Research proposal

PhD in Earth Sciences – XL Cycle

Exploring Natural Hydrogen Reservoirs: Geological Insights for Energy Transition

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1 Introduction and State of the art

Hydrogen is considered one of the fuels of the near future [1]. It offers the chance to simultaneously contribute to decarbonization, enhance energy security, and gain independence from oil and gas imports. Among the different ways to produce hydrogen, the "green hydrogen", obtained through the electrolysis of water using renewable electricity, is the only emission-free one. Unfortunately, at present, the price of green H_2 is three times higher than its grey counterpart (which is produced inexpensively by using coal or natural gas, but with a significant carbon footprint), and the electrolyser technology is not yet sufficiently developed to produce millions of tonnes of H_2 annually [2]. What can complement the urgent supply of green H_2, is the exploration of natural H_2, and its exploitation. Natural H_2, also known as native or white H_2, has been overlooked in the past because it was assumed to be too rare or too difficult to extract. In the last few years, several occurrences of H_2 seeps, ranging from 10% up to more than 90% in concentration, have been reported, many of which were highly unexpected [3-8]. The recent accidental discovery, in Mali, of 98% pure hydrogen in wells targeted to extract water opened new research perspectives [8]. Since then, hydrogen has been found in a wide range of geological settings – in oceanic and continental crust, rift and back-arc basins, within banded iron formations, mid-ocean ridges, orogenic and ophiolitic settings, and in magmatic and hydrothermal systems (Fig. 1). Thousands of other sites showing diffuse H_2 flow at soil - up to 6000 ppm of H_2 - occur worldwide, from Brazil, Eastern Russian Federation, Oman, USA, Ukraine, to Uzbekistan [3-6].

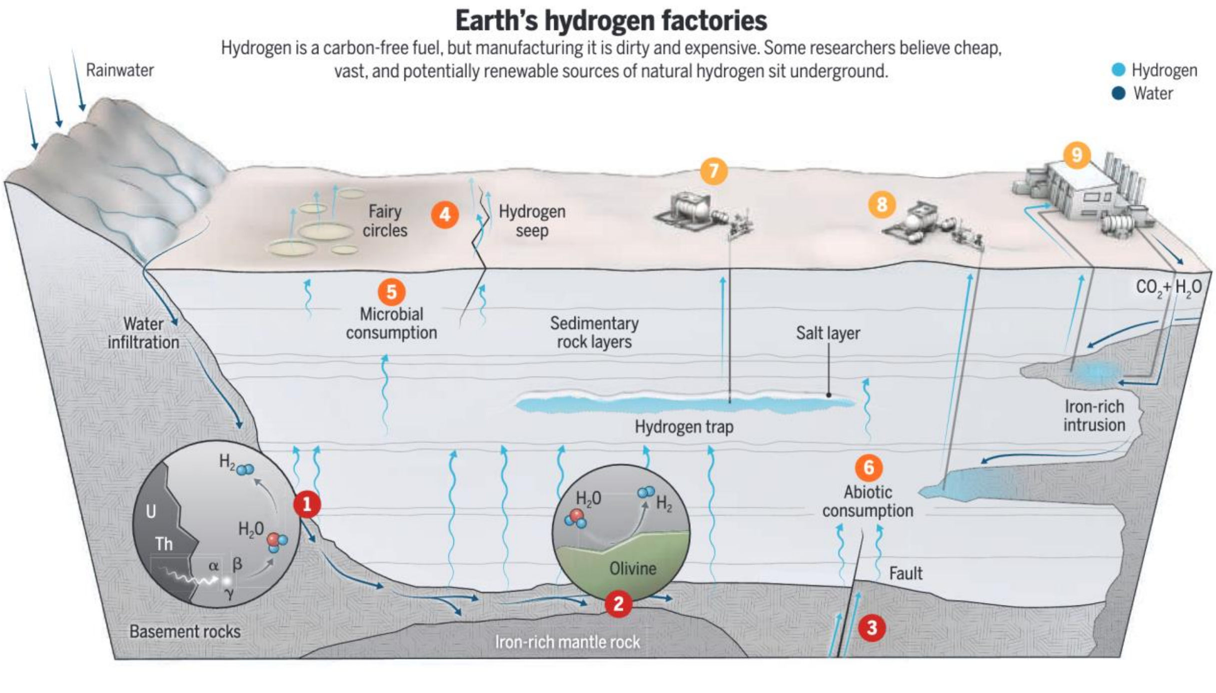

Figure 1: sketch illustrating the (so far known/hypothesized) sources and reservoirs of natural H_2 [10].

The process of serpentinization is addressed as one of the main reactions that can generate H_2 due to the hydration of ferrous iron-bearing minerals. This process consists of the hydrolysis of olivine and pyroxene in peridotite at temperature <300°C, to form serpentine, brucite, and magnetite, with H_2 release [11]. In Italy, unmetamorphosed serpentinites are widespread in the Apennines (e.g. the Ligurides units) [12-13] (Fig. 2).

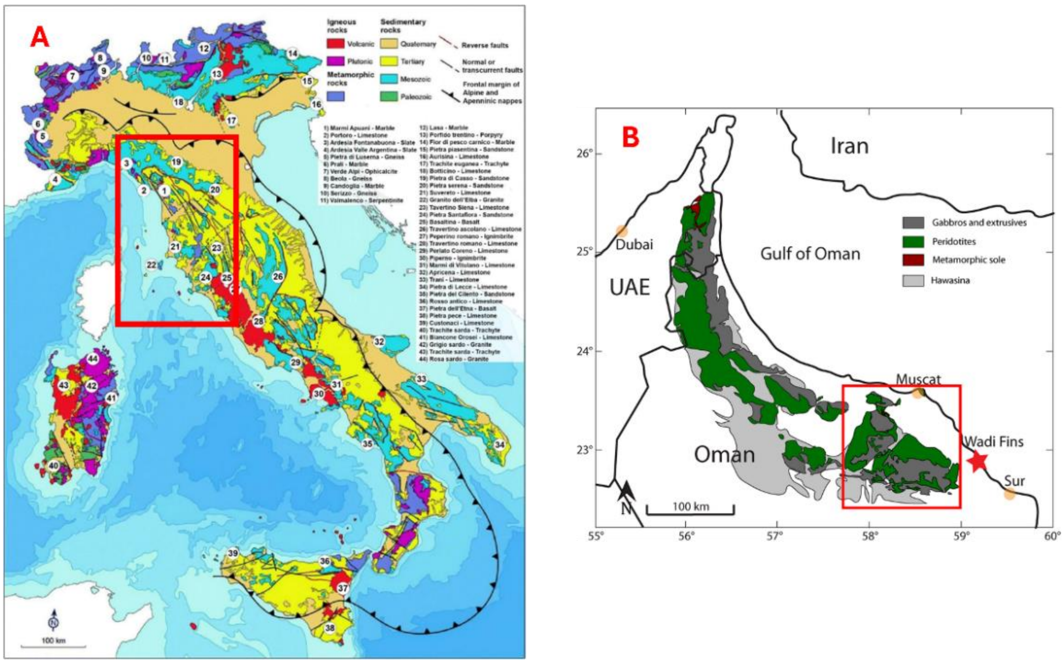

Figure 2 – Red rectangles show potential study area in (A) the Liguride units (Liguria/Tuscany) and (B) in the Semail Ophiolite of Oman.

Despite this, Italy so far is lacking comprehensive studies devoted to identifying and mapping natural H_2 emissions. Several projects, mainly devoted to geothermal energy exploitation in Italy, have produced large databases for geothermal wells, thermal springs, CO_2-rich springs and for fumarolic gases, since the early 70's [14-15]. These data are mainly focused on CO_2-enrichment, but they also show that hydrogen is present in some areas [16-17]. The available scattered data seem to indicate that the known Italian gaseous emissions (relatively) rich in H_2, despite favourable conditions for its formation, are not comparable to other sites reported in the literature [3-9]. This also points out the importance of broader comparative studies: in this scenario, the Semail Ophiolite in Oman, where the largest bodies of mantle rocks crop out, could provide significant insights into these processes [3].

2 Research Objectives

General objectives

Understanding the mechanism of natural hydrogen formation and accumulation, in order to contribute to the development of a key energy source in the context of energy transition.

Specific objectives

a) the understanding of the processes leading to natural hydrogen formation, migration, geological storage and eventual emission
b) the definition of active and past emissions of natural hydrogen in serpentinite-dominated systems (Liguride ophiolite units in Liguria/Tuscany; Oman ophiolites)
c) the formulation of a conceptual approach for natural hydrogen exploration and production.

3 Implications and applications

Achieving this project's objectives could transform approaches to exploring and utilizing natural hydrogen as a clean energy resource. By enhancing detection and mapping of hydrogen reservoirs, this research may offer new methods for locating and evaluating natural hydrogen sources through indirect indicators, especially where surface evidence is sparse. The findings of my research activity could bring to the development of refined exploration models and eventually enable natural hydrogen extraction as an alternative, emission-free energy source.

4 Work plan

The proposed research project will focus on processes controlling H_2 formation in unmetamorphosed serpentinite-dominated ophiolites. Processes controlling both on-going and past H_2 emissions will be investigated. To identify the on-going outflow of natural H_2, the main activities will consist of the exploration of the potential flow of hydrogen via surface flow measurements coupled with structural studies of the main fault zones in the two study areas. The research activity will follow a multidisciplinary approach, involving structural geology, petrology, geochemistry and geophysics. The research activity will be conducted according to the following steps:

- **Preliminary studies (November 2024 - March 2025)**: study of the published literature, geological maps and cross sections, in order to identify the main specific areas of interest.
- **Meso-structural analysis and sampling (April 2025 – January 2026)**: selected fault zones will be characterized by collecting syn-tectonic fault mineralizations and clay-rich fault rocks. Gas samples on active emissions will also be collected in glass bottles. Field activities will be conducted both in Liguria/Tuscany and in Oman, for comparative studies.
- **Micro-Structural and Petrological lab analyses (September 2025 – May 2026)**: Using optical microscopy and cathodoluminescence analysis (Sapienza laboratories), veins and other microstructures will be investigated to reconstruct deformation mechanisms. To define the composition of the collected fault-rock and serpentinite host-rock samples, optical microscopy, SEM, XRD and X-ray diffraction analysis will be performed at Sapienza and CNR laboratories. In third place, chemical and micro-thermometric and Raman spectroscopy analyses will be also performed on fluid inclusions that will be found in collected samples (IGAG-CNR and CNIS-Sapienza laboratories), in order to obtain information on fluid composition and P-T conditions during fluid trapping.
- **Geochemical analysis on gas samples (September 2025- September 2026)**: major and minor gas components (H_2O, H_2, CO_2, He, H_2S, Ar, O_2, N_2, CH_4, Ne) will be analysed using gas-chromatography at IGG-CNR and INGV Palermo. This step is crucial to identify whether in H_2 rich areas, the associated gas components have a specific footprint, allowing an indirect H_2 detection.
- **Analysis of subsurface data (October 2026 – January 2027)**: in order to visualize the distribution of rock volumes and fluids involved in hydrogen-related processes, subsurface data (e.g., wells, seismic profiles and/or geoelectric tomographies) will be processed and interpreted. This will be done both in-house and, thanks to the PNRR funding of this project, also during an internship period at SNAM.
- **Build-up of a conceptual model (November 2026 - April 2027)**: results of geochemical and structural analysis will be used to build a model of H_2 formation, migration and accumulation. Under the guidance of SNAM personnel, conceptual model for natural H_2 exploration will be also developed.

5 Milestones and checkpoints

a) Completion of Field Sampling in Liguria/Tuscany (July 2025) and Oman (February 2026).

Expected Outcome: Detection of indicators of H_2 occurrence in the sampled sites and of associated markers.

b) Completion of Specific Lab Analyses (April 2026) and Subsurface Data Analyses (February 2027).

Expected Outcome: Development of a preliminary model of H_2 formation, migration and trapping.

c) Presentation of Results at the SGI conference (October 2026) and the EGU annual meeting (April 2027).

d) Submission and Publication of Scientific Papers for the Italian case study (February 2027) and the Omani case study (August 2027).

6 Dissemination plan

My goal is to publish scientific papers containing the results of my research activity on peer-reviewed journals starting from the end of the second year of PhD. Field and laboratory data and results of modelling will be described and reported in detail in my PhD thesis. Starting from the second year of PhD, I will attend conferences and meetings organized by universities and scientific institutions and associations (e.g. EGU, SGI and BeGeo annual meetings) to share my results with other researchers.

7 Training activities

The training activities I will attend during the PhD period will focus on increasing my skills in structural geology, geochemistry, petrology, data analysis and geophysics as well as writing scientific papers. With this aim, I will attend courses, seminars and webinars offered by Sapienza DST department and other research institutes. During the research activities, I will benefit from the experience of my tutor(s) and from the collaboration with other institutions (SNAM, IGAG-CNR, IGG-CNR and INGV Palermo) to improve my skills in field and lab work.

8 Details of mobility abroad

During my second year of PhD, I will apply for mobility funds and will visit the laboratories of the Research Center Pétrographiques et Géochimiques, CNRS (Nancy, France), where I will increase my skills in lab measurement analyses of gases and fluid inclusions (tentatively during the second semester of the second year). Part of the foreign mobility will be held also in collaboration with Prof. Andreas Sharf at Sultan Quabus University in Muscat (Oman), where I will perform field work on the serpentinites of the Semail ophiolites (first trimester of my second year).

9 Time schedule (Gantt chart)

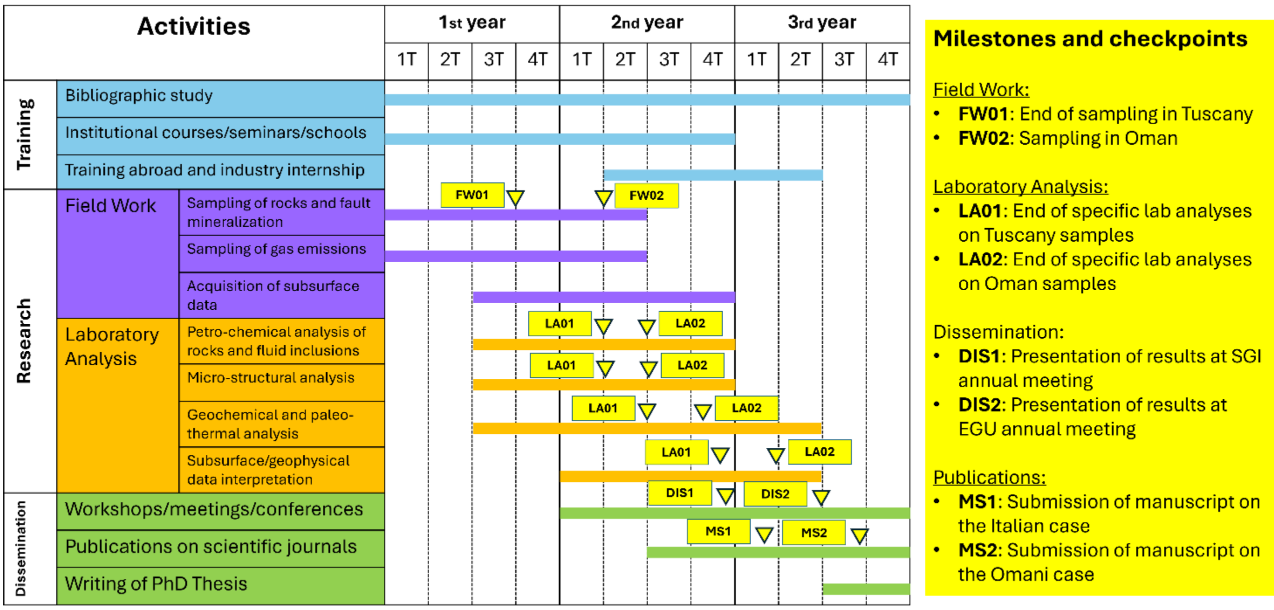

Figure 3 – Gantt chart of scheduled activities. Key milestones and checkpoints are also shown.

10 References

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