Research proposal

PhD in Earth Sciences

XLI cycle

Geodynamic and tectonic controls on fluid sources and migration within the Apennines back-arc

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1. Introduction and state of the art

Fault zones represent fundamental geological archives that record the interplay between deformation, fluid flow, and chemical alteration within the continental crust. Structural studies demonstrate that faults can act as transient high-permeability conduits, particularly during seismic cycles, when sudden stress variations induce transient pressure gradients and open fracture networks that promote fluid migration [1,2]. Mineralizations such as veins and slickenfibers preserve evidence of crack–seal processes driven by pressure and temperature fluctuations, revealing the episodic nature of fluid flow and providing constraints on the timing, mechanisms, and origin of paleo-fluid migration [1–3]. These mineralized structures therefore serve as long-term markers of fluid circulation through the brittle crust, capturing information on fluid chemistry, temperature, and source over successive deformation events.

To decode these geological records, geochemical tracers are indispensable. Stable carbon and oxygen isotopes ($\delta^{13}C$, $\delta^{18}O$), together with clumped-isotope thermometry, provide robust constraints on the composition, origin, and temperature of mineralizing fluids in fault zones [3]. These approaches enable the reconstruction of fluid–rock interaction histories and the distinction between meteoric, crustal, and mantle-derived components. When combined with host-rock paleothermometers—such as illite crystallinity (Kübler index) and mixed-layer illite–smectite geothermometry—clumped-isotope data can reveal thermal disequilibria indicative of externally derived fluids infiltrating the fault system [3].

Noble gases offer a complementary and highly sensitive means of tracing deep volatile contributions. Among them, helium is particularly informative, occurring as primordial ^3He stored in the mantle and radiogenic ^4He produced by U–Th decay in the crust [4]. The $^3He/^4He$ ratio thus represents a powerful tracer of mantle input and crust–mantle coupling, even in regions lacking surface volcanism [4–7]. Because helium is chemically inert, variations in the $^3He/^4He$ ratio primarily reflect changes in fluid pathways and permeability structure within the crust. This isotopic system has proven especially valuable in revealing the hidden connectivity between the upper mantle, lower crust, and active fault zones, offering insights into the mechanisms through which fluids influence the mechanical behavior of the lithosphere.

The Tyrrhenian back-arc (Fig. 1) provides an exceptional natural laboratory to investigate these processes [8]. This region is characterized by widespread CO_2-rich degassing, active normal faulting, geothermal activity, and clusters of upper-crustal seismicity—features that together offer a unique opportunity to explore how fluids migrate and interact with crustal deformation. The Tyrrhenian–Apennine system evolved in response to the retreat and tearing of the subducting slab, leading to a highly heterogeneous lithosphere marked by zones of extension, thinning, and localized upwelling of asthenospheric material. In this setting, fluids derived from both mantle and crustal reservoirs ascend through extensional fault systems, producing a complex geochemical signature recorded in mineralizations and modern gas emissions.

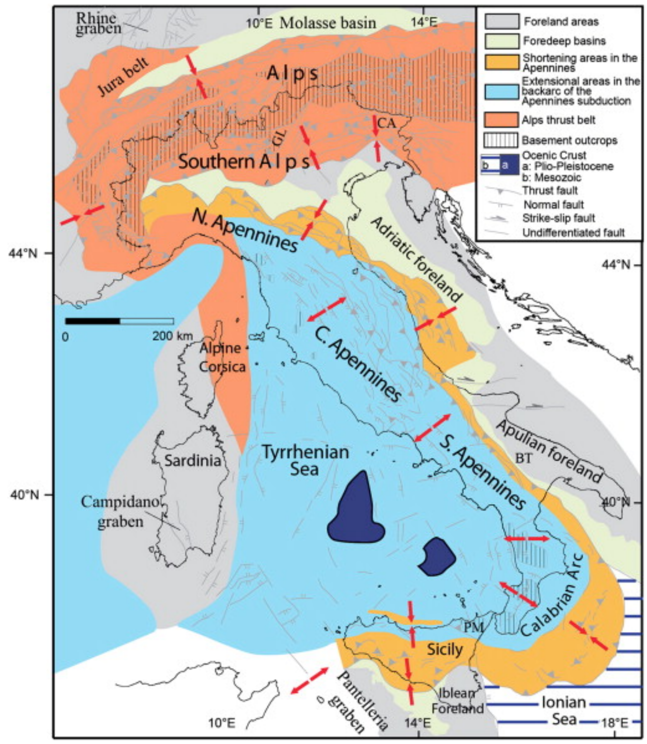


Figure 1. Simplified tectonic map of Italy, showing the major tectonic and geodynamic settings in the region [8].

Regional studies across Italy have revealed a marked north–south variability in $^3He/^4He$, documenting the coexistence of mantle- and crust-derived fluids even far from volcanic systems [5–7]. Importantly, helium degassing appears episodic and modulated by seismicity [9], reinforcing the concept that stress and strain variations influence crustal permeability and govern the periodic release of deep-seated volatiles. This dynamic coupling between deformation and degassing highlights the potential of geochemical monitoring as a tool for probing transient fluid flow during earthquake cycles.

Seismic tomography provides complementary insights into these deep processes. High-resolution teleseismic Vs and Vp/Vs models delineate subducted slab geometry, lithospheric delamination, and fluid-rich mantle domains beneath the Apennines [10,11]. These anomalies spatially coincide with regions of crustal extension, uplift, and CO_2-rich degassing, supporting the interpretation that mantle-derived fluids and melts contribute to ongoing tectonic and magmatic activity. Moreover, recent regional-scale tomographic studies [12] reveal pronounced along-strike variations in crustal and lithospheric structure, reflecting rheological contrasts and fluid-assisted deformation associated with slab retreat, segmentation, and tearing. Integrating these geophysical observations with geochemical evidence offers a powerful means to understand the mechanisms that connect deep geodynamics with surface processes.

Despite this growing body of evidence, critical questions remain concerning the origin, timing, and migration mechanisms of fluids, as well as their broader geodynamic implications. In particular, the integration of structural, geochemical, and seismological perspectives remains limited, and few studies have attempted to quantitatively link fluid signatures with fault architecture, mantle processes, and crustal deformation patterns. The spatial and temporal dynamics of degassing in back-arc environments—especially their relationship with seismic activity and tectonic evolution—are still poorly constrained. Addressing these gaps requires an interdisciplinary approach that combines structural, geochemical, and geophysical datasets to unravel how fluids modulate fault mechanics and contribute to the evolution of extensional systems in the Mediterranean back-arc domain.

2. Research objectives

General objective:

Understanding fluid source, composition, and migration in the Apennines back-arc to constrain the tectonic and geodynamic processes shaping active and inactive (fossil) extensional systems in the Mediterranean.

Specific Objectives

1) Reconstructing the spatio-temporal and compositional evolution of fluid migration in the Tyrrhenian back-arc region.
2) Identifying fluid sources, migration pathways, and their interactions with active faulting and seismicity in space (from north to south) and time (from ~9 Ma in internal to present-day in axial areas of the Apennines)
3) Constraining mantle–crust control on fluid-rock interaction and degassing processes, possibly contributing to the understanding of the role of fluids in modulating fault mechanics and earthquake generation.

The objectives will be achieved through the integration of structural-geological, geochemical, and geophysical analyses. As mentioned above, their integration is necessary to constrain the same geological problem using all the datasets available.

3. Implication and applications

The research planned in this PhD project introduces several innovative and highly interdisciplinary elements, with expected results that span different fields. It will advance our understanding of the links between deep geodynamic processes and their surface expressions, providing new insights into the role of fluids in extensional back-arc settings. By detecting fluid overpressure zones and mantle-derived signatures through integrated geochemical characterization and tomographic imaging, and by better constraining the origin and migration pathways of fluids along faults together with fault structure and stress conditions, this study will advance our understanding of fault mechanics and fluid-induced seismicity and ultimately provide improved constraints on seismic hazard in fluid-active regions of the Apennines back-arc. Moreover, insights into the sources, conditions, and mechanisms of fluid flow may support the sustainable development of geothermal systems, reducing the risk of failure when drilling new production wells and helping define favorable conditions for new geothermal energy sites.

4. Work plan

This PhD project addresses key knowledge gaps through an interdisciplinary approach that integrates multiscale structural analysis**,** geochemical tracers (He, C, O, and clumped isotopes), and seismic tomography to investigate fluid circulation in the framework of Mediterranean geodynamics and extensional tectonics. The research will follow six main steps (Fig. 2):

- ***Targeting data gaps*** *(from November 2025 to February 2026):* Literature review and identification of areas poorly constrained by structural or geochemical data. This will allow the selection of key sites for meso- and micro-structural analysis, and geochemical investigations.
- ***Meso-structural analysis and sampling*** *(from February 2026 to November 2027):* Fieldwork activities will focus on fault mapping, stress-field reconstruction, and the sampling of mineralizations and associated host rocks. Both exhumed inactive and active extensional fault systems in the Tyrrhenian back-arc region will be investigated. The structural observations and collected samples will provide the basis for subsequent microstructural, geochemical, and geochronological analyses.
- ***Microstructural analysis and geochronological dating*** *(from July 2026 to February 2027):* Collected samples will be examined using optical microscopy, cold cathodoluminescence, and scanning electron microscopy (SEM) to characterize deformation textures, fluid-related microstructures, vein chronology, and multiple fluid-injection events. U–Pb dating will constrain the timing of mineralization, fluid pulses, and migration episodes.
- ***Geochemical analysis*** *(from October 2026 to August 2027):* Stable isotope ($\delta^{18}O$, $\delta^{13}C$) and clumped-isotope analyses will be performed on selected samples to determine fluid composition, temperature, and evolution. $^{3}He/^{4}He$ measurements at INGV Palermo, together with additional noble-gas analyses performed during the international mobility period, will trace fluid sources, depth of residence, and migration pathways. Combined with U–Pb chronometry, and comparison with compositions of present-day fluid emissions reported in the literature, these data will enable the reconstruction of the temporal evolution of fluid circulation. REE patterns and $^{87}Sr/^{86}Sr$ ratios will further refine models of fluid–rock interaction.
- ***Seismic tomography*** *(from September 2027 to February 2028):* High-resolution Vp, Vs, and Vp/Vs models will image lithospheric architecture, fluid pathways, and mantle heterogeneities. Integration of tomographic anomalies with structural and geochemical data will allow to link mantle-derived fluids with upper crustal deformation; identification of low-Vp and high-Vp/Vs as potential fluid-saturated or metasomatized domains**.**

Integrated conceptual model *(from March to July 2028):* The final stage will synthesize geological, geochemical, and geophysical results into a comprehensive, interdisciplinary conceptual model describing fluid circulation, degassing, and their relationships with extensional tectonics and geodynamic processes in the Tyrrhenian back-arc. This integration will establish a framework linking deep fluid flow to surface deformation, fault activity, and seismic hazard, ultimately contributing to a geodynamic evolution model of the Apennines back-arc through time and space.

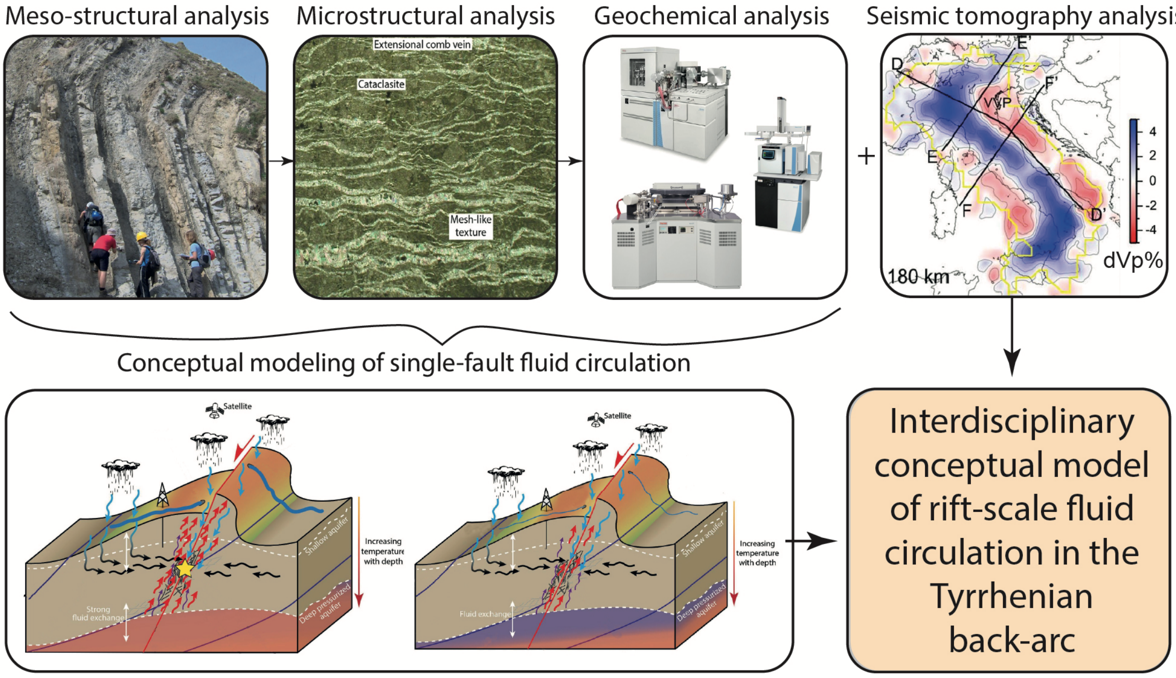


Figure 2. Summary key steps of the PhD project.

5. Milestones and checkpoints

The project milestones are:

1. Sampling and geochronological dating of mineralized fault zones.
2. Geochemical characterization of mineralizations and comparison with present-day fluid compositions.
3. Integration of geological and geochemical results with seismic tomography and geodynamic modeling.

At least two ISI-indexed publications are planned, starting from the second year.

6. Dissemination plan

A core objective of this PhD is the dissemination of scientific results to the international research community. Peer-reviewed publications will be prepared as the project progresses, with the first manuscript planned from the end of the second year. Key findings from field investigations, laboratory analyses and tomographic modelling will be fully presented and discussed in the PhD thesis.

Participation in national and international conferences and workshops will play a central role in disseminating results, fostering scientific exchange and strengthening collaborations. I plan to attend major scientific meetings such as EGU and SGI, as well as thematic workshops relevant to geochemistry, structural geology and seismology, where I will present ongoing developments through oral and poster contributions.

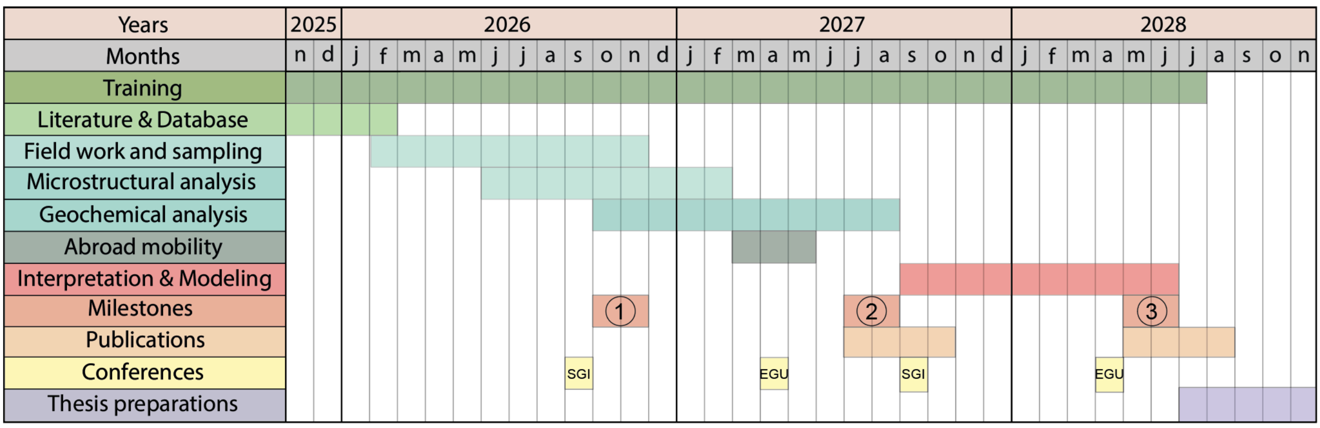
7. Training activities

The training program of my PhD will aim to advance and consolidate my technical and scientific skills across multiple disciplines, including structural geology, geochemistry, seismic data interpretation and quantitative analysis. To achieve this, I will take advantage of courses, seminars and webinars offered by the Department of Earth Sciences at Sapienza University and collaborating research institutions. Hands-on training will be developed through field campaigns, laboratory work and data processing activities. Moreover, collaborations with INGV-Roma and INGV-Palermo will provide additional expertise in noble-gas geochemistry, seismological methods and fluid-fault interaction studies, enabling me to strengthen both analytical capabilities and interdisciplinary research skills.

8. Detail of mobility abroad

During the PhD I will undertake a three-month research period at CRPG (*Research Center Pétrographiques et Géochimiques*) in Nancy, France. Here I will perform analyses on noble gases contained in fluid inclusions of mineralizations and I will interpret analyses results.

9. Time schedule (Gantt chart)



10. References

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