A multi-messenger approach to assess geothermal resources in two southern Italy regions: first results of TOGETHER project

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Keywords: geophysics, imaging, electrical resistivity, elastic/anelastic parameters, local communities, engagement

ABSTRACT

TOGETHER is the acronym for "Sustainable geothermal energy for two Southern Italy regions: geophysical resource evaluation and public awareness." This project is funded by the European Union – Next Generation EU (PRIN-PNRR 2022, CUP D53D23022850001) and has a twofold objective. The first is the geophysical resource evaluation to assess geothermal potential in two regions of Southern Italy — Contursi Terme (SA) and Tramutola (PZ). This involves deploying advanced geophysical sensors to infer information about the subsurface rock formations, water, and gas, which are crucial indicators of geothermal energy potential. The second objective is to enhance public awareness and engagement, fostering societal acceptance of geothermal energy. This is achieved through a targeted communication strategy that includes educational initiatives, stakeholder involvement, and community engagement activities, particularly aimed at younger generations, to encourage dialogue and participation in the sustainable energy transition.

The project's initial results highlight significant advancements in both domains. Preliminary geophysical surveys in the Contursi test area have provided an improved imaging of the subsurface structures, revealing promising geothermal anomalies. Concurrently, the first phase of the social analysis has offered valuable insights into public perceptions, helping to tailor effective communication and engagement strategies. These results mark a crucial step towards the sustainable development of geothermal energy in the region.

1. INTRODUCTION

Geothermal energy is a renewable energy source produced underground that can be utilized for heating or converted into other forms of energy. It has significant growth potential from an economic and public health reason, as it both reduces dependence on fossil fuels and global warming. Assessing its potential exploitation requires understanding the type of geothermal system, the expected temperature, and the characteristics of the reservoir rocks and fluids.

Typically, geothermal systems are defined as a complex system characterized by networks of faults and fractures filled with fluids, which often have high concentrations of dissolved salts that typically exhibit higher electrical conductivity values than the host rocks. Furthermore, the presence of clay minerals resulting from hydrothermal processes that occur in geothermal systems also have a high conductivity signature. Electrical resistivity tomography (ERT) and Magnetotelluric (MT) have been proven to be powerful tools for investigating and characterising geothermal reservoirs on a wide range of depths and at different scales, since measured electrical resistivity depend on temperature, porosity, percentage of fluid saturation, and permeating fluid type (Manzella et al 1999; Tamburiello et al 2018; Rizzo et al 2022).

Local earthquake tomography (LET) (Thurber 1983; Kissling 1988) has been used for imaging the crustal elastic properties in seismically active geothermal settings in terms of 3D P-and S- wave velocity models (Toledo et al 2020; Amoroso et al 2022). On one hand, the V_P and V_S parameters result in being mainly sensitive to lithology changes, on the other one their ratio (V_P/V_S) provides precious hints on the fluid composition and its pore pressure. In addition, ambient noise tomography (ANT) is widely adopted in shallower geothermal settings, especially in areas characterized by a very low seismicity rate (Toledo et al 2022). Due to the strong sensitivity of the quality factor Q to some rheological properties like the temperature and the percentage of fluid saturation in rocks, its crustal imaging is proven to be a key factor in the investigation of occurring subsurface geothermal processes as well (Chiarabba 2021). In this context, scattering and absorption imaging have been demonstrated as new tools for geothermal resource exploration (Napolitano et al 2025).

Though some important findings have been obtained to relate electrical and seismic data to fluid distribution and migration (Balasco et al 2021; Borah and Patro 2022), further work is required in carbonate rocks, more complex with regards to pore size distribution, pore geometry and structures compared to siliciclastic rocks (Tariq et al 2020).

Along with geophysical and geological information, social and environmental aspects are not negligible factors in the sustainable use of geothermal energy resources. In this sense, initiatives of a scientific nature relating to the geophysical characteristics of the territory and the adoption of participatory models aimed at the local population, also through a restitution of the experience of geothermal investments in Lazio and Tuscany (Borzoni et al 2014), would favour the launch of a cumulative process in terms of knowledge and "public decision".

In this study, we present the results of geophysical surveys conducted at the Contursi Terme test site. Multi-parametric geophysical sensors were employed to gather data on subsurface conditions, combining seismic, electromagnetic, and resistivity measurements. The collected data were analysed to estimate geothermal potential based on subsurface temperatures, fluid content, and geological structures. Additionally, we discuss the implementation of a strategic communication plan, which includes stakeholder meetings with residents and public officials to explain the benefits of geothermal energy, as well as educational presentations in schools to engage younger generations with the science behind geothermal energy.

2. TEST AREA

The test areas of the TOGETHER project are in Southern Italy, specifically in the municipalities of Tramutola (High Agri Valley, Basilicata) and Contursi Terme (Campania). In detail, the Contursi Terme area has been selected for new geophysical data acquisition. This area is characterized by an extensive geothermal field with 77 natural springs with temperatures ranging from 21°C to 30°C, as well as 72 wells utilized for balneotherapy and thermal tourism. Recent studies have reported thermal sources with temperatures between 38°C and 47°C and inferred the presence of a geothermal reservoir with hot fluids between 75° and 96 °C at about 3 km depth (Gori et al 2023).

Geologically, Contursi Terme is situated within a complex tectonic setting, where carbonate units of the Apennine Platform are overlain by alluvial deposits and volcanic products (fig. 1). The area is affected by extensional faulting, which facilitates the ascent of deep fluids.

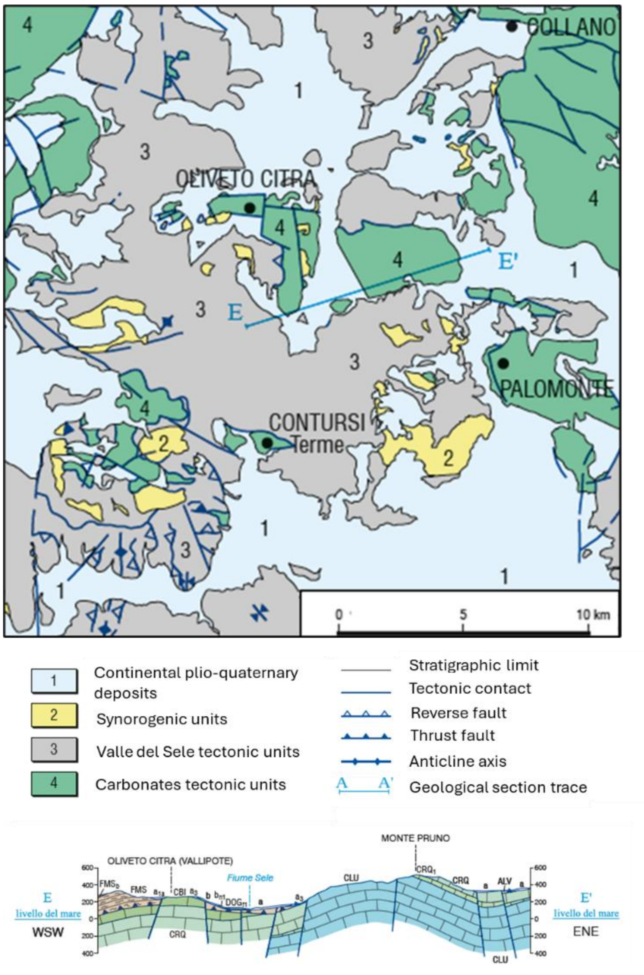


Figure 1: Simplified tectonic map of the Sele river valley. In the E-E' section: FMS = Mt. S. Arcangelo formation, CBI = rudist-rich carbonate, CLU = dolomitic limestones, ALV = Varicoloured clays. Modified from geological sheet 468 - EBOLI (concession and use by ISPRA - Department for the Geological Survey of Italy).

Hydrogeological studies indicate a strong interaction between deep geothermal fluids and shallow aquifers, leading to fluid mixing and dilution effects. Geochemical analyses reveal a significant CO_2 component, suggesting a deep magmatic or metamorphic source. The rheological characteristics of the region, particularly the presence of ductile shear zones at depth, influence fluid flow dynamics and heat transfer processes (Gori et al 2023).

Tomographic studies in this area have provided valuable data on the subsurface structure. Elastic and anelastic imaging revealed the distribution of seismic velocities, allowing for the identification of potential geothermal reservoirs (Amoroso et al 2014, 2017; Improta et al 2014). Electrical resistivity imaging using MT techniques have highlighted conductive anomalies associated with fault zones facilitating fluid circulation (Patella et al 2005).

Some studies suggest that the geothermal potential of the area may be underestimated due to the mixing of hot deep fluids with cooler shallow waters (Chiodini et al 2020; Gori et al 2023). A proper assessment of the geothermal resource is crucial for optimizing its sustainable utilization and integrating geothermal energy into the local energy mix.

3. AVAILABLE GEOPHYSICAL DATASETS

This geographical area can benefit of a geophysical dataset, continuously updated and freely available, coming from the Irpinia Seismic Network (ISNet http://isnet.unina.it/) and the Italian National Seismic Network, operated by INGV (https://doi.org/10.13127/SD/X0FXnH7QfY).
Recently, in the framework of the DETECT experiment (Picozzi et al 2022), new geophysical datasets (seismic and MT) were acquired in the Irpinia area where a Mw 6.9 destructive earthquake occurred in the 1980. The Contursi geothermal field was only marginally interested by the study. The DETECT experiment deployed a dense network of 200 velocimetric stations in the Irpinia region, which allowed for detailed monitoring of microseismic events. Furthermore, 30 broad band Magnetotelluric (MT) soundings were carried out (Balasco et al. 2023).

4. NEW GEOPHYSICAL DATA

The acquisition of new geophysical data in the Contursi (SA) area was carried out in a target sector centred on the hottest sources extending for approximately 6 x 8 km^2 (fig. 2). Over the project life, multi-scale and multi-resolution 3D subsoil electrical resistivity have been estimated in test areas using Electrical and electromagnetic geophysical methods, such as shallow and deep electrical resistivity tomography (ERT) and Magnetotelluric (MT). At the same time, both on-demand and 1-month long continuous ambient seismic noise recordings have been performed to process seismic data by both single-station HVSR analyses and array based seismic techniques.
New geophysical data were acquired using innovative instrumentation purchased as part of two additional scientific projects: ITINERIS (Italian Environmental Integrated Research Infrastructure System, PNRR, MUR, M4C2, Investment 3.1 RI, https://itineris.cnr.it/), financed by European Union – Next Generation EU, and GRINT (Geoscience Research INfrastructure of Italy, INGV, https://progetti.ingv.it/en/pongrint).

4.1 Ambient seismic noise techniques

The ambient seismic noise consists of steady vibrations, existing everywhere and arriving from every direction, due to both natural and anthropogenic sources. Among the most common natural sources there are wind, rainfall, or even ocean waves—even if the sea is far from the sensor's installation site. Notable anthropogenic sources include vehicular traffic and industrial activity. The wide availability of seismic waves travelling through the Earth and belonging to the ambient seismic noise allow seismologists to adopt them to gain insights on subsurface properties.

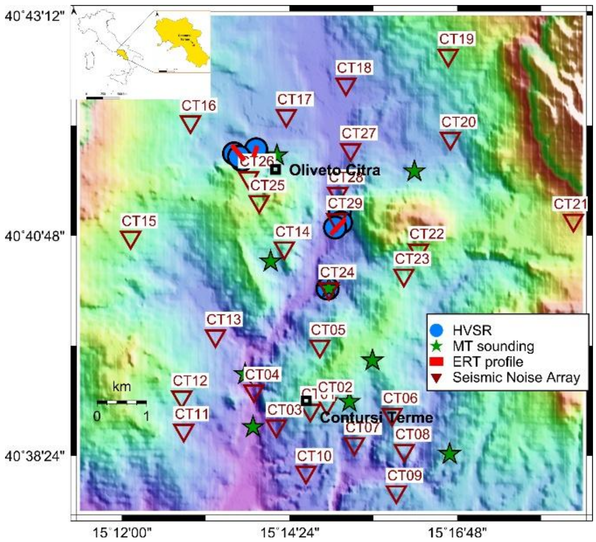


Figure 2: Geophysical surveys in the TOGETHER project test area. Red stars are MT soundings, blue circles identify points where HVSR measurements have been already performed, red lines represent ERT profiles, and red triangles are the seismic array stations.

4.1.1 Single Station measurements: the HVSR technique

The most used technique to achieve soil properties from seismic noise is the horizontal-to-vertical spectral ratio technique (HVSR, Nakamura et al., 1989). The HVSR technique allows retrieving the fundamental resonance frequency (f0) of the soil layer due to the interference of trapped waves between the topographic surface and the surface of the rigid substrate (bedrock). When other information about the site is available, it is also possible to retrieve the thickness (h) (i.e., depth to bedrock) and average shear-wave seismic-velocity (V_S) of the corresponding unconsolidated materials, being $f_0=V_S/4h$.

First, we used a SARA Geobox SS10 (1 Hz) seismic station to record 30 minutes of seismic noise at 6 different sites (fig. 2). These were co-located with the resistivity measurements performed in the same time period, in order to integrate the two complementary methodologies with the aim of characterizing the subsoil properties. To perform the analysis, we adopt the open-source code GEOPSY (Wathelet et al 2020). The results discussed in the 4.1 section refer to the analyses on the introduced dataset.

4.1.2 Array based measurements

A seismic array is a set of sensors which simultaneously record the wavefield propagating through the Earth: the seismometers are located closely enough so that arriving seismic signals may be correlated between couple of sensors. Shapiro and Campillo (2004) experimentally demonstrated that the cross-correlation between simultaneous seismic noise recorded by two sensors may allow retrieving a coherent Green's function. This finding suggests the possibility first to measure the dispersion curves between any couple of stations and then to map the subsurface velocity variations in a 3D tomographic image (Bensen et al 2007; Cabrera-Pèrez et al 2021).

Between March and April 2025, a one-month campaign of continuous ambient seismic noise acquisition was performed in the Contursi Terme test area. The sensors installation phase has been preceded by the cross-correlation analysis of 8 station datastreams from the DETECT seismic array deployed in 2021/22 in Colliano, about 6 km northeast from the Contursi test area. We thus assessed the stability of cross-correlation functions in a very close area to the target one. Then, we theoretically estimated the optimum aperture and the average inter-station distances which would allow the retrieval of reliable dispersion curves within the wavenumber range of interest (Wathelet et al 2020).

On these grounds, we deployed a constellation of 29 seismic sensors in an approximately circular geometry with a radius of about 6 km (Fig. 2): as the direction of noise is unknown, this was the geometry allowing to maximize the directional coverage from all the azimuths. The seismic stations were composed of a six-component instrument (Sentinel-GEO by Lunitek S.r.l.). The velocimetric sensor is characterized by a 4.5 Hz cut-off frequency electronically extended down to 2 s. The seismometers were settled both in private and public sites, at the basement level.

4.2 ERT

The electrical resistivity method consists of experimental determination of the apparent resistivity parameter (ρ_a [Ωm]) through joint measurements of electric-current intensity (I [A]), sent into the subsoil through the means of a pair of electrodes (A and B) embedded in the ground, and voltage (ΔV, [Volt]) at the ends of a second pair of electrodes (M and N), also in direct contact with the ground. As the positions of the injected (AB) and acquired (MN) pairs of electrodes are moved in the investigated area, a tomographic image of the subsoil electrical resistivity is produced (ERT). To move from apparent resistivity to "true" resistivity, inversion software re used. In relatively shallow investigation (e.g., investigation depth < 300 m), ERTs are carried out using multichannel systems able to provide a large number of measurements in a short time making possible to effectively discriminate resistivity contrasts existing in the shallower subsurface, thus providing more reliable information on physical conditions of rocks and the presence of fault surfaces as well as of aquifers and/or fluids of various origins.

In the Contursi Terme test area 5 shallow ERTs (investigation depth lower than 100 m) were carried out in the period between March 2024 and March 2025 (fig. 2). The first very shallow survey (ERT1, 2 m spacing electrodes) was in correspondence of Rosapepe baths where hot fluids (T = 45 °C) rise. An additional deeper survey was carried out reaching an investigation depth of about 80 m (ERT2, electrodes spacing of 10 m). The third survey was in the northern area of Oliveto Citra town where bubbling CO_2 gases rise and form typical forms called "Mofete." Here we acquired 2 ERT with electrodes spacing of 10 (ERT3) and 5 m (ERT4). ERT1 was acquired using a georesistivimeter of MAE, ERT2-4 were acquired using new Syscal Terra (IRIS Instruments) of the ITINERIS infrastructure.

4.3 MT

Magnetotelluric (MT) is a deep geophysical exploration technique for investigating the subsurface in term of electrical resistivity parameter. MT surveys allow us to analyse the physical properties of rocks and gather valuable information about the Earth's internal structure and composition by measuring the natural, time-varying electromagnetic field of the Earth (Chave and Jones 2012). From these measurements, we can derive estimates of subsurface electrical resistivity, from the surface down to tens or even hundreds of kilometres deep.

Up to now, around the Contursi Terme site we have performed 10 soundings in an area of 6x4 km^2 (fig. 2) with an interspacing distance between adjacent sites of about 1 km. The main challenges of this activity were the collection of good coverage and data quality. In each site the MT dataset was collected using the 24bit ADU Metronix receiver. The natural time-varying electromagnetic field was measured by $PbCl_2$ electrodes along two dipoles oriented in N-S and E-W direction distant at least 50 m (electric field Ex, Ey), and likewise two induction coils measuring the magnetic fields (Hx, Hy). MT data were sampled in two frequency bands at 16384 Hz (during the night-time for 15 minutes) and at 256 Hz for 36-48 hrs.

The Magnetotelluric survey will provide the three-dimensional distribution of resistivity values in the Contursi area. Combined with data from other geophysical techniques, direct data from wells and springs, and geological information, we will be able to define in detail the deep geothermal structure of the Contursi area.

5. GEOPHYSICAL RESULTS

The scientific activities of TOGETHER project are devoted to implementing a geophysical multi-messenger approach for improving the imaging of studied geothermal reservoirs in terms physical properties of the reservoir rocks and fluids. This approach is based on the joint evaluation of complementary information carried out by subsoil electrical resistivity and elastic/anelastic characteristics from seismic waves propagation.

5.1 Ambient seismic noise

5.1.1 HVSR

The HVSR measurements revealed well-defined peaks at 3 Hz and 4.5 Hz in sites 4, 5, 7, and 8, which are likely associated with the fundamental resonance frequency of the soil. In contrast, no remarkable shallow impedance contrasts were observed at site 6, where the H/V curve remained consistently below 2 across the entire frequency range and almost completely flat. The H/V curves from the remaining sites (1, 3, and 5) did exhibit neither a clear peak nor a reasonable standard deviation, suggesting the need for further investigation to interpret these results reliably. The fundamental frequency (f_0) has been used to estimate the thickness of the resonant layer (h), based on the average shear wave velocity (V_S) and the relationship $f_0 = V_S / 4h$.

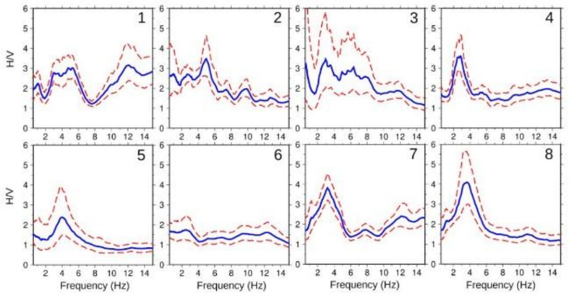


Figure 3: Single-station measurements for noise characterization using HVSR (Horizontal-to-Vertical Spectral Ratio) analysis.

5.1.2 Analyses on continuous ambient seismic noise recordings

The analysis on the data from continuous ambient seismic noise acquisition has started in the late April 2025. Two main outcomes are expected:

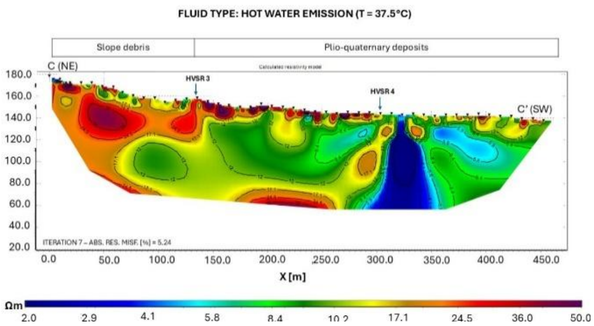
1. A 2D map of the soil's fundamental frequencies, which serve as a sort of "identity card" for the physical properties of the uppermost soil layers and for potentially mapping the depth of the main impedance contrast between stratigraphic layers This parameter is particularly useful for site-specific seismic microzonation and identifying areas that are more likely to amplify seismic waves in the event of an earthquake.

2. A 3D map of subsurface properties in terms of seismic wave velocity. The goal is to detect fluid-rich zones and improve our understanding of the geothermal potential of the area.

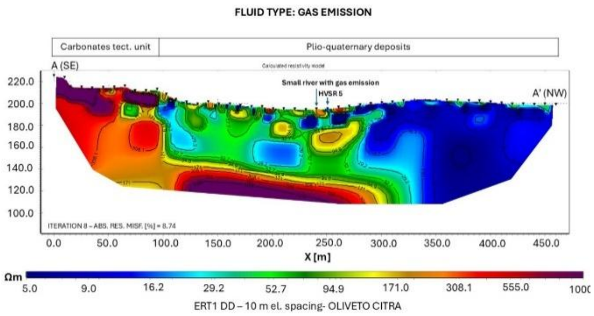
A very preliminary analysis has been devoted to data correction for 6 stations out of 29 that were accidentally rotated during the one-month acquisition.

5.2 ERT

Electrical resistivity data have been inverted using Res2Din software (Aarhus GeoSoftware). Figure 4 shows results of ERT2 and ERT3. Generally, slope debris and alluvial deposits are characterized by low resistivity values while higher resistivity values at depth are associated to buried carbonates. Sharp lateral resistivity contrasts could be associated to the presence of high angle faults boarding carbonates. Near Rosapepe hot spring a vertical low resistivity zone probably outline the presence of highly interconnected porous medium, which facilitates the upward migration of fluids (ERT 2 in figure 4a). On the other hand, in correspondence of Oliveto Citra Mofetes (ERT3 in figure 4b), plio-quaternary deposits generally characterized by very low resistivity values (< 20 Ωm) show, in correspondence of gas emission (CO_2), higher resistivity values (> 100 Ωm).



(a)

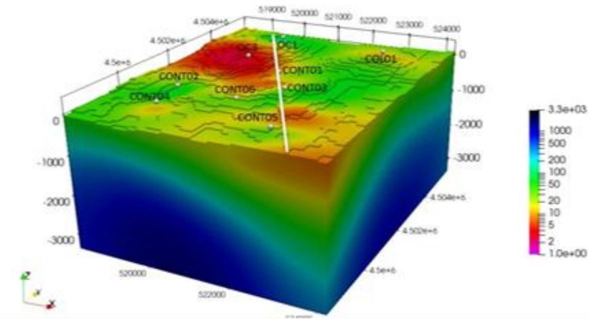


(b)

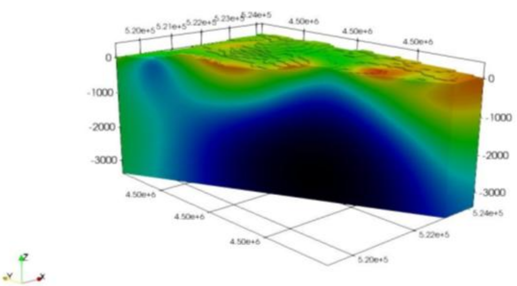
Figure 4: (a) ERT2 and (b) ERT3 results.

5.3 MT

In each site the impedance tensor elements in period ranges between 10^-4-10^3 sec was estimated. In the first step of the process analysis, it was noted that the data are affected by significant anthropic noise due to the presence of power lines, highways, and a railway line located to the south of the investigated area. The analysis procedures have been refined, specifically using the remote reference technique, which is the “quiet” MT station located in Tramutola (Agri Valley, Basilicata region, Romano et al 2014). The whole MT apparent resistivity dataset has been used to build a preliminary 3D resistivity inversion model of the investigated area (fig. 5). The 3D inversion MT model presented was performed using the RLM-3D inversion program in Geotools® (Viridien) software. The survey area is mostly covered by sedimentary basins of Liguridi Unit. Therefore, superficial conductive bodies (< 25 Ωm) can be associated with the Quaternary and Liguride Units deposits outcropping in the Sele River Valley. Resistivity values increase with depth, suggesting a lithological variation corresponding to calcareous-dolomitic rocks of the Apennine Platform as also detect by the deep well Contursi 01 (VIDEPI). Actually, the density of the MT surveys carried out so far does not allow definitive conclusions. In the following months further MT soundings will be carried out.



(a)



(b)

Figure 5: (a) Preliminary 3D MT model of Contursi Terme area. The white line is the trace of the section in (b).

6. COMMUNICATION STRATEGIES

One of the objectives of the TOGETHER project is addressed to promote the acceptance of geothermal energy use by developing innovative communication methodologies.

The used methodology consists in a first phase of analysis of social and cultural aspects and factors that shape the relationship between geothermal technologies and society (individuals, communities, and their interactions in the energy transition) and of a second phase of local communities and younger generations engagement. A key aspect of TOGETHER is its collaboration with high schools, whose students actively participate in field activities, scientific discussions, and practical demonstrations of geophysical survey techniques, including seismic, electromagnetic, and resistivity methods. Educational outreach is designed to enhance awareness, inclusivity, and accessibility. Through interactive seminars, on-site demonstrations, and digital tools, we introduce younger generations to renewable energy challenges, fostering scientific curiosity and informed decision-making. An upcoming educational web platform will further enhance accessibility, allowing students to engage with real-time data and contribute to knowledge dissemination.

The PRIN project also includes a citizen science initiative, "*Adopt a Geophysical Sensor*," through which local communities in the Contursi Terme test area participate in geophysical monitoring hosting on private and public properties ANT and MT sensors. This educational activity allows people to understand the logistics of a geophysical survey campaign and to become familiar with the equipment, taking on the responsibility of ensuring the functioning of the sensors.

7. CONCLUSIONS

The TOGETHER project aims to enhance geothermal exploration and societal awareness through a comprehensive geophysical analysis in the selected areas of Contursi Terme. First geophysical survey highlights critical findings and identifies several recommendations to advance our understanding of the subsurface and improve used geophysical methodologies. In the coming months of the project, further data analyses and potential new measurement investigations will be carried out.

The collected data will be made available to local authorities and thermal operators and will also contribute to the ITINERIS HUB project (https://hub.itineris.cnr.it/).

Ongoing efforts will also focus on refining 3D geophysical models by incorporating all geophysical, geological, geochemical, and rheological data to enhance the understanding of reservoir dynamics. These initiatives aim to provide a comprehensive framework for sustainable energy solutions in Contursi Terme, supporting efficient resource management and regional energy strategies.

Furthermore, the project exemplifies innovative science communication, leveraging Open Science and hands-on learning to bridge the gap between research and societal engagement. By involving students in energy transition dialogues, TOGETHER ensures that the next generation is equipped to tackle future sustainability and energy challenges.

Acknowledgements

This work is supported by projects TOGETHER - Sustainable geothermal energy for two Southern Italy regions: geophysical resource evaluation and public awareness financed by European Union – Next Generation EU, PNRR, M4C2 inv.1.1, CUP D53D23022850001 and ITINERIS - Italian integrated environmental research infrastructures system financed by European Union – Next Generation EU, PNRR, M4C2 inv.3.1, CUP B53C2200215000.

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