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1. Technical references

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2. ABSTRACT

Understanding the geometry, physical properties, and dynamics of seismogenic faults is essential for improving the characterization of earthquake processes and for refining seismic hazard models. Within this framework, the activities of WP5.1 focused on the identification, characterization, and modelling of active and capable faults through an integrated, multidisciplinary approach combining geological, geophysical, and seismological analyses, including advanced signal analysis and data-driven approaches.

Several complementary methodologies were developed and applied across different tectonic environments. High-resolution geological and geophysical investigations were used to characterize fault systems and their structural complexity, including field-based structural mapping, geophysical imaging techniques such as seismic reflection and magnetotelluric surveys, and multiparametric models integrating seismic and electrical data. These approaches enabled improved constraints on the geometry of seismogenic structures and on the physical properties of the crust surrounding active fault zones. In parallel, numerical simulations were developed to explore the role of structural complexity and fault interactions in controlling the spatial distribution of seismic energy release.

Additional investigations addressed the interaction between fluids and fault mechanics, combining laboratory experiments, geochemical monitoring, and conceptual modelling to explore how fluid production and migration may influence earthquake nucleation and rupture processes. These studies highlighted the potential role of fluid pressurization and thermally activated reactions in modulating fault weakening and seismic slip.

Overall, the results of WP5.1 provide new insights into the structural and physical controls on earthquake generation and contribute to improving the characterization of seismogenic faults in complex tectonic settings. The integration of geological observations, geophysical imaging, laboratory experiments, numerical modelling, seismicity analysis, and data-driven approaches represents a key step toward a more comprehensive understanding of fault processes and their implications for seismic hazard assessment.

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3. Introduction

The characterization of seismogenic faults and of the processes controlling earthquake occurrence represents a fundamental component of modern seismological research and a key prerequisite for reliable seismic hazard assessment. Earthquakes occur mainly as a consequence of stress accumulation and release along pre-existing weaknesses in the Earth's crust, typically localized along fault zones that may extend over several kilometres and involve complex structural architectures. Understanding how these structures develop, how they interact with the surrounding crust, and how their physical properties influence earthquake nucleation and rupture propagation remains one of the central challenges in earthquake science.

In many tectonic regions, seismogenic faults are not simple planar structures but rather form complex fault systems composed of multiple segments, branches, and secondary structures. Geological observations, geophysical imaging, and earthquake catalogues increasingly reveal that the spatial organization of seismicity is strongly influenced by such structural complexity. Fault segmentation, structural discontinuities, and lithological contrasts can influence the localization of deformation, the geometry of rupture propagation, and the spatial distribution of seismic energy release. For this reason, the identification and detailed characterization of active and capable faults represent a crucial step toward improving the physical understanding of earthquake generation and toward constraining seismic hazard models.

Recent advances in observational techniques have significantly improved the ability to investigate fault systems across multiple spatial scales. High-resolution geological mapping, geophysical surveys such as seismic reflection and magnetotelluric imaging, and dense seismic monitoring networks now allow researchers to observe fault structures and associated seismicity with unprecedented detail. These datasets provide valuable information on the geometry of fault zones, the physical properties of the surrounding crust, and the spatial distribution of earthquake hypocenters relative to mapped structures. At the same time, the increasing availability of high-quality earthquake catalogues enables statistical analyses that can reveal subtle patterns in seismicity, including clustering behaviour and temporal variations in earthquake occurrence.

A growing body of research also highlights the important role played by physical processes occurring within fault zones themselves. Fault mechanics is influenced not only by the geometry of the fault system but also by the physical and chemical properties of the materials involved. In particular, the presence and migration of fluids within fault zones can strongly affect effective stress conditions and fault strength. Variations in pore fluid pressure may promote fault reactivation by reducing effective normal stress, while fluid-producing reactions triggered by frictional heating during seismic slip may further influence the mechanical behaviour of faults. Laboratory experiments, geochemical observations, and theoretical models increasingly suggest that the interaction between fluids and fault mechanics may play an important role in earthquake nucleation and in the evolution of seismic sequences.

Within this scientific context, the activities developed in WP5.1 aim to improve the understanding of the structural and physical controls on earthquake generation through a multidisciplinary approach integrating geological, geophysical, experimental, and statistical analyses. The work carried out within this task focuses on the identification and characterization of active and capable faults, the investigation of fault-zone properties and structural complexity, the development of advanced methods for source-parameter estimation and microseismic monitoring, and the analysis of fluid-related and data-driven indicators relevant to earthquake processes.

Several complementary research activities contribute to these objectives. Geological and geophysical investigations are used to identify seismogenic faults and to characterize their geometry and structural complexity. High-resolution field studies and geophysical imaging techniques provide insights into the architecture of fault systems and into the physical properties of the crust hosting active deformation. Numerical modelling approaches are employed to explore how structural complexity may influence the spatial distribution of seismic energy release and rupture dynamics.

Additional studies investigate the interaction between fluids and fault mechanics, combining laboratory experiments, geochemical observations, and conceptual modelling to explore how fluid production and migration may influence earthquake processes.

Together, these activities contribute to a more comprehensive understanding of the processes controlling earthquake generation in complex fault systems. By integrating structural observations, geophysical imaging, laboratory experiments, numerical modelling, and statistical analyses of seismicity, the work carried out within WP5.1 provides new insights into the mechanisms governing seismicity and offers improved constraints for the characterization of seismogenic faults and for the assessment of seismic hazard.

4. Characterization of Seismogenic Fault Systems and Earthquake Processes

4.1 Developing new techniques for robust earthquake source parameter estimation (OGS)

4.1.1. Scientific Context and Objectives

The reliable estimation of earthquake source parameters is a fundamental problem in seismology, with important implications both for the understanding of earthquake physics and for practical applications such as seismic hazard and ground-motion modelling. Parameters such as seismic moment, moment magnitude, corner frequency and stress drop provide key information on rupture processes and scaling relations, and they are routinely used to characterize earthquake populations and constrain source models. Accurate and robust estimation of these parameters is therefore essential both for scientific investigations and for operational seismology.

However, the estimation of source parameters from seismic observations is not straightforward. Classical spectral inversion approaches often suffer from strong parameter trade-offs and from the influence of propagation and site effects, which can bias the inferred source characteristics. Most traditional methods are based on fitting the amplitude spectrum of the observed signal with a theoretical spectral model derived from simplified source representations (e.g., the Brune model). In practice, the observed amplitude spectrum is affected not only by source properties but also by attenuation along the propagation path, site amplification, instrument response and noise contamination. As a consequence, several parameters involved in the inversion can compensate each other, leading to non-unique solutions in which different combinations of parameters produce comparable spectral fits.

These limitations become particularly evident when analysing small-to-moderate earthquakes recorded by regional seismic networks, where signal-to-noise ratios and bandwidth limitations can further degrade the reliability of spectral estimates. Within this context, the objective of the present activity was to explore alternative strategies to improve the robustness of source parameter estimation. In particular, the work focused on the development and testing of methodologies that exploit the phase spectrum of seismic signals, which is typically controlled by a smaller number of parameters than the amplitude spectrum and may therefore provide additional constraints on the inversion problem.

4.1.2. Methodological Development

The methodological development carried out within this activity followed three main steps, involving waveform preprocessing, phase spectral modelling and inversion.

The first step consisted in the development of a dedicated Python-based preprocessing workflow aimed at transforming raw seismic recordings into high-quality signals suitable for spectral analysis. The workflow includes several standard operations required for waveform conditioning, such as removal of the instrumental response, filtering, noise reduction and conversion of the signals into the desired physical quantity (acceleration, velocity or displacement). Particular attention was devoted to ensuring the stability of the procedure in the presence of noisy data and to enabling the automatic identification and extraction of the relevant time windows containing the P-wave onset. The resulting preprocessing routine allows the generation of consistent datasets that can be directly used for spectral analysis and inversion.

The second methodological component consists of the implementation of a Phase Spectral Fitting (PSF) routine in Python. The method follows the theoretical formulation proposed in Parolai (2024) and is based on fitting the observed phase spectrum with a theoretical representation derived from wave propagation in layered media. In this implementation, the propagation effects are described using the Haskell matrix formulation, which allows modelling the propagation of seismic waves through horizontally layered structures. By explicitly accounting for propagation effects within the inversion framework, the PSF approach aims to isolate the contribution of the source parameters to the observed phase spectrum.

The methodology was initially tested using synthetic datasets, generated for a range of source parameters and noise conditions. These tests allowed a systematic evaluation of the performance of the inversion procedure and provided a controlled framework for verifying the ability of the PSF approach to retrieve the input parameters. The synthetic experiments confirmed that the method can recover the source parameters with good accuracy and stability, even in the presence of moderate noise levels.

4.1.3. Discussion on Main Results

Following the validation phase with synthetic data, the methodology was applied to real seismic recordings from the Central Italy seismic network. The selected dataset includes local earthquakes recorded at regional distances, providing suitable bandwidth for analysing the P-wave portion of the signal. Each waveform was processed using the developed preprocessing routine in order to extract clean P-wave impulses suitable for phase spectral analysis. The PSF inversion was then applied to estimate the relevant source parameters.

A first consistency assessment of the results was performed by analysing the relationship between moment magnitude and corner frequency, which is commonly used to infer the stress drop associated with the earthquake source. The obtained estimates were compared with theoretical expectations and with typical values reported in the literature for crustal earthquakes. As shown in Figure 1, the inferred parameters define a distribution compatible with stress drop values ranging approximately between 0.01 MPa and 10 MPa, which corresponds to the typical range observed in many tectonic environments.

These results indicate that the proposed methodology provides physically consistent estimates of the source parameters for the analysed dataset. The application to real seismic data also confirms that the approach is sufficiently stable when dealing with waveforms affected by realistic noise levels. At the same time, further work is needed to assess the robustness of the method across larger datasets and different tectonic settings.

Overall, the results obtained within this activity highlight the potential of phase-based spectral analysis as a complementary tool for earthquake source characterization. By exploiting additional information contained in the phase spectrum, the approach may help reduce some of the trade-offs that affect traditional amplitude-based inversions. Future developments will focus on extending the application of the methodology to larger datasets, improving the automation of the preprocessing workflow and exploring possible integrations with conventional spectral inversion techniques.

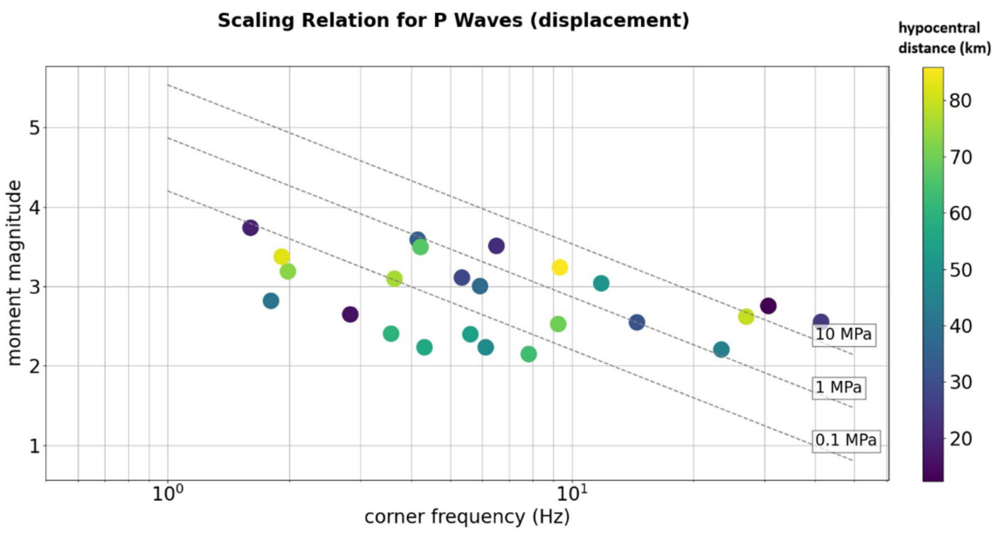

Figure 1. Relationship between moment magnitude (Mw) and corner frequency estimated from the P-wave phase spectral fitting (PSF) analysis of earthquakes recorded by the Central Italy seismic network. The distribution of the inferred parameters is consistent with stress drop values in the range of approximately 0.01–10 MPa, which falls within the typical variability observed for crustal earthquakes.

4.2 Advanced techniques for the detection and characterization of microseismicity and their integration into automated workflows using standard-network, array and fiber station data (UNINA-DF)

4.2.1. Scientific Context and Objectives

The accurate detection and characterization of microseismicity are fundamental for understanding fault mechanics, monitoring active tectonic and volcanic regions, and supporting industrial and environmental applications. In tectonically complex areas, such as continental collision zones and volcanic calderas, small-to-moderate earthquakes provide critical information on stress evolution and rupture processes. However, their analysis requires robust methodologies capable of extracting reliable source parameters from heterogeneous datasets.

The main objective of this activity was to develop and validate advanced techniques for the detection and characterization of microseismic events, integrating data from standard seismic networks, dense arrays, and Distributed Acoustic Sensing (DAS) systems. A key goal was the implementation of automated or semi-automated workflows capable of retrieving physically consistent source parameters (e.g., rupture propagation and duration, source radius, stress drop) and tracking subtle temporal changes in medium properties, with potential applications to real-time monitoring.

4.2.2. Methodological Development

The methodological development focused on building scalable processing pipelines integrating event detection, waveform preprocessing, spectral and time-domain analyses, and automated parameter extraction.

For standard seismic network and array data, time-domain approaches were implemented to track the rupture front and estimate rupture duration, source radius, and stress drop. These methods were tested on datasets from tectonically active regions, including the 2017 Mw 7.3 Ezgeleh and the 2023 Mw 7.8 Kahramanmaraş earthquake. Automated routines were designed to ensure stability in parameter estimation across a broad magnitude range, from microseismic events to moderate/large earthquakes. Particular attention was devoted to maintaining physical consistency in the inversion procedures and minimizing operator-dependent biases.

A major technological advancement concerned the use of Distributed Acoustic Sensing (DAS) for earthquake source characterization. A theoretical framework was developed to directly relate strain-rate spectra recorded along fiber-optic cables to earthquake source parameters, avoiding the intermediate conversion into traditional ground motion quantities (e.g., velocity or displacement). This approach allows the direct exploitation of the native DAS observable and preserves high spatial resolution. The methodology was applied to real field datasets, demonstrating its feasibility for small events (Md ~2–4).

In parallel, automated waveform similarity and cross-correlation techniques were implemented to identify and analyze repeating microearthquakes, particularly in the Val d'Agri area. These procedures enabled the tracking of subtle temporal variations in seismic velocity, interpreted as indicators of evolving stress conditions and medium changes. All methodologies were integrated into semi-automated or fully automated workflows to facilitate continuous and near-real-time operation.

4.2.3. Discussion on Main Results

The application of time-domain source analysis confirmed near self-similar scaling between rupture dimensions and seismic moment, consistent with theoretical expectations. Estimated stress drops were typically in the range of 1–3 MPa, including for the 2017 Mw 7.3 Ezgeleh earthquake. These results demonstrate that automated workflows can reliably retrieve physically meaningful parameters even in structurally complex collision environments. The robustness of the estimates supports the feasibility of large-scale, systematic analyses without manual intervention.

Investigations of large continental strike-slip earthquakes provide complementary insights into dynamic rupture processes. The study of the 6 February 2023 Mw 7.8 Kahramanmaraş earthquake (Türkiye) revealed pronounced along-strike variability in rupture velocity during the early stages of propagation, with localized transitions to supershear speeds spatially correlated with areas of large coseismic slip. These findings indicate strong lateral heterogeneities in fault mechanical properties and demonstrate how rupture velocity variations directly influence slip distribution and high-frequency radiation. Such results reinforce the importance of integrating dense observational constraints and automated analysis techniques to resolve the complexity of earthquake source processes across scales.

The implementation of DAS-based source characterization represents a significant step forward in microseismic monitoring. Field applications showed that strain-rate spectra measured along fiber-optic cables can provide stable estimates of seismic moment and corner frequency for low-magnitude events (Md ~2–4). The extremely dense spatial sampling achievable with DAS systems enhances wavefield resolution and improves detection capability in low signal-to-noise conditions, offering clear advantages over conventional sparse networks.

The analysis of repeating microearthquakes in the Val d'Agri region further demonstrated the potential of automated similarity-based approaches for monitoring subtle temporal variations in seismic velocity. Such variations likely reflect stress perturbations and progressive changes in medium properties. This capability is particularly relevant for industrial and environmental monitoring, where continuous assessment of subsurface conditions is required.

Overall, the integration of standard seismic networks, arrays, and DAS data within unified automated processing chains provides a scalable and flexible framework for multi-sensor monitoring systems. The results confirm that advanced, automated methodologies can enhance both the physical understanding of rupture processes and the operational capabilities of real-time microseismic characterization systems.

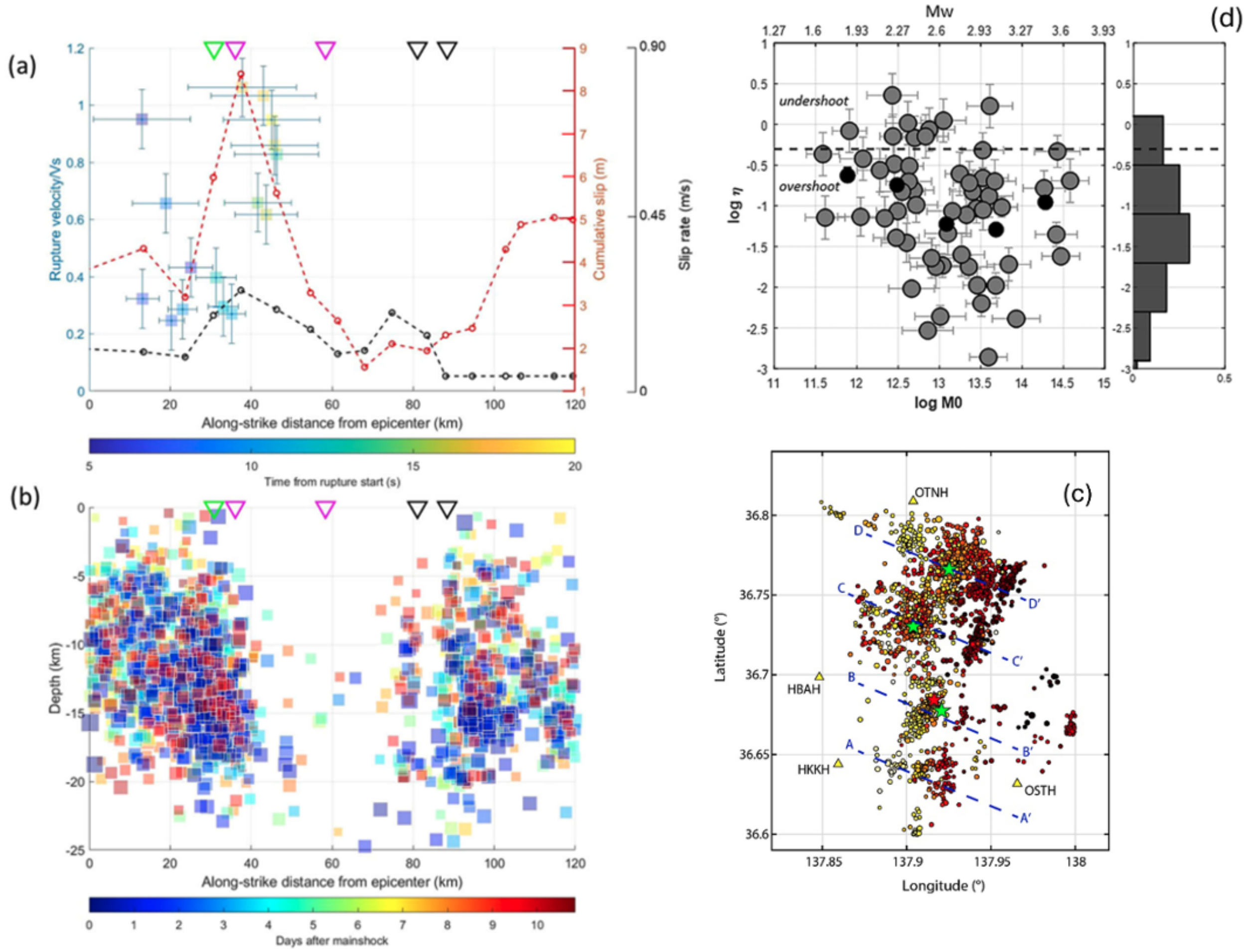

Figure 2. Rupture velocity (a) and aftershock distribution (b) vs along-strike distance of the 2023 Kahramanmaraş earthquake (Palo and Zollo, 2024). (c) Microearthquake distribution of the Nagano sequence (Muzellec et al., 2025). (d) Energy partitioning and radiation efficiency of Campi Flegrei earthquakes (Nazeri et al., 2025).

4.3 Identification and parametrization of seismogenic faults and the role of structural complexities in earthquake phenomenology; Identification of capable faults. (UNINA-DiSTAR)

4.3.1. Scientific Context and Objectives

The identification and parametrization of seismogenic and capable faults represent a key step in seismic hazard assessment, particularly in tectonically complex regions such as the Southern Apennines. In these settings, fault systems commonly record a long and polyphase tectonic history, and the present-day seismic behaviour may reflect the interaction between inherited structures, active deformation, strain partitioning, and fault-segment linkage. A robust characterization of fault geometry, kinematics, and activity through time is therefore essential not only to improve the parametrization of seismogenic sources, but also to assess which structures can be considered capable faults in the sense of surface-faulting hazard.

The main objective of this activity was to refine the geological and geodetic characterization of selected fault systems in the Southern Apennines through a multidisciplinary approach. The work focused on two closely related goals: first, to better constrain the geometry, segmentation and kinematics of major fault systems relevant for earthquake generation; second, to reconstruct their deformation history at different temporal scales, in order to distinguish between inherited structures, currently active faults, and faults that may contribute to surface deformation during future earthquakes. This effort was designed to provide updated information for the parametrization of seismogenic sources and capable faults, and thereby contribute to a more robust evaluation of both regional seismic hazard and fault-displacement hazard.

A further scientific motivation of the activity was to clarify the role of structural complexity in earthquake phenomenology. In fault systems composed of multiple segments, inherited geometries, and interacting structures, the distribution of deformation may not be straightforward, and the seismogenic potential of individual faults cannot be inferred from surface expression alone. For this reason, the activity combined field geology, morphotectonic analyses, paleoseismology, shallow geophysics and geodetic data in order to move from a purely descriptive mapping of faults to a more process-oriented interpretation of their present-day role within the active tectonic framework.

4.3.2. Methodological Development

The methodological approach adopted in this activity was explicitly multidisciplinary and was applied to several key sectors of the Southern Apennines, including the Irpinia region, the Vallo di Diano, and the Matese Mountains (Fig. 3). The strategy combined geological-structural field investigations (Fig. 3a), morphostructural and morphometric analyses, paleoseismological observations, shallow geophysical imaging (Fig. 3b), geodetic measurements (Fig. 3c), and the study of continental deposits linked to Quaternary tectonic evolution.

In the Irpinia region, between the Picentini Mountains–Mt. Marzano structural ridge and the Ofanto Basin, the work initially focused on geological-structural analysis of the Pescopagano Fault. This structure had previously been interpreted as an active and capable fault potentially connected to the 1980 Mw 6.9 Irpinia earthquake. Its geometry and age were reassessed through the integration of three seismic reflection tomography datasets, three paleoseismological trenches, radiometric dating, and site-specific morphometric analyses. This combination of methods was used to test whether the fault shows evidence of recent surface activity and whether it should be retained among the structures relevant for present-day seismogenic and surface-faulting hazard.

In the Vallo di Diano, the activity aimed at refining the geometry and kinematics of the local fault system. Here, morphostructural and morphometric analyses were integrated with geophysical surveys to investigate fault arrangement, continuity and segmentation. The results indicate that the system is not represented by a single simple structure, but rather by multiple segments that may interact mechanically and kinematically. This aspect is particularly relevant for source parametrization, because segmentation and linkage directly influence the expected rupture dimensions and the interpretation of seismic potential.

In the Matese Mountains, the work concentrated on the northern and central Matese fault systems (NMFS and CMFS). Extensive geological-structural surveys were carried out along both systems, and these were complemented by geodetic measurements and analyses, six electrical resistivity tomographies, six seismic tomographies, a geognostic well, and the dating of tephra and soil horizons from a paleoseismological trench. In parallel, clastic continental deposits were mapped and characterized in order to relate them to different morphotectonic stages associated with differently oriented Plio-Quaternary stress fields. Rock-magnetic properties (e.g., magnetic susceptibility) of these deposits were used as proxies of environmental changes and analyzed as time series to investigate possible medium-term cyclicities in seismic activity encoded into the stratigraphic archives.

At the broader scale of the Southern Apennines, geodetic strain-rate data were compiled across the current structural setting, and a dedicated computing tool was developed to derive semi-automatically the strike and dip components of strain referred to the mapped faults. To improve the spatial resolution of the geodetic framework, about 20 new benchmarks were installed in the Matese, Gargano, Irpinia and Vallo di Diano regions. This allowed a more detailed analysis of the geodetic strain field and of its partitioning among distinct fault systems. The activity also included the morphometric investigation and the inversion of fluvial landscape, aiming at the modelling of fault geometry, strain partitioning, and fault propagation/linkage in structurally complex systems, including applications in NE Sicily.

4.3.3. Discussion on Main Results

The main outcome of the activity is a more selective and better constrained parametrization of fault systems in the Southern Apennines, with direct implications for both seismogenic source modelling and capable-fault assessment. One of the most significant results concerns the Pescopagano Fault in the Irpinia region. Although previously regarded as an active and capable structure connected to the 1980 Irpinia earthquake, the integrated geological, geophysical and paleoseismological evidence collected in this study indicates that the fault did not produce surface faulting during the last 20 ka. On this basis, it is more appropriately interpreted as an inherited shallow Plio-Quaternary structure rather than as a fault expected to be activated by Irpinia-1980-type earthquakes (Ferranti et al., 2024). This is an important result because it implies a revision of the role of this structure in seismic-source parametrization and in fault-displacement hazard assessment.

In the Vallo di Diano, the study confirmed that the fault system is internally segmented and possibly composed of interacting fault sections rather than a single through-going structure. From a seismotectonic perspective, this is relevant because segmented systems may rupture either independently or through multi-segment interaction, with consequences for expected rupture length, earthquake size and spatial distribution of deformation. Even where the available data do not yet fully resolve the dynamic behaviour of the system, the refined geometrical framework represents a substantial improvement over oversimplified source representations.

In the Matese area, the integration of geological and geodetic observations provided a clearer picture of strain partitioning between neighbouring fault systems. In particular, the northern Matese fault system was found to accommodate about one third of the strain accumulation affecting the Matese Massif, with rates of approximately 0.7–1.1 mm/yr, whereas the central Matese fault system appears geodetically inactive. This contrast is important because it helps distinguish faults that are currently contributing to deformation from those that may be morphologically evident but not significantly active under the present stress field. The combined use of trench data, shallow geophysics, borehole information, and dated stratigraphic markers further strengthened the interpretation of the timing and style of recent deformation.

Finally, the morphotectonic analysis (paleo-shorelines modelling) and the inversion of fluvial landscape carried out along the Ionian side of NE-Sicily (Pavano, 2025), revealed the time-transgressive southward propagation of the activity of an offshore fault system, arguing about the fault geometry reorganization, strain partitioning, and fault linkage processes.

A broader result emerging from the activity is that structural complexity must be treated as a primary control on earthquake phenomenology, not as a secondary geometric detail. Across the investigated sectors, the data show that inherited structures, segmentation, variable fault activity, and differential strain accumulation all affect how fault systems should be represented in hazard-oriented models. In this sense, the project did not simply produce new fault maps, but contributed to a more critical discrimination between structures that are demonstrably active, structures that are inherited and no longer relevant for present-day seismogenic behaviour, and structures whose role can only be understood when analysed within a system-scale framework.

The results also highlight some natural limitations and future needs. While the integrated approach significantly improved fault characterization in the investigated areas, not all uncertainties are fully resolved, especially regarding fault interaction at depth and the temporal persistence of activity over different seismic cycles. Nevertheless, the activity provides a solid observational basis for updating the parametrization of seismogenic and capable faults in the Southern Apennines and for improving the physical consistency of regional hazard models.

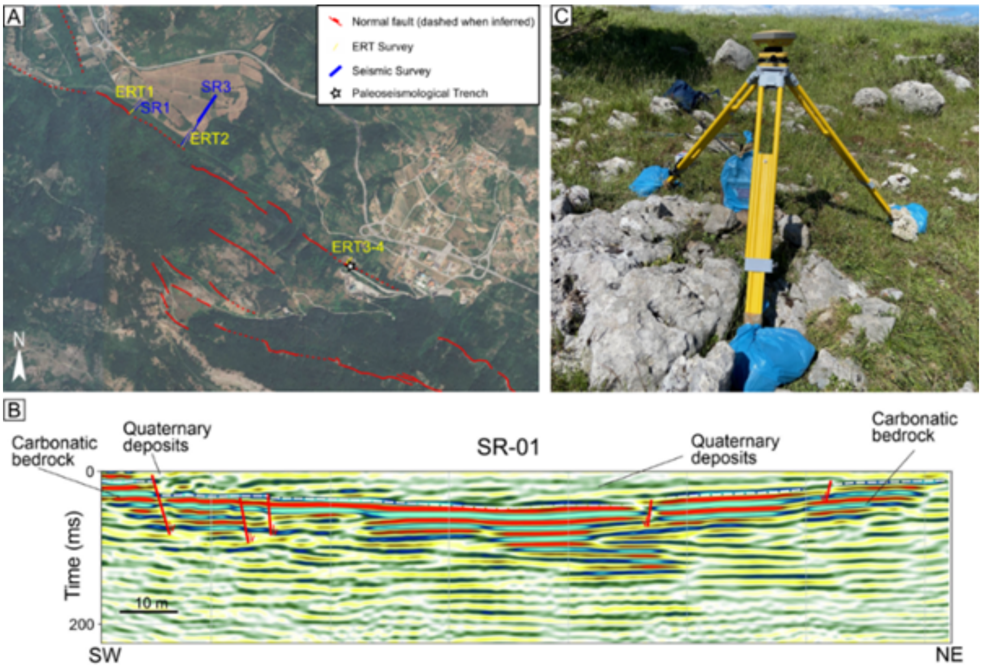

Figure 3. (a) Map of the fault segments identified in the northern Matese area, including the location of electrical resistivity tomography (ERT) and seismic profiles. (b) Example of a seismic reflection profile acquired in the same area, highlighting the main fault structures and the contact between bedrock and Quaternary basin infill. (c) Example of a static geodetic measurement performed in the Vallo di Diano area.

4.4 Multiparametric (seismic and electrical) model of seismogenic faults at depth. Numerical 3D models of seismic energy. (UNIBA)

4.4.1. Scientific Context and Objectives

The characterization of seismogenic faults at depth requires the integration of different types of geophysical observations and modelling approaches. While geological and geomorphological studies provide constraints on the surface expression of fault systems, the processes controlling earthquake nucleation and rupture propagation are largely governed by the physical properties of the crust at seismogenic depths. These include stress distribution, fault geometry, rheology, and the presence of fluids within fault zones.

In tectonically active regions such as Southern Italy, these factors interact within structurally complex crustal environments where inherited faults may be reactivated under the current stress field. In such contexts, the integration of seismic observations, geophysical prospecting and monitoring systems combined with numerical modelling becomes essential to better understand the mechanisms controlling fault reactivation and the generation of seismic energy.

Within this framework, the activity carried out by UNIBA focused on two complementary objectives. The first was the improvement of the observational framework for microseismicity through the development of updated earthquake catalogues and real-time monitoring tools. The second objective was the investigation of the mechanical behaviour of seismogenic faults through extensive magnetotelluric exploration that furnished crustal electrical resistivity models and numerical modelling of the crustal stress field and fault reactivation processes.

These objectives were pursued through activities conducted in two main study areas of Southern Italy. In the Gargano region, seismic monitoring and catalogue development were carried out using data from the OTRIONS seismic network. In the Val d’Agri basin, numerical modelling was performed to investigate the present-day stress field, fault geometry and the potential role of crustal fluids in the reactivation of pre-existing fault systems.

4.4.2. Methodological Development

The first component of the activity concerned the development of an updated microearthquake catalogue for the Gargano area, located in Southern Italy. The catalogue was compiled using seismic recordings from the OTRIONS seismic network covering the time period 2013–2022. The processing and analysis of the seismic data allowed the identification and relocation of a large number of microseismic events, providing an improved dataset for the characterization of seismic activity in the region.

To support continuous monitoring of seismic activity, the SeisComP software platform has been installed and is now fully operational on the OTRIONS laboratory server at the University of Bari Ado Moro. The system enables real-time acquisition and processing of seismic signals recorded by the network, allowing automatic detection and location of seismic events and improving the capability to monitor the seismic behaviour of the Gargano region in near real time.

The second methodological component involved the investigation of the tectonic and mechanical conditions of the Val d’Agri basin, a region characterized by active tectonics and significant hydrocarbon-related industrial activity. In this case, the study focused on understanding the relationship between the present-day stress field, fault geometry and the mechanical properties of the crust.

To address this problem, a two-dimensional elasto-visco-plastic numerical model of the Val d'Agri crust was developed. The model incorporates geological and tectonic constraints on the regional fault system and simulates the mechanical response of the crust under the current stress regime. Particular attention was devoted to the role of fluids within the crust, which may significantly influence fault stability by reducing effective normal stress and promoting the reactivation of pre-existing faults.

By integrating geological information with numerical modelling, the approach allows exploration of the mechanical conditions under which inherited structures may become reactivated and contribute to present-day seismicity.

4.4.3. Discussion on Main Results

The activities carried out within this task produced new observational and modelling results that contribute to a better understanding of seismogenic processes in Southern Italy.

The development of a new microearthquake catalogue for the Gargano area represents an important step toward improving the characterization of seismic activity in this region. The analysis of seismic data from the OTRIONS network for the period 2013–2022 provides a more complete description of the spatial and temporal distribution of microseismicity (Fig. 5). Such datasets are essential for identifying active structures, refining earthquake locations and improving the interpretation of local tectonic processes. The implementation of the SeisComP system on the OTRIONS (Tallarico et al., 2025) server further strengthens the operational monitoring capability, enabling continuous real-time surveillance of seismic activity in the area.

To image the seismogenic area at depth we use an extensive magnetotelluric dataset collected in a large sector of Southern Apennines (Irpinia region) that includes the areas of the main earthquakes that occurred in the last century (1930 and 1980 events). The three-dimensional resistivity model (Fig. 4) clearly defines the behaviour of the resistive bedrock on whose edges the hypocenters of the two main seismic events are located.

The numerical modelling performed for the Val d'Agri basin provides additional insights into the mechanical conditions controlling fault activity in the region (Fig.6). The elasto-visco-plastic simulations highlight the importance of crustal stress distribution and fault geometry in determining which structures may become active under the present tectonic regime. In particular, the modelling results suggest that fluids may play a significant role in facilitating the reactivation of pre-existing faults, by reducing the effective stress acting on fault planes.

These findings are consistent with the broader understanding that fluid pressure variations can strongly influence the mechanical stability of faults, especially in tectonic environments where inherited structures are abundant. The results therefore contribute to a better interpretation of the seismic behaviour of the Val d'Agri region and provide a framework for integrating geophysical observations with mechanical modelling of fault systems.

Overall, the combination of improved seismic monitoring capabilities, updated earthquake catalogues and numerical modelling of crustal processes provides a more robust basis for analysing the dynamics of seismogenic faults in Southern Italy. Future work will focus on extending these approaches to additional datasets and refining the numerical models in order to further investigate the relationship between crustal properties, fluid processes and seismic energy release.

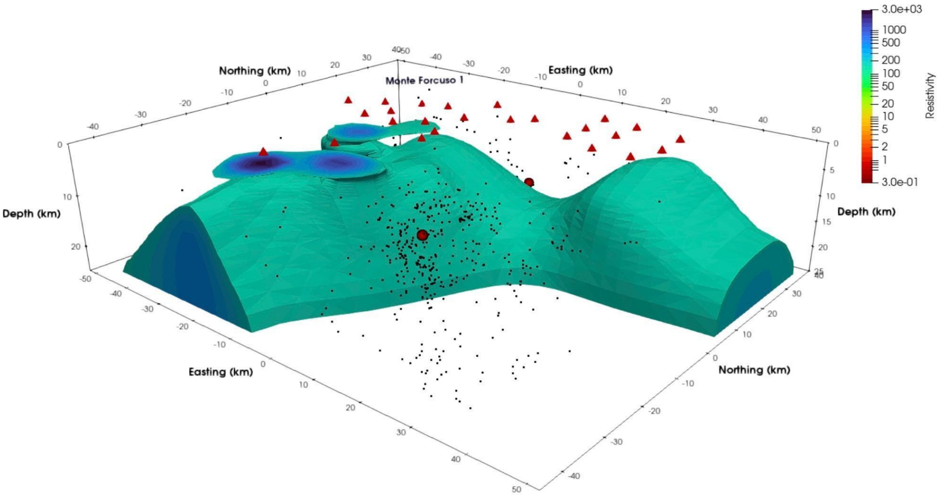

Figure 4. Three-dimensional resistivity structure of the bedrock obtained from the inversion of magnetotelluric data (red triangles) in the Irpinia region. Red dots indicate the hypocenters of the main earthquakes that occurred in the last century (1930 and 1980 events); diffuse seismicity of the last ten years is indicated with black points.

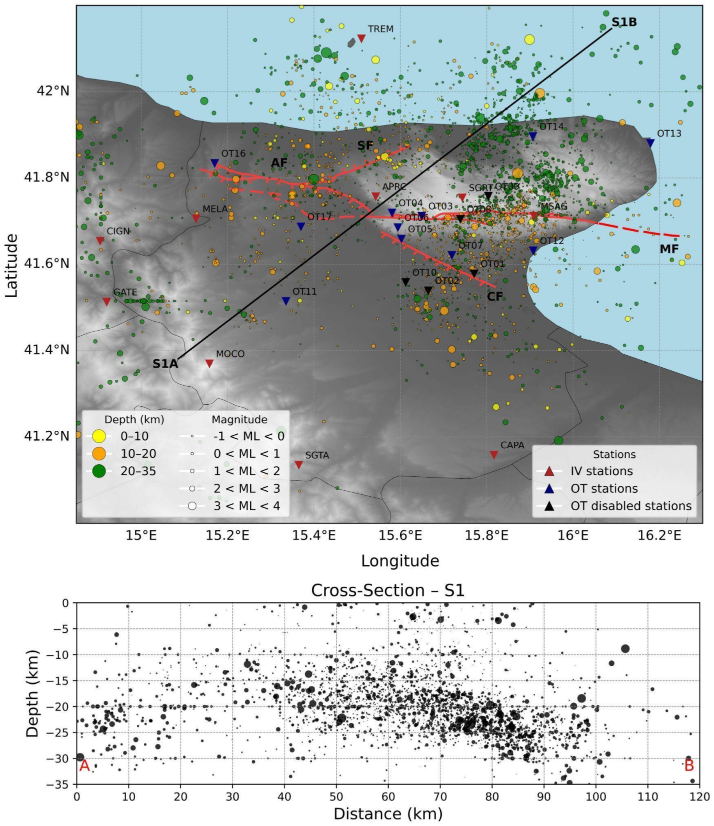

Figure 5. Map of the earthquake epicenters from the seismic catalogue covering the period April 2013 – December 2022, together with a vertical cross-section along the S1A–S1B segment. Red lines indicate the main mapped faults in the study area (from Ferreri et al., 2025).

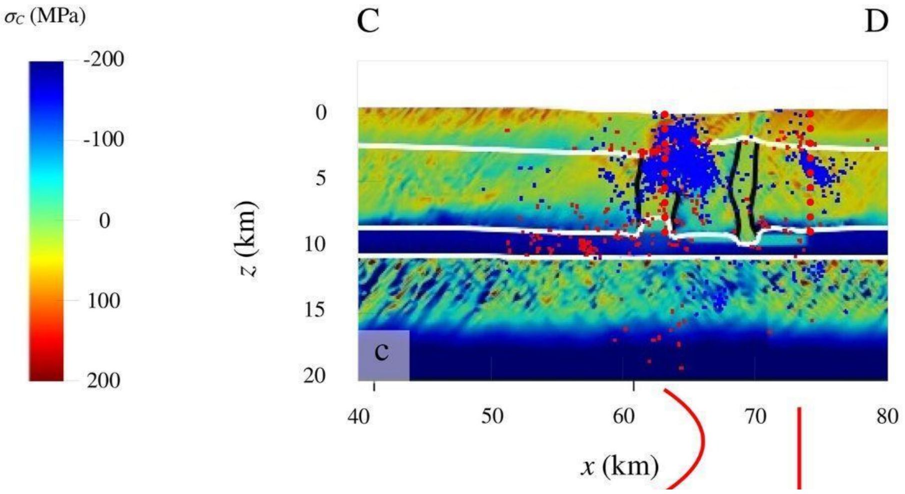

Figure 6. Distribution of Coulomb stress (σC) values derived from the numerical model. Dark blue dots represent hypocenters located within the brittle domain, whereas red dots correspond to hypocenters falling within the ductile domain of the model (modified from Lavecchia et al., 2024).

4.5 High-resolution and modern study of active and capable faults; study of fluid-fault interaction and feedback and its role in earthquake production. (UNIBO)

4.5.1. Scientific Context and Objectives

Understanding the processes that control earthquake generation requires a detailed characterization of active and capable fault systems across a wide range of spatial scales. In complex tectonic regions such as the Apennines, present-day seismicity often develops within structural frameworks that have experienced multiple tectonic phases. As a result, the geometry and mechanical behaviour of active faults are frequently influenced by inherited structural elements formed during earlier stages of the geological evolution of the orogen.

In such polyphased tectonic settings, the reactivation of pre-existing structures may play a fundamental role in controlling the geometry, segmentation, and mechanical behaviour of seismogenic faults. The orientation of inherited structural fabrics relative to the present-day stress field can strongly influence whether faults are reactivated or whether new structures develop. Consequently, identifying the role of structural inheritance is essential for correctly assessing the size, connectivity, and earthquake potential of active fault systems.

Another key factor influencing fault mechanics and earthquake generation is the interaction between faults and circulating fluids. Fluid circulation within fault zones may alter the mechanical properties of rocks, modify the effective stress acting on fault planes, and locally perturb the stress field. These processes can influence both the nucleation of seismic slip and the evolution of fault systems through time.

Within this context, the main objective of this activity was to apply a modern geological–structural approach to the investigation of active and capable faults in tectonically active sectors of the Northern Apennines. The study aimed to identify the main structural factors controlling earthquake production, with particular attention to the role of structural inheritance and fluid circulation in shaping fault geometry and mechanical behaviour. The ultimate goal was to derive deterministic geological parameters that can contribute to improved seismic hazard assessment and support the development of probabilistic seismic models.

4.5.2. Methodological Development

To address these objectives, a multiscale geological–structural approach was adopted, combining detailed field observations with regional-scale tectonic analysis. The methodology integrates structural mapping, fault kinematic analysis, stratigraphic relationships, and the interpretation of structural inheritance across different tectonic domains.

The approach was applied to several sectors of the Northern Apennines, including the Monti Martani area in Umbria, the Mugello basin in Tuscany, the Epiligurian basins of the Emilian Apennines, and the Subliguride Units of the Ligurian Apennines. These areas represent key natural laboratories where the interaction between inherited structures and younger extensional fault systems can be directly observed. The analysis focused on reconstructing the structural evolution of these regions by identifying the relationships between older tectonic fabrics and younger active faults. Particular attention was devoted to recognizing structures inherited from earlier tectonic phases, such as the Jurassic rifting events that affected the Apennine domain, and assessing how these pre-existing structures influence the geometry and distribution of present-day extensional faults.

Among the investigated areas, the Monti Martani Fault System provided the most representative and informative case study. Here, detailed structural mapping and geological analysis were used to investigate the role of pre-orogenic structural inheritance in controlling the development of post-orogenic extensional faults. The structural framework of the area was reconstructed through the integration of outcrop-scale observations, fault kinematic indicators, and regional tectonic interpretation.

In addition to structural mapping, ongoing investigations include the study of carbonate veins associated with the fault system, which provide evidence of fluid circulation during fault activity. The mineralogical and structural characteristics of these veins offer valuable insights into the relationship between fluid flow and fault slip, as well as the possible feedback mechanisms between fluid pressure variations and local stress perturbations.

4.5.3. Discussion on Main Results

The results of this activity highlight the fundamental role of structural inheritance in controlling the geometry and seismic potential of active fault systems in the Northern Apennines. In particular, the analysis of the Monti Martani Fault System demonstrates that the pre-orogenic structural template inherited from Jurassic rifting still exerts a strong influence on the development of present-day extensional faults.

The orientation of inherited structures relative to the current stress field appears to play a key role in determining the geometry and connectivity of seismogenic faults. When pre-existing structures are optimally oriented with respect to the regional extensional stress field, they tend to be preferentially reactivated, favouring the development of longer and more continuous normal faults. These structures can potentially generate larger seismogenic sources due to their greater length and structural continuity.

Conversely, when the inherited structural grain is not optimally oriented relative to the present stress field, the development of long reactivated structures becomes less favourable. In such cases, the extensional deformation tends to be accommodated by the formation of shorter, newly formed normal faults that are approximately perpendicular to the regional extension direction. This leads to a system of shorter and more disconnected seismogenic sources, which may have a substantially different earthquake potential compared to fault systems formed through the reactivation of inherited structures.

Additional insights come from the study of carbonate veins associated with the Monti Martani Fault System, which provide evidence for significant fluid circulation during fault activity. Preliminary observations suggest that fluid flow associated with faulting may induce transient perturbations of the local stress field in the hanging wall of normal faults. In some cases, these processes appear to produce significant rotations of the extension direction, potentially reaching values of up to 90°. Such observations suggest that fluid–fault interaction may play an important role in the evolution of local stress conditions during fault activity.

Ongoing geochronological investigations aim to constrain the timing of these fluid circulation events and their relationship with the tectonic evolution of the fault system. Establishing the temporal framework of these processes will help clarify the role of fluid circulation within the broader tectonic history of the studied structures. Overall, the results of this activity demonstrate that the geometry and seismic potential of active faults cannot be fully understood without considering the combined influence of structural inheritance, tectonic stress orientation, and fluid circulation processes. The insights obtained from the Northern Apennines provide a framework that may also be applicable to other polyphased tectonic regions where inherited structures interact with younger tectonic deformation.

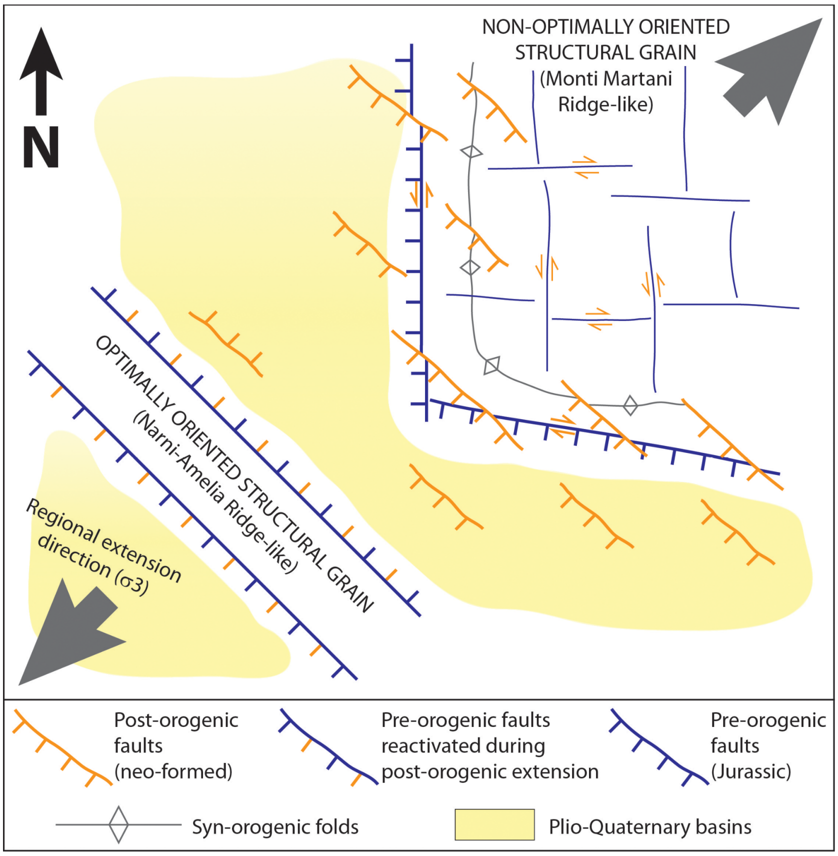

Figure 7. Conceptual model for the development of post-orogenic extensional faults (after Asti et al., 2024). Inherited structures optimally oriented with respect to the regional extensional stress field are preferentially reactivated and favour the formation of longer seismogenic normal faults. In contrast, a non-optimally oriented inherited structural grain promotes the development of shorter, newly formed normal faults approximately perpendicular to the regional extension direction.

4.6 Multiscale analysis of active and fossil seismic structures. Advanced geological mapping and multiscale analysis of key fault systems (inland and offshore). (UNIGE)

4.6.1. Scientific Context and Objectives

Understanding the mechanical behaviour of active fault systems requires the integration of observations across multiple spatial scales, ranging from microstructural analyses of fault rocks to regional-scale geophysical monitoring of seismic activity. In many tectonically complex regions, the seismic behaviour of faults is strongly influenced by the physical and rheological properties of the rocks involved in deformation, as well as by the presence of fluids circulating within fault zones.

Serpentinite-rich fault zones represent a particularly important case in this context. Due to their distinctive mineralogical composition and mechanical properties, serpentinites can strongly influence fault strength, deformation mechanisms, and the transition between ductile and brittle behaviour. The study of such fault systems therefore provides valuable insights into the processes controlling earthquake nucleation and fault slip behaviour.

Within this framework, the objective of this activity was to develop a multiscale and multimethodological approach for the investigation of active and fossil seismic structures in the Ligurian Apennines. The study focused on the hinterland of the city of Genova, particularly within the Voltri metaophiolite massif, which represents a natural laboratory for analysing the interaction between rock deformation, fluid circulation, and seismic activity.

The main goal was to integrate detailed structural mapping and microstructural analyses of serpentinite-rich fault zones with high-resolution seismic observations, in order to better understand the rheological properties of these fault systems and their potential role in present-day seismic activity. The results aim to provide new rheological constraints useful for the development of seismicity models in structurally complex tectonic settings.

4.6.2. Methodological Development

The methodological approach adopted in this activity integrates geological field observations, laboratory-based microstructural analyses, and high-resolution seismic monitoring. The study area is located in the Voltri metaophiolite massif in the hinterland of Genova (northwestern Italy), a region where serpentinite-rich lithologies are widely exposed and where several tectonic lineaments extend both inland and offshore into the Ligurian Sea. This geological setting provides favourable conditions for investigating the relationships between fault rock properties, fluid circulation, and seismic activity.

The research focused on three main methodological components. First, detailed structural mapping and petrographic characterization of fault rocks were carried out in selected serpentinite-rich fault zones. These investigations aimed to reconstruct the deformation history of the faults and to identify the mineral assemblages associated with different deformation stages.

Second, microstructural analyses were performed using a Tescan Clara field-emission scanning electron microscope (FEG-SEM). These analyses allowed the characterization of serpentine polymorphs and mineralogical transformations occurring within fault zones, particularly along shear bands developed within the fault cores. Understanding the distribution and crystallization mechanisms of serpentine minerals is essential for evaluating their influence on fault strength and slip behaviour.

Third, microseismic monitoring was performed using Lunitek Sentinel Geo seismometers, installed as part of a temporary seismic deployment in the Genova hinterland. These instruments, acquired within the framework of the RETURN project, enabled the detection and analysis of low-magnitude microseismic events ($M \leq 2$) potentially associated with active tectonic structures in the region.

By combining structural observations, mineralogical analyses and seismic monitoring, the adopted approach allows linking the physical properties of fault rocks with the spatial distribution of microseismicity and the regional tectonic framework.

4.6.3. Discussion on Main Results

The structural and petrographic analyses revealed a complex deformation history within the investigated serpentinite-rich fault zones. The studied structures show evidence of multiple deformation phases, with older ductile fabrics associated with Alpine subduction and collision processes subsequently overprinted by younger brittle faulting.

The older deformation stage is represented by mineral assemblages including antigorite, ilmenite, chlorite, pyrite, and chalcopyrite, which are characteristic of deformation under higher-temperature conditions during the Alpine tectonic evolution. These structures are crosscut by steeply dipping fault planes striking NNE–SSW, which represent a younger phase of brittle deformation.

These faults display complex internal architectures characterized by multiple anastomosed fault cores composed of serpentinite-rich ultracataclasites, consisting of antigorite clasts embedded within a matrix rich in chrysotile and chlorite. Shear bands within these fault cores locally host polyhedral serpentine, indicating mineralogical transformations associated with deformation processes.

The observed fault rock textures, including foliated and massive cataclasites, together with the mineral assemblages of newly formed shear bands and the presence of thin cryptocrystalline oxide-rich fault mirrors, suggest the occurrence of polycyclic deformation processes involving transitions between creep and brittle slip within the same fault zone.

The orientation of the studied faults, striking approximately NNE–SSW, is consistent with the orientation of Plio–Pleistocene tectonic lineaments identified in the Gulf of Genova. Furthermore, clusters of microseismic events detected in the study area display similar orientations, suggesting that these structures may still be tectonically active. Although seismic activity in the region is characterized by relatively low magnitudes, the spatial correlation between the mapped fault systems and the detected microseismicity indicates that the investigated structures may play an active role in accommodating present-day deformation in the Genova hinterland.

Overall, the results highlight the importance of integrating structural geology, mineralogical analysis and seismic monitoring in order to better understand the mechanical behaviour of complex fault systems. The multiscale approach adopted in this study provides new insights into the relationship between fault rock rheology, fluid circulation and seismic activity, and contributes to improving the physical constraints used in probabilistic seismicity models for structurally complex regions.

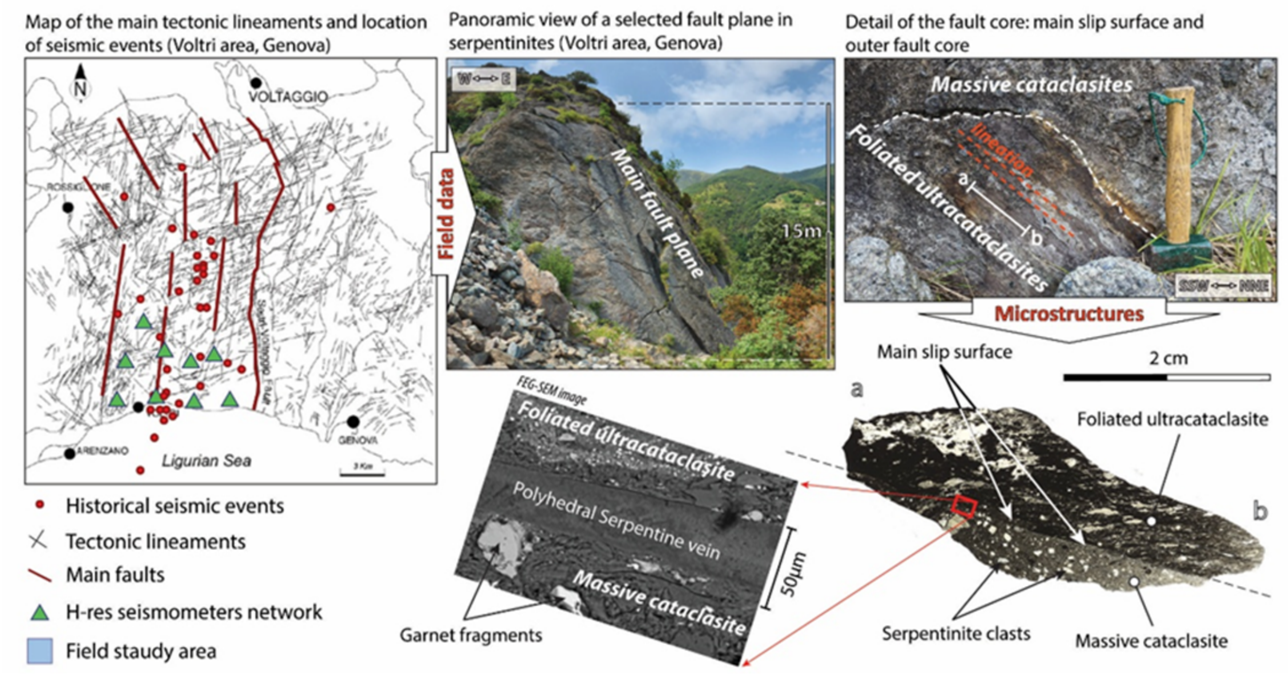

Figure 8. Conceptual scheme of the multiscale and multimethodological approach adopted for the investigation of serpentinite-rich fault systems in the Genova hinterland (Ferriere fault zone). The workflow integrates structural mapping, microstructural and mineralogical analyses of fault rocks, and high-resolution microseismic monitoring to investigate the relationships between fault rock rheology, fluid circulation, and present-day seismic activity.

4.7 Machine learning approaches and fluid–fault interactions for the identification of earthquake precursors (UNIROMA1)

4.7.1. Scientific Context and Objectives

Understanding the physical processes that precede earthquake rupture remains one of the central challenges in seismology. In recent years, increasing attention has been devoted to identifying potential precursory signals associated with fault activation, including variations in seismicity patterns, changes in fluid circulation, and geochemical anomalies related to fluid–rock interactions. These processes may provide valuable insights into the evolution of stress conditions in fault zones and into the mechanisms controlling earthquake nucleation.

A growing body of experimental and observational studies suggests that fluids play a fundamental role in fault mechanics, influencing both the stability of fault slip and the evolution of stress conditions in the crust. Variations in fluid pressure can reduce the effective normal stress acting on fault planes and promote fault reactivation, while fluid–rock interactions may modify the chemical and mineralogical properties of fault zones. Understanding the coupling between fluid circulation and fault slip is therefore essential for interpreting the evolution of seismic processes.

At the same time, recent advances in machine learning (ML) and deep learning (DL) techniques provide new opportunities for analysing large seismic datasets and identifying subtle patterns that may precede earthquake occurrence. Laboratory experiments have shown that ML algorithms can successfully identify precursory signals in acoustic emissions generated during frictional sliding experiments. Extending these approaches to natural seismicity may allow the identification of systematic patterns that distinguish foreshocks from aftershocks or reveal early indicators of fault instability.

Within this framework, the objective of this activity was to integrate structural, hydrogeochemical, experimental, and seismological observations in order to investigate the role of fluids in fault evolution and to explore the potential of ML/DL approaches for identifying earthquake precursors. The study combines field investigations of fluid–fault interactions, laboratory experiments reproducing earthquake-like instabilities, and machine learning analyses applied to seismic catalogues.

4.7.2. Methodological Development

The methodological approach integrates field observations (e.g., Smeraglia et al., 2018), geochemical analyses on fault-related mineralizations (Curzi et al., 2024), laboratory experiments (Volpe et al., 2025), geochemical monitoring (Barberio et al., 2017), and machine learning analyses (Wang et al., 2025). Investigations were conducted from the regional (Curzi et al., 2025) to the nanoscale (Curzi et al., 2026a). Field investigations were conducted in both compressional (e.g., Conero area; Smeraglia et al., 2025) and extensional (e.g., Curzi et al., 2026) tectonic settings. Structural and geochemical analyses were used to investigate the relationships between fault kinematics, fluid circulation pathways, and fluid–rock interactions. Hydrogeochemical monitoring of groundwater was performed through periodic sampling and chemical analysis using ion chromatography and ICP-MS. These analyses allowed the identification of variations in paleofluids and groundwater composition potentially associated with transient fluid circulation processes.

To investigate these processes over time, a long-term monitoring network was established in the Conero area, with bi-monthly sampling of groundwater. This monitoring system provides a unique dataset for detecting potential temporal variations in fluid chemistry that may reflect stress perturbations or fluid migration within fault zones.

Complementary insights were obtained through laboratory friction experiments performed using the Big-Biax apparatus. These experiments reproduce earthquake-like stick–slip instabilities under controlled conditions and generate high-resolution acoustic and mechanical datasets. The resulting experimental signals provide an analogue framework for investigating the evolution of precursory signals prior to failure.

Machine learning and deep learning techniques were then applied to both laboratory and natural datasets. ML/DL algorithms were developed to identify patterns associated with fault instability and to distinguish foreshocks from aftershocks in seismic catalogues. The algorithms analyse variations in signal characteristics and in the frequency–magnitude distribution of earthquakes, allowing the identification of systematic patterns related to evolving fault conditions.

Finally, the activity also included the investigation of paleofluid circulation in fault zones through mineralogical and geochemical analyses of fault rocks. Stable carbon–oxygen isotope analyses and clumped isotope thermometry were used to reconstruct fluid sources and fluid–rock interaction processes during the seismic cycle.

4.7.3. Discussion on Main Results

The integration of structural, geochemical, experimental, and machine learning analyses provides new insights into the role of fluids in earthquake generation and into the potential identification of seismic precursors.

Geochemical analyses on fault-related mineralizations indicate that fluid circulation in fault zones is strongly controlled by fault kinematics and tectonic setting (Curzi et al., 2024; Curzi et al., 2026b; Smeraglia et al., 2025). Structural and geochemical investigations reveal that thrust faults and normal faults host fundamentally different fluid circulation systems. Thrust faults tend to behave as relatively closed systems, where fluid–rock interaction occurs episodically and fluid influx is often associated with transient opening events that may occur during or shortly before seismic slip. In contrast, normal faults often behave as more open systems in which shallow, host-rock and deep-sourced fluids can interact and mix. These observations suggest that extensional tectonic settings may provide favourable conditions for detecting fluid-related precursory signals, since deep fluids may become more active shortly before and during seismic events. The results therefore highlight the importance of monitoring fluid circulation as part of integrated seismic monitoring strategies.

Laboratory experiments further demonstrate that frictional sliding processes can generate systematic acoustic and mechanical signals preceding failure, which can be successfully identified using machine learning approaches. ML/DL algorithms trained on laboratory datasets are capable of predicting time-to-failure and recognizing patterns analogous to natural seismic precursors (Volpe et al., 2025). The integration of laboratory results with natural seismic catalogues suggests that similar approaches may be applied to real seismicity. In particular, ML/DL algorithms show potential for distinguishing foreshocks from aftershocks by analysing evolving statistical properties of earthquake sequences and signal characteristics.

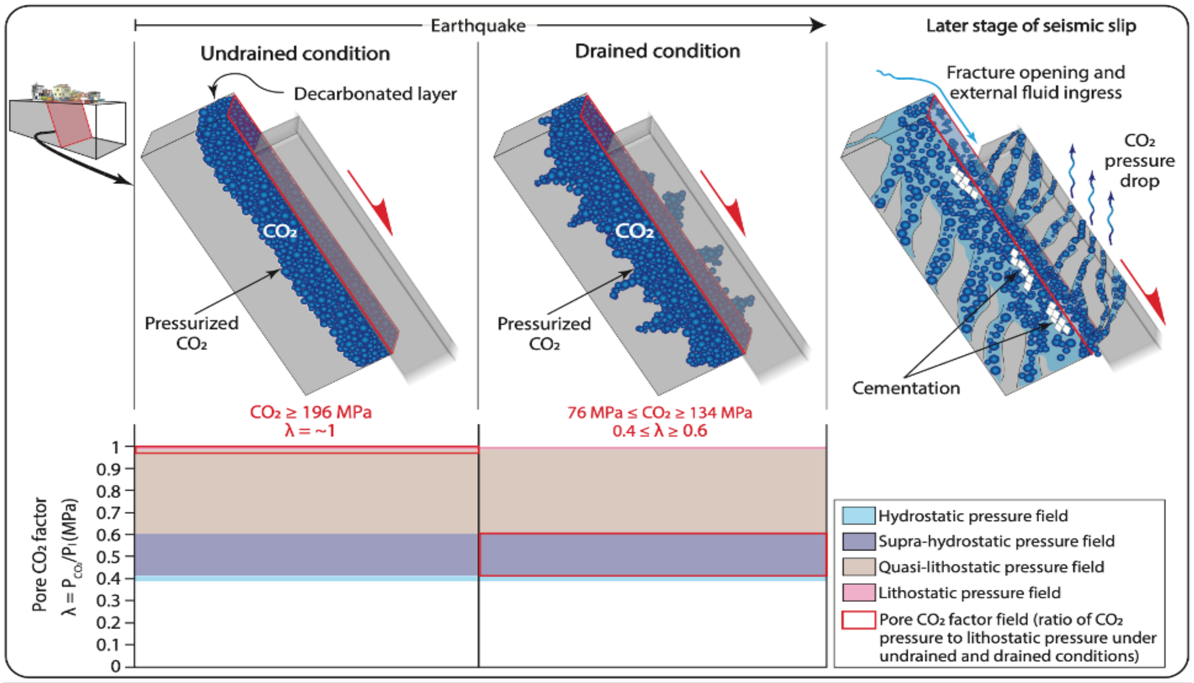

Figure 9. Conceptual model of seismic decarbonation and CO_2 production along a principal slip surface. Frictional heating during seismic slip triggers decarbonation reactions that generate CO_2, which may rapidly pressurize the fault zone, promoting further slip and fracturing. The subsequent pressure drop favours the ingress of external fluids and post-seismic fluid circulation within the fault zone (Curzi et al., 2026a).

Additional insights are provided by the study of seismic decarbonation processes occurring along principal slip surfaces. Thermodynamic modelling indicates that frictional heating during seismic slip may trigger decarbonation reactions capable of producing significant amounts of CO_2 (Curzi et al., 2026a). The rapid generation of CO_2 may increase fluid pressure along fault zones and potentially contribute to sustaining or amplifying seismic slip.

Overall, the results highlight the complex and dynamic coupling between fluid circulation, fault mechanics, and seismicity. By integrating multiscale geological observations, laboratory experiments and machine learning analyses, this activity contributes to developing new approaches for identifying potential earthquake precursors and for improving our understanding of the physical processes governing earthquake generation.

5. Conclusions

The activities carried out within WP5.1 contribute to improving the understanding of the structural and physical processes controlling earthquake generation through a multidisciplinary investigation of seismogenic fault systems. The different studies presented in this chapter combine geological observations, geophysical imaging, numerical modelling, laboratory experiments, and statistical analyses of seismicity. Together, these approaches provide complementary constraints on the geometry, physical properties, and dynamics of fault systems and on the mechanisms that control the occurrence and distribution of earthquakes.

A first important outcome of this work concerns the improved characterization of active and capable faults. Geological investigations, combined with high-resolution geophysical surveys and seismic reflection profiles, allowed the identification and parameterization of fault segments and structural discontinuities that may play a key role in controlling earthquake nucleation and rupture propagation. These studies highlight the importance of fault segmentation and structural complexity in shaping the spatial organization of seismicity and in influencing the distribution of stress and deformation within the crust. The results confirm that seismogenic systems are often composed of multiple interacting structures rather than single planar faults, and that this complexity must be properly accounted for in the interpretation of earthquake sequences and in seismic hazard assessments.

Additional insights were obtained through multiparametric geophysical investigations and numerical modelling of fault systems. The integration of seismic, electrical, and magnetotelluric observations provided improved constraints on the subsurface structure of seismogenic regions, allowing the reconstruction of crustal architectures and the identification of mechanical boundaries between brittle and ductile domains. Numerical models of stress evolution and energy release further contributed to exploring how structural heterogeneity and fault interactions may influence earthquake occurrence and rupture dynamics. These approaches demonstrate the importance of combining observational datasets with physical modelling in order to better understand the processes controlling the distribution of seismic energy in complex tectonic environments.

Another key aspect addressed in WP5.1 concerns the role of fluids and thermally activated reactions in fault mechanics. Laboratory experiments and conceptual models suggest that fluid production and migration within fault zones may strongly influence effective stress conditions and fault stability. In particular, processes such as seismic decarbonation may generate significant amounts of CO_2 during seismic slip, potentially leading to transient pressurization of fault zones and promoting further fracturing and fluid circulation. These results contribute to a growing body of evidence indicating that fluid–fault interactions may represent an important factor in earthquake nucleation and in the evolution of seismic sequences, particularly in carbonate-rich lithologies and in regions characterized by active fluid circulation.

Taken together, the results obtained within WP5.1 underline the importance of adopting an integrated and multidisciplinary perspective when investigating seismogenic processes. The combination of geological, geophysical, experimental, and statistical approaches provides a more comprehensive description of the processes controlling earthquake generation and helps bridge the gap between structural observations, physical modelling, and seismicity analysis. Such integration is essential for improving our understanding of earthquake mechanics and for developing more realistic models of fault behaviour in complex tectonic settings.

Looking forward, several research directions emerge from the results presented in this deliverable. Future work will benefit from the continued integration of high-resolution geological observations with dense geophysical monitoring networks and improved earthquake catalogues. The development of more advanced numerical models capable of incorporating structural complexity, fluid effects, and realistic fault geometries will also represent an important step toward improving the physical representation of earthquake processes. In addition, the increasing availability of multidisciplinary datasets provides new opportunities to investigate the coupling between fault mechanics, crustal structure, and seismicity patterns at multiple spatial and temporal scales.

In this perspective, the results obtained within WP5.1 provide an important contribution toward a more comprehensive understanding of the mechanisms controlling earthquake generation and fault behaviour. By improving the characterization of seismogenic structures and the interpretation of seismicity patterns, these studies contribute to strengthening the scientific basis for future developments in seismic hazard assessment and earthquake process modelling.

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