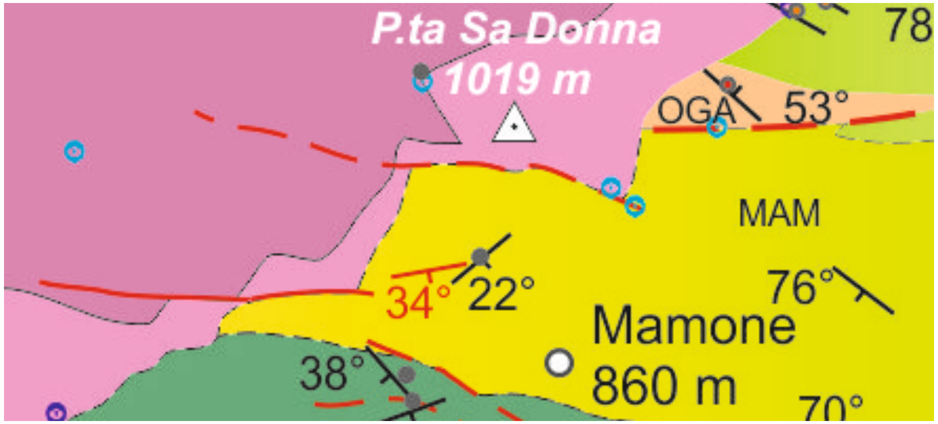
F1 ancient Pseudotachilite vein injected along faults that are derived from shear melting of rocks

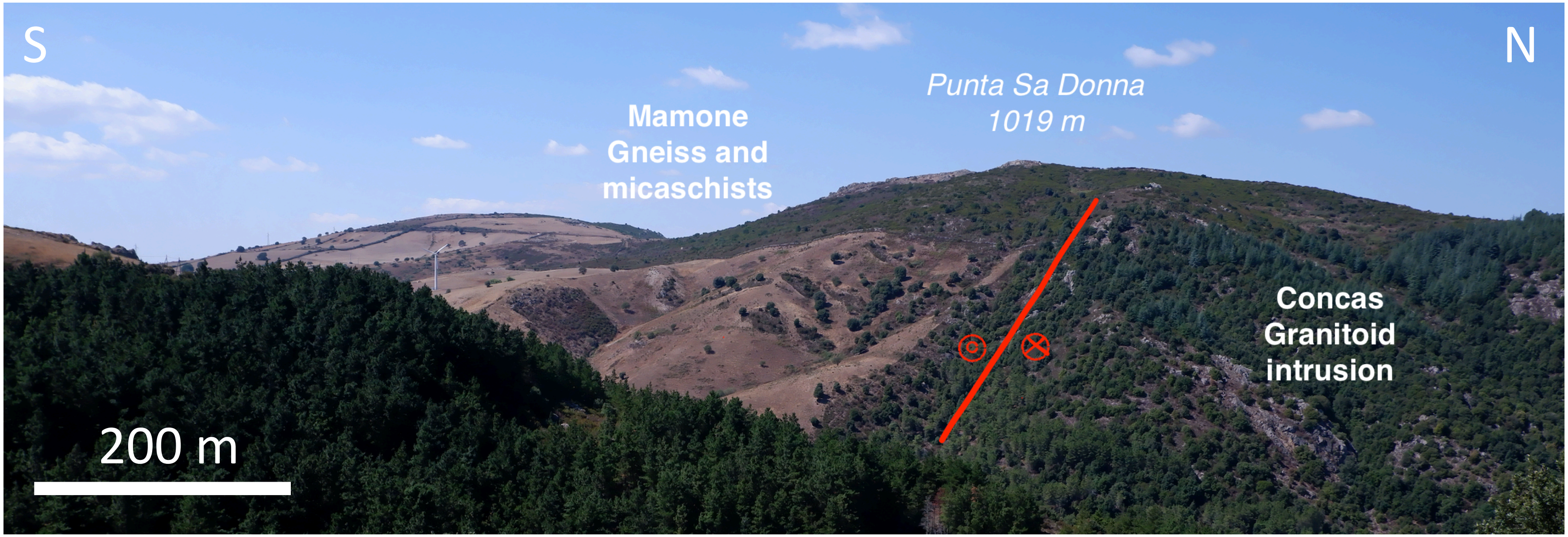
F2 younger NS-oriented fault

Detail of relative cross-cutting relationship between fault structures, ie., F1 and F2, the elder being related to Variscan structures; the second to younger tectonics, possibly of Pliocene age.

LARGE FAULTS (A FEW KM ACROSS)

The intrusive contacts, although "warm" are fault guided, possibly being overprinted during the younger tectonic events that have affected Sardinia (likely early Miocene).





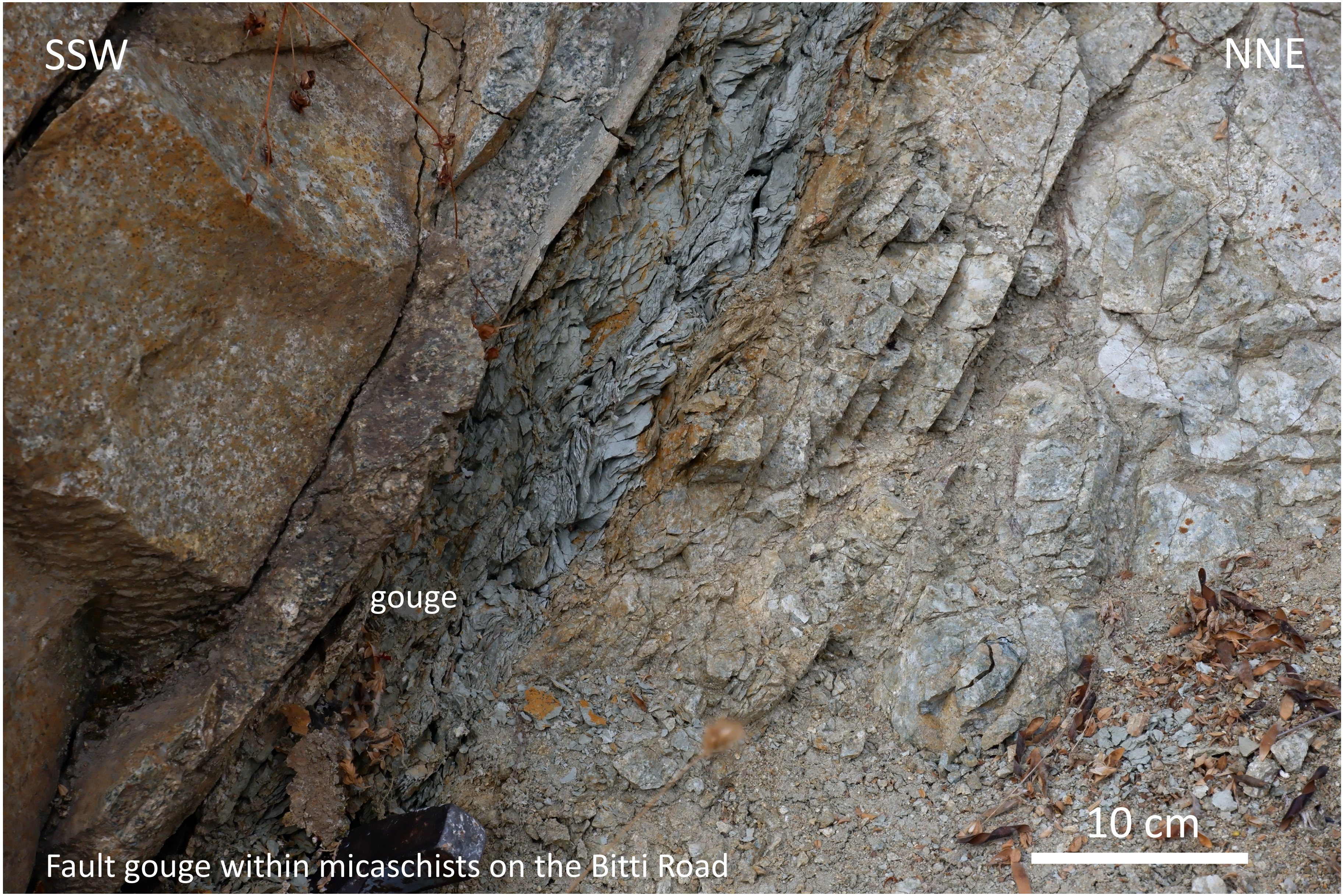
FAULTS TYPES: with ACIDIC INJECTIONS

Detail of micaschists crossed by Qz-veins and cataclasitic bands than can be as thick as a ten of meters. 40°33'39'' N 9°24'21'' E

FAULTS TYPES: with ARENIZED CATACLASITES

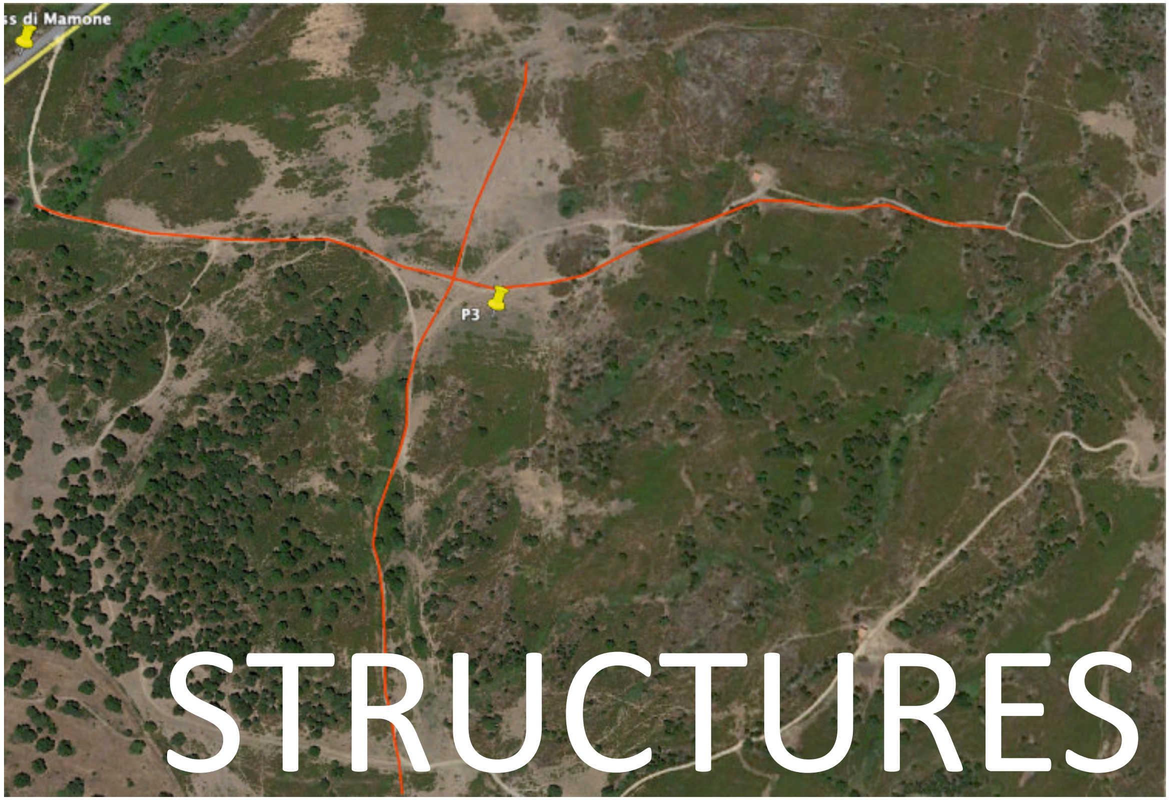
Arenized cataclasite along high-angle faults 40°32'56''N; 9°23'58'' E.

FAULTS TYPES: with IMPERMEABLE GOUGE



FAULTS WITHOUT SIGNIFICANT FRACTURE NETWORK

Bitti granodiorite crossed by greenish bands of epidote and pseudotachilite injections.



STRUCTURES AND MORPHOSTRUCTURES

FRACTURES AT BOREHOLE SITES

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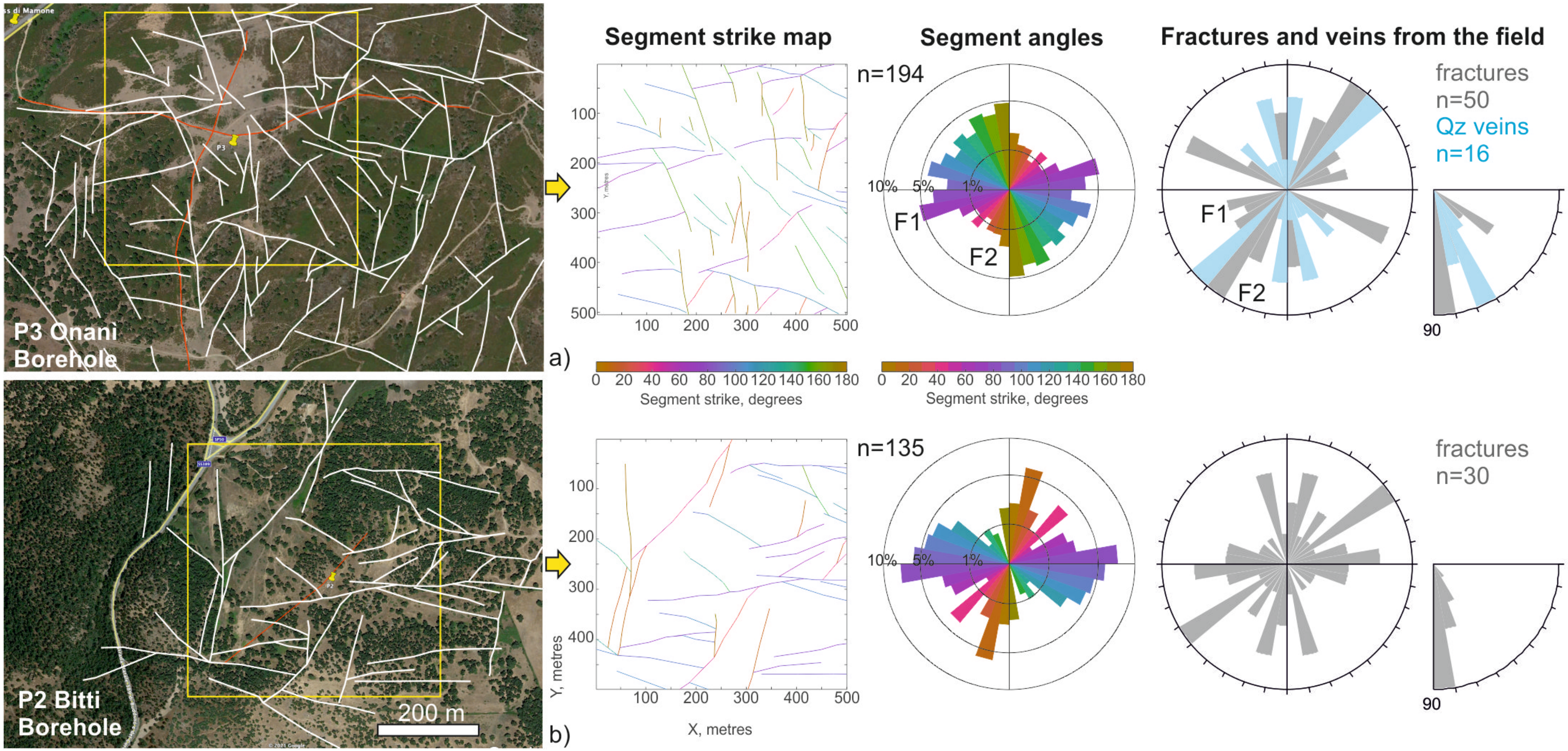
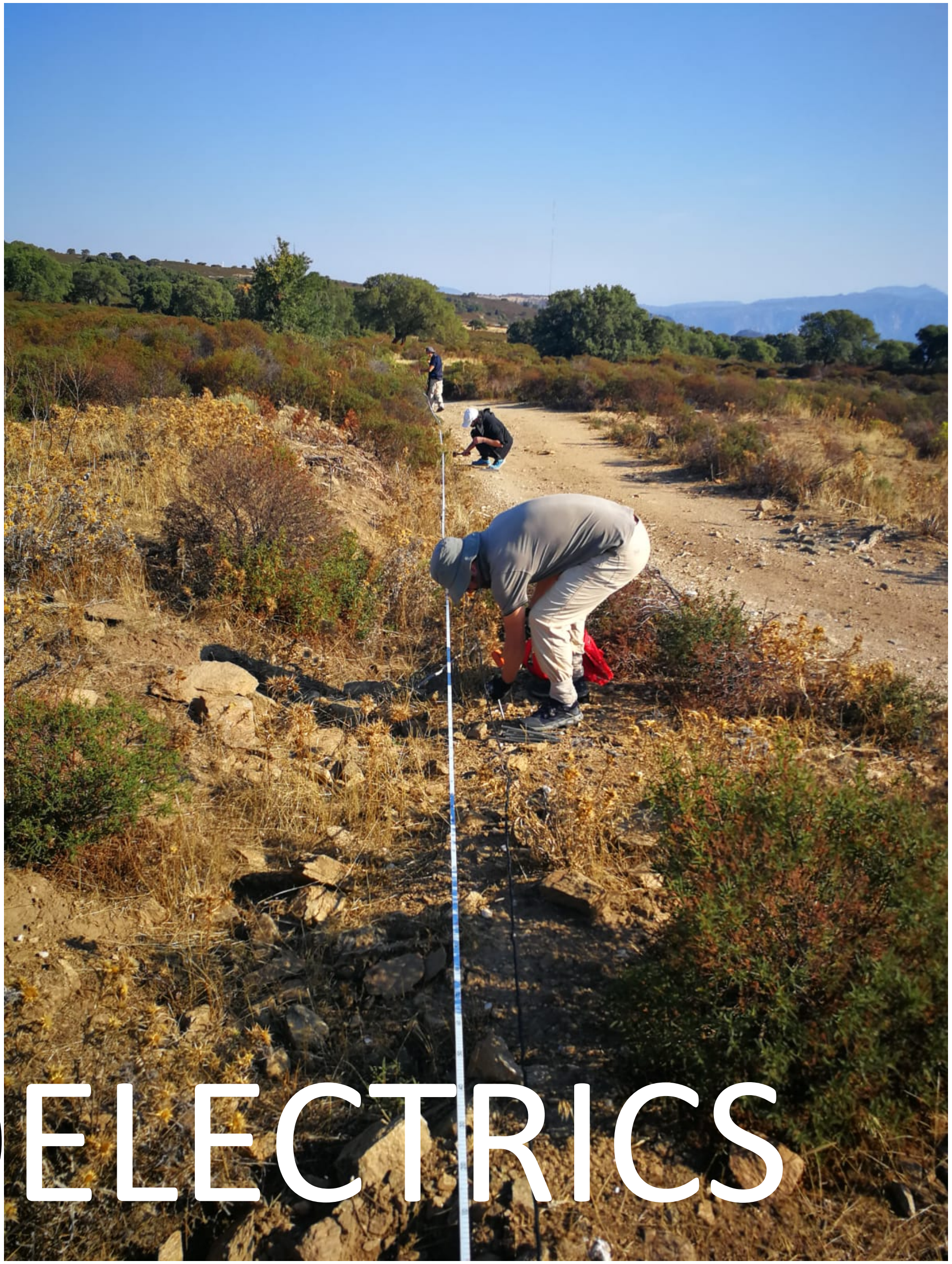
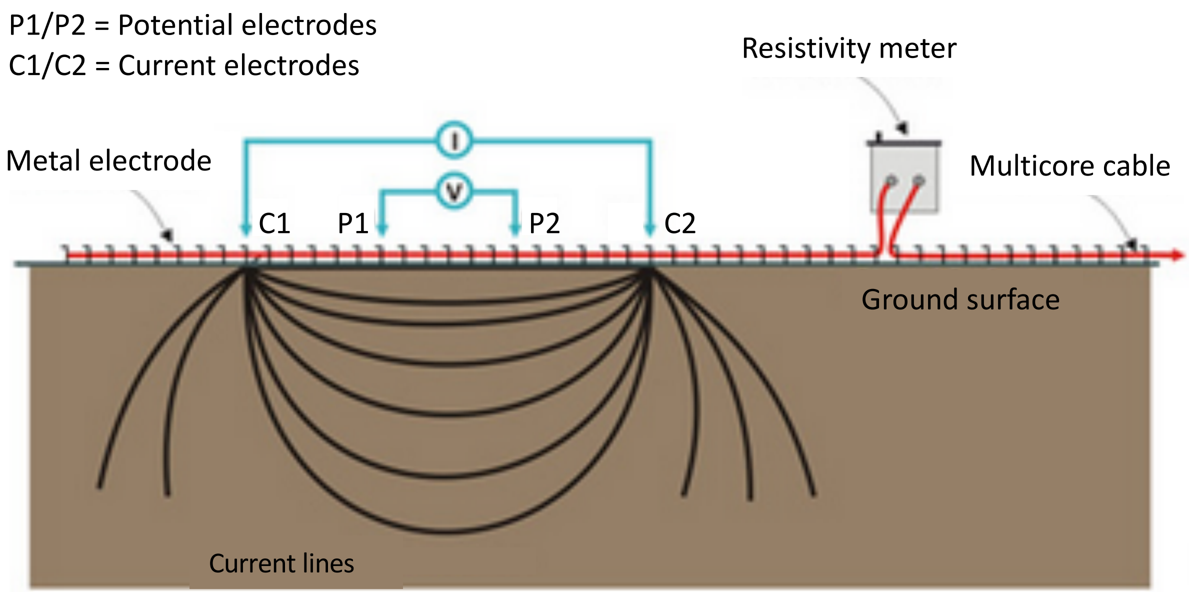


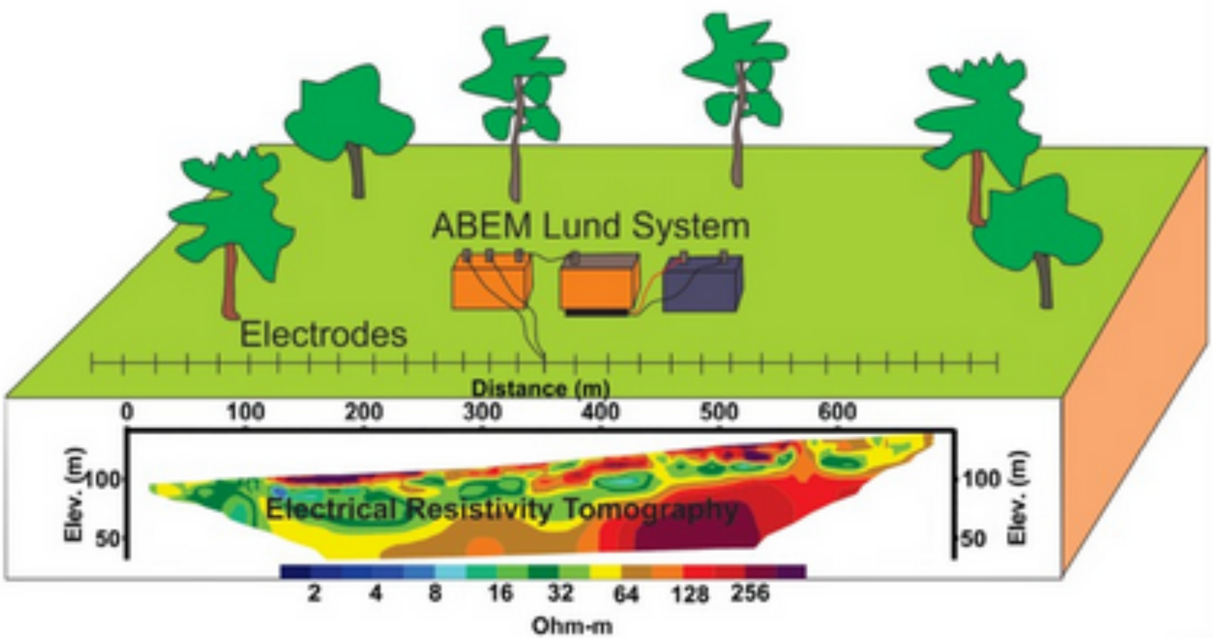
Morpho-structural segment trace maps at P3 and P2 boreholes, created from the interpretation of satellite images, used to estimate fault segment orientation using FracPaQ (Healy et al., 2016). On the right, comparison of stereographic projects of both interpreted segments and measured fractures in the field.



GEOELECTRICS

Electrical Resistivity Tomography (ERT) method





Galvanic coupled resistivity system

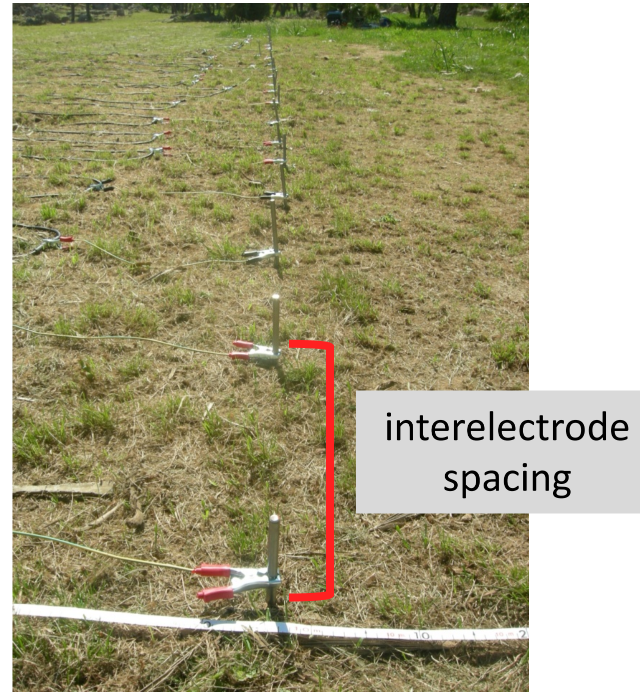
The electrical resistivity (ρ) is an internal parameter of the material and its unit is Ohm·meter [Ω·m];
it quantifies how strongly the material opposes the flow of electric current.

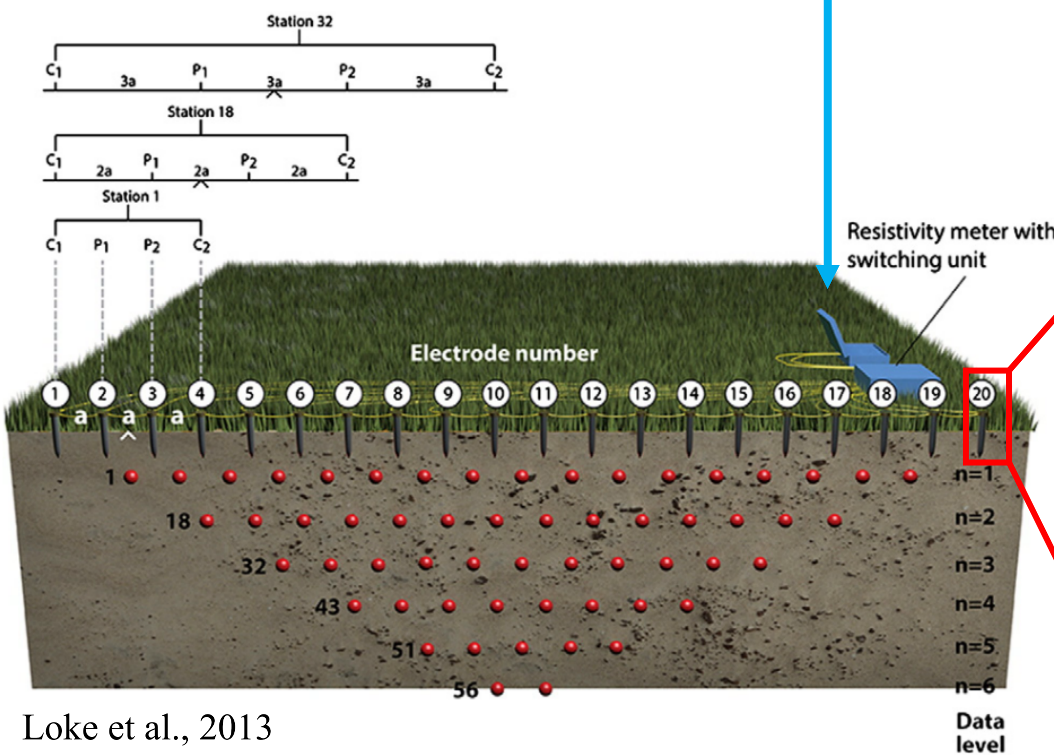
$$\rho_a = K \frac{\Delta V}{I}$$

ρ_a = Apparent resistivity
K = Geometric factor
ΔV = Potential difference
I = Current intensity

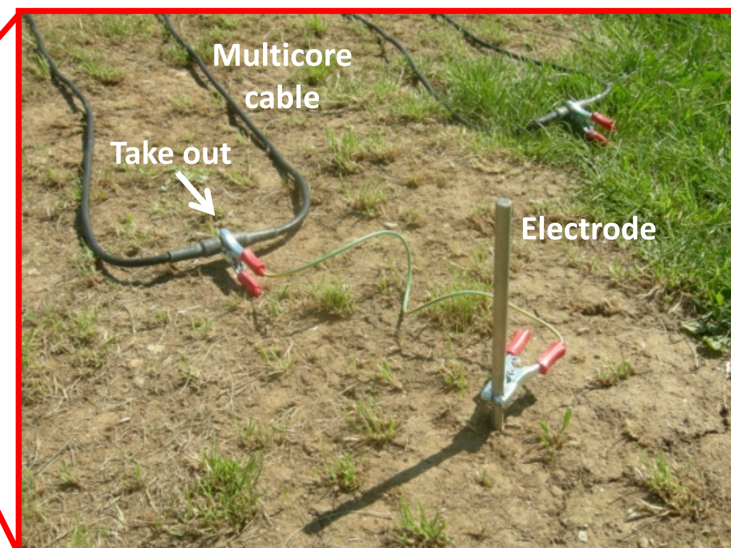
Electrical Resistivity Tomography (ERT) method

Terrameter LS 2 (ABEM instrument)

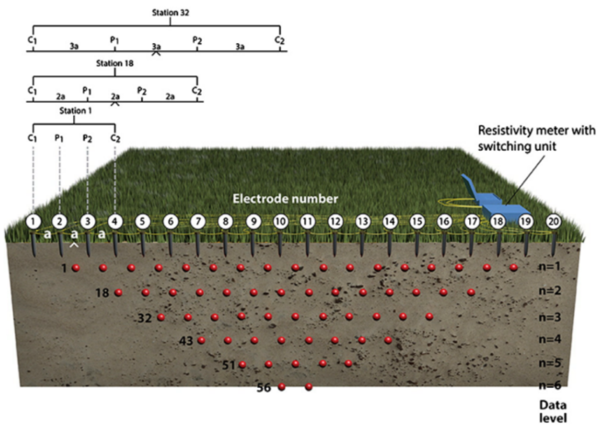




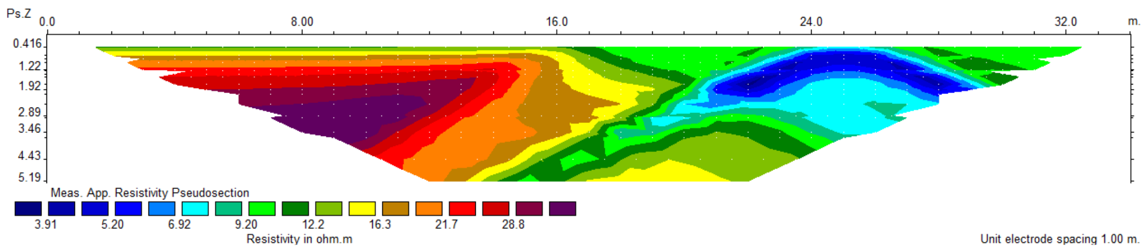
Loke et al., 2013



Electrical Resistivity Tomography (ERT) method

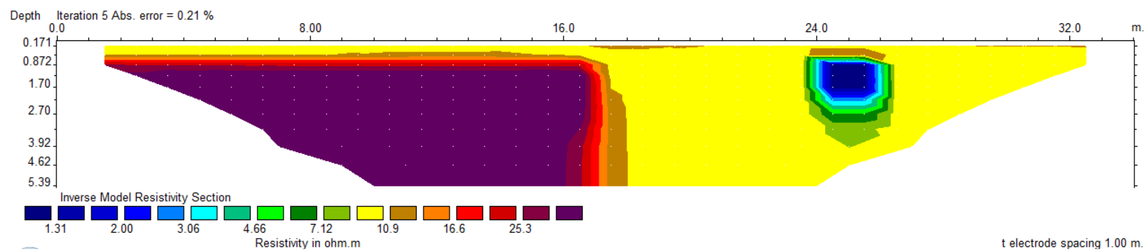


Software RES2DINV



Pseudosection = Approximate picture of the true subsurface resistivity distribution beneath the survey line with measured resistivity values.

Inversion



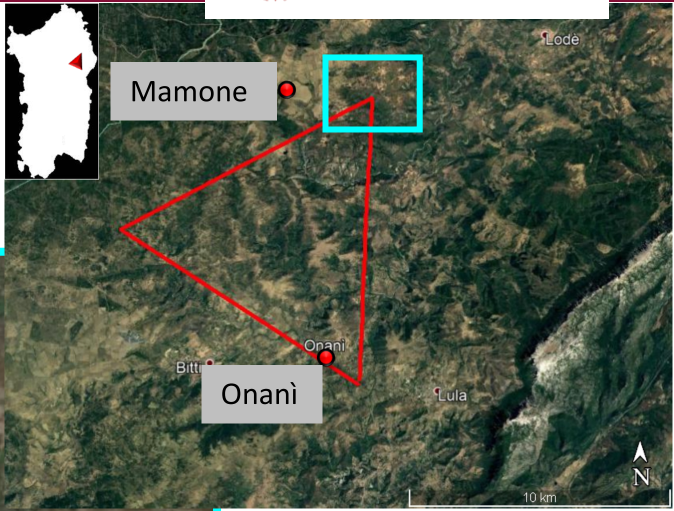
Tomography = high resolution subsurface geological model with calculated resistivity values.

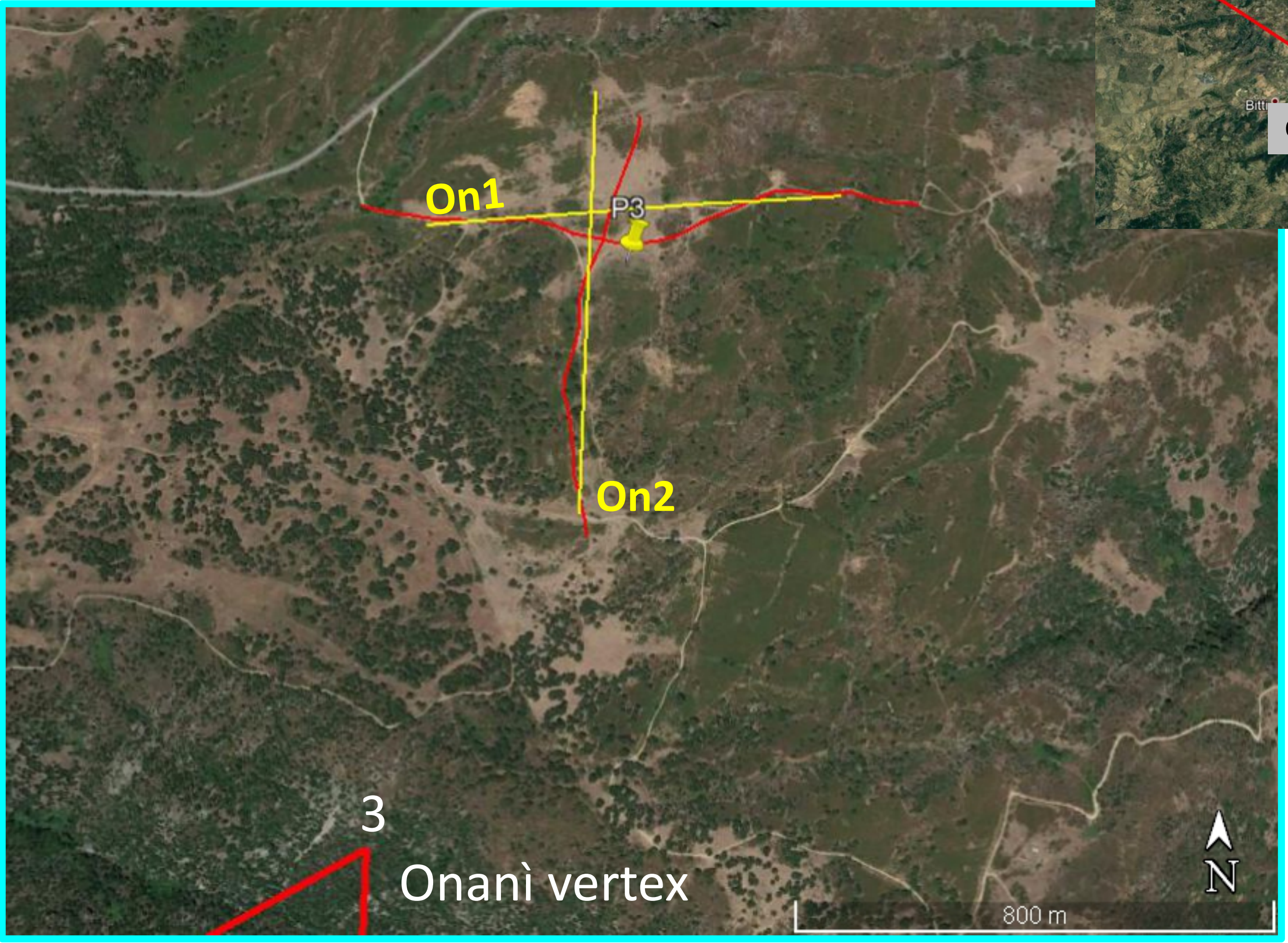
ERT SURVEY AT ONANI' BOREHOLE

- **Two geoelectrical profiles**

On1: length 630 m – interelectrod spacing 10 m – direction 85°N

On2 : length 630 m – interelectrod spacing 10 m – direction 3°N





ERT survey

Active Seismic survey

Borehole P3

ERT RESULTS AT ONANI' BOREHOLE

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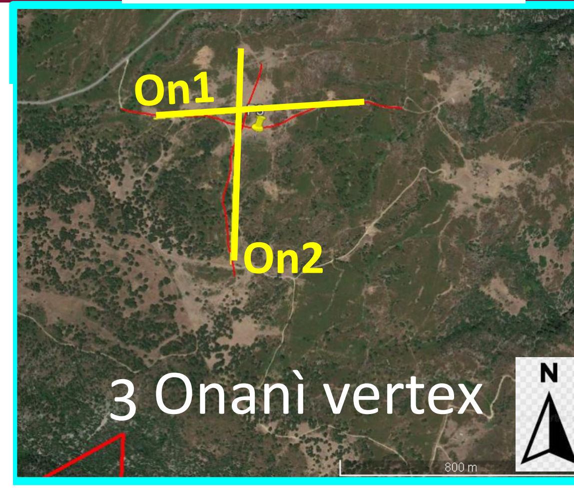
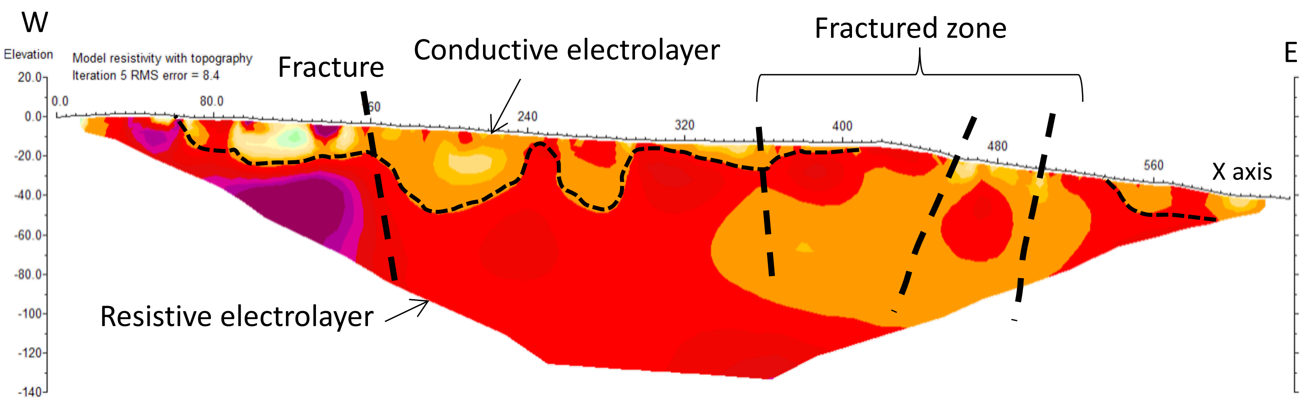
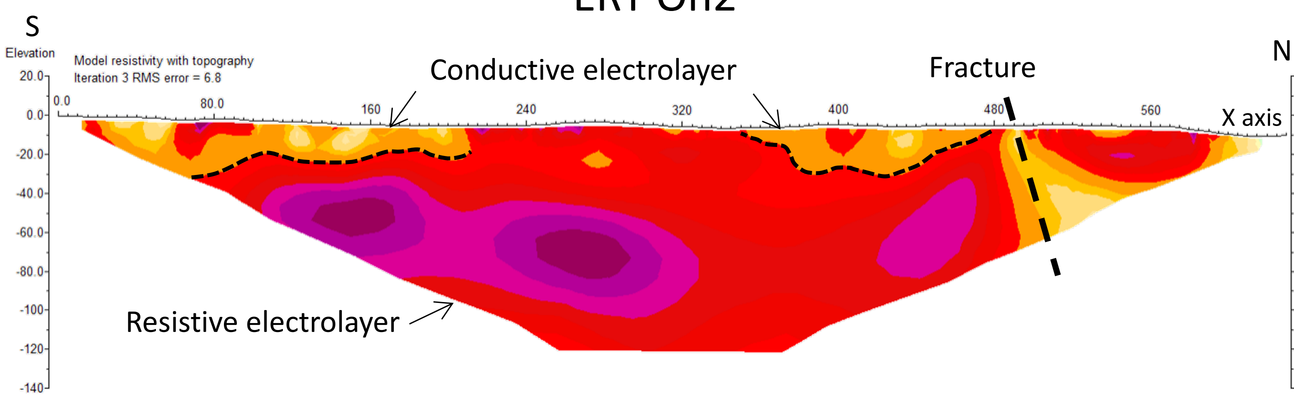
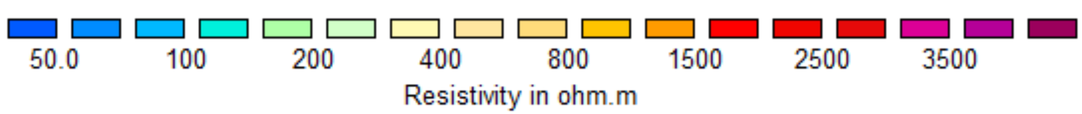


ERT On1



ERT On2





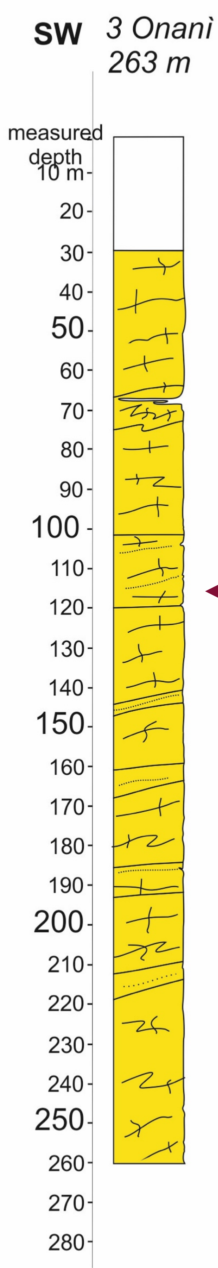
conductive electrolayer:

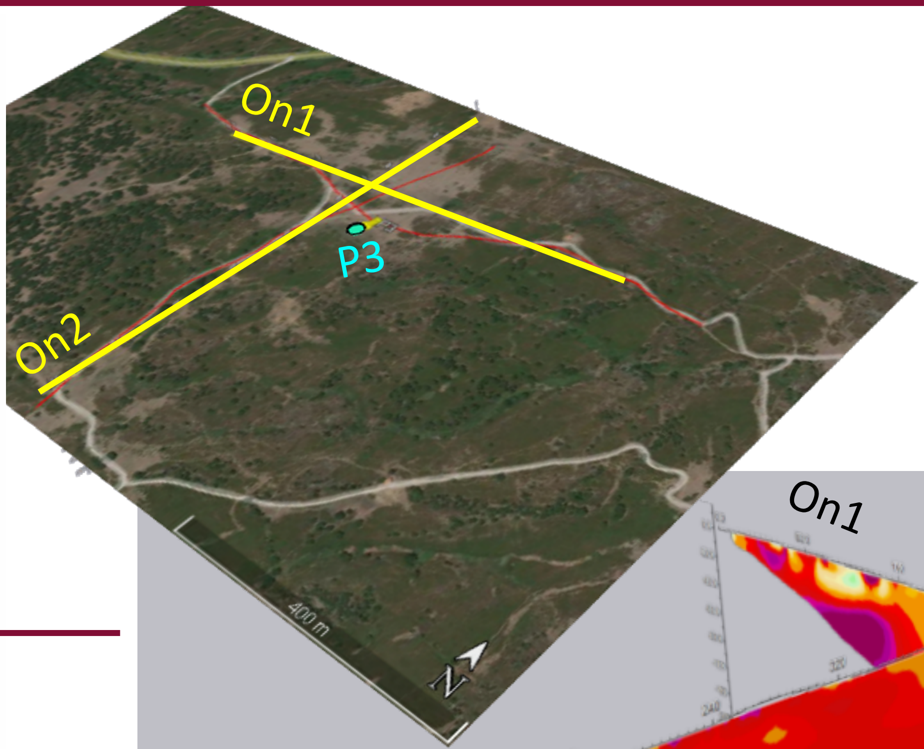
- ρ values 150÷1500 Ω·m
- regolith
- thickness 20 m

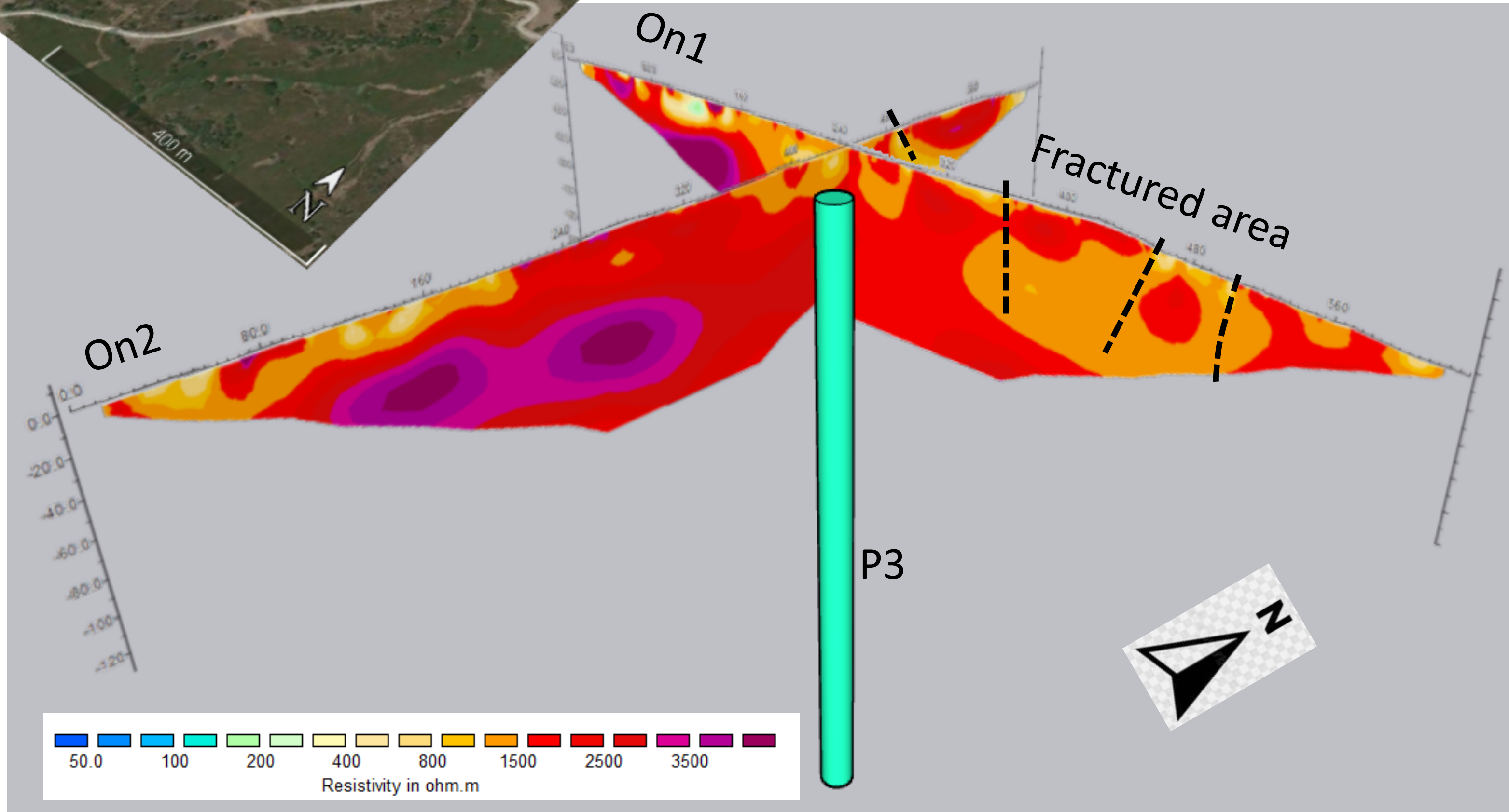
resistive electrolayer:

- ρ values > 1500 Ω·m
- bedrock unaffected

ERT RESULTS AT ONANI' BOREHOLE



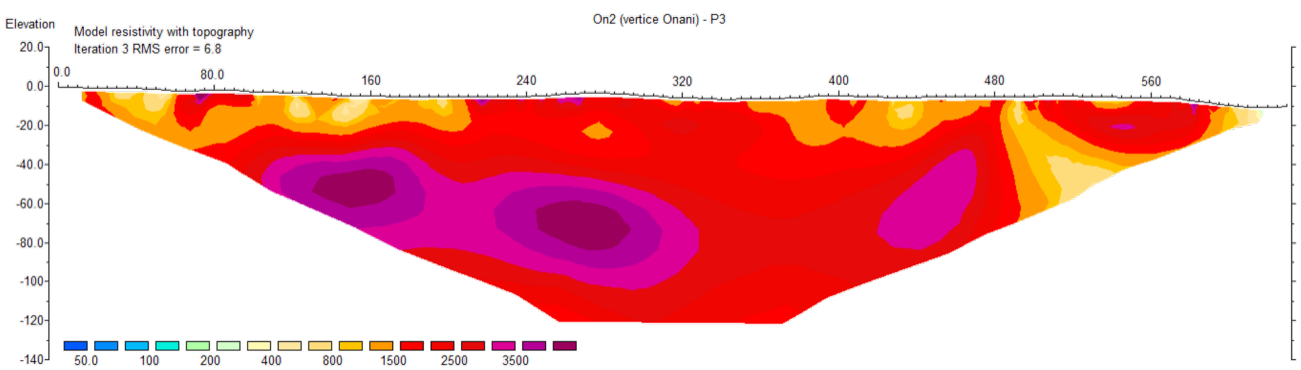




ERT RESULTS AT ONANI' BOREHOLE

The tomographies of the Onanì vertex,
show that the **conductive layer** occurs either as:

i) a discontinuous and well-localized layer near the surface (up to 20 m thick), or as
ii) a broader anomaly zone of values around 1000 Ωm that locally occurs at a depth of 30-90 meters.



ERT SURVEY AT BITTI BOREHOLE

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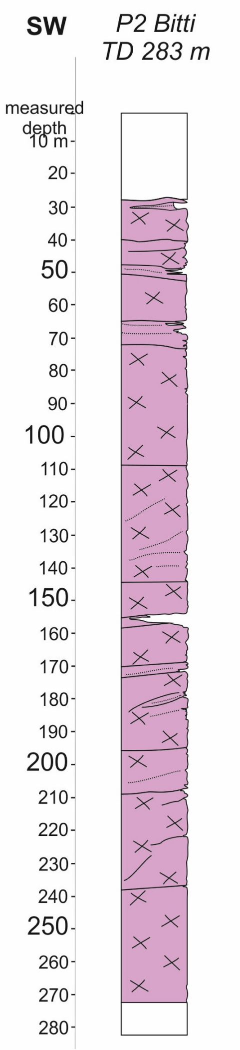
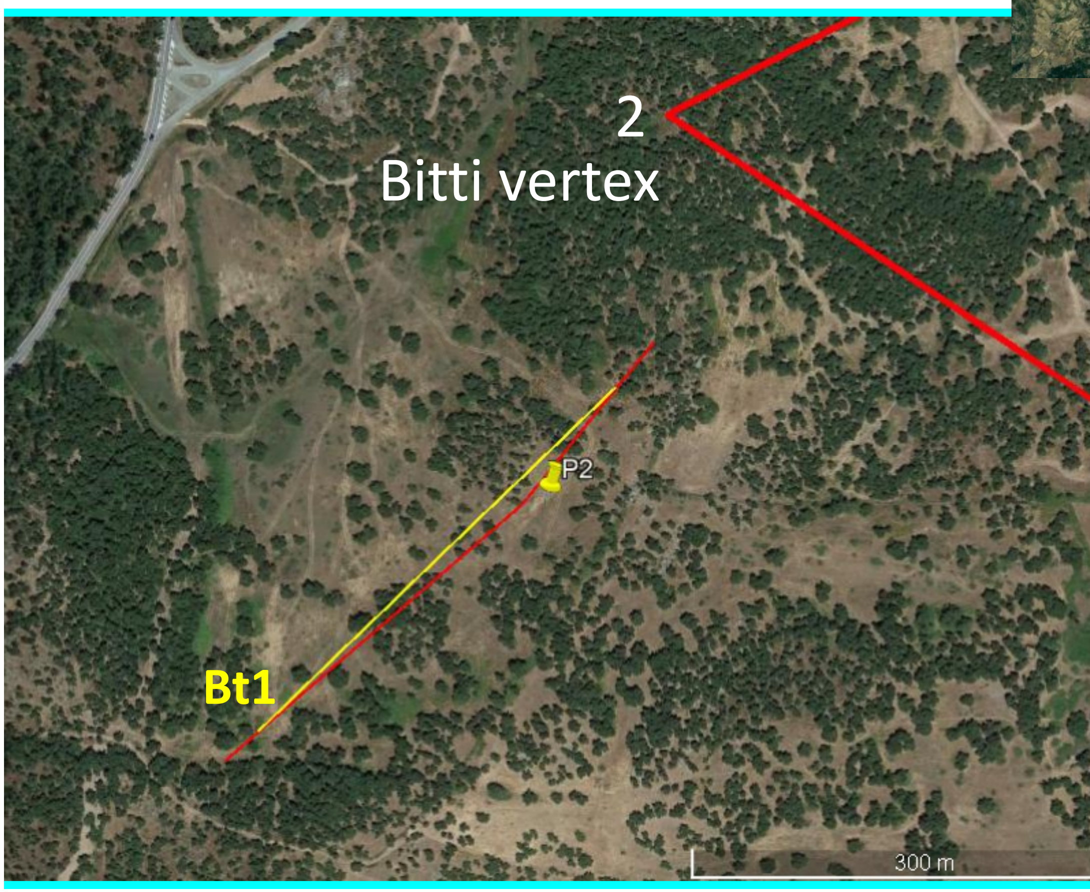
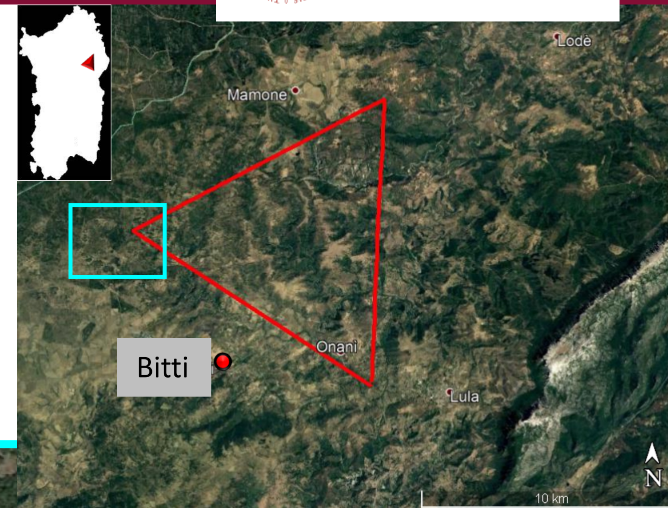
- **1 geoelectrical profile**

Bt1: length 315 m – interelectrod spacing 5 m – direction 47°N





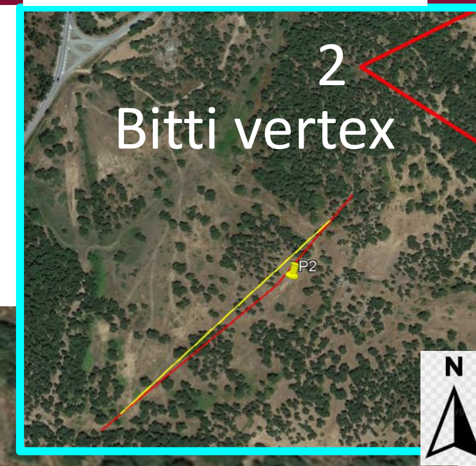


ERT survey

Active Seismic survey

Borehole P2

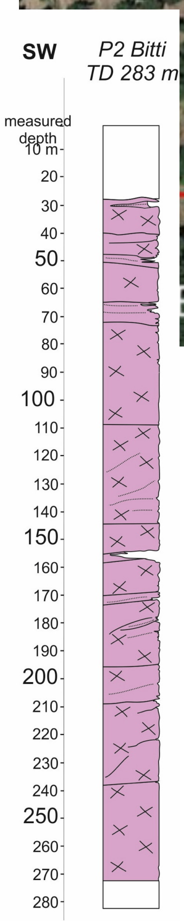
ERT RESULTS AT BITTI BOREHOLE

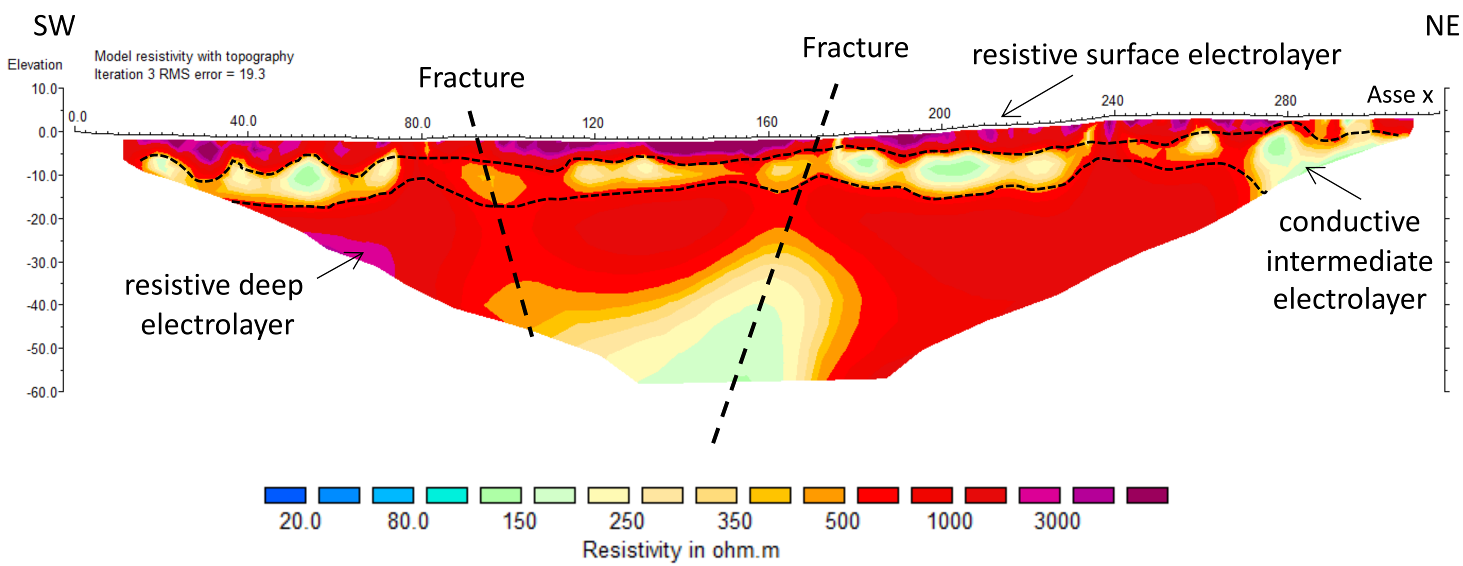


Resistive surface electrolayer: ρ 500÷5000 Ω·m; blocks of granite rocks; thickness 5 m

Conductive intermediate electrolayer: ρ 100÷350 Ω·m; regolith; thickness 10 m

Resistive deep electrolayer: ρ > 500 Ω·m; granite bedrock

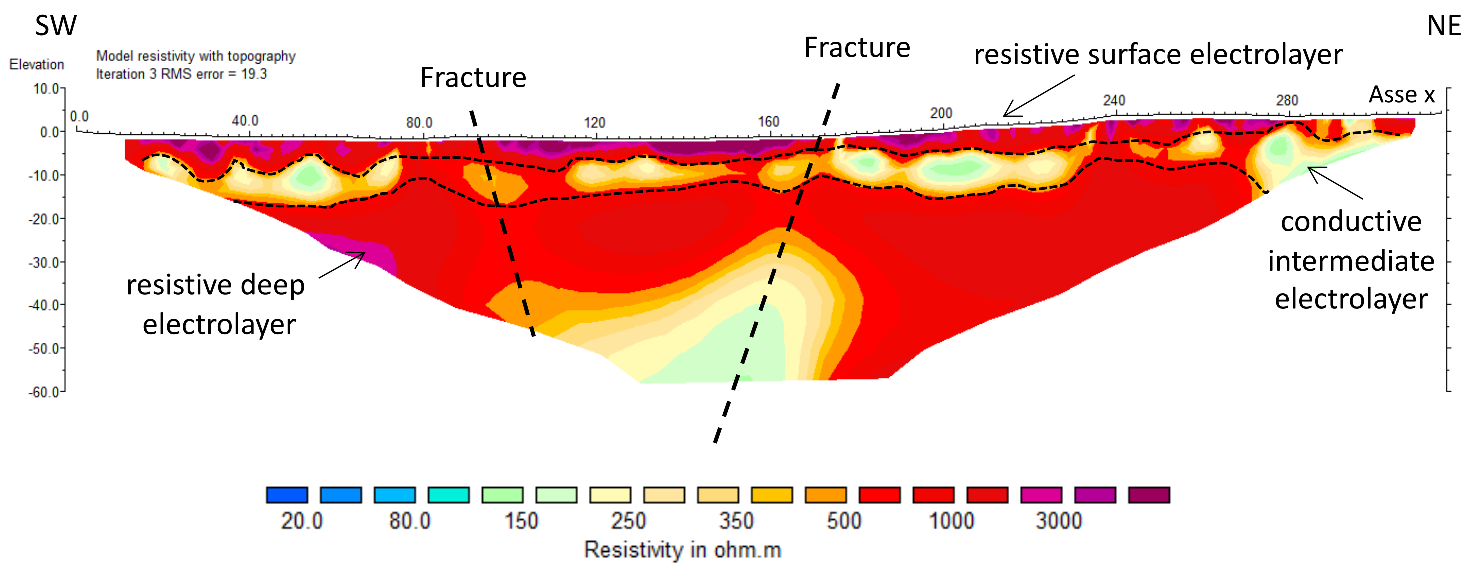




ERT RESULTS AT BITTI BOREHOLE

The tomography of the Bitti vertex
shows a stratified resistivity array composed of:

i) a near-surface resistive electrolayer
ii) an intermediate conductive layer
iii) a resistive deep electrolayer, which is characterized by a large deep conductive anomaly that is bounded by suddenly graded fault-related resistivity drop



ERT RESULTS: A COMPARISON

The hydro-structural setting of the granodiorite of the Bitti vertex consists of a more complex internal structure of the aquifer with respect to the orthogneiss of the Onanì vertex.

Provided that ERT is a low-cost, non-invasive and rapid tool that has allowed characterizing the hydro-structural setting of the ET vertices, survey will be conducted also on the tunnel traces.

GENERAL CONCLUSIONS

Overall, we provide new insights on the lithological distribution and nature of contacts and fault zones, which are relevant for the prediction of mechanic behaviour of the rocks along the tunnel tracks.

Geological results:

- Preliminary structural map of the ET Sardinia area
- Definition of lithologies and structures
- Relative chronology of deformation events

ERT results:

- Recognize the thickness of altered zones above the bedrock
- identify superficial or suspended aquifers
- reconstruct the geometry of fault and fracture systems of limited extension and interconnectivity

QUESTIONS ARISING

How deep do the larger faults root down?
To answer that, geophysics combined with more detailed structural survey can constrain the upcoming geological profiles.

Beside the relative chronology of faults, what are the oldest and the youngest in absolute terms?
To answer that: absolute isotope dating is demanded.