A consistent geological and geophysical model of the Eastern Po Plain (Italy) for the evaluation of geothermal energy

R. Basant [1], V. Cortassa[1], M. Tesauro[1,2], G. Gola [3], T. Nanni[4,3], P. Slupski[4], A. Galgaro[4], A. Manzella[3]

[1] *Dipartimento di Matematica, Informatica e Geoscienze, Università di Trieste.*

[2] *Department of Earth Sciences, Utrecht University.*

[3] *Istituto di Geoscienze e Georisorse, CNR.*

[4] *Dipartimento di Geoscienze, Università di Padova.*

Proper assessment and integration of multi-parameter datasets is critical for the efficient and effective exploitation of geothermal energy resources. The InGEO project (Innovation in GEOthermal resources and reserves potential assessment for the decarbonization of power/thermal sectors) seeks to develop an innovative exploration workflow for combining muti-parameter datasets within the sector of the Northern Apennine buried - structures belonging to the Romagna and Ferrara Folds (RFF), Eastern Po Plain, Italy. Previous assessment of thermal data identified a thermal anomaly within this region attributable to deep fluid circulation within the deep-seated Mesozoic carbonate sequences (Pasquale et al., 2013; Pasquale et al., 2014).

This study develops a consistent geological and geophysical model of the Eastern Po Plain region (Italy). For the model, we first characterized the shallow geological features (< 16 km), by analyzing data from over 200 seismic surveys from the VIDEPI database (www.videpi.com), 700 deep (>1500 m) boreholes (CNR database, www.geothopica.igg.cnr.it) and 160 borehole logs (sonic and lithological logs) (Livani et al., 2023). We developed a 3D geological model comprising of eight horizons ranging in age from the Quaternary to the Permian and depicted the thickness variation of these units, by identifying primary lithological unconformities through seismic reflection interpretations constrained by well stratigraphy.

Next, we classified deeper structural features (16 – 50 km), by applying machine learning algorithms (K-means and Fuzzy c-means) to reconstructed, spatially coincident seismic tomography models (Brazus et al. 2025; Kästle et al., 2025; Lu et al., 2018; Magnoni et al., 2022; Magrini et al., 2022) and new density models inverted using the first pan-Alpine surface-gravity database (Zahorec et al., 2021) shown in Figure 1. We use the seismic tomography datasets as apriori constraints in the inversion to assess uncertainties. The unsupervised classification resulted in the 3D characterization of four classes interpreted as 1) sediments to basement 2) upper crust 3) lower crust and 4) the mantle. We validated the range in geophysical parameters of the four classes with thermo-physical measurements on rocks obtained as part of the InGEO project (Sulpski et al., 2025), high temperature and pressure laboratory data on rocks (Burke and Fountain, 1990; Christensen and

Mooney, 1995) compiled from the literature and sonic logs (Livani et al., 2023). Furthermore, we highlighted the spatial consistency and overlap of the 3D geological horizons with Cluster 1 'sediments to basement'.

The consistent geological/geophysical model will be the main input for a thermal model of the region and the implementation of an open-source and web-based GIS tool that will assess the deep geothermal resource potential for both hydrothermal resources and closed-loop heat exchange. Lastly, the workflow of InGEO project will be used as a decision support system for developing geothermal projects in Italy.

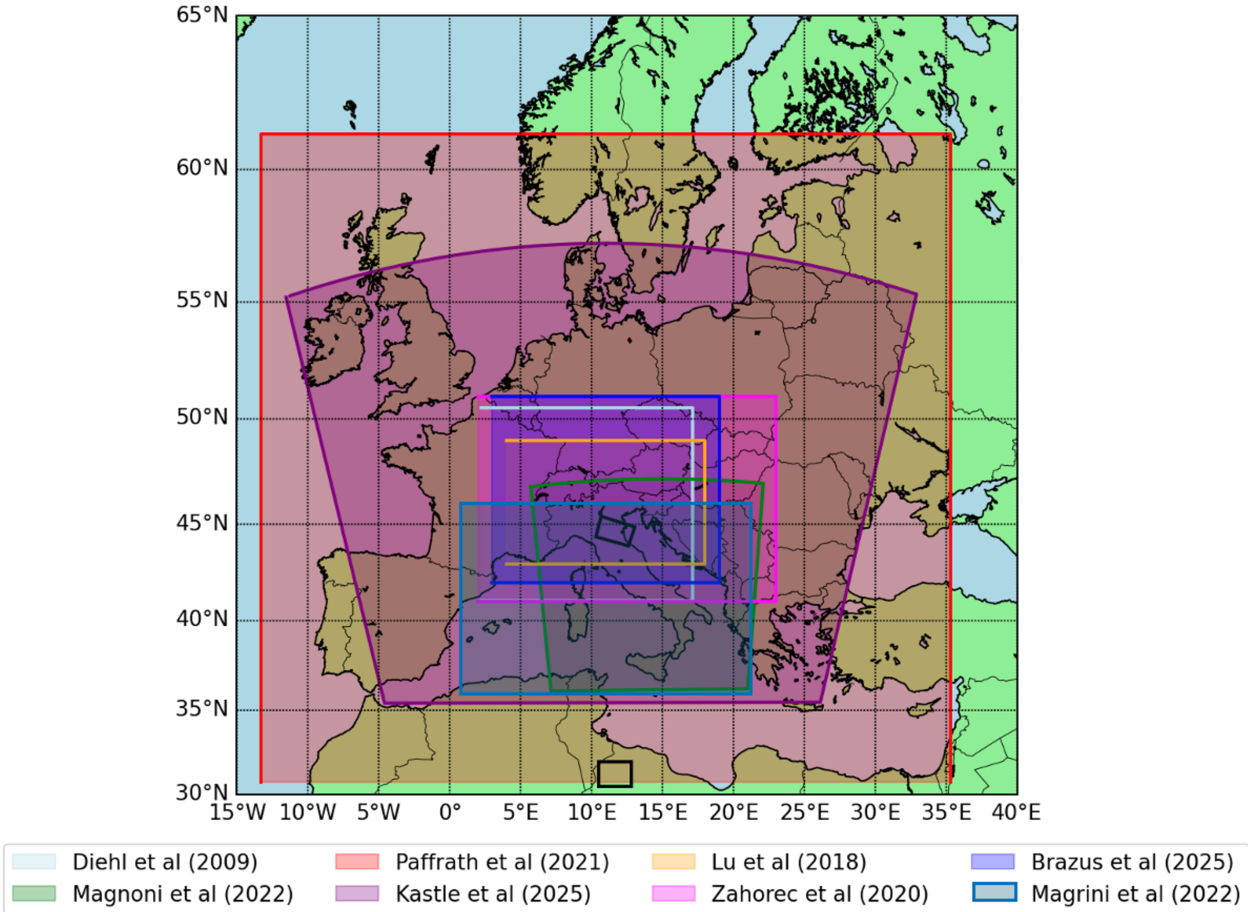

Fig. 1 – Spatial overlap of geophysical datasets.

Acknowledgments

InGEO is a PRIN 2022 PNRR Project and has received funding from the European Union, Next Generation EU.

References

Braszus, B., Rietbrock, A., Haberland, C., 2025: A 3D velocity model for the European Alps: New insights into the crustal structure. Journal of Geophysical Research: Solid Earth, 130(10), p.e2025JB031877, https://doi.org/10.1029/2025JB031877.

Burke, M.M., Fountain, D.M., 1990: Seismic properties of rocks from an exposure of extended continental crust—new laboratory measurements from the Ivrea Zone. Tectonophysics, 182(1-2), 119-146, https://doi.org/10.1016/0040-1951(90)90346-A.

Christensen, N.I., Mooney, W.D., 1995: Seismic velocity structure and composition of the continental crust: A global view. Journal of Geophysical Research: Solid Earth, 100(B6), 9761-9788, https://doi.org/10.1029/95JB00259.

Kästle, E.D., Paffrath, M., El-Sharkawy, A., AlpArray and Swath-D working groups, 2025. Alpine Crust and Mantle Structure From 3D Monte Carlo Surface-and Body-Wave Tomography: Journal of Geophysical Research: Solid Earth, 130(2), p.e2024JB030101, https://doi.org/10.1029/2024JB030101.

Livani M. et al., 2023: Subsurface geological and geophysical data from the Po Plain and the northern Adriatic Sea (north Italy). Earth Syst. Sci. Data, 15, 4261–4293, https://doi.org/10.5194/essd-15-4261-2023.

Lu, Y., Stehly, L., Paul, A., AlpArray Working Group, 2018: High-resolution surface wave tomography of the European crust and uppermost mantle from ambient seismic noise. Geophys. J. Int., 214, 1136–1150, https://doi.org/10.1093/gji/ggy188.

Magnoni, F., Casarotti, E., Komatitsch, D., Di Stefano, R., Ciaccio, M.G., Tape, C., Melini, D., Michelini, A., Piersanti, A., Tromp, J., 2022: Adjoint tomography of the Italian lithosphere. Commun. Earth Environ., 3(1), 69, https://doi.org/10.1038/s43247-022-00397-7.

Magrini, F., Diaferia, G., El-Sharkawy, A., Cammarano, F., van Der Meijde, M., Meier, T., Boschi, L., 2022: Surface-wave tomography of the central-western Mediterranean: New insights into the Liguro-Provençal and Tyrrhenian Basins. Journal of Geophysical Research: Solid Earth, 127(3), p.e2021JB023267. https://doi.org/10.1029/2021JB023267.

Pasquale, V., Chiozzi, P., Verdoya, M., 2013: Evidence for thermal convection in the deep carbonate aquifer of the eastern sector of the Po Plain, Italy. Tectonophysics, 594, 1-12. https://doi.org/10.1016/j.tecto.2013.03.011.

Pasquale, V., M. Verdoya, Chiozzi, P., 2014: Heat flow and geothermal resources in northern Italy. Renewable and Sustainable Energy Reviews, 36, 277-285, https://doi.org/10.1016/j.rser.2014.04.075.

Slupski, P., G. Gola G., Basant, M., Cortassa, V., Facci, M., Nanni, T., Tesauro, M., Manzella, A., Galgaro A., 2025: The importance of measuring thermal and acoustic properties on rock analogues in geothermal potential assessment studies: the example of Northern Apennines Triassic carbonate platform and underlying basement rock. 43° National Conference GNGTS, Bologna, 11-14 February 2025.

Zahorec, P., Papčo, J., Pašteka, R., Bielik, M., Bonvalot, S., Braitenberg, C., Ebbing, J., Gabriel, G., Gosar, A., Grand, A., Götze, H.-J., Hetényi, G., Holzrichter, N., Kissling, E., Marti, U., Meurers, B., Mrlina, J., Nogová, E., Pastorutti, A., Salaun, C., Scarponi, M., Sebera, J., Seoane, L., Skiba, P., Szűcs, E., and Varga, M., 2021: The first pan-Alpine surface-gravity database, a modern compilation that crosses frontiers. Earth Syst. Sci. Data, 13, 2165–2209, https://doi.org/10.5194/essd-13-2165-2021.

Corresponding author: mtesauro@units.it

Multi-Frequency Seismic Noise Analysis of an Extreme Meteorological Event and Its human Impact in Southern Italy

Alfio Marco Borzì[1], Andrea Cannata[1], Francesco Panzera[1]

[1]Department of Biological, Geological and Environmental Sciences (University of Catania, Catania, Italy);

Recent advances in seismology shown that seismic noise can be useful to monitor a wide range of natural and anthropogenic phenomena (Nakata et al., 2019), extending the traditional application such as earthquakes and volcanic monitoring. Different seismic noise sources dominate specific frequency bands, allowing the investigation of processes related to sea state, meteorological forcing, river dynamics, and human activity using existent seismic networks.
On 17 January 2025, a severe meteorological event affected southern Italy, particularly Sicily, producing intense rainfall, strong winds, storm surges, and widespread river flooding. The event also led to a significant reduction in human activity due to civil-protection measures, including the closure of schools and public services. In this study, seismic data recorded by 149 broadband stations belonging to INGV permanent monitoring network were analyzed across a broad frequency range (0.05–45 Hz) to investigate the seismic response to this extreme event and its impact on anthropogenic noise. The seismic data were correlated with meteorological data recorded by about 700 meteorological stations and sea state data obtained from hindcast maps.

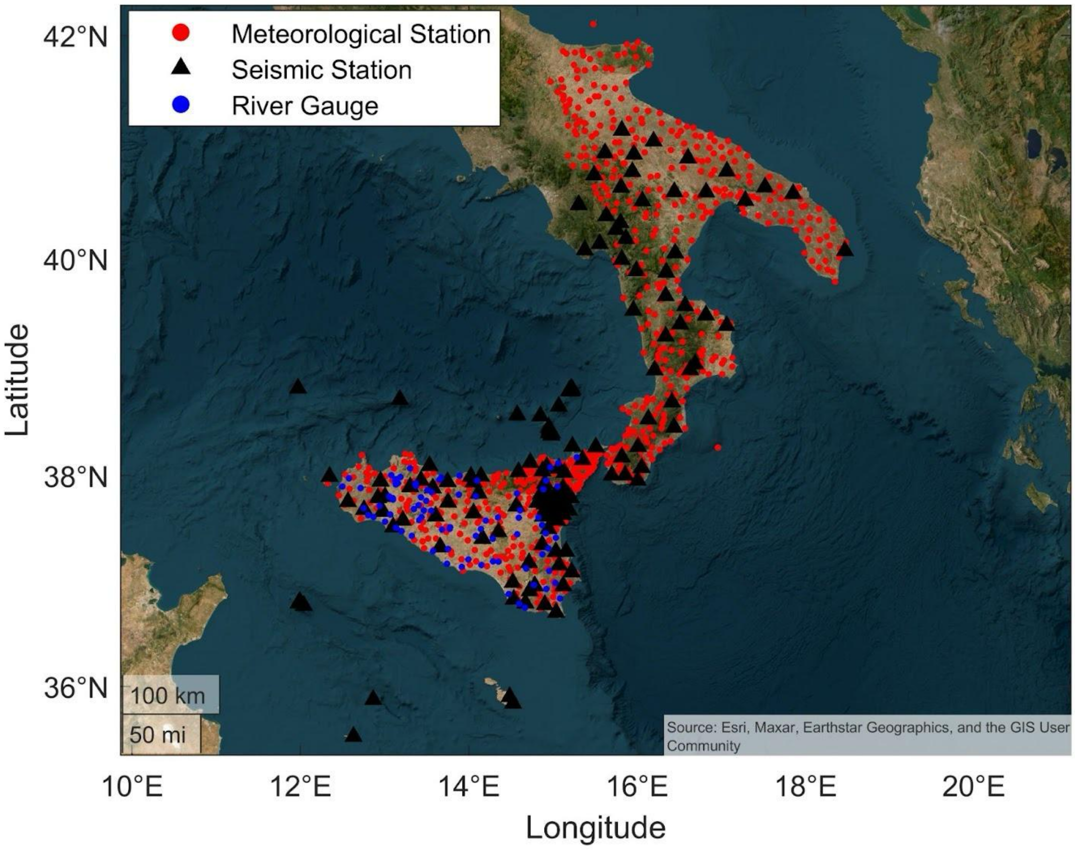

Fig. 1 – A satellite image of the South-Italy area with seismic stations (black triangles), meteorological stations (red dots), and river gauges (blue dots) used in this study. (base image source ©Google Earth).

The seismic noise data were splitted into two different categories, low (< 1Hz) and high frequency (> 5 Hz) data.

Low-frequency seismic noise associated with microseism (0.1–0.2 Hz) shows a clear relationship with sea state conditions. Two distinct amplitude peaks correspond to storm surges occurring before and during the climax of the event, while a progressive shift of frequency peak toward lower frequencies is observed during the most intense phase, consistent with increasing sea-wave periods. These results confirm the sensitivity of microseism to storm-related sea state variability and their capability to track the spatial and temporal evolution of sea state conditions.

At higher frequencies, seismic noise variations reflect the contribution of different environmental sources. The 25–35 Hz band is strongly influenced by both rainfall and wind, capturing in particular the main precipitation fronts and the wind intensification that precedes the arrival of the storm (downburst). The spatial and temporal distribution of seismic amplitudes in this band closely follows the northward propagation of the meteorological system. River flood dynamics are primarily detected in the 1–5 Hz band, which shows strong correlations with river water level measurements and characteristic spectral signatures associated with sediment transport during flood peaks, such as a “V-shaped” characterized by a decrease in frequency peak during the climax of the storm and linked with the sediment dimension (Diaz et al., 2014; Borzì et al., 2025).

Anthropogenic seismic noise, analyzed in the 5–25 Hz frequency range, reveals significant amplitude reductions in areas subjected to red and orange civil-protection alerts, reflecting decreased traffic and human activity during the event. In contrast, stations located in areas under green alert conditions show seismic noise patterns comparable to typical working days.

These results demonstrate that an existing seismic network, originally designed for tectonic and volcanic monitoring, can simultaneously capture multiple environmental and human processes by exploiting the frequency-dependent nature of seismic noise. Seismic observations therefore represent a valuable complementary tool for integrated monitoring of extreme meteorological events and their impacts on both natural systems and human activity.

References

Borzì, A. M., Castiglione, F., Gangemi, M. V., Cannata, A., Cavallaro, L., Foti, E., ... & Panzera, F. (2025b). Exploring the relationship between seismic noise signals and modeled river flow data: A case study from Sicily, Italy. Engineering Geology, 345, 107872. https://doi.org/10.1016/j.enggeo.2024.107872

Díaz, J., Ruíz, M., Crescentini, L., Amoruso, A., & Gallart, J. (2014). Seismic monitoring of an Alpine mountain river. Journal of Geophysical Research: Solid Earth, 119(4), 3276-3289. https://doi.org/10.1002/2014JB010955

Nakata, N., Gualtieri, L., & Fichtner, A. (Eds.). (2019). Seismic ambient noise. Cambridge University Press.

Corresponding author: alfiomarco.borzi@unict.it

Microseism Energy Trends and Spectral Differences between the Mediterranean and Global Oceans

Alfio Marco Borzì[1], Andrea Cannata[1], Sebastiano D'Amico[2], Carlo Lo Re[3], Francesco Panzera[1], Richard C. Aster[2]

[1]*Department of Biological, Geological and Environmental Sciences (University of Catania, Catania, Italy);*
[2] *Department of Geosciences (University of Malta, Msida, Malta);*
[3] *Italian Institute for Environmental Protection and Research (ISPRA, Rome, Italy);*
[4] *Department of Geosciences, Warner College of Natural Resources (Colorado State University, Fort Collins, CO, USA).*

Microseism is the most continuous and ubiquitous seismic signal generated by the interaction between sea waves and solid Earth and was, until recently, considered seismic noise to be discarded. It can be divided into three main frequency bands, based on source mechanisms and spectral content, spanning from 0.05 Hz to 0.4 Hz. Actually, this seismic signal can be helpful to monitoring sea state (Ardhuin et al., 2019; Cannata et al., 2020; Ferretti et al., 2013, 2018; Moschella et al., 2020, Minio et al, 2023), track tropical cyclones (Borzì et al., 2022; Gerstof et al., 2006; Lin et al., 2017; Zhang et al., 2010) and obtain long-term information about sea state parameters linked to the microseism energy and climate change (Aster et al., 2010, 2023; Borzì et al., 2025; Grevemeyer et al., 2000). For example, Aster et al. (2023) analyzed vertical-component data in the 0.05–0.07 Hz frequency band from 52 seismic stations worldwide, spanning the period 1980–2022, to investigate global variations in near-coastal ocean wave energy. Assuming a proportional relationship between sea-wave energy and microseism energy for small variations, the study identified geographically coherent trends, with increasing energy at most stations and decreases at a smaller subset, mainly in the northern and western Pacific regions. The global mean microseism energy exhibits a long-term increase of approximately 0.27% per year, rising to about 0.35% per year when considering data from the early 21st century onward. Following this evidence, we analyzed the data recorded by nine seismic stations installed in the Mediterranean region in the period 1 January 1996 to 15 October 2023 to obtain microseism energy trend for this time period. We also calculated the Wave Power (WP) and WP trend from wave hindcast data for specific sea areas near the seismic stations to explore the relationship between hindcast-estimated WP and microseism energy. Additionally, since the microseism features can be influenced by the different sea waves parameters (Becker et al., 2020), we analyzed the seismic data recorded during the period 2013-2023 by 71 seismic stations installed worldwide to compare Mediterranean and Oceanic microseism features.

In this work, we performed common analysis for both seismic station networks such as spectral and amplitude analysis, correlation analysis between RMS seismic amplitude and spatial significant wave height and specific analysis for each network. In particular, for the Mediterranean network we calculated the long-term trend of a parameter proportional to the microseism energy and WP and successively we calculated the correlation between these independent parameters. Concerning the other network, we divided the seismic stations into six sub-networks based on the position of the station and then we calculated the median spectra for each Ocean and Mediterranean Sea.

Spectral and amplitude analyses clearly show, for both the network, the microseism seasonal modulation already discussed in the literature (Stutzmann et al., 2009; Shabtian et al., 2023; Borzì et al., 2025) for mid latitude stations, and a persistent background noise for equatorial ones. Concerning the correlation analysis between the RMS seismic amplitude and spatial SWH the results are similar for both the networks, with high values of Spearman correlation coefficient (>0.8) for distances up to 500 km from the coastline for the Mediterranean network and 1000 km for the Oceanic one.

The long-term trends calculated for microseism energy and WP show increasing or decreasing trends depending on the considered Mediterranean area, but the most interesting results concern the high correlation (up to 0.95) obtained between the WP and microseism energy trends that, as above mentioned, are two independent parameters.

Finally, the median spectra calculated among each sub-network display that the Oceanic (Atlantic, Pacific, Arctic, Antarctic and Indian) show mutually consistent spectra while the Mediterranean spectrum show a different pattern. Considering the low frequency bands (< 1 Hz), it is possible to observe that the Primary microseism peak (0.05-0.07 Hz) is clearly visible in all the considered spectra, including the Mediterranean one even if with lower PSD values. The Secondary and Short Period Secondary microseism peaks (0.1-0.2 Hz and 0.2-0.4 Hz respectively) are instead visible only in the oceanic spectra, while the Mediterranean spectrum show a peak shifted toward higher frequency (about 0.4 Hz) corresponding to the Mediterranean secondary microseism.

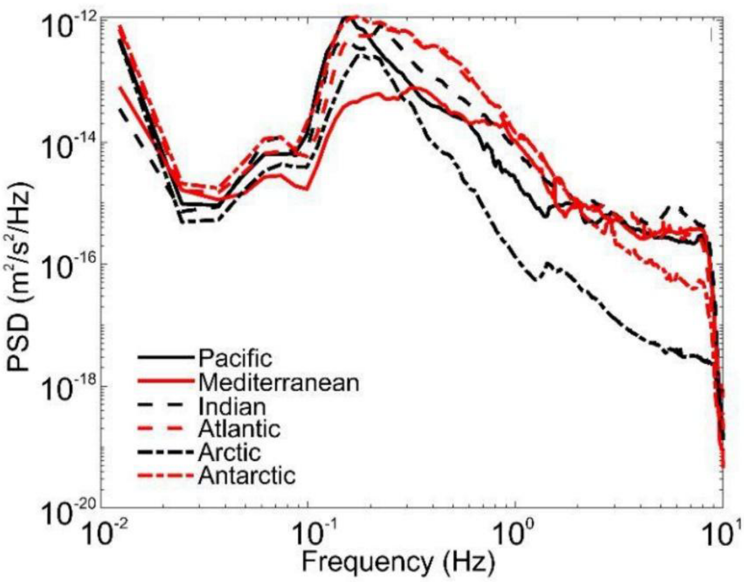

Fig. 1 – Median spectra calculated among the seismic stations belonging to each sub-network based on their position.

Our results confirm the strong link between microseism energy and sea-state parameters at both regional and global scales. The high correlation observed between long-term trends of microseism energy and WP in the Mediterranean region supports the use of seismic data as an independent proxy for monitoring wave climate variability. Furthermore, the spectral differences observed between oceanic and Mediterranean stations highlight the influence of basin geometry and wave features on microseism generation mechanisms. These findings highlight the potential of continuous seismic records for long-term monitoring of ocean wave energy and for investigating climate-related changes in marine environments.

References

Ardhuin, F., Stopa, J. E., Chapron, B., Collard, F., Husson, R., Jensen, R. E., ... & Young, I. (2019). Observing sea states. Frontiers in Marine Science, 6, 124.

Aster, R. C., McNamara, D. E., & Bromirski, P. D. (2010). Global trends in extremal microseism intensity. *Geophysical Research Letters*, *37*(14).

Aster, R. C., Ringler, A. T., Anthony, R. E., & Lee, T. A. (2023). Increasing ocean wave energy observed in Earth's seismic wavefield since the late 20th century. *Nature Communications*, *14*(1), 6984.

Becker, D., Cristiano, L., Peikert, J., Kruse, T., Dethof, F., Hadziioannou, C., & Meier, T. (2020). Temporal modulation of the local microseism in the North Sea. *Journal of Geophysical Research: Solid Earth*, *125*(10), e2020JB019770.

Borzì, A. M., Minio, V., Cannavò, F., Cavallaro, A., D'Amico, S., Gauci, A., ... & Cannata, A. (2022). Monitoring extreme meteo-marine events in the Mediterranean area using the microseism (Medicane Apollo case study). *Scientific Reports*, *12*(1), 21363. https://doi.org/10.1038/s41598-022-25395-9

Borzì, A. M., Cannata, A., Panzera, F., D'Amico, S., Lo Re, C., & Aster, R. C. (2025). Microseism amplitude and wave power in the Mediterranean Sea (1996–2023). *Journal of Geophysical Research: Solid Earth*, *130*(1), e2024JB030528.

Cannata, A., Cannavò, F., Moschella, S., Di Grazia, G., Nardone, G., Orasi, A., ... & Gresta, S. (2020). Unravelling the relationship between microseisms and spatial distribution of sea wave height by statistical and machine learning approaches. *Remote Sensing*, *12*(5), 761.

Ferretti, G., Zunino, A., Scafidi, D., Barani, S., & Spallarossa, D. (2013). On microseisms recorded near the Ligurian coast (Italy) and their relationship with sea wave height. Geophysical Journal International, 194(1), 524-533.

Ferretti, G., Barani, S., Scafidi, D., Capello, M., Cutroneo, L., Vagge, G., & Besio, G. (2018). Near real-time monitoring of significant sea wave height through microseism recordings: An application in the Ligurian Sea (Italy). Ocean & Coastal Management, 165, 185-194.

Gerstoft, P., Fehler, M. C., & Sabra, K. G. (2006). When katrina hit california. *Geophysical Research Letters*, *33*(17).

Grevemeyer, I., Herber, R., & Essen, H. H. (2000). Microseismological evidence for a changing wave climate in the northeast Atlantic Ocean. *Nature*, *408*(6810), 349-352.

Lin, J., Lin, J., & Xu, M. (2017). Microseisms generated by super typhoon Megi in the western Pacific Ocean. *Journal of Geophysical Research: Oceans*, *122*(12), 9518-9529.

Minio, V., Borzì, A. M., Saitta, S., Alparone, S., Cannata, A., Ciraolo, G., ... & Cannavò, F. (2023). Towards a monitoring system of the sea state based on microseism and machine learning. Environmental Modelling & Software, 167, 105781.

Moschella, S., Cannata, A., Cannavò, F., Di Grazia, G., Nardone, G., Orasi, A., ... & Gresta, S. (2020). Insights into microseism sources by array and machine learning techniques: Ionian and Tyrrhenian Sea case of study. Frontiers in Earth Science, 8, 114.

Stutzmann, E., Schimmel, M., Patau, G., & Maggi, A. (2009). Global climate imprint on seismic noise. *Geochemistry, Geophysics, Geosystems*, *10*(11).

Zhang, J., Gerstoft, P., & Bromirski, P. D. (2010). Pelagic and coastal sources of P-wave microseisms: Generation under tropical cyclones. *Geophysical Research Letters*, *37*(15).

Corresponding author: alfiomarco.borzi@unict.it

Indoor radon measurements in three different areas of Campania, with different geological features

P. Addonizio[1,2], G. Buccheri[1], R. Crisci[2], F. Di Guida[2]

[1] INAIL - National Institute for Insurance against Accidents at Work - UOT Naples - Via Nuova Poggioreale (angolo S. Lazzaro) - Complesso INAIL, Edificio 9 - 80143 Naples, Italy
[2] INAIL - National Institute for Insurance against Accidents at Work - UOT Naples - Corso San Giovanni a Teduccio 233 - 80146 Naples, Italy

This study is focused on indoor measurements of radon concentration in three different areas of Campania (Italy), characterized by different geological features. In Naples and in Santa Maria a Vico, the substratum is formed by alkaline volcanic rocks and many buildings are built with volcanic tuff. In Montesano sulla Marcellana and surroundings, the geological substratum is characterized by permeable calcareous and dolomitic rocks, with a very rich hydrogeologic basin and where buildings are built with concrete or even in the rocks.

This research is carried out by using an AlphaGuard device, a mobile radonometer that allows continuous determination of radon concentration together with indoor atmospheric parameters (temperature, relative humidity, atmospheric pressure). Indoor radon samplings, with hourly sampling rate, have a time span of 7 days and are carried out in living environments, located both underground and at ground floor, where higher concentrations of radon can be expected. The continuous periodical monitoring of indoor radon concentrations is very useful in order to observe variations of concentration between the day and the night and to confirm the importance of ventilation in reducing indoor radon concentration (Fig. 1).

For data processing, correlation and regression analyses between radon concentration and indoor meteorological parameters were used. About the buildings, where the correlation coefficient between radon concentration and temperature, air pressure and humidity showed a significant correlation, we describe in detail the diagrams of the measured values, the buildings' features and their locations, as well as connections of radon concentrations with meteorological parameters. About the other buildings, we only show the weekly average values of radon concentration, indoor temperature, air pressure and humidity. We measured high indoor radon concentrations in several buildings, that depended only slightly, or not at all, on the indoor meteorological parameters.

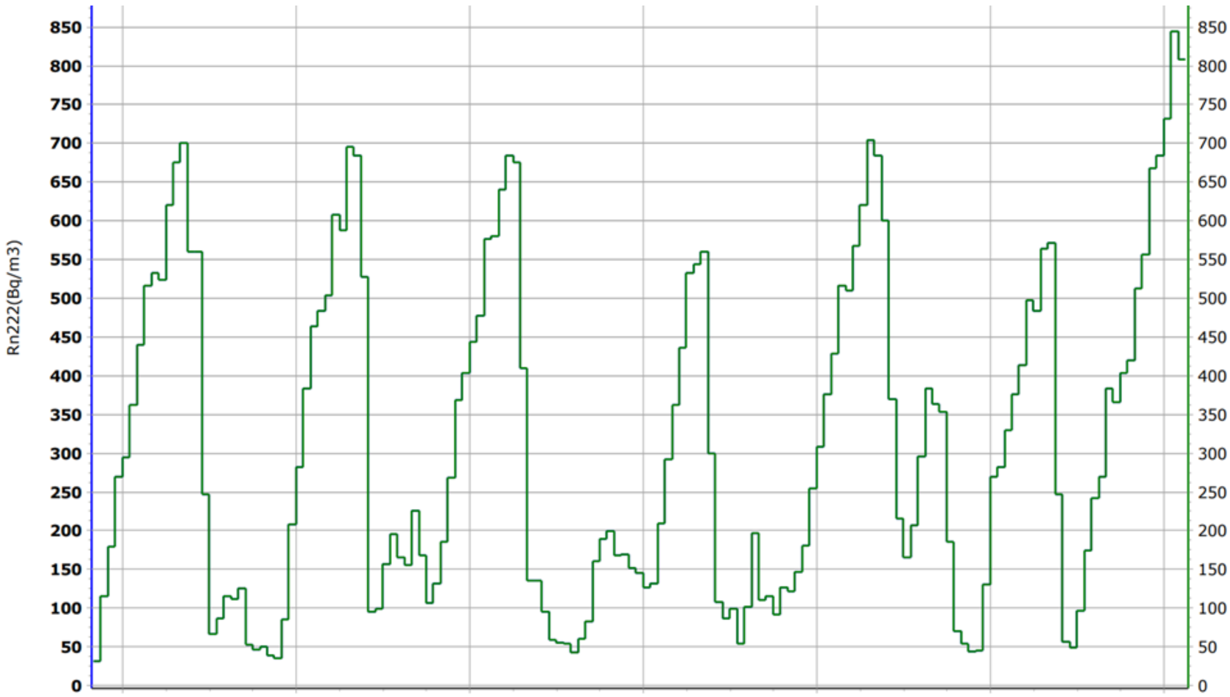

Fig. 1 – Graphic by DataExpert software: radon peaks during a weekly measurement in the urban area of Naples.

Current results show: a prevalence of radon in buildings of the urban areas of Naples and Santa Maria a Vico, in comparison with buildings at Montesano sulla Marcellana; that radon concentrations in the buildings depend on the geology of the territory where the investigated buildings are located, and on the building materials.

Corresponding author: g.buccheri@inail.it

FUSE- A new infrastructure to help derisk site selection for future Underground Hydrogen Storage and White Hydrogen exploration

F. Ferraccioli[1], E. Barison[1], L. Bonini[2], A. Soldati [3,4], C. Marchioli[3], M. Pipan[2], M. De Paoli[3], D. Gei[1], M. Giorgi[1], D. Civile[1], E. Forte[2], C. Bellezza[1], A. Schleifer[1], F. Donda[1], V. Lipari[1], S. Picotti[1], M. Franceschi[2], A. Corradetti[2], A. Del Ben[2]

[1] *National Institute of Oceanography and Applied Geophysics- OGS, Italy*
[2] *University of Trieste- Department of Mathematics, Informatics and Geosciences, Italy*
[3] *University of Udine- College of Engineering, Department of Energy Technology, Italy*
[4] *TU Wien- Institute of Fluid Mechanics and Heat Transfer, Austria*

An increase in the production of clean hydrogen, particularly green hydrogen generated from water electrolysis using only renewable energy, alongside the growing interest in exploring natural (or white) hydrogen deposits (e.g. Hand 2023, Fig. 1), are key elements of Europe's energy transition strategy. These approaches offer large-scale, flexible, and low-carbon solutions towards a Net Zero economy.

In the context of developing a green hydrogen-based economy, Underground Hydrogen Storage (UHS) plays a fundamental role, as UHS can balance the intermittency of renewable sources.

Achieving the objectives of the EU Hydrogen Strategy requires a step change in subsurface investigation capabilities, combining high-resolution imaging, laboratory experimentation, and predictive modelling. Integrated research infrastructures are therefore essential to reduce uncertainty and de-risk site selection and operation for hydrogen-related subsurface activities.

FUSE (Open Infrastructure on Future Underground Hydrogen Storage) is a newly established research infrastructure initiative, launched in April 2025 through a collaboration between OGS, the University of Trieste, and the University of Udine, and funded by Regione Autonoma Friuli Venezia Giulia.

FUSE is designed as an open and distributed platform that brings together advanced geophysical monitoring technologies, dedicated laboratory facilities, and multi-scale numerical modelling tools. Its capabilities include borehole and surface geophysics, seismic and electrical methods, fibre-optic and orbital-vibrator monitoring, airborne and drone-based magnetic and gravity surveys, as well as petrophysical and fluid-dynamics laboratories tailored to hydrogen–rock–fluid processes, both in Italy and elsewhere. The combination of these methodologies and approaches will create an integrated infrastructure for the identification, characterization, and subsequent monitoring of suitable UHS sites, some of which have already been identified in Italy by Barison et al., 2023.

Furthermore, FUSE will acquire new geophysical tools (Fig. 2) to contribute to the study of white hydrogen deposits, which represent a new research frontier. Although these deposits, present in various parts of the world, are still little known compared to conventional hydrocarbon deposits, they are potentially of great importance for the development of the Hydrogen Economy. They could provide both a natural resource to help meet the growing demand for hydrogen and a useful analogue to improve understanding of subsurface processes, a necessary condition for making UHS more efficient, safe, and sustainable.

Here we outline the scientific and technological framework of FUSE and discuss its relevance for UHS and white hydrogen exploration, including links with ongoing initiatives such as the North Adriatic Hydrogen Valley (https://www.nahv.eu/). We illustrate how the infrastructure supports improved characterisation of subsurface heterogeneity, assessment of structural and geohazard controls, and more robust simulations of hydrogen behaviour in geological formations.

By strengthening national and transnational capabilities, FUSE will act as a catalyst for safer, more efficient UHS deployment and for advancing the frontier of white hydrogen exploration within the broader context of the energy transition.

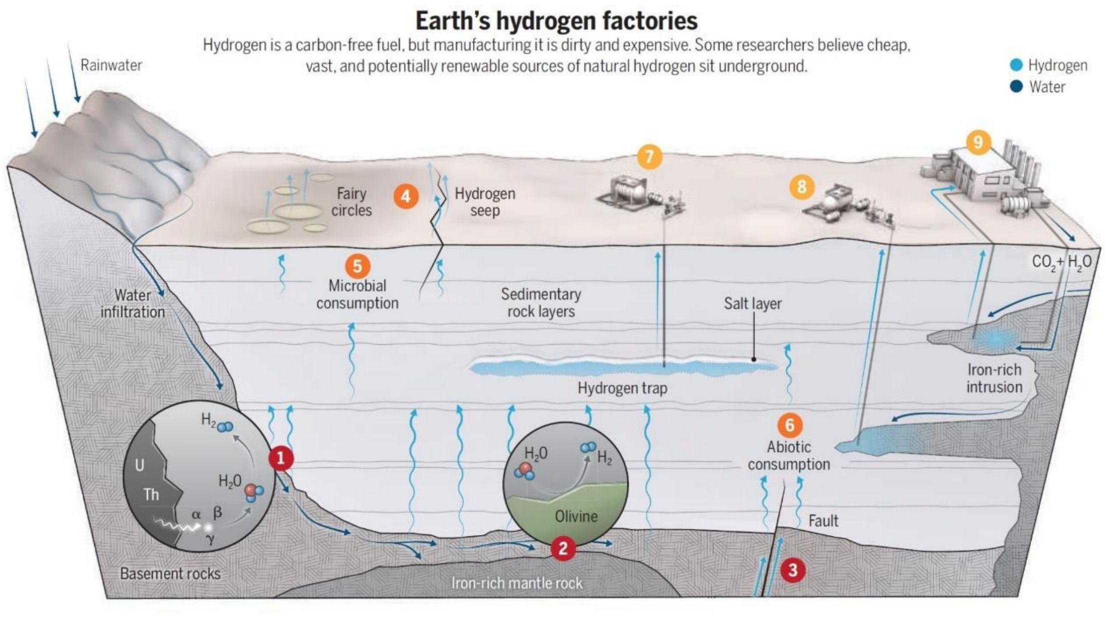

Fig. 1 – Diagram illustrating different geological contexts of formation of white hydrogen, a still little-known subsurface resource (from Hand, 2023).

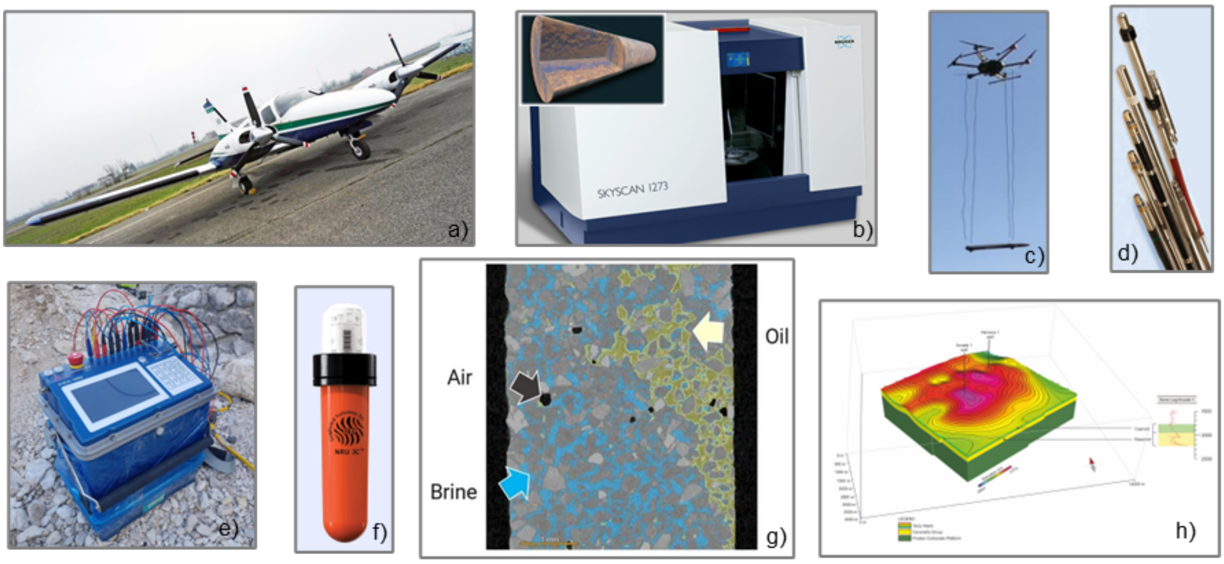

Fig. 2 – Some examples of the instrumentation and tools available within FUSE infrastructure: a) OGS airplane Piper PA-34-220 T Seneca III; b) CT scan for reservoir rock characterization; c) Aeromagnetic drone; d) Geophysical well logs; e) Resistivity & IP surveying system; f) 3C seismic nodes; g) Image acquired via a micro-CT scan at Rigaku laboratories shows the flow of three different phases (air in black, brine in blue, and oil in yellow) within a porous rock (shown in grey); h) Reservoir modelling.

Acknowledgments

FUSE is funded by Regione Friuli Autonoma Venezia Giulia with "LR 13/2023, articolo 7, commi 14 e 15 bis - Avviso per contributi a fondo perduto aventi per oggetto il sostegno alla creazione o all'ammodernamento di infrastrutture di ricerca nel settore dell'idrogeno rinnovabile".

References

Barison E., Donda F., Merson B., Le Gallo Y., Réveillère A.; 2023: An Insight into Underground Hydrogen Storage in Italy. Sustainability 2023, 15(8), 6886; https://doi.org/10.3390/su15086886

Hand E.; 2023. Hidden hydrogen. Science. Feb 17; 379(6633):630-636. doi: 10.1126/science.adh1477.

Corresponding author: fferraccioli@ogs.it

Assessment of seismic noise induced by next-generation wind turbines in the Fulgatore area, NW Sicily

R. Fontana[1], S. Capaccioli[2], M. Razzano[2,3], F. Fidecaro[2,3], G. Saccorotti[4], M. Marsella[3,5], G. Rapagnani[1], S. Gaviano[6], C. Giunchi[4], M. Olivieri[4], D. D'Urso[3,4,7], M. Punturo[3], F. Grigoli[1]

[1] *Department of Earth Sciences, University of Pisa, Pisa, Italy*
[2] *Department of Physics, University of Pisa, Pisa, Italy*
[3] *Istituto Nazionale di Fisica Nucleare (INFN), Italy*
[4] *Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy*
[5] *Department of Civil, Building and Environmental Engineering, Sapienza University of Rome, Rome, Italy*
[6] *Seismix Srl, Italy*
[7] *Department of Chemical, Physical, Mathematical, and Natural Sciences, University of Sassari, Sassari, Italy*

The detection of gravitational waves with large-scale laser interferometers such as LIGO and Virgo has opened a new era in physics, and the scientific community is now planning to build the Einstein Telescope (ET), a next-generation detector with significantly higher sensitivity. These instruments are susceptible to seismic noise from natural and anthropogenic sources; among these, wind turbine vibrations can adversely affect detector performance. For this reason, investigating wind farm-generated seismic noise is crucial for assessing and mitigating its potential impact. One candidate site to host the ET is in Sardinia (Italy), one of the world's seismically quietest regions. However, since next-generation wind turbines have been proposed for installation in this area in the near future, assessing their prospective influence is essential.

To evaluate their possible effect on the proposed ET site, we analyzed the seismic noise generated by the same new class of wind turbines – taller and heavier than previous models – already operating at Fulgatore (TP), Sicily. A one-month seismic acquisition campaign was conducted using six broadband three-component seismometers: four installed at the bases of different turbines and two deployed approximately 12–13 km from the wind farm at the archaeological park of Segesta. Turbine operational data (10-minute resolution) provided by the wind farm owner, EDP Renewables, and hourly wind data from SIAS were used to correlate wind and turbine activity with seismic observations. Power spectral densities (PSDs) computed over 10-minute waveforms revealed distinct narrow peaks across all channels (HHZ, HHE, HHN). Spectrograms indicated that below 2 Hz, the dominant signal corresponds to the Blade Pass Frequency (BPF, 0.30–0.54 Hz) and its harmonics. In the 2–10 Hz band, stable peaks appeared at approximately 2.45 Hz and 5.25 Hz, with an additional signal at 8.60 Hz in the HHZ channel.

Principal Component Analysis (PCA) on data covariance matrices showed that the BPF and its harmonics produced predominantly linear oscillations with dips below 30°, consistent with the higher amplitudes in the horizontal components. The 5.25 Hz signal exhibited nearly linear polarization with an average incidence angle of approximately 60° and maximum amplitude in the HHZ channel, while the 8.60 Hz peak showed vertical linear polarization with dips of 80-85°, explaining its presence only in the vertical channel. Furthermore, the azimuths of the dominant polarization directions varied with nacelle orientation, which in turn changes with wind direction. At Segesta, the wind-farm-related signals were not visible in the spectra, suggesting that they might have been strongly attenuated at such a distance of 12-13 km (Figure 1).

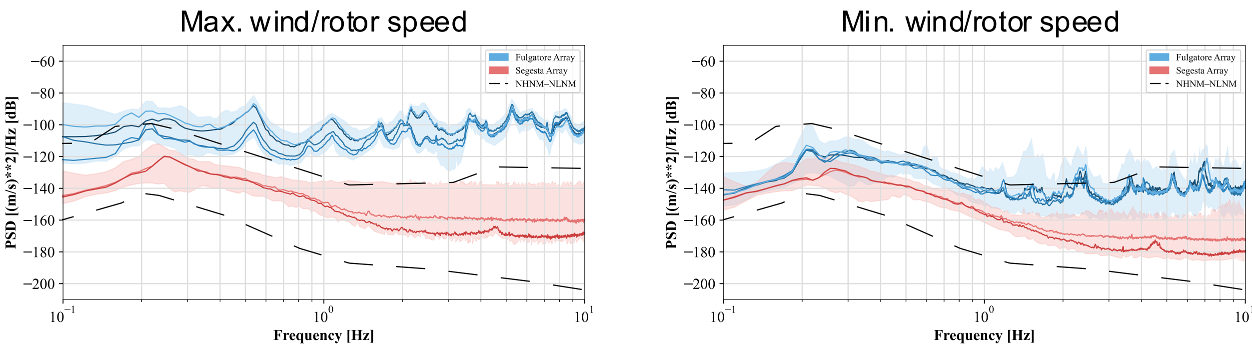

Figure 1: *Power Spectral Densities comparison between the Fulgatore (light blue) and Segesta (red) sites at the highest (left) and lowest (right) wind and rotor speed conditions. Each PSD refers to a different station (channel: HHZ). Dashed lines represent the New Low- and High-Peterson Noise Models (NLNM-NHNM). Shadings mark the 5th-95th percentile interval.*

A source time function representing turbine vertical motion at maximum activity was modelled using four sinusoids (0.54 Hz, 1.08 Hz, 2.45 Hz, and 5.25 Hz) with random phases and amplitudes estimated from RMS ground velocity statistics during maximum turbine operational conditions (Figure 2).

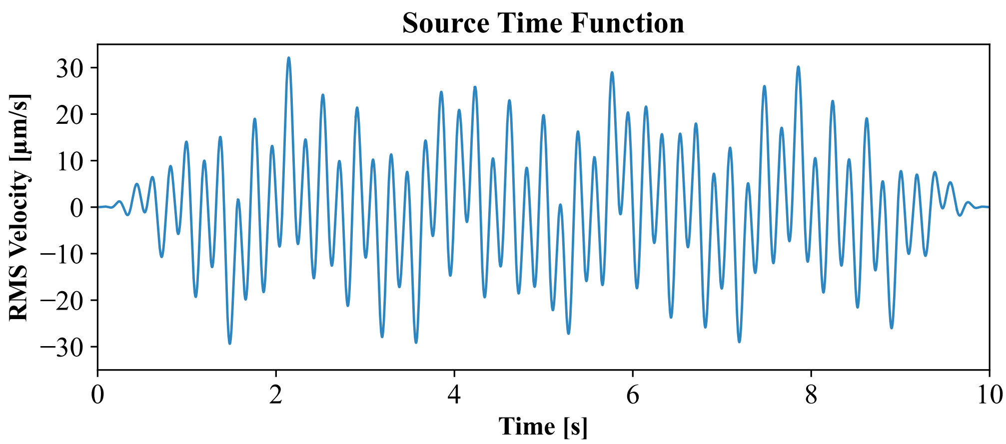

Figure 2: *Source Time Function.*

Cross-correlation analysis revealed random phase relations among turbines, indicating the absence of temporal coherence. Using the derived source time function, we employed a spectral element method to simulate the propagation of the turbine-induced seismic wavefield. The resulting models provide a basis for future studies to predict wind–farm–generated wavefields under realistic geological conditions.

Acknowledgements

This study has been funded by the project “PNRR ETIC IR0000004 - EINSTEIN TELESCOPE INFRASTRUCTURE CONSORTIUM”–CUP 53C21000420006 MISSIONE 4, COMPONENTE 2, INVESTIMENTO 3.1. Sincere acknowledgements are expressed to the Center for Instrument Sharing of the University of Pisa (CISUP) for their support in purchasing the seismic stations.

Corresponding author: Roberto Fontana, r.fontana8@studenti.unipi.it

A Physics-Based Protocol for Quantifying Geothermal Potential Across Reservoir, Wellbore, and Surface Systems

G. Gola[1], R. Basant[2], M. Cornetto[3], V. Cortassa[2], A. Galgaro[4], T. Nanni[4], P.M. Slupski[4], M. Tesauro[2], F. Vagnon[3], A. Manzella[1]

[1] *Institute Geosciences and Georesources, National Research Council, Italy*

[2] *Department of Mathematics, Informatics and Geosciences, University of Trieste, Italy*

[3] *Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino*

[4] *Department of Geosciences, University of Padova, Italy*

In the framework of InGEO Project, we propose a standardized workflow for geothermal potential assessment (Fig. 1) that integrates three complementary modelling domains: (1) Geological modelling, which reconstructs the upper crustal architecture using seismic and well data and constrains deeper crustal geometries through the joint interpretation of seismic tomography and gravity models; (2) Thermal modelling, which incorporates the geological framework, petrophysical parameters, and corrected temperature data to estimate the three-dimensional distribution of subsurface temperatures; and (3) Geothermal potential evaluation, which quantifies the available thermal energy using approaches tailored to the quality and quantity of available data, ranging from simplified heat-in-place calculations to advanced thermo-hydraulic simulations.

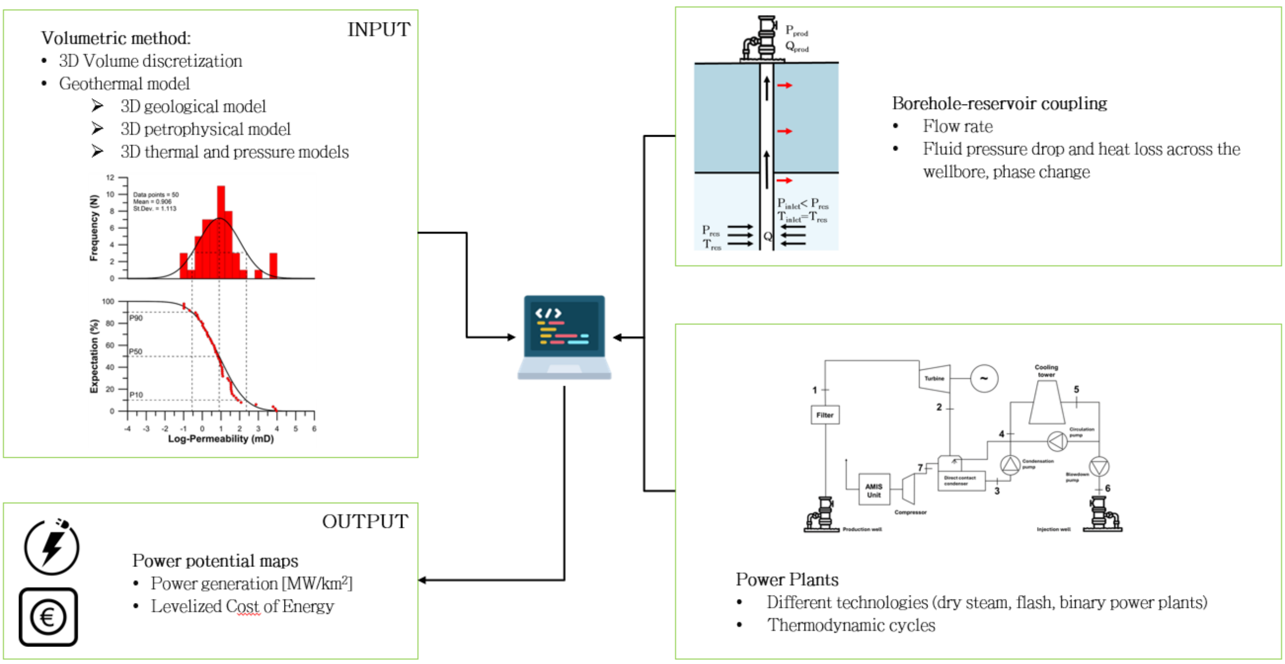

Fig. 1 – Geothermal assessment workflow

By integrating multi-scale geological and geophysical data with robust thermal modelling strategies, this workflow provides a consistent framework for estimating geothermal potential and for comparing results across different regions. Additionally, the uncertainty management bases on systematic data quality checks, spatial coverage analyses, and accounts for multiple interpretations when alternative structural scenarios are plausible. This approach ensures that uncertainties in shallow and intermediate crustal structures are explicitly acknowledged and propagated through the modelling chain. For the resource assessment purpose, Monte Carlo simulations are then employed to derive probabilistic estimates of recoverable heat and electrical potential (e.g., P10, P50, and P90 values) by explicitly propagating uncertainty across selected key geological, thermal, and petrophysical parameters. Stochastic variability is assigned to reservoir geometry (e.g. net pay thickness), reservoir thermal and pressure regimes (e.g., temperature gradients, pore-pressure distribution), as well as petrophysical properties (e.g. density, heat capacity, permeability). The combined effect of these uncertainties is sampled through repeated realizations, yielding probability distributions that quantitatively reflect the range of likely resource and power estimates rather than a single deterministic outcome.
Our approach recognizes that geothermal potential is not a single quantity but a sequence of progressively refined metrics, ranging from heat in place to recoverable heat estimates, energy conversion, and ultimately economically viable output. In accordance with the state-of-the-art assessment methods (Ciriaco et al., 2020), we structured and developed an open-source code around those tightly connected domains. Each of theme relies on distinct physical-mathematical formulations and specialized computational tools, yet their coupling is essential to ensure internal consistency and reliable decision support.

Acknowledgments

InGEO is a PRIN 2022 PNRR Project and has received funding from the European Union, Next Generation EU.

References

Ciriaco, A.E, Zarrouk, S.J., Zakeri, G. (2020). Geothermal resource and reserve assessment methodology: Overview, analysis and future directions. Renewable and Sustainable Energy Reviews 119, 109515. https://doi.org/10.1016/j.rser.2019.109515

Corresponding author: gianluca.gola@cnr.it

Time-lapse monitoring at the Svelvik CO_2 Field Lab: QC and preliminary results

E. Ligas[1], G. Pantaleo[1], G. Roncoroni[1], E. Forte[1], M. Pipan[1]

[1] *University of Trieste, Italy*

The safe geological storage of carbon dioxide (CO_2) requires reliable monitoring strategies capable of detecting subsurface migration and identifying potential leakage pathways (Lee et al., 2016), particularly in the near-surface where small amounts of CO_2 may escape conventional monitoring coverage. Understanding CO_2 behaviour above the injection interval and across the caprock is therefore critical to ensure storage integrity and long-term containment. While seismic methods are well established for imaging CO_2 migration at reservoir depth, their sensitivity decreases in the near-surface, motivating the integration of complementary geophysical techniques.

This study is conducted within the framework of the Svelvik Borehole Electromagnetic Monitoring (SBEM) project at the Svelvik CO_2 Field Lab in Norway, a controlled experimental site designed for small-scale CO_2 injection and monitoring (https://www.sintef.no/projectweb/svelvik-co2-field-lab/). The SBEM project integrates active seismic surveys, Ground Penetrating Radar (GPR), and Electrical Resistivity Tomography (ERT) acquisitions, providing a unique multi-physics dataset for near-surface leakage detection.

The main objective of this work is the characterization of the caprock and shallow overburden, with particular emphasis on high-resolution near-surface imaging and on the detection of CO_2 migration above the injection zone. Previous monitoring studies at the site indicated that CO_2 leakage preferentially occurs toward the northern sector of the field lab, beyond the area typically covered by cross-well seismic surveys (Jordan et al., 2022). Based on these findings, a pseudo-3D geophysical acquisition was designed and deployed in this area to improve spatial coverage and enhance sensitivity to potential leakage features, as shown in Figure 1.

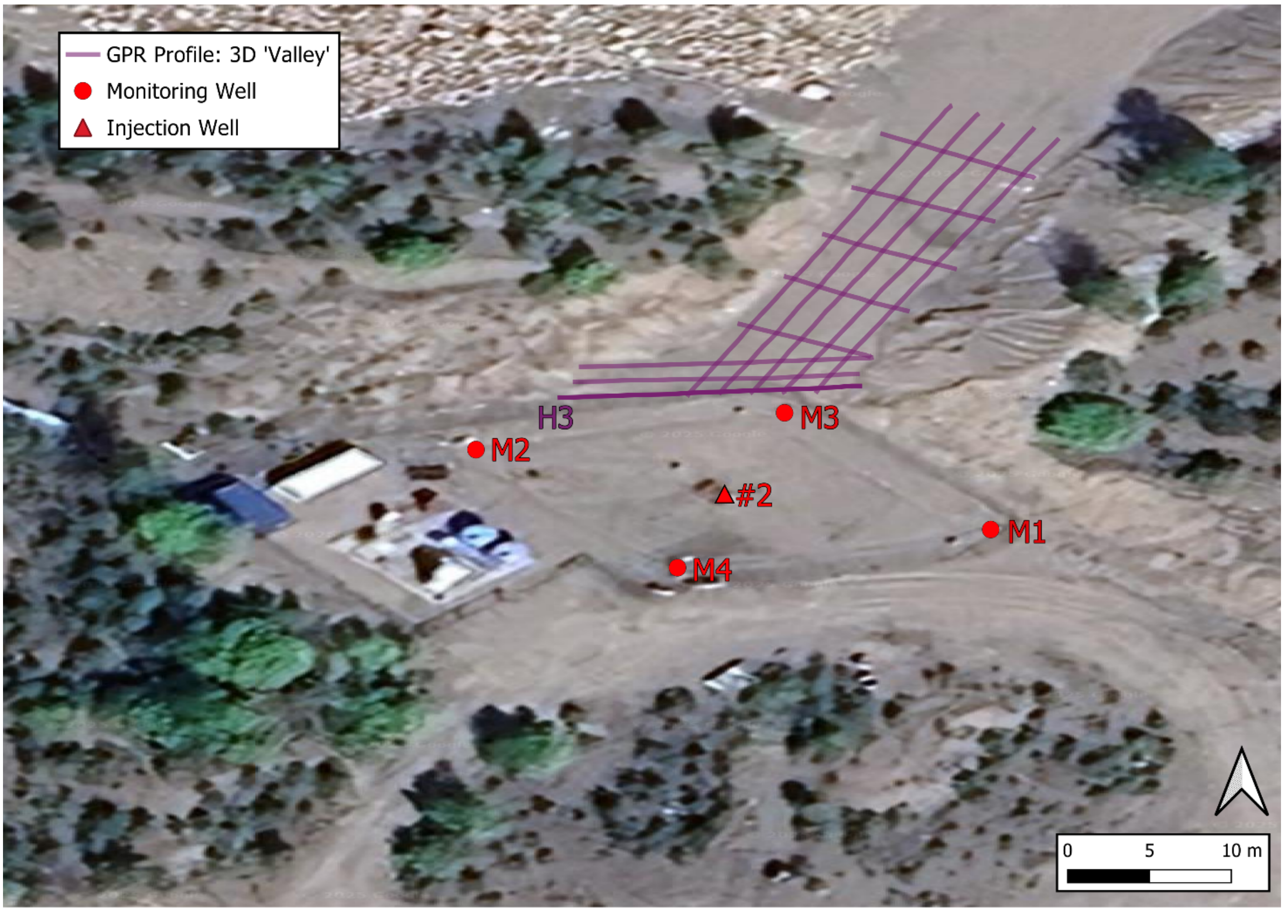

Fig. 1 – Aerial view of the Svelvik CO_2 Field Lab showing the layout of the pseudo-3D geophysical acquisition deployed in the northern sector of the site. Monitoring wells (M1–M4) and the injection well (#2) are indicated. Purple lines represent the GPR pseudo-3D grid, designed based on previous evidence of preferential northward CO_2 migration. The highlighted H3 profile is used as a representative example for time-lapse amplitude analysis (see Figure 2).

Current work focuses on the processing and time-lapse analysis of the integrated datasets. As an example of preliminary results, Figure 2 presents a comparison between pre-injection (Day 3) and injection-phase (Day 7) GPR data along the H3 profile, together with the corresponding amplitude residual. The right panel highlights a strong amplitude variation within the first ~40 ns, which is interpreted as being primarily related to water table fluctuations. In addition, localized amplitude variations, highlighted by red circle, are observed at greater travel times and may potentially be associated with CO_2 migration. These observations are currently being analysed in combination with seismic velocity and electrical resistivity variations to assess their possible relationship with near-surface CO_2 migration and leakage pathways.

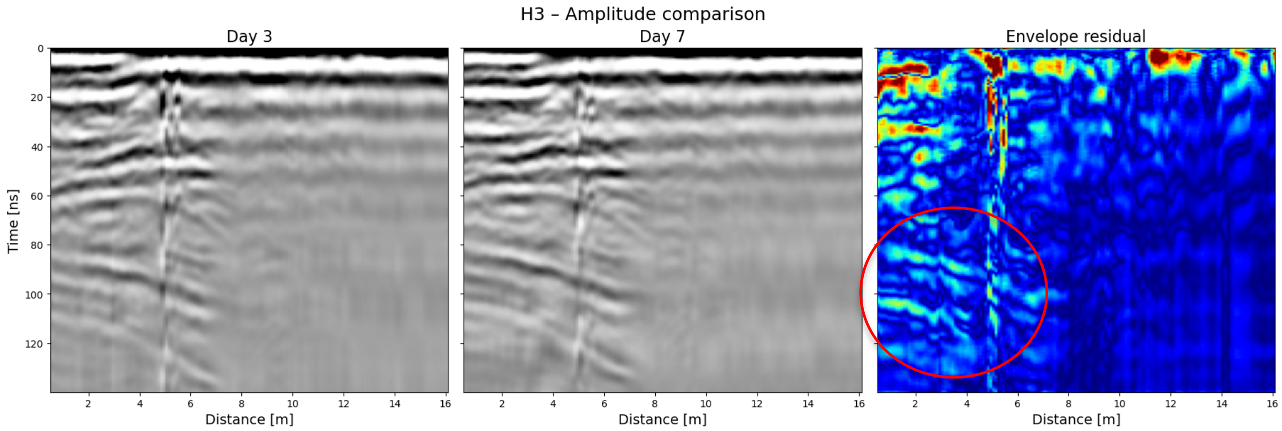

Fig. 2 – Time-lapse comparison along the H3 GPR profile. Left: pre-injection data (Day 3). Centre: data acquired during CO_2 injection (Day 7). Right: envelope residual obtained by differencing instantaneous amplitude of Day 7 and Day 3 sections, highlighting localized amplitude variations in the near-surface. These anomalies are interpreted as potential indicators of CO_2-induced changes and are currently under investigation to assess their relationship with near-surface migration pathways.

This work represents a step toward the definition of an integrated and transferable geophysical monitoring protocol for CO_2 storage sites, combining seismic and electromagnetic methods for the detection and characterization of near-surface CO_2 migration and potential leakage.

Acknowledgements

This work is based on the preliminary results from the SBEM project, funded by the European Commission (through GEO-Inquire) under project number 101058518 within the HORIZON-INFRA-2021-SERV-01 call. We thank Marcin Duda and Michael Jordan, both SINTEF, for their help and support during the fieldwork.

References

Lee KK., et al.; 2016: Shallow groundwater system monitoring on controlled CO_2 release sites: a review on field experimental methods and efforts for CO_2 leakage detection. Geosciences Journal 20, 569–583. https://doi.org/10.1007/s12303-015-0060-z

Jordan M. et al.; 2022: Learnings from the Pre-ACT campaign at the Svelvik CO2 Field Lab, In GHGT-16 conference. https://doi.org/10.2139/ssrn.4286508

Corresponding author: Elisa Ligas
elisa.ligas@phd.units.it

A generalized machine learning approach for modelling subsurface CO_2 plume through time-lapse gravity data.

C. Messina[1], M. Milano[1], M. Fedi[1]

[1] Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università di Napoli 'Federico II', Naples.

This work aims at the definition of new geophysical monitoring and forecasting tools for Carbon Capture and Storage (CCS) activities through the development of Machine Learning algorithms, which could be able to solve non-linear problems of considerable complexity through self-learning mechanisms based on Transfer Learning (TL).

The geologic storage of CO_2 is a promising and increasingly deployed technology for dealing with increasing concentrations of carbon dioxide in the atmosphere and climate change crisis. The development of precise site characterization and continuous monitoring during both the injection and post-injection phases is essential to the planning of CO_2 storage activities. The risks associated with CO_2 leakage include the accumulation of CO_2 in overlying geological formations. It could occur a potential deterioration of groundwater resources or it could eventually be discharged to the atmosphere, resulting in a failure in reducing greenhouse gas emissions (Keating et al., 2010). In this scenario, an appropriate monitoring strategy is essential in each phase of the storage (i.e.: injection and post injection phase) to remotely evaluate the migration of the CO_2 plume (Appriou et al., 2020).

In recent decades, geophysical techniques have proved decisive for this aim. Seismic methods are often used to monitor CO_2 migration in the deep geologic storage sites. However, this method is expensive and invasive. On the other hand, the subsurface monitoring in CCS context through time-lapse gravity data represent a complementary, low-cost and non-invasive approach to more conventional geophysical methods (Celaya et al., 2023). A time-lapse gravity survey consists of studying at repeated stations the changes in the gravity acceleration due to the redistribution of fluids in the porous medium. By repeating the measurements at different times, it is in fact possible to directly estimate the variation in the mass and density of CO_2, induced by fluid migration and changes in saturation (Milano and Fedi, 2023).

Most current studies, however, are based on the development of multiphysics simulations which, as the degree of complexity of the sites in question increases, require significant computational capacity and time as well as information on the temporal variations of numerous physical parameters. Moreover, in addition to being computationally expensive, this approach also exhibits a strong site dependence, which limits its generalizability and robustness across different geological contexts.

In this way we improved network adaptability and performance across diverse geological scenarios, while significantly reducing computational time.

We created a synthetic training dataset starting from a representative geological model, varying operational (i.e. injection rate) and physical (i.e. porosity, permeability) parameters and performed simulations using the MATLAB Reservoir Simulation Toolbox (MRST). For each simulation, we produced both the CO_2 saturation models and the corresponding gravimetric responses (Figure 1), which served as the labels and features for training a starting Convolutional Neural Network (CNN).

Then, we applied Transfer Learning to adapt the pretrained CNN to different and more complex geological settings, so the network can interpret time-lapse gravity data from different scenarios and monitoring the evolution of CO_2 plume. TL allows a model developed for a given task to be reused as the starting point for a related one, significantly reducing both computational cost and data requirements (Zhuang et al., 2020). We tested our approach on the Kimberlina site model (California, USA), a geological model characterized by a stack of sandy layers and a permeable fault which may favour the CO_2 leakage into the shallow aquifers.

Our method aims to improve the prediction of CO_2 plume geometry and saturation while enhancing model generalization across heterogeneous geological scenarios, thereby providing an efficient and computational effective workflow for geophysical monitoring in CCUS projects.

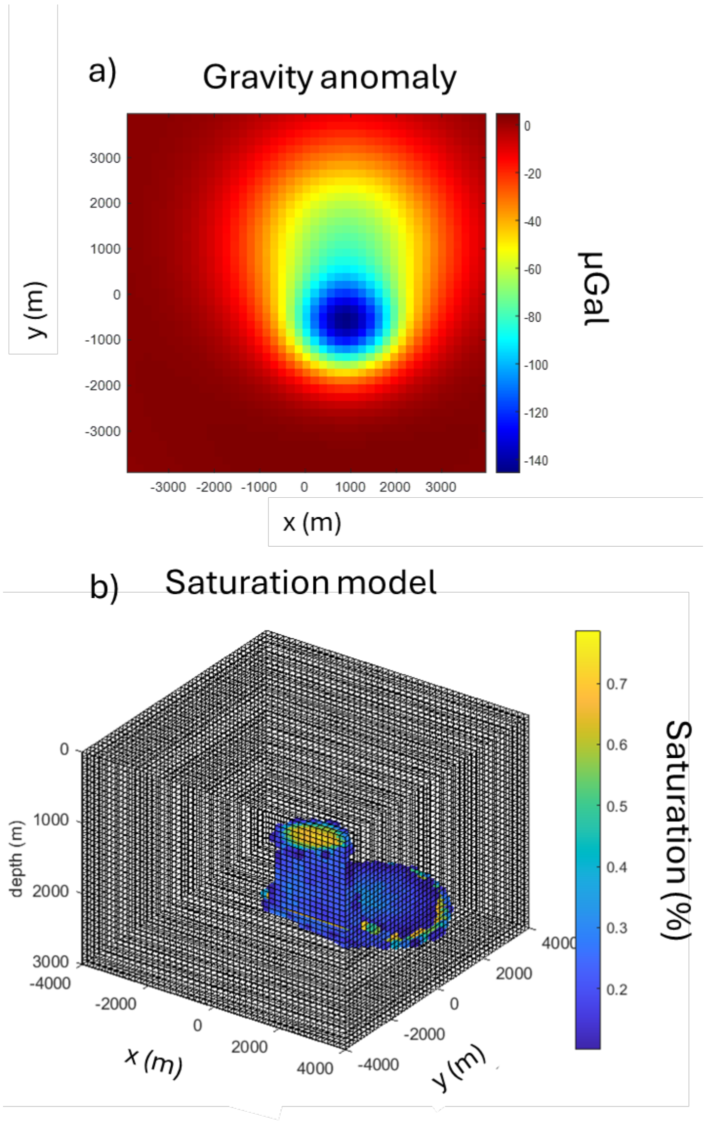

Fig. 1- Forward gravity response (a) of the CO_2 plume (b) deriving from the simulation of leakage scenarios.

References

Appriou, D., Bonneville, A., Gasperikova, E., & Zhou, Q. (2020). *Time-lapse gravity monitoring of CO_2 migration based on numerical modeling of a faulted storage complex*. *International Journal of Greenhouse Gas Control, 95*, 102956. https://doi.org/10.1016/j.ijggc.2020.102956

Celaya, A., Denel, B., Sun, Y., Araya-Polo, M., & Price, A. (2023). *Inversion of time-lapse surface gravity data for detection of 3-D CO_2 plumes via deep learning*. IEEE Transactions on Geoscience and Remote Sensing, 61, 1–11. https://doi.org/10.1109/TGRS.2023.3273149

Keating, E. H., Hakala, J. A., Viswanathan, H., Carey, J. W., Pawar, R., Guthrie, G. D., & Fessenden-Rahn, J. (2013). *CO_2 leakage impacts on shallow groundwater: Field-scale reactive-transport* *simulations informed by observations at a natural analog site*. *Applied Geochemistry*, 30, 136–147. https://doi.org/10.1016/j.apgeochem.2012.08.007

Milano, M., & Fedi, M. (2023). *Surface gravity response of CO_2 storage in the Johansen deep reservoir*. IEEE Transactions on Geoscience and Remote Sensing, 61, 1–14. https://doi.org/10.1109/TGRS.2023.3330778

Zhuang, F., Qi, Z., Duan, K., Xi, D., Zhu, Y., Zhu, H., Xiong, H., & He, Q. (2021). *A comprehensive survey on transfer learning*. *Proceedings of the IEEE, 109*(1), 43–76. https://doi.org/10.1109/JPROC.2020.3004555

Corresponding author: ciro.messina@unina.it

Time-lapse monitoring at the Svelvik CO_2 Field Lab: survey design

G. Pantaleo[1], E. Ligas[1], G. Roncoroni[1], E. Forte[1], M. Pipan[1]

[1] *University of Trieste, Italy*

Introduction

Geological storage of energy-related fluids has emerged as a critical component of the clean energy transition. Carbon Capture and Storage (CCS) offers a way to directly reduce emissions by capturing CO_2 from industrial sources and injecting it into the subsurface to permanently isolate the CO_2 from the atmosphere. The main geological storage options in terms of their relative potential for storing large volumes of CO_2 are saline aquifer formations (Ringrose 2020). A variety of geophysical techniques can be employed to observe subsurface changes during and after CO_2 injection, including: active seismic methods, especially time-lapse 3D seismic (or 4D seismic), are the primary tools for imaging and quantifying changes in the subsurface by comparing a baseline survey recorded before injection with monitor survey record during and after injection; electrical and electromagnetic (EM) methods, to detect changes in the electrical resistivity of reservoir rocks delineating the plume extent, making EM an effective complement to seismic monitoring (Fawad and Mondol, 2021).

Geophysical campaign overview: test site and survey design

In this context, we carried out a geophysical project aimed at testing the integration of seismic and EM methods and assessing the performance of different borehole seismic sensing technologies for the detection and quantification of CO_2 migration at the Svelvik CO_2 Field Lab, Norway (see Figure 1.a for geographical location). The Svelvik CO_2 Field Lab (SFL) was specifically designed for controlled CO_2 injection experiments and for developing and testing technologies for detection and quantification of CO_2 storage. This geophysical campaign was part of the SBEM (Svelvik Borehole Electromagnetic Monitoring) campaign, funded by GEO-INQUIRE.

The SBEM project involved a controlled injection of CO_2 and subsequent geophysical monitoring using seismic and EM methods. Figure 1.b shows the area of investigation and the localisation of the wells at the SFL. The SFL consists of an injection well (#2, up to 90 m deep), and four monitoring wells (M1 to M4, up to 100 m deep) positioned at the corners of a rhombus with the injection well in the centre (Figure 1.b). The injection well is designed for injecting CO_2 at 64-65 meters depth. The inside of the casing is available for non-permanent instrumentation. Behind the casing, each monitoring well is equipped with research fibre-optic cables comprising straight (LIN) and helically wound (HWC) fibres. These configurations enable various Distributed Acoustic Sensing (DAS) measurements with different directional sensitivities, allowing comparative analyses of their performance under different acquisition settings.

The geology of the SFL is characterised by unconsolidated sandy sediments with local gravel and boulders down to approximately 35 m depth, underlain by interbedded sand, silt, and clay layers with highly variable permeability. Below this depth, the subsurface is dominated by an alternation of sand-, silt-, and clay-rich units. Gamma-ray logs indicate the presence of a permeable aquifer at approximately 65 m depth (NTNU, 2018), which represents the target reservoir for CO_2 injection.

During our campaign at the SFL, a comprehensive dataset of baseline, injection, and post-injection integrated geophysical surveys was acquired within a time-lapse framework. The pre-injection baseline survey is hereafter referred to as BL, while the monitoring surveys acquired during CO_2 injection are denoted as MO, followed by the number of days since the start of injection (e.g., MO3 and MO5 correspond to surveys acquired after 3 and 5 days of injection, respectively). This timelapse strategy enabled tracking the CO_2 plume evolution over time allowing the identification of potential seismic or radar anomalies that might indicate migration or leakage beyond the expected boundaries or other peculiar behaviours.

Two main survey categories were conducted: i) electrical and EM surveys, including Electrical Resistivity Tomography (ERT), Vertical Radar profile (VRP), surface GPR, and cross-well GPR measurements; ii) seismic surveys, in both cross-well and Vertical Seismic Profile (VSP) configurations. The main acquisition parameters for each geophysical method are summarised in Table 1. Seismic and EM surveys were conducted in parallel using same source-receiver geometries, in order to allow direct comparison and integration of the two datasets. Although the monitoring campaign comprises multiple geophysical techniques, this contribution addresses the integrated survey design and presents a preliminary analysis of the seismic cross-well dataset.

Fig. 1 – a) Multi-scale locator maps of southern Norway. The red square highlights the Oslo region. The yellow square is the satellite image showing Verket with the Svelvik ridge in Drammensfjorden, which is an east-west running sandy ridge of recessional moraine where the test site is located. The white square highlights the exact location of the SFL that occupies a non-active part of a sand and gravel quarry. b) overview of the geophysical acquisition carried out at the SFL.

Method	Type	Array configuration	Spatial sampling	Sampling rate	Recording length
Seismic	Hydrophones	2x12m hydrophone strings	1 m - 2 m	16 kHz	512 ms
	DAS	4x100 m fibre-optic cable	1.02 m	4 kHz	10000 ms

GPR	100, 250, 500, 800 MHz	4x13 profiles (see Fig. 1.b)	0.1 m	1.4 kHz	900 ns
ERT	Wenner–Schlumberger	48 electrodes	2 m	-	-

Table 1 – Acquisition parameters of the geophysical surveys conducted during the campaign.

Seismic data: DAS and hydrophones

For the cross-well seismic measurements, a borehole P-wave sparker source was deployed in well M4 at multiple depths to generate seismic waves. Borehole hydrophones were also installed to allow a direct comparison with Distributed Acoustic Sensing (DAS) measurements and were deployed exclusively in monitoring well M3. Owing to the limited length of the hydrophone strings (24 m), the hydrophone recordings acquired during both MO3 and MO5 surveys cover a depth interval between approximately 3 and 50 m, with different sensor spacing between the two surveys. In contrast, the DAS measurements provide continuous seismic coverage along the entire fibre length, spanning the full depth of the monitoring wells (approximately 100 m). Due to logistical constraints, no baseline (BL) hydrophone survey was acquired. Details on the acquisition geometry and recording parameters for the seismic surveys are reported in Table 1.

Figure 2 presents a comparison between hydrophone recordings (Figure 2.a-d), and DAS recordings for both LIN (Figure 2.b-e) and HWC configurations (Figure 2.c-f), using a P-wave source deployed at 45 m depth in M4. Panels (a-b-c) correspond to the MO3 survey, with hydrophones spaced at 1 m intervals, while panels (d-e-f) show the MO5 survey, where the hydrophone spacing was increased to 2 m. The DAS data were band-pass filtered between 100 and 1700 Hz to attenuate high-frequency noise, whereas the hydrophone data were left unprocessed, except for stacking of the six repeated shots. Moreover, S-waves are detected by DAS, which is more sensitive to shear deformation, whereas they are not expected in the hydrophone recordings.

The DAS datasets were pre-processed through the following steps: (1) stacking six repeated shots acquired keeping the source at the same depth; (2) stacking of the downgoing and upgoing DAS segments for both LIN and HWC configurations; (3) band-pass filter 100–1700 Hz to remove diffuse high-frequency noise. One particular feature consistently observed across all surveys is a strong linear signal highlighted by the black arrows in Figure 2. This event is preliminarily interpreted as a guided wave, generated at the ground/air interface by the direct wave coming from the deep source, which then propagates downward along the entire length of M3 well as a direct arrival. Its travel-time linearly increases with increasing depth along the well, being recorded from both DAS and hydrophones positioned along the well M3.

Figure 3 shows a comparison between linear (LIN) and helical (HWC) DAS records in M3, employing P-wave source at 45 m depth. Figure 3.a shows baseline survey on 28/05/2025 recorded with LIN cable, while Figure 3.b shows baseline survey on 28/05/22025 recorded with HWC cable. Figure 3.c and Figure 3.d show the same but for the monitor survey on 04/06/2025. The comparison between the LIN and HWC measurements reveals several differences in the recording performance of P- and S-wave arrivals. In particular, the P-wave direct arrivals are clearly identifiable in both the cable configurations. However, at depths where the incident wavefronts from the source are nearly perpendicular to the cable orientation, the HWC configuration, as expected, provides enhanced visibility of these arrivals, owing to its improved directional sensitivity. In addition to P-waves, Swaves were also generated and effectively recorded by the DAS configurations from 0.06 s, despite the source being designed to emit primarily P-waves. In this case, the LIN cable exhibits higher Swave amplitudes than the HWC one, suggesting that the S-wave particle motion is predominantly oriented along the vertical direction, to which the LIN cable is more sensitive.

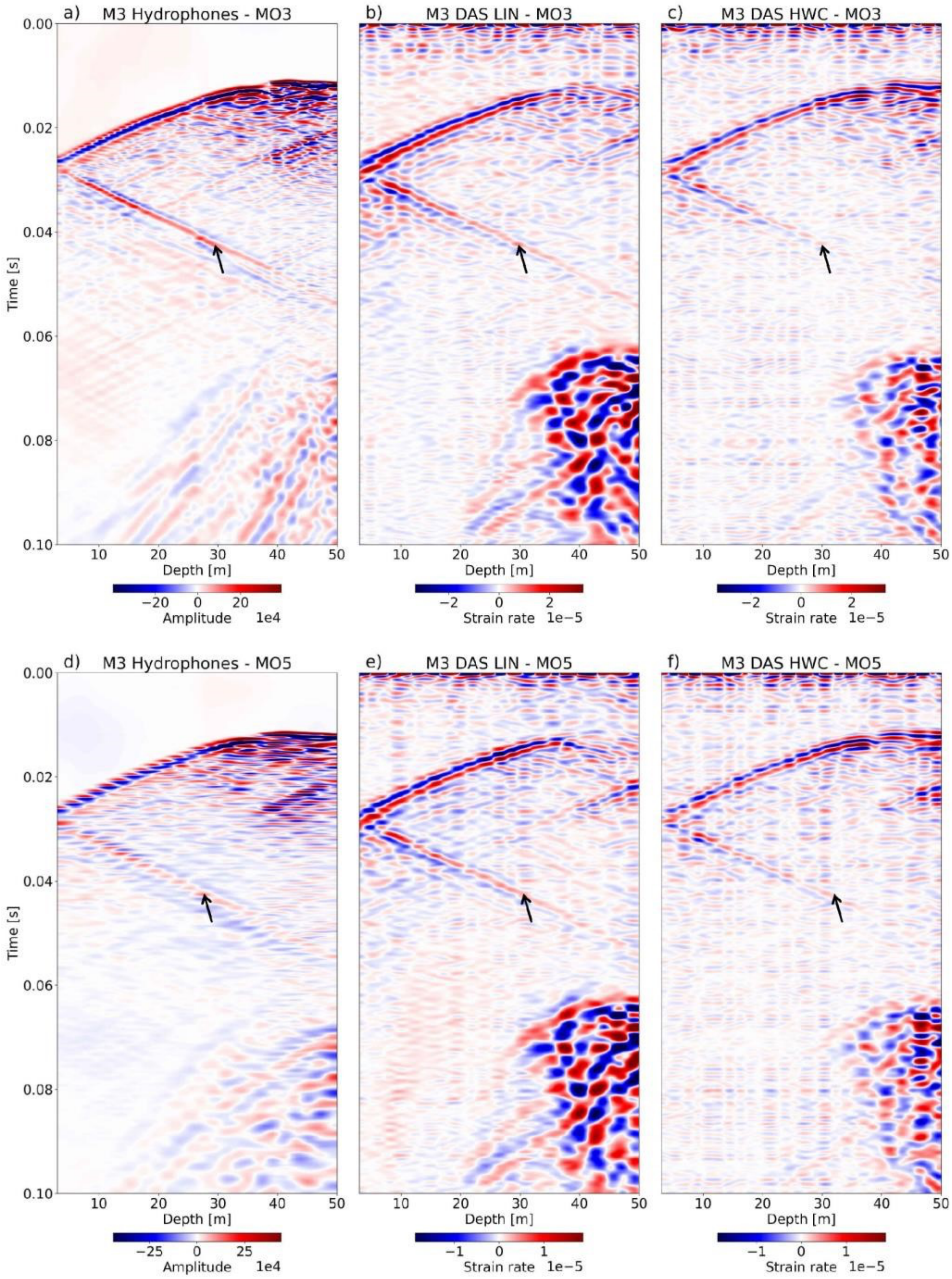

Fig. 2 – Comparison between hydrophone and DAS recordings collected in well M3 for MO3 survey (Panels a-b-c) with hydrophones spacing of 1 m, and MO5 survey (Panels d-e-f) with hydrophone spacing of 2 m. In both cases, the DAS data are shown for the LIN and HWC cable configurations. The P-wave source was positioned at 45 m depth. DAS recordings were cropped for plot purpose between same depth range covered by hydrophones string in well M3.

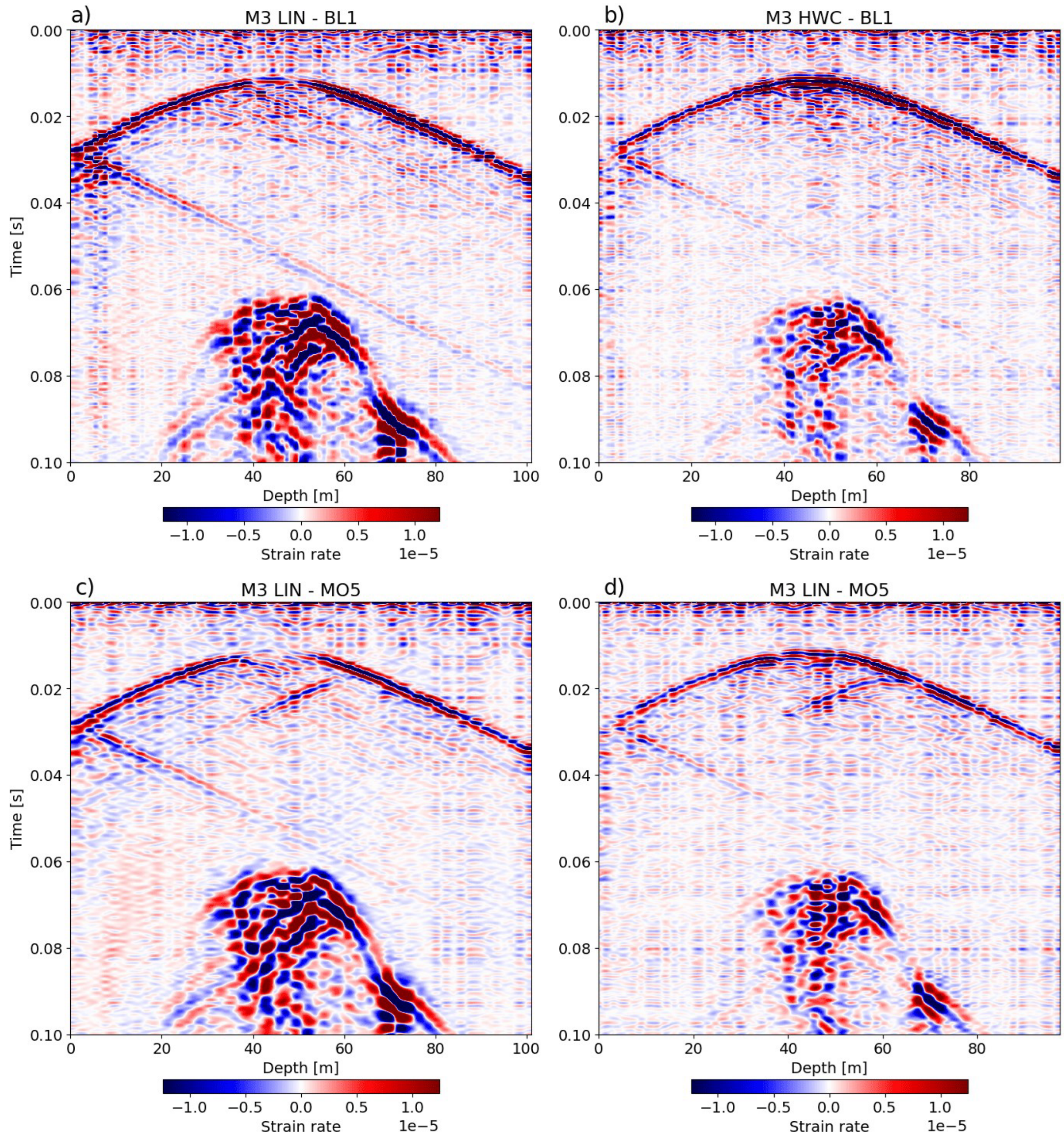

Fig. 3 – Comparison between LIN and HWC DAS recordings: (a) baseline survey BL1 acquired with LIN and (b) with HWC, while in (c) the monitor survey MO5 acquired with LIN, and HWC in (d). As indicated by the x-axis, the recordings are collected along the entire length of well M3.

Conclusions

The active seismic monitoring campaign conducted at the Svelvik CO_2 Field Lab successfully demonstrated the feasibility of integrating Distributed Acoustic Sensing (DAS) and conventional hydrophone surveys for near-surface CO_2 monitoring. The time-lapse acquisition strategy allowed for a direct comparison between the baseline and injection/post-injection phases, ensured by the consistent survey geometry. The permanent DAS installation within the casing provided high repeatability of the measurements, ensuring that observed changes were not related to variations in instrumentation or sensors geometries. The DAS system, installed in both straight (LIN) and helically wound (HWC) configurations, proved capable of capturing high-quality seismic data with accurate spatial sampling and extensive depth coverage. The comparison between LIN and HWC fibres confirmed the higher sensitivity to P-waves of the helical geometry due to the nearly perpendicular incidence of the wavefront, while the linear fibre provided stronger responses to Swaves, consistent with its axial sensitivity. The use of hydrophones allowed benchmarking of the DAS performance. The results confirmed that the DAS shows greater sensitivity to shear deformation, while the hydrophones provide clearer arrivals of P-waves. The monitoring campaign also included Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) measurements, targeting the shallow subsurface. These datasets are currently under analysis and will be integrated with the seismic results to provide a multi-physics characterisation of CO_2 migration at the site. The datasets acquired at the Svelvik CO_2 Field Lab will therefore serve as a valuable benchmark for developing and validating new approaches aimed at quantitative assessment of CO_2 migration and leakage phenomena.

Acknowledgements

This work is based on the preliminary results from the SBEM project, funded by the European Commission (through GEO-Inquire) under project number 101058518 within the HORIZON-INFRA2021-SERV-01 call. We also thank Marcin Duda and Michael Jordan, both SINTEF, for their help and support during the fieldwork.

References

Fawad M., Mondol N.H.; 2021: Monitoring geological storage of CO_2: a new approach. Scientific Reports. 11, 1 (2021), 5942. https://doi.org/10.1038/s41598-021-85346-8.

NTNU; 2018: Modelling Medium- Depth CO_2 Injection at the Svelvik CO_2 Field Laboratory in Norway. NTNU, Trondheim, Norway. https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2562292.

Ringrose P.; 2020: How to store CO_2 underground. Insight from early-mover CCS projects. Vol. 21915369. Springer, Swit<zerland. 1-129 pages. https://doi.org/10.1007/978-3-030-33113-9.

SINTEF; 2024: ECCSEL Svelvik CO_2 Field Lab website. https://www.sintef.no/projectweb/svelvik-co2field-lab/.

Corresponding author: giovanni.pantaleo@phd.units.it

Preliminary results of a Deep Electrical Resistivity Tomography (DERT) in the Campi Flegrei area (Italy).

E. Rizzo[1,2], S. Piscitelli[2], M. Balasco[2], J. Bellanova[2], G. Calamita[2], G. De Martino[2], L. Galasso[2], V. Giampaolo[2], E. Gueguen[2], A. Perrone[2], V. Serlenga[2], D. Mianulli[1], E. Galletti[1], M.G. Caielli[3], R. De Franco[3], I. Gaudiosi[3], F. Polpetta[3], M. Simionato[3], M. Mancini[3], S. Giallini[3], D. Tentori[3]; G. Fiorentino[3], E. Tempesta[3], F. Davani[3], M. Moscatelli[3], F. Stigliano[3], V. Lapenna[2]

[1] *University of Ferrara (Dipartimento di Fisica e Scienze della Terra, Ferrara, Italy)*
[2] *National Research Council (Istituto di Metodologie per l'Analisi Ambientale-IMAA, Tito, Italy)*
[3] *National Research Council (Istituto di Geologia Ambientale e Geoingegneria-IGAG, Roma, Italy)*

Keywords: DERT, Microzonation, volcanic area, Campi Flegrei,

In the framework of the activities of the Geophysical Prospecting Unit (UR2) planned in the project MS Campi Flegrei (funded by Dept. of Civil Protection), geoelectric tomography surveys, both shallow and deep, and passive seismic surveys, both single station and 2D array, were carried out to contribute to the definition of a geological model of the subsoil in the survey area for seismic microzonation purposes. In this work the preliminary results concerning a Deep Electrical Resistivity Tomography (DERT) with an investigation depth of about 2 km are presented and discussed.

The Campi Flegrei, located in the western part of Naples, represents one of the most active and studied volcanic areas in the world, known for their volcanic activity. It is a large caldera that formed as a result of massive explosions thousands of years ago. In recent decades, the area has experienced increasing seismic activity and bradyseism, which manifests as changes in the elevation of the ground, either rising or subsiding, caused by underground magmatic processes. In recent years, the region has seen an intensification of seismic tremors, accompanied by an increase in ground uplift. Managing the seismic and bradyseism risk is therefore essential to prevent potential damage and ensure the safety of the population. Some geological and volcanological aspects of the Campi Flegrei caldera are still under debate within the scientific community. Just as many questions remain unresolved regarding the magmatic systems that produce caldera-forming eruptions. A single unifying theory that brings together the majority of researchers is still lacking, but new investigations are continuously being proposed to better understand the dynamics of the Campi Flegrei caldera. Although these are limited due to the high population density, which does not allow for appropriate geophysical surveys to be carried out, anyway taking particular attention to ad hoc logistics and appropriate geophysical instrumentation, these limitations can be overcome.

The ERT methods is a strong geophysical approach to characterize volcanic areas (Finizzola et al., 2006) due its ability to obtain the electrical resistivity distribution associated with volcanic features, such as hydrothermal systems, fluid interactions and temperature variations. The used DERT apparatus is a multichannel system designed and implemented by the CNR-IMAA (Rizzo et al.2004; Rizzo et al., 2022). The acquired DERT data set was processed and elaborated through a procedure built ad hoc for this type of geoelectric surveys. The fig.1 shows the DERT profile which is 11km long from Cuma archaeological site to Bagnoli area. One of the main aspects of the project is the operating mode, which, through a zonal system, has made it possible to overcome the logistical difficulties of the area (heavy urbanisation, traffic, restricted traffic area, etc.). The investigated area was divided into two sub-areas, allowing for the installation of 12 multi-channel data loggers which enabled the acquisition of the electric fields produced by the injected current. In general, a square wave current with an amplitude varying between 1000mA and 9500mA was sent, acquiring the drop of potential through dipoles arranged at a variable distance from the injected stations (from 500m to 10,000m). This configuration made it possible to obtain an electrical resistivity tomography with an investigation depth of about 2000m. All the data acquired was appropriately processed to obtain a model of the subsoil resistivity, providing useful information on the subsoil of the Campi Flegrei volcanic area.

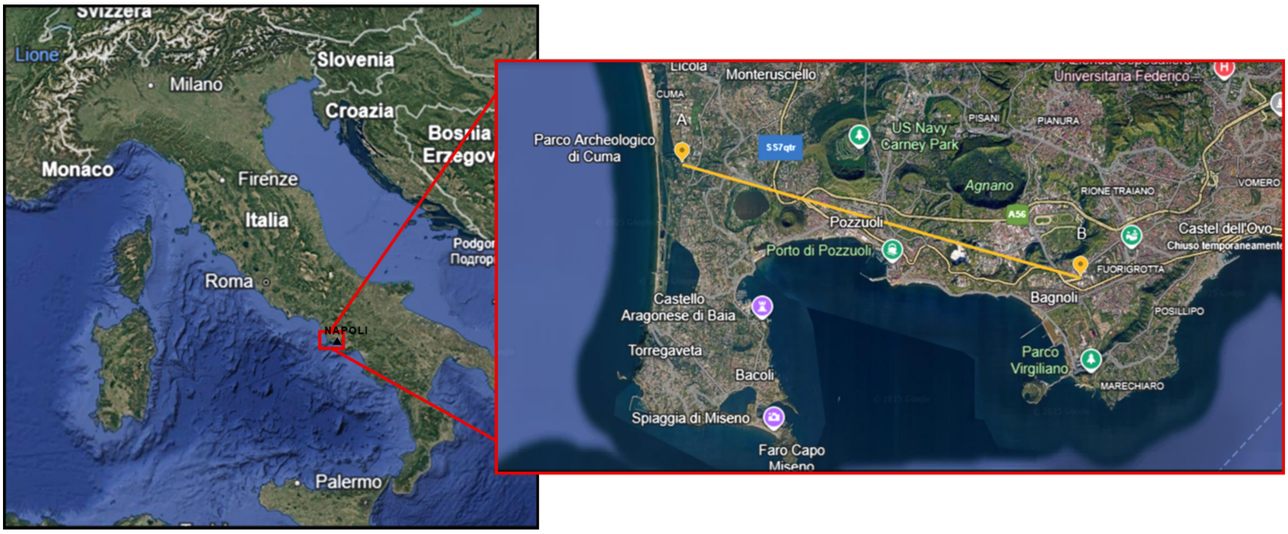

Fig.1 – DERT profile in the Campi Flegrei volcanic area.

References

Finizola, A. Revil, E. Rizzo, S. Piscitelli, T. Ricci, J. Morin, B. Angeletti, L. Mocochain, and F. Sortino (2006). Hydrogeological insights at Stromboli volcano (Italy) from geoelectrical, temperature, and CO2 soil degassing investigations. Geophysical Research Letters, vol. 33, l17304, 2006

Rizzo E., Colella, A., Lapenna, V. and Piscitelli, S. (2004). “High-resolution images of the fault controlled High Agri Valley basin (Southern Italy) with deep and shallow Electrical Resistivity Tomographies”. Physics and Chemistry of the Earth, 29, 321-327

Rizzo E., V. Giampaolo, L. Capozzoli, G. De Martino, G., Romano, A. Santilano, A. Manzella (2022). 3D deep geoelectrical exploration in the Larderello geothermal sites (Italy), Physics of the Earth and Planetary Interiors, volume 329-330, 106906 doi: https://doi.org/10.1016/j.pepi.2022.106906

Corresponding author: Enzo Rizzo enzo.rizzo@unife.it