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INGV meeting on Georesources

Rome, 14 February 2023

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Preface

Georesource studies at INGV and the role of Geoscientists – a day of debates

Monia Procesi* & Mario Anselmi**

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On February 14th, 2023, INGV-Rome hosted a working day focused on studies, led by INGV researchers, having as the main topic the geo-resources.
The geo-resources and more in general, the geo-energy themes, have particular importance considering the continuous increase in the global energy demand and the urgent need to devise strategic energy plans to promote low-carbon technologies and energy independence of the Countries.

Furthermore, the current global geopolitical context and the potential long-term impacts of the Russia-Ukraine conflict pose a threat to the energy supply of numerous countries that rely heavily on fossil fuels, such as Italy. In this framework, the substantial increase in the use of renewable energy sources, such as geothermal, wind, hydro, and solar energies represents a mandatory choice that needs to be encouraged; as well as the approach to new exploration frontiers, as the hydrogen, and new-unconventional exploitation techniques, for example, for raw-strategic materials.

On the other hand, addressing climate change is a top priority and requires immediate action. In this framework, the industrial technologies that can decrease CO_2 emissions must be implemented without delay to eventually eliminate them.

The presented context, which is also highlighted in the United Nations *Sustainable Development Goals* (SDGs) and formally supported also by INGV, emphasizes the crucial role of Geoscientists in the field of georesources. Their contribution will be crucial in addressing society's future challenges, ensuring the availability of vital resources, providing access to clean and sustainable water supplies, sourcing and extracting critical minerals for green technologies, understanding the subsurface potential for geothermal energy exploitation, developing safe carbon capture and storage infrastructure and technologies, mitigating climate change, and influencing government policies by comprehending past climates, modeling potential future outcomes, and understanding climate impacts on the environment, likelihoods, and natural hazards (see Fig. 1).

In this context, the "INGV-Georesource Day" assumes a particular relevance by putting together geoscientists with expertise in this sector and creating a moment of knowledge sharing and discussion.
The day was divided into four thematic sessions: i) Carbon Capture, Usage, and Storage - CCUS (abstracts n.1-4), ii) Geothermics (5-9), iii) Fracturing and seismicity (10-13), iv) Government Assignment (14-15). Two additional presentations were added, one relative to natural hydrogen research and the other on water supply in small Italian islands (16-17).

During the day, ongoing projects and completed ones were presented, by passing through the global overview of CCUS and the Italian geothermal potential and then focusing on dedicated projects and specific investigation approaches such as structural-geological field surveys and geological modeling, survey geophysical methods useful for geothermal exploration, fluid geochemistry, and numerical geochemical modeling. Potential synergies and useful inputs have been offered by the presentations focused on the anthropogenic seismicity associated with the exploitation of georesources, in the framework of the EPOS web-portal. Moreover, in the framework of the ERC-FEAR project (Fault Activation and Earthquake Rupture), the role of the fluid injection at depth and the pore-pressure variations has been described to better understand natural and induced/triggered earthquake nucleation.

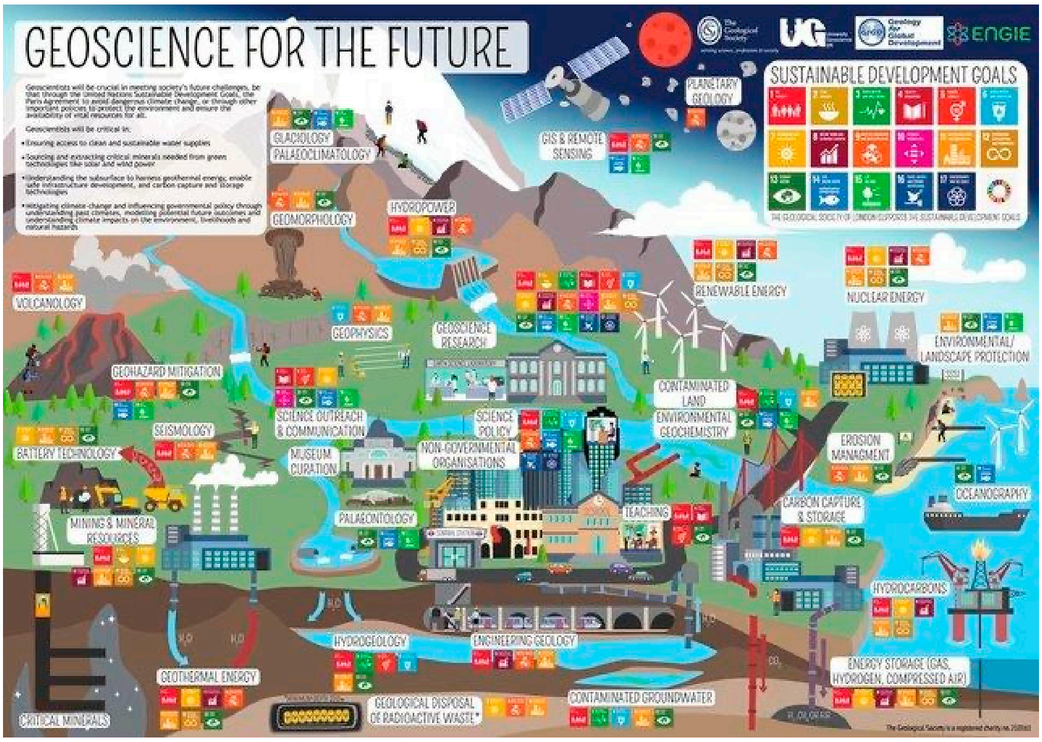

Figure 1 The Geoscience for the Future poster published by the Geological Society of London showing the 17 UN Sustainable Development Goals and the many geoscience subdisciplines related to the SDGs (https://www.geolsoc.org.uk/~/media/shared/documents/education%20and%20careers/Resources/Posters/Geoscience%20for%20the%20Future%20poster.pdf?la=en)

The extensive final discussion allowed for a real debate among the researchers, highlighting several criticisms of the Italian research system dedicated to the georesource field, putting attention on the lack of dedicated government programs. An important assessment, which has had a wide convergence of views, highlighted how the INGV has the human expertise and laboratory infrastructure to carry out a high-level georesource research activity, both at the national and international levels of leadership.

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CARBON CAPTURE, USAGE, AND STORAGE

Microseismic monitoring and CO_2 storage: The "Sotacarbo Fault Lab" case

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Nowadays, the coincident needs of both the strategic energy supply sources and the reduction of Greenhouse Gases emissions, focuses the choices of the governments worldwide to invest in the energy mixing and the energy transition technologies.
The geological storage of CO_2 represents, for sure, one of the most important "bridge technology" in order to reduce the carbon emission. It could pass through the assessment and mitigation of risks, potentially induced or increased by the disposal activity. As well known, injection of moderate to large quantities of CO_2 in the sub-surface may unbalance local stress and trigger earthquakes if faults are critically stressed, condition that is not easily verifiable. Pilot sites are therefore the best way to proceed further to address such challenging issues. In this study, we present the results of the Sotacarbo Fault Lab (Sulcis, South-Western Sardinia) pilot site, which is located in a very low seismic hazard region of central Mediterranean.
In this study we show the results from a prolonged experiment designed around the pilot site. As expected, seismicity is poor and absent down to small magnitude close to the future injection-test well. Seismic imaging of the sub-surface layers with ambient noise tomography permits to resolve the presence of a seismicity-free fault located in the first 100 mt below the surface, which last episode of activity is difficult to assess.

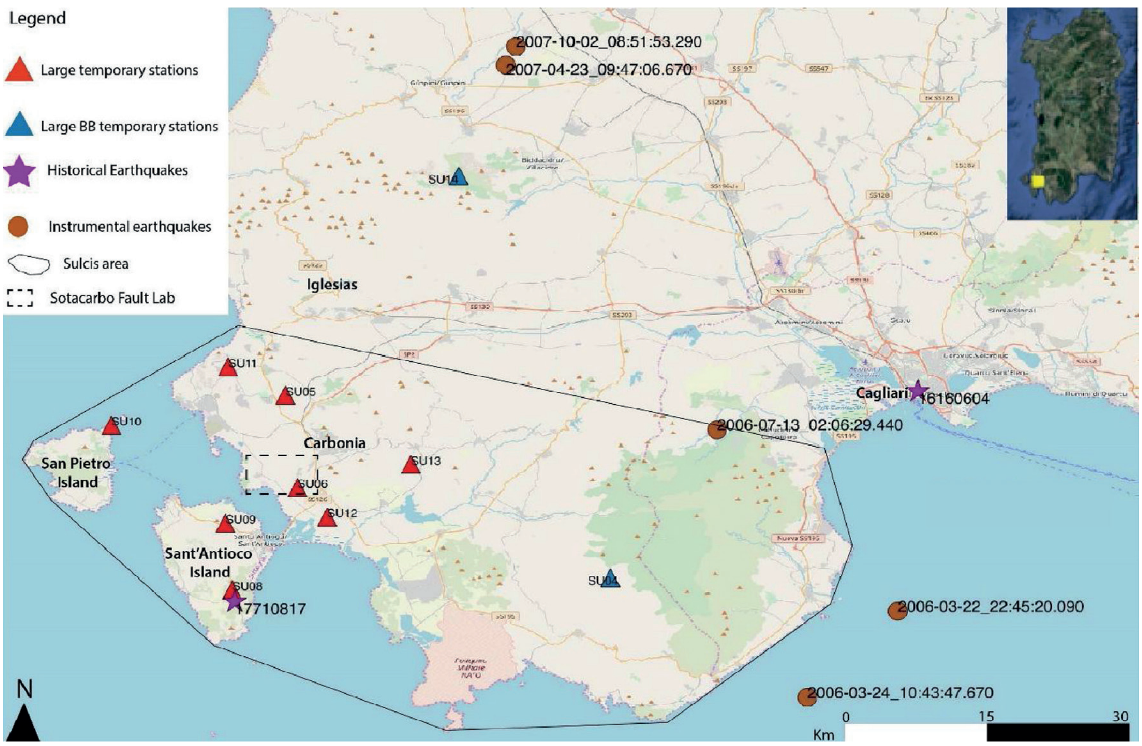

Figure 1 Map of the study area in South-Western Sardinia.

3D geological modeling for the sustainable use of geo-resources

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The geological modeling of underground structures has always been one of the main topics involving the scientific geology community to give quantitative answers to the vast demands of geo-resources, like water (drinking water and agriculture), minerals for technological applications, energy production (coal, oil, methane, nuclear, hydroelectric, geothermal), building materials, and waste storage (wastewaters, carbon dioxide) and disposal (nuclear).

The understanding and modeling of buried geological structures progressively become a strategic objective for evaluating and sustainable management of the subsurface resources (capacity evaluations for extraction and storage) and the associated hazard assessments (e.g., induced seismicity, leakage, surface degassing).

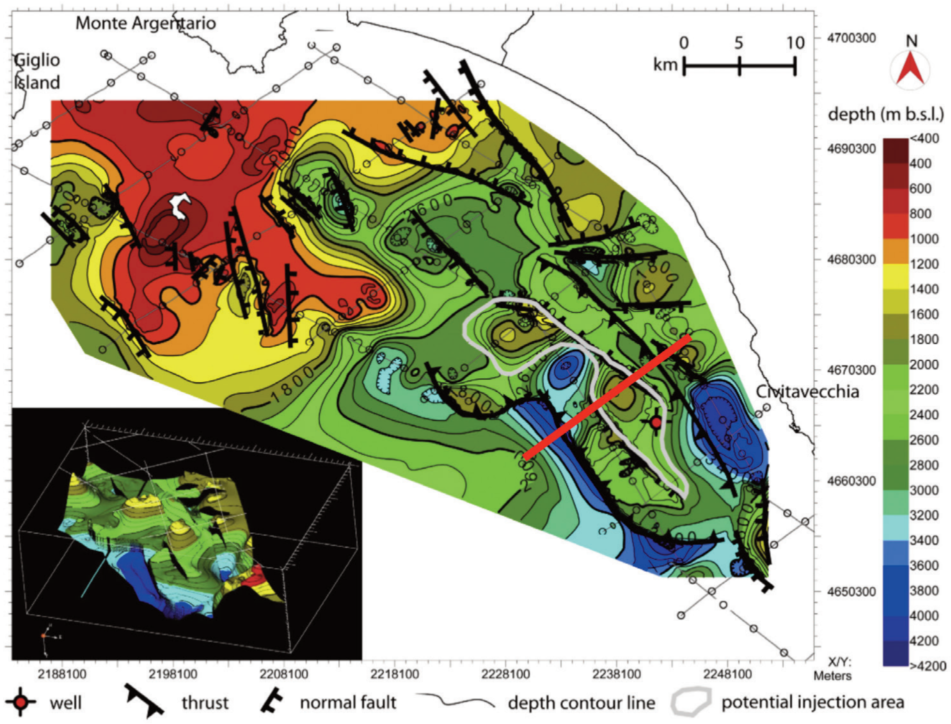

Figure 1 Upper Panel: geological modeling of a potential geological site for carbon dioxide or natural gas storage in the Tyrrhenian offshore of central Italy [Procesi et al., 2013].

Some impelling actions must be made to tackle the reduction of anthropogenic gas emissions into the atmosphere and the transition to a more green and sustainable way to get the massive amount of energy the human society needs. In that view, the geological modeling perfectly fits such an approach for a new way of geo-resources recovery thanks to integrating various types of data (e.g., geological, geophysical, geochemical, etc.) throughout a multi-scale and multi-disciplinary approach.

INGV could realistically cover all the modeling aspects at different scales for such purposes, having the human and infrastructural architecture built throughout the participation in national and international projects to evaluate resources and their potential uses and associated natural hazards.

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Geochemical reactions in CO_2 Geological Storage

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CCS (Carbon Capture and Storage) has been recognized as being able to efficiently mitigate the climate change induced by greenhouse gases [IPCC, 2014]. This technique requires the capture of CO_2 from industrial flue gas plants and the subsequent injection, after compression, into suitable natural geological formations at depth above 1000 m [Holloway 1996]. Suitable storage sites are exhausted hydrocarbon reservoirs, saline aquifers and unmineable coal beds.
Investigation of geochemical reactions between CO_2-rich fluids and host rocks is a prerequisite to ensure safe storage at depth. Indeed, CO_2 is highly reactive gas and, once injected into a saline aquifer partially dissolves, lowering the pH of formation waters and promoting mineral dissolution. The mixing between the acidic plume and the formation waters (Figure 1) favours the precipitation of previously dissolved salts as secondary minerals, consuming CO_2 and trapping it permanently [Gunter et al., 2004].

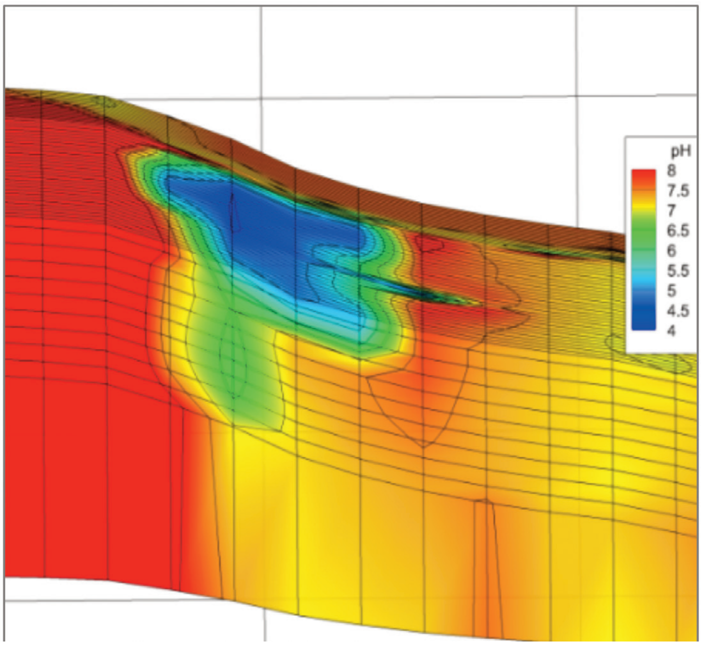

Figure 1 pH distribution after 100 years from the end of CO_2 injection in a clastic reservoir.

In the last 20 years INGV has carried out several projects with the aim to evaluate these processes in different deep structures, both in Italy and abroad. We used numerical models of CO_2 reactive transport to look at how geochemical reactions change porosity and permeability and to see how CO_2 moves through porous media over time [Cantucci et al., 2009; Cantucci et al., 2015]. Leakage scenarios throughout heterogeneous shaly caprock and along open-circuit faults were also investigated.
The main outcomes show that permeability distribution has the main impact on CO_2 migration pathways and geochemical reactions. In low-permeability rocks, the precipitation of minerals

can create geochemical barriers to CO_2 transport, reducing injectivity and increasing the overpressure of the system.

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Carbon capture or hazard release? Geoscience opportunities, strategic assets, and a couple of headaches

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EU and global commitments for CO_2 reduction [UNFCCC, 2022] include removal of major volumes, to be captured and stored underground. For such efforts to affect current concentrations, CCUS at the Gton/yr scale is required, far greater than the Mton/yr delivered by pilot projects [Wang et al., 2021], and upscaled in the future, as population growth [UN, 2022] will drive construction, thereby cement, and steel, whose emissions are inherently hard-to-abate [IEA, 2022].

However, although promising and needed, massive-scale CCUS is not devoid of potential associated hazards (including induced seismicity) [Cheng et al., 2023]. Also, it requires unevenly distributed subsurface conditions and dictates major understanding of pre-existing geophysical processes [GCCSI, 2016; Zoback and Gorelick, 2021]. Albeit fantasy-ridden, a visual synthesis of such a conundrum was provocatively depicted by submitting a metaphor encompassing most of these facets to a renown generative AI tool (Figure 1). However, whatever AI/ML procedure can be exploited to explore the conflicting complexities such as those hinted at here, geoscientists should undoubtedly be centerstage to drive energy policies and hazard assessment in these endeavours.

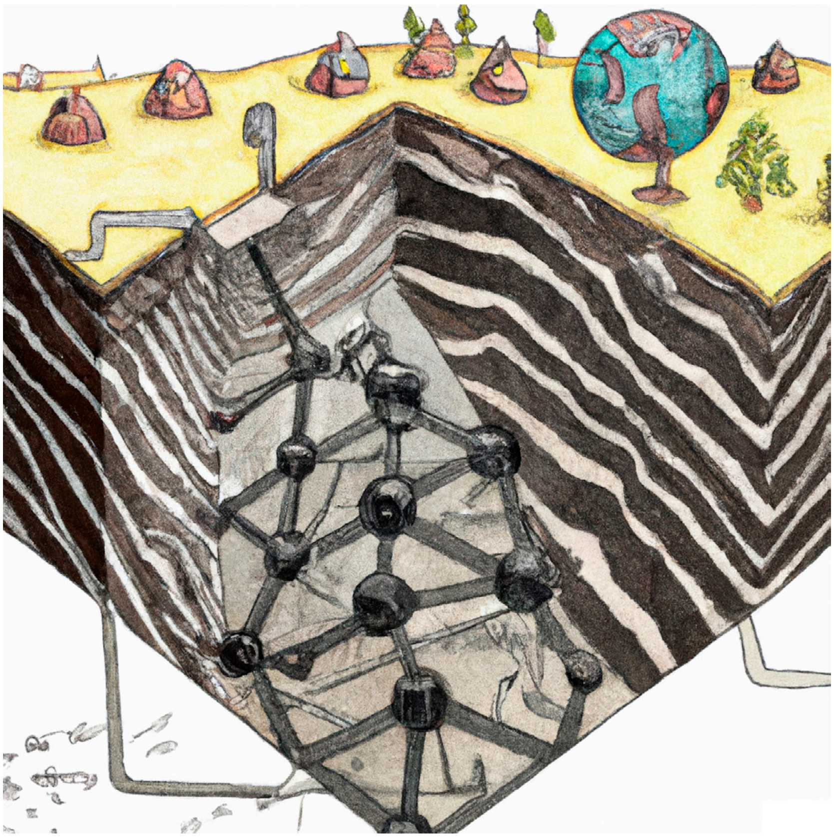

Figure 1 "A fantasy geological subsurface sketch connected with carbon capture storage, in Escher style", © DALL·E-2, https://labs.openai.com/c/PLmx3hKXtmlNdY3wiklSbt7e.

This applies all the more to CCUS, which is but one potential tool that may contribute to long-term energy strategies, in turn prospectively influencing the CO_2 stock that contemporary and future societies need to turn from foe to friend. Any of these pivotal elements go through stored sources of energy, mineral resources, subsurface location, geophysical hazards to be monitored and predicted – the Earth Sciences.
The investigative tools that geoscientists (as cross-and trans-disciplinary as they can and will be) can probe, devise, deliver, and monitor are manifold, long-standing, and instrumental for the well-being of humankind as it entered one century of ample, multiple, concurrent complexities bridging needs, strategies, and hazards.

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GEOTHERMICS

Magnetotelluric surveys for the exploration of geothermal resources

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All the projects for geothermal energy exploitation need the development of a preliminary research phase which is fundamental to assessing resources. This phase aims to identify the surface extent, volume, and rock and fluid properties of the geothermal resource and collects all necessary information for investing in a type of geothermal use.

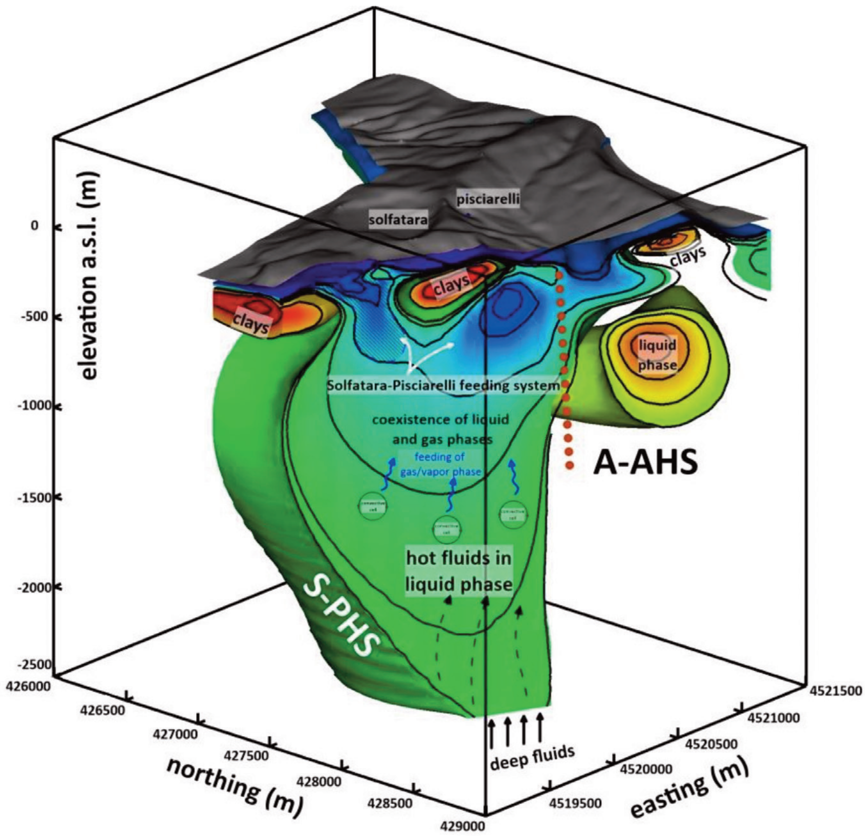

Figure 1 Sketch model of the central sector of Campi Flegrei Caldera obtained through MT survey. The 3D resistivity imaging detects a reservoir permeated by a mixture of fluids in coexisting liquid and vapor phases, confined below the 200 m depth b.s.l., of about 1300 m thickness and feeding Solfatara and Pisciarelli fumarole fields.

Geothermal systems generally consist of rock volume with different porosity with a system of faults and fractures filled with hydrothermal fluids. The most proficient sources of information aimed to evidence the role and distribution of geothermal fluids, their interactions with the meteoric recharge and the main structural lineaments, and the effects of their circulation on the surrounding rock are the electrical resistivity-based prospections [Spichak and Manzella, 2009]. The high sensibility of this parameter to the presence of conductive fluids in the rock matrix and to factors such as temperature, porosity, permeability, saturation, fractures, and rock/soil type makes these techniques widely employed in the exploration of geothermal areas [Ussher et al., 2000; Cumming, 2009]. The magnetotelluric (MT), in particular, is the standard tool for investigating resistivity structures at depths from hundreds of meters to several km. It is a non-invasive method through which the detail of the electrical resistivity contrasts present in the subsoil can be reconstructed by analyzing the electric and magnetic fields naturally induced in the subsoil by external sources. In recent years, many papers have been published about using MT for exploring geothermal zones [Munoz, 2014; Di Giuseppe et al., 2017]. Figure 1 shows an example of a 3D MT model of the central sector Campi Flegrei caldera [Troiano et al., 2022]. Volcanic geothermal areas are usually characterized by a low resistivity clay-cap layer (few tens of Ω·m) overlying a resistive zone where the reservoir is located. The application of MT method can easily detect such resistivity contrast.

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The geothermal potential of eastern Sicily

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Eastern Sicily is one of the most promising areas in terms of geothermal potential in Italy, since it is an area rich in geological and geodynamic elements that allow very favourable conditions for the development of geothermal systems of various extensions and depths. First of all, there are various active volcanic areas (Etna, Stromboli, Vulcano, Lipari, Panarea) or areas that were active in recent geological times (northern Iblei Mountains: last eruptive activity around 1.2 ma). Moreover, there are several regional lithospheric faults, many of which are seismically active (Iblean-Maltese escarpment, Messina-Comiso system, Tindari-Letojanni fault) and allow, with their movement and accumulation of tectonic stress, the development of intracrustal conditions for geothermal anomaly.

Figure 1 Drilling VU2bis at Vulcano island during the test for production of dry vapour in 1955 [from Sommaruga, 1984].

Already back in the 1930s there was an attempt to exploit steam emissions near the summit of Etna [Ponte, 1927; 1931]. Until 1971 a persistent fumarole, called “Vulcarolo”, was existing at

3100 m asl and it was exploited for about 30 years to condense the volcanic steam and convey it towards the nearby Etna Observatory for heating and drinking purposes. However, the first geothermal explorations for energy production took place on the island of Vulcano in the early 1950s [Occella, 1951; Sommaruga, 1984]. At the end of August 1950, in fact, the first exploratory drilling was carried out near the Grotta del Faraglione, which produced emissions of steam under pressure for several hours. However, the wells were abandoned as the geothermal systems found were very unstable and not optimal for the prospecting technology existing at the time.
Recent studies on the geothermal favourability in Sicily [Trumpy et al., 2015] have highlighted many interesting areas for potential geothermal exploitation on the island, but in-depth and coordinated research is still needed to better define the actual geothermal potential of this area according to the different types of exploitation of the resource.

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An example of multidisciplinary approach for investigating the shallow portion of an active geothermal system

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A multidisciplinary approach involving fluid geochemistry, structural geology and seismology has been adopted for investigating the shallowest portion of the Larderello-Travale geothermal field (Tuscany, Italy). Field works were performed in the natural degassing area of Le Biancane, where the geothermal reservoir outcrops for the local absence of the impervious caprock [Ceccarelli et al., 1986].
Compositional data of local high-T fumaroles confirmed that H_2O is the main geothermal component (98-99 % mol), followed by CO_2 (0.5-1 % mol), and minor amounts of H_2S, CH_4, N_2, H_2, He, Ar, CO and COS. The stable isotope compositions of steam condensates indicate that some deep fluids have compositions consistent with the fluids feeding geothermal wells affected by re-injection of spent steam, while others have similarities with the composition of geothermal wells before re-injection and therefore with the primary steam and local springs [Granieri et al., 2023].

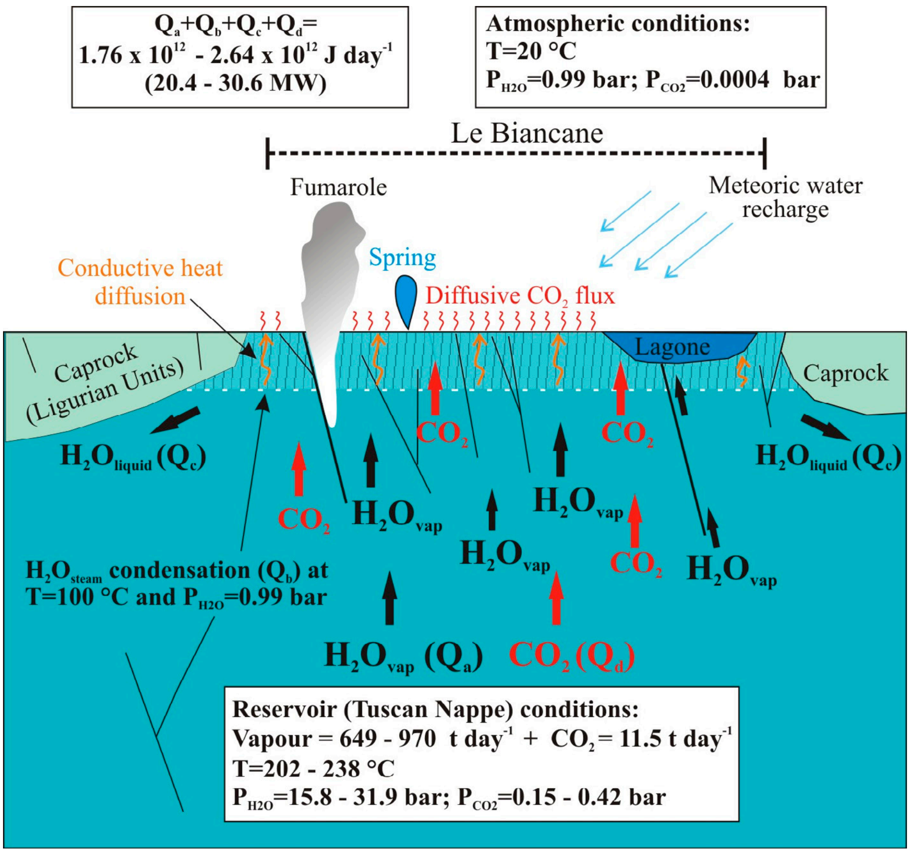

Figure 1 Sketch showing the surface manifestations and the general movement of fluids and heat at Le Biancane. Fluids upflow along cracks, faults or fractures with very steep dips and preferential NW-SE and NE-SW orientation (the base of the sketch is from Hurvitz et al. [2012], modified).

A total output of 11.5±0.77 t day^{-1} CO_2 was estimated from an area of about 60,000 m^2 by using geostatistical processing of soil CO_2 flux measurements. The locations with the most notable CO_2 degassing lie in some spots of the investigated area where the highest soil temperatures were recorded. Because the "anomalous" zones coincide with local well-connected cracks (faults and fractures), preferentially NW-SE and NE-SW trending, we believe that these cracks provide preferential but temporary pathways for fluids and heat to migrate to the surface. We estimated a thermal energy associated with the natural degassing of Le Biancane ranging from 20.4 MW to 30.6 MW (Fig. 1). This energy heats conductively the near-surface layer, producing a spatial distribution of the surface temperatures that is correlated with the soil CO_2 flux in some sectors of Le Biancane [Granieri et al., 2023].

In addition, we verified that the fluid degassing produces continuous seismic noise in the typical range 3.0-9.0 Hz.

Our findings suggest that the multidisciplinary approach is a suitable method for a better comprehension of geothermal dynamics, both in productive and exploratory stages.

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Geothermal potential of Italy

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Geothermal energy in Italy could be a valid choice to facilitate the energy transition toward sustainable energy choices. It certainly does not represent the unique solution, but geothermal energy certainly is one of the main resources in Italy capable of leading this transition, not only through the production of electricity but also through the direct use of resources. This consideration is strongly linked to the wide distribution on the Italian territory of geothermal resources interesting for both direct (thermal) and indirect uses, such as geothermal power production.

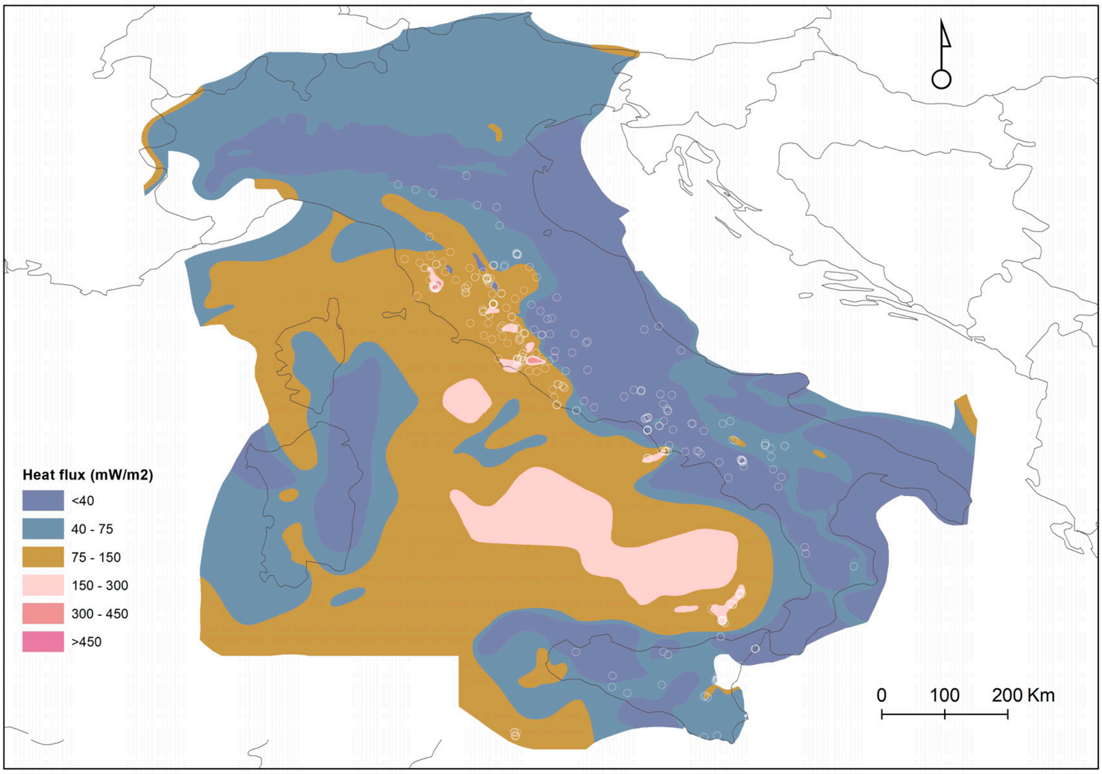

Figure 1 Heat flux map of Italy, the white dots represent hydrothermal manifestations (data from MaGa portal http://www.magadb.net/) [modified from Della Vedova et al., 2001].

The distribution of geothermal resources is driven by the geological setting of the Country, characterised by two large mountain ranges, the Alps and the Apennines and by intrusive and effusive volcanic complexes, linked to post-collisional extensional tectonics and lithospheric thinning. These volcanic complexes are located along the peri-Tyrrhenian margin, in eastern Sicily (including the Aeolian Islands and Pantelleria) and in the Campidano graben also, and are characterised by medium-high geothermal gradients (>30°C/km) and hydrothermal manifestations such as thermal waters, diffuse degassing, bubbling pools and fumaroles (figure 1). Conventional (hydrothermal) geothermal systems are located in these active and inactive volcanic areas. The Tuscan geothermal fields of Larderello and Monte Amiata exemplify that. Localised thermal anomalies can also be found in areas not characterised by peculiar hydrothermal manifestations, such as the Po Valley and some sectors of the Adriatic coast, where above-average heat flows (>70mW/m^2) can be found. These areas can host potential geothermal systems of both low (<100°C) and medium temperature (<150°C), interesting for thermal uses, but also indirect uses, employing the most modern technologies to allow geothermal production even in areas with non-typical hydrothermal-geothermal features. Despite the huge Italian geothermal potential and the strong know-how of the Italian scientific and industrial community, exploration and production, it has not been possible over the years to spread the virtuous Tuscan model to other equally promising regions. Unfortunately, this represents a big evolutionary gap for the national energy plans.

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Large-scale climate-neutral energy geostructures in district heating & cooling systems

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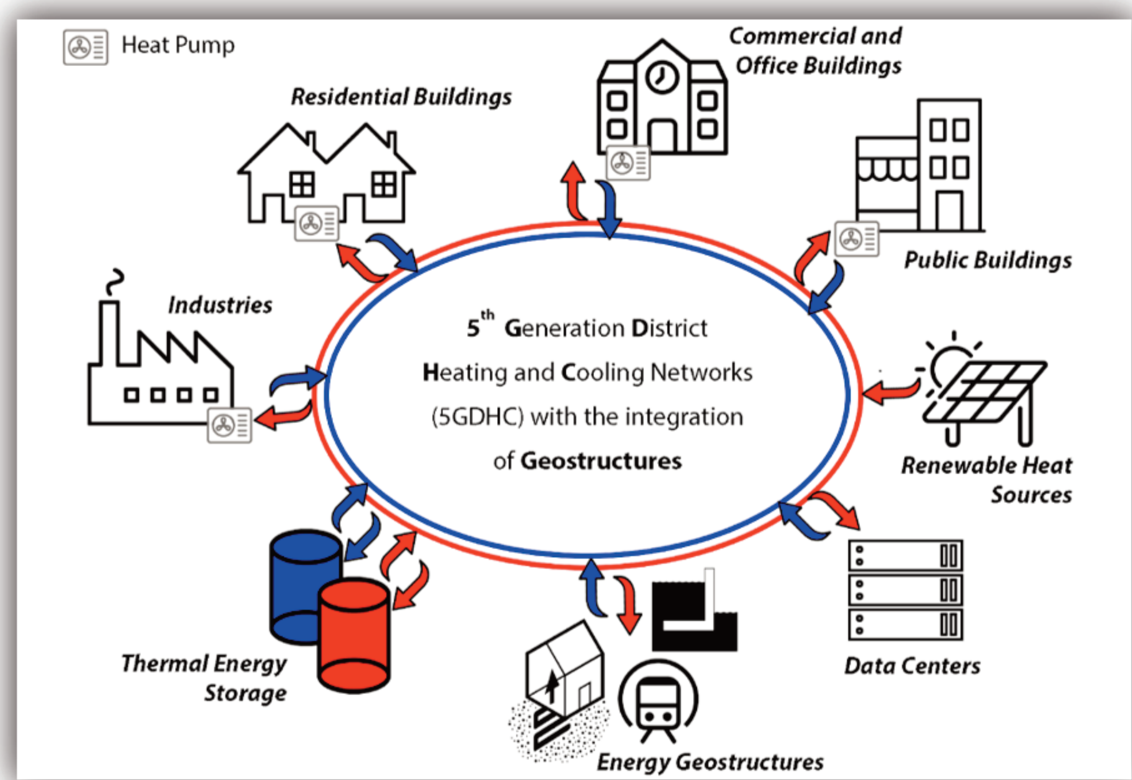
Energy Geostructures (EGs) represent an environmentally friendly and cost-effective way of heating or cooling a building. EGs combine the dual role of supporting loads and generating a thermal exchange with the surrounding soil [Laloui and Rotta Loria, 2019]. They are becoming increasingly popular as the demand for renewable energy continues to grow. Some examples of energy geostructures include foundations (Energy Piles, EPs), walls, and tunnels, but EPs remain by far the most common application [Di Donna, 2017]. The main advantage with respect to other conventional closed geothermal systems (probes) is the significant reduction in initial installation costs; this reduction being due to the use of geostructures that would be constructed anyway. This technology is still under development, but the number of structures and buildings based on heat exchanger piles is increasing exponentially in Europe without any slowdown being expected at present. The recent introduction of the fifth-generation district heating and cooling (5GDHC) networks can pave the way for the exploitation of energy geostructures as ground-coupled low-temperature energy sources and stores for providing energy demands of a wider range of energy users in districts rather than single buildings [Meibodi and Loveridge, 2022].



Recently, a European network for FOstering Large-scale ImplementAtion of energy GEostructure (FOLIAGE) (https://www.cost.eu/actions/CA21156/) has been funded to address the main technical and non-technical barriers that still prevent actual implementation of the EGs at a large scale. Some of the challenges may be related to: *a*) integration issues, including shallow geothermal energy with other renewables, and EGs with other shallow geothermal sources, *b*) upscaling from the mastering of individual structures to the planning of geothermal district heating and the connection with the city scale, *c*) sustainability in the long term in terms of Environmental Impact Assessment and knowledge of the long term energy performance, *d*) lack of legislation, financial incentives, standardization or under-developed skills.

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FRACTURING AND SEISMICITY

Fault reactivation by fluid injection: insights from laboratory friction experiments with multiple reactivation sequences

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Several human activities involve the underground injection of fluids under pressure: disposal of wastewater, CO_2 storage, and production of geothermal energy. However, fluid injection and increase of pore pressure at depth can perturb the stress state, create new fractures, and reactivate nearby faults. When reactivated, faults might produce induced or triggered earthquakes eventually damaging and making the human use of georesources unsustainable. The increase of pore fluid pressure is known to promote fault reactivation by reducing the effective stress on the fault. However, the style of reactivation, whether seismic or aseismic, is not clearly constrained. By combining laboratory experiments and numerical simulations, the pore pressure increase was shown to produce aseismic slip at the fluid injection point. However, the stress changes related to pore pressure increase triggered seismic slip nearby [Cappa et al., 2019]. The ERC-SYG FEAR project aims at studying the physical processes underlying induced earthquakes by combining fluid stimulation in the Bedretto Underground Laboratory for Geosciences and Geoenergy (BULGG), numerical models and laboratory experiments.

We run experiments under fluid pressurized conditions in a true triaxial machine [Collettini et al., 2014] and in a rotary shear machine [Di Toro et al., 2010] on a fault gouge sampled directly from the fault targeted for fluid stimulation in BULGG. We show that the fault gouge is a strong, velocity strengthening and therefore inherently stable material that can be effectively reactivated and de-stabilized by the action of pore fluid pressure increase [Volpe et al., 2023]. Moreover, we imposed two subsequent fluid stimulation and reactivation sequences on the same fault gouge using the rotary shear apparatus employing a novel experimental setup [Aretusini et al., 2021] (Figure 1). In the first reactivation slip accelerated up to a velocity V=0.1 m/s, whereas in the second slip accelerated and decelerated cyclically (0.1<V<1 mm/s) before accelerating up to V=0.1 m/s. The second reactivation occurred for a higher pore pressure (6.8-6.9 MPa) than the first reactivation (6.5 MPa), indicating an increase in fault strength. Meanwhile, fault-normal permeability decreased from ca. 10^{-16} m^2 to 3.10^{-17} m^2 after one reactivation and then remained constant at 3.10^{-17} m^2 before and after the second reactivation.

These results provide a first step toward the further understanding of the physical process controlling seismic fault reactivation by pore pressure increase. Here we suggest that complex slip histories during fault reactivation cycles induced by pore pressure increase result in an increase of frictional strength, fault dilatancy and frictional instability.

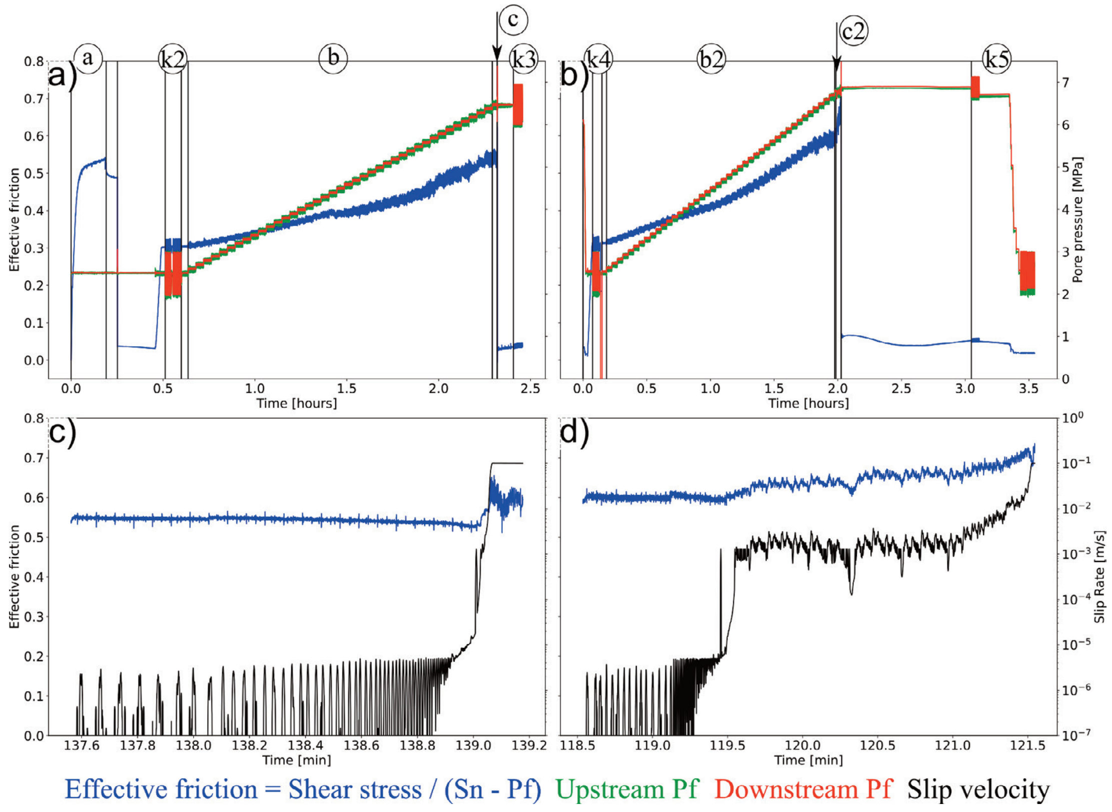

Figure 1 Experimental protocol of the fault reactivation by pore pressure increase. a) First and b) second reactivation cycles. (a) is a low velocity slip, (b) and (b2) are the fluid injection stages leading to fault reactivation (c) and (c2), intertwined with several measures of permeability by the pore fluid pressure oscillation method (k2), (k3), (k4), and (k5). Reactivation stage: starting from the last or second-to-last pore pressure increase step, the fault either evolves into: c) a dynamic instability (Pf=6.5 MPa), or d) into a slip oscillation stage (Pf=6.8 MPa) which is forced into a dynamic instability by one further step increase in pore pressure (Pf=6.9 MPa).

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Experimental studies for georesources: sustainability, feasibility and safe exploitation, at the HPHT laboratory INGV

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The High Pressure – High Temperature (HPHT) laboratory of INGV – Rome (Italy) has state-of-the-art equipment and facilities in several disciplines including experimental petrology, experimental volcanology, rock and earthquakes mechanics, and microanalysis. These facilities find application in problems related to the human activity of environmentally sustainable use of geo-resources. To name some, the efficiency of mineral carbonation for CO_2 storage, the hazard associated to fault reactivation by fluid injection (human-induced seismicity), the stability of subsurface waste disposal, the petrophysics of deep reservoir rocks. The HPHT lab is a playground for addressing these scientific and societal goals under controlled environmental and loading conditions (stresses, pore fluids, etc.). The rock and earthquake mechanics laboratory avails of three prototypal and versatile apparatuses designed to study friction and faulting in the presence of pressurized fluids (Figure 1).

BRAVA (Brittle Rock deformation Versatile Apparatus, [Collettini et al., 2014], Figure 1a), works as a uniaxial, triaxial or true-triaxial apparatus. It imposes up to 1.5 MN of horizontal and vertical forces on rock samples with dimensions of few to tens of centimeters, 30 MPa of fluid pressure and slip velocities ranging from 0.1 μm/s to 25 mm/s. BRAVA has been used to determine rate and state frictional properties of fault rocks [e.g., Collettini et al., 2019], the spectrum of fault slip behaviour and precursory changes in seismic velocity [Scuderi et al., 2016a]. BRAVA activities have also a link with geo-energy industry and deals with the characterization of physical properties of oil-bearing rocks [Trippetta et al., 2020, Ruggieri et al., 2021], and the role of fluid pressure in induced vs. triggered seismicity [Scuderi et al., 2016b].

SHIVA (Slow to HIgh Velocity Apparatus, [Di Toro et al., 2010], Figure 1b) is a rotary shear apparatus designed to impose slip velocities form 10 μm/s to 10 m/s under a horizontal force of 75kN and fluid pressure of 15 MPa on cylindrical samples of 5 cm of diameter. It has been designed to study the frictional behavior of experimental faults undergoing extremely fast (seismic) slip rates (m/s). It has been also applied to investigate fault seismic slip under fluid pressurized conditions in fault gouges [Aretusini et al., 2021], in faults lubricated by viscous fluids [Cornelio et al., 2019] and fluid-rock interaction and mineral carbonation associated with human-induced seismicity [Giacomel et al., 2018].

MEERA (Mechanics of Earthquake and Extended Ruptures Apparatus, [Spagnuolo et al., in prep.], Figure 1c) is a biaxial horizontal apparatus which applies fault slip velocities up to 100 mm/s, a modular normal stress up to 30 MPa and pore fluid pressures up to 6 MPa on samples of 30 x 8 x 5 cm in size. MEERA has been designed to study rock deformation and propagation of dynamic slip. It includes a dedicated vessel to study fluid-rock interaction under controlled environmental conditions.

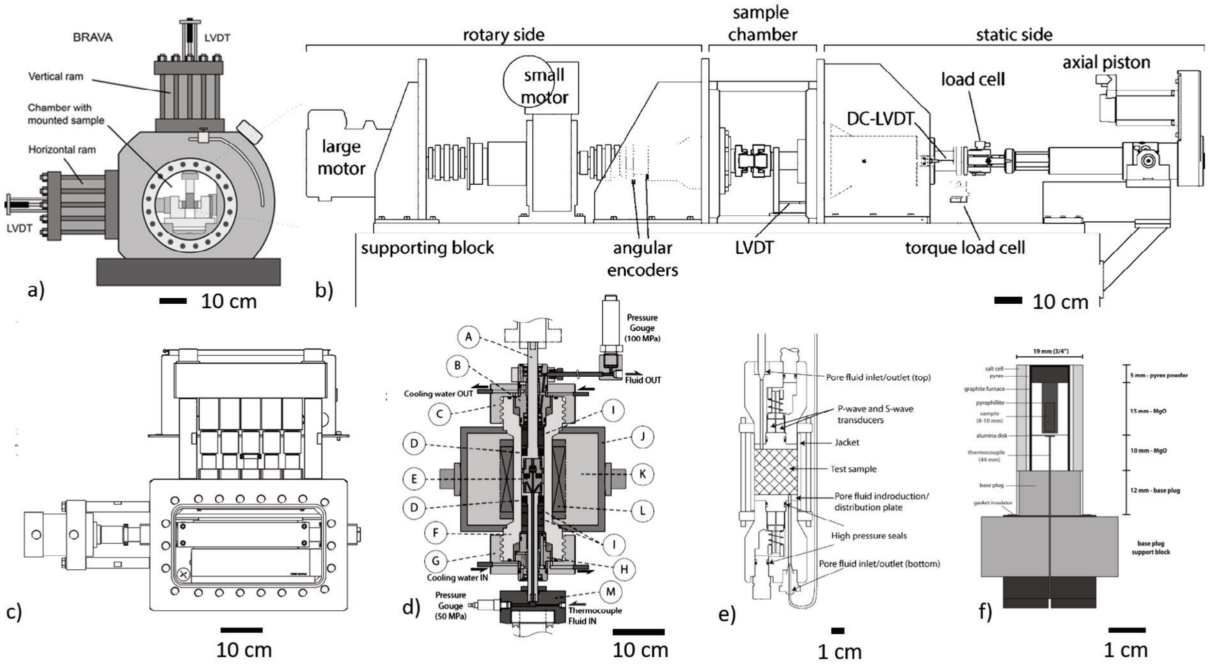

Figure 1 a) The uni - bi- true tri – axial apparatus BRAVA (Brittle Rock deformation Versatile Apparatus, Collettini et al., 2014, funded by the ERC StG GLASS); b) The rotary shear apparatus SHIVA (Slow to High Velocity Apparatus, [Di Toro et al., 2010] funded by the ERC StG USEMS); c) the horizontal biaxial apparatus MEERA (Mechanics of Earthquakes and Extended Ruptures, [Spagnuolo et al., in prep.], funded by the project DPC-EXTEND); d) Schematics of the vessel HYDROS installed on the rotary shear apparatus ROSA at the University of Padua (details in Feng et al. under review, funded by the project DPC-EXTEND); e) schematics of the vessel of the permeameter (details in [Vinciguerra et al., 2005], funded by the project MIUR FUMO); f) schematics of the non-end loaded piston cylinder apparatus QuickPress® (details in [Masotta et al., 2012] funded by the project Premiale NORTh).

The HPHT lab has a 15 years-long cooperation with the laboratory of rock mechanics at the University of Padua which avails of a rotary shear apparatus equipped with a novel hydrothermal pressurized vessel (HYDROS, Feng, [Gomila, Di Toro et al., under review Nature Comm], Figure 1d) which extends the working conditions of all the other machines up to 450°C temperature and 70 MPa pore fluid pressure.
Moreover, the laboratory of experimental petrology avails of two machines of great interest for geo-resources studies. A permeameter [Vinciguerra et al., 2005], Figure 1e which applies up to 80 MPa of confining pressure, servo-controlled steady-state-flow (also with acid fluids) at pressures of up to 65 MPa and temperatures up to 100 °C on samples up to 38 mm in diameter. This machine allows measurements of permeability [Smeraglia et al., 2014] and Vp & Vs of reservoir rocks [Trippetta et al., 2020] while fluxing fluids across either intact, or pre-cut bare rocks or rock gouges. The Quick-press® (Depths of the Earth) is a non-end loaded piston cylinder apparatus designed to attain low (ambient) to high temperatures (up to 1600°C) at low (150 MPa) to high (2500 MPa) pressure on cylinder of 13-25 mm diameter [Masotta et al., 2012], Figure 1f. This apparatus, designed to study phase equilibria and chemical reaction kinetics, is used to parametrize the crystallization, exsolution and reaction processes with pressure, temperature, volatile composition and oxygen fugacity and can be used to simulate temperature zoning in reservoirs by applying thermal gradients during the experiment [Pontesilli et al., 2019; Masotta et al., 2020].
In conclusion, thanks to 20 years of experience in rock mechanics, petrology and petrophysics

and close cooperation with universities, the HPHT laboratory can make a substantial contribution to the development of new technologies and experimental studies aimed at the safe and sustainable exploitation of georesources.

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Structural analysis of carbonate multilayer Formation (Southern Apennine): implication about fluid-flow

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The Calcari con Selce Formation (CsF), belonging to Lagonegro Succession, is a naturally fractured carbonate multilayer, resulting a well know regional reservoir, extensively outcropping in the Southern Apennines. In surface, CsF is a relevant water recharge area rich of springs, while at depth hosted potential confined aquifers.

In order to well understand the structural setting of this key layer and the role of the fractures network and faults on fluid-flow, a detailed structural analysis was conducted along the Pignola basin (Lucanian Apennine).

Results led to recognition of background (pre- to syn-orogenic periods) structures such as: i) strata-bounded sub-vertical fracture sets and bedding-parallel solution seams, related to lithostatic load; and: ii) oblique-to-bedding solution seams, induced by syn-orogenic flexural slip. The aforementioned structural setting was overprinted by two different sets of normal faults: low-angle normal faults, which exploited mainly along bedding interfaces, and high-angle normal faults whose architecture changes according to the maturity of the fault itself.

The conceptual model (Figure1) provide an interpretation of the structural evolution of the CsF and as fracture network interferes with the fluid-flow. The background structures developed a primary permeability (Figure 1A), while inibith it where oblique solution seams frequency is higher (Figure 1B).

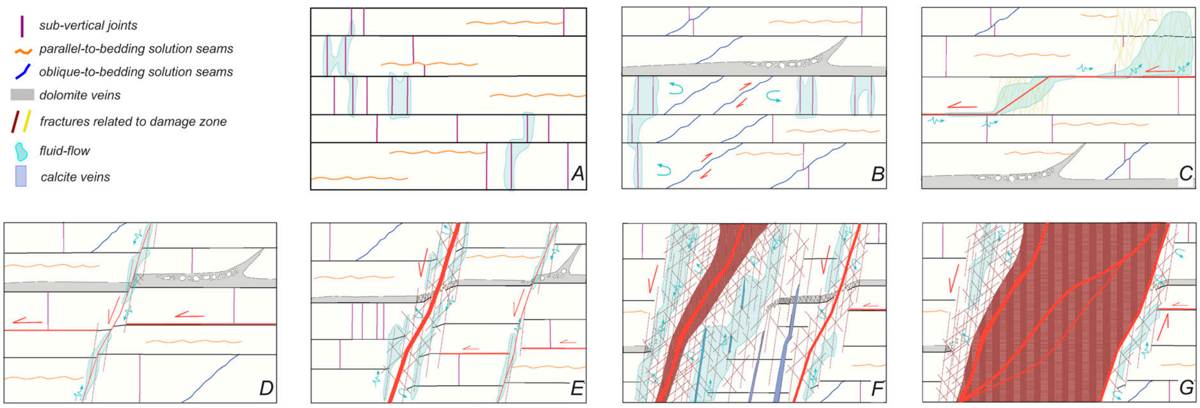

Figure 1 Structural evolution and fluid-flow conceptual model of the Calcari con Selce Formation.

Low-angle normal faults can promote permeability enhanced according to localized damage-zones (Figure 1C). The slip-surface represent a preferential way for fluid-flow in the incipient phase of the high-angle normal faults formation (Figure 1D). The evolution of these fault-zone, promote the cementation of the fault-core and the thickening of the damage-zone, whose fracturing represents a preferential way for the fluid-flow (Figure 1E and F). In the advanced mature phase, fault-zone represents a barrier according to development of highly-fragmented (low-permeable) damage zone (Figure 1G).

Integrated Infrastructures for Research and Innovation in the Area of Anthropogenic Seismicity Associated with the Exploitation of Geo-resources: the Thematic Core Service Anthropogenic Hazards of EPOS

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The EPOS Thematic Core Service ANTHROPOGENIC HAZARDS (TCS AH) integrates research infrastructures in which researchers interested in hazards posed by the seismicity induced by georesource exploration and exploitation, can access both data and software services. The Data, in this context, is a set of time-correlated geophysical and technological data and other relevant geo-data that comprehensively report anthropogenic seismicity cases (confirmed or suspected) and the industrial and geological conditions of these processes. Such data packages are called 'Episodes'.

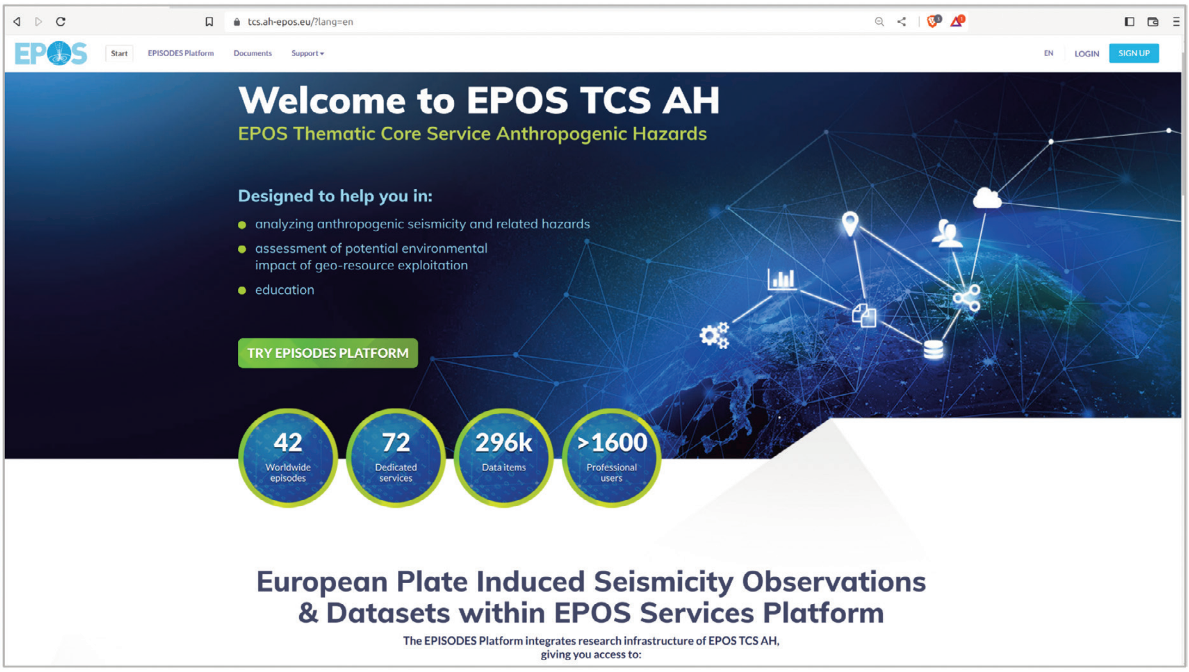

Figure 1 View of the home page for accessing the EPISODES infrastructure.

On the other hand, the Software are tools to process and analyse the data; they are mostly focused on supporting the user in tasks for relating seismicity and technological factors for hazard assessment and other scientific targets. The data and software services provided by the TCS AH are accessible through an open-access infrastructure called EPISODES (https://tcs.ah-epos.eu). The platform provides the user's workspace, adequate hardware resources, including HPC systems and other facilities that grant quick and efficient execution of commissioned tasks. In this talk we present and describe the structure and details of this open-access facility, and demonstrate the potential of the integrated infrastructures for developing innovative practical solutions. Detailed descriptions of the research infrastructure contents and capabilities can be found, e.g., in [Orlecka-Sikora et al., 2020 and Lasocki et al., 2022] and references therein.

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GOVERNMENT ASSIGNMENT

The INGV center for geophysical monitoring of underground technologies (CMS)

Andrea Morelli & the CMS staff*

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The INGV center for monitoring underground technologies (*Centro per il Monitoraggio delle attività di Sottosuolo*, CMS) is the organizational structure devoted to collecting, analyzing, understanding, and modelling geophysical data related to areas where natural resources are exploited (such as hydrocarbon extraction, produced water injection, natural gas storage, geothermal power plants, carbon capture and storage, mineral extraction, water impoundments) or that may present other anthropogenic risks.

The CMS mainly works as an officially appointed actor charged with continuous geophysical observation (*Società Preposta al Monitoraggio*, SPM) following certified guidelines for monitoring seismicity, ground deformation, and pore pressure in subsurface industrial activities [Dialuce et al., 2014] designated by the pertinent National regulatory body (currently, a branch of the ministry of environment and energy safety, *Ministero dell'Ambiente e della Sicurezza Energetica*, MASE). This general framework has been set following specific recommendations from the *International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Region* (ICHESE), that advise that data from apt geophysical monitoring networks are continuously analyzed to detect deviations from typical background [ICHESE, 2014].

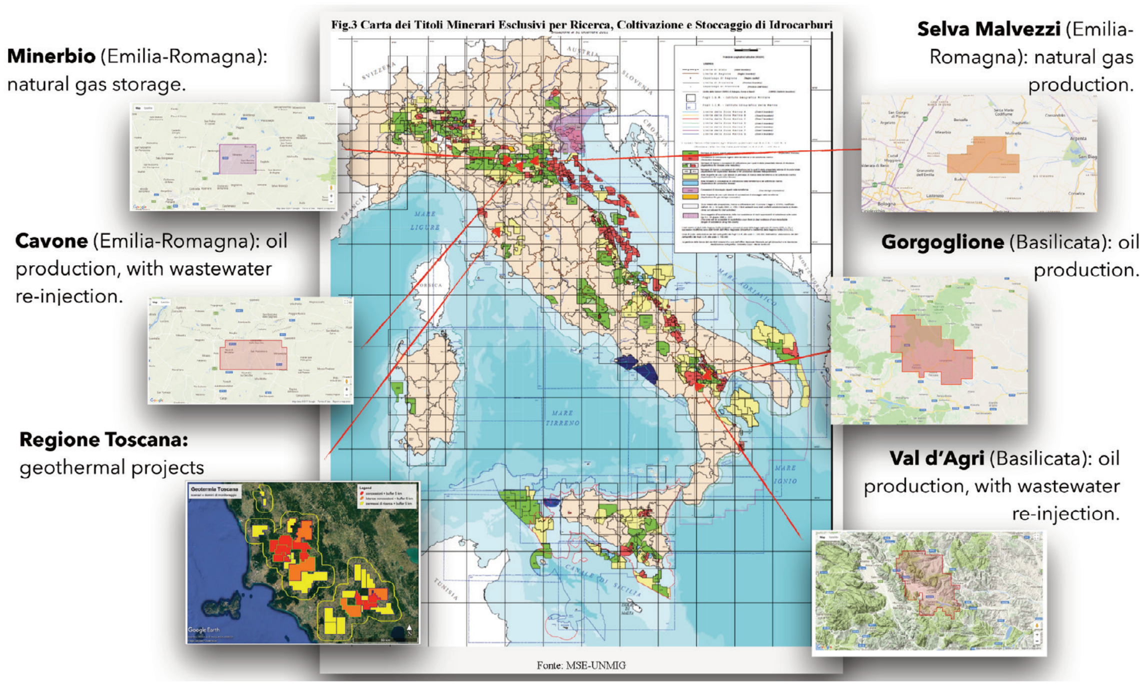

Figure 1 The National involvement of CMS in Italy (activity at Minerbio and Cavone has ceased).

Seismographic data flow in real time from apposite local networks to a data acquisition, analysis, and storage center at INGV headquarters in Bologna, where automatic earthquake detection and hypocentral location routines run. Automatic determinations are daily reviewed by an expert remote operator, 7 days a week, with the goal of early reporting any possible variation from the background. Geodetic data are also analyzed regularly. Data center hardware is duplicated for fault tolerance, and a disaster recovery system runs on a virtual machine at INGV main headquarters in Rome. The whole system has been set up and started test operations in virtual mode at the beginning of the Covid-19 lockdown [Pezzella, 2020]. Involved earlier in testing the mentioned ILG guidelines, the CMS is now engaged in their routine implementation in several areas all over Italy (see Figure). Up-to-date information can be found on the web page http://cms.ingv.it.

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Subsidence at Po plain and North Adriatic Sea: a workflow for analysis and monitoring, in the INGV-MATE research agreement context

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Ground deformation is one of the most impacting processes on human activities and safety, worldwide. In particular the subsidence has effects on build stability, floods, rivers discharge or coastline retreats. The Po Plain and the Adriatic off-shore area (Northern Italy) are among the most susceptible areas of Italy and are affected by subsidence and local uplift [e.g., Gambolati et al., 1991; Gambolati and Teatini, 2015; Benetatos et al., 2020; Coti et al., 2018; Polcari et al., 2022]. Ground displacements can be caused by natural or anthropogenic factors like tectonics, glacial isostatic adjustment, natural sediments compaction, reclaimed peatland oxidation, groundwater withdrawal, oil and gas extraction, and storage [Bertoni et al., 1995; Carminati and Martinelli, 2002; Carminati et al., 2003; Teatini et al., 2005; Fiaschi et al., 2017]. Quantify and differencing the contributions of each deforming phenomenon is a tricky challenge, due to the lack or inhomogeneity of data, in addition to the geostructural and sedimentological complexities of the area.

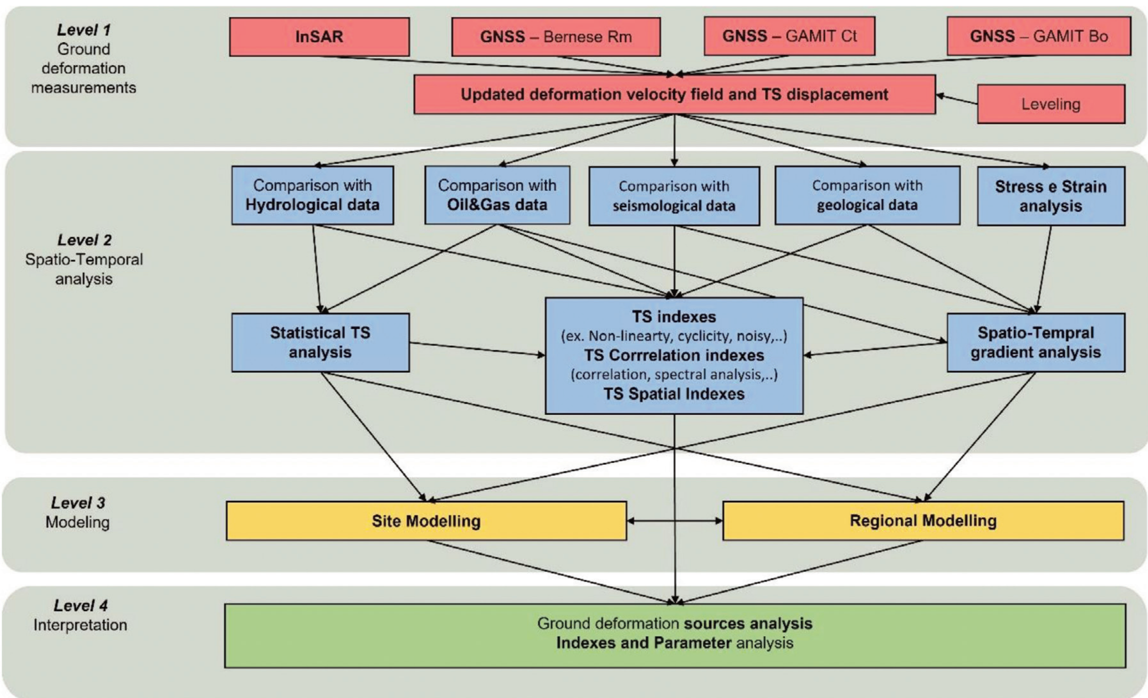

Figure 1 Block scheme of the ground deformation monitoring workflow.

In this context, the INGV and MATE (Ministry of Environment and Energy Security) signed a research agreement to develop a methodology for the monitoring, analysis, modeling, and interpretation of soil subsidence, in areas affected by the extraction and storage of hydrocarbons. The activity is structured in 4 operational levels:
Level_1: On- and offshore subsidence measurement through the measurement procedures standardization and the integration of different geodetic techniques.
Level_2: Spatial-temporal analysis of data through statistical methods and time series correlation.
Level_3: Modeling of subsidence, at site and regional scale.
Level_4: Results integration and interpretation: key indices and parameters identification in subsidence monitoring.

Procedure standardization and data homogenization allow to define, test, and make operative a workflow for the subsidence monitoring at different temporal and spatial scales.

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Natural hydrogen (H_2), a new C-free energy resource? Prospectives and uncertainties

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Exploration for subsurface energy resources has recently shifted its focus to natural hydrogen (H_2), a gas produced by a range of abiotic reactions in several igneous rocks. Beyond its use in petroleum refining and ammonia production, H_2 is a vector of zero-carbon energy, and natural H_2 can serve as a bridge to a future hydrogen economy. Thus, global research on natural H_2 started with the participation of the International Energy Agency (IEA), numerous research institutes, and petroleum and private companies. However, there are no guidelines for H_2 exploration, and many actors involved in H_2 exploration have limited experience and knowledge of natural gas geochemistry, as is now developed for petroleum exploration, in order to understand the complex picture of H_2 origin, migration, and accumulation in reservoirs. Although the presence of H_2 in soil and springs can reveal subsurface reservoirs, similar to hydrocarbon seepage in petroleum systems [Etiope, 2023], defining the amount of H_2 at the surface that can indicate a potentially economic resource is impossible, and recognizing its geological origin is difficult because H_2 concentrations and isotopic composition can overlap with the in-situ biological signature (Figure 1).

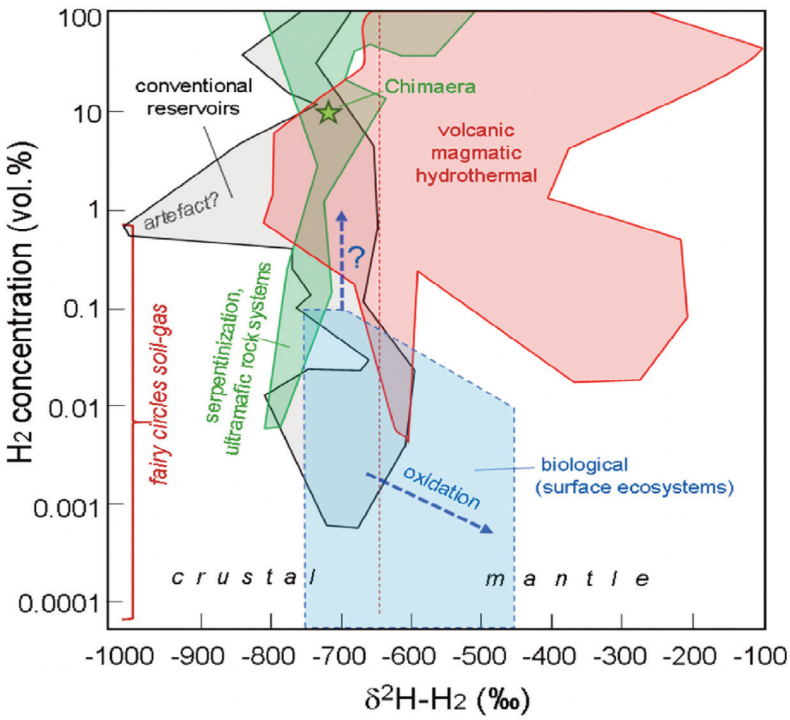

Figure 1 Concentration vs isotopic composition for H_2 in geological systems [from Etiope, 2023]. The figure shows the overlap of biological (modern) and geological H_2, in terms of amount and isotopic signature, at the relatively low concentrations that can be observed in soils, springs and aquifers.

The potential for H_2 generation in surface environments due to microbes (e.g., fermentation), corrosion of iron particles or minerals, or even drilling (artificial H_2), must be thoroughly evaluated. Despite these limitations, similarities to hydrocarbon systems suggest that the presence of surface advective gas fluxes (detectable using gas flux detectors such as the closed chamber) can, unlike diffusion, serve as a proxy for a subsurface source and even pressurised H_2 accumulations [Etiope, 2023]. Analyses of the gases associated with H_2 (e.g., CO_2, CH_4, N_2, He) are however recommended. Basically, a holistic approach, integrating multiple geochemical, ecosystem and geological data, is necessary to assess the potential of a geological H_2 resource.

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Water resources in small islands: strategies for sustainable exploitation in the climate change era

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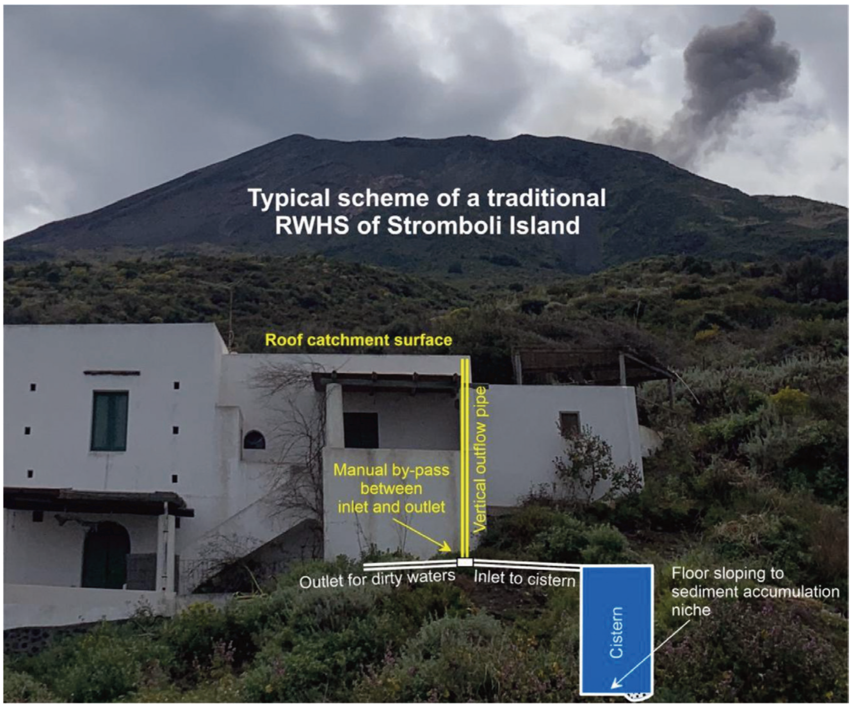
Water resource exploitation is a key issue in small islands, populated by small communities not served by large-scale facility networks. Additionally, volcanic islands are affected by the release of chemicals potentially toxic/noxious for humans. The volcanic Aeolian Archipelago (south Mediterranean) is a paradigmatic case study because of i) scarcity of suitable water resources, ii) costly water supply granted by desalinators or transport by tankers from the mainland, iii) population one order of magnitude higher in the touristic season than in late autumn-winter), iv) the absence of wastewater treatment plants. Before the advent of the technological era, the unique water source was rainwater, stored in underground cisterns after being harvested by Roof Water Harvesting Systems (RWHS), presently used as a sustainable source in other parts of the world [Haut et al, 2015]. These cisterns are treated with lime, which buffers the pH on moderately basic values, avoiding unsafe concentrations of dissolved metals, granting a quality comparable with that of water transported by tankers [Madonia et al., 2013]. Surface runoff catchment systems are unsuitable, due to the elevated solid transport caused by the high erodibility of most of the volcanic deposits, further exacerbated by the rising rainfall intensity triggered by climatic changes. Regarding groundwater, the smallest islands, namely Alicudi, Filicudi and Panarea, do not host coastal plains suitable for the development of significant groundwater bodies. Salina, Lipari and Stromboli host small coastal plains and some gently steeping slopes, compatible with the presence of small aquifers. Vulcano island has a wide coastal plain developed over a volcanic caldera, hosting a significant aquifer, both in terms of renewable resources and reserves, but affected by the release of volcanogenic chemicals, as at Stromboli [Madonia et al., 2015; 2021], which makes often problematic the safe exploitation of groundwater.



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