GNGTS 2024

APPLIED GEOPHYSICS FOR ENERGY, ENVIRONMENT AND NEW TECHNOLOGIES

Session 3.1

Energy transition and resources

Convenors of the session:
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Contributions recommended for this session:

- **Innovative geophysical technologies;**
- **Integration of geophysical methods;**
- **Petrophysical characterization of the subsurface;**
- **Geophysical data processing;**
- **Geophysical borehole logging;**
- **Geophysics to characterize georesources (i.e., Oil & gas, mining, geothermal, water);**
- **Geophysics for reaching the net zero carbon (i.e., CCS, hydrogen storage);**
- **Artificial intelligence techniques applied to Geophysics;**
- **Natural Hazard;**
- **Case studies.**

Geophysical prospecting is widely used to both identify and store natural resources underground.
Different investigation techniques characterize the subsurface with different resolutions and at
different depths, such as reflection and refraction seismic, gravimetric, magnetic, electrical methods.
These technologies and tools also contribute to the mix of strategies to address anthropogenic CO2 emissions and to achieve net-zero carbon emissions goals.
The session welcomes contributions that illustrate methodological innovations, processing methods, case studies and applications in the fields of exploration of georesources, as well as in the field of resource and greenhouse gas storage.

Sustainable geothermal energy for two Southern Italy regions: geophysical resource evaluation and public awareness

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The deployment and sustainable use of Italy's geothermal resources could represent a key asset to increase renewable energy production and reduce greenhouse gas emissions in the coming years. The primary benefits of geothermal energy generation and geothermal heating and cooling are that the sources are local, adaptable, and resistant to the price volatility that impacts fossil fuels. Furthermore, they are renewable energy sources that allow for energy mix diversification, resulting in less energy dependency and higher supply security. As a result, geothermal energy is a realistic choice and an urgent cure for reducing Italy's reliance on the import of fossil energy resources and improving energy efficiency in building air conditioning and the execution of numerous industrial operations. Finally, recent studies have shown that high- to low-enthalpy fluids could represent an unconventional source of lithium, a critical material for the energy transition (Dini et al., 2022).

In this setting, there is an obvious need for programs to improve subsurface geothermal resource extraction while maintaining environmental sustainability. These designs need knowledge of the subsurface, which, owing to its complexity, renders traditional diagnostics ineffective. Assessing the potential exploitation requires knowing the type of geothermal system, the likely temperature and characteristics of the reservoir rocks and fluids. The volumetric or stored heat method (White and Williams, 1975) and its revised versions are the most widely used tools for quantifying geothermal resource capacity. However, these methods suffer from several major uncertainties depending on reservoir temperature, porosity, saturation, and resource size (volume) (Ciriaco et al., 2020).

To reduce these uncertainties, it is possible to estimate these parameters by adopting geophysical methods. Electrical and electromagnetic ones, such as Magnetotelluric (MT) and deep electrical resistivity tomography (DERT), 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., 2008; Rizzo et al., 2022). Local earthquake tomography (LET) 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), while ambient noise tomography (ANT) is widely adopted in shallower geothermal settings (Toledo et al., 2020). The VP and VS parameters result in being mainly sensitive to lithology changes, whereas their ratio (VP/VS) provides precious hints on the fluid composition and its pore pressure Mavko et al. (2009). Finally, the anelastic parameters, described by the quality factor Q, strictly depend on some rheological properties like the temperature and the percentage of fluid saturation in rocks, key factors in the investigation of occurring subsurface geothermal processes (Chiarabba, 2021).

Social and environmental considerations are important in the long-term utilization of geothermal energy resources. Recently, the procedures of assessing and mitigating the environmental impact of energy exploitation have included the engagement of the local community to avoid any potential environmental dispute. The increased attention of public opinion to issues of environmental sustainability and ecology in general has favored the emergence of both greater sensitivity and a risk-predictive culture over time, enhancing the conflict between fears about human health risks and scientific knowledge beliefs. In this regard, geothermal energy, for example, is frequently not presented as a renewable energy source (Benighaus and Bleicher, 2019). This implies that planning procedures must be distinguished by the pursuit of common solutions via an appropriate assessment technique.

In this study we propose a novel geophysical multi-messenger technique, which provides unique and useful insights into the features and activities of examined geothermal reservoirs. These findings stem from the complementary information carried by subsoil electrical resistivity and elastic/anelastic characteristics related to fluid presence. The proposed method will be tested in two test regions in Southern Italy that are appropriate for low to medium-enthalpy geothermal extraction. The initiative is specifically focused on field investigations in: 2) Contursi Terme (Campania) and Tramutola (Basilicata). Contursi Terme is one of the most appreciated thermal sites in the whole Campania region. Here, 77 springs with temperatures ranging from 21°C to 30°C are present, furthermore, 72 shallower and deeper wells for the pumping of hot waters with temperatures ranging from 38°C to 43°C are used for balneotherapy (Celico P. et al 1979). The Tramutola test site is located on the western side of the Agri Valley which is home to Europe's biggest onshore hydrocarbon reserve. During the drilling of the "Tramutola2" well (404.4 m) in 1936, a significant volume of sulphureous hypothermal water (28 °C with a flow rate of 10 l/s) with accompanying gases (mostly CH_4 and CO_2) was discovered (Cazzini, 2018).

At the same time, we propose appropriate communication strategies in order to contribute to the acceptance of geothermal energy sources based on its raising awareness and direct involvement of stakeholders on the studied territories.

Acknowledgements

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The European project SUCCEED for coupling Geothermal Energy and CCUS: innovative monitoring technologies by active-source seismic data acquisition

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Geothermal energy is a natural and renewable energy source, but geothermal power production generates greenhouse gas (GHG) emissions, in particular CO_2. Some studies estimated that the GHG emission from geothermal power plant can be higher than 1000 g/kWh (Fridriksson et al., 2017).

In the view of reducing CO_2 emissions from geothermal power plants, for climate change mitigation (carbon capture utilization and storage - CCUS) purposes, the Synergetic Utilisation of CO_2 Storage Coupled with Geothermal Energy Deployment (SUCCEED) ACT project (2019-2023) aims to prove the feasibility of re-injecting the emitted CO_2 into the same geothermal system to improve its performance and in the meanwhile to permanently storage the CO_2 by mineralization.

The project investigated two different existing geothermal power plants, one is the Kizildere geothermal field, located in the East of Büyük Menderes graben in Western Anatolia, Turkey, the other is the Hellisheiði geothermal field, in Iceland. Here we present the work done for the geophysical monitoring and the results achieved at the Hellisheiði geothermal field.

In the framework of the project, our research focused on the development of innovative reservoir-monitoring technologies at the Hellisheiði geothermal field, an active geothermal power plant located in the southern part of the Hengill volcanic system in the southwestern Iceland, close to the city of Reykjavik. The Hengill volcanic system is constituted by a central volcano and a fissure swarm with a graben structure that extends to the northeast and southwest and it is located at the junction of Reykjanes Volcanic Belt (RVB), the Western Volcanic Zone (WVZ) and the South Iceland Seismic Zone (SISZ) (Jóhannesson and Sæmundsson, 1998).

The Hellisheiði geothermal field has a temperature higher than 300°C at a depth of 1000 m below sea level and the steam combined heat and power plant is one of the biggest in the world with an installed production capacity of 303 MWe and 210 MWh of energy. The CO_2 is added to the re-injected geothermal fluid as dissolved gas. The monitoring experiment consisted in a baseline survey and a time lapse survey after a long-lasting, continuative (a few months) injection of CO_2. The monitoring is performed by active-source seismic data acquisition using a novel electric seismic vibrator source (E-Vibe) and permanently installed Helically Wound Cable (HWC) fibre-optic distributed acoustic sensors (DAS) in shallow trenches. We present the resulting time-stacked section from the baseline HWC DAS acquisition (July 2021) to investigate the complex basaltic system prior the CO_2 injection. At the same time, two co-linear acquisitions have been done with two- and three-components geophones to validate the results from the baseline HWC DAS system. The results showed a good consistency in the reflected events and helped to define the reservoir where we expect the injected CO_2 to be stored (Bellezza et al., 2023, under revision). We also show the preliminary results from the time-lapse acquisition acquired by the only HWC DAS system (June 2022) to highlight the variation in the reflected events after the injection of the CO_2.

Acknowledgements

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Salt domes modelling through magnetic data: an unconventional tool for challenging scenarios

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We demonstrate that the analysis of magnetic data in salt basins could often represent a fundamental tool. The analysis was carried out on the data of a deep-water area in the Eastern Mediterranean, offshore Egypt. The reduced to pole (RTP) magnetic anomalies were filtered for the regional-residual separation with the discrete wavelet transform (DWT). The resulting magnetic anomalies were interpreted as generated by the contrast between the salt bodies and the surrounding sedimentary layers. We extracted many lineaments representative of the salt bodies from the multiscale boundary analysis of the produced anomalies. Moreover, we inverted the data using a 3D non-linear non-iterative inversion technique jointly with Euler deconvolution. This procedure has led to an interesting salt map, which is by the fact exclusively based on magnetic data. This result agrees well with the seismic interpretation of the top of the salt. This is a not obvious result, which demonstrates an advantageous and low-cost use of magnetic surveys for the exploration of salt basins, especially when seismic data are inaccessible or suffer of possible pitfalls in such scenarios.

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Monitoring and No-Money-toring of Oil & Gas exploitation in Italy

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The Val d'Agri basin (VA) is a Quaternary extensional basin bounded by two parallel and oppositely dipping normal fault systems. A M~7 earthquake that struck the VA in 1857 testifies the high seismic hazard of the region. The VA basin hosts the largest on-shore oil field in on-shore Europe, producing hydrocarbon since the 1990s from a high-productive reservoir consisting of fractured, low-porosity Cretaceous limestones from production wells drilled at 2 to 3 km depth below sea level (Buttinelli et al., 2016).

The ENI petroleum company is the main concessionaire in VA, operating 25 productive wells located between the eastern side of the basin and the eastern ridge, and reaching production rates around 90000 oil barrels/day. Since 2002, the operator installed a local seismic network to monitor the seismicity of the area and to study the potential influence of industrial activities on it. On 2014, the Italian Government decided to assign the monitoring duties to an independent external consultant (Struttura Preposta al Monitoraggio, SPM, in Italian) and published experimental guidelines (ILG) (Dialuce et al., 2014) describing the recommendations to be followed for the geophysical monitoring of hydrocarbon production, waste-water injection and gas storage.

Only in the case of the injection of incompressible fluids, the ILG propose the application of a Traffic Light System that defines a response scheme when seismic parameters exceed specific thresholds. Parameters like Peak Ground Velocity (PGV), Peak Ground Acceleration (PGA) and magnitude (ML) must be monitored when hypocentres are located within a defined spatial domain around the injection well. (Braun et al., 2020).

In 2017, the Italian Ministry for Economic Development commissioned INGV to act as monitoring agency (SPM) for the VA concession for exploiting hydrocarbons. In the standard operation mode, the SPM is responsible for monitoring seismic parameters in near-real time, and analysing them in conjunction with ground deformation (GPS and INSAR) and pore pressure fluctuations on a biannual basis. The ILG define the monitoring domains (Figure 1): an Extended (DE) and an Internal Domain (DI) based on the border of the Oil-Water contact of the reservoir, as well as a Reference Domain (DR), a cylindrical volume with a radius of 5 km along waste-water reinjection well Costa Molina 2 (CM2). Important to note that the Traffic Light Protocol only applies to the DR (Braun and Danesi, 2022).

Wastewater associated with oil production has been re-injected into the CM2 well, an unproductive marginal section of the carbonate reservoir, from 2890m to 3096m depth (well bottom) since June 2006. The variable injection rates have reached maximum values of 2800–3000 m^3/d (normal 2000 m^3/d), while the well-head pressure has never exceeded 13–14 MPa. CM2 can be classified as a long-term, high-rate disposal well (e.g., Stabile et al. 2014, Improta et al., 2015).

The two-year experimental period of the ILG came to an end in the middle of the COVID-19 pandemic in April 2021, and for the sake of simplicity it was extended for a further 12 months. Due to an unfavourable superposition of individual administrative difficulties by the involved public administrations, the originally common target of a straight and uninterrupted transition from the experimentation to the application of the ILG, could not be realized. This led to a contractual and financial discontinuity for a period of more than 20 months, which will now probably end with the signing of a long-term agreement between the different parties.

Mother nature does not mind if monitoring agreements are active! … and sometimes earthquakes may also occur during times, when monitoring is not adequately covered by fundings. The question rises whether monitoring should continue anyway, or should rather follow the economic availability? with other words: "In case that financing funds may temporarily thrust out should the SPM still continue monitoring?". This is the inauspicious circumstance, when "No-Money-toring" starts.

Without deepening this issue, INGV decided, however, to continue the monitoring activity; a decision that turned out to be useful, due to a non-neglectable seismic activity, occurring during 2023 (Figure 2). Our contribution will report about scientific and non-scientific aspects experienced during Monitoring and No-Money-toring phase of the VA project.

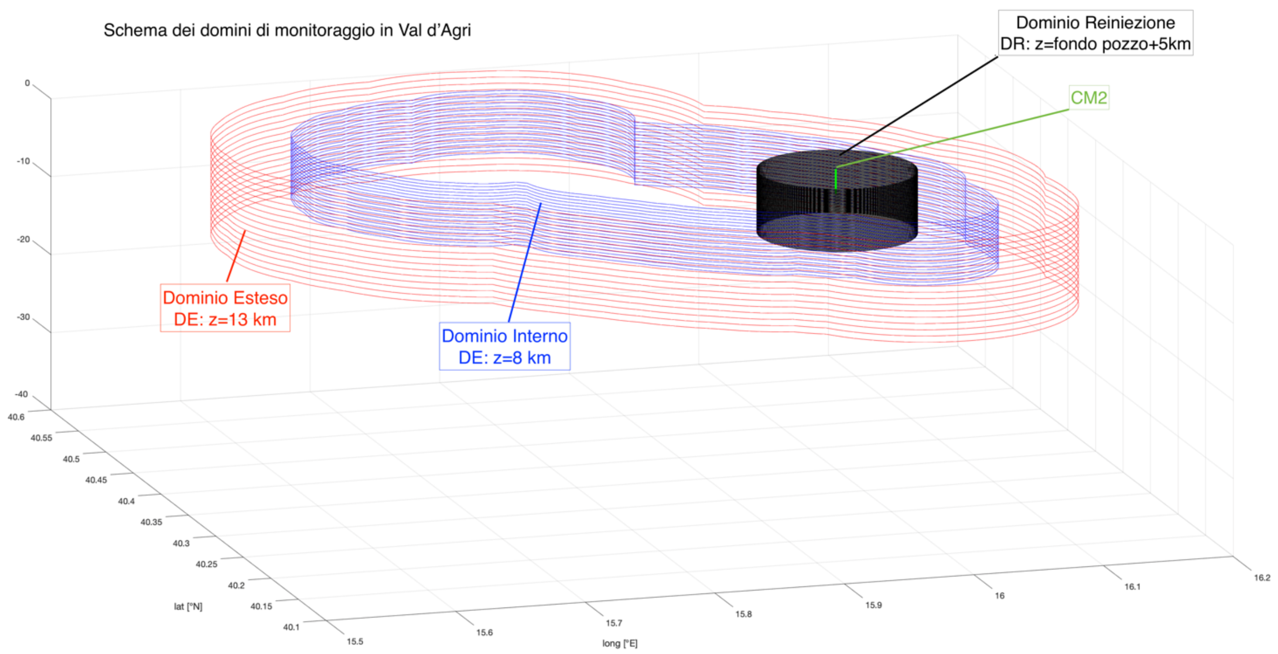

Fig. 1 – Monitoring domains DE, DI and DR defined for the monitoring of the hydrocarbon exploitation in VA (after Danesi et al., 2021)

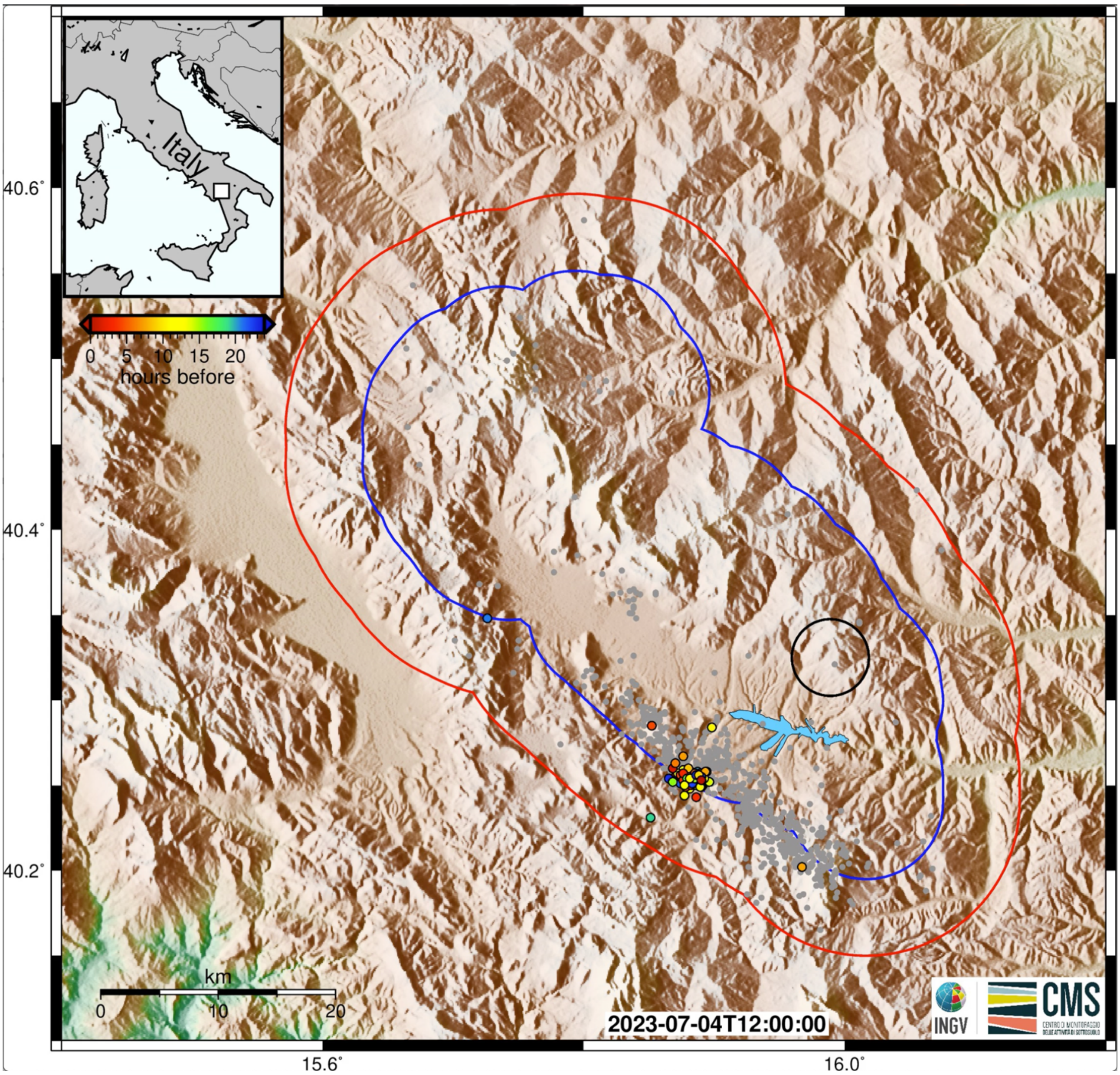

Fig. 2 – Example screenshot of the seismic activity in VA recorded in 2023 by INGV.

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Comparison and calibration of Traffic Light Protocols applied in different countries, in the framework of the ENSURE-project

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Innovative strategies for risk reduction are feasible in the context of induced seismicity, as it is possible to manage risk through hazard control, in contrast with standard seismic risk mitigation that considers only vulnerability and exposure (Bommer et al., 2006). Traffic Light Protocols have been proposed to determine the risk level condition associated with induced seismicity, with the goal of reducing or stopping industrial operations in case it reaches an unacceptable level. The protocol also includes restarting operations once the situation is deemed safe on the basis of quantitative criteria (Figure 1). Country specific regulations defined by national laws and different types of operation have led to specific TLPs customized for the different anthropogenic activities, as e.g., proposed by (Bommer et al., 2006; Zoback, 2012; Grigoli et al, 2017; Bohnhoff et al., 2018; Baisch et al., 2019; Braun et al., 2023). In the first instance, TLPs are used to classify monitoring results ad report them to the authorities according to a "communication scheme". Sometimes, TLPs serve as "reaction scheme", to take action in respect of the operations and reduce or interrupt, and eventually restart anthropogenic activities.

With regard to Italy, the Ministry of Economic Development proposed "Guidelines for the monitoring of seismicity, soil deformation, and pore pressure in relation to anthropic activities" (Dialuce et al., 2014; Braun et al., 2020), to be applied for the monitoring in Italy of artificial water basins, mining drilling (caves, mines, hydrocarbons), tunnel excavations, methane gas and CO_2 storage. The ILG describe standards for monitoring relevant geophysical observables; outline roles and responsibilities of the different actors involved in monitoring activities; define procedures to be followed in case of significant changes of the monitored parameters, propose a decision-making model based on the exceeding of predetermined thresholds, a so-called traffic light protocol (TLP). The TLP becomes exclusively applied in case of reinjection of incompressible fluids (production waste waters, but not methane or CO_2).

For concessions of national competence, the ILG define the constitution of a "Committee", composed by the Ministry representatives on a national level (DGS-UNMIG), the regional government, the industrial operator and the monitoring agency (in Italian: Struttura Preposta al Monitoraggio SPM). The role of the Committee is to manage the monitoring of a concession, on the basis of the monitoring recommendations. The primary SPM's task is to calculate hypocentral coordinates of seismic events and discriminate whether they are within previously defined monitoring volumes (spatial threshold). For events that meet the specified criteria, the SPM computes the seismic parameters Magnitude, PGV (Peak Ground Velocity), and PGA (Peak Ground Acceleration), determines if any of these parameters exceed the thresholds established in the TLP (parametric threshold), and reports the outcome to the committee (==> communication process). On the basis of the SPM's analyses, three of the committee members (UNMIG, Region, Concessionaire) are then responsible for deciding on the type of intervention to be applied, classified as “Ordinary” (green), ”Attention” (yellow), “Reduction” (orange) or “Suspension” (red) of the industrial activities (==> reaction scheme). The definition of the intervention measure is a political decision, based on the SPM's technical assessment.

The project “Effective moNitoring of long-term site Stability for transparent carbon captUre and storage hazaRd assEssment” (ENSURE) aims to (i) identify common traits between seismicity occurring in different settings with respect to calibrate TLPs, (ii) correlate seismological with reservoir engineering parameters, (iii) compare results to existing TLPs from other industrial monitoring systems. As a deliverable it is planned to propose an evaluation of monitoring parameters (as e.g., M, PGV, PGA, Hypo) and their uncertainties for a conversion into effective TLPs- threshold values, especially for the case of Carbon Capture and Storage (CCS). As CCS will be introduced soon also in Italy, and based on the experiences of INGV as SPM during the experimental monitoring phase of pilot concessions, a revision of the ILG is absolutely essential. We will present the preliminary analyses achieved in the framework of ENSURE, which give important indications for calibrating also the national TLPs, effective for 10 years.

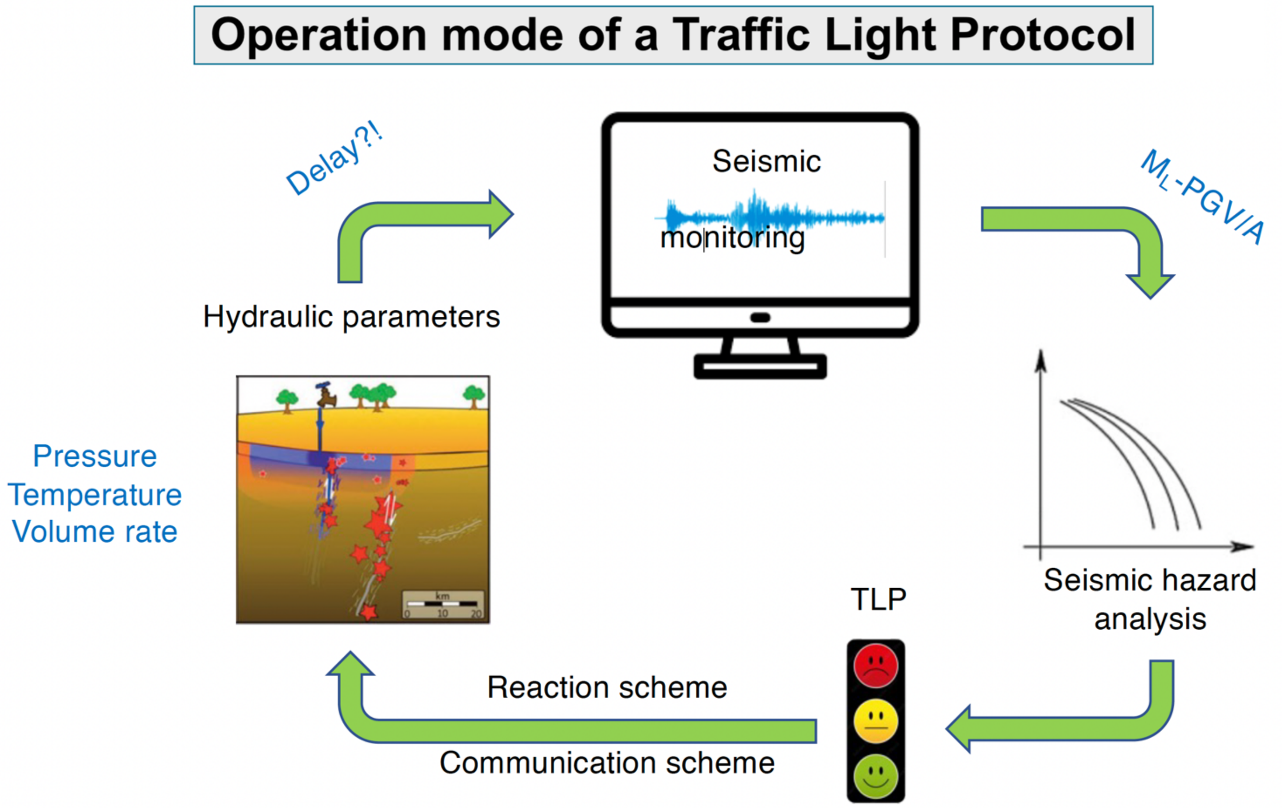

Fig. 1 – Operation principle of a Traffic Light Protocol

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The MARE (MARine Energy) project Assessment of energy production potential from marine waves and currents: a case study from Aegadian archipelago

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Introduction
World energy consumption will grow considerably in the next decades, as well as that of the European Union. At the same time, the Member States' awareness that traditional energy production seriously contributes to environmental pollution, making the need for a non-polluting generation of energy. As part of the technological evolution of renewable energy, the marine energy is emerging. In fact, this source arouses growing interest from governments and industries, despite being relatively new, and with non-competitive costs such as wind power.

An important characteristic of the sea is that it has the highest energy density of all renewable sources. The most important advantages are the high availability and high predictability of the resource, while the technology is characterized by a low visual impact and no CO2 emissions. Marine waves and currents can thus contribute to a renewable energy mix to help curb the current dependence on fossil fuels. Italy has a geographical position that allows exploitation of different sources of renewable energy; among these sources, the sea should have a prominent role due to the large amount of Italian coastline.

After more than thirty years confined to academic research, the progress of marine energy has reached an almost mature stage, presenting itself as a potential industry for the future. The sea contains an enormous amount of energy, which theoretically can be exploited by man for his own energy needs. It is present in several forms, including tides, surface waves, currents, the thermal gradient and the salinity gradient. We refer to kinetic energy with regard to tidal currents or sea currents, which are moved by gravitational forces, while the waves of the sea, pushed by the wind, derive indirectly from solar energy . All these different forms can be used for the generation of electricity, through the use of the most modern technologies.

The estimated global potential resource for each of these sources is as follows:

- Wave energy 80000 TWh/year,
- Tidal energy > 300 TWh/year,
- Current 800 TWh/year,
- Salinity gradient 2000 TWh/year,
- Thermal gradient 10000 Twh/year.

The idea of converting surface wave energy into useful forms of energy is not a recent one. The first patent, known for using the energy of sea, dates back to 1799, and was filed in Paris by Girard and his son. Recently, following the problems of climate change, a new interest in renewable energy has grown around the world and the scientific community examined the potential for generating electricity from the sea.

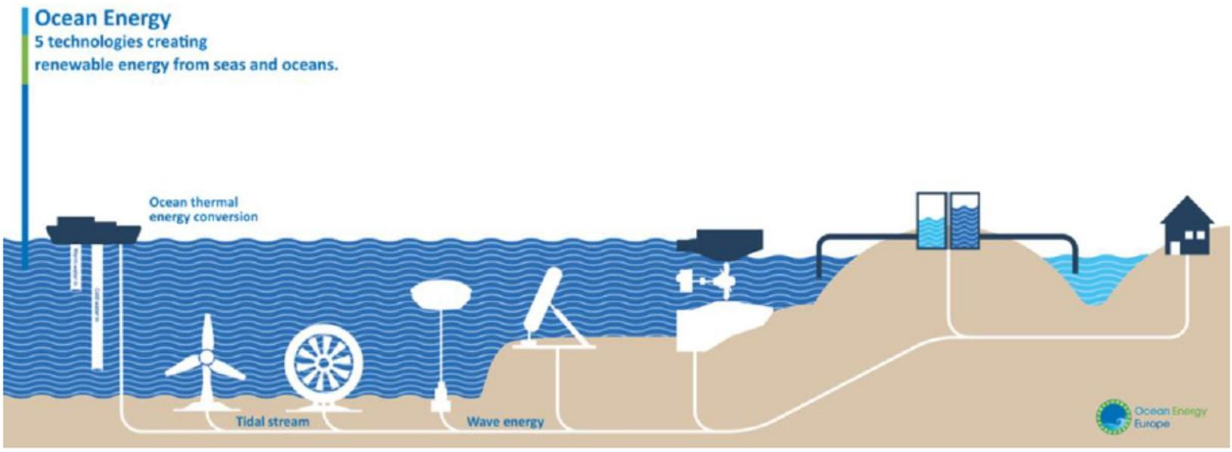

Fig. 1 – Different types of technologies for the exploitation of marine energy (Energy, 2017).

A large number of technologies (Fig. 1) have been developed for the exploitation of sea energy. More than a thousand patents have been registered around the world, but none of these technologies has yet established itself as the dominant one. The most used parameters to distinguish the different technologies are: the position with respect to the coast, the principle of operation and the power take-off system. A detailed description of the technologies currently available is outside the topics of interest; therefore, reference should be made to the available scientific literature.

Many are the projects dedicated to marine energy that have been funded and implemented in Europe like: Pico, Lysekil Project, European Marine Energy Centre, DanWEC Hanstholm, Wave Hub, Yongsoo, Bimep, Oosterschelde Tidal Project, Belmullet, Santoña wave farm, FlanSea Project, Pilot Zone, Perth Wave Energy Project, Limpet, Mutriku, Aguçadoura, Bernera, Aegir, Lewis Wave Energy Farm, Reedsport OPT Wave Park, Coos Bay OPT Wave Park. Some of these led to the creation of wave farms in Italy like: Iswec (La Spezia, Alghero and Pantelleria), SouthEnergy (Tuscan Archipelago, Punta Righini - Castiglioncello) and Rewec (several italian ports).

Recently, atlases of wave energy of the Italian coasts have been developed, using wave parameters measured by buoys positioned off the coast (ENEA, 2011). Wave buoys provide accurate and direct measurements of wave parameters. However, the time series obtained from the buoys describe swell climates only locally, and often have large data gaps caused by temporary buoy failures, or by maintenance operations routine. Wave height and period do not generally show high spatial gradients in the open ocean, but substantial spatial variations are observed in enclosed seas, where ground obstacles strongly influence wave generation and propagation. We can therefore conclude that at the moment, an accurate and detailed estimate of wave energy of the Italian seas is not yet available.

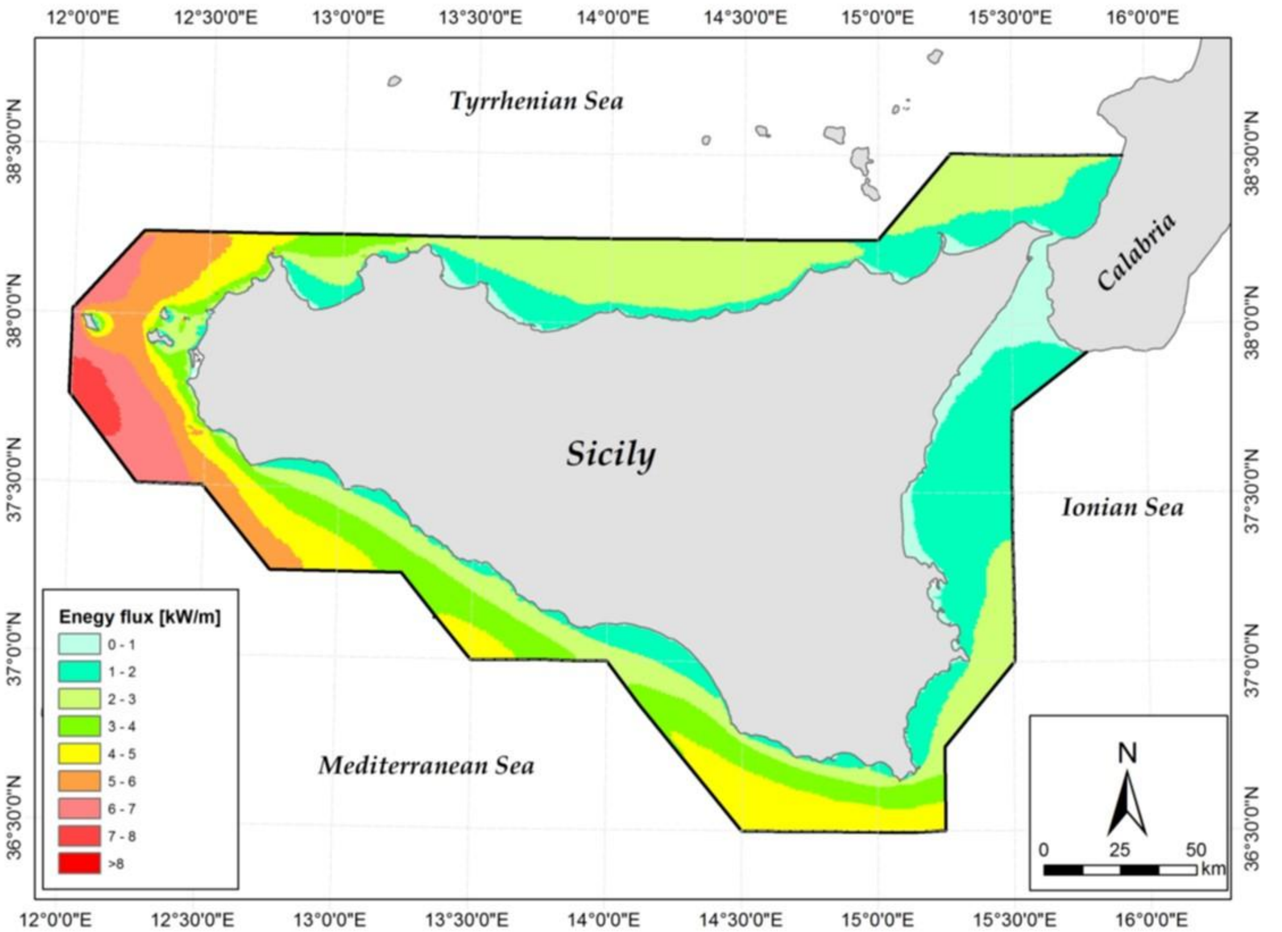

Fig. 2 – Distribution of the average wave energy flux per unit crest length within the computational domain (from Iuppa et al., 2015).

The MARE (MARine Energy project), funded in the framework of PRIN PNRR, arises from the premise that for the energy production from marine sources, becoming an important piece in the mosaic of renewable energies, the available resource must be well assessed, in order to demonstrate the real productive possibilities and attract investors. The activity presents the potential tools identified for the definition of a methodology capable of determining the potential of energy producibility from sea waves and marine current along the territorial waters of the Aegadian Archipelago.

As regards energy supply, most of the Minor Islands are not interconnected to the National Transmission Grid (NTG) being managed by small vertically integrated electricity companies and 8 are managed by ENEL Produzione. The production plants are currently made up of diesel units, whose overall power is always oversized to ensure the quality and continuity of the service. The supply of fuel takes place with tankers, with inevitable associated environmental risks, (pollution, greenhouse emissions, etc).

To assess the potential for the marine energy it is opportune to employ the most suitable methodologies for the analysis of such a particularly complex system. The MARE project aims to contribute to the necessary knowledge so that the energy production from marine waves and currents may become a real resource for small islands. The Aegadian archipelago is proposed as a case study.

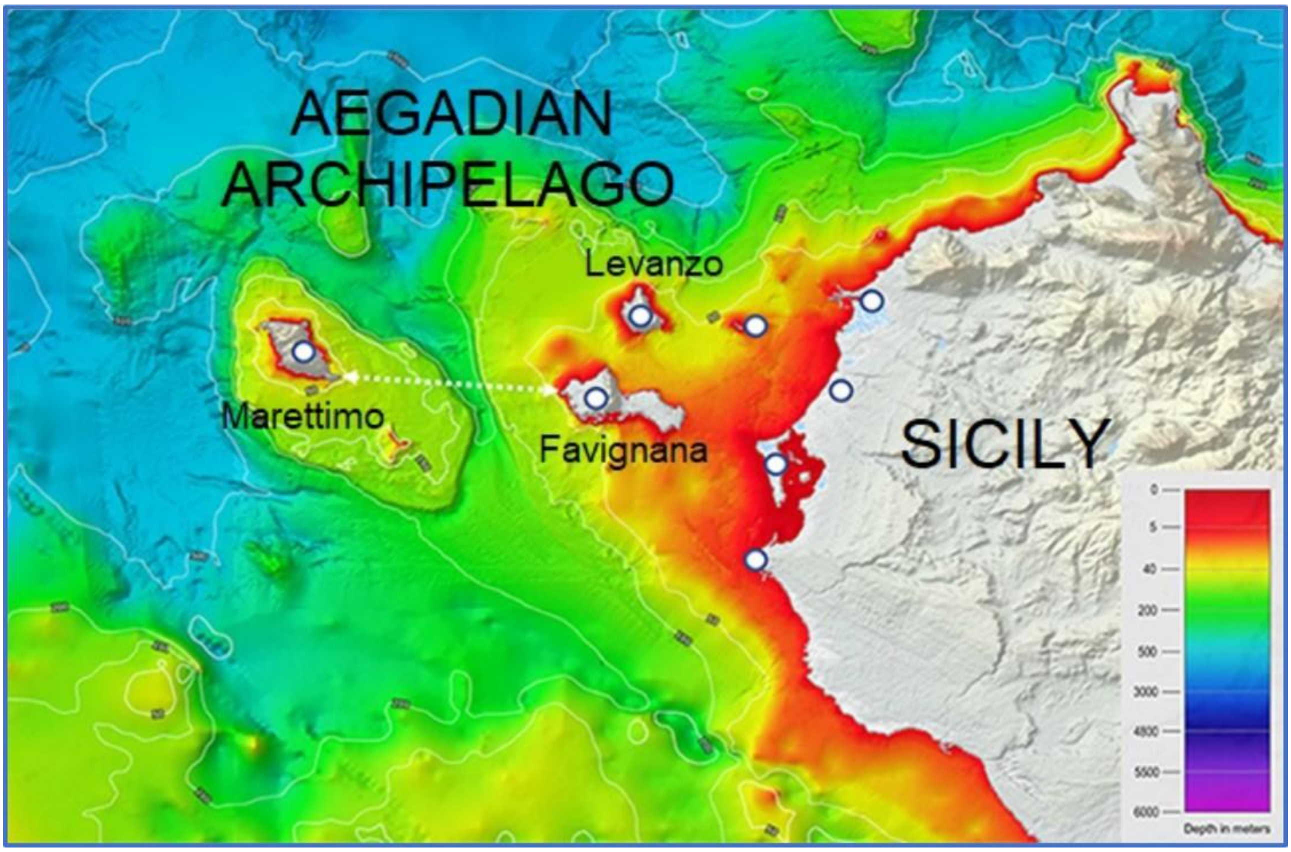

Fig. 3 – Bathymetric map of the study area.

The Aegadian Archipelago is composed of the islands of Favignana, Levanzo and Marettimo and it is located off the -western coast of Sicily. The population of the whole archipelago is not distributed equally, Favignana is the larger island (37 km2) with 3,407 inhabitants, Marettimo (12 km^2) has 648 inhabitants, while Levanzo (6 km^2) is the smallest of the three with 208 inhabitants. Favignana, Levanzo and Marettimo are not interconnected with the mainland and neither among themselves, each Island has a local Distribution System Operators that provides electric energy using diesel plants. In the last years, the Municipality of Favignana has strongly pushed several clean energy-oriented projects. At present, the whole archipelago hosts only about 300 kW of photovoltaic power, since the regional regulatory framework forbids the establishment of any wind power plants.

Wave energy atlases are based on measurements from buoys, satellite observations and from models. In recent years, several authors have presented global wave energy atlases. These works do not include observations from the Mediterranean Sea; rather they are based on models, with a spatial resolution too coarse, to be able to distinguish, on a smaller scale, the spatial variations of the availability of wave energy. These details are important to identify suitable sites for the production of electricity in relatively small basins like the Mediterranean, and especially for minor islands.

Generally speaking, islands are the ideal laboratory of sustainability and they are today, all over the world, in a dimension of great interest where ambition and concreteness are combined. The challenge is to make the smaller Italian islands a vanguard in the world in the dissemination of innovative and economically sustainable solutions on energy and water, in the circular economy and sustainable mobility. A perspective that, as the international experiences, can help to revive the economy and attract tourism to the islands because it preserves these unique ecosystems, making them attractive precisely for their landscape and environmental qualities (Legambiente, 2018).

Previous studies have shown that wave farms could be implemented at some sites. For example, Vicinanza et al. (2011) reported the offshore wave energy potentials of the Italian seas. The results highlighted that the west coasts of Sicily are the most energetic among the Italian coasts. Indeed, the highest energy values were obtained for the buoys of Mazara del Vallo, which corresponded to 4.75kWm-1. Fig. 2 shows the average wave energy of the Sicilia coasts (Iuppa et al., 2015a). The average wave energy has a not negligible spatial variability even over distances of the order of 20km. This variability cannot be adequately described by local buoy measurements, or by models with a lower spatial resolution. The average power is a useful parameter to identify promising areas for the production of wave energy, its value however is presented as a contribution of the individual states of the sea, distributed over a range of wave heights, periods and directions. On the west coast of Sicily, the average power flow is between 5 and 6 kW/m, which increases gradually, up to average value of 6 kW/m, in the Aegadian Archipelago (Iuppa et al., 2015a,b). The Aegadian islands are among the most productive in the Mediterranean Sea and surely the most promising of the Italy.

The MARE project focused on two main lines:

- The collection, organization and analysis of available environmental data, with particular reference to those strictly related to the studied problem;

- The identification, on the basis of geological, geophysical and geochemical investigation of the potential for energy production of the highlighted case of study.

And includes the following types of surveys in the Aegadian Archipelago and surroundings:

- bathymetric surveys

- seismic microtremor investigations
- current meter surveys
- investigations of temperature and salinity parameters

For the following purposes:

- Assessment of Energy Production Potential from marine waves motion;
- Assessment of Energy Production Potential from marine currents.

The first main aim of the MARE project is to assess the marine wave motion in terms of amplitude, frequency and seasonal stability by exploiting an indirect method widely tested in the literature. Sea waves are among the important sources of seismic noise recorded by seismic stations.

The second main aim of the MARE project is to assess the current velocity characteristics at different depths and estimate their theoretical potential. The objective is to calculate the potential energy generated from streams at different depth layers and detect the optimal one.

The final objective of the project is the production of maps of marine energy potential indicators with different spatial resolution, from a few km to a few hundred meters for the case of study proposed that will be characterized by a significant energy potential. For the latter it will also be possible to evaluate the real amount of energy that can be extracted according to the different exploitation technologies that can be used.

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Airborne and Ground IP: an integrated approach for exploration

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Introduction

The Iberian Pyrite Belt (IPB) is one of the oldest and still active mining districts in the world. In the last decade, a renewed mining activity and scientific research have led into a wealth of new data and new geological hints for explorers and for the academic community, making the IPB one of the most important and dynamic mining districts in Europe (Inverno et al, 2015). In this region, the great number of different signatures related to the ore body and to its vectors call for an integrated use of complementary geophysical methods. The sulfides targets show contrast in both density and electrical properties, and historically gravity has played a crucial role for exploring in the IPB. These methods have been later accompanied by EM methodologies, both airborne and ground, given their high sensitivity to conductive targets (Menghini et al, 2022).

With this contribution we will focus on an application of a novel modelling approach that aims to properly extract the Induced Polarization (AIP) effects from the Airborne Electromagnetic (AEM) data. The AEM survey has been acquired in the IPB for mineral exploration to localize the VMS deposit. After the AIP modelling, we will show a comparison between the airborne chargeability and some overlapping ground IP models from the same area. This comparison aims to better understand the potential in the use of AIP for exploration and to attempt an improvement in the definition of the sensitivity field of the airborne technique, as well as its relationships with ground IP. Then, a joint inversion between the two methods will be presented.

Inductive Induced Polarization - theory and modelling

It is known and accepted that the Electromagnetic methods are sensitive to Induced Polarization effects (AIP) when acquired over a polarizable medium (Kratzer and Macnae, 2012; Viezzoli et al., 2013). From a physical point of view, the polarization processes generate currents in the ground (polarization currents) with an opposite direction respect to the pure EM currents (eddy currents) that proceed downward with a diffusive regime. These effects generate a distortion of the recorded electromagnetic signal which often culminate in its change of sign at late times when the halfspace is particularly polarizable. In general, the distortions generated from IP have two signatures in the EM data: a faster decay (respect to the purely resistive forward response) and/or negative voltages. Under these conditions, the standard EM modelling, which does not account for

polarization currents, ceases to be valid (Smith and Klein, 1996): the negative data cannot be fitted and the fast-decaying signals are modelled as strong resistors, generating artifacts.
To avoid the mis-modelling of EM-IP affected data, it is necessary to use a dispersive-resistivity model (such as the Cole & Cole one) to compute the forward response and considering the capacitive nature of the ground. This approach gives the opportunity to map, as well as the resistivity, the chargeability of the ground that is often related to significant economic (or signatures of) mineralization. At the same time, it complicates the inversion process adding three more parameters and expanding the model space generating equivalent domains. It follows that an appropriate parameters management during the inversion process is crucial to properly retrieve the ground description and to maximize the AIP sensitivity to geological and mineral targets.

Geophysical and geological description

The Airborne EM data have been acquired in spring 2022 with the NRG XCite Time Domain system, with a 25Hz base frequency, and the acquisition lines are illustrated in black lines in *figure 1*. In the same area, 18 Iris VIP 1000 (transmitter) lines (0.125Hz of base frequency, 50% duty cycle) of ground Time Domain DCIP have been acquired (red lines in figure 1).

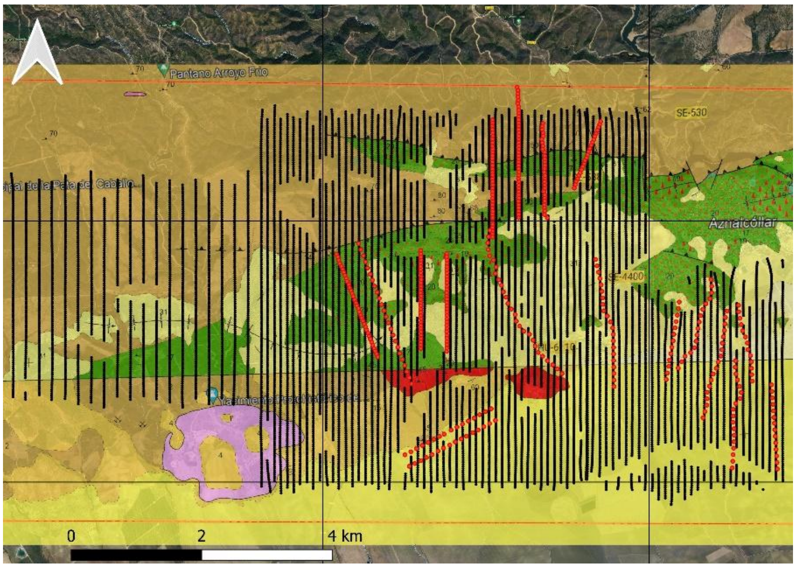

Figure 1. Survey location. In black the Airborne EM lines are displayed, in red the DCIP.

In the base map of *figure 1* the local geology is shown. Two main domains are visible: a volcanic intrusive one in the north, where Rhyolite and Dacite are presented in red and green, and a more recent sedimentary domain that covers the outcrop is in yellow in the southern area. The main tectonic features are represented in black and outcrops in the northernmost part of the investigated area.

Data modelling and inversion

Among the differences between Airborne and Ground IP, the most obvious are in the in footprint, depth of investigation and spectral content, with AEM data’s frequency bandwidth usually a couple

of orders of magnitudes higher than that of ground IP data. Beside these problems, another major issue, not always recognized, is the difference in the modelling approach. Ground IP data is usually modelled dropping the spectral information, e.g., turning a full secondary voltage decay into a single value of integral chargeability (e.g. Oldenburg and Li, 1994). Moreover, the effect of current waveform is often not modelled, resulting in inversion models in which the retrieved polarization magnitude strongly depends on the acquisition settings of the current waveform, making a quantitative comparison between AIP and Ground IP impossible (Olsson et al., 2019).
On the contrary, in this study we model the IP spectral content in both AIP and Ground IP data with the same modelling approach, in terms of data-preparation, model space management and inversion approach.
In particular, the galvanic data have been modelled in 2D in terms of full-voltage decay (instead of the integral chargeability), taking into account the transmitter waveform and the receiver transfer function (Fiandaca et al., 2012; Fiandaca et al., 2013; Bollino and Fiandaca, 2024). The inductive data have been modelled in 1D, and to reduce the model space and to enhance the spectral resolution, the frequency dependence and time constant parameters have been set to vary only horizontally (while resistivity and maximum phase change also with depth).
For both the methos, the Maximum Phase Angle (MPA) re-parametrization of the Cole & Cole model has been used (Fiandaca et al., 2018). In the MPA Cole-Cole model, the maximum phase φ_{max} of the complex conductivity and the phase relaxation time τ_φ are used instead of m_0 and τ_ρ (of the classic Cole & Cole model). The phase of the complex conductivity can be defined in terms of both *equations 1 and 2* as:

$$\varphi(\omega) = tg^{-1}\left(\frac{\sigma''(\omega)}{\sigma'(\omega)}\right) = -\,tg^{-1}\left(\frac{\rho''(\omega)}{\rho'(\omega)}\right) \qquad \text{(eq. 1)}$$

The phase reaches his maximum φ_{max} at an angular frequency $\omega \equiv 1/\tau_\varphi$ as:

$$\varphi_{max} = tg^{-1}\left(\frac{\sigma''(1/\tau_\varphi)}{\sigma'(1/\tau_\varphi)}\right) = tg^{-1}\left(\frac{\rho''(1/\tau_\varphi))}{\rho'(1/\tau_\varphi)}\right) \qquad \text{(eq. 2)}$$

Finally, the model space of the MPA Cole-Cole model can be written as:

$m_{MPA\ Cole\text{–}Cole} = \{\rho_0, \varphi_{max}, \tau_\varphi, C\}$

The MPA parametrisation replace the strongly-correlated parameters m_0 and C of the classic Cole-Cole model with the weakly-correlated parameters φ_{max} and C (Fiandaca et al., 2018), to improve the resolution retrieved from inversion IP data of the classical Cole-Cole model.
The inversions have been performed with the inversion with EEMverter (Fiandaca et al., 2024), following a modelling scheme that uses voxel model mesh to map the solved parameters via an interpolation of the forward mesh solutions. The decoupling of the model mesh and the forward mesh allows to work with more flexible and manageable spaces (forward and model) to perform joint inversions and time laps inversions. In our inversion procedure, in order to increase the parametrical resolution and the phase sensitivity in depth, we parametrized the spectral parameters (τ_φ, C) on an independent mesh respect to resistivity and phase, with different lateral constraints and vertically fixed (as proposed by Viezzoli and Fiandaca in 2021).

Results

In *figure 2a* and *2b* the results are shown, with a comparison between a portion of the airborne and the ground DCIP modelled chargeability (phase) with our modelling approach.

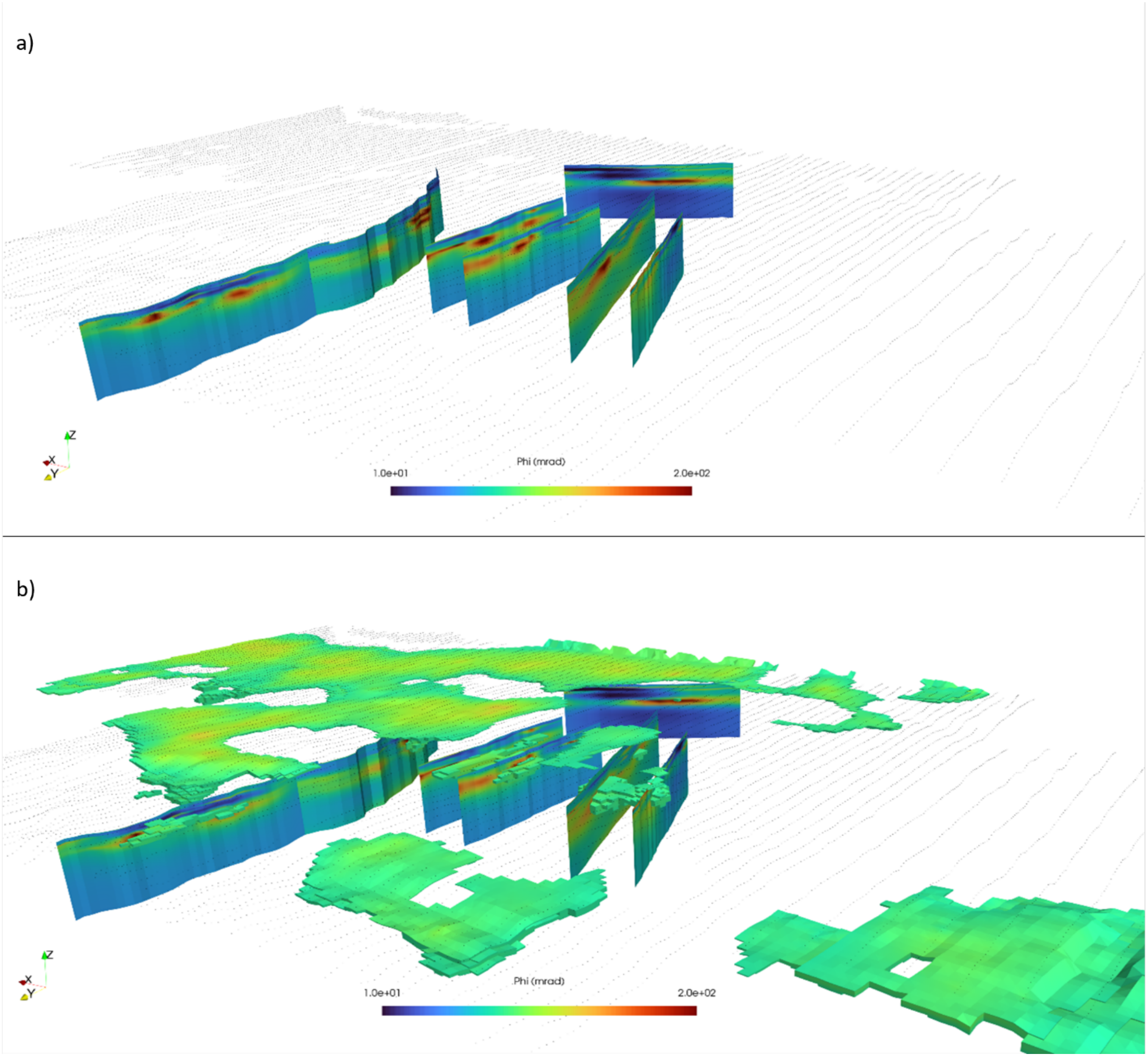

Figure 2. a) Example of ground DCIP phase results and, in dashed line, the AEM survey flown above; b) Partial Ground DCIP vs Airborne IP phase results

As visible from the figures, a great correlation between the airborne and ground is obtained when modelling with the presented approach. The airborne chargeability model shows a consistent structure with the ground model in depth and a geology-controlled behaviour in the shallower near surface. A known mineralization has also been mapped with the AIP. The differences in the near surface are a consequence of the big electric dipoles dimension used for the ground DCIP

(100m). For this dataset, all the airborne IP chargeability anomalies have been confirmed from the ground IP.

After this, we performed a joint inversion between all the ground DCIP lines (17) and the entire AEM survey. For the joint inversion we used the AEM model (for all the parameters) as starting model for the joint inversion. In *figure 3* the results are shown.

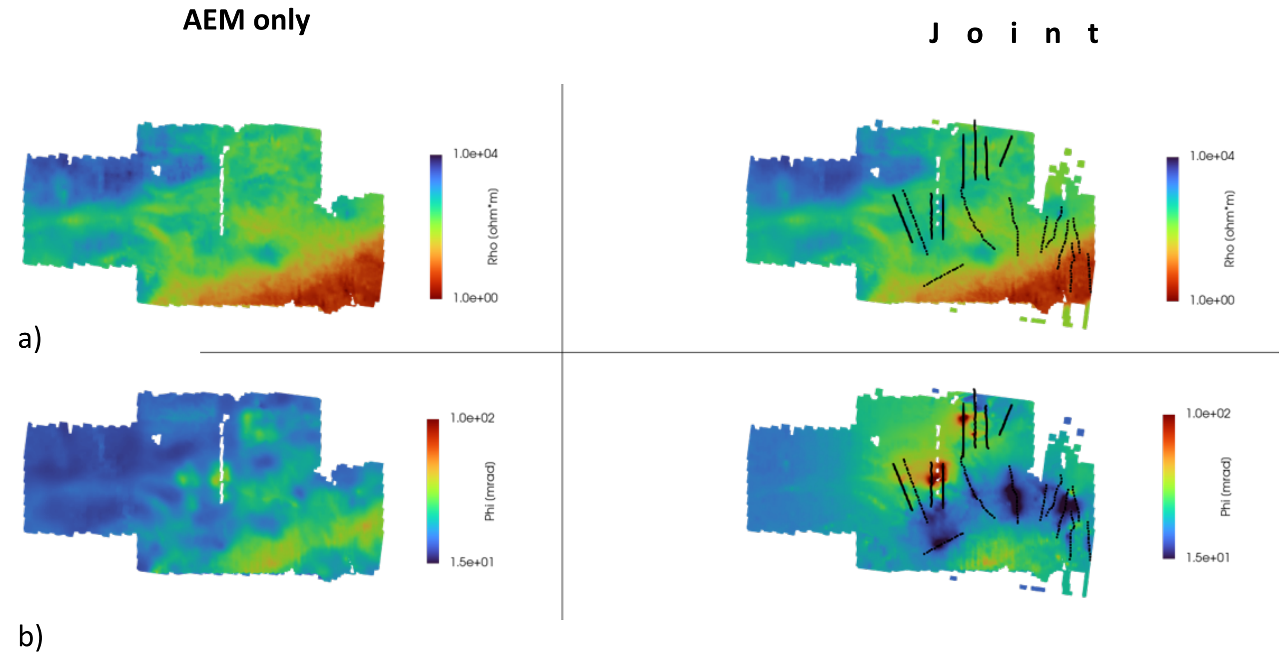

Figure 3. Comparison between AEM only model (on the left) and Joint Inversion model (on the right) for a slice at 60 m of depth. Figure 3a shows a comparison between the resistivities while figure 3b a comparison between chargeabilities.

In *figure 3a* a comparison between the AEM only and joint inversion resistivity is presented. As visible, the main structural are mantained in the inversions. Differently, in *figure 3b*, it appears that introducing the ground DCIP lines in the inversion add structure in the chargeability model for the entire survey area. In terms of misfit, the general misfit of the AEM only inversion is 1.6 while the misfit for the joint inversion is 1.7, confirming how the AEM data accept the jointly obtained chargeability model obtained together with the ground IP.

Conclusions

This study shows encouraging results in the using of the Airborne Induced Polarization for chargeability mapping for airborne-scale areas. In particular it results that:

- Reducing the equivalences in the AEM-IP modelling is a key to unlock the understanding of the AIP sensitivity to geological and mineral targets.
- For this case study, the airborne chargeability shown sensitivity to deep chargeable bodies.
- All of the airborne chargeability anomalies have been confirmed from the ground DCIP models, demonstrating an overlapping field of sensitivity between the methods.
- Known mineralizations have been mapped with the AIP.
- The joint inversion between the DCIP and the AIP is possible and shows how the AEM data not only is compatible with the joint model, but also contribute in the chargeability mapping.

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UAS photogrammetry analysis for coastal hazard assessment: the case study of Maronti landslide (Ischia, 2022)

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Continental and marine processes drive coastal areas' landscape changes. The morphoevolution results from both rapid catastrophic events and slower continuous processes such as landslides, storms, and coastal land use, influenced by sea actions. The cliff erosion rates are linked to geological features, including rock mass strength and fracture system properties. The assessment of erosion processes and quantification of coastal retreat are crucial for effective coastal planning and engineering mitigation (Callaghan et al., 2009). Various methods, including geological processes monitoring, are used to assess coastal hazards (Quesada-Román and Peralta-Reyes, 2023).

The present study focuses on Maronti Bay's coastal evolution on Ischia Island, which has historically been affected by slope stability issues due to volcanic activity, earthquakes, and coastal erosion (Del Prete and Mele, 1999). In this perspective, researchers of the INGV (Istituto Nazionale di Geofisica e Vulcanologia) carry out periodical surveys of the Ischia territory. Drone surveys were used to evaluate the difference between pre- and post-landslide Digital Surface Models (DSMs) to focus on the November 26th, 2022 landslide event (Figure 1b). That event affected the volcanic cliff and can be classified as debris avalanche (Hungr et al., 2014) causing severe problems to the nearby structures and a remarkable scarp retreat of about 20 m. Consequently, debris and large blocks with the creation of a deposition area invaded the beach.

The pre (acquired on December 15th, 2021) and the post (acquired on January 31, 2023) datasets have been orthorectified and georeferred with PPK (Post Processing Kinematic) workflow (Famiglietti et al., 2021) using as GNSS base the station SANT (Santantuono) managed by INGV and located onto the Ischia island. Thanks to very high spatial resolution of products (1.7 cm) this analysis estimates mobilized volumes (Figure 1c) allowing the comparison with results presented by other authors (Massaro et al., 2023). The adopted approach offers a geometric understanding of coastal cliff evolution after the landslide impact. These insights are crucial for managing landslide risks on Ischia and for other similar environments, guiding the development of mitigation strategies to protect the environment and ensure residents' and visitors' safety.

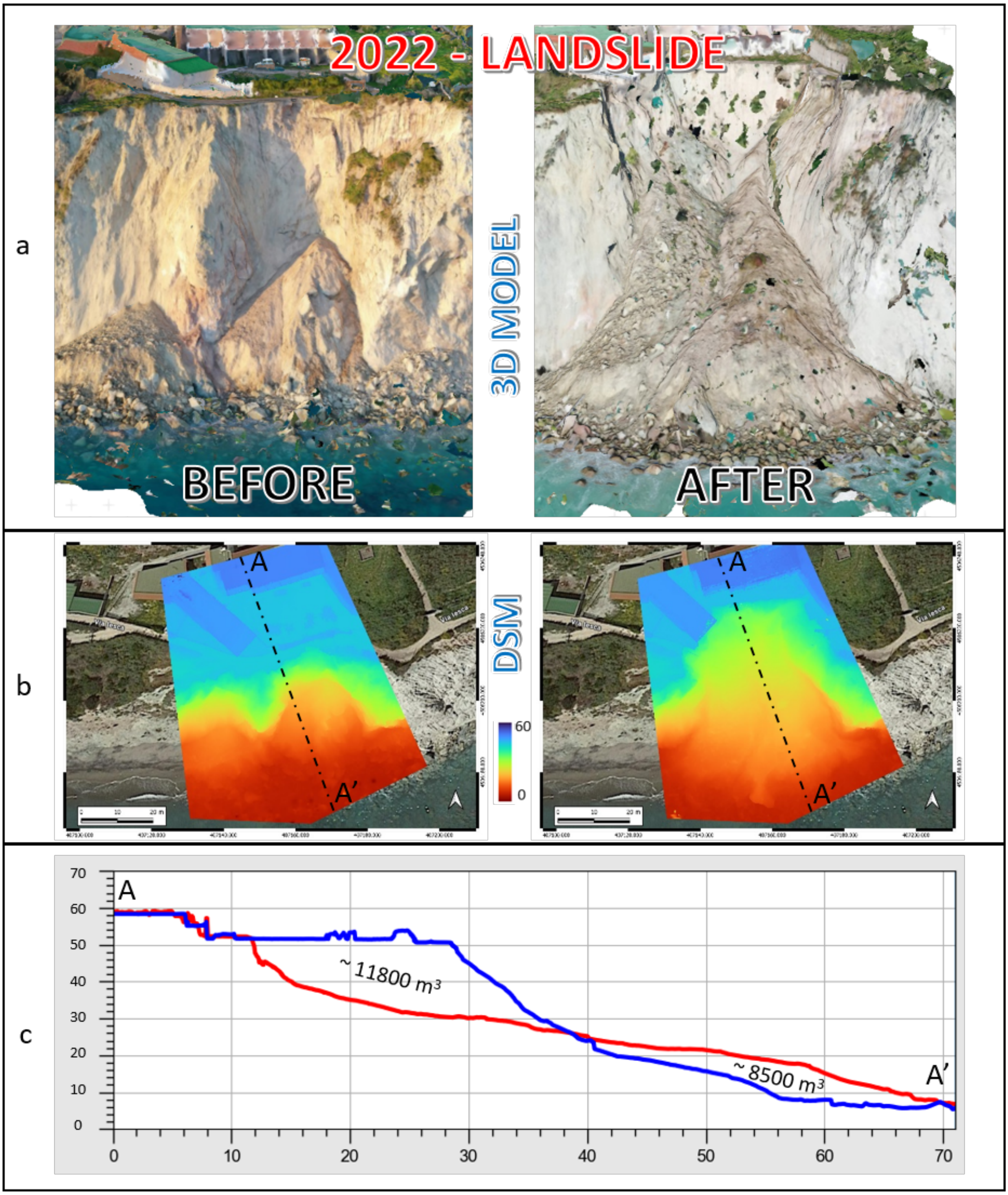

Fig. 1 – Pre and post 3D models, DSMs and section of the investigated area.

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InGEO: Innovation in geothermal resources and reserves potential assessment

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In agreement with the European Green Deal, setting the ambitious target of reducing CO2 and climate-altering gas emissions by 55% by 2030 (from 1990 levels) and climate neutrality by 2050, the geothermal energy sector is expected to grow steadily. For many decades geothermal energy has been used on a large scale by tapping into hot water-bearing layers at 0 – 4 km depth. The geographical limitation of large-scale geothermal plants is going to be overcome by recent advancements, which demonstrate that it is possible to produce energy also by deep closed-loop heat exchanger systems in the subsurface (Gola et al., 2022). While research in this field develops, it is strategic to estimate - on a regional scale, down to a depth of 10 km - how much energy can be concentrated and extracted from upper-crustal layers.

The InGEO project (Innovation in GEOthermal resources and reserves potential assessment for the decarbonization of power/thermal sectors) aims to define a method to quantify the energy realistically producible from deep geothermal energy sources at the regional level to be used for specific technologies, e.g. to generate electricity or for district heating. Starting from a review of the existing techniques for the evaluation of the technical and economical-technical potential based on the volume method (Trumpy et al., 2016), further innovations will be included. Key challenges, considering a regional scale example as a test site, consist of: (i) developing a robust assessment of the deep geothermal resources, considering the local geological conditions, the thermal regime and the heat exchange capacity; (ii) defining operative solutions for heat extraction, including the exploitation of natural hydrothermal systems, the deep closed-loop heat exchangers as well as the thermal energy storage technologies, to optimise the thermal performance; and (iii) validating the regional scale approach with site-specific information.

The study area includes the sector of the buried fold and thrust belt of the Northern Apennine belonging to the Romagna and Ferrara Folds (Figure 1). This area has been the target of previous studies focused on both hydrocarbon and geothermal exploration activities. More than 500 boreholes with available lithostratigraphic and bottom hole temperature information have been selected. Locally, thermal data highlight positive heat flow anomalies attributable to the deep fluid circulation within the deep-seated carbonate sequences of Mesozoic age (Pasquale et al., 2013).

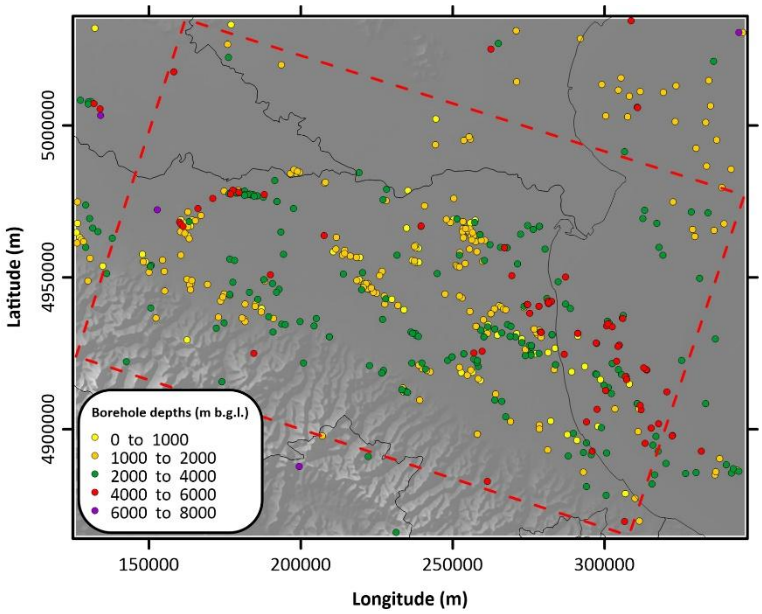

Figure 1. Area of study (dotted rectangle) and location of the selected deep boreholes as function of the total depth (meters below ground level).

The project will demonstrate an innovative exploration workflow to integrate geophysical data (e.g. Spada et al., 2013; Magnoni et al., 2022) to reconstruct the crustal and subcrustal structures (Figure 2). Moreover, taking advantage of the different sensitivity that geophysical data have on physical rock's parameters (temperature and composition), the optimized geological and thermal models will be the input of the resource assessment. The calculation of the deep geothermal energy potential for hydrothermal systems, deep closed-loop heat exchangers and thermal storage technologies will be performed by developing an open-source and web-based GIS tool, namely GEOTHERMOS.

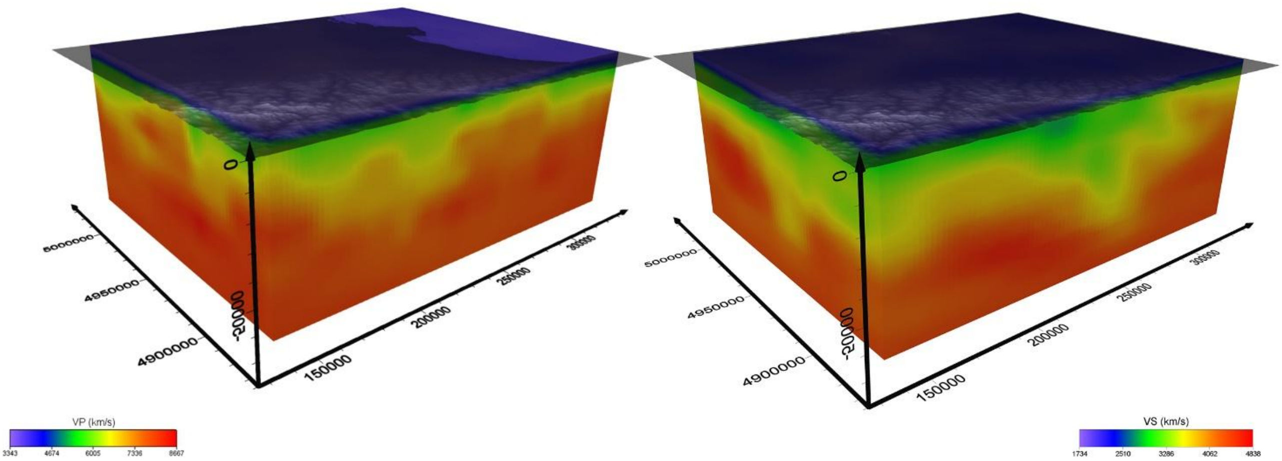

Figure 2. Distribution of the seismic velocities (Vp on the left, Vs on the right) beneath the area of study (from Magnoni et al., 2022).

The project is expected to have a significant impact on the geothermal community. The outcomes of InGEO are designed for use by investors, regulators, governments and consumers. InGEO sets the cornerstone for comprehensive deep geothermal potential estimation at the regional level.

Stakeholders will have the opportunity to compute the potential for any area where deep geological and thermal models will be available. The research units involved into the project will continue to improve the GEOTHERMOS tool by inserting their data also for other regions in Italy and will invite the scientific and industrial community to contribute to the feasibility.

Acknowledgements

The InGEO project has received founding from the European Union – NextGenerationEU

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Time-lapse Gravity Monitoring at surface and Excess Mass Estimation of CO_2 Stored in Deep Saline Aquifers

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This study regards the assessment of surface gravity surveying for CO_2 plume monitoring in a deep saline aquifer (Milano and Fedi, 2023). We simulated surface gravity monitoring of CO_2 storage for the injection and post-injection phases and using different injection rates. We show that time lapse gravity data can be used to successfully estimate the CO_2 stored mass by means of DEXP multiscale analysis, even when the anomaly is incompletely defined, due to a not proper areal coverage of the survey. The DEXP method has proven to be very stable with respect to noise and to be an efficient technique for simultaneously determining the CO_2 plume depth, its geometrical features and stored mass.

We used the available benchmark model of the Johansen reservoir to conduct the simulation. We calculated the gravity response at surface from the estimated models of reservoir density and saturation at different time intervals and for different injection rates. We used a new approach for monitoring the mass stored into the reservoir based on the DEXP method. DEXP allows an effective reduction of interference effects from nearby sources and it can be applied to high-order vertical or horizontal gradients of the field, maintaining high stability with respect to high-wavenumber noise. Moreover, this technique does not require any a-priori information about the geometry and physical parameter (density) of the source.

The results show that the baseline scenario of 15 kg/s of CO_2 injected for 25 years resulted in a weak gravity response. Conversely, for a rate of 60 kg/s we observe a maximum amplitude of about -16 µGal at the end of the injection period, while preserving low bottom hole pressure within the reservoir. We also show that we can track the migration of the CO_2 plume and contemporary the migration of the brine with respect to the well position. We also show that, by using the DEXP method, we can easily estimate the mass changes associated with the stored CO_2 for each injection rate, which we found to be very close to the true values. DEXP analysis has also proven to be very stable vs. noise. Compared to the results inferred from other methods, we showed that the DEXP analysis can simultaneously provide results about the depth to the source, the source geometry and, most importantly, an accurate estimate of the stored mass.

This study clearly shows that the appropriate choice of the injection rate strongly impacts on the ability to recover useful gravity signal at the surface, beyond the measurement error threshold. We provide an in-depth analysis of the effect of noise on the mass change estimates. Our approach could be a valid tool for conducting real time monitoring of the CO_2 as it could accurately determine the effective mass stored in the reservoir. This is particularly important as it does not require information about the source and could make surface gravity surveying as an independent monitoring strategy.

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SpiderTherm: Optimizing Geothermal Extraction for Sustainable Energy Transition

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The geothermal resource presents at least three advantageous aspects: i) it is a ubiquitous and continuous source of energy; ii) it can contribute to the thermal and electrical energy needs in residential and industrial sectors; iii) it can aid the energy transition process towards renewable energy sources. Geothermal fluids are valuable energy sources with various applications depending on their temperature range: between 40°-60°C, they are mainly used for greenhouse heating and aquaculture; between 60°-70°C, common applications include building conditioning and domestic water heating; above 70°-80°C, water can be integrated into industrial processes or used for absorption chillers in refrigeration cycles; and starting from 100°C, the primary fluid can be used in binary geothermal systems for electricity production.

Conventional geothermal applications utilizing natural hydrothermal systems face challenges in exploration due to uncertainty in subsurface lithology and fluid distribution, corrosion and mineral precipitation during production, and environmental impacts such as subsidence and induced seismicity. Economic feasibility is another limitation, primarily due to high drilling costs, but retrofitting abandoned wells, originally drilled for the oil industry, offers a cost-effective alternative.

An unconventional approach to harness geothermal energy is the deep borehole heat exchanger (DBHE), involving coaxial pipes in single wells. However, its low efficiency restricts its applicability in geothermal power production compared to conventional systems. Recently, deep closed-loop geothermal systems (DCHE) have been proposed to enhance efficiency by connecting multiple wells horizontally, demonstrating potential for geothermal power production under favourable conditions.

The energy performance of DCHE depends on various parameters, such as environmental, design, and operational variables. With respect to the different parameters, Gola et al. (2022) demonstrated by a sensitivity study that the following factors play a primary role: the undisturbed geothermal gradient, the dimensions (vertical depth and horizontal length) of the closed-loop, , the flow rate, , and injection temperature.

This study aims to analyze the long-term performance of an innovative DCHE configuration, varying the number of reused exploration wells (N), vertical (H) and horizontal (L) lengths, flow rate per well (q), injection temperature (Tin), heat exchange (DT), and geothermal gradient (Ggeo). The goal is to identify conditions that achieve the recommended minimum long-term production temperature of 100°C for binary geothermal power plants.

We did this with a numerical simulation approach using COMSOL 6.1. However, numerical simulations can suffer high computational time , which can become a limitation.Machine learning, specifically Long-Short Term Memory (LSTM) neural networks, is explored for predicting long-term production temperatures based on the mentioned variables, offering a faster alternative to numerical simulations.

To do that, we used the COMSOL results of each DCHE as a training set for the LSTM system. So far, the tested LSTM system is a very shallow network with three hidden layers with 24, 14, and 7 neurons, respectively. Given the low number of training instances, we were interested in testing different learning strategies to observe which was faster in convergence and determine the best in temperature forecasting after ten years of production. These strategies are the curriculum and the non-curriculum learning (standard).

We applied the proposed concepts in a specific case study in Cesano, integrating available geological and geothermal information. The simulation assessed the production temperature after 10 years for a 3-branch DCHE configuration in the Cesano area, known for its abundance of abandoned or depleted wells and a high geothermal gradient.

The results from the numerical simulation indicate that the production temperature in such a DCHE configuration would be 139.57 °C. Our analysis using a Long-Short Term Memory (LSTM) neural network trained with curriculum and non-curriculum learning strategy predicted a value of 136.8 °C and 95.7 °C with an absolute error of 2.77 °C and 41.1°C, respectively. This suggests that the LSTM can provide accurate predictions for long-term production temperatures, offering an efficient alternative to more time-consuming numerical simulations.

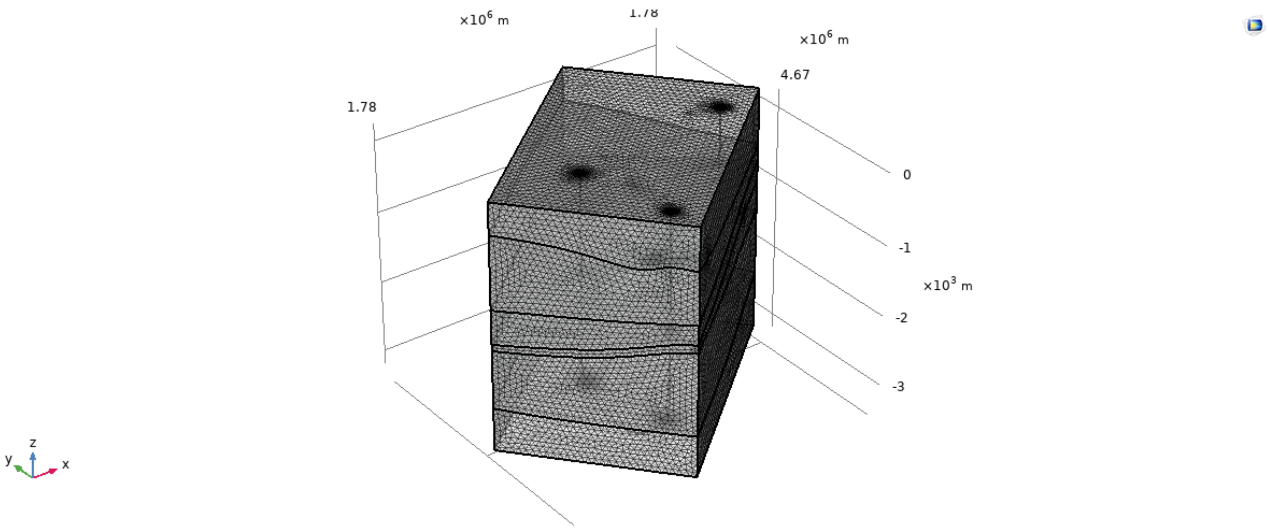

Figure 1 3D view of the Deep Closed-Loop Heat Exchanger (DCHE) model in the Cesano area made up of three reused geothermal wells (2 injections and 1 production boreholes). The surfaces delineating the lithothermal units as well as the numerical mesh are displayed.

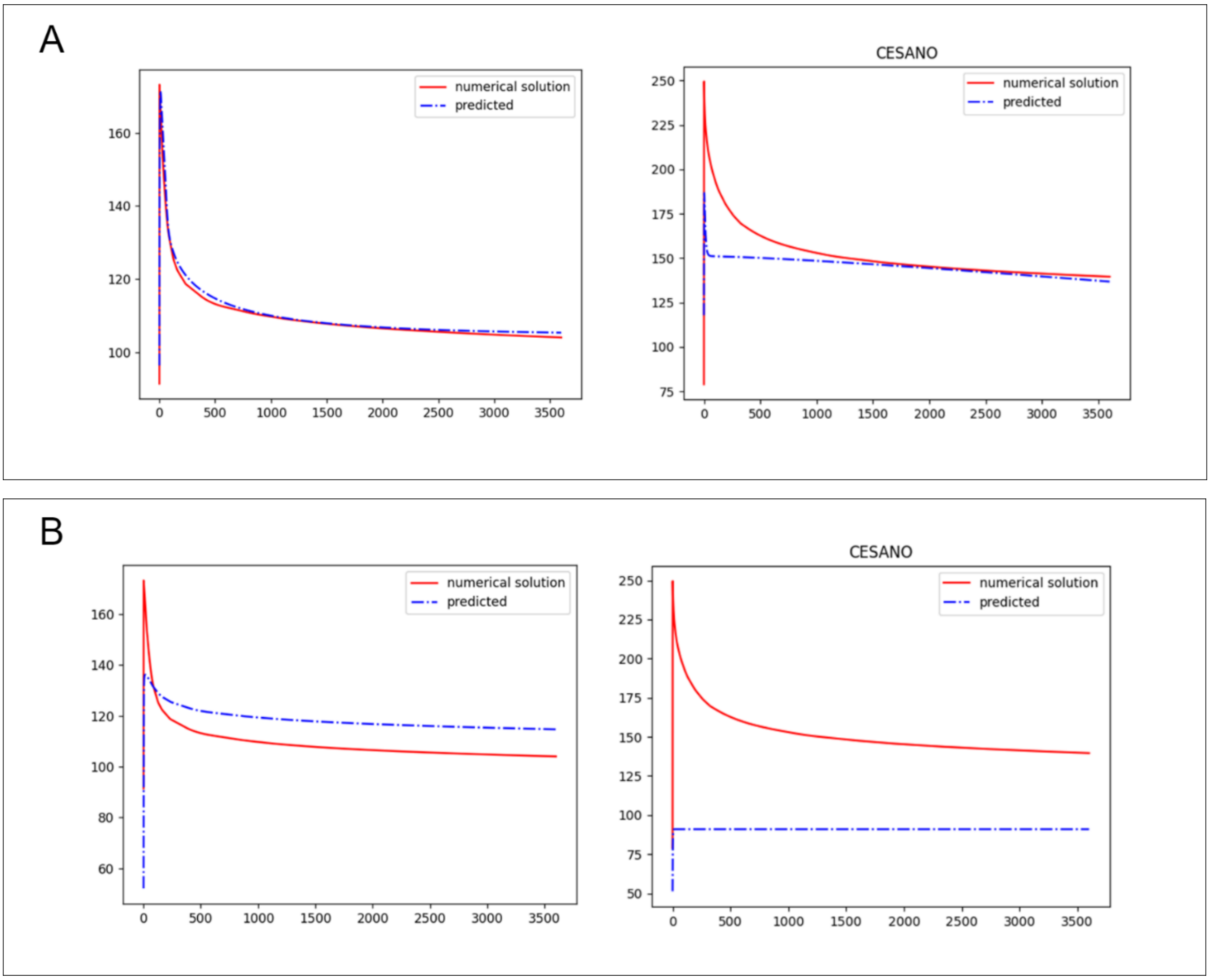

Figure 2. LSTM production temperatures forecasting versus simulated ones obtained by curriculum-learning (a) and non-curriculum (b) strategies. On the left the results refer to the synthetic scenarios and on the right to the Cesano area case study.

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Machine learning classification of seismic tremor associated with the Mefite d'Ansanto CO_2 gas emission.

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The focus of this study is framed around the development of automatic methods to track the spatio-temporal evolution of deep-origin, non-volcanic gas emissions. It is widely recognized that crustal fluids play a crucial role in the earthquake nucleation process, and the characterization of their emissions on the surface can be essential for better understanding crustal source mechanisms.

We investigated seismic tremors recorded at the gas-emission of Mefite d'Ansanto, situated within one of the highest seismic hazard areas of Southern Apennines, at the northern end of the fault system that generated the Mw 6.9 1980 Irpinia Earthquake. Mefite d'Ansanto is currently considered to be the largest natural emission of deep-source, non-volcanic, CO_2-dominated gases on Earth, with an estimated total gas flux of about 2000 tons per day.

We studied seismic tremor recorded between 30-10-2019 and 02-11-2019 recorded by a dense temporary seismic network (4 broadband and 7 short-period sensors) deployed around the emission area. Tremor signals were identified by developing an automated detection algorithm, based on non-parametric statistics of the recorded signal amplitudes. At the same time, we extracted signals characteristics parameters like the RMS amplitude and the statistical moments of amplitude distributions, both in time and frequency domains. These were used as features for training and optimizing station-based KNN (k-Nearest-Neighbors) binary classifiers, which were then used to classify and discriminate the target tremor from anthropogenic and background noise. The trained classifiers showed good performances, with a median overall accuracy of 92.8%. The comparison of the classified tremor across all stations revealed common features: a variable duration (16 s to 30-40 mins), a broad-frequency band (4-20 Hz) with varying amplitudes peaks at different stations, and two kinds of signals: (a) long-duration, high-amplitude tremors, (b) pulsating tremors. The higher amplitude of classified tremors recorded at stations located close to bubbling and pressurized vents suggests the presence of multiple local sources.

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Mapping the thermophysical properties of Apennines rocks (Central Italy): implications for the temperature state of crust.

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This work presents the results obtained from the laboratory analysis of the thermophysical properties of carbonate rocks and turbidites present in the northern Apennines. The aim was to determine and relate the thermophysical properties of outcropping carbonate rocks belonging to the main geological formations that characterize western Umbria (central Italy). The determinations were carried out to observe the heat transfer capacity of these rocks, with varying temperatures and both in dry and saturated conditions; the porosities, that results less than 5%; the densities and the mineralogical composition of 70 samples.

The thermal conductivity values measured in dry conditions with three different devices based on the transient technique, differ by percentages of less than 10%.

Mineralogical analysis indicates that the formations under examination are mainly composed of calcite, with an abundance of quartz for some samples.

The thermal conductivity values at ambient temperature of 20 – 25°C measured in dry conditions vary from 1.8 to 3.0 W/mK for samples with predominant calcite, and greater than 3.6 W/mK for samples with larger quantities of quartz. The decrease in conductivity up to 200°C is about 30% for most samples.

Theoretical equations based on the mineralogical composition and porosity were analysed to find the right fit with the measured values, with the possibility of extending the results to other parts of the world.

The results obtained from the study represent the basis for a more complete evaluation of the temperature trend with depth, useful for the evaluation of geothermal systems and for defining the rheological behaviour of the crust.

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ISTRICI - STRUCTURAL INVERSION OF COMMON IMAGE GATHERS

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In this paper, we present a free package consisting of codes developed by us and Seismix Unix (SU; Cohen and Stockwell, 2008), an open-source software package for seismic data analysis, to determine the seismic velocity field in different geologic settings. This package, called ISTRICI, was developed to facilitate the use of Seismic Unix, a free software designed to process seismic data. Seismic Unix is a powerful tool for performing pre-stack depth migration and using the residual parameters to update the seismic velocity model based on the pre-stack depth migration results. What is missing are codes and scripts that allow practical, interactive, and easy application of the Seismic Unix algorithms. Therefore, ISTRICI was developed to fill this gap.

ISTRICI consists of three workflows (INTER, CIG and TRAD; Tinivella and Giustiniani, 2023) for interactively performing residual velocity analysis and pre-stack depth migration, switching from one workflow to the next depending on the characteristics and type of seismic data. The PreStack depth migration (PSDM) adopted in SU is based on the method of Liu and Bleistein (1995); the PSDM output consists of two migration sections characterised by the same phase, but different amplitudes. The algorithm performs the PSDM using the input and perturbed velocity models. The ratio of the amplitudes of these two PSDM sections is used to evaluate the residual velocity (i.e.,Vargas-Cordero et al., 2010). The result of the migration can be organized into CIGs: if the migrated reflections in the CIGs are flat, it means that a correct migration velocity was used to migrate the data (Yilmaz 2001). By contrast, the slope of the reflections in the CIGs indicates an error in the migration velocity, which can be corrected by analyzing the residual energy and then updating the velocity (code available in SU; Liu and Bleistein, 1995). The residual energy (called the r-parameter) is a measure of the flatness deviations of the reflections along the offset in each CIG (i.e., Tinivella et al., 2009). A zero value for the r-parameter means that the velocity is corrected at the corresponding reflection. If the r-parameter has a negative/positive value, it means that the velocity must be increased/decreased. Then, using the theory of Liu and Bleistein (1995), the r-parameter is converted to a residual velocity used to update the input velocity. It is important to remember that, when the medium has strong lateral velocity variations, the algorithm works adequately even with small velocity corrections. All steps, such as PSDM, CIG analysis, r-parameter evaluation, velocity update, are performed iteratively until all reflections in the CIGs are reasonably flat, i.e. when the variation of the depth of the reflector versus offset is sufficiently small in each CIG (Vargas-Cordero et al., 2010).

The novelty of the ISTRICI package is to propose three different ways to organize the CIGs to improve the seismic velocity analysis depending on different elements, such as targets and characteristics of the data, optimizing the result quality and reducing the time needed to analyze the r-parameters in the residual semblances. ISTRICI has been developed on the basis of the most common cases: (i) the continuity of some reflections along the seismic line, such as the seafloor, suggests that the picking procedure can be performed semi-automatically in the residual semblance; (ii) the availability of the interpretation of the seismic section suggests that the velocity analysis can be performed along the interpreted reflectors; (iii) in complex geological settings and/or in the presence of non-continuous reflectors, the velocity analysis can be performed as a function of depth rather than in a layer-stripping approach. The user can choose and move from one workflow to another in order to better resolve the targets and/or scientific questions on the basis of the characteristics of the data. Moreover, for the same purposes, the user can update and modify the codes related to the velocity analysis. The STEP 1 of all workflows consists of performing PSDM obtaining two outputs: the standard migration and the additional migration with extra amplitude (see details in Liu and Bleistein, 1995). Before this step, an initial velocity model has to be created, which is input into the workflow along with the seismic data for the first step. In the INTER workflow, the r-parameter analysis is performed along a selected reflector. The procedure of INTER consists of four steps (Fig. 1). First, after PSDM, the migrated section is interpreted by picking the selected reflector; then, the picks are interpolated to obtain one pick for each migrated trace (STEP 2). Then, in a selected range of CIGs, residual propagation analysis is calculated over the depth of the selected reflector with a defined window based on the wavelength of the reflection.Then, the operator simply selects the r-parameter along the reflector; the selections are interpolated to obtain an r-parameter value for each CIG (STEP 3). STEP 4 consists of evaluating the velocity and updating the reflector depth for each CIG based on the r-parameter value and migration results. The procedure is repeated from STEP 1 to STEP 4 until the difference between two successive iterations is less than a certain threshold. The final velocity model is composed of the selected layers. In each layer, the velocity changes in horizontal direction, but is constant in depth.

In the CIG workflow, the analysis of the r-parameters is performed along a selected reflector, but unlike the INTER workflow, the picking is performed by analysing the total semblance at each selected CIG (see also Vargas-Cordero et al., 2010). This workflow also requires four STEPS, as described in Fig. 2. In STEP 2, the migrated section is interpreted and the picking of a reflection is performed. As in the INTER workflow, the picks are interpolated along the seismic section. STEP 3 consists of picking the r-parameter at depth in proximity of the picked reflector at selected CIGs. To help the user, the code specifies the depth of the selected reflector at the semblance to pick the r-parameter where the energy is higher. In this way, the interpretation of the seismic line (i. e., the depth of the target interface) is changed according to the maximum coherence of the semblance. STEP 4 is the same as the one in the INTER workflow as well as the final result. Also in this case, STEPs 1-4 are repeated until the difference between successive iterations is less than a certain threshold.

The TRAD workflow is different from the other two workflows because STEP 2, dedicated to the interpretation of the migration section, is not required. In fact, only two STEPs are required in this workflow in addition to STEP 1 (Fig. 3). STEP 2 consists in selecting the maximum energies in the semblance at selected CIGs. Of course, the number of models in selected layers when an interpretation of the seismic line is provided. In this way, it is possible to switch from one workflow to another at each stage of the inversion. Once the procedure is completed, ISTRICI can include a velocity gradient below the last inverted layer or a defined surface before performing the final

PSDM to improve the seismic imaging.

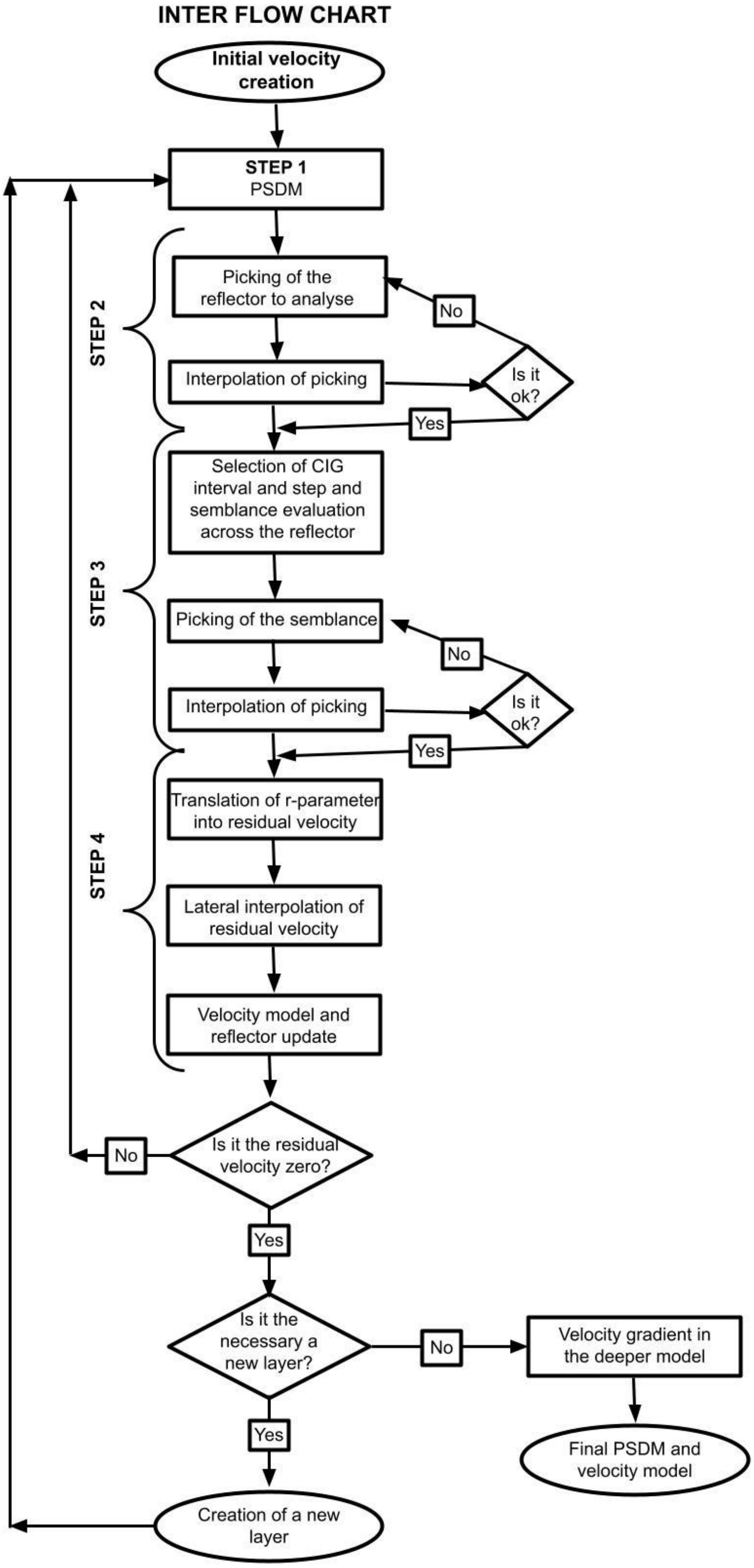

Fig. 1 - Flowchart of INTER

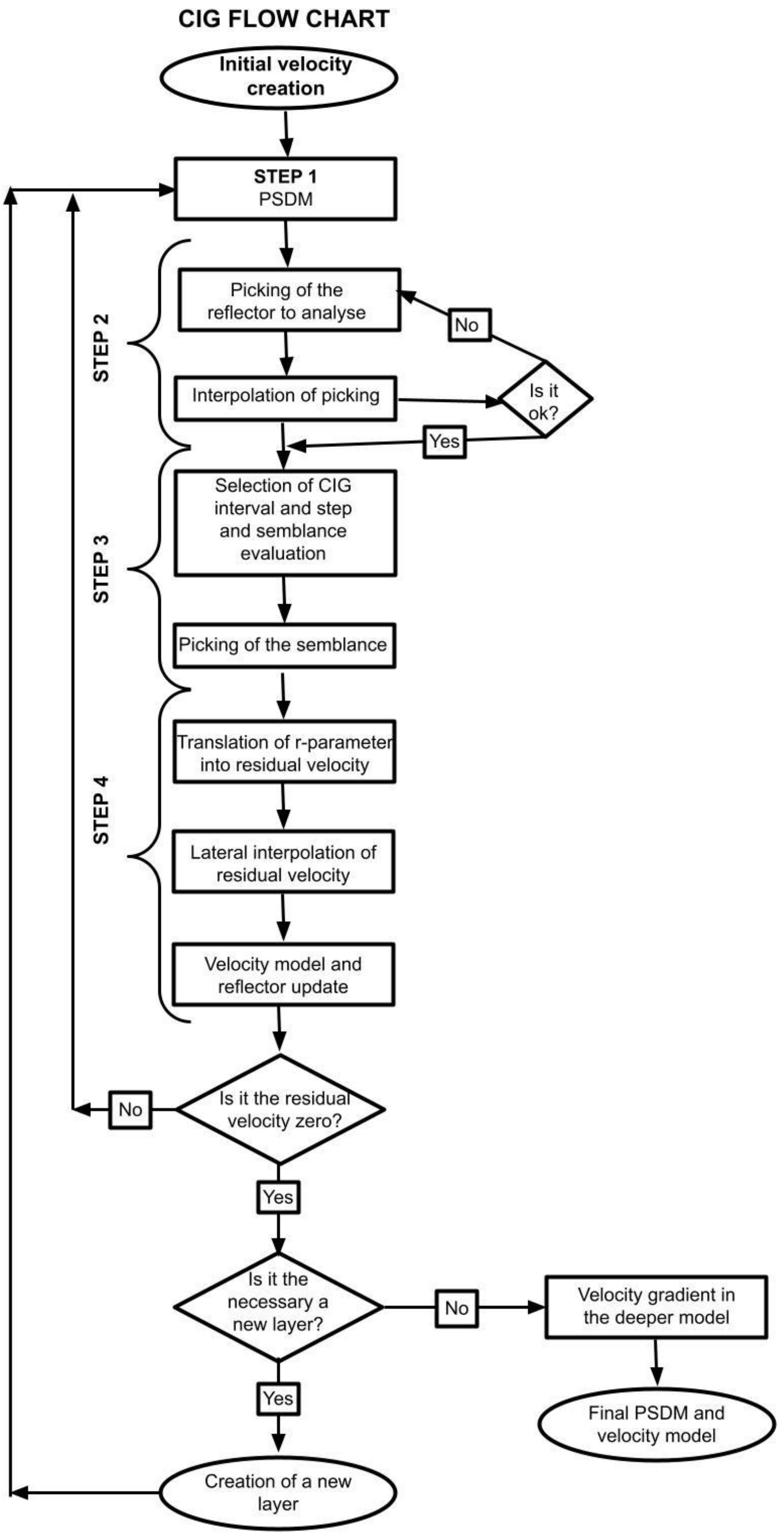

Fig. 2 - Flowchart of CIG

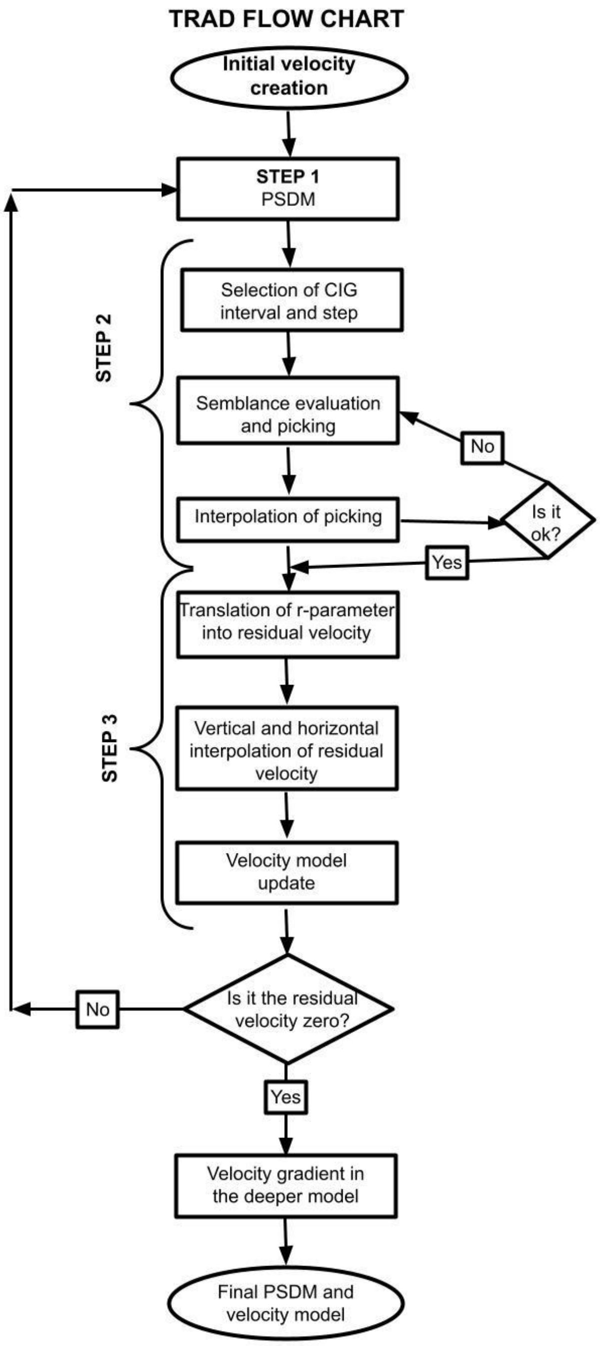

Fig. 3 - Flowchart of TRAD

ISTRICI package has been tested on different dataset with excellent results (i.e., Tinivella et al., 2009; Vargas et al., 2010; Vargas et al., 2016). Our codes were developed and improved after many tests that allowed identifying critical steps. As mentioned before, it is worth highlighting that the codes and scripts can easily be modified by the user if necessary. ISTRICI can be downloaded from the following public repository: https://github.com/utinivella/ISTRICI; a README file is provided for each workflow (INTER, CIG, and TRAD); an example is also available. ISTRICI uses codes from

Seismic Unix, free software that can be downloaded here: https://wiki.seismic-unix.org/doku.php. Information about the use of ISTRICI at the Authors is appreciated. Finally, ISTRICI can be used in the present form for multichannel seismic data, ocean bottom seismometer data, ocean bottom cable data as well as land data.

Acknowledgements

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Methane recovery and carbon dioxide disposal in natural gas hydrate reservoirs

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The present paper presents the results obtained in a three-year national research project on natural gas hydrate exploitation and carbon dioxide disposal. The consortium of partners is led by University of Perugia (UNIPG), which includes the Applied Physics group and the Structural Geology group. The other partners are the University of Camerino (UNICAM), the Politecnico di Torino (POLITO), the Istituto di Oceanografia e Geofisica Sperimentale (OGS) and the University of Ferrara (UNIFE).

The proposed project aims to develop an innovative technological solution for the extraction of methane from marine natural gas hydrates and the simultaneous sequestration of carbon dioxide in a single process (Fig. 1; Gambelli et al., 2021). The obtained fuel is neutral in terms of climate changing emissions and therefore equivalent to renewable energy sources. The multidisciplinary expertise of the consortium is focussed on the pursuit of five specific objectives:

1. Analysis of marine hydrate reservoirs, potentiality and infrastructures for their exploitation

2. Reproduction of hydrate sediments in the laboratory and determination of kinetic and thermodynamic parameters

3. CO2 replacement in methane hydrates

4. Development of a scalable technology for CO2 injection/CH4 extraction in natural hydrate reservoirs

5. Theoretical model applicable of marine hydrate reservoir and energy/environmental assessment of the proposed process.

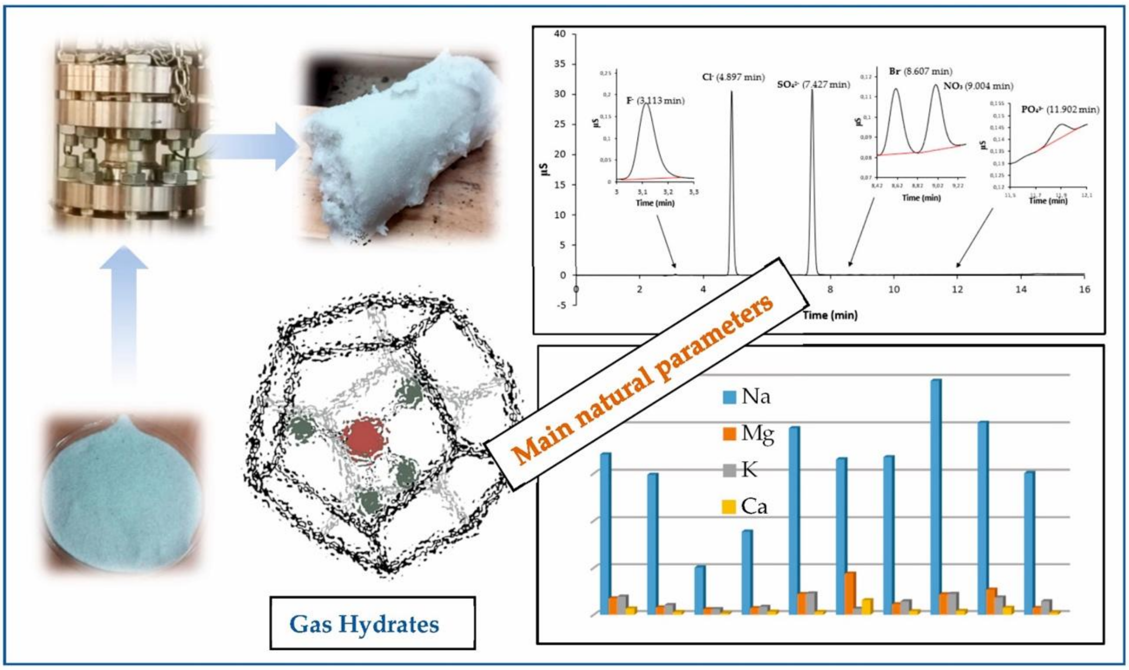

Fig. 1 – Simplified scheme of the adopted approach

The first three objectives aimed at gaining a body of knowledge on the chemical, physical and geotechnical properties of marine natural gas hydrates and on the CH4-CO2 replacement mechanism. For the activities in these three objectives, laboratory facilities of UNIPG and UNICAM are used. In addition, laboratory facilities of "D'Annunzio" University of Chieti-Pescara (UNICH) are employed since UNICH has available a patented reactor to study the kinetics of the hydrate formation process. Objective 4 concerns the design and construction of a scalable device for methane extraction and CO2 replacement. It is integrated with a methane purification and CO2 recirculation section and tested in a seafloor simulator, where water-rich natural gas hydrates sediment reproduction and in-situ measurements will be performed. Finally the last objective focuses on the development of a theoretical geophysical model of the marine natural gas hydrates reservoir and final evaluations on energy, environmental and economic impact of the proposed process and technological solution. The starting point for the development of a theoretical model is the method proposed by Tinivella (1999), which is based on the Biot-Geerstma-Smit equations. The input data are the results of laboratory analysis, which provide various parameters such as bulk density, P-wave velocity, S-wave velocity and porosity. To estimate the stiffness and compressibility of the sediments and the hydrate, these two parameters were varied until obtaining the P-wave and S-wave velocity obtained in the laboratory.

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Seismic attribute analyses for geothermal applications: a case study from the geothermal potential assessment in the Valle Latina area (Central Italy).

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Introduction

We reprocessed the seismic public profiles acquired in the Valle Latina in the last century for a Ph.D. project focused on identifying potential geothermal reservoirs. Our main target was to depict faults, fracture zones, and strong AI contrast, reprocessing the VIDEPI seismic reflection profiles with the application of an advanced Matlab code (i.e., WIGGLETOSEGY by Sopher, 2018). Using this code allowed us to digitize the seismic traces of the vintage seismic profiles to obtain major quality data for seismic attribute analysis to detect faults and fracture zones that may have a great influence in the behavior of a geothermal reservoir.

The main goal of this integrated PhD project is to provide an accurate characterization of specific geothermal systems located in central Italy. The focus is defining their potential for geothermal energy planning and elaborating a potential reservoir assessment. The ultimate aim is to develop a map of the geothermal potential structures and identify one or more case studies in the southern Latium, particularly in the Valle Latina area of interest. In the southernmost part of Latium, in correspondence with the Mesozoic carbonate reservoir, hot waters were found within 1-1.4 km depth in the areas of (i) Latina (60 °C at 1.4 km); (ii) Fogliano (80 °C at 1 km); (iii) in the Valle Latina (50-70 °C at 1-2 km); and (iv) near the Terme di Suio (50-100 °C at 0.5-1 km) (Buonasorte et al., 2011).

Data and Methods

In order to describe the structural features of Valle Latina, we analyzed a huge hydrocarbon exploration dataset consisting of geophysical and stratigraphic well-logs, along with seismic reflection profiles. The geophysical data comprised public data from the ViDEPI project database and literature and private data provided by Pentex Italia Ltd. The seismic profiles were recorded from various acquisition surveys conducted in the 1980s and 1990s by AGIP, Sovereign, and Pentex for hydrocarbon exploration. The seismic dataset includes both the stack and the migrated versions.

WIGGLE2SEGY is a code developed by Sopher in 2017 using Matlab. It is available to the scientific community to convert scanned images of stacked reflection seismic data to the standard SEG-Y format. The code is designed to work directly on the image characteristics and can recognize and eliminate the signal associated with timelines and baselines. This code is particularly useful in removing noise associated with paper data due to the storage and retention of the data itself. Moreover, WIGGLE2SEGY applies a frequency filter to eliminate artifacts with frequencies outside the bandwidth of the data, as described in Buttinelli et al. (2022). Before the application of seismic attribute analysis, an AGC (automatic gain control) was applied to seismic data to bring up weak signals. The further step is the application of seismic attributes to highlight and identify some discontinuities in the seismic data that are helpful for fault and fracture characterization (Fig. 1).

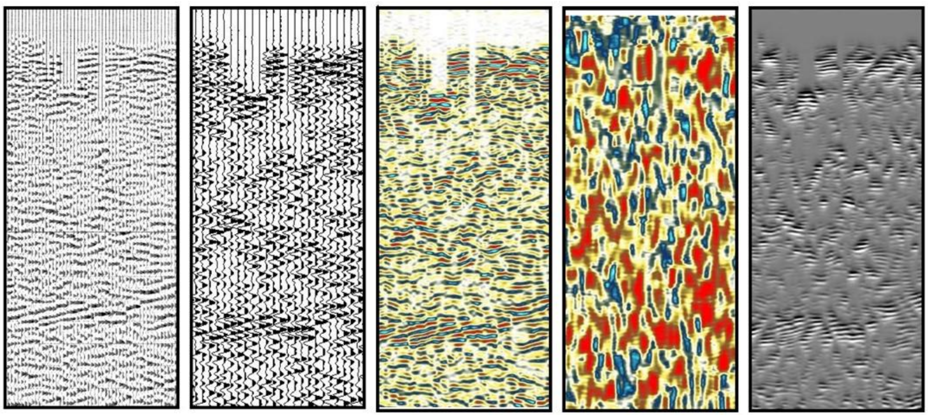

Fig. 1 - An example of vectorization results from the VIDEPI dataset, using the process described in this study. a) Scanned image of line FR-309-80. b) SEG-Y file extracted from the scanned image in a), plotted with similar parameters to the original, c) same SEG-Y data as in b) plotted with a variable density display. d) application of seismic attribute "semblance"; e) application of seismic attribute "pseudo-relief".

Results

Analysis of attributes integrated into the reflection seismic interpretation, mainly for 2D and 3D seismic data, allowed better detection of faults and fractures of the carbonate reservoir in the project's area of interest. Some vintage 2D seismic lines were tested using several post-stack attributes, including semblance/coherence and pseudo-relief, using OpendTect software.

This method has created a dataset of vectorized seismic profiles that can be shared with the scientific community. This helped with the structural interpretation of the study area, improving the public structural isochrone maps available in the public database. In this case, we have used scientific analyses like seismic attributes despite having only 2D seismic data. Seismic attributes can detect faults and fractures, stratigraphic discontinuities, and identify hydrocarbon volumes. Our study displays the outcome of vectorization and enhancement of seismic data by applying attributes like automatic gain control and convolve and other seismic attributes such as coherence, curvature, and pseudo-relief, which are suitable for characterizing geothermal reservoir structures (Fig. 2).

Thanks to the new digitalized and vectorized dataset and the application of seismic attributes analysis, it has been possible to a better definition and interpretation of the interface between

Upper Miocene siliciclastic deposits and Mio-Cretaceous carbonate platform in the area of study, characterized by strong acoustic impedance contrast. The identified reservoir structures will be simulated according to their geothermal potential. Seismic attributes (i.e., semblance and pseudo-relief) were applied to identify discontinuities caused by faults in the fractured carbonates.

Conclusions

This approach of seismic attribute analysis is extremely useful for geothermal exploration of similar fields and reservoirs with a strong AI contrast and the construction of more predictive static and dynamic reservoir models based on discontinuity detected by attribute analysis and seismic interpretation. Seismic attributes are very useful in characterizing faults and fractures also in 2D seismic data volumes. The pseudo-relief attribute application made the interpretation of the main unconformities and structural features possible.

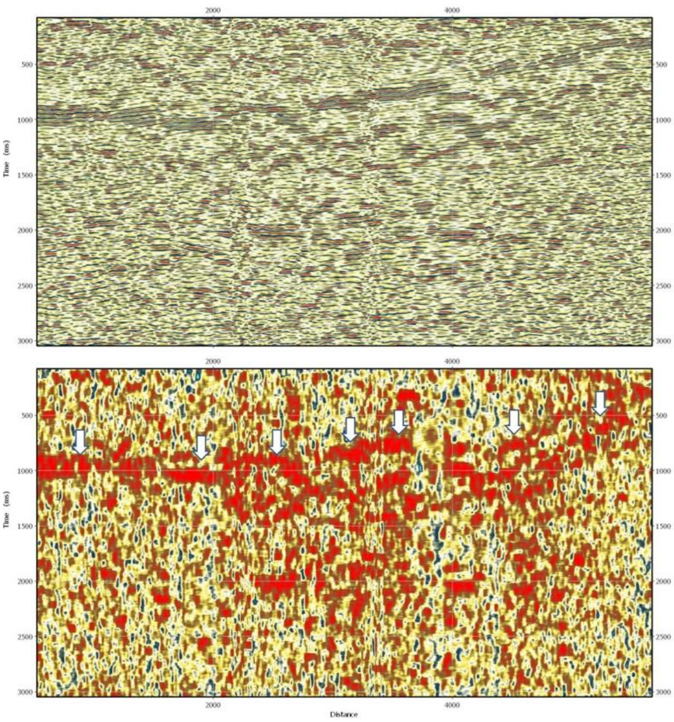

Fig. 2 - (a) FS-03-90 available publicly stack seismic profile in vectorized SEG-Y format via WIGGLE2SEGY Matlab-based tool. (b) The second panel shows the semblance attribute calculated in OpendTect software to detect AI contrast, faults and fractured reservoirs.

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Electromagnetic Induction Data Inversion: Realistic Prior Models and Spatial Regularization with Respect to Known Structures

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Introduction

Geophysical techniques, including electrical resistivity tomography (ERT) and electromagnetic induction (EMI), play a crucial role in non-invasive subsurface characterization. While ERT involves galvanic contact with the ground of arrays of electrodes, EMI enables contactless measurements and is frequently employed for (quasi-)3D resistivity mapping, particularly in large-scale surveys, often carried out with helicopter-mounted systems (Karshakov, 2017; Yin, 2007). Calibration differences between the two methods pose challenges, as ERT relies on internal resistances, while EMI demands meticulous adjustments for absolute measurements (Finco, 2023; Minsley, 2012). Both ERT and EMI inversions are ill-posed problems. The selection of a unique and stable solution relies on prior knowledge, incorporated either as regularization term (deterministic approaches) or as prior distribution (probabilistic strategies) (Tarantola, 1982; Zhdanov, 2002). The present study focuses on enhancing 1D EMI inversion by making use of: 1) realistic prior samples, ensuring compatibility with subsurface expectations, and 2) spatial constraints with geologically meaningful features (e.g., from 2D ERT sections or their geological interpretations). We verified the performance of the proposed approach in a field test by comparing our results against ground-penetrating radar (GPR) measurements.

Methodology

Within this research, a strategic shift was undertaken to significantly enhance computational efficiency. The proposed approach consists of formulating the prior information in terms of an ensemble P consisting of 1D resistivity models m and the corresponding forward response $d = F(m)$ computed for the model m. The core principle underpinning this approach involves an exploration of the solution space for the inverse problem using a substantial number of pre-computed (d, m) couples, typically in the range of 10^5 - 10^6 samples. Consequently, the challenge no longer revolves around the continual generation of a solution, which is computationally intensive, but instead centers on the search for a suitable one from the pre-existing array of possibilities. When correctly implemented, particularly by harnessing the computational power of Graphics Processing Units (GPU), this method demonstrates a speed advantage of at least two orders of magnitude over traditional deterministic algorithms (McLachlanet al. 2021).

The discrimination criterion is given by the chi-squared value, defined as

$$\chi^2 = N^{-1}\left\|\delta^{-1}\left(F(m) - d\right)\right\|_2^2, \qquad (1)$$

where N is the number of frequencies for each observation, δ represents the uncertainty associated with each of the measured data d and $F(m)$ is the forward response of the model m. Clearly, retrieving the inverse model m by simply minimizing Eq. 1 would be challenging because of non-uniqueness and instability of the solution with respect to the data. In the deterministic inversion framework, the originally ill-posed problem is turned into a conditionally well-posed one by minimizing a stabilizing term (formalizing the available prior information; e.g. the presence of smooth transitions between lithologies) with the constraint that $\chi^2 = 1$. A common choice for the stabilizing term is $s(m) = \left\|m - m_{apr}\right\|_2^2$; in this specific case, the solution m is selected as it produces a response compatible with the observed data ($\chi^2 = 1$) while being as close as possible to the reference model m_{apr}. Within this research, the reference models are the 1D models constituting the 2D resistivity section crossing the survey area (Fig. 1b), obtained through the inversion of ERT data. However, in the proposed scheme, this spatial constraint enforced by the stabilizing term acts uniquely in the lateral direction, whereas, along the vertical direction, the prior information is incorporated by selecting the possible solutions among the realization of the ensemble P. In this way, the information provided by the reference model is laterally propagated across the entire survey and the possibly very complex (and realistic) prior information is infused into the solution by selecting it among the element of the ensample P (supposedly generated in accordance with our expectations about the subsurface).

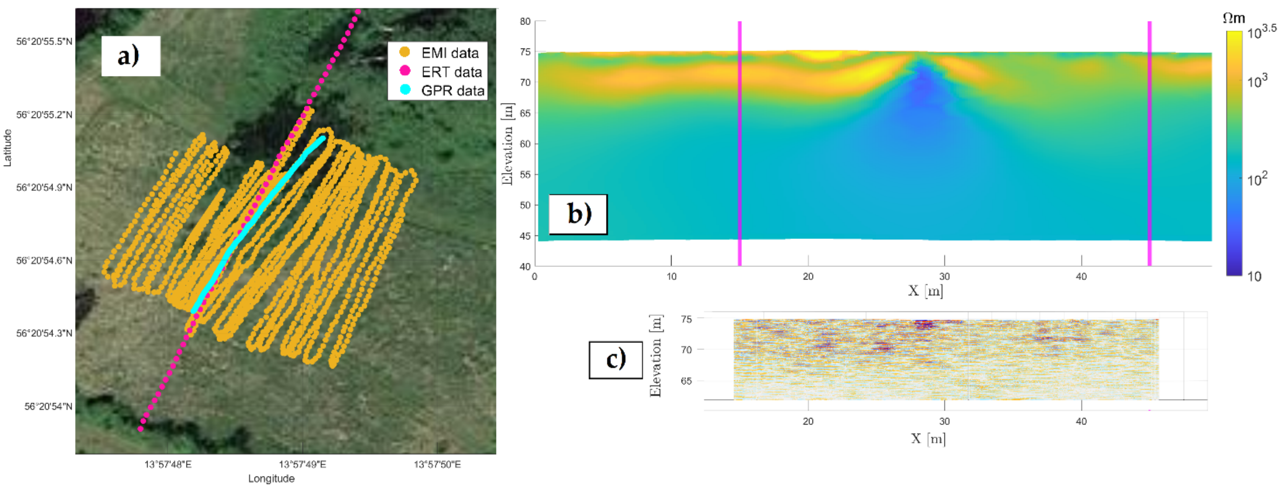

Fig. 1 – Field data. **a**) the location of the collected EMI, ERT and GPR data; **b**) the result of the ERT inversion (the vertical lines delineate the portion crossing the EMI survey area); **c**) the GPR section.

To validate the proposed approach, we conducted various geophysical measurements on a test site located in the south of Sweden. Specifically, we acquired 1550 frequency soundings using the Profiler EMP-400 from GSSI at three frequencies: 5, 10, and 15 KHz. Additionally, an ERT line was collected across the EMI area using the Terrameter LS2 instrument from GuidelineGeo (Fig. 1). Lastly, we performed a grid of Ground Penetrating Radar (GPR) measurements that overlapped with the EMI area. It's important to note that the GPR data was utilized uniquely for validating the results of the EMI-ERT constrained inversion and was not incorporated into the inversion process itself.

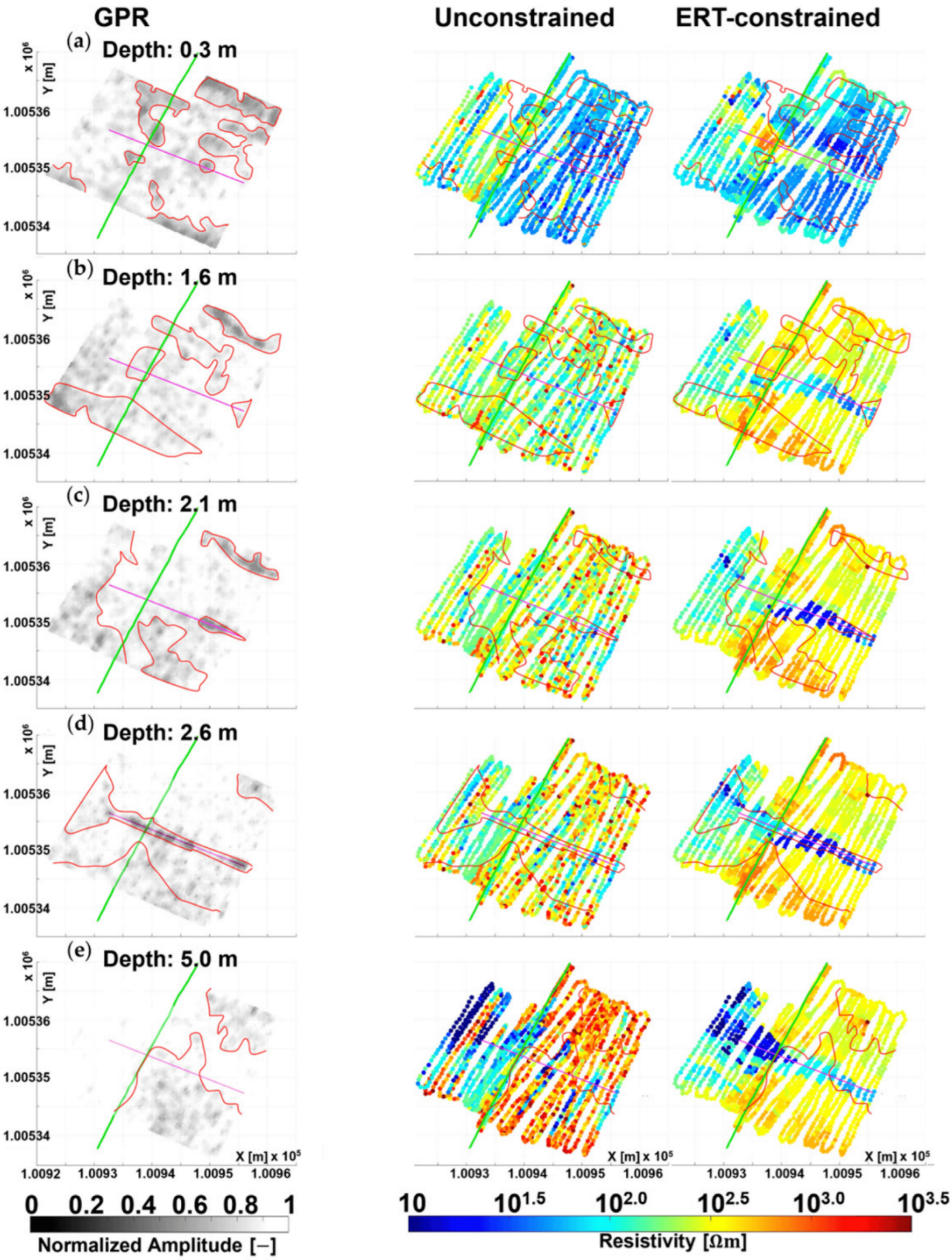

Figure 2 - Horizontal sections of the GPR and of the resistivity volumes obtained with and without constrain. Each row corresponds to a different depth: (**a**) 0.3 m; (**b**) 1.6 m; (**c**) 2.1 m; (**d**) 2.6 m and (**e**) 5.0 m. The location of the ERT section (and its geoelectrical interpretation) is shown as a green solid line. The assumed position of a pipe is plotted in purple. The red contours are shown as references to the GPR anomalies; their purpose is merely to make the comparisons easier, and they are not necessarily connected to any specific geological features.

Results

The field test produced the two EMI inversions shown in Figure 2, showcasing: 1) the unconstrained outcome (Figure 2a-f, middle column), in which the solutions are obtained by simply minimizing Eq. 1 within the ensemble P, and 2) the constrained inversions (Figure 2a-f, rightmost column) that incorporates information from both the ensemble P and the 2D ERT section. The unconstrained result tends to be more resistive than the constrained inversions, illustrating the impact of ancillary information from the ERT section on spatial consistency and on the reduction of erratic variations between adjacent 1D models. Figure 2 offers a comparative analysis at different depths, in which horizontal slices of GPR reflections' envelope can be checked against the corresponding slices of EMI volumes obtained with and without the ERT constraint. This comparison highlights the effectiveness of schemes incorporating ancillary information, as seen in the detection of a conductive anomaly related to a pipeline, particularly visible in Figure 2c-d at the depth of 2.1 m to 2.6 m. Differently from existing spatially constrained schemes, the present approach does not rely (vertically) on smooth/sharp regularizations (Klose et al. 2022; Klose et al.2023); still vertical consistency is enforced by selecting the model in the ensemble P that, by construction, is generated in accordance with our expectations (Zaru et al. 2023). In summary, the proposed inversion scheme, utilizing an arbitrarily complex prior distribution and ancillary information, generates a unique EMI inversion result. The ability to formalize information through prior distribution samples and reference models proves crucial for achieving spatially consistent and reliable reconstructions. In addition, the method effectively integrates ancillary data, presenting a robust solution that aligns with geological descriptions, GPR reflections, and borehole logs.

Conclusion

In conclusion, this research presents some of the results discussed in Zaru et al. 2023 which introduces an inversion scheme for EMI data, employing a realistic prior distribution for vertical conditioning and incorporating ancillary information from an ERT cross-sections for lateral consistency in the final (pseudo-)3D resistivity volume. Our results highlight the severe non-uniqueness of EMI data inversion, emphasizing the importance of formalizing information through prior distribution samples and reference models. The proposed constrained scheme, integrating ancillary observations ab initio, demonstrate their effectiveness in addressing the ill-posedness of the original problem. Comparisons with the GPR cross-sections validate the proposed approach's capability to detect lithological interfaces and resistivity contrasts with decent resolution, considering the amount of information provided by the EMI survey is contained in just 3 frequencies. The computational efficiency of the strategy, coupled with its ability to provide a single reliable model, opens avenues for future exploration, including the potential implementation of a probabilistic solution to assess feature probabilities across different realizations of the posterior distribution. Overall, the proposed inversion strategy enhances the reconstruction of 3D resistivity volumes from EMI measurements, offering improved agreement with independent geophysical observations.

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Probabilistic Petrophysical Inversion of Ground-Based FDEM Data for Alpine Peatland Characterization: A Case Study in the Italian Dolomites

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Introduction

Peatlands, vital carbon reservoirs, often pose challenges in efficiently and reliably characterization of their geometry and volumes, particularly in alpine settings (Silvestri et al., 2019). Here, we investigate a probabilistic petrophysical method applied to ground-based frequency-domain electromagnetic induction (FDEM) data to quantify peat thickness and extension in an alpine bog situated in the Italian Dolomites, where peat overlays an electrically conductive clay substrate. While traditional FDEM inversion retrieves electrical resistivity, a direct estimation of the probability of peat or clay occurrence is preferable as that is the ultimate goal of the geophysical investigation (Grana et al., 2022). Additionally, the proposed probabilistic strategy addresses the limitations of oversimplified constraints and has practical applications for real-time fieldwork optimization. Generally, the ill-posedness of FDEM data inversion necessitates prior information. Traditional deterministic approaches utilize regularization terms, such as the L2-norm of the model gradient, which may oversimplify complex geological structures (Klose et al., 2022; Klose et al., 2023). The proposed probabilistic approach is capable to accommodate more complex (and realistic) prior information. Additionally, it naturally provides uncertainty estimates, crucial for the assessment of the reliability of inferred geological features. In this study, we apply probabilistic petrophysical inversion to an FDEM dataset collected on an alpine peatland, comparing results against traditional deterministic Occam's inversions and borehole logs.

Methodology

The research is focused on characterizing Alpine peatland structures in the Italian Dolomites through ground-based Frequency Domain Electromagnetics (FDEM). The study area is situated near Danta di Cadore in the North of Italy, encompassing a peatland of particular interest. A systematic survey was conducted across this targeted peatland area using the GEM-2 instrument

from Geophex (Haoping & Won, 2003). FDEM measurements were collected at the following frequencies: 1025, 1525, 2875, 5825, 7775, 12775, 15325, 25525, 36225, 63025, and 80225 Hz. A total of 153,621 soundings were acquired. To model uncertainties inherent in the petrophysical properties of the peatland structure, a probabilistic inversion procedure was employed. The procedure utilized an independent extended Metropolis algorithm - a variant of the conventional extended Metropolis algorithm proposed by Mosegaard and Tarantola (1995). In our specific implementation, an infinitely long step-length was selected; this implies that each new model proposal from the prior distribution represented a completely independent realization. Based on our expectation about the target, we created a prior ensemble of 10^5 1D models consisting of 200 layers (each 0.1 m thick),. The synthetic set of 1D models is realized by establishing a prior distribution based on the assumption of two distinct lithologies: peat and clay. Each geological model is considered made of three lithological units, allowing for varied configurations without imposing specific vertical arrangements, with interface depths and lithology assignments randomly generated. Resistivity values for each layer are drawn from distributions representing expected resistivity ranges for peat and clay, followed by a smoothing process to introduce vertical spatial coherence. The resistivity ranges associated with each category are consistent with relevant literature examples for peat and clay soils. For each sounding location, the response $F(m)$ of each prior realization was compared
against the observed data d using the conditional probability (and assuming normally distributed noise in the measurements):

$$p(m) = k_d exp\left(-\frac{1}{2}\left(d - F(m)\right)^T C_d^{-1}\left(d - F(m)\right)\right), \quad (1)$$

where k_d is a normalization factor, C_d takes into account the data covariance, and often selected such that $diag\left(\sigma_d\right)^{-2} = C_d^{-1}$, with each component of the vector σ_d being the standard deviation of the corresponding data element. Notably, this inversion scheme was implemented using the SIPPI toolbox (Hansen et al., 2013a; Hansen et al., 2013b).

Results

Figure 1 shows the horizontal slices at the depths of 3.0 m and 7.0 m, depicting the realization of the posterior distribution with maximum likelihood and the probabilities of encountering peat and clay. Peat is predominant in the northern-central area, extending from the surface to depths exceeding 7.0 m, with a shallower deposit in the southern part. The spatial coherence of the results is noteworthy, considering that each sounding was inverted separately without spatial constraints.
Verification against boreholes reveals the geophysical reconstruction aligns well with the morphology of the peat unit (Fig. 2). Some mismatches can be potentially attributed to 3D effects (Bai et al. 2021) or actual distance from the inverted and the borehole locations (for instance, borehole B31* is approximately 4 m away from the inverted section). Moreover, boreholes were originally drilled aiming at reaching the top of the clay layer but that was not always possible. In this respect, only those actually hitting the top of the clay unit are denoted with an asterisk, such as B31*. The maximum likelihood model exhibits spatial coherence without explicit regularization, emphasizing the impact of prior information on stability. Comparisons in terms of data fitting show the maximum likelihood model closely matches the observations, exhibiting a chi-squared value

generally lower than 1 (Fig. 2 – top panel). For sake of completeness, the probabilistic inversion was

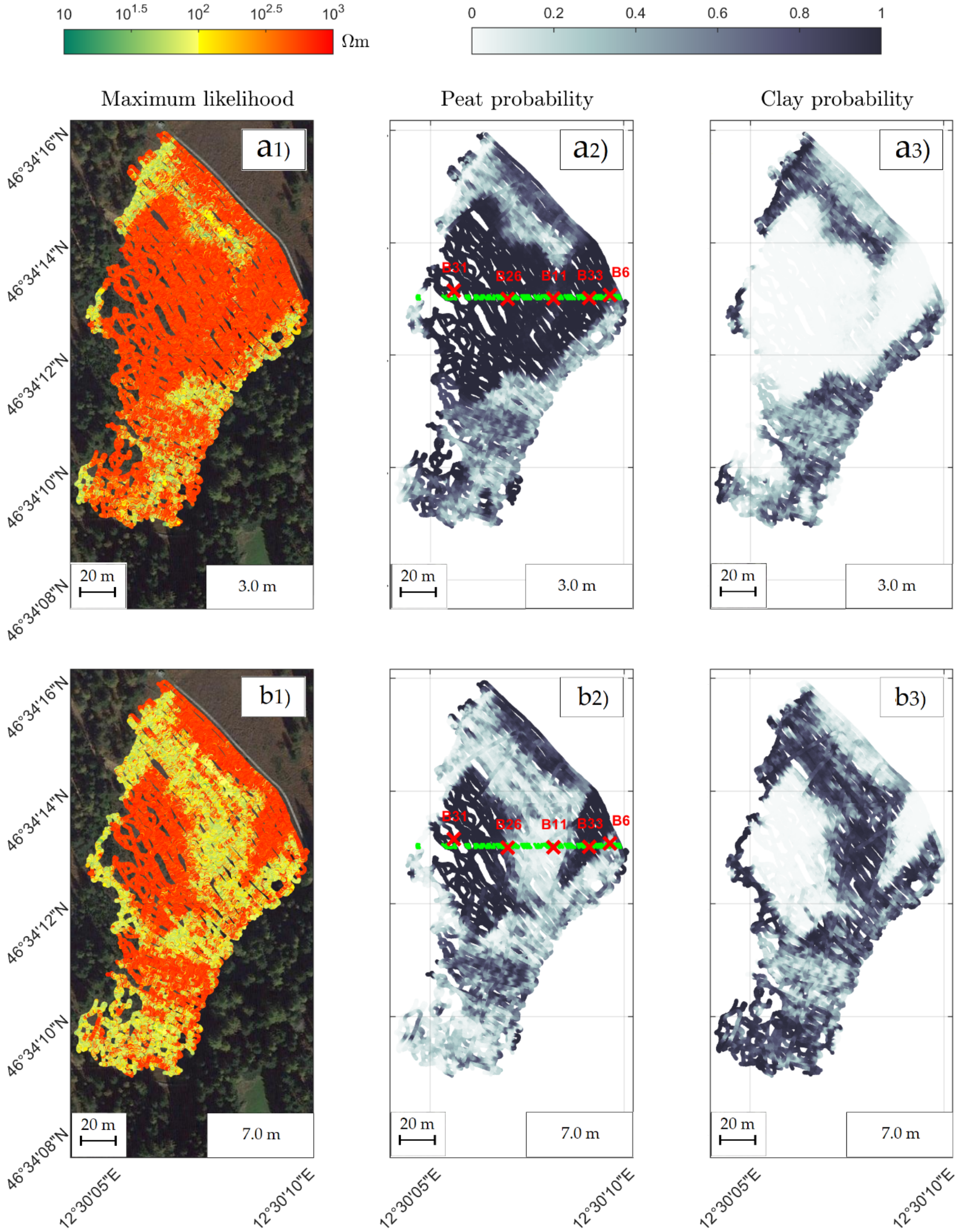

Fig. 1 – Horizontal slices presenting the inversion outcomes derived from the Frequency-Domain Electromagnetic Induction (FDEM) data collected across the Danta peatland in Italy. Each row shows the resistivity model with maximum likelihood and the probability of encountering peat or clay. Rows (a-b) depict these models and probabilities at depths of 3.0 m and 7.0 m respectively. In the third column, above the peat probability, the figure displays the profile's location shown in Figure 2 (highlighted in bright green), along with the positions of associated boreholes marked by red X.

compared against the traditional Occam's inversion (Fig. 2 – middle panel) obtained by using EMagPy (McLachlan et al., 2021). In the case of deterministic inversion, special care was devoted to the selection of the Tikhonov's parameter to reach the chi-squared values in the range of the optimal value 1 (Fig. 2 – top panel). Despite the similar data fitting, the deterministic inversion seems to favor vertically elongated structures (opposite to our expectation about the presence of a peat-clay interface and the information from the boreholes). In contrast, the probabilistic approach, whose spatial consistency is attributed to complex prior information, seems to offer a more accurate portrayal of the peat unit's morphology.

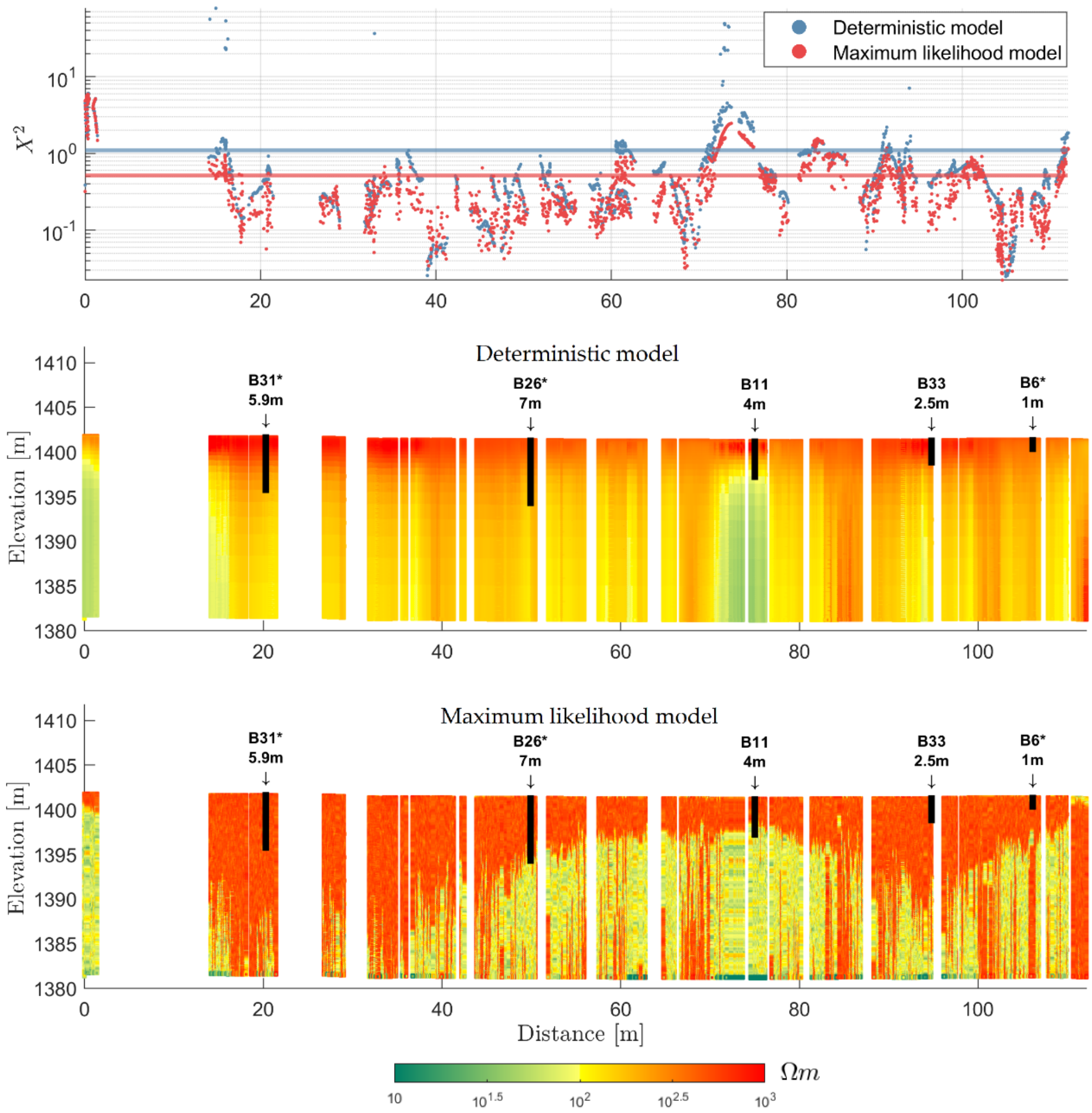

Fig. 2 – Vertical profile presenting the chi-squared value of the deterministic (blue) and maximum likelihood (red) models in the top panel. The deterministic model obtained with the standard Occam's inversion is shown in the middle panel; the maximum likelihood model obtained with the probabilistic inversion in the bottom panel. The horizontal blue and red lines in the fist panel represent the average chi-squared values associated with the two models.

Figure 3 depicts the probability of having peat and clay in the examined section. Clearly, the portion between the boreholes B26* and B11 is well correlated with the peat-clay interface. The big difference between the peat probability and the Occam's result highlights one more time the influence of different prior information in the two approaches (probabilistic and deterministic): the detailed information represented by samples in the prior distribution facilitates the reconstruction of a geologically consistent structure of the peat unit, whereas the deterministic method is forced to provide (vertically) smooth solution. It is worth noting that B26* is the most reliable borehole as, unlike the others, its core has been extracted and analyzed (Poto et al., 2013), proving the presence of 6 meters of peat followed by roughly 1 meter of gyttja (more decomposed peat).

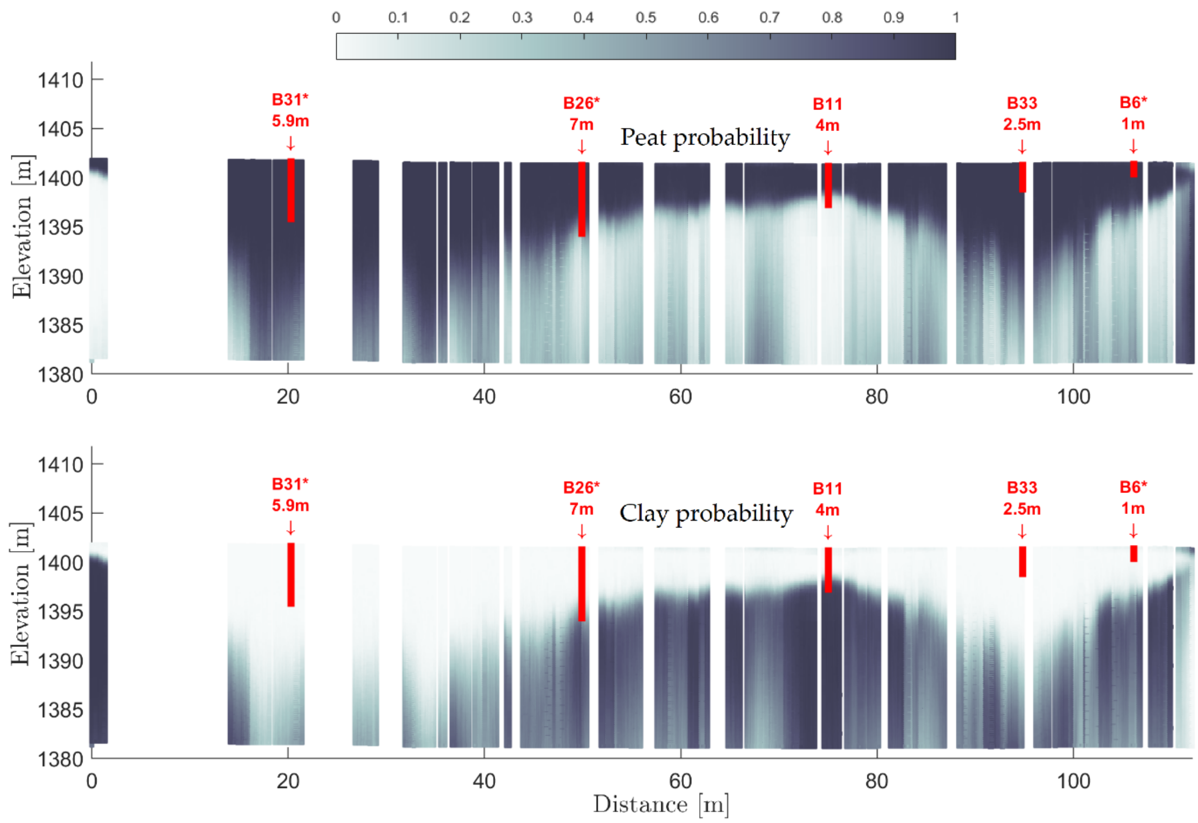

Fig. 3 – Vertical profile presenting the inversion outcomes derived from the Frequency-Domain Electromagnetic Induction (FDEM) data collected across the Danta peatland in Italy.

In terms of inversion performance, the probabilistic approach, relying on forward calculations of prior samples, proves computationally efficient and parallelizable. The calculation of conditional probability for the entire dataset takes around one hour, while generating prior samples and associated measurements adds another hour. In contrast, a deterministic inversion of the entire dataset was computationally infeasible as it required more than a day for the inversion of the 2D section considered here.

Conclusion

This research demonstrates the efficacy of a probabilistic petrophysical inversion approach in characterizing the complex subsurface structures of alpine peatlands. By applying ground-based frequency-domain electromagnetic induction (FDEM) technology to an Italian Dolomite peatland, where peat overlays a conductive clay substrate, the study surpasses the limitations of traditional deterministic Occam's inversions. The probabilistic approach, rooted in Bayes' theorem, allows for the incorporation of realistic prior information, offering a more geologically meaningful representation of the subsurface. The spatial coherence observed in the results highlights the stability and accuracy of the proposed approach, even if each sounding is independently inverted without explicit spatial constraints (Zaru et al. 2023). Verification against boreholes and comparisons with deterministic results highlights the reliability and efficiency of the proposed strategy. Moreover, the probabilistic approach inherently provides an estimation of the uncertainty of the results that is quite problematic in deterministic framework.

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