Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate Codice progetto MUR: **PE00000005** – E63C22002000002

**Deliverable title: Guidelines for earthquake hazard forecasting under uncertainties**

**Deliverable ID: DV3.5.3**

**Due date: 31st March 2026**

**Submission date: 31st March 2026**


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# 1. Technical references

| | |
|---|---|
| Project Acronym | RETURN |
| Project Title | multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate |
| Project Coordinator | Domenico Calcaterra<br>UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II<br>domcalca@unina.it |
| Project Duration | December 2022 – November 2025 (36  months) |

| | |
|---|---|
| Deliverable No. | DV3.5.3 |
| Dissemination level* | PU |
| Work Package | WP5 - Earthquake source processes and wave impact on structures |
| Task | T3.5.3 - Earthquake hazard forecasting under uncertainties |
| Lead beneficiary | UNINA |
| Contributing beneficiary/ies | UNIBO, UNIROMA1, OGS |

* PU = Public

PP = Restricted to other programme participants (including the Ministry Services)

RE = Restricted to a group specified by the consortium (including the Ministry Services)

CO = Confidential, only for members of the consortium (including the Ministry Services)

# Document history

| Version | Date | Lead contributor | Description |
|---|---|---|---|
| 0.1 | 28/02/2026 | $$ | First draft |
| 0.2 | 05/03/2026 | $$ | Critical review and proofreading |
| 0.3 | 10/03/2026 | $$ | Edits for approval |
| 1.0 | 15/03/2026 | $$ | Final version |

# 2. ABSTRACT

*This deliverable presents a set of methodological developments and case studies aimed at improving the analysis, monitoring, and forecasting of seismic activity and the associated seismic hazard. The activities reported here address complementary aspects of earthquake occurrence and seismic hazard assessment, including machine-learning forecasting models, time-dependent recurrence models for individual faults, geophysical investigations of subsurface structures controlling site effects, multi-parameter monitoring of possible earthquake precursors, and the development of advanced procedures for testing and combining earthquake forecasting models.*

*A first line of research focuses on the development of data-driven approaches for forecasting strong aftershocks. In particular, the NESTORE (NExt STrOng Related Earthquake) algorithm applies machine-learning techniques to estimate the probability that a seismic sequence following a strong mainshock will generate a subsequent large event. The method analyses the evolving characteristics of seismic sequences shortly after a mainshock and was tested across several tectonically diverse regions, demonstrating promising forecasting performance in different seismotectonic environments.*

*A second activity investigates time-dependent models for earthquake occurrence on individual faults, using the Messina Strait region as a case study. By comparing classical homogeneous Poisson assumptions with alternative stochastic recurrence models such as the Brownian Passage Time and Slip Predictable models, the study highlights how different representations of earthquake recurrence can significantly influence short-term seismic hazard estimates when hazard analyses are performed at the scale of individual seismogenic sources.*

*Additional work addresses the characterization of local geological structures that control seismic site effects. Through a combination of microtremor measurements, surface-wave analysis, borehole information, and geomorphological observations, the geometry of the seismic bedrock in the tectonically active Mugello basin was reconstructed in two and three dimensions. The results demonstrate that relatively simple geophysical field procedures can provide important constraints on subsurface structure and ground-motion amplification in areas where geological and geophysical information is limited or uncertain.*

*Another line of investigation explores the integration of geochemical, geodetic, and seismological observations in order to identify possible relationships between fluid circulation, crustal deformation, and seismic activity. Hydrogeochemical monitoring networks, laboratory analyses, and geodetic datasets (GNSS and InSAR) were combined to investigate the role of fluids in fault processes and to develop a conceptual workflow for multi-parameter monitoring of seismic activity.*

*The deliverable also presents methodological developments in earthquake forecasting within the framework of the Collaboratory for the Study of Earthquake Predictability (CSEP). New statistical procedures and ensemble modelling approaches were developed to improve the evaluation and testing of forecasting models and to better quantify epistemic uncertainty. In addition, high-resolution earthquake catalogues were analysed to investigate the statistical properties of seismicity and their relationship with fault structures, including the assessment of potential biases affecting magnitude–frequency distributions.*

*Although the individual activities address different aspects of seismic hazard and earthquake forecasting, their combined results contribute to identifying methodological principles that can guide future developments in the field. Rather than providing prescriptive operational procedures, the experiences and results collected in this deliverable highlight a set of emerging directions for future research, including the importance of integrating heterogeneous observational datasets, explicitly accounting for model uncertainties through ensemble approaches, improving the testing and validation of forecasting models, and strengthening the links between physical understanding of seismic processes and operational seismic hazard assessment. In this sense, the deliverable provides a first set of methodological guidelines for the continued development of advanced approaches to seismic hazard analysis and earthquake forecasting.*

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# 4. Introduction

Understanding and forecasting earthquake occurrence remains one of the most challenging problems in seismology and seismic hazard assessment. Earthquakes result from complex interactions among tectonic stress accumulation, fault mechanics, crustal heterogeneity, and fluid circulation, processes that operate over a wide range of spatial and temporal scales. Despite decades of research, large uncertainties still affect the characterization of earthquake occurrence, the identification of possible preparatory processes, and the prediction of ground shaking and associated impacts. These uncertainties arise from several sources, including incomplete knowledge of fault systems, limitations in observational data, and the intrinsic complexity of earthquake nucleation and rupture processes.

Traditional seismic hazard assessment approaches, such as probabilistic seismic hazard analysis (PSHA), have provided an effective framework for estimating long-term seismic hazard by combining earthquake recurrence models, ground-motion prediction equations, and geological information. However, these approaches often rely on simplifying assumptions that may not fully capture the temporal and spatial variability of seismic processes. For example, earthquake occurrence is frequently modelled using time-independent stochastic processes, while the mechanical behaviour of faults, the role of fluids, and the evolution of seismic sequences may exhibit strongly time-dependent behaviour. Similarly, the characterization of seismic site effects and subsurface structures is often limited by the availability and resolution of geological and geophysical observations.

In recent years, several developments have opened new opportunities to address these limitations. The increasing availability of high-resolution datasets—ranging from dense seismic catalogues to geodetic measurements, geochemical monitoring networks, and remote sensing observations—has significantly improved the observational basis for studying earthquake processes. At the same time, advances in statistical modelling, machine learning, and computational methods have enabled the development of new approaches for analysing seismicity patterns, forecasting earthquake sequences, and quantifying the uncertainties associated with competing models.

Within the framework of the RETURN project, WP5 aims to improve the understanding and modelling of earthquake occurrence and seismic hazard through the integration of statistical, physical, and observational approaches. In this context, the activities presented in WP5.3 focus on methodological developments and case studies that explore different aspects of earthquake forecasting, time-dependent seismic hazard modelling, and the characterization of geological and geophysical processes controlling seismic activity.

Improving seismic hazard assessment increasingly requires the integration of multiple methodological perspectives. Earthquake forecasting models must be able to capture the evolving behaviour of seismic sequences, while hazard models must account for the time-dependent behaviour of individual faults and the variability of local geological conditions. At the same time, observational studies aimed at characterizing subsurface structures and monitoring crustal processes provide essential constraints for interpreting seismic activity and for reducing epistemic uncertainties in hazard assessments.

The activities presented in this deliverable explore several complementary methodological directions that contribute to addressing these challenges. A first line of research focuses on data-driven and statistical approaches for earthquake forecasting, including machine-learning techniques applied to the prediction of strong aftershocks and the development of ensemble forecasting models capable of representing the dispersion among alternative forecasts. These approaches aim to better exploit the information contained in seismic catalogues and to explicitly account for uncertainties in forecasting models.

A second line of research investigates the time-dependent modelling of earthquake occurrence on individual faults, exploring how stochastic recurrence models can provide a more realistic representation of seismicity compared with classical time-independent assumptions. Such approaches are particularly relevant when seismic hazard analyses are performed at the scale of specific seismogenic sources located near critical infrastructures.

A third research direction concerns the improved characterization of geological and geophysical structures controlling seismic site effects. Integrated geophysical field procedures are applied to reconstruct the geometry of the seismic bedrock in tectonically active basins, providing important constraints on subsurface structure and ground-motion amplification where detailed geological and geophysical information is limited.

Finally, the deliverable also explores the integration of heterogeneous observational datasets, including geochemical, geodetic, and seismological measurements, in order to investigate possible relationships between fluid circulation, crustal deformation, and seismic processes. Although the identification of reliable earthquake precursors remains an open scientific challenge, multi-parameter monitoring approaches offer valuable opportunities for improving the understanding of fault dynamics and the evolution of seismic sequences.

Although the individual studies presented in this deliverable address different aspects of earthquake occurrence and seismic hazard, they share a common objective: improving the methodological tools available for analysing seismic processes and developing more robust approaches to earthquake forecasting and hazard assessment. Rather than providing prescriptive operational procedures, the activities reported here collectively highlight methodological directions emerging from recent research and practical applications. In this sense, the deliverable contributes to identifying guiding principles that may support future developments in seismic hazard analysis, earthquake forecasting methodologies, and the integration of multi-disciplinary observational datasets.

The remainder of this chapter presents the individual contributions in detail. The following sections describe methodological developments in machine-learning-based forecasting of strong aftershocks, time-dependent modelling of earthquake occurrence on individual faults, geophysical investigations of subsurface structures controlling seismic site effects, integration of geochemical and geodetic observations for monitoring crustal processes, and the development and validation of ensemble earthquake forecasting models within the framework of the Collaboratory for the Study of Earthquake Predictability (CSEP).

# 5. Methodological Developments for the Analysis and Forecasting of Seismic Activity

## 5.1 Using a machine learning approach for quasi real time operational forecasting of large magnitude aftershocks. (OGS)

### 5.1.1 Scientific Context and Objectives

Aftershocks following large earthquakes may substantially increase the overall impact of the mainshock, as they can impose additional stress on already damaged structures and interfere with rescue and recovery operations. Because strong earthquakes are commonly followed by sequences including multiple events with magnitude ≥ 5, reliable estimates of the probability of strong aftershocks represent an important component of post-seismic decision-support systems supporting emergency response and early recovery planning.

Recent advances in the availability of high-quality seismic catalogues, together with the increasing application of machine-learning techniques in seismology, provide new opportunities to improve the forecasting of aftershock activity. Within this context, we developed NESTORE (NExt STrOng Related Earthquake), a data-driven algorithm designed to estimate the probability that a seismic sequence triggered by a strong mainshock of magnitude Mm will include a subsequent earthquake with magnitude equal to or larger than Mm–1.

The approach aims to provide rapid probabilistic information on the expected evolution of seismic sequences shortly after the occurrence of a mainshock, thus contributing to short-term seismic hazard assessment in the immediate aftermath of large earthquakes. The method was tested across tectonically diverse regions, including California, Italy, western Slovenia, Greece, Japan, and New Zealand, allowing the evaluation of its robustness in different seismotectonic environments (Gentili et al., 2023, 2024, 2025, 2026a; Brondi et al., 2025; Petrillo et al., 2026; Caravella and Gentili, 2026).

### 5.1.2 Methodological Development

NESTORE provides probabilistic forecasts by classifying seismic clusters into two categories according to the magnitude difference between the mainshock and the largest aftershock. Type A clusters correspond to sequences in which the magnitude difference between the mainshock and the strongest aftershock is ≤1 magnitude unit, whereas Type B clusters correspond to sequences in which the difference is greater than one magnitude unit.

The forecasting algorithm relies on seismological features extracted from earthquake catalogues at progressively increasing time intervals following the mainshock. These features describe different aspects of the physical evolution of the seismic sequence, including radiated seismic energy, the spatio-temporal evolution of seismicity, and the growth of the cumulative source area associated with the cluster.

Using a supervised-learning framework, NESTORE trains a set of simple one-node decision trees based on individual features derived from the seismic catalogues. The most informative classifiers are then selected and combined within a Bayesian framework in order to estimate the probability that the evolving seismic sequence will develop into a Type A cluster. In this way, the algorithm progressively updates the probability estimate as new seismic events occur and additional information becomes available during the evolution of the sequence (Figure 1).

The method has been implemented in the NESTOREv1.0 MATLAB software, which can be used both for retrospective analyses and for near-real-time applications. During the course of the project, several methodological improvements were introduced. In particular, the REPENESE procedure was developed as an outlier-detection strategy aimed at mitigating the effects of class imbalance in the training dataset, while the GRETAS algorithm was introduced as an advanced cluster-identification method combining ETAS modelling with graph-theory concepts to improve the identification and characterization of seismic clusters.

### 5.1.3 Discussion on Main Results

The NESTORE algorithm was applied to seismic catalogues from California, Italy, Greece, Japan, Slovenia, and New Zealand in order to evaluate its forecasting performance across different tectonic environments and catalogue characteristics.

Applications to the seismic catalogues of California, Italy, and Greece produced correct classifications of approximately 86% in Italy and 92% in Greece and California, indicating a high predictive capability of the algorithm across different regional datasets. Tests performed using the Japanese seismic catalogue achieved 93% retrospective forecasting success, successfully identifying major sequences such as the 2011 Tohoku earthquake sequence. Validation using the New Zealand catalogue, performed through k-fold cross-validation, resulted in 88% correct classifications, including the 2010–2011 Canterbury–Christchurch sequence.

Additional analyses were conducted using the RAMONES database, which includes approximately 25,000 earthquakes recorded between 2005 and 2023. Within this dataset, 34 seismic clusters with mainshock magnitude ≥4 were identified in central Italy. The analysis revealed systematic differences between Type A and Type B clusters. In particular, Type A sequences tend to exhibit greater variability in apparent stress over time, larger changes in epicentral position and focal depth, a higher number of aftershocks, and larger normalized cumulative source areas compared to Type B clusters.

Further comparisons between alternative cluster-identification approaches using seismic data from New Zealand and the Sumatra region highlighted the importance of robust and consistent cluster definitions for improving forecasting performance. These results indicate that reliable cluster identification is a critical step in the development of operational aftershock forecasting tools.

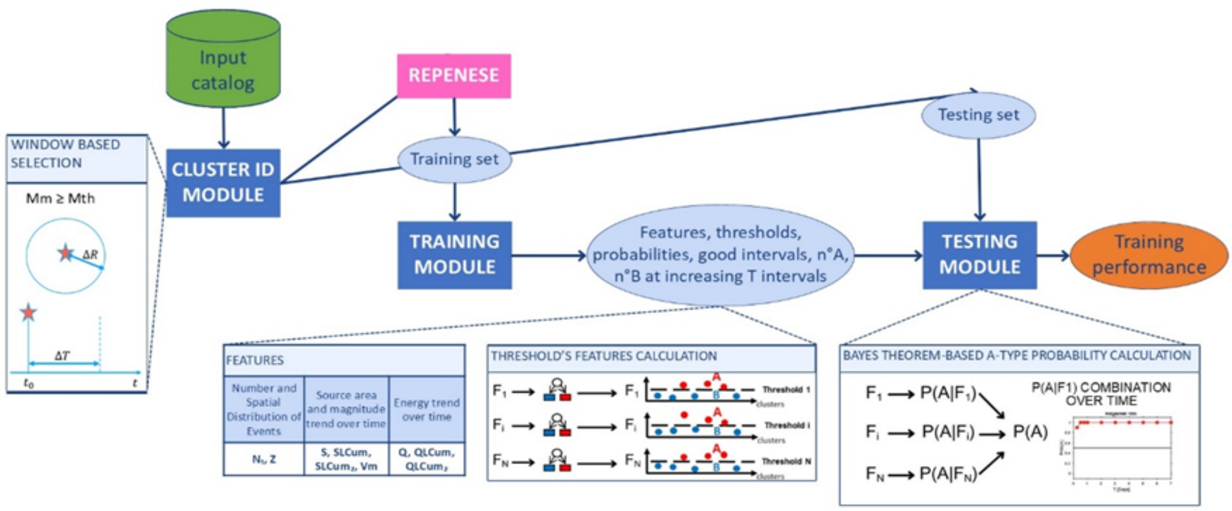


**Figure 1.** Flowchart of the NESTORE algorithm for probabilistic forecasting of strong aftershocks. Seismological features describing the temporal evolution of a seismic sequence are extracted from earthquake catalogues and used within a supervised-learning framework to classify clusters and estimate the probability that the sequence will produce a strong aftershock (≥ Mm–1).

Overall, the analyses performed within this activity demonstrate that NESTORE provides a promising machine-learning framework for probabilistic forecasting of strong aftershocks, offering a data-driven approach that can support the development of operational short-term seismic hazard assessments following major earthquakes.

## 5.2 Time-variant and short-term modelling of seismic hazard (UNINA-DiSt).

### 5.2.1 Scientific Context and Objectives

Probabilistic Seismic Hazard Analysis (PSHA) traditionally relies on the modelling of earthquake occurrence using large seismogenic source zones and assumes that mainshocks follow a homogeneous Poisson process (HPP). This assumption implies that earthquake occurrence is memoryless, meaning that the probability of future events does not depend on the time elapsed since the last earthquake. The HPP formulation has been widely adopted in seismic hazard studies because it is relatively simple to implement and often provides satisfactory results when large regional source zones are considered (Iervolino, 2019).

However, when PSHA is performed for sites hosting strategic or critical infrastructures, hazard analyses are frequently based on individual faults located close to the site of interest, either in addition to or instead of large seismic source zones. In such cases, the assumption of a homogeneous Poisson process becomes questionable, because earthquake recurrence on individual faults is expected to depend on the time elapsed since the last event. As a consequence, time-dependent stochastic models may provide a more realistic description of earthquake occurrence (Polidoro et al., 2013).

Within this context, the activity presented here investigates the impact of time-variant recurrence models on seismic hazard estimates for the Messina Strait area, one of the most seismically hazardous regions in Italy. The study focuses on the ITIS013 fault, a well-known seismogenic source associated with large historical earthquakes, including the 1908 Messina earthquake. The occurrence of major earthquakes on this fault is modelled using stochastic recurrence models calibrated on the available geological and geophysical information describing the seismic history of the source.

### 5.2.2 Methodological Development

The analysis considers the seismic sources identified in the Database of Individual Seismogenic Sources (DISS) for the Messina Strait region. In particular, the ITIS013 fault is analysed together with neighbouring sources in order to provide a consistent seismotectonic framework for the study area.

Previous studies provide parameter estimates for recurrence models associated with faults in the Calabria region. In particular, Akinci et al. (2017) suggest modelling earthquake occurrence on each seismic fault using the Brownian Passage Time (BPT) model and provide parameter values for the main sources. For the ITIS013 fault, the recommended parameters are a mean recurrence time $\tau = 739$ years and a coefficient of variation $\alpha = 0.5$.

An alternative approach is provided by the Slip Predictable Model (SPM) proposed by Faccioli et al. (2008), which relates earthquake recurrence to slip accumulation on the fault. For the ITIS013 source, this model suggests a return period for M7.0 earthquakes ranging between 700 and 1500 years. These estimates are consistent with the recurrence intervals reported in the DISS database, which indicate minimum and maximum recurrence times of 710 and 1527 years, respectively.

To compare the implications of different recurrence assumptions, the probability density functions (PDFs) of interarrival times were derived for the BPT, SPM, and HPP models. While the BPT model is fully defined by the parameters τ and α, the SPM requires selecting a specific return period. In this preliminary analysis, the lowest value reported in the literature (700 years) was adopted.

Additionally, a Weibull distribution was calibrated to reproduce a coefficient of variation equal to 0.5, matching the variability assumed in the BPT model. The resulting Weibull parameters are $a = 1.2667 \times 10^{-3}$ and $b = 1.9522$.

It should be noted that the relationship between interarrival time and earthquake magnitude is not explicitly considered in this analysis. The objective of this preliminary investigation is instead to analyse differences among recurrence models describing the occurrence of earthquakes, independently of magnitude-dependent effects.

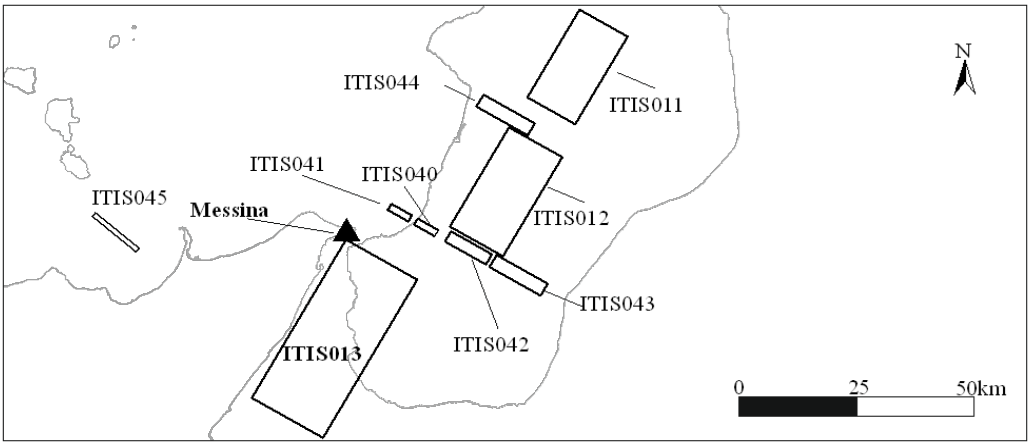


**Figure 2.** Seismogenic sources in the Messina Strait area according to the DISS database. The ITIS013 fault considered in this study is highlighted together with neighbouring sources (ITIS011, ITIS012, ITIS040–045) forming the main seismogenic framework of the region.

### 5.2.3 Discussion on Main Results

The comparison between recurrence models highlights significant differences in the temporal evolution of earthquake probabilities for the ITIS013 fault. While the BPT and SPM models produce similar probability density functions for interarrival times, the HPP model exhibits the typical exponential distribution associated with memoryless processes.

The second panel of the figure illustrates the probability of observing at least one earthquake within a 200-year time window, from time t to t + 200, conditional on the elapsed time since the previous earthquake. In contrast to the constant probability predicted by the HPP model, the time-dependent models produce probabilities that evolve with time.

When the elapsed time since the last earthquake is less than approximately 300 years, both non-homogeneous models yield probabilities significantly lower than those predicted by the Poisson assumption. This behaviour reflects the fact that time-dependent recurrence models incorporate the physical concept of stress accumulation on the fault.

The last major earthquake associated with the considered source occurred in 1908, corresponding to an elapsed time of 117 years. For this value of t, indicated by the dotted line in the figure, the HPP model yields a probability of 0.237 of observing at least one earthquake within the next 200 years. In contrast, the BPT and SPM models produce lower probabilities of 0.060 and 0.134, respectively.

These results are consistent with previous studies and suggest that, for the fault under consideration, the adoption of time-dependent recurrence models may lead to less conservative hazard estimates than those obtained using the homogeneous Poisson assumption when models are calibrated to comparable recurrence times. However, the situation evolves as time passes: both the BPT and SPM models begin to yield probabilities larger than those predicted by the HPP model after approximately 300 years from the last event.

Overall, the results highlight the importance of considering time-variant earthquake occurrence models when performing seismic hazard assessments for sites located near well-characterised seismogenic faults. The comparison performed here provides a preliminary evaluation for the Messina Strait region and illustrates how the choice of recurrence model may significantly influence short-term hazard estimates.

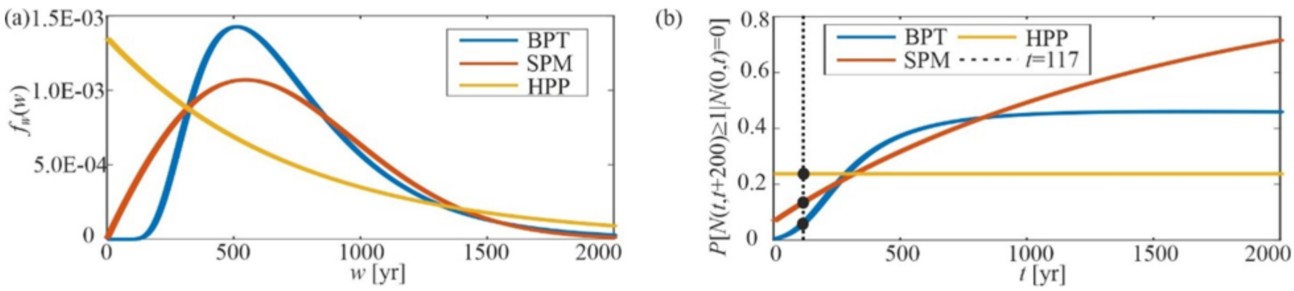


**Figure 3.** Probability density functions of earthquake interarrival times derived from the BPT, SPM, and HPP recurrence models (panel a), and corresponding probabilities of observing at least one earthquake within a 200-year interval (from t to t+200) conditional on the elapsed time since the last event (panel b)

## 5.3 Development of simple field procedures to map 2D-3D seismic bedrock geometries and to assess the corresponding seismic site effects and uncertainties. (UNIBO)

### 5.3.1 Scientific Context and Objectives

Local geological and geophysical conditions can strongly influence ground-motion amplification during earthquakes, producing significant seismic site effects that may substantially modify the expected shaking levels. In tectonically active intermontane basins, these effects are often controlled by the geometry and physical properties of sedimentary deposits overlying the seismic bedrock. Reliable reconstructions of the seismic bedrock geometry are therefore essential for improving seismic hazard assessment and for correctly interpreting site response in complex tectonic environments.

However, in many intramontane basins of the Northern Apennines, the subsurface geometry of the sedimentary fill and the depth to seismic bedrock remain poorly constrained. This situation is often due to the limited availability of geophysical surveys and deep borehole data, which makes it difficult to reconstruct robust 2D or 3D subsurface models. As a consequence, seismic site effects in these basins are often associated with significant uncertainties.

The objective of this activity was therefore to develop and test simple and efficient geophysical field procedures capable of reconstructing the geometry of the seismic bedrock and the associated sedimentary thickness in tectonically active intermontane basins. Particular attention was devoted to methods that can be implemented with relatively limited field effort while still providing robust constraints on subsurface geometry and related seismic site effects.

### 5.3.2 Methodological Development

The proposed approach was tested in the Mugello basin, a tectonically active intermontane basin located in the Northern Apennines. This basin represents a particularly suitable case study because its seismotectonic framework remains debated, largely due to the scarcity and ambiguity of available geological and geophysical constraints.

To reconstruct the subsurface geometry of the basin, we applied the Microtremor Horizontal-to-Vertical Spectral Ratio (MHVSR) method. This technique is widely used to estimate the fundamental resonance frequency of sedimentary deposits and to infer the depth of the sediment–bedrock interface.

More than 150 single-station MHVSR measurements were performed across the basin. The measurements were distributed along five transects oriented both parallel and perpendicular to the basin axis, allowing the investigation of the spatial variability of the resonance frequency and the reconstruction of the basin geometry in both two-dimensional and three-dimensional perspectives.

To better constrain the shear-wave velocity structure of the subsurface, the MHVSR analysis was complemented by Multichannel Analysis of Surface Waves (MASW) surveys. These measurements provided independent constraints on the velocity model, allowing a more robust conversion between the observed fundamental frequency and the thickness of sedimentary deposits.

The interpretation was further supported by a dense dataset of well logs, which allowed the conversion of the site's fundamental frequency derived from MHVSR into estimates of sediment thickness. Finally, the geophysical results were integrated with a geomorphological analysis of the river network, which provided additional constraints on the potential surface expression of tectonic structures identified in the subsurface.

This multi-method approach allowed the reconstruction of the basin geometry while reducing the uncertainties associated with the interpretation of individual datasets.

### 5.3.3 Discussion on Main Results

The combined geophysical and geomorphological analyses allowed the reconstruction of the geometry of the seismic bedrock (top-basement surface) beneath the Mugello basin. The resulting model indicates a synform-shaped basin geometry, with the main depocentre located in the central portion of the basin and a progressive reduction in post-orogenic sediment thickness toward the basin margins.

The results also suggest the presence of SSW-dipping, kilometre-scale normal faults along the northeastern margin of the basin. These structures may represent potentially active and capable faults, contributing to the tectonic evolution of the basin.

This interpretation is consistent with independent seismological observations, which indicate that seismicity in the area tends to cluster along SSW-dipping seismogenic sources located along the northeastern margin of the basin. The consistency between the geophysical reconstruction and the observed seismicity patterns supports the reliability of the proposed interpretation.

Beyond the local geological implications, these results provide important constraints for seismic hazard assessment in the Mugello area, where the geometry of sedimentary deposits may significantly influence ground-motion amplification. More broadly, the study illustrates how relatively simple and cost-effective geophysical field procedures can provide valuable constraints on subsurface structure in tectonically active regions where detailed geophysical datasets are lacking or difficult to obtain.

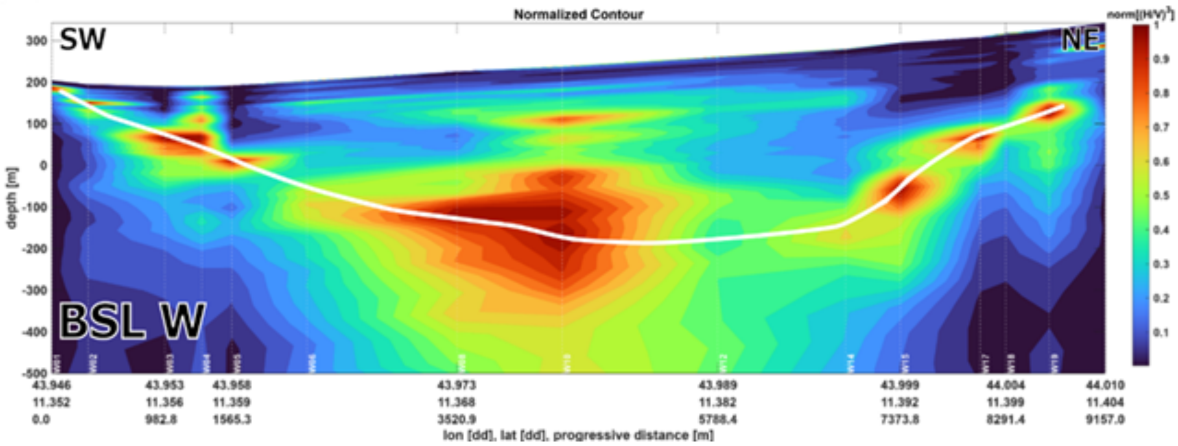


**Figure 4.** H/V contour plot obtained along one of the transverse transects crossing the Mugello basin (west of Borgo San Lorenzo; Asti et al., submitted). The white line marks the interpreted position of the sediment–bedrock interface derived from the MHVSR analysis. Individual H/V curves are normalized so that the colour scale ranges from 0 (blue) to 1 (red).

## 5.4 Integrating results from precursors studies to define a workflow for earthquake prediction based on the combination of seismic, geochemical precursors and geodetic (GNSS and SAR) information. (UNIROMA1)

### 5.4.1 Scientific Context and Objectives

Earthquake precursors are physical or chemical phenomena that may occur prior to a seismic event as a consequence of progressive stress accumulation and deformation within the Earth's crust. The study of such signals is important for improving the understanding of the processes that lead to fault rupture and for exploring the potential contribution of multi-parameter observations to seismic hazard monitoring.

Several classes of possible precursory signals have been proposed in the literature. Geochemical precursors include variations in the chemical composition and physical properties of underground fluids, such as groundwater and gases circulating along fault systems. Among the most frequently investigated signals are variations in radon concentration, a radioactive gas that may be released when rocks fracture or permeability increases. Additional indicators include changes in groundwater pH, temperature and electrical conductivity, as well as sudden variations in the concentration of trace elements such as As, V and Cr.

Geodetic precursors correspond to slow ground deformations produced by the progressive accumulation of strain along active faults. These deformations can be measured with high precision using geodetic techniques such as Global Navigation Satellite Systems (GNSS) (fully 3D technique) and satellite radar interferometry (InSAR) (presently, substantially 2D technique only, since deformations along the North-South direction are bad estimated). Spatially heterogeneous deformation patterns of the Earth's surface, observed from months to years before major earthquakes both close to and at some distance from the epicentral area, have been considered possible indicators of evolving stress conditions in the crust. However, the density of GNSS permanent stations is not yet generally enough to timely detect potentially critical situations about strain accumulation at the local scale (e.g. locked faults), useful for understanding the earthquake preparation process. Therefore, considering the known tectonic setting of the Apennines, the availability of a number of GNSS permanent stations in this area for some years/decades and, much more recently (2022), of the new Copernicus European Ground Motion Service (EGMS) based on SAR data (https://egms.land.copernicus.eu/), a methodology has been investigated to integrate GNSS and SAR data (Calibrated solution) to better constrain in space and time the current earthquakes prediction.

Seismological precursors include variations in seismic activity preceding large earthquakes, such as the occurrence of seismic swarms or changes in the statistical and physical properties of seismic waves. These signals may reflect evolving physical conditions within the fault zone, including increasing fracture density, fluid migration, or progressive weakening of the fault.

Within this context, the objective of this activity was to explore the integration of geochemical, geodetic and seismological observations in order to develop a conceptual workflow for multi-parameter monitoring of seismic activity. By combining laboratory investigations, field observations and modelling approaches, the study aimed to identify potential relationships between fluid circulation, crustal deformation and seismic processes, while explicitly accounting for the uncertainties associated with each dataset.

### 5.4.2 Methodological Development

The research combined field monitoring, laboratory analyses and conceptual modelling in order to investigate the role of fluids and deformation processes in the preparation phase of earthquakes.

A key component of the activity focused on the characterization of fault-related fluid circulation in both compressional and extensional tectonic environments. Groundwater samples were analysed using ion chromatography and ICP–MS techniques to determine the hydrogeochemical composition of fluids circulating within fault systems. These analyses allowed the identification of characteristic hydrogeochemical signatures and mixing processes that may evolve during periods of tectonic stress accumulation.

A long-term hydrogeological monitoring network was established in the Conero area (Marche region), representing a compressional tectonic setting. The monitoring programme produced a bi-monthly dataset of groundwater chemistry, providing a robust baseline for the identification of transient anomalies potentially associated with variations in fluid pressure and fault activity.

Field observations were complemented by laboratory and modelling investigations aimed at understanding the mechanical role of fluids during fault slip. Thermodynamic and mechanical analyses of principal slip surfaces indicate that co-seismic shear heating may induce carbonate decarbonation reactions, generating transient $CO_2$ overpressures that can locally weaken the fault. Experimental results suggest that such processes may produce overpressures equivalent to approximately 12 tons of $CO_2$, which may contribute to the reduction of fault strength and facilitate rupture propagation.

The study also considered the integration of geodetic datasets, including GNSS and InSAR data, together with seismic observations. These complementary datasets provide information on crustal deformation patterns and evolving seismic activity, which may be associated with the migration of fluids and stress redistribution in the crust.

Regarding the integration of GNSS and SAR data, at first the Calibrated solution has been used; later, it has been recognized that the Calibrated solution is dependent on an interpolation criterion applied to link all the interferometric stacks and to refer them to ETRF2000 reference frame realized by GNSS permanent stations. To avoid undesired effects of this interpolation criterion, a different approach has been designed based on the

Basic solution; this approach is presently under implementation and testing, starting from the unification of the reference frame of the different interferometric stacks, also leading to their intrinsic accuracy evaluation, achieved through an original approach (named *SAR leveling*) based on the overlapping areas among the different interferometric stacks.

During a recent project meeting, a preliminary analytical workflow was discussed to integrate seismic, geodetic and geochemical time-series within a unified framework. The proposed workflow includes procedures for data preprocessing, uncertainty propagation and cross-correlation analysis among different observables, with the aim of identifying possible temporal relationships between the different signals.

### 5.4.3 Discussion on Main Results

The results obtained during this activity highlight the important role of fluids in the evolution of fault systems and their potential influence on seismic processes. The hydrogeochemical analyses conducted in the Conero monitoring network provide a robust baseline dataset that can be used to detect transient variations in groundwater chemistry potentially associated with fault activity and fluid overpressure.

The integration of field observations with laboratory experiments and modelling results suggests that fluid circulation within fault zones may significantly influence fault strength through time. In particular, the thermodynamic analyses indicate that decarbonation reactions induced by co-seismic shear heating may generate transient $CO_2$ overpressures capable of promoting fault weakening and dynamic rupture propagation.

These results support the hypothesis that fluid-related processes may play a significant role in both the triggering and evolution of seismicity, particularly in tectonic environments where fluid circulation is active.

The activity also represents a first step toward the development of a multi-parameter framework for seismic hazard monitoring, combining geochemical, geodetic and seismological observations. Regarding the integration of GNSS and SAR data, an application has been carried out on the seismogenetic region of Irpinia. We implemented a workflow to evaluate the East velocity profile along the transects (Panza et al., 2018; Crespi et al., 2020) using the data provided by EGMS. This area was covered by ten transects, along which we computed the velocity profile considering SAR acquisitions from ascending and descending orbits. The quality and density of the data clearly highlight millimetric anomalies along the velocity profiles.

Although the integration workflow discussed within the project is still under development, the preliminary results demonstrate the potential value of combining heterogeneous datasets to improve the understanding of earthquake preparatory processes.

At the current stage, the proposed workflow remains a conceptual and methodological framework, and its full implementation and validation will require further development and testing. Nevertheless, the results obtained provide an important basis for future research aimed at developing integrated monitoring strategies and advanced analytical approaches, potentially including AI-assisted analysis of multi-sensor datasets for seismic hazard assessment.

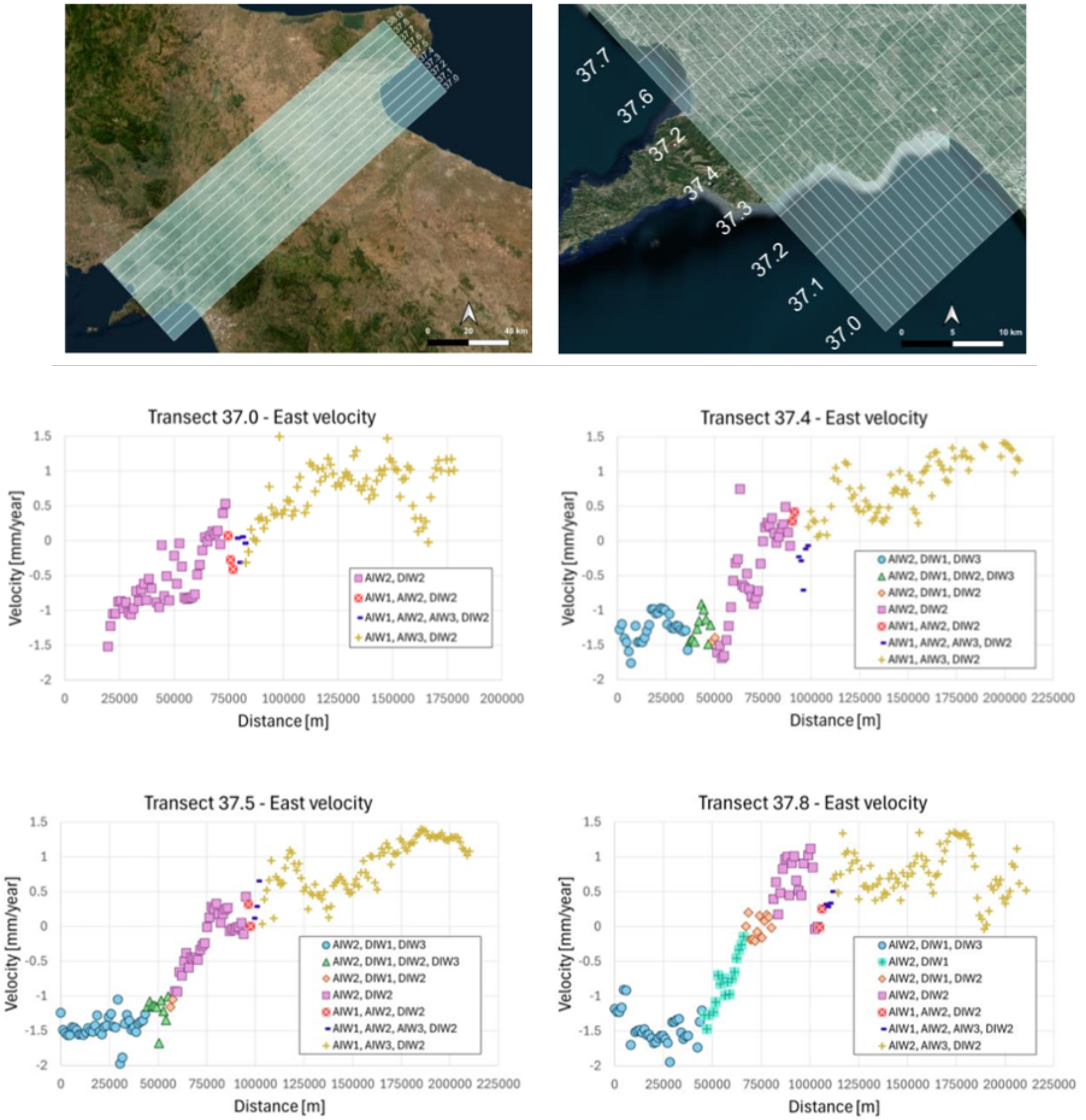


**Figure 5**. Transects across Irpinia region and East velocity plots for the transects 37.0, 37.4, 37.5, and 37.8.

## 5.5 Development and testing of ensemble earthquake forecasting models and validation procedures within the CSEP framework. (UNINA-DiSTAR)

### 5.5.1 Scientific Context and Objectives

Testing and validating earthquake forecasting models is a fundamental step toward improving short-term seismic hazard assessment. In recent years, the Collaboratory for the Study of Earthquake Predictability (CSEP) has become the main international framework for the objective evaluation and comparison of earthquake forecasting models through prospective testing experiments. These experiments allow different models to be evaluated using standardized statistical tests and common datasets.

Despite these advances, several methodological challenges remain. In particular, forecasting models often differ substantially in their assumptions, input parameters and spatial–temporal forecasting windows. As a consequence, evaluating model performance and comparing competing forecasts requires robust statistical procedures that can account for both model uncertainty and structural differences among forecasts.

Within this context, the objective of this activity was twofold. First, the study aimed to extend the capabilities of the CSEP testing framework by developing improved statistical evaluation procedures for earthquake forecast models. Second, the activity aimed to explore the development of ensemble forecasting approaches capable of representing the dispersion among alternative forecasts to express the epistemic uncertainty and thereby providing a more comprehensive description of our knowledge in seismic hazard and earthquake forecasting. This extension shapes the novel concept of ontological ensemble modeling to represent the full distribution of possible forecasts rather than a single one (Marzocchi & Jordan, 2014). Compared to conventional forecast models, an ontological ensemble model quantifies forecast reliability, which allows for a meaningful model validation by testing whether the physical process is represented correctly.

### 5.5.2 Methodological Development

To address the first objective (extending the capabilities of CSEP), the study involved collaboration with researchers from the Karlsruhe Institute of Technology (KIT) and the Heidelberg Institute for Theoretical Studies (HITS). This collaboration enabled the development of new statistical evaluation approaches grounded in mathematical theory and compatible with the CSEP testing philosophy.

The proposed methods were applied to three short-term forecasting models belonging to the Operational Earthquake Forecasting system for Italy (OEF-Italy, Marzocchi et al., 2014), and two ensemble models thereof: the Score Model Averaging (SMA, the main model of OEF-Italy) and the Logistic-Regression-based Weighted Average (LRWA, Herrmann & Marzocchi, 2023).

The work demonstrated the connection between the proposed statistical procedures and existing CSEP-style evaluation tests, and suggested improvements to the comparative CSEP T-test by correcting the variance estimation according to the Diebold–Mariano test. Using statistical tools derived from isotonic regression, the study also investigated forecast reliability and applied score decompositions that distinguish between calibration and discrimination components of model performance (see Figure 6a).

The second objective focused on the development of an ontological ensemble forecasting model, which represents a new class of earthquake forecast models. Building upon previous work on weighted-average ensembles (Herrmann & Marzocchi, 2023), the study introduced a probabilistic modelling of forecast uncertainty as a Beta distribution whose parameters are determined from the weighted average and dispersion of the candidate forecasts used in the LRWA ensemble.

When applied to OEF-Italy, the ontological ensemble produces a probabilistic forecast distribution that typically spans approximately one order of magnitude in terms of earthquake occurrence probability (see Figure 6b).

Finally, to formally test the ontological ensemble forecasts, the study extended the CSEP N-test (focusing on the total earthquake count) and S-test (focusing the spatial component) so that they can account for the distribution of forecasts rather than a single forecast. This extension was implemented by considering various percentiles of the forecast distribution. While extending the N-test was relatively straightforward by additionally sampling from each percentile, extending the S-test required sampling from probabilities, exchanging the loglikelihood function, computing spatial quantile scores for individual forecast days and percentiles, building Q–Q plots for each percentile (see Figure 6d), and testing if they follow a uniform distribution (1:1 diagonal in the Q–Q plot).

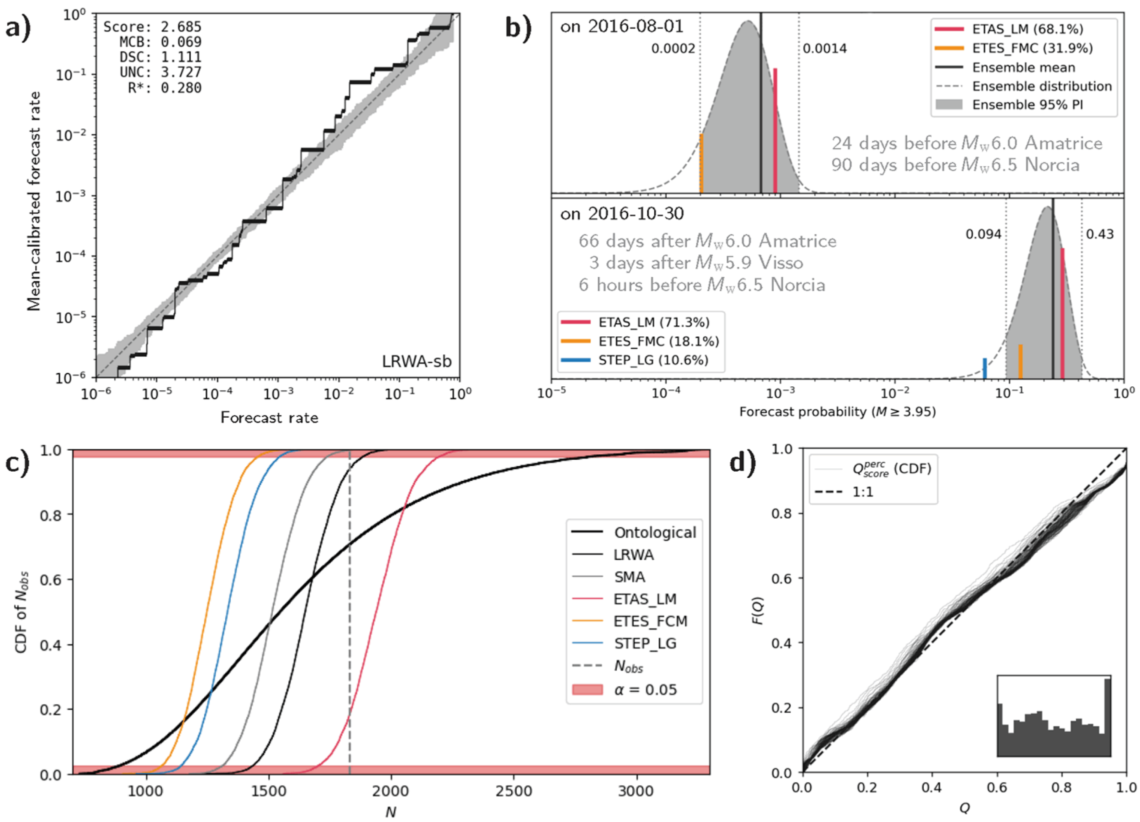


**Figure 6.** A variety of outcomes from applying the proposed evaluation procedures to the OEF-Italy: (a) reliability diagram and score decomposition for the weighted-average ensemble (LRWA); (b) ontological ensemble forecast distributions at the location of the Mw 6.5 Norcia mainshock for two different dates; (c) CSEP-style N-test comparing the ontological ensemble with individual forecast models; (d) Q–Q plot of expected versus observed spatial quantile scores used in the extended CSEP-style S-test of the ontological ensemble.

### 5.5.3 Discussion on Main Results

The application of the proposed procedures to the OEF-Italy provided several insights into the behaviour and reliability of conventional and ensemble earthquake forecasting models.

From the newly introduced statistical evaluation procedures, evolving the CSEP T-test to the Diebold–Mariano test is an important correction to perform adequate statistical inference when comparing forecasts. The reliability analysis and score decomposition, instead, allowed the identification of situations in which certain models outperform others and revealed significant calibration deficiencies in several forecasting models. The results of this work were published in Brehmer et al. (2025).

The ontological ensemble approach extends conventional forecast modeling by explicitly quantifying and accounting for epistemic uncertainty. The reliability of the ontological ensemble was evaluated with the extended CSEP tests in two different aspects. Compared to most individual models, it did not fail the extended

N-test (see Figure 6c), indicating that the ensembled models collectively describe the total earthquake count well. It can be attributed to the larger dispersion of the forecast distribution and the corresponding epistemic uncertainty. However, the ontological ensemble failed the extended S-test (see Figure 6d), indicating that the spatial distribution of the ensembled forecast models differed systematically from the observed one. Particularly, high quantile scores are overrepresented, which suggests that the forecasts are spatially too smooth. The corresponding publication is in preparation.

## 5.6 Characterization of the magnitude-frequency distribution (MFD) inside a fault and the differences with the MFD outside faults. (UNINA-DiSTAR)

### 5.6.1. Scientific Context and Objectives

The magnitude–frequency distribution (MFD) of earthquakes, commonly described by the Gutenberg–Richter relationship, is one of the most fundamental statistical properties of seismicity. The slope of this distribution, quantified by the b-value, reflects the relative proportion of small and large earthquakes and is widely used to investigate the physical processes controlling earthquake occurrence and fault mechanics.

However, the estimation of b-values from earthquake catalogues can be strongly affected by observational biases and methodological issues. In particular, short-term catalog incompleteness (STI) occurring immediately after earthquakes and nonlinear magnitude scaling can distort magnitude statistics and produce misleading interpretations of seismicity patterns.

Within this framework, the goal of this activity was to investigate the factors that bias or control the estimation of the b-value in earthquake catalogs. In particular, the analyses aimed to:

a. identify the effect of short-term catalog incompleteness (STI) and magnitude scaling issues on magnitude statistics (Corrado et al., 2025);

b. assess how structural heterogeneities influence temporal variations of the b-value during seismic sequences (Piegari et al., 2025);

These analyses were conducted using high-resolution earthquake catalogues and synthetic datasets in order to better understand how observational biases and structural complexity affect the statistical characterization of seismicity.

### 5.6.2. Methodological Development

The analyses were performed using both real earthquake catalogues and synthetic seismicity catalogs in order to isolate the mechanisms responsible for biases in magnitude statistics.

A first case study focused on the 2019 Ridgecrest foreshock sequence (Corrado et al., 2025), which provided an ideal dataset for investigating the influence of magnitude scaling and catalog incompleteness on MFD analyses. In this sequence, conventional magnitude-frequency analyses were first performed using local magnitudes (ML).

In order to evaluate the effect of magnitude scaling, the ML values were converted to moment magnitude (MW) and the resulting magnitude-frequency distributions were compared. This allowed the identification of biases introduced by the nonlinear scaling of local magnitudes.

To address the effect of short-term incompleteness, the b-positive method was applied. This method considers only positive magnitude differences between consecutive earthquakes, which reduces the influence of undetected small events occurring shortly after larger earthquakes. To further test the influence of STI, synthetic earthquake catalogs were generated. These catalogs were produced both under complete conditions and with artificially introduced short-term incompleteness. The resulting synthetic sequences were analysed using the same procedures applied to the real catalogs in order to evaluate how STI influences the estimation of b-values and the apparent correlations between earthquake magnitudes.

A complementary analysis was performed using the entire Southern California earthquake catalog. The temporal evolution of earthquake magnitudes following mainshocks of different sizes was analysed in order to quantify the duration of short-term incompleteness. For each sequence, the STI duration was estimated using the empirical relation proposed by Helmstetter et al. (2006).

In addition to these analyses, the relationship between magnitude statistics and structural heterogeneity was investigated through the analysis of the Norcia seismic cluster (Piegari et al., 2025). Using density-based clustering (DBSCAN) and principal component analysis (PCA), the seismicity was divided into distinct structural domains corresponding to different fault geometries.

### 5.6.3. Discussion on Main Results

The analysis of the 2019 Ridgecrest foreshock sequence (Corrado et al., 2025) shows that conventional magnitude-frequency distribution analyses can produce biased estimates of the b-value due to two main effects: nonlinear scaling of local magnitudes and short-term catalog incompleteness.

When the sequence is analysed using ML magnitudes, the resulting MFD exhibits an unusually low b-value together with a strong magnitude correlation between successive earthquakes. However, after converting ML to MW, the b-value increases significantly. This result indicates that nonlinear magnitude scaling can artificially decrease b-value estimates.

To address the influence of short-term incompleteness, the b-positive method was applied. Using this method, the estimated b-value increases further and becomes statistically consistent with the tectonic background value. At the same time, the previously observed magnitude correlation disappears. These results demonstrate that both magnitude scaling and short-term incompleteness can produce misleading signatures in seismic catalogs, including artificially low b-values and apparent correlations between earthquake magnitudes.

The analysis of synthetic earthquake catalogs confirms these interpretations. When synthetic sequences are generated without incompleteness, the b-value distribution is centered around the expected value of 1.0 and no magnitude correlation appears. When STI is artificially introduced, the estimated b-values decrease and significant magnitude correlations emerge. Applying the b-positive method to the incomplete catalogs restores the correct b-value distribution and removes the artificial correlations. These results confirm that magnitude correlation in real catalogs is largely a consequence of undetected short-term incompleteness rather than a physical interaction between earthquake magnitudes.

The complementary analysis performed on the Southern California earthquake catalog provides additional evidence for this interpretation. By examining the temporal evolution of the average magnitude after mainshocks of different sizes, a clear decay pattern is observed. This decay indicates that catalog incompleteness persists for several minutes after moderate earthquakes and lasts longer for larger mainshocks. Magnitude correlation analyses further show that correlation strength increases with mainshock magnitude and with lower completeness thresholds. This behaviour is reproduced by synthetic catalogs only when STI is included. When only positive magnitude differences are considered, most correlations disappear. Overall, these results strongly support the interpretation that magnitude correlations observed in earthquake catalogs are mainly artifacts produced by short-term catalog incompleteness.

The study of the Norcia seismic cluster (Piegari et al., 2025) provides additional insight into the causes of temporal variations in b-values during earthquake sequences. Using DBSCAN clustering and PCA analysis, two distinct structural domains were identified within the seismicity: a fragmented high-angle fault structure (V-type) and a homogeneous sub-horizontal structure (H-type). These two structural domains exhibit systematically different magnitude–frequency distributions, with the H-type structure consistently showing higher b-values than the V-type structure.

When events from both structures are analysed together, an apparent temporal increase of the b-value appears before the Norcia mainshock. However, this increase disappears when the two structures are analysed separately. This demonstrates that spatial heterogeneity of fault structures can produce apparent temporal changes in b-values that do not reflect real physical variations in stress conditions or earthquake processes.

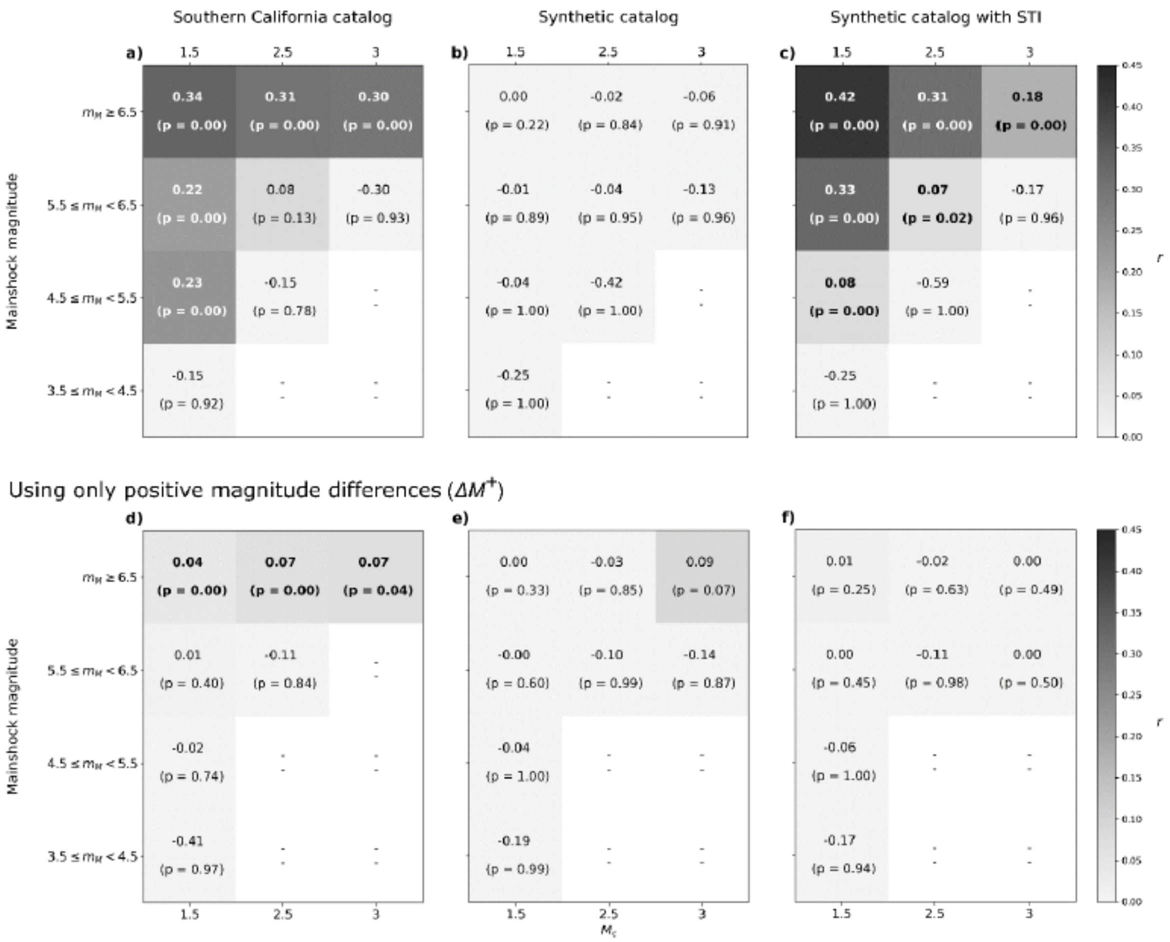


**Figure 7.** Analysis of the magnitude–frequency distribution and magnitude correlations in earthquake sequences. Comparison between real earthquake catalogues and synthetic catalogues used to evaluate the effects of short-term catalogue incompleteness (STI) and magnitude scaling. The results show that apparent magnitude correlations and anomalous b-values may arise from observational biases rather than from physical interactions between earthquake magnitudes.

# 6. Conclusions

The activities presented in this deliverable explore a set of complementary methodological developments aimed at improving the analysis, monitoring, and forecasting of seismic activity and its associated hazard. Although the individual studies address different aspects of earthquake occurrence and seismic hazard assessment, they collectively contribute to advancing the methodological tools available for analysing seismic processes and interpreting the complex dynamics of seismic systems.

A first important outcome of this work concerns the development and testing of new approaches for earthquake forecasting based on the analysis of seismic sequences and the application of advanced statistical and machine-learning techniques. The results obtained with the NESTORE algorithm demonstrate that data-driven approaches can provide valuable information on the short-term evolution of seismic sequences, particularly for estimating the probability of strong aftershocks following major earthquakes. At the same time, the development and testing of ensemble forecasting models within the CSEP framework illustrate the importance of explicitly accounting for epistemic uncertainties when evaluating competing earthquake forecasting models. These approaches highlight the need for robust statistical frameworks capable of comparing models and quantifying their reliability under prospective testing conditions.

A second set of contributions concerns the modelling of earthquake occurrence on individual seismogenic sources. The comparison between classical homogeneous Poisson assumptions and time-dependent recurrence models, performed for the Messina Strait region, illustrates how different representations of earthquake recurrence can significantly influence seismic hazard estimates, especially when analyses focus on individual faults rather than on large regional source zones. These results confirm that time-dependent stochastic models can provide a more physically meaningful description of earthquake recurrence in certain tectonic contexts, although their practical application remains strongly dependent on the availability and quality of geological and seismological constraints.

Another important aspect addressed in this deliverable is the improvement of observational constraints on subsurface structures controlling seismic site effects. The reconstruction of the seismic bedrock geometry in the Mugello basin through integrated geophysical methods demonstrates how relatively simple and cost-effective field procedures can provide valuable insights into the geometry of sedimentary basins and the associated ground-motion amplification processes. These results emphasize the importance of combining different geophysical datasets to reduce uncertainties in the characterization of local geological conditions relevant for seismic hazard assessment.

In parallel, the integration of geochemical, geodetic, and seismological observations provides new perspectives for investigating the role of fluids and crustal deformation in the evolution of seismic processes. Although the identification of reliable earthquake precursors remains an open scientific problem, the development of multi-parameter monitoring strategies represents an important step toward a more comprehensive understanding of the processes governing fault behaviour and seismic sequence evolution. The conceptual workflow proposed in this deliverable highlights the potential of combining heterogeneous datasets to explore possible links between fluid circulation, crustal deformation, and seismicity.

Taken together, the results obtained in the different activities highlight several methodological directions that may guide future developments in seismic hazard analysis and earthquake forecasting. First, the integration of heterogeneous observational datasets is essential for improving the characterization of seismic processes and for reducing uncertainties associated with individual measurement techniques. Second, the explicit treatment of epistemic uncertainties through ensemble modelling approaches represents a key step toward more transparent and robust earthquake forecasting methodologies. Third, improved constraints on geological structures and fault behaviour are necessary to better link observational data with physical models of earthquake occurrence.

At the same time, the studies presented here also highlight several limitations and challenges that still characterize the field. Forecasting models based on statistical or machine-learning approaches remain strongly dependent on the quality and completeness of available seismic catalogues, and their predictive capability may vary significantly across different tectonic environments. Similarly, time-dependent recurrence models require reliable information on fault histories and recurrence intervals, which is often difficult to obtain. Geophysical reconstructions of subsurface structures are inevitably affected by uncertainties related to data resolution and modelling assumptions, while the interpretation of potential precursory signals remains complicated by the complex and often ambiguous nature of geochemical and geodetic observations. These limitations underline the need for continued efforts to improve data quality, monitoring networks, and modelling frameworks.

Looking forward, several research directions appear particularly promising for advancing the methodologies explored in this deliverable. Future work should focus on improving the integration of multi-disciplinary datasets within unified analytical frameworks, allowing seismic, geodetic, geochemical, and geological observations to be analysed jointly. The increasing availability of large observational datasets and advances in data science also offer new opportunities for applying machine-learning techniques to the analysis of seismicity patterns and the identification of subtle signals associated with evolving fault processes. At the same time, further developments in model testing frameworks, such as those provided by the CSEP initiative, will be essential for objectively evaluating forecasting models and for understanding the sources of uncertainty that affect earthquake hazard assessments.

In this perspective, the studies presented in this deliverable should be interpreted not as definitive operational procedures but as methodological contributions that collectively help define guiding principles for the future development of seismic hazard and earthquake forecasting approaches. By combining advances in statistical modelling, geophysical observations, and multi-parameter monitoring, these activities contribute to strengthening the scientific basis for more reliable and transparent assessments of seismic hazard in tectonically active regions.

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