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PhD Thesis

***Uncertainty in Probabilistic Fault Displacement Hazard
Analysis: a sensitivity study and application to the Rieti
Basin (Central Italy)***

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Premise

This Doctoral Thesis has been carried out within the framework of GEOSCIENCES IR – A Research Infrastructure for the Italian Geological Surveys Network, funded by PNRR – European Union – NextGenerationEU – Mission 4 “Education and Research” – Component 2 “From Research to Business” – Investment 3.1 “Fund for the realization of an integrated system of research and innovation infrastructures.”

The GEOSCIENCES IR project establishes a national digital infrastructure designed to integrate data, services, and expertise of the Italian Network of Geological Surveys (RISG): it constitutes the coordination framework linking ISPRA (Italian Institute for Environmental Protection and Research), the Geological Survey of Italy, to the Regional Geological Surveys. This infrastructure provides interoperable platforms for the acquisition, standardization, storage, and dissemination of geological, geophysical, and geochemical datasets, fully aligned with the FAIR (Findable, Accessible, Interoperable, Reusable) data principles. Conceived as a backbone for collaborative research, it supports investigations into Italy’s complex geological framework, natural resources, and geohazards, connecting the capabilities of regional and national surveys with academic and research institutions to enable interdisciplinary studies on tectonics, seismic risk, hydrogeology, and environmental change.

The initiative seeks to reinforce the scientific and operational capacities of the Regional Geological Surveys in priority domains, including geological and thematic mapping, three-dimensional geological modelling, landslide and sinkhole hazard assessment, geohazard monitoring and risk management, and the observation of geo-resources and territorial evolution. Central to this objective is the facilitation of open and interoperable access to geoscientific data and services within a merged cloud environment, ensuring compliance with the interoperability and metadata requirements of the INSPIRE Directive. GEOSCIENCES IR is implementing a robust, scalable cloud-based research infrastructure to support the storage, processing,

and advanced analysis of heterogeneous geological datasets, thereby enabling standardized data integration, promoting collaborative research, and enhancing decision-support capabilities at both the national and European scales.

The GEOSCIENCES IR project is organized into eight distinct Work Packages (WPs). WP1 oversees overall coordination and project management, while the thematic WPs (WP2, WP3, WP4, and WP5) address data-related activities and the development of tools and services. WP6 is dedicated to data standardization and harmonization processes, whereas WPs 7 and 8 are focused on the design, implementation, and validation of the research infrastructure.

The study has been developed under Work Package 4 (WP4): “Risk Monitoring and Management”, which addresses the monitoring and mitigation of geological and hydrogeological hazards through integrated satellite and in situ observations, as well as the investigation of active and capable faults, with particular attention to their seismic potential and the implications for critical infrastructures. WP4 involves a wide collaborative network comprising 18 Operating Units from three national research institutes, CNR, OGS, and ISPRA, and seven universities: University of Cagliari, University of Salerno, Politecnico di Torino, University of Insubria, University of Bari, University of Palermo, and University of Naples. The University of Insubria, where this doctoral research was developed, plays an active role within this collaborative framework, contributing to the advancement of knowledge and innovative strategies for geological risk management.

Within this framework, my research has been focused on the study of active and capable faults (ACFs), with a specific focus on Probabilistic Fault Displacement Hazard Analysis (PFDHA). This study encompasses three main activities aimed at improving the implementation and reliability of PFDHA: (i) the integration of surface rupture data from the FDHI into the SURE 2.0 database, enhancing dataset consistency and reliability; (ii) a sensitivity analysis of key input parameters using a One-At-a-Time (OAT) approach, which highlights the influence of parametrization choices on hazard curves; and (iii) the application of the methodology to the

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Abstract

This doctoral research was conducted within the framework of GEOSCIENCES IR, a Research Infrastructure for the Italian Geological Surveys Network, funded by the PNRR – European Union – NextGenerationEU program. The GEOSCIENCES IR project aims to establish a national digital infrastructure integrating geological, geophysical, and geochemical data and services from the Italian Geological Surveys Network (RISG), promoting interoperable and FAIR-compliant data access. Within this initiative, Work Package 4 (WP4) focuses on *Risk Monitoring and Management*, addressing geological and hydrogeological hazards, active faulting, and their implications for critical infrastructure.

The doctoral research specifically investigates active and capable faults, with emphasis on Probabilistic Fault Displacement Hazard Analysis (PFDHA), a key methodology for assessing the likelihood and intensity of surface faulting during seismic events. The study is structured around three main activities: (i) a sensitivity analysis of PFDHA input parameters using a One-At-a-Time (OAT) approach, which represents the core focus of this research; (ii) the application of the PFDHA methodology to the Southern Boundary Fault (SBF) of the Rieti Basin (Central Italy), serving as a case study for testing and contextualizing the analytical results; and (iii) the integration and harmonization of surface rupture datasets from selected earthquakes of the Fault Displacement Hazard Initiative (FDHI) into the SURE 2.0 database, an ongoing task aimed at improving the standardization and completeness of fault rupture data for future analyses.

Dataset integration focused on ensuring consistency between FDHI and SURE 2.0 standards through systematic review and correction of rupture geometries and classification schemes. This effort improved the completeness and reliability of the SURE 2.0 database, strengthening its role as a reference for future fault displacement hazard analyses.

The sensitivity of PFDHA results to the adopted parametrizations was investigated by evaluating the contribution of different input parameters to fault displacement hazard. The analysis was performed using a One-At-a-Time (OAT) strategy, in which each parameter is modified with respect to three kinematic-specific baseline scenarios. The resulting outputs

were examined in relation to regression models and scaling laws commonly applied in the literature.

The effects of (i) magnitude inferred from rupture area ($m|area$), (ii) magnitude–frequency distributions (MFD), (iii) probability of surface rupture (PSR), (iv) average displacement as a function of magnitude ($AD|m$), and (v) the displacement-to-average displacement ratio (D/AD) were assessed. For all kinematic settings, consistent values of b -value, slip rate, fault area, and minimum magnitude were maintained to isolate the influence of the tested parameters. Hazard curves were computed using a MATLAB script, and percentage differences in the annual frequency of exceedance were quantified by comparing each simulation with the baseline.

Results indicate that the choice of scaling relations, regression coefficients, and associated standard deviations exerts a measurable influence on hazard curves, with $m|area$, MFD, and PSR primarily affecting the plateau region (i.e., for smaller displacements), and $AD|m$ and D/AD controlling the tail region (i.e., for larger displacements).

Overall, the analysis underscores the importance of transparent model selection and explicit uncertainty treatment in PFDHA applications. By clarifying how modeling choices affect hazard estimates, it contributes to a better understanding of methodological variability and supports more reliable and informed use of PFDHA in seismic hazard assessment.

Finally, the case study on the Southern Boundary Fault of the Rieti Basin applied the PFDHA framework to three rupture scenarios—Western Segment (WS), Eastern Segment (ES), and Total Boundary Fault (TBF)—evaluating both principal and distributed ruptures. Hazard curves were generated for different exceedance probabilities (1%, 2%, 10%) over a 200-year period and varying distances from fault traces. The results provide a preliminary characterization of fault displacement hazard for the Rieti Basin, contributing to the integration of fault-based seismic hazard assessment into regional seismotectonic analyses.

1. INTRODUCTION

Active faults and earthquakes

In seismotectonics, the classification and understanding of faults, intended as seismogenic sources, are essential for seismic hazard assessment and land-use planning. Faults are generally classified according to their recent activity and/or their potential to produce permanent surface deformation. An active fault is defined as a tectonic structure that has experienced displacement during a seismic event in the past and, based on geological evidence and the regional geodynamic setting, has a credible likelihood of reactivation within a timeframe relevant to future generations (International Atomic Energy Agency, 2022, IAEA SSG-9 hereafter; ITHACA, 2019). When such a fault has the potential to produce permanent deformation of the Earth's surface, it is designated as a Capable Fault (IAEA SSG-9).

The classification of active faults is rooted in early work by Wood (1916) and Willis (1923), who identified four fundamental diagnostic criteria: (i) evidence of surface displacement within the current seismotectonic regime, (ii) likelihood of future reactivation or surface deformation, (iii) geomorphological indicators of recent activity, and (iv) the potential to generate associated seismicity. The definition of fault activity inherently involves a temporal component, the length of which varies depending on the methodological approach. From a uniformitarian perspective, the time window considered may differ according to the regional tectonic context, fault slip rates, earthquake recurrence intervals, and the resolution limits of available dating techniques.

International regulations reflect these variations. In the United States, a fault is considered inactive for nuclear facility siting purposes if it has not moved in the past 500,000 years or has experienced only a single movement in the last 35,000 years (USNRC, 1997; USNRC, 2007; USNRC, 2020). In Japan, the Nuclear Regulatory Authority (NRA) revised its guidelines after the Fukushima Daiichi accident in 2011, extending the active fault assessment window to 400,000 years. Capability is generally defined based on fault movements during the late Pleistocene (~125,000

years), but when younger horizons cannot be dated with confidence, the broader 400,000-year criterion is applied (Nuclear Regulatory Authority, 2013). The International Atomic Energy Agency (IAEA) guidelines recommend evaluating fault capability over geological timeframes ranging from the Upper Pleistocene–Holocene in highly active regions to several million years in less active tectonic settings (IAEA, SSG-9).

Capable faults hold particular significance due to their direct implications for land stability and the safety of critical infrastructure, including nuclear installations. In Italy, their identification and classification are compiled in the ITHACA (Italy Hazard from Capable Faults) catalogue, which adheres to IAEA documents SSG-9 (Rev. 1, 2022) and TECDOC 1767 (2015). According to ITHACA–ITALY HAZARD FROM CAPABLE FAULTS INVENTARIO DELLE FAGLIE CAPACI IN ITALIA (2022):

“[...] a fault is defined as capable when it is considered able to produce, within a time interval relevant to society, a deformation or displacement of the ground surface and/or in its vicinity”.

While ITHACA generally adopts the IAEA temporal criterion of 125,000 years, alternative thresholds are also used in the Italian context, such as the 40,000-year limit specified in the Guidelines for Land-Use Planning in Areas Affected by Active and Capable Faults (FAC), approved by the Conference of Regions and Autonomous Provinces in 2015.

Under these guidelines, a fault is classified as FAC if it satisfies at least two of the following conditions: (i) evidence of activation within the last 40,000 years (Late Pleistocene–Holocene), (ii) intersection with the topographic surface producing visible fracturing or displacement along the principal fault plane, and (iii) location within the epicentral area of historical earthquakes with magnitudes exceeding Mw 5.5. The adoption of such multi-criteria approaches reflects the need to integrate geological, geomorphological, and historical datasets to more accurately delineate

areas susceptible to seismogenic surface deformation, thereby reducing territorial vulnerability and improving seismic risk mitigation strategies.

Surface faulting

Surface faulting, also termed “surface fault displacement”, constitutes a critical earthquake-related hazard with substantial implications for the safety and resilience of infrastructure (e.g., Katona, 2020; Valentini et al., 2021). It is expressed as a permanent displacement or offset of the ground surface along a fault trace, resulting from coseismic rupture during a seismic event (IAEA-TECDOC-1987). This phenomenon reflects the surface expression of slip on a fault at depth.

Surface faulting can be expressed in different forms and degrees of offset localization, including: i) localized or continuous ground breaks, ii) scarps with an exposed free face, flexural scarps associated with dip-slip movements, iii) folding, bending, or warping of surface markers and geomorphic features.

In the context of fault displacement hazard assessment (FDHA), surface faulting is classified into two main categories.

Principal (or primary) fault rupture occurs directly along with the earthquake-generating fault. Distributed ruptures include secondary ruptures and triggered displacements that occur away from the principal fault trace, often along subsidiary or sympathetic structures (Figure 1.1).

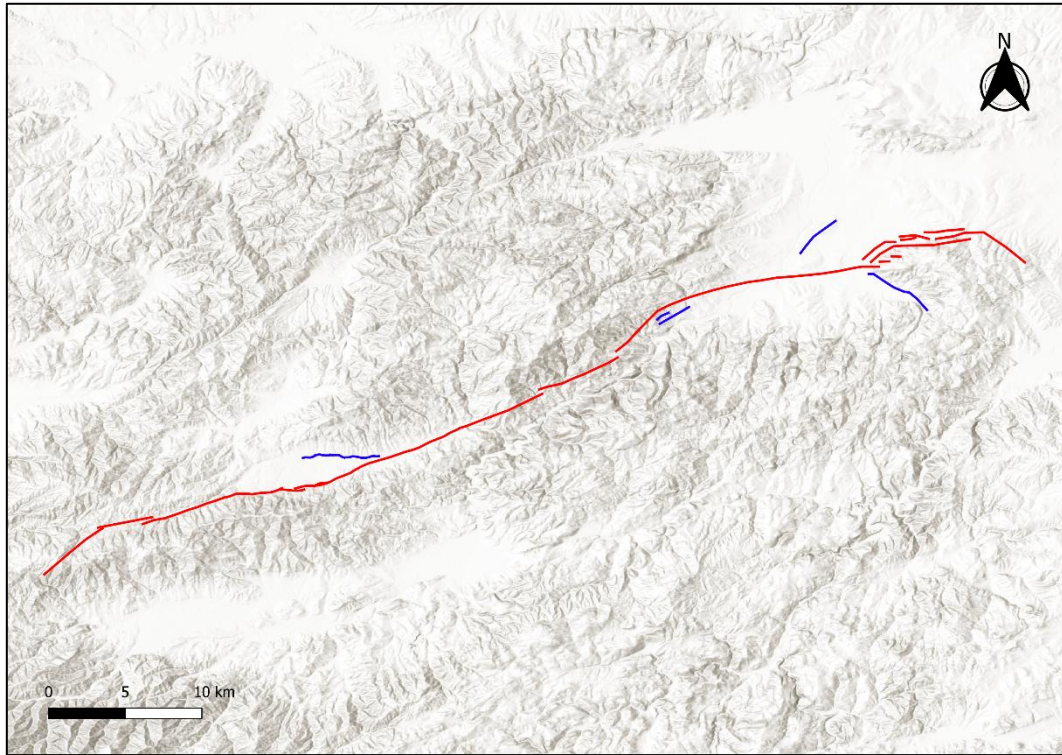


Figure 1.1 Example of a surface rupture map from the Yenice–Gönen earthquake (March 18, 1953, Turkey). Red lines represent principal (primary) fault rupture traces, while blue lines indicate distributed rupture traces. Data are derived from the FDHI project database (Sarmiento et al., 2021).

In Nurminen et al. (2022), a ranking scheme is proposed (Figure 1.2), introducing six different categories: the aforementioned principal and distributed faults are categorized as Rank 1 and Rank 2, respectively, and an additional class is introduced: the Primary Distributed Rupture (Rank 1.5). It includes off-fault ruptures on pre-existing structures with a direct linkage to the principal fault. Another category (i.e., Rank 3) accounts for triggered ruptures, which generally occur at greater distances compared to other distributed ruptures and are expected to have no deep connection with the main structure. The Authors appropriately point out that this category includes also surface ruptures dynamically triggered by other seismogenic sources (e.g., Brodsky et al. 2014). Faults associated with Rank 3 ruptures may have variable activity rates and could have behaved as principal faults

in past events. Bending-moment (Rank 21) and flexural-slip (Rank 22) ruptures are

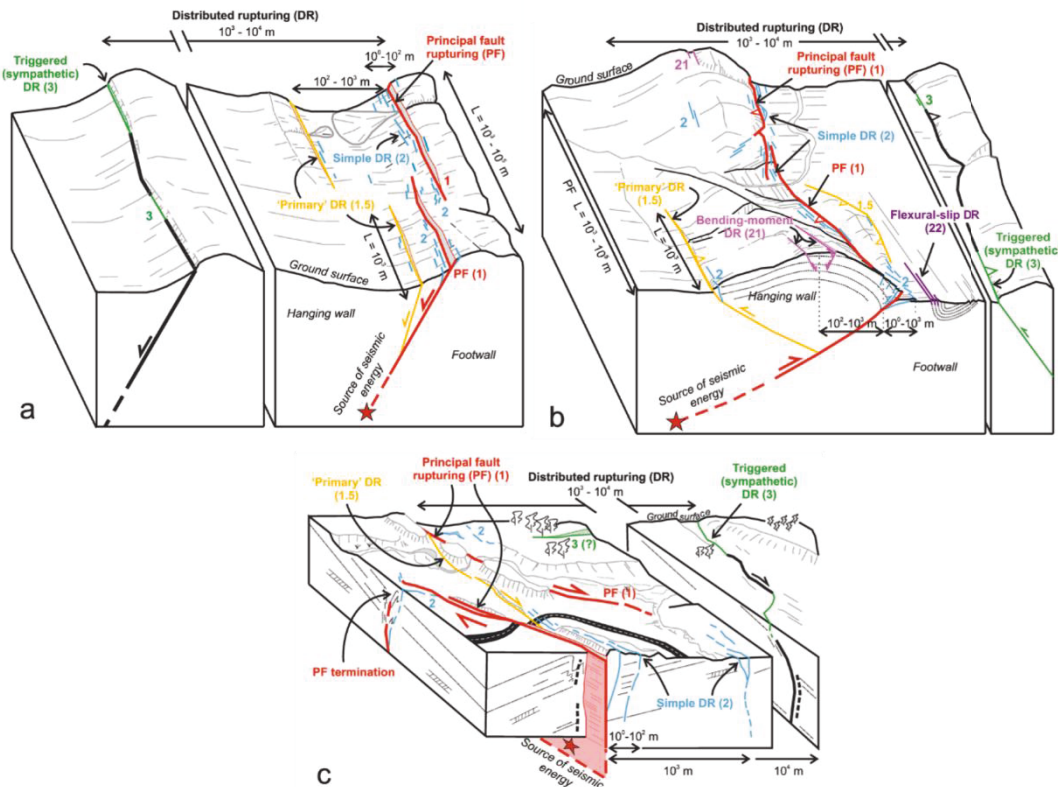


Figure 1.2 Schematic diagram showing rupture ranking for normal (a), reverse (b), and strike-slip (c) kinematics. From Nurminen et al. (2022) [<https://doi.org/10.1038/s41597-022-01835-z>]. Licensed under Creative Commons CC BY 4.0.

deformation styles associated with large-scale folding induced by compressional stress in reverse faulting settings.

Probabilistic approach

Historical and instrumental earthquake records provide numerous examples of direct damage from fault rupture, including the failure or near-failure of bridges and dams (Chi-Chi, Taiwan, 1999), viaducts (Duzce, Turkey, 1999), railways (Kaikoura, New Zealand, 2016), tunnels (Norcia, Italy, 2016; Noto, Japan, 2024), and pipelines (California, 1971; Alaska, 2001). Such cases highlight that even well-engineered facilities can suffer severe or irreparable damage when intersected by coseismic fault displacement.

From an engineering and risk management perspective, accurate characterization of surface faulting hazard is essential for facility siting, land-use planning, and the

development of mitigation strategies. Over the past decades, different methodological strategies have been proposed to achieve this goal, reflecting the need to capture the complexity and variability of fault displacement phenomena. These strategies can be broadly categorized into deterministic approaches, which rely on scenario-based evaluations of maximum expected displacements, and probabilistic approaches, which instead quantify the likelihood of exceeding specific displacement levels within a given time frame. While both perspectives have contributed significantly to hazard assessment, the probabilistic framework offers a more comprehensive treatment of uncertainty and a direct link to risk-informed decision-making. For this reason, the present Thesis concentrates exclusively on the probabilistic approach.

The first application of the Probabilistic Fault Displacement Hazard Analysis (PFDHA hereafter) approach was described in the early 2000s in the studies carried out for the proposed Yucca Mountain nuclear waste repository in Nevada, USA (Valentini et al., 2025). Youngs et al. (2003) formally described the PFDHA methodology to assess hazards posed by active faults near the site.

Within this framework, two different methods are presented: a displacement-based approach and an earthquake-based approach. In the displacement-based approach, hazard estimation is derived from fault displacements collected at the site of interest, and it does not rely on a specific mechanism. Each modeled event is therefore assumed to involve displacement, with uncertainty concerning only the amount of offset rather than its occurrence. Reliable applications need sufficiently detailed site-specific data derived from paleoseismic and/or historical investigations (IAEA-TECDOC-1987). The earthquake-based approach is conceptually adapted from the probabilistic seismic hazard analysis (PSHA) framework, but it substitutes ground motion models with fault displacement models and incorporates the occurrence of site probability of surface rupture. Unlike PSHA, which assumes that ground shaking will always reach the site once an earthquake occurs, PFDHA explicitly treats surface faulting as a probabilistic

phenomenon, acknowledging that only a subset of earthquakes generates surface ruptures.

After the initial application of the PFDHA methodology to normal faults by Youngs et al. (2003), the earthquake-based approach has subsequently been expanded to other styles of faulting, comprising Moss et al. (2011) for reverse and Petersen et al. (2011) for strike slip kinematics. New models are implemented through updated empirical regressions to evaluate the probability of surface rupture related to principal fault, including normal (e.g., Pizza et al., 2023), reverse (e.g., Moss & Ross, 2011; Moss et al., 2013; Takao et al., 2013; Yang et al., 2021; Pizza et al., 2023) and strike-slip faulting (e.g., Takao et al., 2013; Moss et al., 2013; Pizza et al., 2023).

In recent years, numerical simulations (e.g., Zhou et al., 2024; Mammarella et al., 2024) have been proposed alongside empirical regressions. These methods are particularly suitable when empirical regressions are transferred beyond the tectonic context in which they were calibrated. Indeed, numerical models can explicitly incorporate physical parameters, such as seismogenic depth, fault width, and hypocentral location, that empirical datasets often do not include.

Regarding the conditional probability of distributed rupture, the first formulation, based on a *gridding* approach was introduced by Youngs et al. (2003). The area of interest is subdivided into cells of a given size, and the frequency of cells intersected by one or more distributed ruptures is evaluated as a function of their distance from the main fault trace. This procedure has since been adopted and refined in several subsequent models (e.g. Petersen et al. 2011; Takao et al., 2013; Ferrario and Livio, 2021), thereby establishing gridding as one of the most widely used methodologies for quantifying the probability of distributed faulting. Moreover, recent studies (e.g., Nurminen et al, 2020 and Visini et al., 2025), have pointed out that this technique may underestimate rupture occurrence due to the incompleteness of available datasets, as rupture traces are not always systematically mapped. To address this limitation, alternative strategies such as the *slicing* approach have been developed, in which the interest zone is divided into fault-parallel strips rather than square cells,

allowing the probability of distributed rupture to be evaluated along strike without assuming exhaustive mapping.

Together with the earliest fault displacement models, developed to estimate displacement for a single principal rupture (*single principal displacement* after Sarmiento et al., 2025) or distributed ruptures, the past few years have seen the emergence of models capable of estimating displacement across multiple rupture strands. In particular, the development of new probabilistic fault displacement models (FDMs) has been strongly advanced by the Fault Displacement Hazard Initiative (FDHI) (Sarmiento et al., 2025). Within this framework, these new approaches generate probability distributions of principal and aggregate surface fault displacements, which can be directly applied in probabilistic hazard assessments. Specifically, two of the models (Lavrentiadis et al., 2023 and Chou et al., 2025) calculate displacement by summing values across multi-stranded principal ruptures, an approach referred to as *sum-of-principal displacement*, while two others (Lavrentiadis et al., 2023 and Kuehn et al., 2024) adopt the definition of *aggregate displacement*, obtained by combining displacements from both principal and distributed ruptures.

In summary, over the past twenty-five years remarkable progress has been achieved in the development of probabilistic models and in the implementation of standardized databases, which have considerably advanced the quantitative characterization of surface faulting hazard. It is well established that Probabilistic Fault Displacement Hazard Analysis (PFDHA) requires multiple input parameters, related both to the characterization of the seismogenic source and to the expected amount and along-strike distribution of coseismic displacement. These parameters are typically incorporated into logic-tree frameworks in order to capture epistemic uncertainties.

Despite its central role, only a limited number of published studies have explicitly addressed the sensitivity of hazard curves to parameter choices within PFDHA (e.g., Gao et al., 2022; Moss and Ross, 2011; Wells and Kulkarni, 2014; Sarmiento et al.,

2025). For instance, Gao et al. (2022) presented a case study of the 2018 Hualien earthquake, applying a logic-tree framework to demonstrate how epistemic uncertainties can be incorporated into hazard calculations through alternative model branches. Another important contribution is provided by Melissanos et al. (2017a, 2023), who explored the PFDHA methodology and offered a detailed discussion of alternative empirical fault-scaling relations, highlighting how parameter choices such as the Gutenberg–Richter b -value, maximum earthquake magnitude, fault length, and site location strongly affect hazard estimates.

A recent benchmark study by Valentini et al. (2025) shows that when identical input data are provided to different expert groups, the resulting hazard curves can vary by two to three orders of magnitude of annual frequency of exceedance. They also demonstrated that large uncertainties often arise in cases where practitioners must assign parameter values close to the limits of the ranges for which empirical relations were originally calibrated, a problem particularly evident in reverse-fault case studies (e.g., the 11th of Nov. 2019, Mw 4.9, Le Teil earthquake).

Finally, an additional key contribution is represented by Sarmiento et al. (2025), who presented a systematic comparison of newly developed Fault Displacement Models (FDMs) within the FDHI Project. Their work highlights differences in datasets, modeling assumptions, and predictive performance, while also benchmarking the new models against widely used earlier formulations (e.g., Youngs et al., 2003; Petersen et al., 2011; Moss and Ross, 2011; Wells and Coppersmith, 1994).

Research Project

Building upon the advances achieved in the past two decades, this Thesis is conceived as a contribution to the application and critical evaluation of PFDHA.

The Thesis is structured to address two interconnected challenges and open topics both dealing with the uncertainty in PFDHA: i) the updating of standardized rupture datasets and ii) the evaluation of sensitivity in hazard outputs to different modeling choices.

Finally, I'll discuss the application of PFDHA within a specific case study flawed by significant uncertainties in the characterization of the Capable Fault under investigation. It is indeed this the case where an earthquake-based PFDHA could provide more insights to the practitioner.

The availability of homogeneous and internally consistent datasets is a prerequisite for reliable hazard assessment. Historical catalogues of surface rupture data, while extensive, are often fragmented, heterogeneous in format, and often inconsistent in the description of slip parameters and rupture geometries. This work therefore contributes to the ongoing implementation of the SURE (SURface Ruptures due to Earthquakes) database (Baize et al., 2020; Nurminen et al., 2022), a repository designed to enhance completeness, reliability, and geological contextualization, by migrating information from the Fault Displacement Hazard Initiative (FDHI) database into SURE 2.0. Particular attention is being devoted to the reassignment of rupture geometries, the repositioning of slip observation points, and the adoption of the SURE ranking system. These ongoing efforts aim to address inconsistencies and progressively increase the empirical robustness of the dataset, thereby strengthening its use in future PFDHA implementations.

A further line of investigation focuses on quantifying the sensitivity of PFDHA results to different input parameters and regression choices. Despite the methodological maturity reached by PFDHA, only a limited number of studies have systematically examined how parameterization influences hazard curves. This thesis addresses the issue by applying a One-At-a-Time (OAT) sensitivity analysis to a set of kinematic simulations, varying key elements such as magnitude–area scaling laws, magnitude–frequency distributions, probability of surface rupture, $AD|m$ regressions, and D/AD models. By maintaining other seismotectonic conditions constant, the analysis isolates the specific contribution of each parameter to annual frequency of exceedance vs displacement outputs. The results provide quantitative evidence of how regression coefficients, scaling laws, and their uncertainties affect both the plateau and tail regions of hazard curves, underlining

the necessity of transparent model selection and explicit treatment of epistemic uncertainty in applied studies.

Finally, the methodological framework is tested through an application to the Southern Boundary Fault of the Rieti Basin in the Central Apennines (Italy). Despite the tectonic significance of this structure, available knowledge remains limited and largely based on outdated investigations, recently complemented by new paleoseismological insights. Within this context, the thesis applies the earthquake-based PFDHA methodology to evaluate the annual frequency of exceedance for different rupture scenarios, involving distinct fault segments. Hazard curves are computed for multiple distances from the fault trace, yielding a preliminary characterization of surface displacement hazard in the area. The case study demonstrates how PFDHA can be integrated into regional seismotectonic assessments and provides a template for the evaluation of active structures of comparable scale and complexity.

In sum, this research seeks to advance the empirical and methodological bases of PFDHA by clarifying the role of parameter uncertainty, exemplifying the application of probabilistic fault displacement approaching a real case study and reinforcing the quality of input datasets. The integration of these components not only improves the transparency and robustness of hazard estimates but also contributes to ensuring that future applications of PFDHA can more effectively support risk-informed decision-making for critical infrastructure and land-use planning.

2. MATERIALS and METHODS

2.1. Comparison of SURE and FDHI databases

To support PFDHA, systematic and standardized datasets of earthquake surface ruptures are required. Historically, fault rupture data were scattered across heterogeneous sources, reported with varying standards and mapping scales and often lacked consistency in describing slip components and rupture traces.

The homogenization and standardization of such datasets provide the robust empirical foundation required for probabilistic fault displacement hazard analysis (PFDHA), which is increasingly applied in seismic hazard assessments and regulatory frameworks. Moreover, the reliability of PFDHA strongly depends on datasets that are both comprehensive and aligned with regional geological and tectonic contexts, enabling the derivation of regression models tailored to site-specific conditions. Currently, two major global databases, SURE (Surface Ruptures due to Earthquakes) (Baize et al., 2020; Nurminen et al., 2022) and the Fault Displacement Hazard Initiative (FDHI) (Sarmiento et al., 2021, Report GIRS 2021-08), represent the most advanced efforts to compile, standardize, and disseminate surface rupture information.

The SURE project emerged as an effort to consolidate such data into a unified framework. The first release of the database, SURE 2020 (Baize et al., 2020), represented the first worldwide attempt to homogenize surface rupturing data from both historical and modern earthquakes. This dataset proved valuable for fault displacement studies, but its scope was limited by data completeness, quality issues, and the absence of geological ranking criteria to distinguish different rupture types.

The second release, SURE 2.0 (Nurminen et al., 2022), addresses these limitations through a comprehensive update. The database now contains information from 50 crustal earthquakes that occurred between 1872 and 2019, spanning a wide range of magnitudes (from Mw 4.9 to Mw 7.9) and faulting mechanisms (strike-slip,

normal, and reverse). A key innovation of SURE 2.0 is the introduction of a fault rupture ranking scheme, which differentiates between principal fault ruptures (PF) and several categories of distributed ruptures (DR), and further subdivides the latter in the categories described above. This classification reflects geological and structural contexts, thereby enabling more accurate regression analyses tailored to site-specific conditions.

Another significant improvement lies in mapping precision and data integration. Compared to the initial release, rupture traces in SURE 2.0 were refined using georeferenced maps, LiDAR-derived digital elevation models, and satellite imagery, ensuring higher spatial accuracy. Slip measurements were systematically linked to rupture traces within shapefiles, producing an internally consistent dataset of over 75,000 mapped rupture traces and nearly 19,000 slip observations. The database also underwent rigorous quality control: incomplete or poorly constrained cases were excluded, while others were revised with multiple bibliographic sources to enhance accuracy and consistency.

From a statistical perspective, the database highlights important patterns in surface faulting. Principal fault ruptures account for roughly 60–70% of the rupture length and slip measurements, confirming their dominance in seismic energy release. However, distributed ruptures, particularly rank 2, are common and can extend kilometers away from the main fault trace, sometimes even at large distances. The level of detail varies widely across events, with some characterized by extensive datasets while others have only sparse coverage.

The applications of SURE 2.0 are manifold. By standardizing and expanding the available dataset, it provides a robust empirical basis for PFDHA models, which are increasingly required in seismic hazard assessments and regulatory frameworks. The introduction of geological ranking enables hazard analysts to derive regression parameters that more accurately reflect the complexity of surface faulting processes. Furthermore, the dataset is openly accessible through Zenodo (DOI: 10.5281/zenodo.7020265) and encourages community contributions, ensuring that

the database remains dynamic and evolutive. New events can be integrated, and existing data can be refined, making SURE 2.0 not only a research product but also a collaborative platform for the broader seismological community.

The FDHI database was designed to support the formulation of new fault displacement models, with particular emphasis on completeness and on systematic quality assurance and control. Covering 75 historical earthquakes between 1872 and 2019 (Mw 4.9–8.0), it includes over 87,000 georeferenced observations, among them 40,000 direct displacement measurements. Each record is accompanied by metadata, including earthquake source parameters, displacement type (principal or distributed), cumulative versus total displacement, and contextual information such as surficial geology and terrain metrics. The database also classifies ruptures as either principal or distributed, distinguishing hanging wall from footwall positions in the latter. To capture more complex observations, new ranking categories (cumulative and total) were introduced, accommodating cases with multiple ruptures or wide measurement intervals. In addition, an event-specific coordinate system (ECS) was implemented for each earthquake, complementing standard geographic references with strike-parallel and strike-normal distances for each data point to better reflect rupture trace curvature and segmentation.

SURE 2.0 and FDHI databases represent fundamental tools for the documentation of surface ruptures, both designed for direct use in GIS environments. Their standardized, georeferenced, and quality-controlled structure enables advanced spatial analyses and provides the empirical foundation for modern probabilistic fault displacement hazard assessments.

Integration of Additional Seismic Events into the SURE Database

During my doctoral studies, I was involved in the ongoing update of the SURE 2.0 database. This activity aims to enhance the completeness and reliability of the SURE 2.0 database through the incorporation of 31 additional seismic events from the Fault Displacement Hazard Initiative (FDHI) database. It is being carried out in

collaboration with doctoral colleagues Selina Bonini (University of Bologna) and Lisa Mammarella (University “G. d’Annunzio” of Chieti-Pescara), under the supervision of Professors Oona Scotti and Stéphane Baize (ASNR-Autorité de sûreté nucléaire et de radioprotection) and Professor Paolo Boncio (University “G. d’Annunzio” of Chieti-Pescara).

The Table 2.1 below reports the list of earthquakes selected for integration from the FDHI database into the SURE catalogue. The selected events span a broad temporal range, from the 1892 Laguna Salada earthquake (Mw 7.76, Mexico) to the 2018 Palu earthquake (Mw 7.5, Indonesia). Magnitudes vary between 5.2 (Galway Lake and Homestead Valley, California) and 7.8 (Kaikoura, New Zealand; Kunlun-Kokoxili, Tibet), thereby covering a representative spectrum of moderate to large surface-rupturing earthquakes. The dataset encompasses diverse tectonic environments and geographic regions, including North and Central America (California, Mexico), Asia (China, Japan, Taiwan, Tibet), Oceania (New Zealand, Australia, Philippines), the Middle East (Iran, Turkey), Russia, and Pakistan.

In terms of kinematics, strike-slip mechanisms dominate the sample, accounting for most of the events (e.g., Balochistan 2013, Düzce 1999, Palu 2018), but the dataset also includes reverse (e.g., Kern 1952, Bohol 2013, Mikawa 1945) and normal/oblique ruptures (e.g., Acambay 1912, Iwaki 2011, Laguna Salada 1892).

Earthquake	Style of faulting	Magnitude	Magnitude type	Date	Region	FDHI EQ_ID
Balochistan	Strike-Slip	7.7	Mw	2013-09-24	Pakistan	4
Duzce	Strike-Slip	7.14	Mw	1999-11-12	Turkey	11
Yushu	Strike-Slip	6.9	Mwc	2010-04-13	China	14
Hualien	Strike-Slip	6.4	Mw	2018-02-06	Taiwan	15
Kaikoura	Reverse-Oblique	7.8	Mw	2016-11-13	New Zealand	20
Parkfield 2004	Strike-Slip	6	Mw	2004-09-28	California	22
Bohol	Reverse	7.1	Mww	2013-10-15	Philippines	26
Acambay	Normal-Oblique	6.9	mB	1912-11-19	Mexico	27
Imperial 1940	Strike-Slip	6.95	Mw	1940-05-19	California	28
Parkfield 1966	Strike-Slip	6.19	Mw	1966-06-28	California	29
GalwayLake	Strike-Slip	5.2	ML	1975-06-01	California	32
Kern	Reverse	7.36	Mw	1952-07-21	California	35
Chalfant Valley	Strike-Slip	6.19	Mw	1986-07-21	California	36
Zirkuh	Strike-Slip	7.2	Mw	1997-05-10	Iran	37
Laguna Salada	Normal-Oblique	7.76	Mw	1892-02-23	Mexico	40
Iwaki 2011	Normal	6.6	Mw	2011-04-11	Japan	41
Cadoux	Reverse	6.1	Mw	1979-06-02	Australia	45
Meckering	Reverse	6.59	Mw	1968-10-14	Australia	48
San Miguel	Strike-Slip	6.8	Ms	1956-02-09	Mexico	53
Yutian	Strike-Slip	6.9	Mw	2014-02-12	China	54
Luzon	Strike-Slip	7.7	Mwc	1990-07-16	Philippines	55
Rikuu	Reverse	6.7	U	1896-08-31	Japan	59
Mikawa	Reverse	6.6	Mw	1945-01-12	Japan	60
Izu Peninsula	Strike-Slip	6.5	Ms	1974-05-08	Japan	61
Izu Oshima	Strike-Slip	6.6	Mwc	1978-01-14	Japan	62
Iwate Inland	Reverse	5.8	Mwc	1998-09-03	Japan	63
Neftegorsk	Strike-Slip	7	Mwc	1995-05-27	Russia	65
Kunlun-Kokoxili	Strike-Slip	7.8	Mwc	2001-11-14	Northern Tibet	67
Homestead Valley	Strike-Slip	5.2	ML	1979-03-15	California	70
Palu	Strike-Slip	7.5	Mww	2018-09-28	Indonesia	71
Yenice Gonen	Strike-Slip	7.3	Mw	1953-03-18	Turkey	75

Table 2.1 List of additional seismic events from the FDHI database to be integrated into the SURE database. The fields “Style of faulting”, “Magnitude”, “Magnitude type”, “Date”, “Region”, and “FDHI_EQ_ID” are derived from

Migration of FDHI events into the SURE structure database

To enable the integration of selected earthquake events documented in the FDHI Database but not yet included in SURE, a dedicated data migration procedure was implemented using MATLAB. The workflow was designed to ensure consistency with the structure and field requirements of the SURE database schema, while maintaining the original content of the FDHI *flatfiles*.

The procedure began with the initialization of an empty table reproducing the structure of the SURE database, with the same variables and column organization, and all entries initially set to missing values. At this stage, a correspondence framework was also established to map FDHI variables onto the standardized SURE format, providing the basis for the subsequent data transfer.

An automated mapping routine then iterated across all fields defined in the SURE structure. For each field, the code verified whether a corresponding FDHI variable existed. If a match was identified, the values from the FDHI dataset were transferred into the equivalent column of the new SURE table. Fields that are not present in the FDHI input were left unassigned, maintaining *NaN* placeholders. This ensured both flexibility and traceability in cases where the FDHI dataset lacked information required by the SURE schema.

Finally, the consolidated table was exported as a CSV file, formatted according to the SURE standards. This dataset can now be used as an intermediate product for integrating FDHI-derived data into the SURE database, ensuring harmonized metadata, consistent variable naming, and improved compatibility across the two databases.

Post-import verification and reclassification of rupture geometry and measurement points

The migrated events are currently in a validation phase, carried out through GIS-based visualization of rupture traces and measurement points. Several aspects are being systematically examined, including the comparison of mapped rupture traces with satellite imagery and high-resolution topographic data, in order to verify, where possible, their correct positioning relative to recognizable morphological features such as fault scarps. Measurement points are also being carefully checked to ensure their accurate spatial association with the corresponding rupture trace (Figure 2.1).



Figure 2.1 Detail of the rupture map for the 1940 Imperial Valley earthquake (California). Example of a measurement point not in accurate spatial association with the corresponding rupture trace. The point, whose label indicates the amount of recorded displacement (in meters), is located more than 100 m away from the rupture trace to which it should refer. Red line represents principal (primary) fault rupture trace, red dot indicates measurement point.

Furthermore, consistency between the ranking of individual measurements (i.e., principal vs. distributed ruptures) and the assigned ranking of their associated rupture traces is being evaluated (Figure 2.2). Where possible, inconsistencies in

ranking are being corrected, while issues related to the precise relocation of measurement points remain under review. At this stage, exact repositioning can only be undertaken after a detailed case-by-case assessment, since a definitive strategy has not yet been established. Future developments are expected to involve defining tolerance thresholds based on the distance between rupture traces and measurement points, to guide systematic relocation efforts.

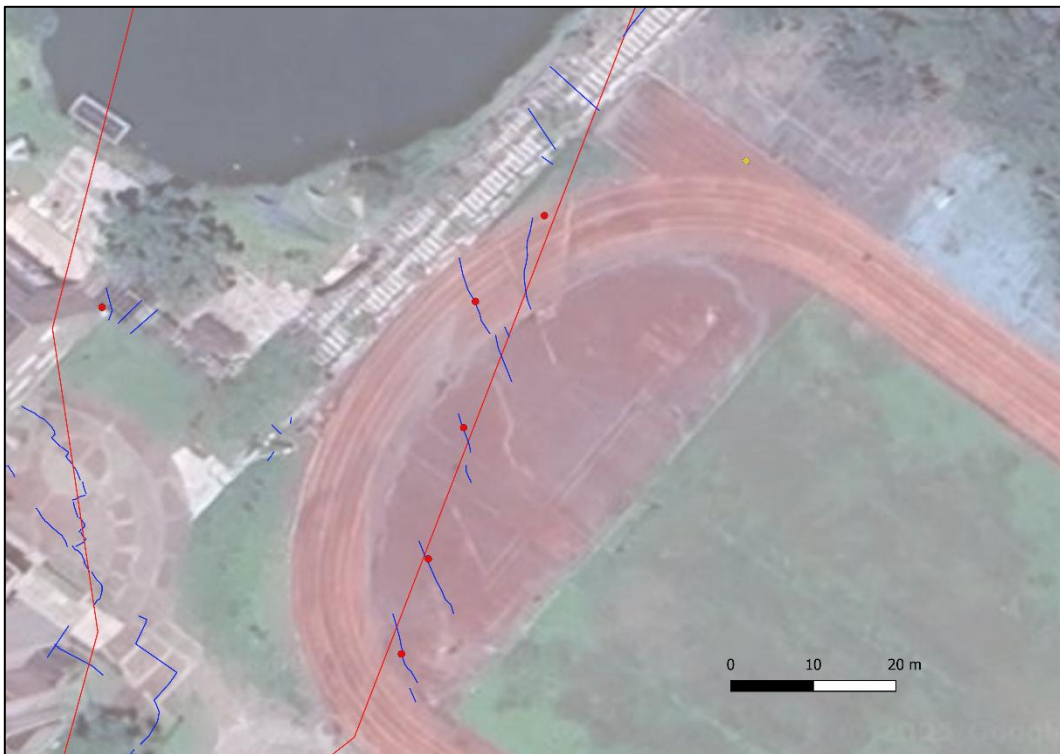


Figure 2.2 Detail of the rupture map for the 2018 Hualien earthquake (Taiwan). Example of inconsistency between the ranking of rupture traces and that of the associated measurement point. Red lines and dots indicate principal (primary) fault rupture traces and measurement points, respectively, while blue lines and dots indicate distributed rupture traces and measurement points, respectively.

A key objective of this implementation process was to reassess the rupture ranking of FDHI-derived elements according to the more detailed classification scheme adopted in the SURE database. This involved both a general review of the ranking assignments and a targeted reclassification of specific cases where FDHI categories did not align with the SURE framework (e.g., the introduction of Rank 1.5 for primary distributed ruptures). The reassignment of rankings considered parameters such as the magnitude of measured displacement and the mapped

length of rupture traces. In particular, for cases reclassified as Rank 1.5, it was verified that the structure under review had been mapped prior to the considered seismic event, thereby confirming that these features corresponded to pre-existing faults reactivated during the earthquake. To carry out this task, additional information was gathered by consulting the reference documents cited for each event within the FDHI database, as well as by examining data plots directly derived from the *flatfiles*. These plots, provided in the electronic supplement as HTML notebooks, display maps of rupture traces, measurement points, and the event-specific coordinate system (ECS) reference line path.

2.2. PFDHA sensitivity analysis

The PFDHA was performed according to the general formulation proposed by Youngs et al. (2003). Following the earthquake approach, the annual rate at which a fault displacement D exceeds a given value (d), during an individual seismic event, can be expressed as:

$$v_k(d) = \sum_n \alpha_n(m^0) \int_{m^0}^{m^u} f_n(m) \left[\int_0^\infty f_{nk}(r|m) \cdot P_{kn}^*(D > d|m, r) \cdot dr \right] \cdot dm \quad (1)$$

Where $\alpha_n(m^0)$ is the of engineering significance (m^0); $f_n(m)$ is the probability density of seismic event size between a minimum (m^0) and a maximum (m^u) magnitude value; $f_{nk}(r|m)$ correspond the conditional probability density function for distance r between the fault trace and a site k ; $P_{kn}^*(D > d|m, r)$ is the attenuation function associated at the fault displacement that occurs on or near the fault trace.

The attenuation function is defined as the product of two components:

$$P_{kn}^*(D > d|m, r) = P_{kn}(Slip|m, r) \cdot P_{kn}(D > d|m, r, Slip) \quad (2)$$

The first term represents the conditional probability of surface rupture at site k , given the magnitude m , estimated at distance r from the site. The second term in Equation (2) denotes the probability that the displacement exceeds a threshold value d , if slip occurs. This latter probability is obtained by convolving two probability distributions: one that captures the natural variability of slip along the fault strike,

expressed as the ratio of displacement to average displacement (AD/D) and another that relates the average displacement as a function of magnitude ($AD|m$). The D/AD distribution is expressed in terms of the position along the rupture, represented by the normalized distance x/L , where x is the distance from one rupture end to the point of interest, and L is the total rupture length. Following previous studies (Wesnousky, 2008; Biasi and Weldon, 2006), displacement measurements were normalized to rupture length and treated as symmetric by folding them about the rupture midpoint ($x/L=0.5$).

This sensitivity analysis aimed to explore the PFDHA outcomes derived from applying models and scaling relations available in the literature to evaluate key parameters, including maximum magnitude from rupture area ($m|area$), magnitude–frequency distributions (MFD), probability of surface rupture (PSR), average displacement for a given earthquake magnitude ($AD|M$), and the displacement-to-average displacement ratio (D/AD).

Since a full exploration of a logic tree would have generated more than 2000 models (for terminology, see Baker et al., 2021), I adopted a One-At-a-Time (OAT) strategy. In this approach, a single parameter varies with respect to three kinematics-specific baselines (BL), and separate simulations are performed for each style of faulting (i.e., normal, reverse, and strike-slip kinematics; Table 2.2).

For all fault kinematics, identical values of b -value, slip rate, fault area, and minimum magnitude were adopted (Table 2.3). These parameters were held fixed across the simulations to highlight the differences related to the adoption of one out of several published empirical equations rather than inherent uncertainties arising from the knowledge of the seismogenic structure.

The probability of exceedance was evaluated by convolving the probabilities within a narrow range of x/L values, located close to the fault center (i.e., the central 20% of the fault length). To complete the OAT sensitivity analysis, the obtained hazard curves were compared against the baseline results. The outcomes are expressed as

percentage differentials (PD; Equation 3), which quantify the relative deviation between each simulation and the baseline:

$$PD = \left(\frac{Simulation - Baseline}{Baseline} \right) \cdot 100 \quad (3)$$

Tornado plots were produced to illustrate a final comparison of the influence of the analyzed parameters in the sensitivity analysis, showing the absolute maximum PD evaluated for different displacement-of-exceedance thresholds, (namely 10 cm, 1 m and 2 m).

The calculations for the sensitivity analysis and the derivation of hazard curves were carried out using a MATLAB script adapted from the code originally provided by Moss et al. (2022). The implementation was extended to allow the selection among different magnitude–frequency distribution (MFD) models, alternative regressions for the probability of surface rupture, and empirical relationships for both AD|m and D/AD, with separate formulations for normal, reverse, and strike-slip kinematics. The workflow follows a stepwise probabilistic framework, combining MFDs, rupture probabilities, and displacement models through Monte Carlo simulations to derive hazard curves expressed as annual frequencies of exceedance. A detailed description of the code structure, discretization scheme, parameter settings, and stochastic sampling strategy is provided in the Appendix A.

	m area	MFD	PSR	AD m	D/AD
Normal kinematic simulations	Wells & Coppersmith, 1994 Leonard, 2010 Thingbaijam et al., 2017 Shaw, 2023 – Ellsworth-B Shaw, 2023 – Ellsworth-C	Gutenberg–Richter truncated (Gutenberg & Richter, 1944) Characteristic earthquake (Schwartz & Coppersmith, 1984) Composite magnitude (Youngs & Coppersmith, 1985) Maximum magnitude (Wesnousky, 1986)	Youngs et al., 2003 (Cordillera) Pizza et al., 2023	Wells & Coppersmith, 1994 Thingbaijam et al., 2017	Youngs et al., 2003
Reverse kinematic simulations	Wells & Coppersmith, 1994 Leonard, 2010 Thingbaijam et al., 2017 Shaw, 2023 – Ellsworth-B Shaw, 2023 – Ellsworth-C	Gutenberg–Richter truncated (Gutenberg & Richter, 1944) Characteristic earthquake (Schwartz & Coppersmith, 1984) Composite magnitude (Youngs & Coppersmith, 1985) Maximum magnitude (Wesnousky, 1986)	Moss et al., 2011 Moss et al., 2013-stiff Moss et al., 2013-soft Takao et al., 2013 Yang et al., 2021 Pizza et al., 2023	Wells & Coppersmith, 1994 Moss et al., 2022 Takao et al., 2013 Thingbaijam et al., 2017	Moss et al., 2022 Takao et al., 2013
Strike slip kinematic simulations	Wells & Coppersmith, 1994 Leonard, 2010 Thingbaijam et al., 2017 Shaw, 2023 – Ellsworth-B Shaw, 2023 – Ellsworth-C	Gutenberg–Richter truncated (Gutenberg & Richter, 1944) Characteristic earthquake (Schwartz & Coppersmith, 1984) Composite magnitude (Youngs & Coppersmith, 1985) Maximum magnitude (Wesnousky, 1986)	Pizza et al., 2023 Takao et al., 2013 Moss et al., 2013-stiff Moss et al., 2013-soft	Wells & Coppersmith, 1994 Takao et al., 2013 Thingbaijam et al., 2017	Petersen et al., 2011 -bilinear model Petersen et al., 2011-quadratic model Petersen et al., 2011-elliptical model Takao et al., 2013- >10km Takao et al., 2013- <10km

Table 2.2 OAT sensitivity parameters. Baseline formulations, one for each kinematic style, are highlighted in bold. Alternative models for scaling laws of magnitude with respect to area ($m|area$), magnitude-frequency distribution (MFD), probability of surface rupture (PSR), average displacement for a given earthquake magnitude ($AD|m$), and displacement to average displacement ratio (D/AD) are presented for normal, reverse, and strike-slip faulting.

b-value	Slip rate (cm/yr)	Fault area (km ²)	Minimum magnitude
1	0.1	250	5.5

Table 2.3 Fixed seismotectonic parameters adopted in this OAT sensitivity analysis.

The following section introduces the scaling laws, models, and empirical regressions tested in the sensitivity analysis. Further details on related parameters are provided in the Appendix B.

Magnitude with respect to area scaling laws

To estimate the magnitude, several magnitude vs area scaling laws were adopted. The maximum magnitude value was obtained by adding 0.3 units to the calculated m which was then adopted as the characteristic magnitude in the magnitude–frequency distribution models. The +0.3 increment is well supported in the technical literature (Kramer, 1996; Field et al., 2014) and reflects the typical variability associated with empirical models.

For the baseline of each kinematics, I considered the relationships proposed by Wells and Coppersmith (1994). These Authors developed empirical regressions for normal, reverse and strike slip kinematics, linking earthquake magnitude to rupture parameters. These regressions were based on a global database of 421 shallow continental earthquakes, of which 244 high-quality events were selected for analysis. These scaling laws show that the relationship between magnitude and rupture area is particularly robust, with high correlation coefficients (r-squared ranging between 0.92–0.96) and relatively small standard deviations (i.e., 0.23–0.25). Although these equations are no longer universally recommended (Shaw, 2023), they still remain widely used by practitioners and have been used in past analyses.

Under these considerations, I compared the relationships after Wells and Coppersmith (1994) with those published by Leonard (2010), Thingbaijam et al. (2017), and Shaw (2023).

Leonard (2010) proposes magnitude–area scaling relations that are self-consistent, and that are calculated from a larger and more comprehensive database than the

previous ones, by incorporating additional events. Unlike purely empirical scaling laws (e.g., Wells and Coppersmith, 1994), Leonard's *self-consistent* relations ensure mutual coherence among fault parameters. This implies relations that allow seismic moment, fault length, width, area, and displacement to be derived from one another, with all quantities remaining consistent with the definition of seismic moment. Separate relations are provided for dip-slip and strike-slip mechanisms, ensuring a stronger statistical robustness and broader applicability if compared to earlier studies.

Thingbaijam et al. (2017) derived updated empirical scaling laws for normal, reverse (shallow crustal), and strike-slip kinematics using a comprehensive database of finite-fault models spanning Mw 5.4–9.2. By applying general orthogonal regression, that accounts for measurement errors in all the variables involved, these Authors obtained mutually consistent relations, i.e. scaling equations that remain coherent with each other and with the definition of seismic moment. Their results show that a magnitude vs area scaling is broadly consistent with a self-similar behavior, which indicates that any variation in seismic moment entails corresponding proportional changes in rupture width, length, and average slip, with the notable exception of normal-faulting earthquakes which deviate from this trend. Indeed, unlike other faulting regimes, in normal faulting the reduced growth of rupture width is not compensated for a faster increase in rupture length. As a result, the total rupture area departs from the expected behavior. This deviation has been linked to the geometry and mechanics of normal faults, which often occur on steep or listric fault planes.

In his 2023 study, Shaw critically reassesses existing magnitude–slip relationships and proposes a streamlined framework of scaling laws suitable for application in fault-based seismic hazard models. For the sensitivity analysis carried out in this work, the equations specifically formulated for Plate Boundary Faults were selected and applied consistently across all three kinematic regimes considered. These relations, based on the general logarithmic area-magnitude law (i.e., $m = \log_{10}(\text{area}) + C$), originate from empirical formulations first introduced in the Working

Group on California Earthquake Probabilities (WGCEP, 2003), where the Ellsworth-B ($C = 4.2$) and Ellsworth-C ($C = 4.1$) forms were developed as benchmark magnitude–area correlations. In Shaw’s framework, these formulations are retained and evaluated as part of a reduced, physically grounded set of scaling options intended to capture epistemic uncertainty while maintaining internal consistency across tectonic contexts.

Magnitude-frequency distribution (MFD) models

In this study, several of the most used time-independent MFD models, commonly adopted in probabilistic seismic hazard analysis, were tested. These include i) the truncated Gutenberg–Richter model, ii) the characteristic earthquake model and iii) the maximum magnitude model.

The truncated Gutenberg–Richter (GR) model that follows a classic exponential decay in frequency with magnitude, bounded by minimum and maximum magnitude limits (Gutenberg & Richter, 1944).

The characteristic earthquake model, proposed by Schwartz and Coppersmith (1984), incorporates a hybrid distribution in which a fraction of the total seismic moment is uniformly distributed within a narrow interval above a characteristic magnitude, with width $\Delta m = 0.1$.

A variant of this, known as the composite magnitude model and developed by Youngs and Coppersmith (1985), introduces a delta formulation by concentrating a fraction of the moment at a single bin centered at magnitude characteristic, while the remainder follows a truncated exponential distribution below the magnitude characteristic value.

Finally, the maximum magnitude model described by Wesnousky (1986) assumes a truncated normal distribution centered at magnitude characteristic controlled by a standard deviation SD_m , representing aleatory variability around a most probable magnitude. For the baseline adopted in the calculation of differential percentages, the truncated Gutenberg–Richter model was employed.

The analytical formulations of the four adopted magnitude–frequency distribution models are reported below.

- Truncated Gutenberg–Richter model

$$f(m) = \begin{cases} \frac{\beta \cdot e^{-\beta(m-m_{min})}}{1 - e^{-\beta(m_{max}-m_{min})}}, & m_{min} \leq m \leq m_{max} \\ 0, & otherwise \end{cases}$$

Notation:

$m \in [m_{min}, m_{max}]$

$\beta = b \ln(10)$

- Characteristic earthquake model (Schwartz and Coppersmith, 1984)

$$f(m) = \begin{cases} \frac{(1-p) \cdot e^{-\beta(m-m_{min})}}{1 - e^{-\beta(m_{char}-m_{min})}}, & m < m_{char} \\ \frac{p}{\delta m}, & m_{char} \leq m \leq m_{char} + \delta m \\ 0, & otherwise \end{cases}$$

Notation:

m_{char} : characteristic magnitude

δm : width of the characteristic peak

p : fraction of total moment released by characteristic events

Composite magnitude model (Youngs and Coppersmith, 1985) $f(m) =$

$$f(m) = \begin{cases} \frac{(1-\alpha) \cdot \beta \cdot e^{-\beta(m-m_{min})}}{1 - e^{-\beta(m_{char}-m_{min})}}, & m < m_{char} \\ \alpha \cdot \delta(m - m_{char}), & m = m_{char} \\ 0, & otherwise \end{cases}$$

Notation:

m_{char} : characteristic magnitude

α : fraction of the moment concentrated in a single bin at $m=m_{char}$

Note: In numerical implementation, the delta function is approximated as a sharp peak over one bin width Δm .

- Maximum magnitude model (Wesnousky, 1986)

$$f(m) = \begin{cases} \frac{1}{Z} \cdot \frac{1}{SD_m \sqrt{2\pi}} \cdot e^{\left(-\frac{(m-m_{char})^2}{2SD_m^2}\right)}, & m_{min} \leq m \leq m_{max} \\ 0, & otherwise \end{cases}$$

where $Z = \int_{m_{min}}^{m_{max}} NormPDF(m) dm$

Probability of Surface Rupture (PSR) equations

For the baselines of the normal, reverse, and strike-slip kinematics simulations, I respectively adopted the equations after Youngs et al. (2003), Moss et al. (2011), and Pizza et al. (2023).

Youngs et al. (2003) derived an empirical logistic regression for normal-fault earthquakes in the Extensional Cordillera, using the dataset compiled by Pezzopane and Dawson (1996), which includes about 100 earthquakes (Mw 4.5–7.6, depth <20 km) that occurred between 1830 and 1995.

Moss et al. (2011) proposed a regression specific to reverse-fault kinematics, building on the dataset compiled by Lettis et al. (1997) and incorporating six further earthquakes, for a total of 129 continental reverse-faulting events worldwide between 1905 and 2008, with magnitudes ranging from Mw 5.4 to 8.2.

Pizza et al. (2023) derive updated regressions from a global dataset of 363 onshore strike slip earthquakes (Mw ≥ 5.5, depth <20 km) that occurred between 1992 and 2018. The analysis provides separate empirical models for each kinematics, with the strike-slip relationship, as already mentioned, considered as the baseline.

In the OAT analysis, these baselines were then tested against the equations after Pizza et al. (2023; normal style), Takao et al. (2013; reverse and strike-slip styles), Moss et al. (2013; reverse and strike-slip styles under stiff and soft soil conditions), Yang et al. (2021; reverse style), and Pizza et al. (2023; reverse style).

The regressions proposed by Takao et al. (2013) derive from a dataset of 107 strike-slip and reverse earthquakes that occurred in Japan between 1885 and 2008 (Mw 5.4–7.4) and are thus representative of the Japanese tectonic setting. Likewise, Yang et al. (2021) based their regressions on 11 surface-rupturing earthquakes (Mw 4.7–

6.6) that occurred between 1900 and 2020 within the stable, non-extended cratonic crust of Australia, reflecting the characteristics of that specific geodynamic environment.

Moss et al. (2013) developed new regressions for reverse and strike-slip kinematics, testing several predictor variables and identifying VS30 (a proxy for near-surface soil stiffness) as the most effective in forecasting the probability of surface rupture.

AD|m regressions

In the baselines of the three kinematics simulation, I adopted the AD|m equations after Wells and Coppersmith (1994). These regressions are derived from the same dataset used to establish the magnitude–area scaling laws. According to the statistical analyses, strike-slip regressions are the most robust, exhibiting strong correlations (correlation coefficient ≈ 0.89) and low variability (standard deviation ≈ 0.29), whereas reverse-slip regressions are weakly constrained and not predictive. These equations were compared with those proposed by Thingbaijam et al. (2017) for all three kinematic styles, by Takao et al. (2013) for reverse and strike-slip faults, and by Moss et al. (2022) for reverse faults.

The AD|m regression after Takao et al. (2013) for reverse and strike slip event is based on the same Japanese earthquake dataset that was previously cited to derive empirical regressions for the probability of surface rupture (PSR). After analyzing the Japanese records, the difference in the constant term for AD with respect to the global regression of Wells and Coppersmith (1994) was found to be less than 0.1. Therefore, Takao et al. (2013) retained the Wells and Coppersmith (1994) formulation for all faulting styles without modification.

The AD|m regressions derived by Thingbaijam et al. (2017) are based on the same dataset used for the magnitude–area relations. Importantly, these AD|m relations use the average displacement of the entire rupture source, rather than the average surface displacement, as is the case for the other relationships considered in the simulations. Likewise, the regressions are statistically consistent with self-similar

scaling; however, those obtained for normal-faulting earthquakes represent a critical exception, deviating from this self-similarity.

The AD|m regression proposed by Moss et al. (2022) for reverse and reverse-oblique earthquakes is based on 32 events, with information derived primarily from the FDHI database (Sarmiento et al., 2021) and Wells and Coppersmith (1994). Average displacement values were calculated from multiple field measurements of vertical offset.

The selected equations were included into the calculations by accounting for both the regression parameters and their associated standard deviations.

D/AD models

For simulations involving normal fault kinematics, the baseline relied on the regression of Youngs et al. (2003), without testing alternative formulations since no alternative equations are presently available, up to my knowledge.

Reverse-fault simulations adopted Moss et al. (2022) equations as a baseline, whereas strike-slip simulations adopted the bi-linear relationship introduced by Petersen et al. (2011). The reverse and strike-slip baselines were tested against the equations after Takao et al. (2013), as well as the quadratic and elliptical functional forms of Petersen et al. (2013), with the latter applied only to the strike-slip faulting cases.

The D/AD regressions formulated by Moss et al. (2022) are based on displacement distributions of binned x/L data, which had best fits to the gamma distribution. The gamma distribution parameters were expressed as functions of the x/L and treated as linear, since no evidence was found to justify a higher-order fit.

The D/AD regressions proposed by Takao et al. (2013) distinguish between fault segments longer and shorter than 10 km. For long segments, the distributions were expressed as a function of normalized distance along the fault, with larger displacements at the center and smaller values near the tips, while for short segments a uniform pattern was assumed. In both cases, the regressions were modeled using a gamma distribution.

Petersen et al. (2011) derived their regressions using a dataset that includes displacements from nine large strike-slip earthquakes ranging from Mw 6.5 to Mw 7.6, supplemented with additional data from 13 global events compiled by Wesnousky (2008), who considered earthquakes up to Mw 7.9. The Authors presented three alternative statistical models: bilinear, quadratic, and elliptical. In the bilinear model, D/AD is fixed at 1.0 in the central portion of the fault, with two linear branches intersecting at $x/L \approx 0.3$. This formulation yields the lowest aleatory variability near the fault center but the highest variability toward the fault tips. The quadratic model represents $\ln(D/AD)$ as a second-order polynomial of x/L , while the elliptical model uses a transformed regression to approximate the displacement distribution with part of an elliptical shape. The quadratic and elliptical formulations show nearly identical levels of aleatory variability, but both provide a smoother representation of displacements along the fault.

3. RESULTS

3.1. SURE database implementation

This chapter presents a selection of preliminary outcomes from the ongoing task of implementing additional earthquake events into the SURE database. The results shown here are not intended as an exhaustive report of the entire implementation effort but rather focus on the specific subset of strike-slip events that were assigned to me within the broader set of selected earthquakes. These cases are presented to illustrate the methodological steps adopted for data integration, validation, and reclassification, and to highlight the main challenges encountered during the process.

Illustrative Example 1: The Imperial Valley Earthquake (1940)

As a first illustrative example of the procedures described above, I selected the 1940 Imperial Valley earthquake (Figure 3.1). On May 18, 1940, an earthquake of approximately magnitude 7 struck the Imperial Valley, at the border between California and Mexico. The event generated nearly 60 km of surface rupture along the Imperial fault, cutting across farmland and infrastructure. It was one of the first

major earthquakes to be recorded by strong-motion instruments, providing a unique opportunity to combine field observations with instrumental data.

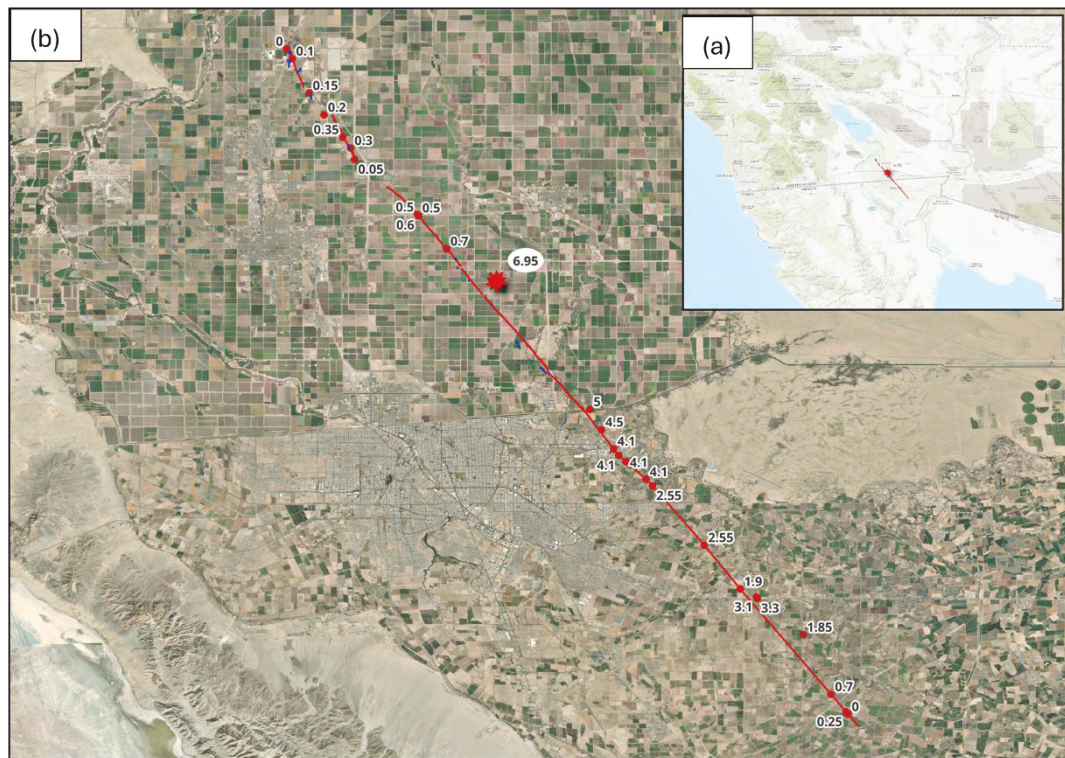


Figure 3.1 The Imperial Valley earthquake of May 18, 1940. Panel (a): location of the event at the California–Mexico border. Panel (b): detailed view of the rupture trace, with red lines indicating the principal ruptures and blue lines the distributed ruptures. Measurement points of fault-parallel slip are shown using the same color coding according to rupture rank. The red star marks the epicenter provided by the database, together with the magnitude value.

According to the FDHI project database, the bibliographic sources cited for this case are as follows:

FDHI Measurements Source:

- Rockwell and Klinger (2013)
- pers. comm., Dawson, T.

FDHI Ruptures Source:

- FDHI Manual Compilation based on: California Geological Survey (2019)
Rockwell and Klinger (2013), Trifunac and Brune (1970)

On the basis of the earlier cited works, direct field measurements were carried out within days after the earthquake, but these were sparse and mostly taken at road crossings or canals, missing the areas of maximum offset (Trifunac and Brune,

1970). Later investigations using high-resolution aerial imagery, taken soon after the event, allowed researchers to quantify offsets along a 15 km stretch of the rupture covered by the photographs. These analyses indicated an average slip of roughly 5.5 m, with peak displacements approaching 7 m (Rockwell and Klinger, 2013). Comparison with J.P. Buwalda's early field notes shows overall consistency, although the aerial imagery analyses tend to yield slightly larger values, likely because they captured the full near-fault deformation more accurately (Trifunac and Brune, 1970; Rockwell and Klinger, 2013).

Seismological investigations in the 1970s (Trifunac and Brune, 1970) demonstrated that the 1940 earthquake was not a single rupture but rather a sequence of multiple subevents, propagating southeastward along the fault. This interpretation highlighted the complexity of energy release during the mainshock. More recent geological and photogrammetric studies (Rockwell & Klinger, 2013) refined the picture of surface rupture, showing that displacement varied substantially along strike. Sharp reductions in slip were identified at specific locations, interpreted as boundaries between rupture segments. The overall evidence suggests a heterogeneous rupture process, with highly variable slip distribution and shallow asperities at the surface that may not directly correspond to the zones of largest moment release at depth.

During the import of measurement point from FDHI, all entries flagged with *rank cumulative* (Figure 3.2, Figure 3.3) were provisionally excluded, as this information is not compatible with the SURE schema.

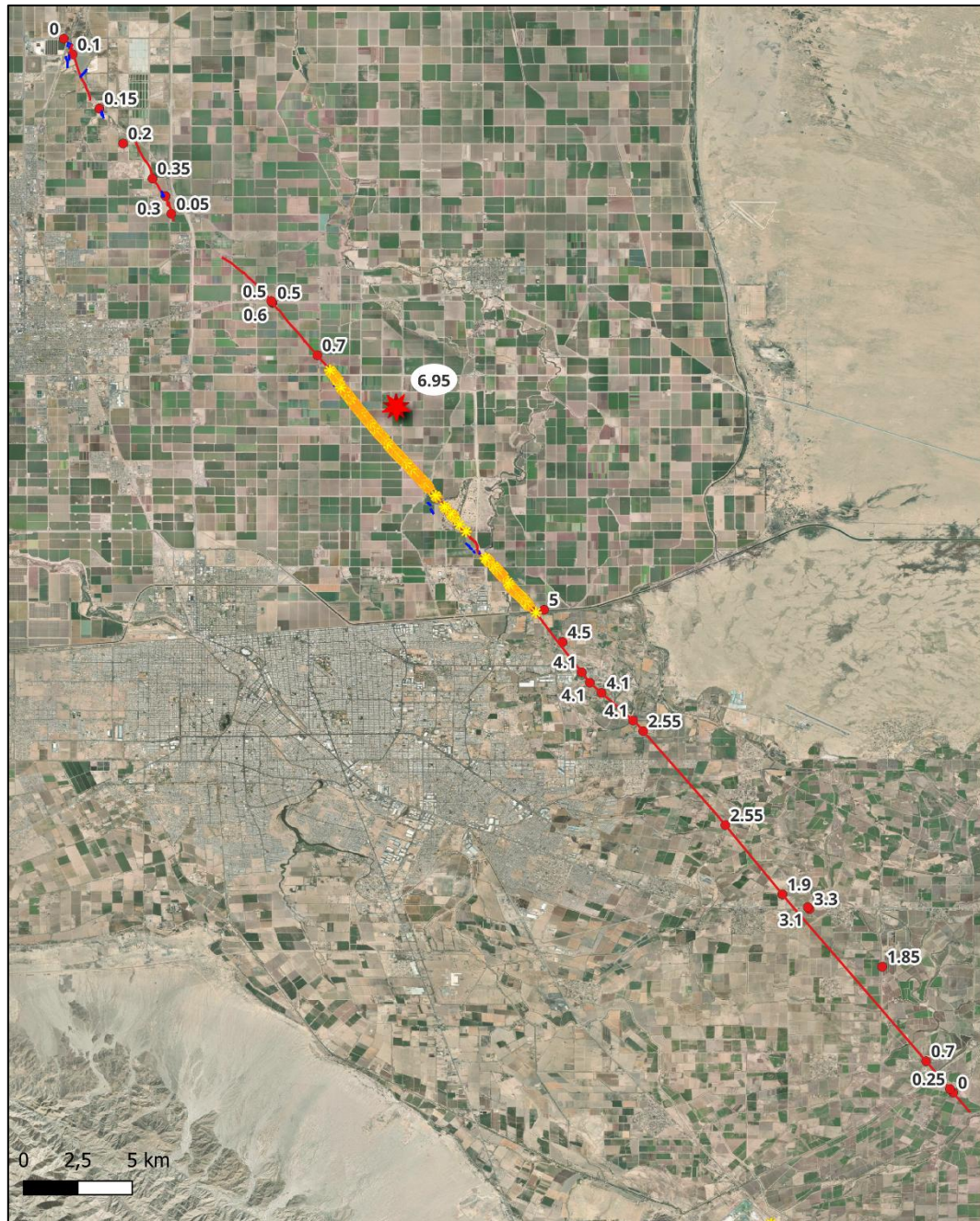


Figure 3.2 Detail along the rupture trace of the Imperial Valley earthquake (May 18, 1940, $M_w \approx 7$), showing the measurement points positioned along the fault. Points marked with yellow stars indicate the entries flagged with cumulative rank.



Figure 3.3 Detail along the rupture trace of the Imperial Valley earthquake (May 18, 1940, $M_w \approx 7$), showing the measurement points positioned along the fault. Points marked with yellow stars indicate the entries flagged with cumulative rank.

In a subsequent step, discrepancies between the ranking assigned to measurement points and the classification of their associated rupture traces were identified and corrected. In addition, a relocation procedure was applied to a number of measurement points that were not positioned precisely on the mapped rupture traces (Figure 3.4).

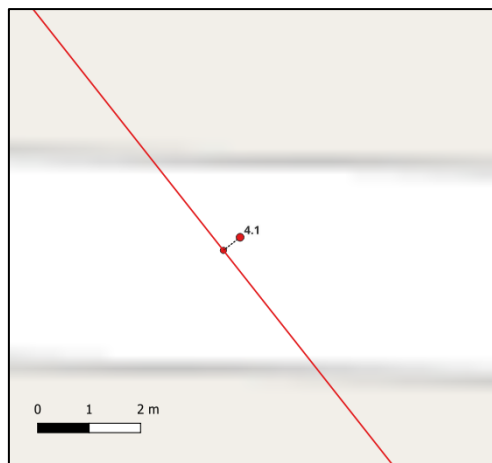


Figure 3.4 Examples of the relocation procedure applied to measurement points that were not originally positioned precisely on the mapped rupture traces.

Finally, several points (Figure 3.5) classified with a *principal* ranking were identified as being located along roadways; however, they were not linked to any rupture trace, a condition that required further consideration within the data migration assessment.

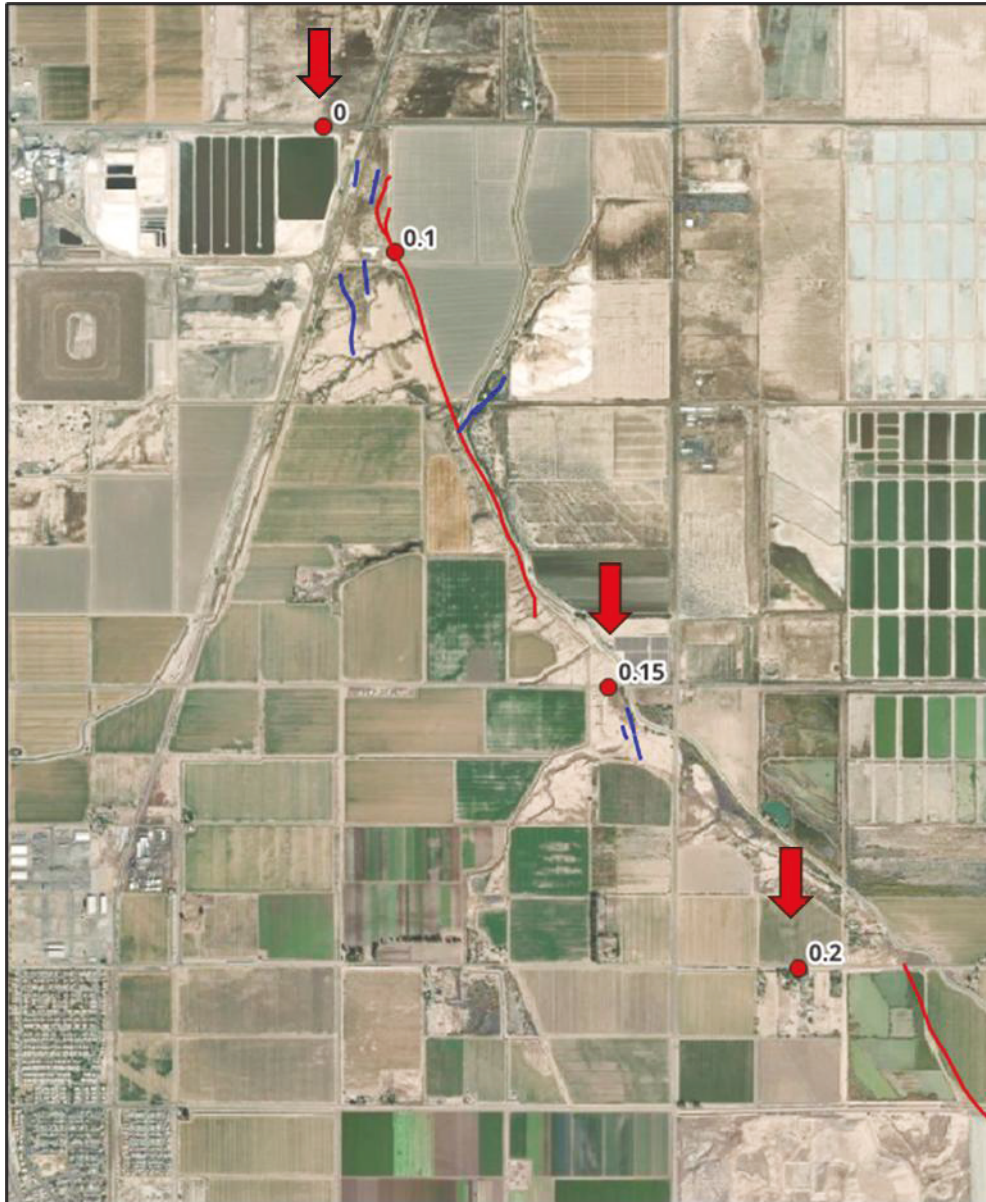


Figure 3.5 Examples of measurement points assigned a principal ranking that were mapped along roadways without direct connection to rupture traces.

In general, the classification provided by the FDHI project database for distinguishing between principal and distributed ruptures was confirmed during the process. Through the analysis of the mapped features in GIS and the consultation

of the available references, no rupture segments were identified that could be considered suitable for reclassification into a 1.5 ranking.

Illustrative Example 2: The Chalfant Valley Earthquake (1986)

The second example regards the Chalfant Valley earthquake sequence occurred in July 1986, north of the town of Bishop, California, within the Volcanic Tableland and adjacent to the White Mountains Fault Zone (WMFZ), in the western Basin and Range Province (Figure 3.6). The mainshock reached Ms 6.2 (NEIS, 1986a; de Polo and Ramelli, 1987) and was followed by four additional events with magnitudes above Ms 5.

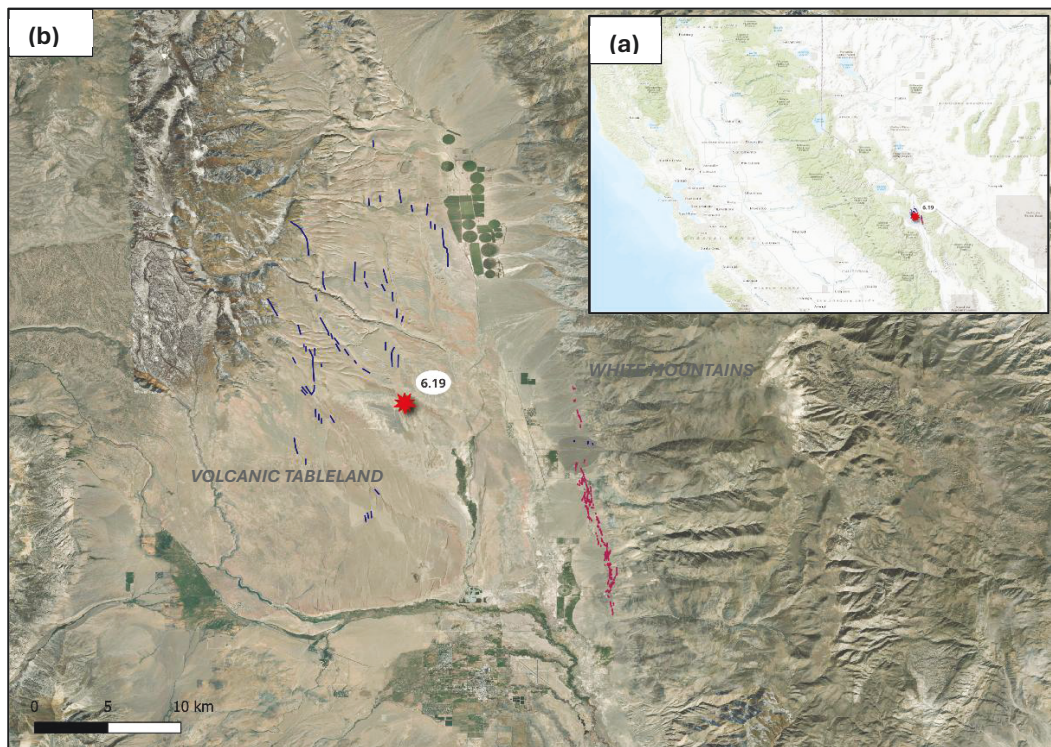


Figure 3.6 The Chalfant Valley earthquake sequence of July 1986, north of Bishop, California, in the western Basin and Range Province. Panel (a): location of the sequence in eastern California. Panel (b): detailed view of the mapped rupture traces, with red lines indicating the principal ruptures and blue lines the distributed ruptures. Measurement points are shown using the same color coding according to rupture type. The red star marks the epicenter provided by the database, together with the magnitude value.

The FDHI project database indicates the following sources for this event:

Measurements Source:

- Kahle et al. (1986)
- Lienkaemper et al. (1987)

FDHI Ruptures Source:

- FDHI Manual Compilation based on: Lienkaemper et al. (1987); dePolo and Ramelli (1987)

Field investigations initiated immediately after the mainshock documented extensive but small-scale surface rupturing. Along the WMFZ (Figure 3.6 b), fractures were mapped for a total length of about 15 km, including a continuous zone of approximately 10 km from Silver Canyon to Piute fan, and additional discontinuous breaks farther north (dePolo & Ramelli, 1987). The kinematics of these fractures indicated normal right-lateral oblique displacement, consistent with the orientation of the WMFZ relative to the regional stress regime (dePolo & Ramelli, 1987).

Measured displacements were generally small, typically only a few millimeters to a few centimeters, with localized offsets of up to ~4–5 cm. In rare cases, displacements reached ~15 cm, though these values were likely enhanced by gravitational or shaking effects rather than purely coseismic motion (dePolo & Ramelli, 1987). In the Volcanic Tableland (Figure 3.7 a), the rupture pattern was more complex, consisting of en-echelon, sinistral fractures developed in unconsolidated deposits, where apertures of 1–5 cm were observed (Lienkaemper et al., 1987). Because of the loose nature of the sediments, many of these features were short-lived and rapidly degraded by wind and rain (Lienkaemper et al., 1987).

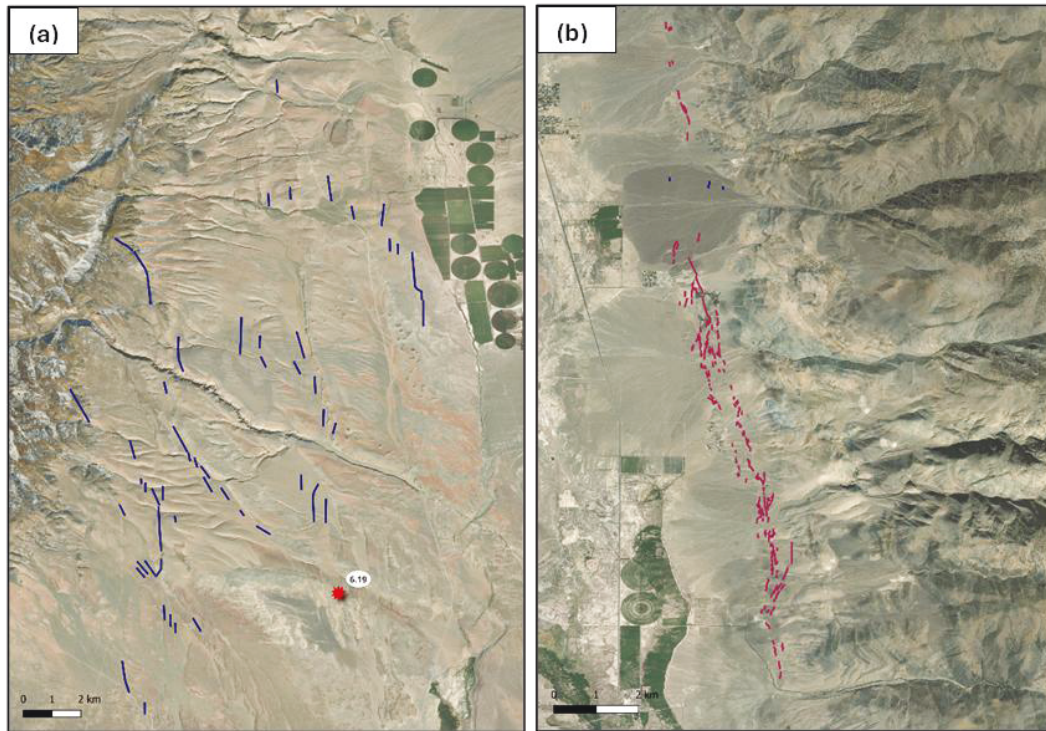


Figure 3.7 Detail of rupture traces from the Chalfant Valley earthquake sequence (July 1986). Panel (a): rupture pattern within the Volcanic Tableland. Panel (b): rupture traces associated with the White Mountains Fault Zone (WMFZ).

Field teams from the USGS, the California Division of Mines and Geology, and the University of Nevada-Reno measured slip along individual fractures. Right-lateral displacements up to 4.6 cm were reported in en-echelon sets along the WMFZ (dePolo & Ramelli, 1987). Some fractures were noted to have propagated progressively after the mainshock, possibly associated with aftershocks such as the Ms 5.2 event of 31 July (NEIS, 1986b), suggesting that the surface expression of rupture evolved over several days (dePolo & Ramelli, 1987).

A *snapping* procedure was applied to adjust measurement points that were located outside the mapped rupture trace. Additional verification was necessary for some points positioned a few hundred meters away from the fault trace, to ensure proper association. It should be noted that no slip values are available for the fractures classified as *distributed*.

With regard to rupture classification, no modifications were introduced to the principal ranking proposed by the FDHI project database.

Furthermore, the digitalization of a continuous rupture trace was proposed to replace the fragmented geometry provided in the FDHI dataset. This fragmentation is likely the result of the seismogenic source being located at depth, which in such cases may limit the expression of a clear and continuous principal rupture at the surface.

3.2. PFDHA sensitivity analysis

In the following sections, the results of the performed OAT sensitivity analysis are presented. The hazard curves obtained for each of the considered fault kinematics are illustrated, together with the differential percentage (PD) calculated with respect to the chosen baseline. The hazard curves are displayed in logarithmic space and, in general, they show two distinct regions: a plateau for smaller displacements (i.e., less than about 10 cm), where the annual frequency of exceedance (AFOE) remains nearly constant, and a negative sloped region (or tail region) for larger displacements, where the AFOE decreases with increasing displacement.

Overall, the resulting hazard curves show that the choice among the tested parameters exert different controls on the two regions: magnitude–area scaling laws, MFD, and PSR equations predominantly influence the plateau region, whereas $AD|m$ and D/AD regressions mainly affect the tail region.

m|area scaling laws

The use of the $m|area$ scaling laws indicates that, for normal faulting, some relationship (e.g., Shaw, 2023 – Ellsworth-B & C; Leonard, 2010) produce nearly constant but negative PD values (about -12% and -22%) at small displacements. Around ~1 m of displacement, the curves intersect the baseline (i.e., a “crossover”, hereafter) and beyond this point they diverge toward progressively larger positive PD values. In contrast, the formulation of Thingbaijam et al. (2017) shows the opposite trend, although the crossover occurs at approximately the same displacement (Figure 3.8 a).

A similar pattern is observed for strike-slip kinematics, although the crossover is positioned at lower displacements, on the order of a few decimeters (Figure 3.8 e).

Reverse faulting simulations, instead, produce a markedly different result, with PD values remaining nearly constant across the entire displacement range (Figure 3.8 d). Among the considered models, the Leonard (2010) equation shows the closest agreement with the baseline for normal and strike-slip simulations. For reverse faulting, instead, the simulation based on the Shaw (2023 – Ellsworth-C) formulation shows the closest consistence with the baseline. Overall, PD ranges from about +100% to –50% for normal faulting (Shaw, 2023 – Ellsworth-B and Thingbaijam et al., 2017, respectively), from +45% to –45% for strike-slip (Shaw, 2023 – Ellsworth-B and Thingbaijam et al., 2017, respectively), and between +10% and –10% for reverse kinematics (Leonard, 2010 and Shaw, 2023 – Ellsworth B).

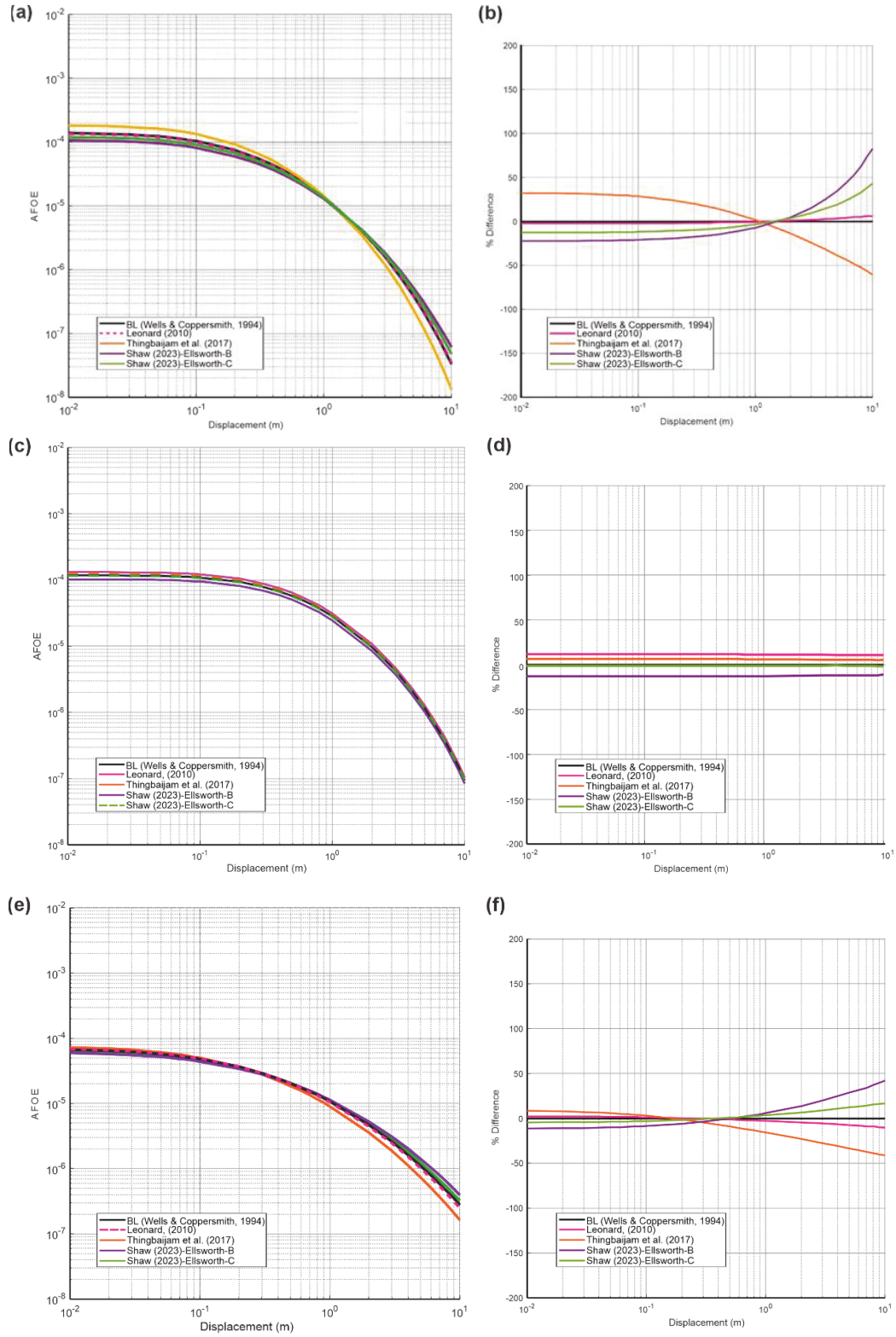


Figure 3.8 Hazard curves (left) and percentage differences (right) for scaling laws of magnitude with respect to area. Panels a-b refer to normal kinematic simulations, panels c-d refer to reverse kinematic simulations and panels e-f refer to strike slip kinematic simulations.

Magnitude-frequency distribution models

The PD curves obtained using alternative MFD models display trend, when referenced to the baseline, comparable to those discussed above. For normal and strike-slip simulations, the crossover occurs at displacements of about 1 m (Figure 3.9 b) and ~10 cm (Figure 3.9 f), respectively. In contrast, reverse-faulting scenarios result in nearly constant PD values over the entire displacement interval (Figure 3.9 d). Across all three kinematic simulations, the largest deviations from the baseline (i.e., PD up to ~60%) arise from simulations adopting the maximum magnitude distribution (Wesnousky et al., 1986), while the Youngs and Coppersmith (1985) model produces outcomes more consistent with the truncated Gutenberg–Richter distribution.

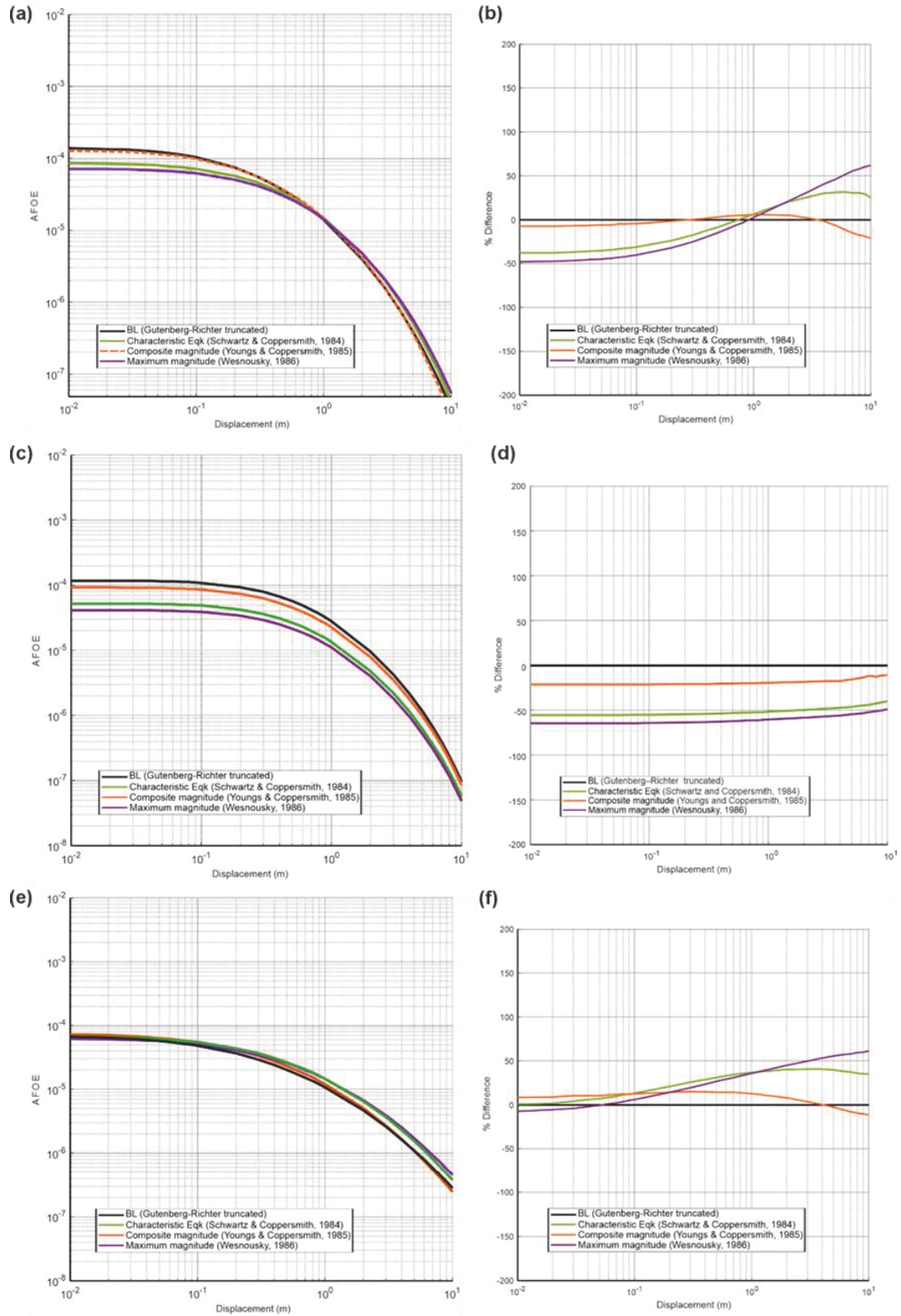


Figure 3.9 Hazard curves (left) and percentage differences (right) for magnitude-frequency distribution (MFD). Panels a-b refer to normal kinematic simulations, panels c-d refer to reverse kinematic simulations and panels e-f strike refer to slip kinematic simulations.

Probability of surface rupture (PSR) equations

By testing different PSR equations, the simulation outputs yield nearly constant PD curves for normal faulting (ca. 35% for Pizza et al., 2023; Figure 3.10 b) and reverse kinematics (from 40% for Yang et al., 2021 to –60% for Pizza et al., 2023; Figure 3.10 d). In strike-slip simulations (Figure 3.10 f), the relations proposed by Moss et al. (2013) lead to convergence at larger displacement values, with PD decreasing from ca. 180% to 21% under stiff conditions and from ca. 144% to 10% under soft conditions. Conversely, the Takao et al. (2023) equation yields persistently negative PD values, close to –30%.

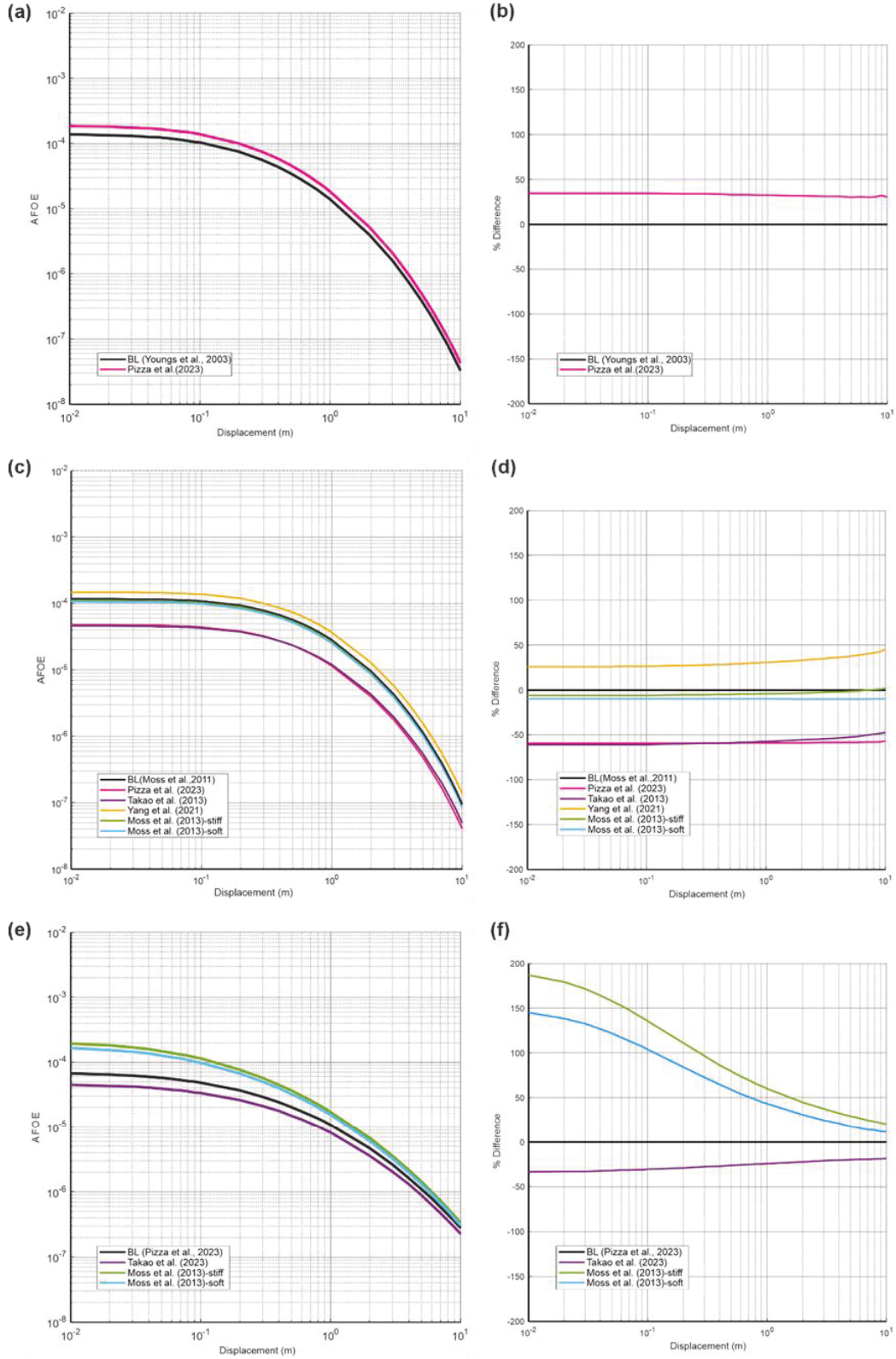


Figure 3.10 Hazard curves (left) and percentage differences (right) for probability of surface rupture (PSR). Panels a-b refer to normal kinematic simulations, panels c-d refer to reverse kinematic simulations and panels e-f refer to strike slip kinematic simulations.

AD|m regressions

Simulations employing different AD|m equations reveal comparable trend for both normal and reverse faulting (Figure 3.11 b, d). At displacements below 0.1 m, the PD is essentially negligible. As displacement increases, however, PD progressively decrease toward more negative values, reaching approximately –100% before stabilizing between –1 and –2 m.

In the case of strike-slip kinematics (Figure 3.11 f), the PD curves diverge relative to the baseline depending on the adopted equation. For displacements exceeding a few centimeters, the equation after Takao et al. (2013) departs toward strongly positive values, surpassing 100%, whereas the regression by Thingbaijam et al. (2017) records a relative maximum around +25% before declining to negative values (ca. –45%), crossing the baseline at roughly 2 m of displacement.

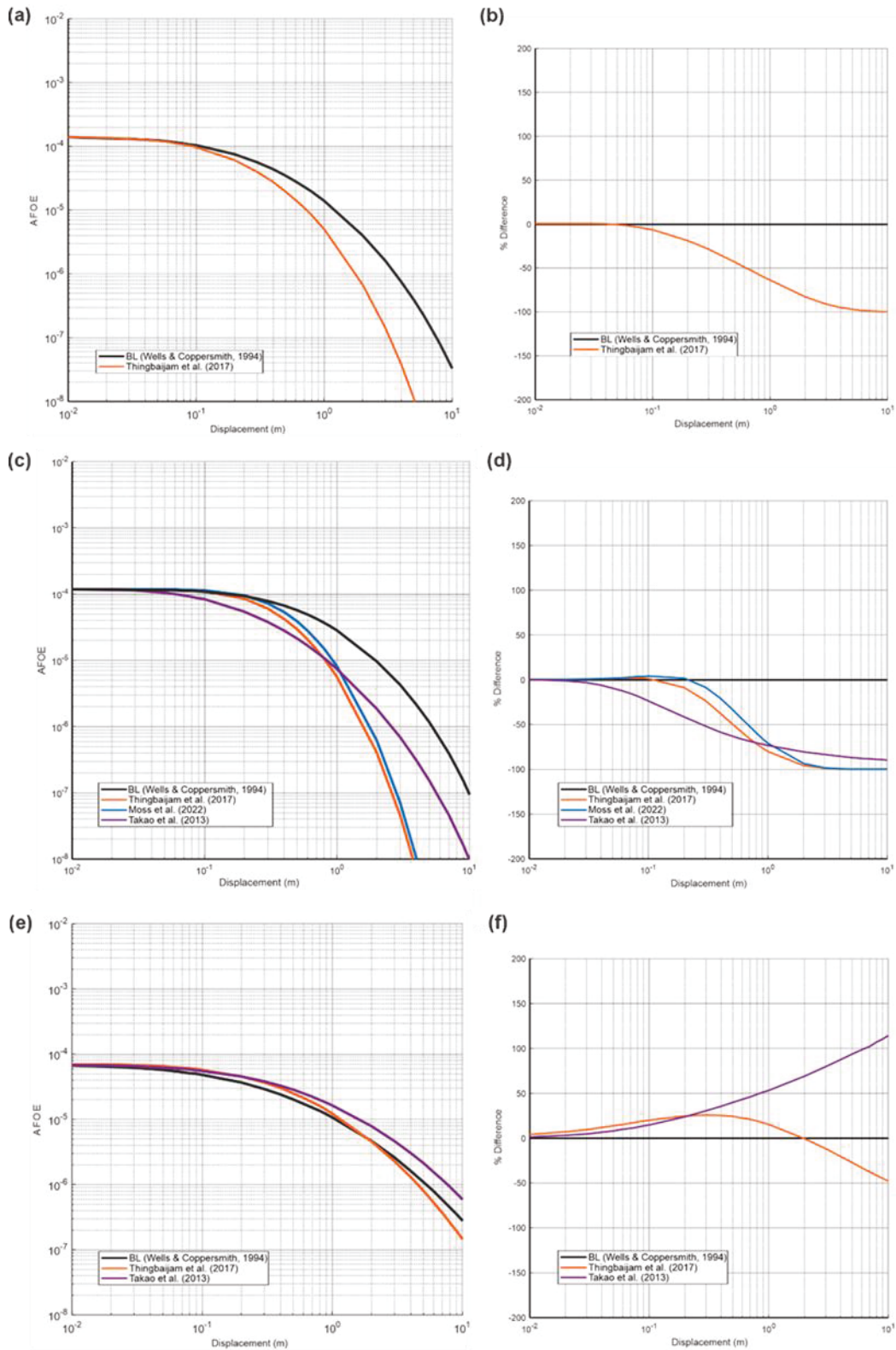


Figure 3.11 Hazard curves (left) and percentage differences (right) for average displacement for a given earthquake magnitude (AD|m). Panels a-b refer to normal kinematic simulations, panels c-d refer to reverse kinematic simulations and panels e-f refer to strike slip kinematic simulations.

D/AD models

The sensitivity analysis related to the adopted D/AD equations could be performed only for simulations involving reverse and strike-slip kinematics (Table 2.2).

For reverse faulting, the curves exhibit low differential values for displacements below ca. 10 cm (Figure 3.12 d), followed by a progressive divergence toward increasingly positive PD values at larger displacements. The formulation proposed by Takao et al. (2013) for fault segments exceeding 10 km has a particularly strong influence on the PD curve at large displacements, producing PD values greater than 300%.

For strike-slip kinematics, the tested formulations display more scattered trends, mostly skewed toward negative PD values (Figure 3.12 f). The equations after Takao et al. (2013) generate small positive PD values at small displacements but then diverge toward –100% with increasing displacement. Conversely, the quadratic and elliptical models proposed by Petersen et al. (2011) yield negative PD values (as large as –30%) across a broad displacement range, before gradually converging back to the baseline at higher displacements.

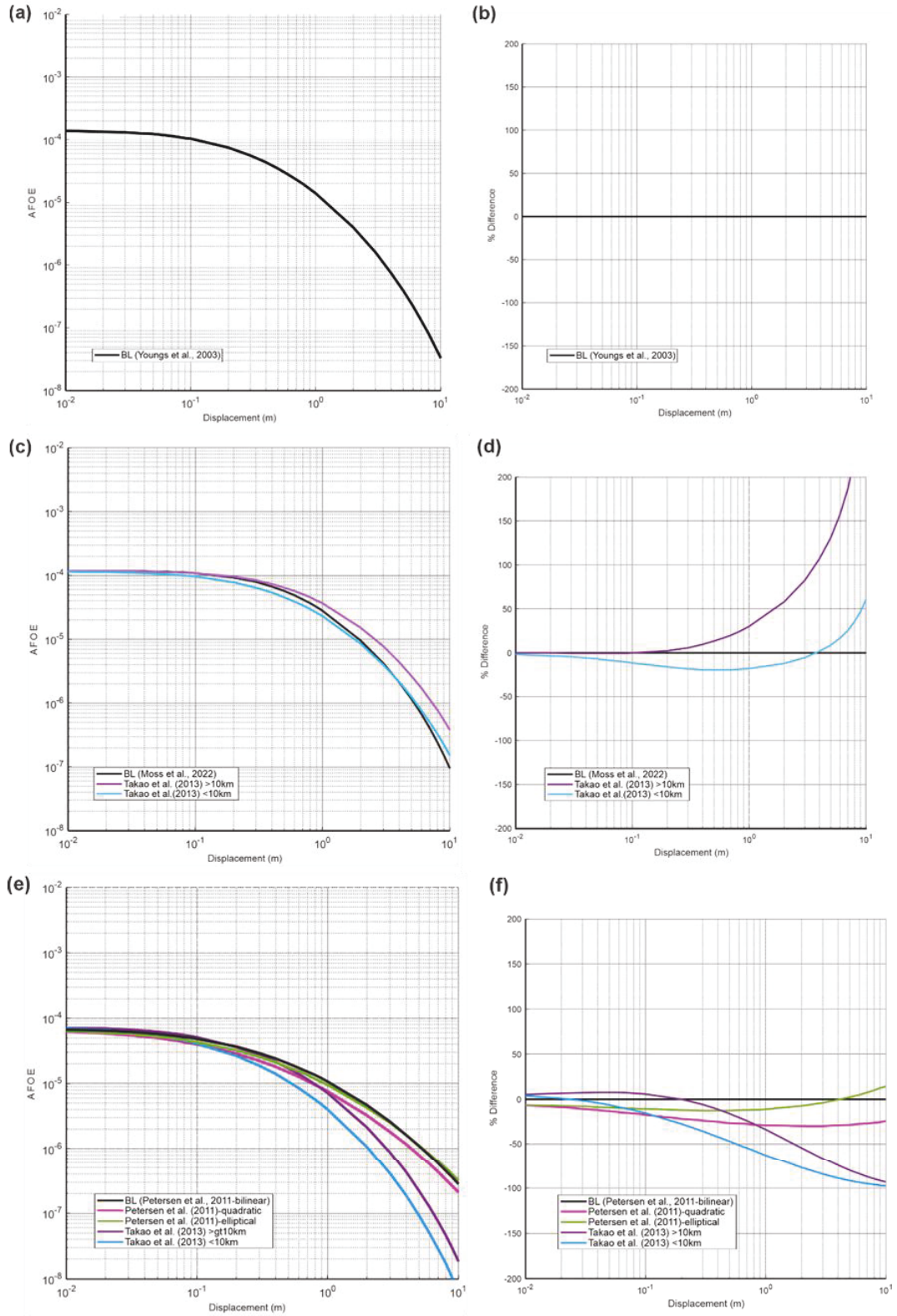


Figure 3.12 Hazard curves (left) and percentage differences (right) for displacement to average displacement ratio (D/AD). Panels a-b refer to normal kinematic simulations, panels c-d refer to reverse kinematic simulations and panels e-f refer to strike slip kinematic simulations.

4. DISCUSSION

4.1. SURE database implementation

The considerations presented in this chapter should be regarded as preliminary observations and exploratory operations, rather than definitive outcomes. The examples discussed do not aim to provide a comprehensive treatment of all cases encountered during the ongoing integration of FDHI data into the SURE database. Instead, they illustrate a selection of representative situations that highlight the main methodological issues raised during the review and data preparation process. By focusing on these case studies, the discussion emphasizes the practical challenges of handling rupture trace geometries, associating displacement measurements, and treating cumulative data, while also suggesting possible approaches that may be further evaluated and refined in future stages of the work.

Handling measurement points not directly associated with rupture traces

The first methodological issue concerns the treatment of measurement points that are not directly located on a mapped rupture trace. In several cases, a small offset between the point and the adjacent rupture can plausibly be explained by digitization inaccuracies or by the resolution of the original cartographic products. Under such circumstances, relocating (“*snapping*”) the point onto the nearby rupture trace appears to be a reasonable correction. Conversely, when the distance between the point and the rupture is significant (on the order of tens of meters or more), this operation introduces an artificial association. In these cases, a more suitable approach would be to create short rupture segments in correspondence with the isolated measurement points. This approach allows the observation to be retained in the database by creating short rupture segments that carry the same rank as the associated measurement point. In this way, the completeness of the dataset is preserved, while at the same time the rupture mapping is refined using guidance from published maps and high-resolution satellite imagery.

Re-evaluating rupture geometries

The GIS-based review further indicated that in some cases the mapped rupture traces may require re-evaluation. Certain events show traces that appear overly simplified compared to the geomorphic evidence of coseismic deformation or markedly discontinuous. The Chalfant Valley earthquake case, discussed in Section 2.1, is one example. In such instances, revising rupture geometries necessitate the use of high-resolution imagery to identify geomorphic indicators that can guide the editing of new linework. However, this process inevitably involves interpretative choices. For this reason, it is recommended that such modifications be carried out in consultation with experienced professionals who can validate the geological plausibility of the revised traces.

Treatment of cumulative-rank measurements

Another important issue relates to the management of displacement measurements categorized in the FDHI database as cumulative rank. Excluding this data during import would result in the loss of a substantial body of information for several earthquakes. By definition, cumulative measurements represent aggregated offsets across multiple principal rupture strands and/or the inclusion of distributed off-fault deformation. For this reason, they cannot be reassigned to individual traces classified as principal or distributed. A possible solution would be to create a dedicated field in the SURE database to retain and systematically document cumulative data. This would preserve the integrity of the original datasets while allowing future users to decide on their inclusion or exclusion depending on the modeling context.

Re-evaluation of rupture traces with Rank 1.5

Another aspect that emerged during the review concerns the possible reclassification of some FDHI rupture traces as Rank 1.5 features. This is not a straightforward operation and must be considered with caution. The decision is often debated and should only be validated when supported by comprehensive geological and geomorphological information. In particular, relevant indicators include the presence of geometric or structural continuity with the main fault,

displacement values that are relatively higher than those observed in nearby distributed ruptures, and evidence of a pre-existing fault trace. Such traces may be recognized from geological maps, geomorphological markers, or detailed field investigations. In practice, such evaluations require cross-checking the traces with published literature, geological maps, and satellite imagery, as well as extracting supporting information directly from the database (e.g., displacement magnitudes, rupture continuity). Only when these multiple lines of evidence converge can the reclassification to Rank 1.5 be considered justified.

4.2. PFDHA sensitivity analysis

This section examines the differences among the functional forms adopted in the OAT sensitivity analysis, with the objective of identifying the potential factors responsible for variations in the AFOE.

Impact of the $m|area$ scaling laws

A key factor influencing the hazard curves is the selected $m|area$ scaling law (Figure 4.1), which directly affects the maximum magnitude estimated for a given fault size and kinematics.

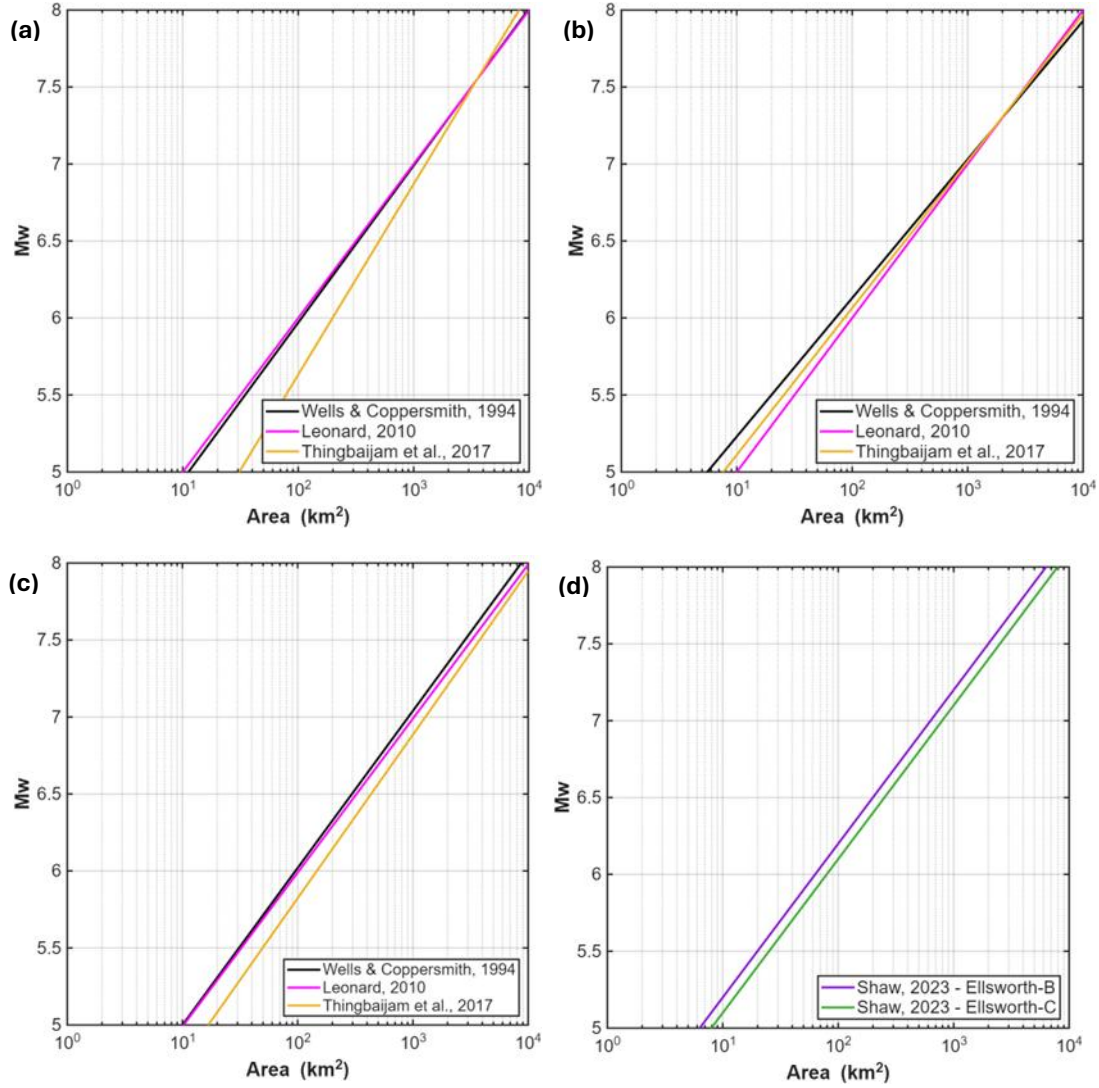


Figure 4.1 Comparison of regressions, considered for this work, between magnitude and area applicable to normal (panel a), reverse (panel b), strike slip (panel c) kinematics and specifically derived for Plate Boundary Faults (panel d).

Among the tested relations, Thingbaijam et al. (2017) systematically provide lower maximum magnitudes for both normal and strike-slip faulting. This outcome likely reflects the deviation of their model from self-similar scaling (Thingbaijam et al., 2017), that may explain the systematic underestimation of magnitude for a given rupture area. In contrast, Shaw (2023, Ellsworth-B model) yields the highest maximum magnitudes. These differences are manifest in turn, in different earthquake magnitude intervals, over which the MFDs are tested.

For normal and strike-slip kinematics (Figure 3.8 a, e), the curves show a crossover at approximately 1 m of displacement. At smaller displacements, the AFOE from

Thingbaijam et al. (2017) is comparatively higher, while at larger displacements Shaw (2023) is higher.

Consequently, the hazard curves display a distinct crossover of the Thingbaijam et al. (2017) curve relative to the others, located at ca.1 m of displacement. At small displacements (i.e., <1 m), the lower maximum magnitude predicted by Thingbaijam et al. (2017) results in higher earthquake rates, as the hazard is primarily controlled by frequent, lower-magnitude events. In contrast, for larger displacement values (>1 m), the higher maximum magnitudes from the other scaling relations produce higher AFOE values, since they incorporate less frequent but larger earthquakes capable of generating remarkable displacements.

Moreover, all the terms involved in PFDHA calculation highlights how the contribution of large-magnitude events to small displacements is limited, as large ruptures are more likely to produce higher displacements, whereas many small events dominate the hazard for low displacements, resulting in the higher rates after Thingbaijam et al. (2017).

The sensitivity analysis testing the magnitude–area relationships is being conducted by consistently applying the same magnitude–frequency distribution (i.e., truncated Gutenberg–Richter model). The probability density function, $f_n(m)$, decreases pointwise as the interval spanning the minimum to maximum magnitude widens. This occurs because the denominator increases with the range of magnitudes, effectively distributing the same total probability mass over a broader domain.

For reverse-faulting scenarios (Figure 3.8Figure 3.8 c), these differences are much less pronounced, as the maximum magnitudes predicted by the different equations are more consistent across the various formulations.

Impact of MFD models

For normal and strike-slip cases (Figure 3.9 a, e), the application of the maximum-magnitude model, expressed as a Gaussian distribution around the characteristic magnitude(Figure 4.2), leads to the greatest AFOE at larger displacements, owing to its preferential weighting toward large-magnitude events. A similar outcome is

obtained by applying the characteristic earthquake model (Schwartz & Coppersmith, 1984), which also yields elevated hazard estimates at large displacements, as it concentrates a significant portion of the seismic budget on events around the characteristic magnitude value up to the maximum magnitude.

In contrast, the composite magnitude model (Youngs and Coppersmith, 1985) results in comparatively lower AFOE values at large displacements. This behavior arises because the model allocates most of the seismicity budget around the characteristic event without achieving the maximum magnitude, (i.e., point-mass distribution of seismic frequency).

The truncated Gutenberg–Richter model predicting the highest hazard levels at small displacements but lower probabilities for larger displacements.

Although a direct comparison across the three kinematic settings should be treated cautiously, given that the baseline assumptions differ, it is worth highlighting the specific outcome of reverse-faulting simulations (Figure 3.9 c). While normal and strike-slip kinematics exhibit broadly similar responses across the tested MFD models, the reverse faulting simulations yield a nearly constant PD over the entire displacement interval (Figure 3.9 d).

A plausible explanation for this discrepancy lies in the role of the AD|m models used as baselines. In particular, the Wells and Coppersmith (1994) AD|m scaling law for reverse faulting produces a less steep increase of average displacement with increasing magnitude compared to the other kinematics. As a result, the contribution of small-to-moderate events is amplified, while the relative impact of large-magnitude earthquakes is diminished.

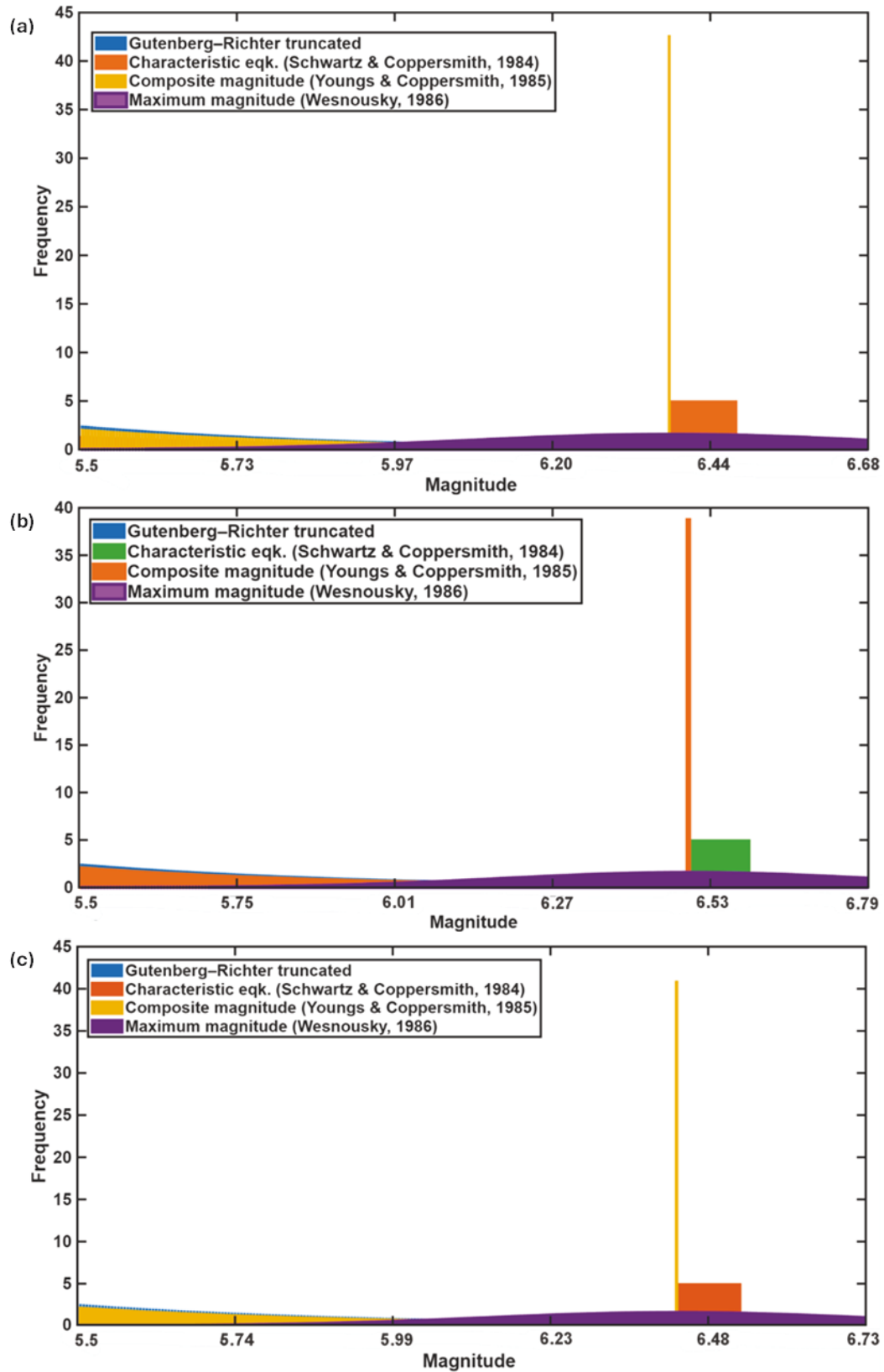


Figure 4.2 Comparison of magnitude–frequency models used in the sensitivity analysis, considering the interval of magnitude values (m_{min} – m_{max}) adopted for the calculations, for normal (panel a), reverse (panel b), and strike-slip (panel c) kinematics.

Impact of the PSR equations

The influence of the PSR equation on the hazard curve appears truly remarkable in the case of strike-slip simulations for small displacement to be exceeded, where PD values can rise to nearly 150% (Figure 3.10 f). Unlike this, in most cases, deviations hover around 50%, with PD exhibiting an almost constant trend relative to the baseline. For normal-faulting simulations, the regression after Pizza et al. (2023) systematically results in higher AFOE compared to the widely adopted Youngs et al. (2003) model, across the considered magnitude range (Figure 3.10 a).

The calculated PD is primarily controlled by the shape of the logistic curve (Figure 4.3) described by each PSR formulation.

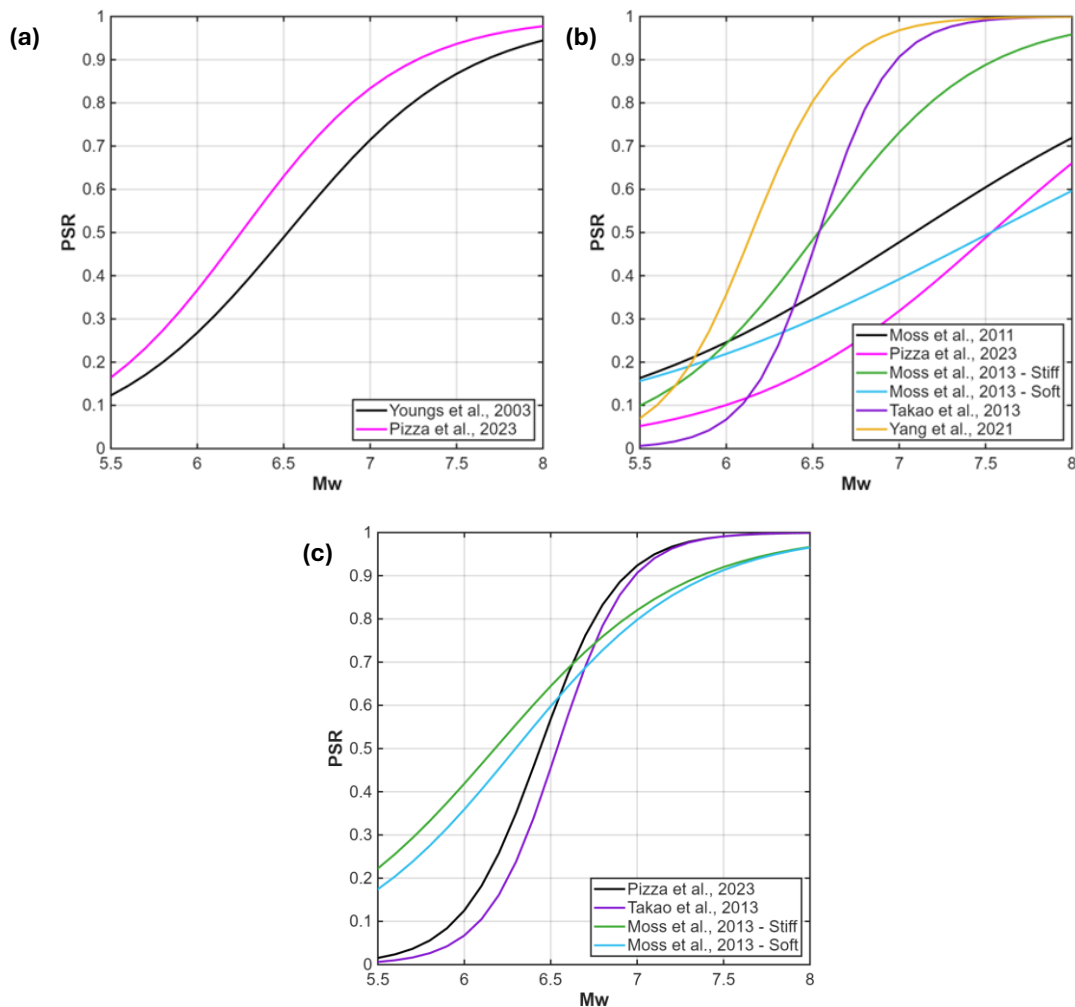


Figure 4.3 Comparison of probability of primary surface rupture curves at a given moment magnitude considered for the sensitivity analysis for normal (panel a), reverse (panel b), strike slip (panel c) kinematics.

The position of the inflection point of the logistic function exerts the strongest influence on the hazard curves, while the background probability of rupture associated with very low-magnitude earthquakes (i.e., around $m=5.5$ in the present simulations) provides a secondary effect. Lower inflection magnitude values combined with higher background probabilities systematically lead to higher AFOE values.

A further aspect concerns the comparison, performed in this sensitivity analysis, between global and region-specific regressions. Regionally calibrated equations generally display steeper slopes than global formulations, which combine datasets from diverse tectonic contexts (e.g., variability in seismogenic thickness or fault dip angle). Beyond empirical regressions, numerical modeling (Mammarella et al., 2024) or earthquake-cycle simulations (Gomez-Novell et al., 2025) represent promising alternatives to empirical models.

Impact of the $AD|m$ regressions

The $AD|m$ relations employed in the reverse-faulting simulations follow loglinear functions (Figure 4.4), whose coefficients and standard deviations strongly shape the resulting hazard curves. Although their influence is negligible for small displacement thresholds, the effect becomes increasingly evident at larger displacements, (i.e., in the tail region).

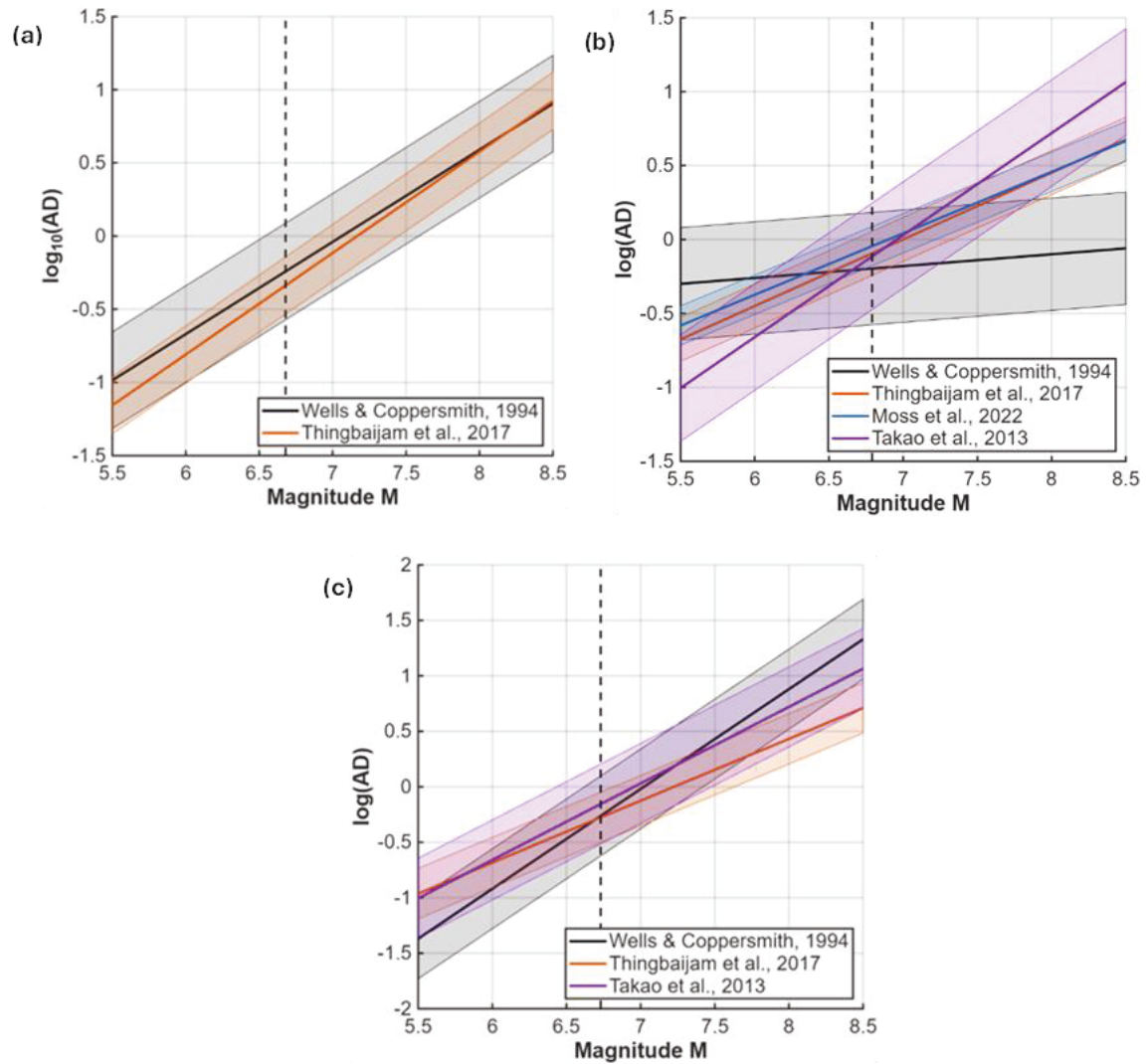


Figure 4.4 Comparison of loglinear relations between average displacement (AD) and magnitude for normal (panel a), reverse (panel b), strike slip (panel c) kinematics. Solid lines represent the linear fits for the models considered for the sensitivity analysis. Shaded areas indicate one standard deviation. The dashed vertical line marks the maximum magnitude calculated for each kinematic setting using the scaling relationships of Wells and Coppersmith (1994).

The Wells and Coppersmith (1994) scaling low produces considerably higher hazard level at large displacements than more recent models (e.g., Thingbaijam et al., 2017; Moss et al., 2022). This can be attributed to its larger associated standard deviation, which allows for the inclusion of extreme displacement values. Among the considered relations, Takao et al. (2013) hazard curve occupies an intermediate position. Although its predicted AD is lower at small magnitudes than other regressions, the faster growth of its loglinear functions with magnitude (Figure 4.4) partially compensates for the initial underestimation. By contrast, Thingbaijam et al. (2017) and Moss et al. (2011), both defined by smaller standard deviations, exhibit

steeper tails beyond ca. 10^{-1} m, implying a lower probability of very large displacements (Figure 3.10 c).

Despite these differences identified at high displacements, the hazard curves derived from all the regressions tend to converge for small displacement values, in the plateau region. This convergence is expected, since all the scaling laws and their associated uncertainties largely overlap, thereby minimizing differences in the hazard curve representation.

A similar effect to that observed in the reverse faulting simulations is also evident in the normal faulting case, when comparing the curves derived from the scaling relationships after Wells and Coppersmith (1994) and Thingbaijam et al. (2017). In both situations, the curves converge at small displacement values, leading to a minimization of PD. At larger displacements, however, the Wells and Coppersmith (1994) scaling law yields considerably higher hazard levels, a behavior primarily driven by its larger associated standard deviation.

Regarding the simulations for strike-slip faulting, another set of loglinear functions was evaluated. Takao et al. (2013) regression predicts the largest displacements for the considered magnitude interval, resulting in higher AFOE at moderate to large displacements compared to the Wells and Coppersmith (1994) model. Thingbaijam et al. (2017) predicts intermediate AFOE values, with its relatively small standard deviation helping to counterbalance the effects of aleatory uncertainty (Figure 3.10 e). Overall, the results indicate that the dominant source of differences in the hazard curves is the choice of AD|m regression parameters rather than their associated standard deviations. This is illustrated by the contrast between Wells and Coppersmith (1994) and Takao et al. (2013), which share identical standard deviations yet produce the largest differences.

It should also be noted that, as shown in Fig. 3.11, although the Thingbaijam et al. (2017) regressions are defined in terms of average displacement over the whole source, the resulting hazard curves sometimes exhibit lower hazard levels than those obtained using the other tested regressions. A possible explanation may be

related to the geostatistical approach adopted (see Thingbaijam et al., 2016) to characterize rupture dimensions, which are inferred from the autocorrelation width of the spatially variable slip distribution. Under this approach, if a fault hosts multiple, spatially separated asperities, the source average slip is computed over an effective rupture area that can include large portions of the fault plane between the asperities, where slip is very low or nearly zero. As a result, the average displacement over the whole source may be reduced, even when peak slip on the asperities is significant, potentially contributing to the lower hazard levels obtained with the Thingbaijam-based regressions in some cases.

In the following figures (Figure 4.5, Figure 4.6, Figure 4.7, the graphical comparison between theoretical and simulated probability density functions (PDFs) of average displacement (AD) provides a direct illustration of the performance of the different AD|m scaling models across the three kinematic settings (normal, reverse, and strike slip faulting). For each selected magnitude ($m = 5.5, 6.0, 6.3, 6.5$, and 6.7), PDFs were computed analytically by assuming a lognormal distribution of AD, parameterized using the regression coefficients and standard deviations of each model. In parallel, Monte Carlo simulations were performed by sampling truncated lognormal distributions (± 3 SD) using the *trlrnd* MATLAB routine, in order to reproduce the expected variability while excluding unrealistically extreme values.

The resulting plots show, for each magnitude and kinematic style, both the continuous theoretical PDF and the simulated distribution represented by normalized histograms. The theoretical curves and simulations coincide very well, confirming that the *trlrnd* MATLAB procedure correctly samples from the truncated lognormal distribution. As magnitude increases, the distributions systematically shift toward larger displacement values, reflecting the scaling of AD with earthquake size magnitude. Furthermore, models associated with larger standard deviations (e.g., Wells and Coppersmith, 1994, or Takao et al., 2013) exhibit broader PDFs, indicating greater dispersion and an increased probability of extreme displacement values. This dual representation allows a direct evaluation of the impact of the different regression models on the probability of displacement and

highlights the consistency between analytical expectations and stochastic sampling.

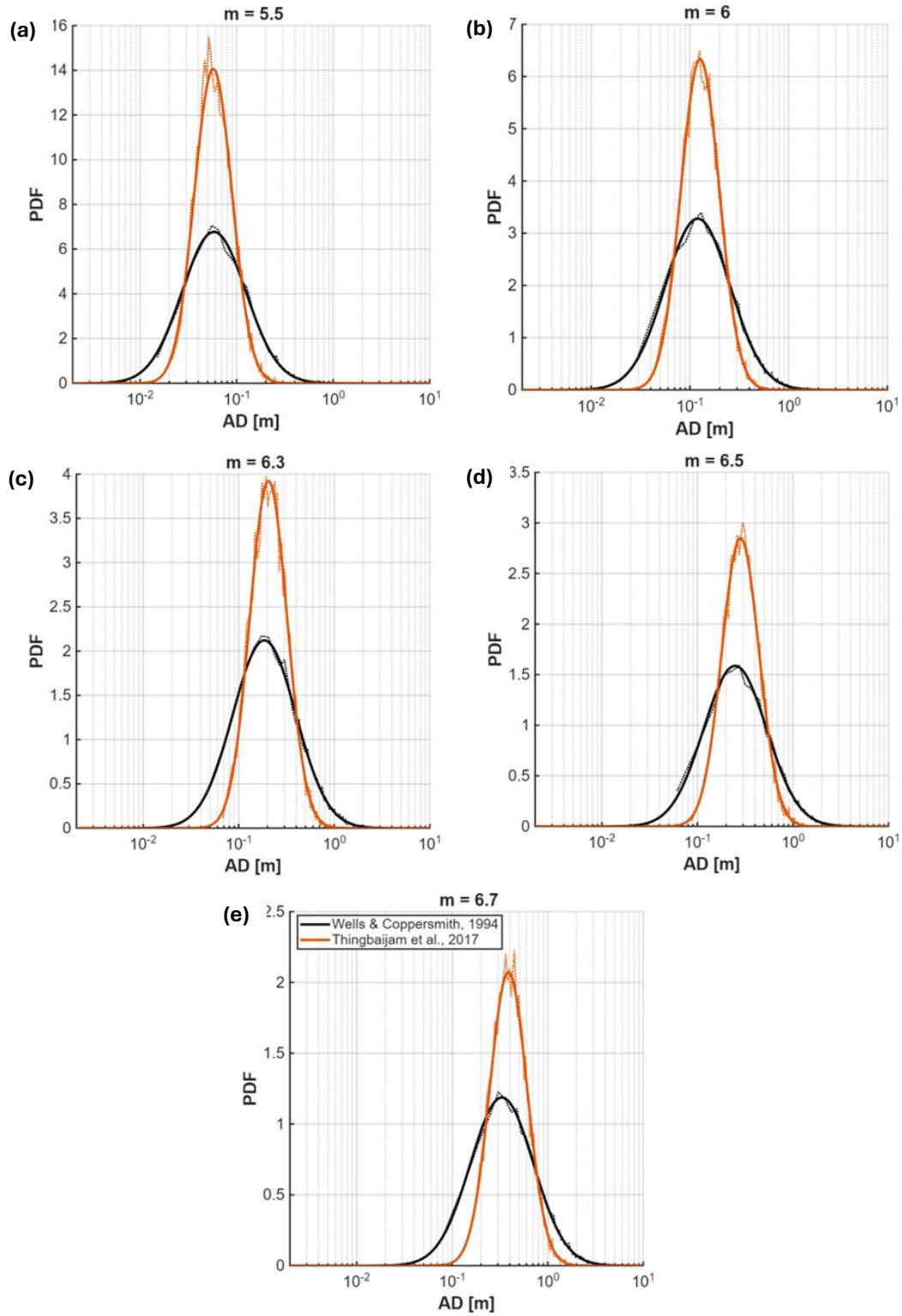


Figure 4.5 Graphical comparison between theoretical and simulated probability density functions (PDFs) of average displacement (AD) for different AD/ m scaling models for normal kinematic settings. Panels (a–e) correspond to results for the selected magnitudes: $m = 5.5$, 6.0, 6.3, 6.5, and 6.7.

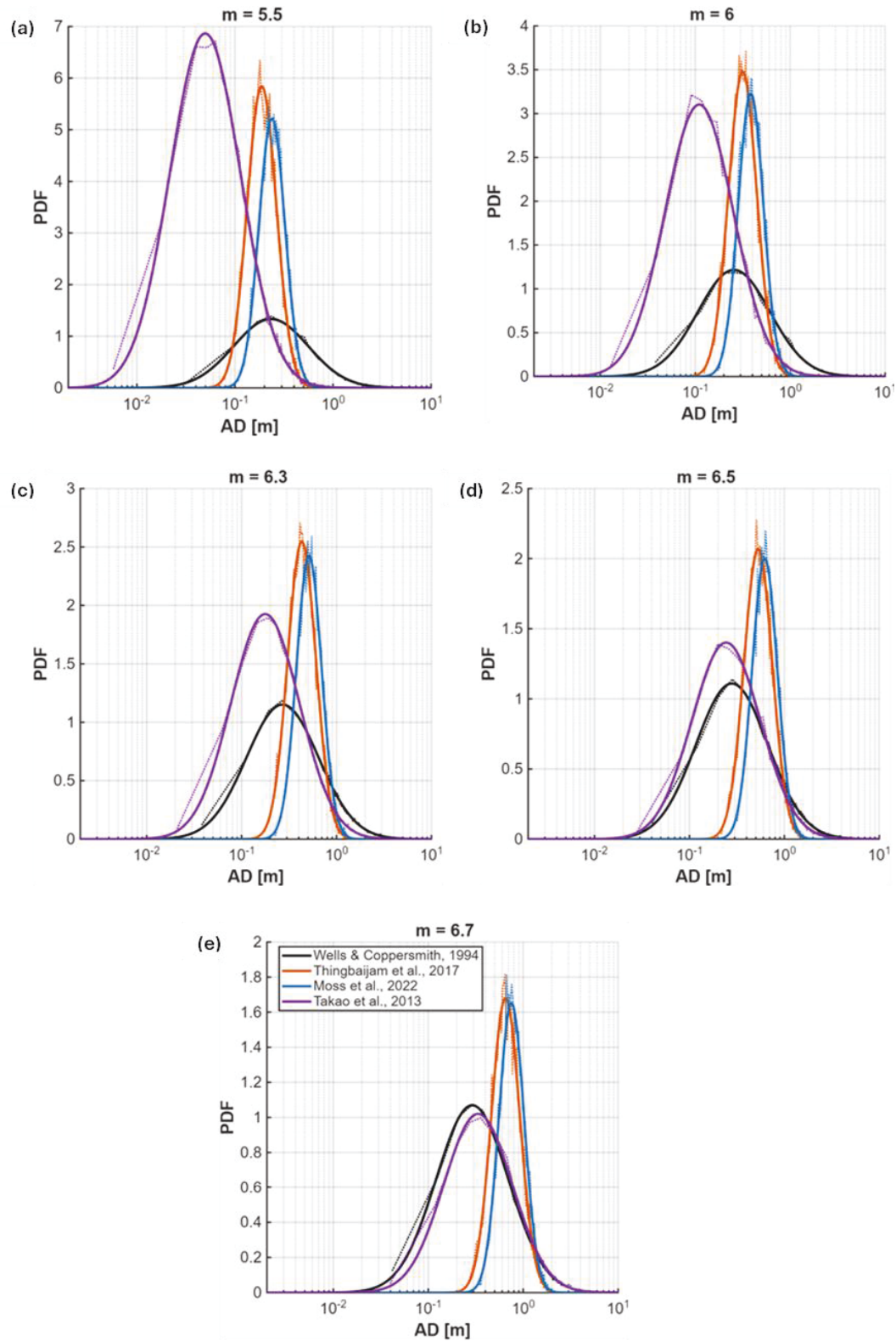


Figure 4.6 Graphical comparison between theoretical and simulated probability density functions (PDFs) of average displacement (AD) for different AD/ m scaling models for reverse kinematic settings. Panels (a–e) correspond to results for the selected magnitudes: $m = 5.5$, 6.0, 6.3, 6.5, and 6.7.

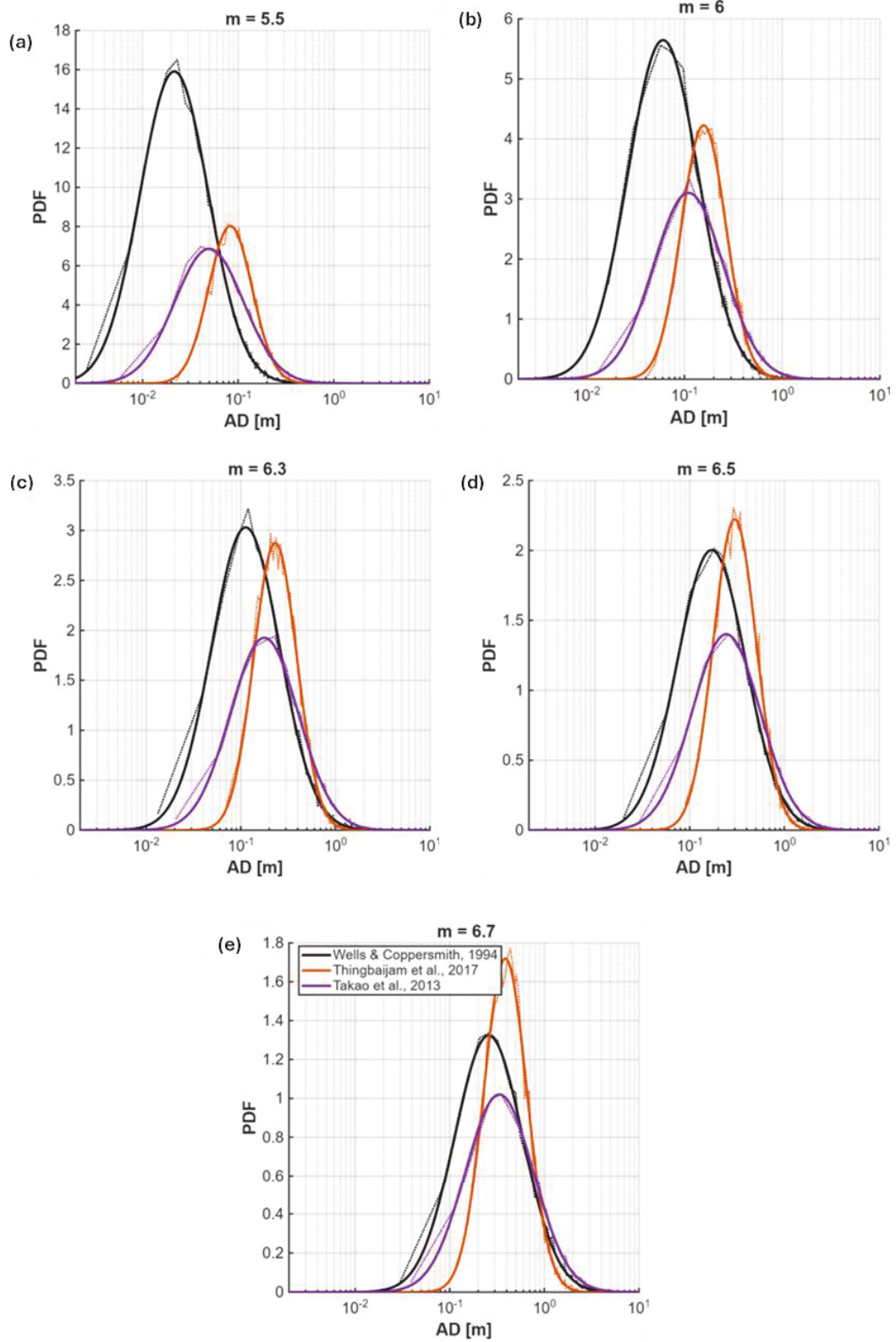


Figure 4.7 Graphical comparison between theoretical and simulated probability density functions (PDFs) of average displacement (AD) for different AD/ m scaling models for strike slip kinematic settings. Panels (a–e) correspond to results for the selected magnitudes: $m = 5.5$, 6.0, 6.3, 6.5, and 6.7.

Impact of the D/AD models

In the reverse-faulting simulations, the gamma distribution proposed by Moss et al. (2022) was contrasted with the two formulations of Takao et al. (2013). Moss et al. (2022) parameterizes the gamma distribution through a linear dependence on x/L , whereas Takao et al. (2013) adopt an exponential dependence for fault segments ≥ 10 km and constant coefficients for shorter segments (< 10 km).

Although the plateau region exhibits comparable AFOE values across all models, the tail region reveals more substantial divergence. The higher AFOE associated with the Takao et al. (2013) model for segments ≥ 10 km arises from the model admitting very large D/AD values with a non-negligible probability. A similar arrangement emerges for the short-segment formulation of Takao et al. (2013), though the differences are less marked.

For strike-slip simulations, the comparison included both Takao et al. (2013) models and the bilinear, quadratic, and elliptical models of Petersen et al. (2011). Within the plateau region, the differences among the hazard curves calculated remain below approximately 20%. Conversely, for larger displacements, the hazard curves diverge more distinctly, reaching PD values around 100%. This result reflects the statistical characteristics of the respective distributions: the Petersen et al. (2011) models allow for relatively higher D/AD values compared to Takao et al. (2013), thereby assigning a non-negligible probability to large D/AD values, even if such events are infrequent. This issue has been revisited in the recent work of Chiou et al. (2025), who proposed an updated model based on a broader dataset and adopting a negatively exponentially modified Gaussian distribution. Nonetheless, direct application of the Chiou et al. (2025) formulation in this study is not straightforward, since their predictions rely on the sum of principal displacements, whereas the models analyzed here are based on single principal displacements only.

PDF of D/AD models at selected positions along faults

To further investigate the probabilistic behavior underlying the hazard trends described above, the probability density functions (PDFs) of D/AD were examined at

multiple locations along the fault. These distributions offer additional insights into how model-specific assumptions about the D/AD shape the resulting hazard curves.

Figure 4.8 illustrates the probability density functions (PDFs) of the normalized displacement ratio D/AD calculated at three representative positions along the fault: $x/L=0.1$, 0.3 , and 0.5 . These positions correspond to the fault tip, an intermediate location, and the fault center, respectively, and are chosen to reflect the spatial variability in displacement behavior under the assumption of fault symmetry. Each subplot corresponds to a specific model considered in this sensitivity analysis at a given location.

The models fall into two broad categories: gamma-based formulations (Youngs et al., 2003; Moss et al., 2022; Takao et al., 2003 for both >10 km and <10 km segments) and lognormal-based formulations (Petersen et al., 2011; bilinear, quadratic, elliptical).

For the gamma-distribution models, both the shape and scale parameters may vary with x/L through linear or exponential relationships, leading to positively skewed probability density functions with well-defined modes at relatively low values of D/AD and a decay of probability density with increasing D/AD . However, exceedance probability calculations demonstrate that tail behavior among gamma-based models is not uniform. While some formulations, such as Moss et al. (2022), exhibit moderate and decreasing tail probabilities toward the fault center, others, most notably Youngs et al. (2003) and the Takao et al. (2013) long-segment model, predict non-negligible right-hand tail probabilities at central fault positions. The Takao et al. (2013) short-segment formulation, which employs constant parameters, yields identical PDFs at all positions and a spatially invariant exceedance probability, indicating no explicit dependence on x/L .

By contrast, the lognormal-based models of Petersen et al. (2011) show parameterization-dependent variations in PDF shape that are more evident than those observed for the gamma-based formulations. The bilinear and elliptical

formulations predict markedly elevated probabilities of large D/AD values at intermediate and central locations, whereas the quadratic formulation yields more moderate but still significant tail contributions. Importantly, the overlay plots do not indicate a systematic narrowing of the lognormal PDFs toward the fault center; instead, changes in peak amplitude and distribution shape reflect a redistribution of probability density rather than a consistent reduction in spread.

A direct comparison between the Takao et al. (2013) and Petersen et al. (2011) formulations indicates that the Petersen models generally allow higher right-hand tail probabilities, particularly at intermediate and central fault positions. While the Takao long-segment model exhibits increasing tail weight toward the fault center, exceedance probabilities remain lower than those predicted by the Petersen bilinear and elliptical formulations.

Overall, the combined visual and quantitative analyses demonstrate that differences in extreme D/AD predictions cannot be attributed solely to whether a gamma or lognormal distribution is adopted. Instead, the functional form governing parameter variation with x/L exerts a primary control on tail behavior and displacement hazard estimates. As a result, model-specific assumptions regarding spatial variability play a critical role in determining the likelihood of large fault displacements and should be carefully considered in hazard assessments.

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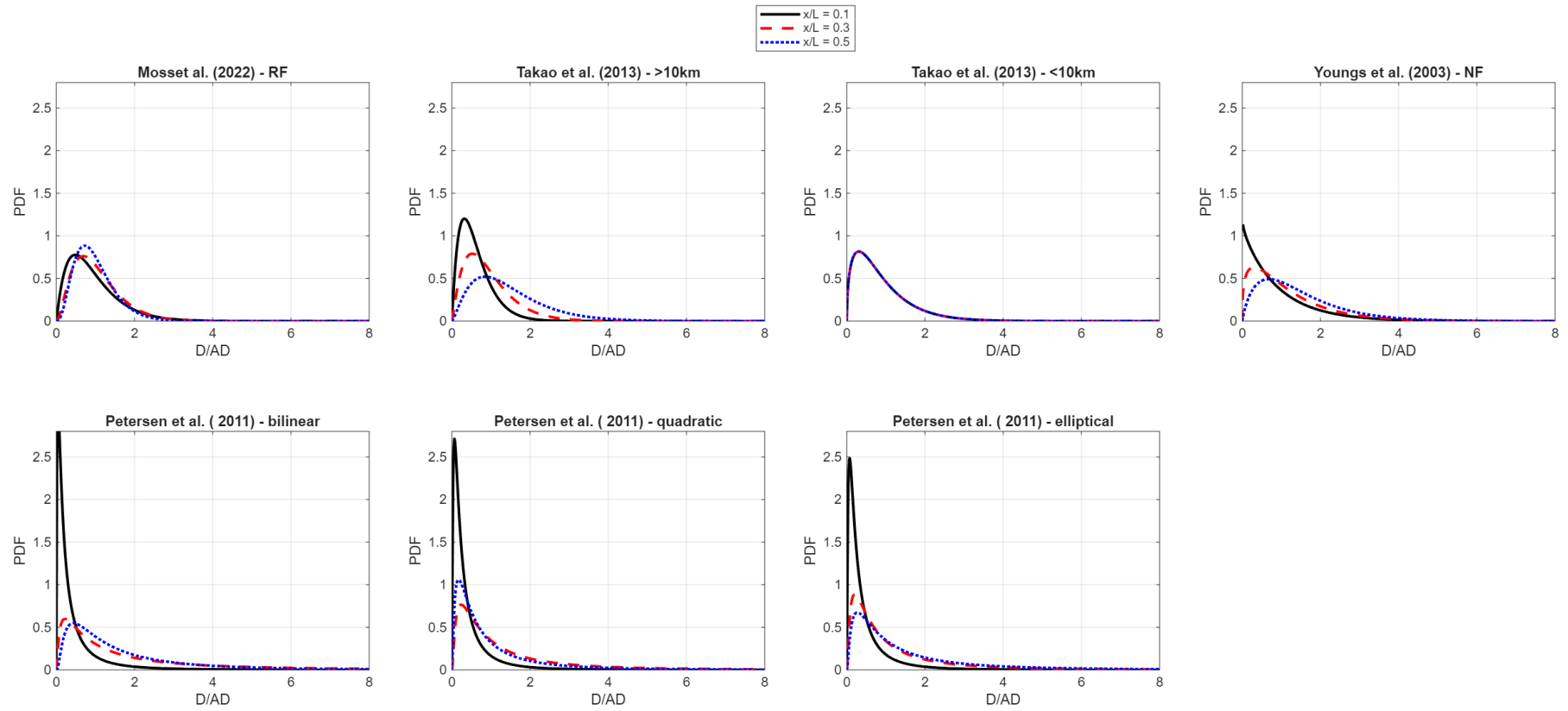


Figure 4.8 Overlay of the probability density functions (PDFs) of the normalized displacement ratio (D/AD) evaluated at three representative fault positions ($x/L = 0.1, 0.3, 0.5$), corresponding to the fault tip, an intermediate location, and the fault center. Each panel shows a single empirical model of the predicted D/AD distribution. Models include gamma-based formulations (Moss et al., 2022; Takao et al., 2013 for >10 km and <10 km segments; Youngs et al., 2003) and lognormal-based formulations (Petersen et al., 2011: bilinear, quadratic, and elliptical).

Tornado-plot summary of key findings

In the following, the summary tornado plots (Figure 4.10, Figure 4.10) are presented, which rank the percentage differentials computed with respect to each adopted baseline. This ranking allows for highlighting the relative influence of the selected formulations both in the plateau region of the hazard curves, corresponding to the 10 cm displacement value, and in the tail region, associated with the 1 m and 2 m displacement value.

As illustrated by the graphical representation of the results, the selection of regression models for the PSR primarily influences the plateau region of the hazard curves, where it induces upward or downward shifts and consequently alters the estimated mean annual frequency of events. This effect is mainly evident for small magnitude values (Valentini et al., 2025), such as those assumed in the sensitivity analyses carried out in this study.

The simulations performed with alternative AD|m and D/AD models further reveal that the shape and positions of the hazard curves are influenced not solely by the values of the regression coefficients, but also, by the corresponding standard deviations. Previous studies (e.g., Valentini et al., 2025; Sarmiento et al., 2025) have underscored that the choice of standard deviations exerts a critical influence on the slope of the hazard curves in the tail region. This sensitivity reflects the intrinsic precision of the models themselves, and it is important to note that simply enlarging the training dataset does not reduce the component of aleatory uncertainty inherent to these models.

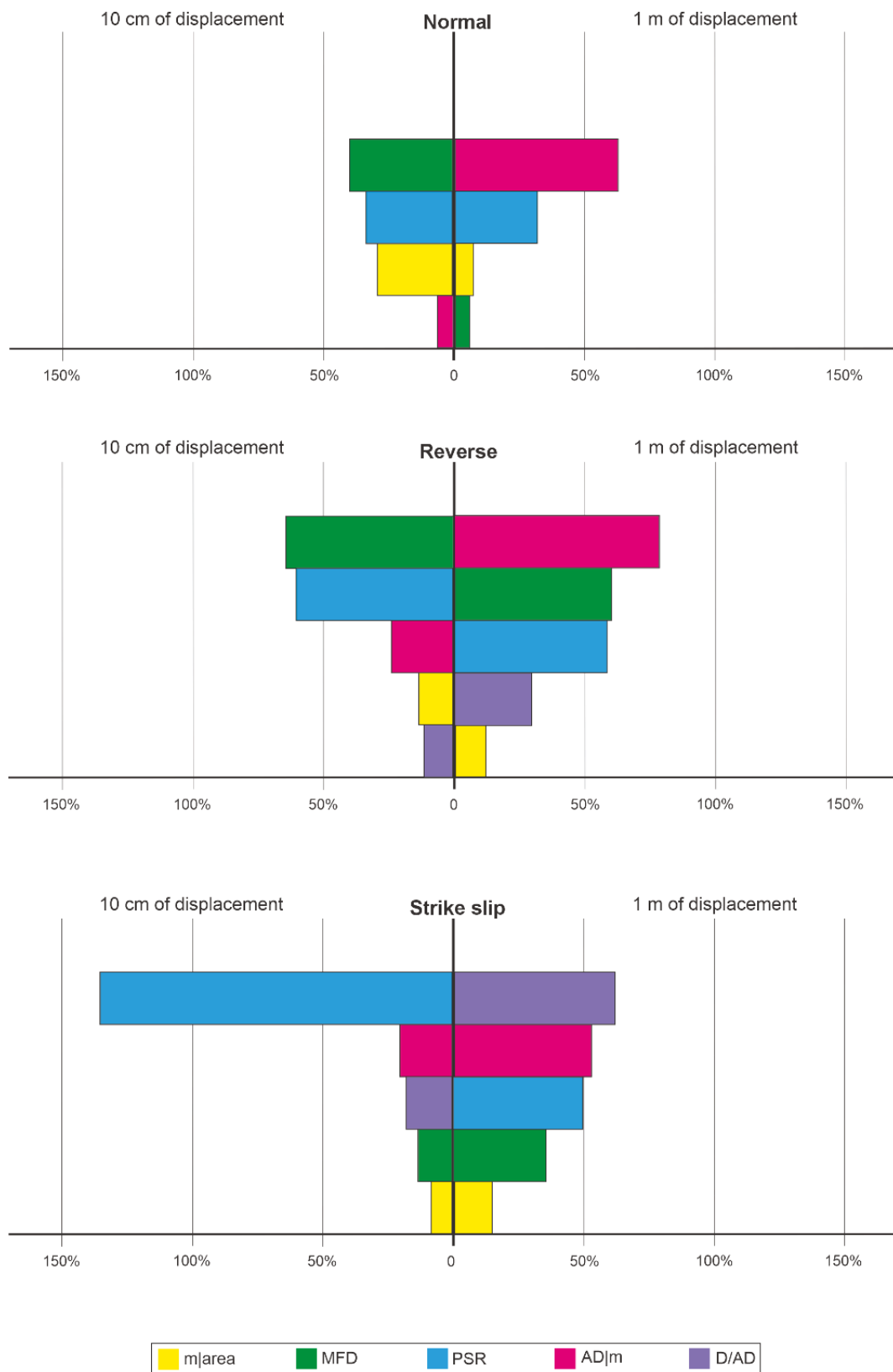


Figure 4.9 Tornado plots ranking the percentage differences for normal, reverse, and strike-slip kinematics. The plots refer to displacement values of 10 cm and 1 m (see text for details).

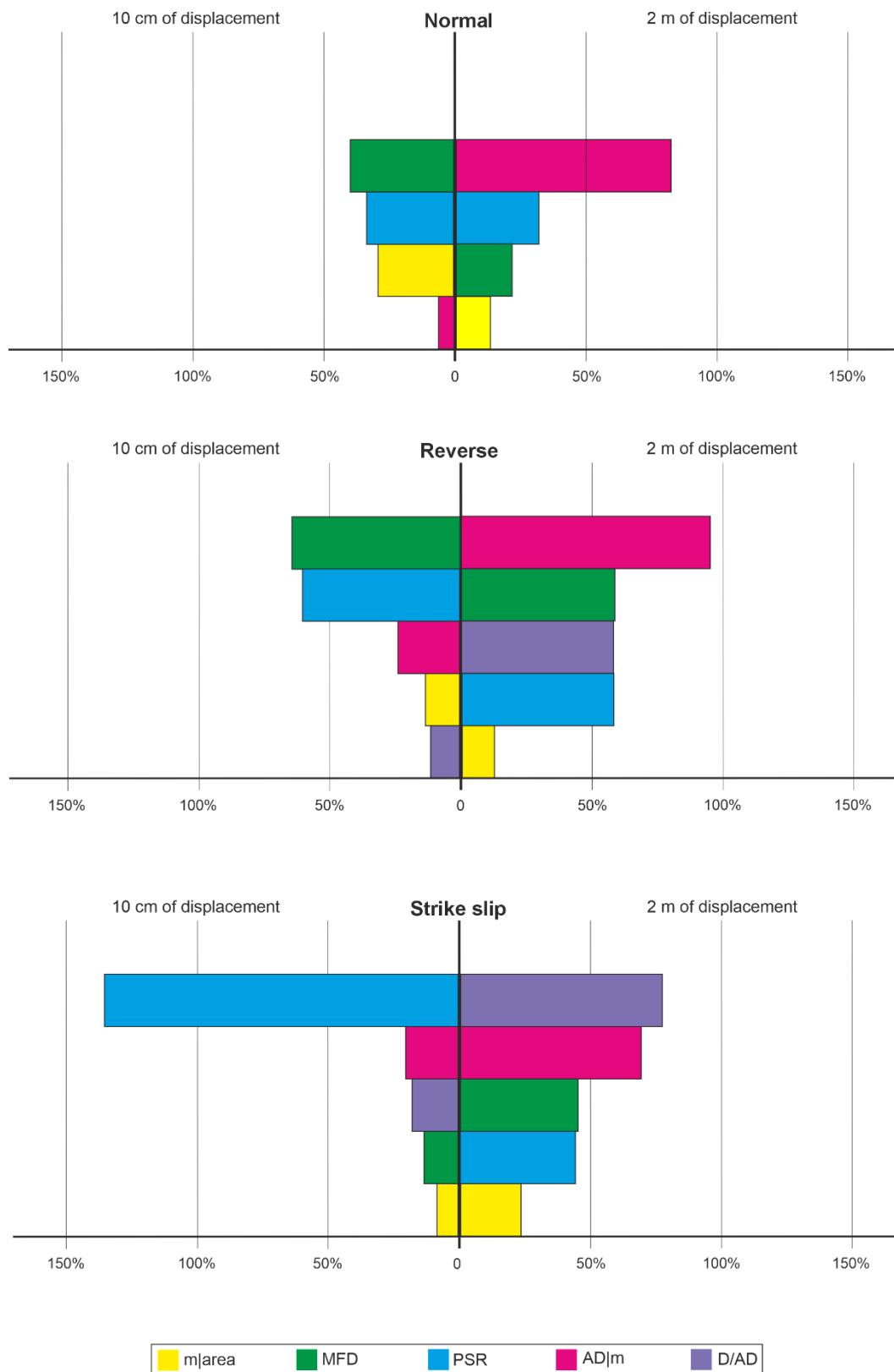


Figure 4.10 Tornado plots ranking the percentage differences for normal, reverse, and strike-slip kinematics. The plots refer to displacement values of 10 cm and 2 m (see text for details).

5. PFDHA: Application to a Case Study

5.1. INTRODUCTION

In this chapter, PFDHA methodology is applied to evaluate the potential annual frequency of exceedance (AFOE) associated with three different scenarios involving the Southern Border Fault (SBF) of the Rieti intramontane basin (Central Apennines – Italy).

The intermontane basins of the Central Apennines record an initial compressional phase followed by extension related to Adria slab rollback, with NW–SE striking high angle normal faults that possibly reactivate older thrust, or, conversely, cut through those structures (e.g., Galadini et al., 2000; Cosentino et al., 2017). This system of longitudinal normal faults (i.e., parallel to the axis of the chain), has played a fundamental role in shaping the intermountain basins, accommodating extensional tectonics since the Quaternary (Galadini et al., 2000, Capotorti et al., 2024) (Figure 5.1).

In addition to the dominant NW–SE striking structures, a secondary system of ca. E–W striking border faults, which intersect the main fault network, is bounding the Rieti basin (Cavinato et al., 1999). Their tectonic role, however, is less well constrained: their activity is poorly documented and their kinematic compatibility with the current NE–SW extensional stress field has been the subject of considerable debate (Michetti et al., 1995; Galadini et al., 1999; Micarelli et al., 2003).

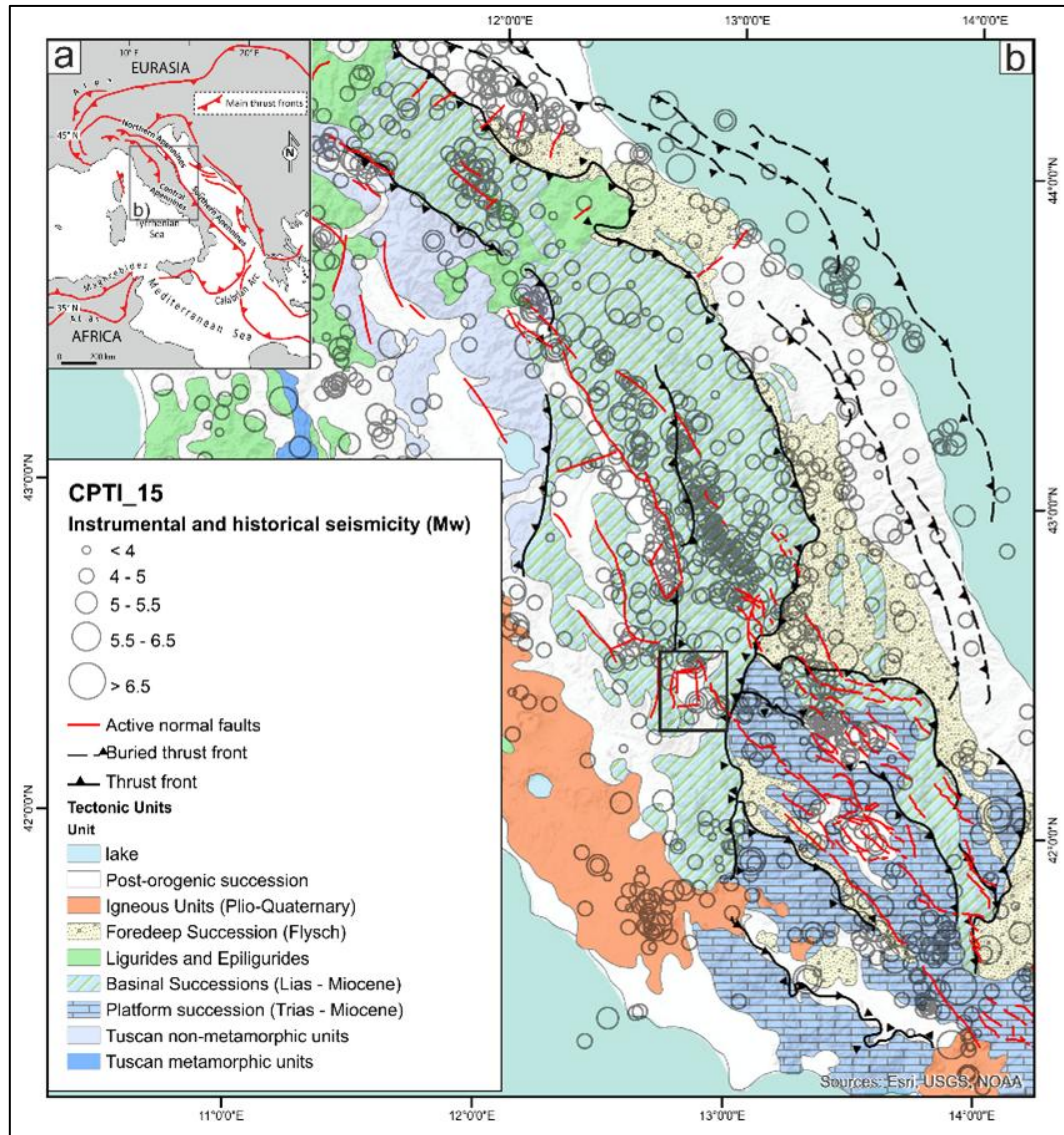


Figure 5.1 Panel (a): regional tectonic framework. Panel (b): Central Apennines simplified geological map showing thrust fronts, active normal faults along the chain axis, and seismicity (CPTI15 Catalogue, Rovida et al., 2022; CFTI5Med Catalogue, Guidoboni et al., 2018, 2019; Baranello et al., 2024, for the 1743 Rieti earthquake). Modified after Capotorti and Muraro, (2024). From Livio et al., (2025, preprint). Licensed under Creative Commons CC BY 4.0.

The Rieti Basin represents a key seismotectonic domain in the Central Apennines (Figure 5.2), yet knowledge of its Southern Border Fault (SBF) remains limited and, in many respects, outdated. The study of SBF is particularly important because it exemplifies the uncertainties surrounding the role of E–W oriented structures, which remain difficult to reconcile with the current NE–SW extensional stress field. Despite its significance, no systematic paleoseismological investigations have been carried out on this structure, and only a few historical earthquakes have been

documented within the basin. This scarcity of direct evidence hampers a robust assessment of the long-term seismic potential of the fault system.

The only paleoseismological study available until recently was the work of Michetti et al. (1995), who interpreted normal displacements at Pié di Colle and Caporio sites, as evidence of past surface faulting events. However, since then, no further investigations have specifically addressed the seismic behavior of the SBF, leaving a substantial gap in the reconstruction of its earthquake history. A new contribution is now emerging from the studies after Livio et al. (2025, under review), which provides the first comprehensive paleoseismological analysis of the basin and offers unprecedented insights into its surface-rupturing events.

The historical seismic record of the Rieti Basin reveals at least two major destructive earthquakes. The earliest occurred in 76 BCE ($I_o = X$ MCS; $M_e = 6.4$), though evidence is limited to damage reported in the city of Rieti (Guidoboni et al., 2018, 2019), and a second event on December 1st, 1298 ($M_w 6.26$; $I_o = X$ MCS), likely centered north of the basin and preceded by a $M_w 4.4$ foreshock in its southern sector.

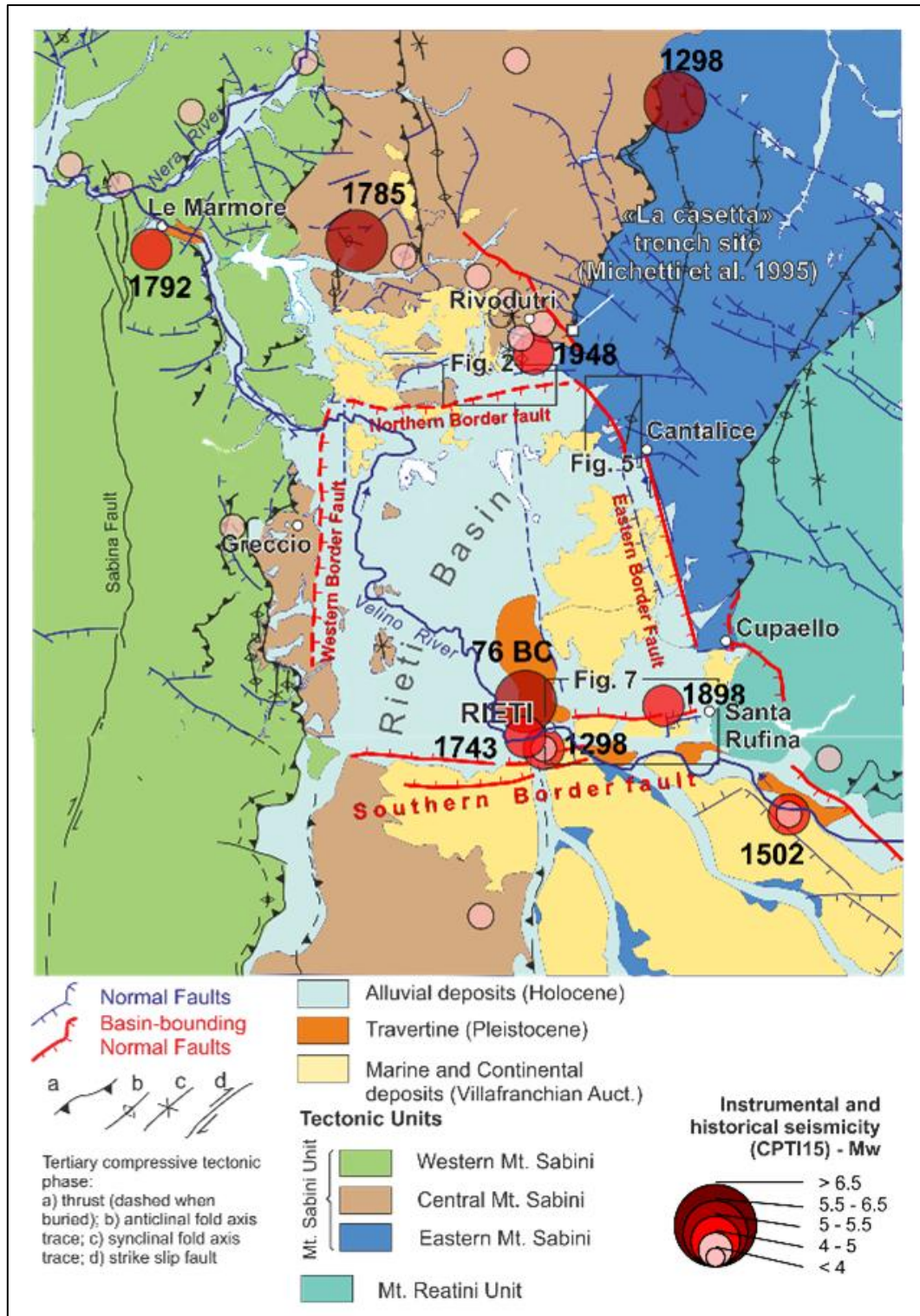


Figure 5.2 Simplified seismotectonic map of Rieti Basin area. Modified after Capotorti and Muraro, (2024). From Livio et al., (2025, preprint). Licensed under Creative Commons CC BY 4.0.

The case study for the application of the PFDHA methodology focuses on the southern border of the Rieti Basin, where two fault segments have been identified based on the ITHACA fault mapping database (Figure 5.3). In this work, they are referred to as the Western Segment (WS) and the Eastern Segment (ES). Three seismic scenarios are considered: the first two involve the independent activation of each segment, whereas the third assumes the simultaneous rupture of both faults (Total Border Fault, TBF), implying a structural connection at depth between the WS and ES.

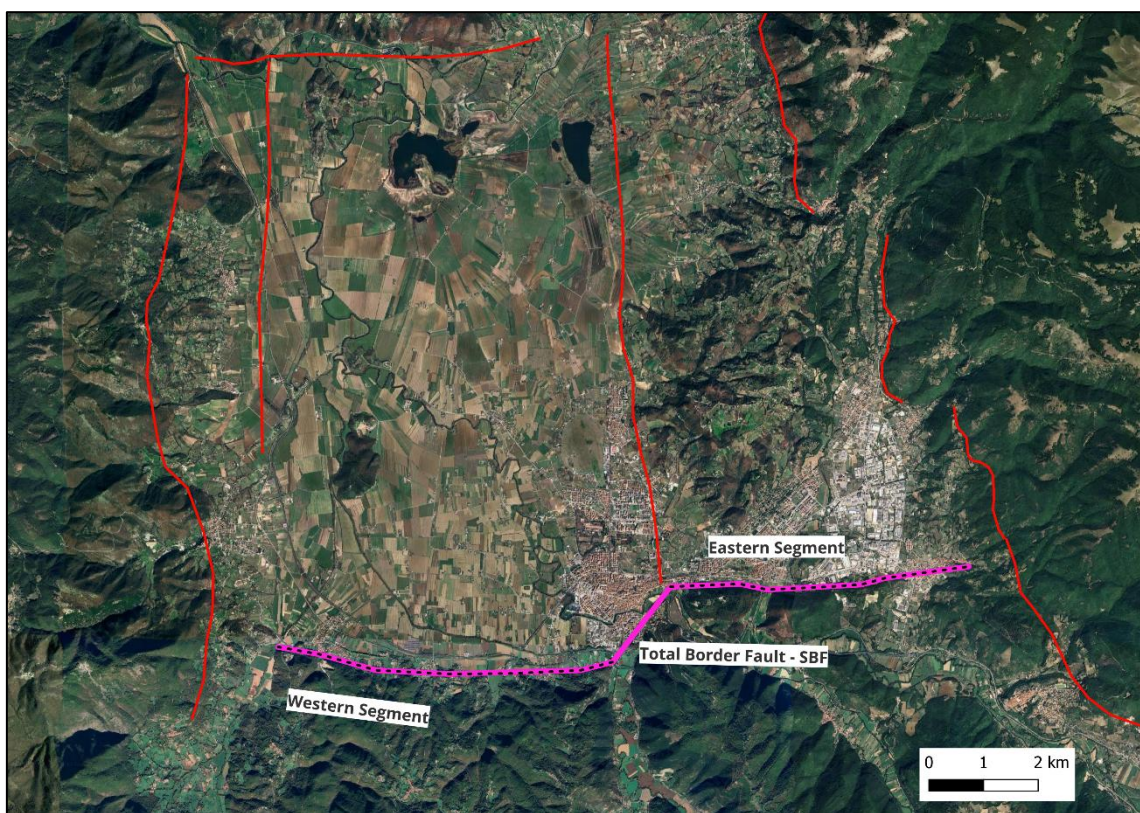


Figure 5.3 Extract of the map showing two fault segments from the ITHACA fault mapping database, displayed as black dashed lines. These are referred to as the Western Segment (WS) and the Eastern Segment (ES). The connecting segment between WS and ES, and the Total Border Fault (TBF), are highlighted in pink.

Although there is no evidence to support this assumption, it cannot be ruled out that the two segments may form a single structure capable of generating a fault displacement of greater magnitude than that produced individually.

Despite this historical record discussed above, the seismic potential of the SBF remains difficult to evaluate due to the scarce and poorly constrained

paleoseismological evidence and the apparent segmentation of the fault, which complicates estimates of rupture length, magnitude potential, and fault interactions. Nevertheless, a probabilistic assessment, such as those derived from PFDHA methodologies, would be of high value, especially considering that the fault trace could directly affect urbanized areas and critical infrastructure, including the Edison gas pipeline.

5.2. GEOLOGICAL AND TECTONIC SETTING

The Apennines are a portion of a more complex fold-thrust belt correlated with the orogenesis that affected the peri-Mediterranean area during the Neogene (e.g., Cosentino et al. 2010). Their evolution is linked to the subduction of both oceanic and continental lithosphere (Lanari et al., 2023), which caused the migration of the trench and back-arc system through the western and central Mediterranean region. Between ca. 30 and 15 Ma, southward slab rollback in the Western Mediterranean triggered compression along the pro-wedge (i.e. in the eastern flank of the chain) and extension along the retro-wedge (i.e., in the western flank of the chain; Faccenna et al., 1997, 2007; Lanari et al., 2023). The resulting extensional regime produced both east and west-dipping normal faults, responsible for the development of marine and continental basins (Cavinato & De Celles, 1999). In most areas, both basins and fault systems display a systematic eastward rejuvenation (Carminati et al., 2004; Barchi et al. 2006). The timing of extension and basin development in the Central Apennines remains a matter of debate. According to Cosentino et al. (2017) and Lanari et al. (2023), normal faulting and the onset of intermontane basins were broadly coeval, beginning almost simultaneously around 2.5 Ma. In contrast, Fellin et al. (2022), on the basis of stratigraphic and thermochronological data, argue for a diachronous evolution, with exhumation and cooling initiating earlier in the western sector (≤ 4 Ma) and progressively later toward the southeast (≤ 1 Ma), suggesting a spatially variable and non-synchronous tectonic history.

Building on this long-term evolution, different models have been proposed to explain the present-day geodynamics of the Apennines, with particular emphasis

on the Central sector, where uplift, exhumation, and basin development show distinctive patterns compared to the rest of the chain.

Faccenna et al. (2014) argue that the present-day elevation of the Apennines results from the combined action of surface processes, crustal structure, and mantle dynamics, and cannot be explained by crustal isostasy alone (Faccenna et al., 2014). Residual topography analyses indicate that mantle upwelling beneath the Central Apennines has produced anomalous uplift, whereas subduction-related downwelling beneath the Northern Apennines and Calabria accounts for slower uplift or relative subsidence. Moreover, morphological and structural observations highlight that in the Northern Apennines, asymmetric topography and drainage divide geometries are mainly controlled by crustal thickness and local faulting, whereas in the central sector more symmetric patterns are associated with mantle-driven uplift related to slab break-off (Lanari et al., 2023). Thermochronological and stratigraphic records support this interpretation, showing that until the Late Miocene–Early Pliocene the chain evolved under slab roll-back, but since ~2.5 Ma the Central Apennines underwent rapid exhumation, uplift, and intermontane basin formation, consistent with the onset of slab break-off (Fellin et al., 2022). Additional studies (e.g., Scrocca et al., 2007), however, point to the persistence of slab retreat. According to Scrocca et al. (2007), geological and geophysical data from the Northern and Central Apennines document Late Quaternary contraction, active shortening exceeding 1 mm/yr, and foredeep subsidence, all consistent with flexural retreat of the Adriatic lithosphere still being active today. Koulakov et al. (2015) add yet another perspective, as seismic tomography images elongated high-velocity anomalies beneath the chain, which are best interpreted as delaminated portions of the Adriatic lithosphere: while the crust was accreted into the Apennine wedge, the lithospheric mantle detached and sank into the asthenosphere. The northwestern portion of this body appears completely separated, whereas its southeastern end remains connected to the Ionian–African foreland. Taken together, these studies highlight Central Apennines as a key region where different geodynamic processes converge. Competing models, including slab retreat, slab

break-off, and lithospheric delamination, provide alternative but complementary explanations for the observed patterns of uplift, subsidence, exhumation, and seismic structure.

The central Apennine intermontane basins reflect a tectonic evolution marked by different stages (Cosentino et al., 2017). The earliest phase was dominated by compressional tectonics related to the construction of the Apennine chain, during which thrust-top basins developed within the advancing foreland system between the Late Miocene and the Pliocene. A subsequent tectonic phase was triggered by the rollback of the Adria plate and the opening of the Tyrrhenian back-arc basin. This process established an extensional regime that promoted orogenic collapse and led to the development of half-graben basins such as the Fucino, L'Aquila, and Rieti basins. bounded by active faults generally trending N–S or NW–SE.

These structures are organized into two main parallel systems, an eastern and a western set, which converge in the L'Aquila region where they are separated by less than 10 km. These fault systems largely result from the reactivation of pre-existing compressional structures, subsequently exploited as normal faults under the extensional regime established since the Early Pleistocene (Galadini & Galli, 2000). Detailed stratigraphic, structural, and geomorphological analyses have shown that fault kinematics underwent significant changes between the Early and Middle Pleistocene. Some NW-trending normal faults ceased activity, while others with similar orientation developed left oblique-slip or strike slip components. Conversely, faults trending N125° to E–W maintained a purely normal kinematics (Galadini, 1999). This variability in fault behavior has been interpreted as a direct consequence of the progressive growth of salients of the Apennine belt. This phenomenon introduced a geometrical incompatibility between inherited compressional lineaments and the regional stress field, requiring the development of oblique and strike-slip kinematics to accommodate extension (Galadini, 1999). Thus, the present organization of fault families in the Central Apennines reflects both the reactivation of inherited compressional structures and the kinematic

adjustments imposed by arc formation and the migration of the compressional front.

The Rieti Basin

The Rieti Basin provides an illustrative case of an intermontane depression situated in the axial portion of the Central Apennines (Figure 5.4). After the contractional phase responsible for the construction of the chain, the area was affected by repeated Plio–Quaternary extensional phases that shaped its present morphology. At present, the basin is expressed as a flat alluvial plain with a box-shaped configuration, delimited by normal faults that intersect at nearly orthogonal angles (Figure 5.4).

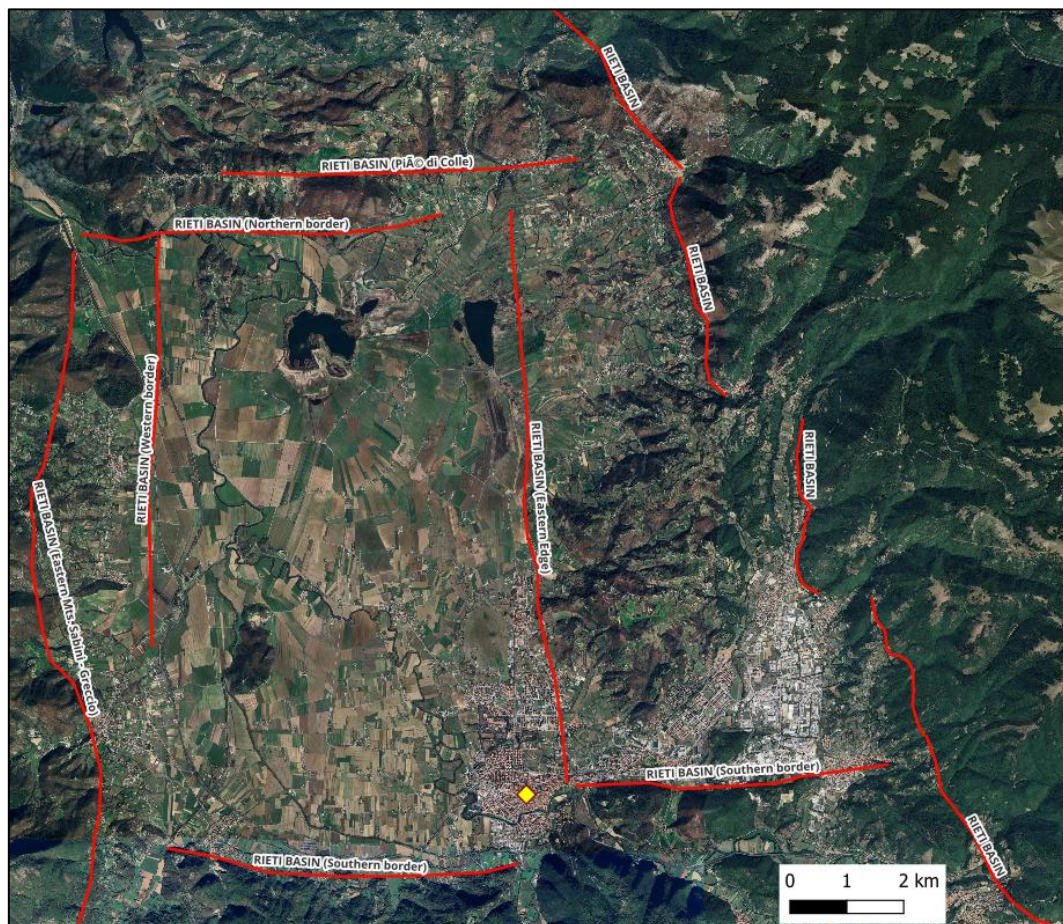


Figure 5.4 Detail of the Rieti basin area, showing its box-shaped alluvial plain bounded by normal faults intersecting at nearly orthogonal angles. The yellow diamond marks the location of Rieti. Fault traces are taken from the ITHACA database (Catalogo delle Faglie Capaci, ISPRA – Dipartimento per il Servizio Geologico d'Italia) [<https://sgi.isprambiente.it/ithaca/viewer/index.html> (last accessed May 2025)].

The main structure controlling the evolution of the basin is the ca.21 km long Eastern Border Fault (EBF), commonly referred to as the Rieti Fault (Roberts &

Michetti, 2004). This fault, part of the broader system of active Quaternary normal faults along the western Apennines, including the Fiamignano and Fucino systems (Michetti et al., 1996; Cowie & Roberts, 2001; Mildon et al., 2022), acted as the master structure driving half-graben subsidence and the accumulation of thick sedimentary sequences.

During the Pleistocene, slip rates of 0.2–0.4 mm/yr produced progressive basin deepening, while regional uplift enhanced fluvial incision and led to the capture of the Velino River by the Nera River through the Le Marmore threshold (Michetti et al., 1995; Guerrieri et al., 2006). Subsequent tectonic phases generated additional fault sets and established the present-day orthogonal fault pattern. Fault activity also influenced groundwater circulation and travertine deposition, particularly along the northern and southern margins (Carrara et al., 1992). During the Holocene, the rapid vertical aggradation of the Le Marmore travertine platform obstructed the course of the Velino River, leading to the progressive infilling of the Rieti Plain (Guerrieri et al., 2006; Archer et al., 2019). In this context, sedimentary and fluvial dynamics proved to exert a stronger influence than tectonic factors in shaping the present-day morphology of the basin.

Beyond the two destructive earthquakes (i.e., the 76 BCE and the 1298 events) () mentioned in the introductory chapter, the Rieti Basin has also been significantly affected by several large regional earthquakes ($M > 6$) within ca. 40 km, including the 1349 Valle del Salto earthquake (Me 6.1), the 1639 Amatrice earthquake (Me 6.2), and the 1703 Norcia earthquake (Me 6.7). More moderate events have been documented as well, such as the 1785 Rieti earthquake (Mw 5.76), along with shocks clearly associated with the basin-bounding faults, including the 1898 Santa Rufina earthquake (Mw 5.5) on the northern fault and the 1948 Rivodutri earthquake (Mw 5.3) on the southern fault.

Recent paleoseismic investigations proposed after Livio et al., (2025, in preprint) have provided new constraints on the seismic history of the Rieti Basin. The excavation of 17 trenches revealed at least 6 surface-faulting earthquakes over the

last ca. 20 ka, affecting three sides of the basin and defining a recurrent rupture pattern involving the Eastern Border Fault followed by the northern or southern border faults activation. These data establish the first comprehensive baseline of tectonic activity for this basin and suggest a maximum credible earthquake of $M_w \sim 6.5$, consistent with the broader Central Apennines seismicity. Although chronological resolution prevents distinguishing single large ruptures from clusters of closely spaced events, and paleoseismic records are intrinsically biased toward surface-rupturing events, thus overlooking moderate earthquakes that may still have caused significant damage, the Authors clearly demonstrate the seismic potential of the Rieti Basin.

This historical seismicity, when considered together with the structural framework of the basin, highlights the persistent activity of its border faults and their key role in accommodating Quaternary extension. Consequently, the Rieti Basin represents an area of primary relevance for understanding fault behavior and assessing seismic hazard in the Central Apennines.

New insights into the paleoseismic activity of the Southern Border Fault of Rieti Basin

The results presented in this section derive from the data collected through the excavation of seven exploratory trenches along the Southern Border Fault (SBF). These findings, which are discussed in the preprint by Livio et al. (2025) and provide new constraints on the late Quaternary behavior of the fault and refine our understanding of its role within the Rieti Basin fault network.

The SBF was investigated east of Rieti, extending as far as Santa Rufina (Cittaducale), where three trenches (named in Livio et al., 2025 as TR1, Villa Stoli South, and TR3, Figure 5.5) yielded unequivocal evidence of surface-rupturing earthquakes, while additional trenches (named TR4 and TR5, Figure 5.5) revealed secondary deformation structures. The integrated use of geophysical prospecting (ERT and GPR) prior to excavation proved essential in locating buried fault strands and constraining the geometry of the deformation zones.

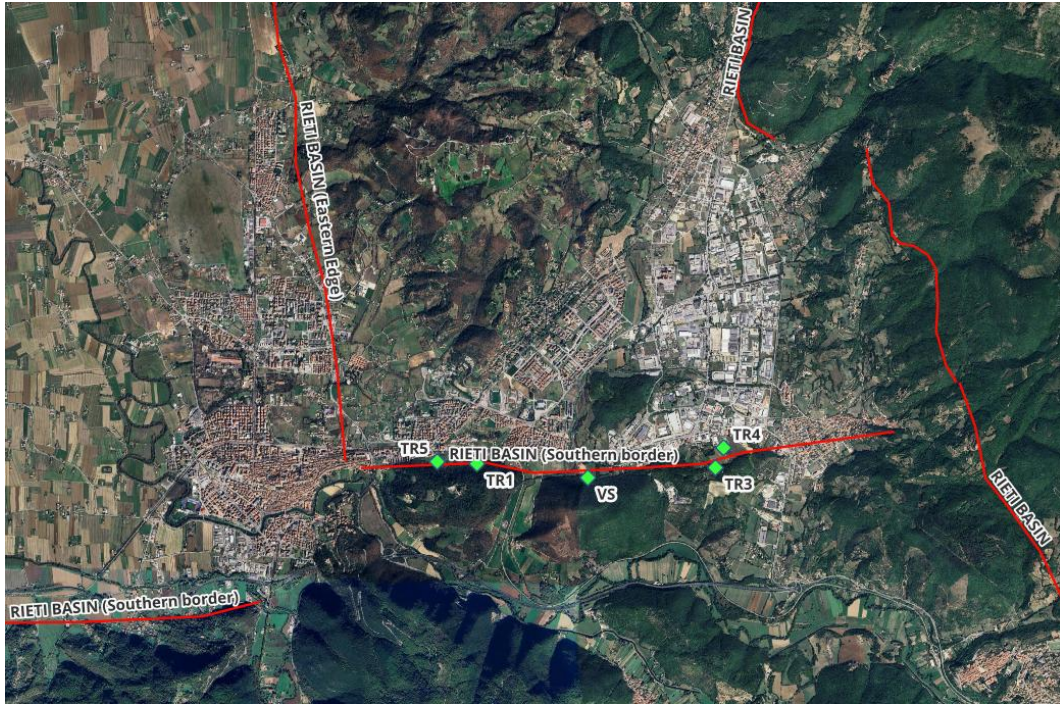


Figure 5.5 Detail of Figure 5.4 showing the locations of the paleoseismological trenches along the Southern Border of the Rieti Basin: TR1, TR3, TR4, TR5, and Villa Stoli (VS).

Trench TR1 exposed a fault system displacing the Monteleone Sabino Synthem (Early Pleistocene, Upper Villafranchian), extensively altered by pedogenesis in this area, together with the overlying colluvial deposits.

The sequence exposed in TR1 is dominated by a pedogenized unit, that is capped by a more recent soil horizon, radiocarbon dated to 7818–7597 BCE. A NW-dipping, NE-striking fault displaces the Monteleone Sabino Synthem; the same structure also cuts through the overlying colluvial succession. This feature is interpreted as the main fault at the base of the Cappuccini–Villa Potenziani northern slope. Along the upper section of the trench wall, the fault juxtaposes the pedogenized Monteleone Sabino Synthem against a soil colluvium. the calibrated radiocarbon determination from the samples falls between 7818 and 7597 BCE and 3811–3701 BCE, constraining a rupture event postdating the latter interval. Along the lower section of the trench wall, the fault juxtaposes the pedogenized deposits with a colluvial wedge, radiocarbon-dated to 20,919–20,458 BCE, implying a preceding rupture that generated at least 15 cm of surface displacement.

Nearby trench TR5 exposed multiple small-scale dislocations within the Monteleone Sabino Synthem. These are regarded as secondary faults probably associated with a main strand immediately to the north.

In the Villa Stoli area, geophysical prospecting revealed three major fault zones. In the first zone, a discontinuity was identified that displaces the Lower Pleistocene breccias of the Fosso Canalicchio Synthem together with their overlying deposits, the offset being subsequently sealed by the present-day soil horizon. The second fault zone juxtaposes the same breccias against Monteleone Sabino deposits and cuts the colluvium dated to 21.3–21.0 ka, indicating a surface rupture event likely coeval with that recognized at TR1. Further, the third fault zone displaces the interface between colluvium and pedogenized sediments with ca.30 cm throw; the youngest dislocated layer dates to 11.8–11.6 ka, constraining a subsequent paleoearthquake.

At TR3, the excavation targeted a fault exposure within cemented breccias (Fosso Canalicchio Synthem), where several open fractures were identified and subsequently found to be infilled by colluvial deposits. Brown paleosols infilling a fracture were collected at several stratigraphic horizons. Radiocarbon calibration places the deeper sample between 4988–4797 BCE, while the upper sample yielded a younger age of 326–424 CE.

The deposits of the Monteleone Sabino Synthem exposed in trench TR4 dip northwestward; the grey silts taper downward and are bound by two fault planes. Analogous to TR3, the geometry suggests bedding-parallel slip. However, the faults are closed by ploughed soil, and no deposits younger than the Lower Pleistocene show evidence of deformation.

Taken together, the stratigraphic and chronological evidence from TR1, Villa Stoli South, and TR3 allows for the reconstruction of a long-term earthquake history along the southern margin of the basin, as summarized in Table 5.1 and illustrated in Figure 5.6. The analysis of trench TR1 revealed two distinct surface-rupturing episodes: an early event, older than ~20 ka, inferred from the deposition of a

colluvial wedge, and a subsequent displacement that occurred after 3811–3701 BCE, with an estimated offset in the order of several decimeters. In the Villa Stoli South trench, two additional ruptures were identified. The earliest (ca. 21–20 ka) appears broadly coeval with the oldest evidence from TR1, suggesting a basin-wide event, whereas the younger rupture must postdate 11.8–11.6 ka, marking persistent activity into the Late Glacial–Early Holocene transition. Finally, the TR3 documented at least three deformation episodes: one predating 4988–4797 BCE, a second between ca. 4th–3rd millennium BCE, and the most recent prior to 326–424 CE, which places surface faulting well into the historical period.

Collectively, these results confirm that the southern margin of the basin has accommodated repeated earthquake ruptures from the Late Pleistocene through historical times (Figure 5.6). Linking paleoearthquakes documented at separate trench sites is affected by substantial uncertainty, and in the Rieti Basin such links are considered improbable because of the broad temporal constraints on many events. However, these potential associations are still explored, as they provide a cautious basis for evaluating upper-bound earthquake magnitudes and related seismic hazards.

Trench	Earthquake	Younger than	Older than	Offset	Notes
TR3	3		326-424 CE		A*
TR3	2	3711-3627 BCE	3243-3102 BCE	13 cm (min)	C
TR3	1		4988-4797 BCE		D*
TR1	2	3811–3701 BCE		30 cm	A, B, C
TR1	1		20919–20458 BCE	15 cm (min)	F*
VS2	2	11835-11630 BCE			B, C, D, E
VS1	1	21261-20961 BCE			B, C, D, E, F

Table 5.1 Summary of radiocarbon dating results and paleoearthquake evidence from the Southern Border Fault of the Rieti Basin. The table reports calibrated ages and associated deformation features identified in trenches TR1, Villa Stoli South, and TR3 (see also Figure 5.6). The Notes column provides additional details on the interpretation of the paleoearthquake evidence: asterisks indicate the events considered as key ruptures

(Events A–F), while the other entries denote possible correlations between sites. (Adapted from Livio et al., 2025). Licensed under Creative Commons CC BY 4.0.

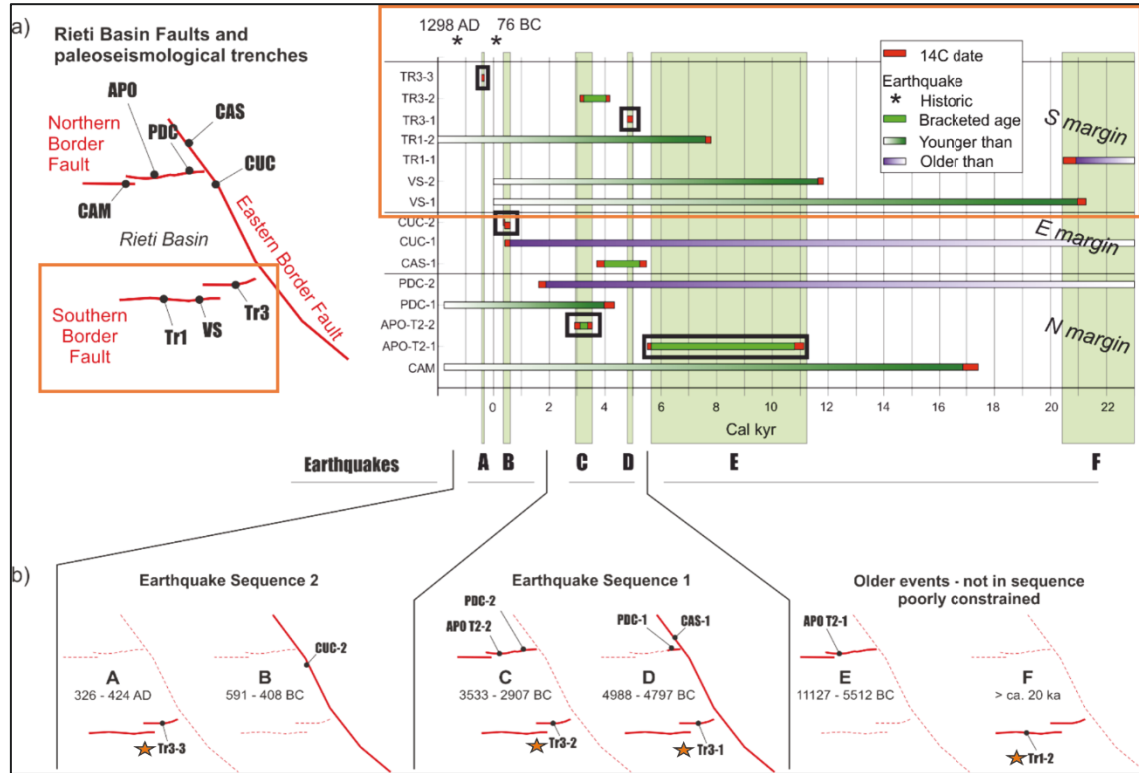


Figure 5.6 Panel (a): schematic reconstruction of the paleoseismic history of the Rieti Basin. The figure summarizes the events recognized in the exploratory TR1, Villa Stoli South (VS), and TR3 trenches. Radiocarbon ages of dated samples, with red bars marking the calibrated ranges and their correlation to the interpreted surface-faulting events. Schematic summary of identified paleoearthquakes, highlighting the chronological clusters of events. Panel (b): synthesis of surface-faulting episodes along the marginal faults of the basin, derived from securely dated evidence. Events and trench data related to the Southern Border Fault (SBF) are emphasized in orange boxes and stars. (Adapted from Livio et al., 2025). Licensed under Creative Commons CC BY 4.0.

5.3. PFDHA METHODOLOGY

As previously discussed in Chapter 2 (Materials and Methods), this work applies the probabilistic fault displacement hazard analysis (PFDHA) using the earthquake-based approach proposed by Youngs et al. (2003). In the present chapter, this methodological framework is implemented for the case study of the Rieti Basin, with the calculation of the Average Frequency of Exceedance (AFOE) for both primary (on-fault) ruptures and distributed ruptures across the three seismic scenarios defined for the southern border fault system.

Principal faulting PFDHA

In accordance with Equation (2), the probability of surface rupture for the principal fault was estimated using the logistic regression model proposed by Youngs et al. (2003). To capture the spatial variability along the fault, the probability of exceedance was assessed by convolving the probabilities within a restricted interval of x/L , centered on each of the three fault traces considered, corresponding to the central 20% of the fault length. The resulting conditional probability of exceedance, $P_{kn}(D > d|m, r, Slip)$, is obtained convolving two probability distributions: the first represents displacement normalized by maximum displacement (D/MD); the last computes the maximum displacement as a function of earthquake magnitude ($MD|m$).

Table 5.2 lists the PSR parameters and the coefficients of functional forms that fit the beta distribution for D/MD and the loglinear function for $MD|m$.

Term of Equation	Functional form	Coefficients	References
$P(slip m)$	$P(slip m) = \frac{e^{a+b*m}}{1 + e^{a+b*m}}$	$a = -12.53$	Youngs et al. 2003
		$b = 1.921$	
D/MD	$F(y) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} \int_0^y z^{a-1} (1-z)^{b-1} dz$	$a = e^{(-0.705+1.138 \cdot x/L)}$	Youngs et al. 2003
		$b = e^{(0.421-0.257 \cdot x/L)}$	
$MD m$	$\log(MD) = a + b * m$	$a = -5.90$	Wells & Coppersmith, 1994
		$b = 0.89$	

Table 5.2 Probability of surface rupture parameters and coefficients of the functional forms adopted to fit the beta distribution for D/MD and the log-linear function for $MD|m$, used in the calculation of the Average Frequency of Exceedance (AFOE) vs displacement for primary ruptures in the Rieti Basin case study.

Distributed rupturing PFDHA

The regression equations proposed by Ferrario and Livio (2021) (Table 5.3Table 5.3) were applied to evaluate the probability of distributed ruptures associated with normal-faulting earthquakes. The study develops new regressions for the conditional probability of distributed faulting as a function of distance, considering two alternative approaches: a regular scenario, based on the mean values of conditional probability across distance classes, and a conservative scenario, which

only accounts for events where distributed ruptures were observed at a given distance. The Authors follow a gridding methodology by rasterizing the maps containing the rupture traces and using a 500-meter resolution grid. Their equations are based on a dataset originally analyzed by Youngs et al. (2003), which was enhanced with data from an additional 21 earthquakes.

Equations	Coefficients		References
	HW	FW	
$P(x) = \frac{e^{(a+b \cdot (\ln(x+c)))}}{1 + e^{(a+b \cdot (\ln(x+c)))}}$	a= -2.254	a=-3.459	Ferrario and Livio, 2021
	b= -1.175	b=-1.903	
	c=1x10 ⁻⁵	c=1.008x10 ⁻⁵	

Table 5.3 PSR coefficients adopted in the calculation of the Average Frequency of Exceedance (AFOE) versus displacement for distributed ruptures considered for the Rieti Basin case study.

To compute the probability of slip exceedance on distributed faults, I adopted the approach proposed by Youngs et al., (2003), which involves a distribution describing the ratio between the displacement occurring on a distributed rupture (d) and the maximum displacement (MD) of the corresponding principal fault rupture. The exponential functions (Youngs et al., 2003), which describe this attenuation relationship as a function of the distance (x) from the principal fault, are as follows:

$$\frac{d}{MD} = 0.35 \cdot e^{-0.091 x} \text{ for hanging wall}$$

$$\frac{d}{MD} = 0.16 \cdot e^{-0.137 x} \text{ for footwall}$$

I considered three different distances from principal fault (0.1, 0.2, 0.5 km) for the assessment of probability of distributed ruptures and the displacement exceedance probability for the scenarios of this case study.

Fault parametrizations

The parameters necessary for the PFDHA performed for each scenario are summarized in Table 5.4.

Parameters	WS	ES	TBF
length [km]	6.2	5.5	13.5
minimum magnitude	5.5	5.5	5.5
maximum magnitude	5.91	5.84	6.35
seismogenic thickness (km)	13		
dip	60° (conservative)		
slip_rate (cm/yr)	0.05		
b_value	1.1		
shear_modulus (dyne/cm²)	3.0×10 ¹¹		

Table 5.4 Faults and seismological parameters used in the calculation of the Average Frequency of Exceedance (AFOE) versus displacement for the Rieti Basin case study.

The lengths of the Western Segment (WS) and the Eastern Segment (ES) are derived from the ITHACA database, that currently it remains the most valuable source of information regarding the capable faults present in the Italian territory. For the TBF scenario a new trace has been drawn by connecting the two segments of the Southern Border, and obtaining a segment of 13.5 km.

Minimum magnitude of 5.5 is identified as the most plausible in the case of surface faulting during a seismic event in Central Italy; smaller values are not plausibly supported. Maximum magnitude is defined for the three scenarios applying the Wells and Coppersmith (1994) empirical regression related to the normal kinematic:

$$m = 4.86 + 1.32 * \log (SRL)$$

Due to the uncertainty of the actual length of the seismic source at depth, the Surface Rupture Length (SRL) (*sensu* Wells and Coppersmith, 1984) has been considered instead of the Subsurface Rupture Length (RLD).

The fault areas are calculated from the thickness of the seismogenic layer that is assumed to be 13 km, in accordance with what is indicated in Peruzza and Pace (2002) for the Rieti master fault, and an average 60° dip angle.

A slip rate post LGM value of 0.05 cm/yr was chosen by averaging the values proposed by various authors for the Central Apennines (Calamita et al., 1994, Cello et al., 1997a, Roberts and Michetti 2004).

According to Taroni and Carafa (2023) a similar b -value of 1.1 for the for the Central-Southern Apennines extensional region was considered.

5.4. RESULTS

In this section, the results of applying the PFDHA methodology to the case study are presented. For each scenario considered, the annual frequency of exceedance (AFOE) was estimated for both principal and distributed ruptures. The outcomes are expressed in the form of hazard curves, which account for different exceedance probabilities (1%, 2%, and 10%) over a 200-year interval and for three distinct distances (i.e., 100 m, 200 m, 500 m) from the principal fault traces.

Principal fault results

The hazard curves calculated for principal fault related to WS, ES and TBF are compared in Figure 5.7.

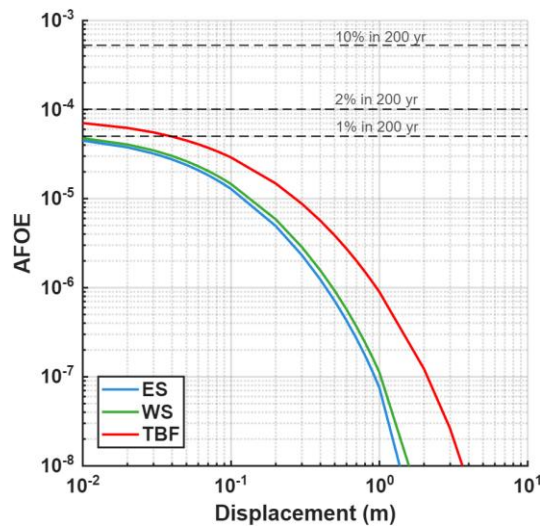


Figure 5.7 Hazard curves calculated for the principal fault segments: the Western Segment (WS), the Eastern Segment (ES), and the Total Border Fault (TBF). Dashed horizontal lines indicate different exceedance probabilities (1%, 2%, and 10%) over a 200-year interval. The curves refer to the AFOE calculations computed within a restricted x/L interval centered on each of the three fault traces considered, corresponding to the central 20% of the fault length.

The WS and ES graphs show comparable results, given the similarity in the size of their seismic sources and, consistently with its source characteristics, TBF exhibits higher hazard values.

The hazard curves corresponding to the two individual segments indicate displacements of 0.01 meters at a 1% probability of exceedance over 200 years,

whereas the hazard curve for the entire TBF reaches a displacement of 0.04 meters for the same exceedance level. None of the curves computed for the three scenarios, however, attain the thresholds associated with 2% or 10% probabilities of exceedance within the 200-year time window.

Distributed rupturing results

Figure 5.8 present the hazard curves for distributed rupturing, assessed on both the hanging wall and footwall across the three studied scenarios.

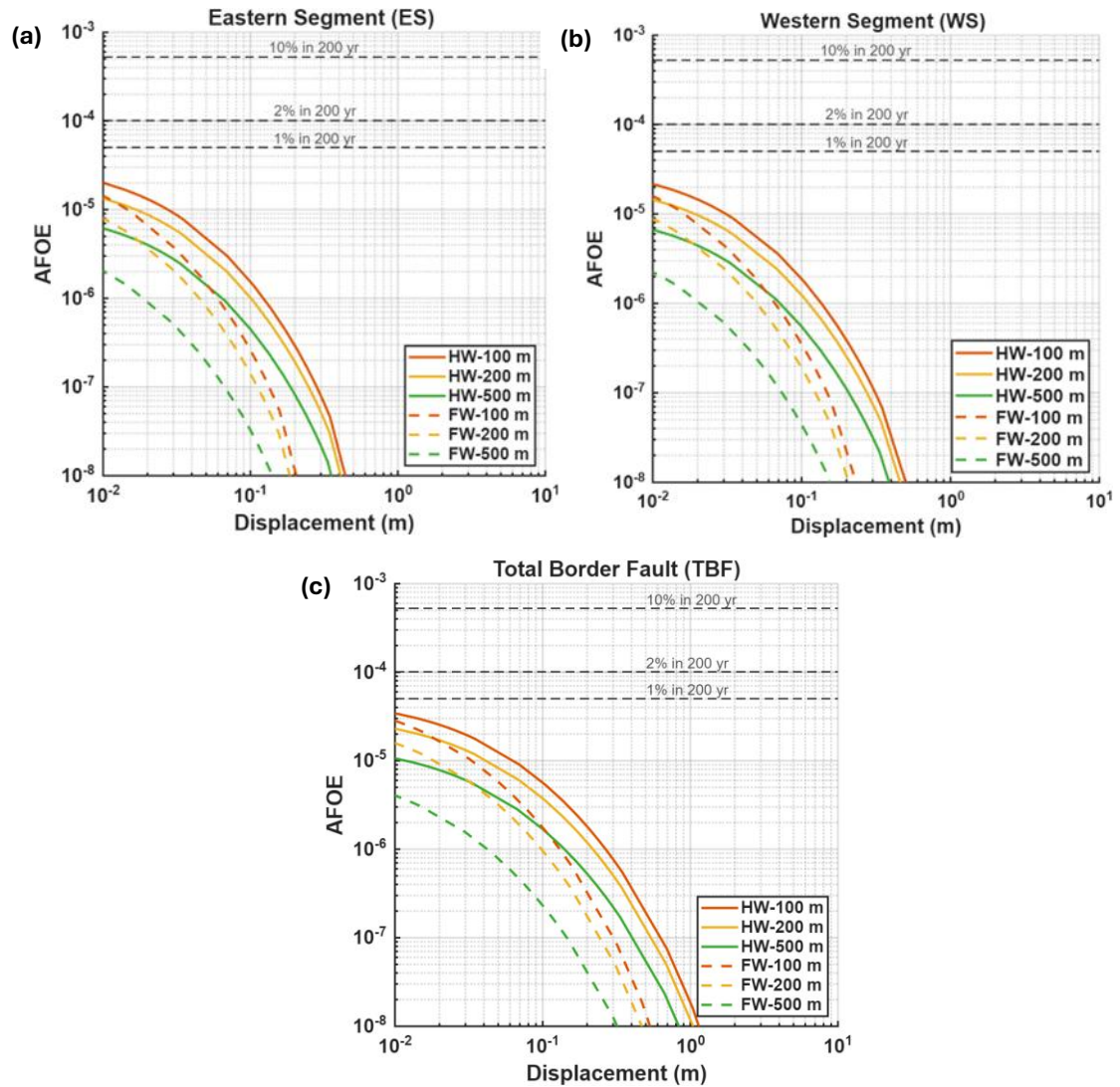


Figure 5.8 Hazard curves for distributed ruptures computed for the three considered scenarios: Panel (a) Eastern Segment (ES), Panel (b) Western Segment (WS), and Panel (c) Total Border Fault (TBF). Curves are calculated for three distinct distances from the principal fault traces (100 m, 200 m, and 500 m), for both the hanging wall (solid lines) and the footwall (dashed lines). Dashed horizontal lines indicate different exceedance probabilities (1%, 2%, and 10%) over a 200-year interval.

None of the hazard curves computed for distributed ruptures related to the three scenarios, for both the hanging wall and the footwall, reach the thresholds corresponding to 1%, 2% or 10% probabilities of exceedance within the 200-year time window.

Only the hazard curve derived from the distributed rupture scenario on the hanging wall, at a distance of 100 m from the principal trace of the TBF, yields values approaching the 1% threshold within 200 years. Specifically, an AFOE of $3.4 \cdot 10^{-5}$ approximately is obtained for a displacement of 0.01 meters, which corresponds to a 0.68% probability of exceedance over a 200-year interval. Moreover, as in the case of the principal fault graphs, the WS and ES graphs show comparable results.

5.5. DISCUSSION

Before delving into conclusions, it is necessary to provide some clarifications regarding the choice to construct the TBF trace by combining the Eastern and Western segments. The connecting segment could potentially be interpreted as a relay structure, which, in tectonic terms, typically accommodates strain through distributed deformation rather than displays the highest displacements along the main fault trace (principal fault, e.g., Cowie and Roberts, 2001). In the present case, the segment connecting the two selected fault sections is a purely geometric construct. Given its central position along the total fault trace, it is plausible, within the constraints of the model, that this segment will register the highest displacement values.

The actual mechanical behavior of this artificial segment cannot be reliably established or modeled, due to the lack of supporting geological and geophysical data, particularly regarding the dip angles of the two fault sections at depth. An initial dip value of 70° was assumed based on surface observations; however, a more conservative value of 60° was adopted, as dip directly influences the estimated fault area and therefore affects the results of the Probabilistic Fault Displacement Hazard Analysis (PFDHA).

Ultimately, the connecting segment is a geometrical assumption, nonetheless, the hypothesis of a common structural plane, where the faults are rooted, at depth, remains plausible and has already been proposed in the literature (Micarelli et al. 2003). Another piece of geological evidence that could support this hypothesis concerns the structural setting of the Upper Pliocene fluvial and slope deposits (see

Guerrieri et al., 2004), which were presumably deposited across the entire basin area and now appear faulted along the basin's southern margin. It is plausible that the southern border of the basin initially developed as a single structure, and that the subsequent initiation and activity of a roughly N–S-striking fault, located more internally with respect to the basin's master fault, displaced the eastern and western segments with a left-stepping (sinistral) geometry. On the basis of the deposits involved, it is reasonable to infer that this step-over between the two segments occurred between the Lower and Upper Pleistocene.

The inclusion of this segment was necessary for constructing the third scenario, which represents the longest fault configuration considered in the analysis.

The application of the PFDHA methodology to this case study yields very low AFOE values, both for the principal fault and for distributed faulting. This outcome is most likely attributable to the fact that the analysis was performed on structural elements with relatively short surface lengths. Such values have a tangible impact on the AFOE vs displacement outputs. In addition, the slip rate adopted for the calculations in the three different scenarios is also a significant factor influencing the resulting AFOE values. It is therefore crucial to assess whether these results may lead to an underestimation of the hazard associated with the behavior of relay structures during seismic events.

It is plausible that the adoption of alternative approaches, such as mechanical or physical-based modeling, could produce higher hazard estimates. Mechanical approaches have been applied at different spatial scales to investigate fault rupture processes. At the laboratory and site scales, Moss et al. (2018) and García and Bray (2022) used analog and distinct-element models to reproduce near-surface fault propagation through soils and layered media. At the regional scale, Wang and Goulet (2021) validated dynamic rupture simulations against the 1992 Landers earthquake, while Chiama et al. (2023) applied distinct element approach to analyze surface deformation in reverse-faulting scenarios. At the crustal or fault-system scale, Zielke and Mai (2023) developed a multicycle earthquake simulator to

explore long-term rupture recurrence, and Gómez-Novell et al. (2023) employed earthquake-cycle models to assess the probability of coseismic surface rupture as a function of fault geometry.

From a geological perspective, it is reasonable to assume that these transverse faults, which intersect the main bounding faults of the Central Apennine basins, may not exhibit independent seismic activity; rather, their activation is likely triggered by slip occurring on the principal fault systems (*sensu* Destro, 1995). Nevertheless, the seismic hazard related to their potential activity should not be underestimated, given their role as significant structural components of the Apennines.

Another key consideration concerns the way in which practitioners apply the PFDHA methodology through computational codes, as well as the inherent limitations of the approach itself. Computational tools are designed to always return output, even when parameterization choices are made by users with limited awareness of the underlying assumptions. However, the validity and robustness of the results strongly depend on the plausibility and geological consistency of the data introduced into the model. The more the input parameters are well constrained and supported by geological investigations, the more reliable the PFDHA outcomes will be. Consequently, high-quality, geologically controlled datasets represent a fundamental requirement for the effective implementation of the PFDHA methodology.

6. CONCLUSIONS

This Doctoral Thesis investigated different aspects of Probabilistic Fault Displacement Hazard Analysis (PFDHA), with the purpose of improving its consistency, transparency, and practical applicability in fault displacement hazard studies.

The first component of the study focused on improving the completeness of the SURE 2.0 database through the integration of surface rupture information from the Fault Displacement Hazard Initiative (FDHI) database. This activity required the design of a structured data migration workflow, the reassessment of rupture rankings, and the spatial verification of slip measurements and fault geometries. The work carried out so far is expected to lead to a more coherent and traceable dataset, ensuring compliance with the quality and robust standards defined by the SURE database framework and improving its suitability for probabilistic analyses. Moreover, the integration process not only underscored the importance of shared data standards and interoperability between international initiatives but also highlighted the need for more comprehensive and standardized acquisition and recording of earthquake-related information. Achieving this goal requires the systematic use of advanced monitoring and surveying technologies now available, which can greatly enhance the completeness, precision, and long-term usability of empirical rupture catalogues.

Although the implementation phase is still ongoing, the performed operations should contribute to reducing geometric and descriptive inconsistencies within the original database. The ongoing activities, including the reassignment of rupture ranks, the spatial verification of slip points, and the adoption of a specific metadata structure, are progressively strengthening the empirical foundation of the dataset and are expected to further improve its reliability for future probabilistic applications once completed.

In particular, the inclusion of ruptures reclassified as Rank 1.5 will offer the scientific community involved in fault displacement hazard assessment an opportunity to

develop new empirical relationships and updated probabilistic models, thereby enhancing the representation of surface faulting complexity in hazard analyses.

The One-At-a-Time (OAT) sensitivity analysis performed on a set of kinematic simulations showed that the selection of alternative scaling laws and regression equations can substantially affect the resulting hazard curves. The analysis revealed deviations of up to about two hundred percent in the annual frequency of (such as magnitude–area scaling and MFD models) exerting the strongest influence in the smaller-displacement interval, while displacement regressions ($AD|m$ and D/AD) dominate the larger-displacement domain.

The study also quantitatively demonstrated that the standard deviations associated with the adopted scaling laws and regression models can modify the AFOE by more than one order of magnitude. This variability among published models represents a significant source of epistemic uncertainty that must be explicitly considered in hazard analyses.

Overall, the results emphasize the importance of transparent model selection, detailed documentation of parameter choices, and explicit uncertainty treatment in applied PFDHA studies. Moreover, the sensitivity outcomes provide practical guidance for identifying the parameters that most strongly affect the hazard estimates and therefore require the most careful calibration in future applications.

The application of PFDHA to the Southern Border Fault of the Rieti Basin represents one of the first attempts to quantify surface rupture hazard in a transverse fault system of the Central Apennines. Despite the structural and kinematic complexities, the results indicate overall low AFOE values for both primary and distributed ruptures, reflecting the relatively limited fault dimensions and the scarcity of very large-magnitude events in the historical and paleoseismological record. Nevertheless, the analysis emphasizes that even structurally subordinate fault systems can play a significant role in accommodating strain and influencing the distribution of surface deformation within intramontane basins. The study further highlights the critical importance of integrating geological and geophysical

constraints into model parameterization to ensure physically meaningful outcomes.

Overall, the findings presented in this Thesis confirm that the robustness of PFDHA outputs strongly depends on the quality of input data and the transparency of modeling assumptions. The research contributes to improving the reproducibility of PFDHA, providing both a methodological framework for uncertainty evaluation and a practical example of its application in a real tectonic setting.

Future work should aim at expanding region-specific datasets, refining empirical regressions through statistically consistent updates, and integrating PFDHA with mechanical models. Such developments will enhance the predictive capability of the method, ultimately supporting more reliable, risk-informed decision-making for land use, infrastructure design, and seismic safety.

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APPENDIX

A) DETAILS ON THE CODE FOR THE PROBABILISTIC FAULT DISPLACEMENT HAZARD ANALYSIS (PFDHA) CALCULATION

The MATLAB implementation follows a stepwise procedure to quantify the annual frequency of exceedance using a probabilistic framework. The workflow integrates empirical scaling laws with stochastic simulations to propagate uncertainties from earthquake occurrence down to surface displacement.

1. Input Parameters

The analysis starts with the definition of seismotectonic and mechanical parameters: fault slip rate, shear modulus, fault area, minimum and maximum magnitudes, and the Gutenberg–Richter b-value. The magnitude interval is bounded between a minimum value (here 5.5) and a maximum value derived from different empirical regressions. The step size Δm is defined by the interval between minimum and maximum magnitudes.

To properly capture variability, the analysis space is discretized into three sets of bins:

- Magnitude bins: 250 intervals between the minimum and maximum magnitude
- Normalized rupture position bins (x/L): 50 intervals along with the fault strike
- Displacement thresholds: 28 discrete values of surface displacement, ranging from centimeters to several meters

This discretization allows numerical integration of the probabilistic model across the entire parameter space.

2. Magnitude Frequency Distribution (MFD)

The recurrence of earthquakes is modeled via alternative MFDs. For each of the 250 magnitude bins, the corresponding probability density function $f(m)$ is calculated and normalized through the moment-balance condition:

$$\sum f(m_i) \cdot M_0(m_i) \cdot \Delta m = \mu \cdot A \cdot \dot{u}$$

where M_0 is the seismic moment, μ is the shear modulus, A the fault area, and $\dot{u}$ the slip rate. This ensures consistency between seismic moment release, fault slip rate, area, and shear modulus.

3. Probability of Surface Rupture

For each magnitude bin, the conditional probability that rupture reaches the surface is modeled via a logistic regression:

$$PSR = P(slip|m) = \frac{e^{a+b \cdot m}}{1 + e^{a+b \cdot m}}$$

with coefficients calibrated from empirical datasets.

This step assigns a probability value to each of the 250 magnitude bins.

4. (AD|m)

For each magnitude bin, the expected average displacement given magnitude is modeled as a lognormal random variable. Parameters (mean and standard deviation in log-space) are defined according to empirical regressions. To account for aleatory variability, the model generates 10,000 random samples of AD for each magnitude bin using a truncated lognormal distribution. A truncated lognormal distribution was adopted for average displacement, to exclude the extreme tails of the distribution (beyond ± 3 SD). This truncation avoids unrealistically small or excessively large displacement values that have no physical justification, while retaining the central portion of the distribution consistent with empirical data. This Monte Carlo approach transforms the deterministic regression into a probabilistic description of displacement.

5. D/AD

The ratio of displacement to average displacement is modeled as a function of rupture position (x/L). Several alternative models are tested (bilinear, quadratic, elliptical, or gamma-based). For each of the 50 x/L bins, 10,000 Monte Carlo

samples are generated, capturing the stochastic variability of displacement scaling along the fault.

These samples represent the statistical variability of local displacement relative to the fault-average value.

The Monte Carlo procedure then combines the sampled $AD|m$ values with the D/AD ratios to obtain 10,000 synthetic realizations of displacement (D) for each magnitude–position pair.

6. Construction of Exceedance Probabilities

The synthetic D samples are post-processed as follows:

- i. Histograms with 1,000 displacement bins are constructed
- ii. The cumulative distribution function (CDF) is obtained
- iii. The exceedance probability curve $P(D > d | m, x/L, slip)$ is derived as the complement of the CDF

The result is a three-dimensional probability matrix indexed by:

- 250 magnitude bins
- 50 x/L bins
- up to 28 displacement thresholds D

7. Annual Frequency of Exceedance

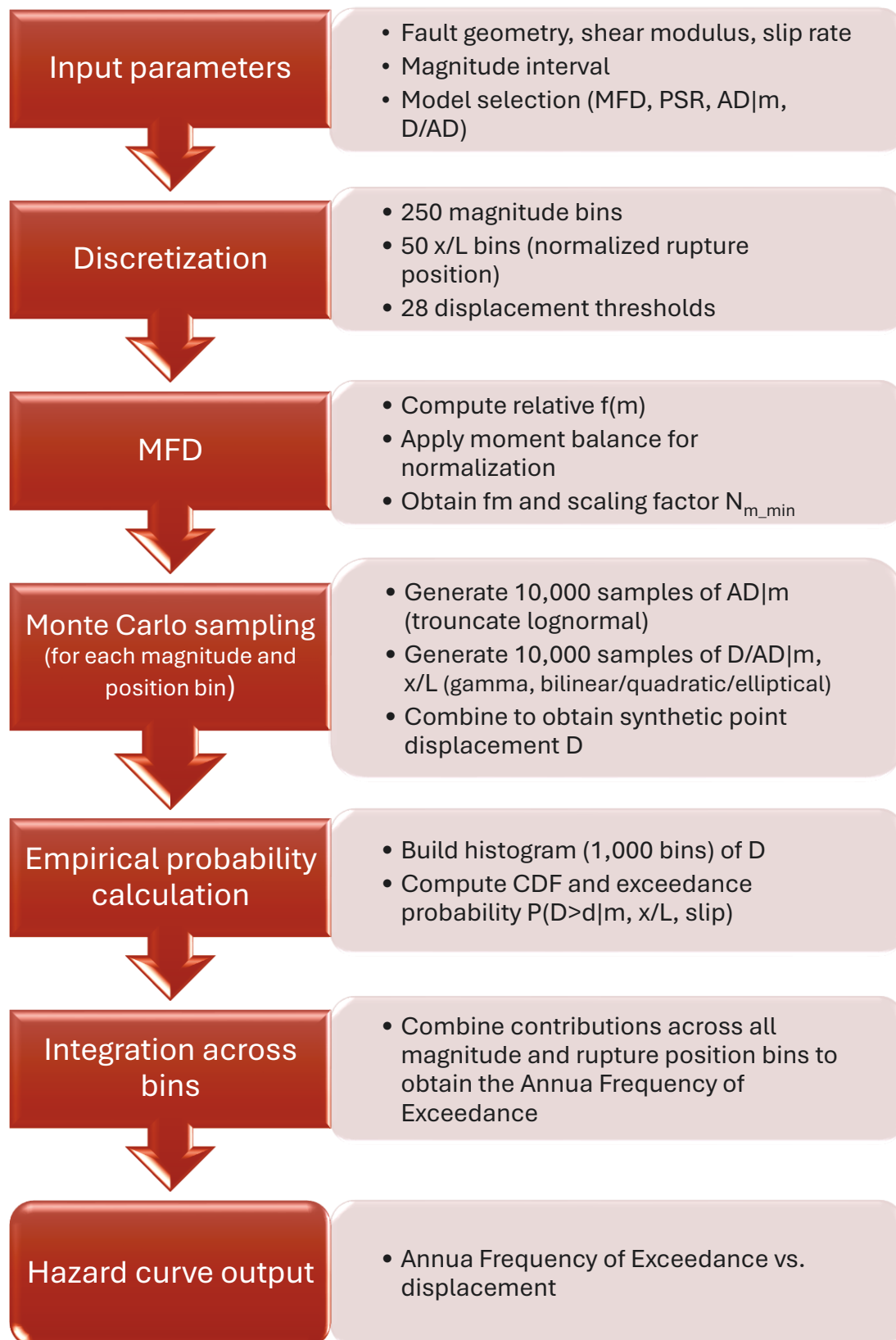
The final hazard calculation integrates across all bins of magnitude and rupture position:

$$\lambda(D > D_0) = \sum_{m=1}^{250} \sum_{x/L=1}^{50} f(m) \cdot PSR \cdot P(D > D_0 | m, x/L, slip) \Delta m \cdot \Delta x/L$$

This discrete summation corresponds to a numerical integration of the full probabilistic model. The result is the annual frequency of exceedance of displacement for each of the 28 displacement thresholds.

8. Hazard Curves

Finally, hazard curves are plotted in log–log space, with displacement on the x-axis and the corresponding annual exceedance probability on the y-axis. These curves quantify the annual frequency of exceedance given displacement levels at the surface.



A 1. Flowchart of the code applied for the Probabilistic Fault Displacement Hazard Analysis (PFDHA) calculation. The workflow illustrates the sequence from input parameter definition and model selection, through Monte Carlo sampling and probabilistic integration across magnitude and rupture-position bins, to the generation of final hazard curves.

B) SUMMARY OF THE EMPIRICAL EQUATIONS ADOPTED IN THE SENSITIVITY ANALYSIS.

m|area

Kinematics	a	b	Equation	Reference
N	3.93	1.02	$m = a + b \cdot \log(A)$	Wells & Coppersmith, 1994
R	4.33	0.9		Wells & Coppersmith, 1994
SS	3.98	1.02		Wells & Coppersmith, 1994
N, R	4	1		Leonard, 2010
SS	3.99	1		Leonard, 2010
N	-2.551	0.808	$\log(A) = a + b \cdot m$	Thingbaijam et al., 2017
R	-4.362	1.049		Thingbaijam et al., 2017
SS	-3.486	0.942		Thingbaijam et al., 2017
Plate boundary faults- Ellsworth-B	4.2	-	$m = a + \log(A)$	Shaw, 2023
Plate boundary faults- Ellsworth-C	4.1	-		Shaw, 2023

Table A1. Summary of the parameter values for magnitude and rupture area relations tested in this work.

MFD

MFD model	
Characteristic earthquake (Schwartz & Coppersmith, 1984)	m_char = from Wells & Coppersmith (1994) $\Delta m = 0.1$ $F_{\text{char}} = 0.5$
Composite magnitude (Youngs & Coppersmith, 1985)	m_char = from Wells & Coppersmith (1994) $\alpha = 0.2$ [Fraction of the total seismic moment allocated to a discrete magnitude bin centred at the characteristic magnitude]
Maximum magnitude (Wesnousky, 1986)	m_char = from Wells & Coppersmith (1994) $\sigma = 0.3$

Table A2. Summary of the parameter values for the MFD models.

PSR

Kinematics	a	b	Equation	Reference
N	-12.53	1.921	$\frac{e^{a+b \cdot m}}{1 + e^{a+b \cdot M}}$	Youngs et al., 2003 (105 extensional cordillera)
N	-13.5	2.159		Pizza et al., 2023
SS	-28.56	4.436		Pizza et al., 2023
R	-10.75	1.427		Pizza et al., 2023
R&SS	-32.03	4.9		Takao et al 2013
R	-24.59	4		Yang et al., 2021
R	-10.75	1.427		Pizza et al., 2023
R	-7.3	1.03	$\frac{1}{1 + e^{a+b \cdot m}}$	Moss et al., 2011
R (stiff)	-13.9745	2.1395		Moss et al., 2013
R (soft)	-6.2548	0.8308		Moss et al., 2013
SS (stiff)	-11.4071	1.8465		Moss et al., 2013
SS (soft)	-12.2908	1.9520		Moss et al., 2013

Table A3. Summary of the parameter values for the probability of occurrence for principal surface faulting tested in this work.

AD|m

Kinematics	a	b	SD	Equation	Reference
N	-4.45	0.63	0.33	$\log(AD) = a + b \cdot m$	Wells & Coppersmith, 1994
R	-0.74	0.08	0.38		Wells & Coppersmith, 1994
SS	-6.32	0.9	0.36		Wells & Coppersmith, 1994
N	-4.967	0.693	0.195		Thingbaijam et al., 2017
R	-3.156	0.451	0.149		Thingbaijam et al., 2017
SS	-4.032	0.558	0.227		Thingbaijam et al., 2017
R	-2.87	0.416	0.133		Moss et al., 2022
R&SS	-4.8	0.69	0.36		Takao et al., 2013

Table A4. Summary of the parameter values for log-linear relations between AD and moment magnitude for principal surface faulting tested in this work.

D/AD

Kinematics	a	b	Reference
N	$e^{(-0.193+1.628 \cdot x/L)}$	$e^{(0.009-0.476 \cdot x/L)}$	Youngs et al 2003
R	$4.2797 \cdot x/L + 1.6216$	$0.5003 \cdot x/L + 0.5133$	Moss et al., 2022
R&SS (fault segment > 10 km)	$e^{(-0.70+0.34 \cdot x/L)}$	$e^{(-1.40+1.82 \cdot x/L)}$	Takao et al., 2013
R&SS (fault segment < 10 km)	1.53	0.58	Takao et al., 2013

SS (bilinear)	$\ln(D/AD) = 8.2525 \cdot x/L - 2.3010$ if $x/L < 0.3008$ $\ln(D/AD) = 0.1816$ if $x/L > 0.3008$	Petersen et al., 2011
SS (quadratic)	$\ln(D/AD) = 14.2824 \cdot x/L - 19.8833 \cdot (x/L)^2 - 2.6279$	Petersen et al., 2011
SS (elliptical)	$\ln\left(\frac{D}{AD}\right) = 3.2699 \cdot x^* - 3.2749$ $x^* = \sqrt{1 - \frac{1}{0.5^2} \cdot [(x/L) - 0.5]^2}$	Petersen et al., 2011

Table A5. Summary of the parameter values for fault displacement prediction equations at different positions for principal surface faulting tested in this work.

C) SEISMOTECTONIC CHARACTERIZATION OF THE SOUTHERN BORDER FAULT OF THE RIETI BASIN

		Western segment	Eastern segment
GENERAL IDENTIFICATION	Fault Code	21009	21007
	Fault Name	RIETI BASIN (Southern border)	RIETI BASIN (Southern border)
	Region Name	Lazio	Lazio
	Tectonic Environment	ND	ND
	System Name	RIETI BASIN	RIETI BASIN
	Synopsis		
	Rank	Primary	Primary
GEOMETRY AND KINEMATICS	Segmentation	Single Segment	Single Segment
	Average Strike (°)	260	260
	Dip (°)	Undefined	Undefined
	Dip Direction	N	N
	Fault Length (km)	6.2	5.5
	Mapping Scale	1:100000	1:100000
	Fault Depth (m)		
	Kinematics	Normal Oblique DX	Normal Oblique DX
ACTIVITY	Surface Evidence	ND	ND
	Last Activity	Late Pleistocene	Late Pleistocene
	Evidence for Capability		Paleoseismology (Holocene-latest Pleistocene)
	Lithology		conglomerates and breccias
FINAL REMARKS	Capability Consensus	High reliability	
	Study Quality	FAIR	

	Notes	Right-lateral component observed on subvertical fault planes in the Villafranchian conglomerates (e.g., Cavinato, 1990)
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Table A6. Extract from the Fault Details table of the ITHACA database (Catalogo delle Faglie Capaci, ISPRA – Dipartimento per il Servizio Geologico d'Italia). The listed information refers to the fault segments forming the southern border of the Rieti basin, here renamed as the Western and Eastern Segments.

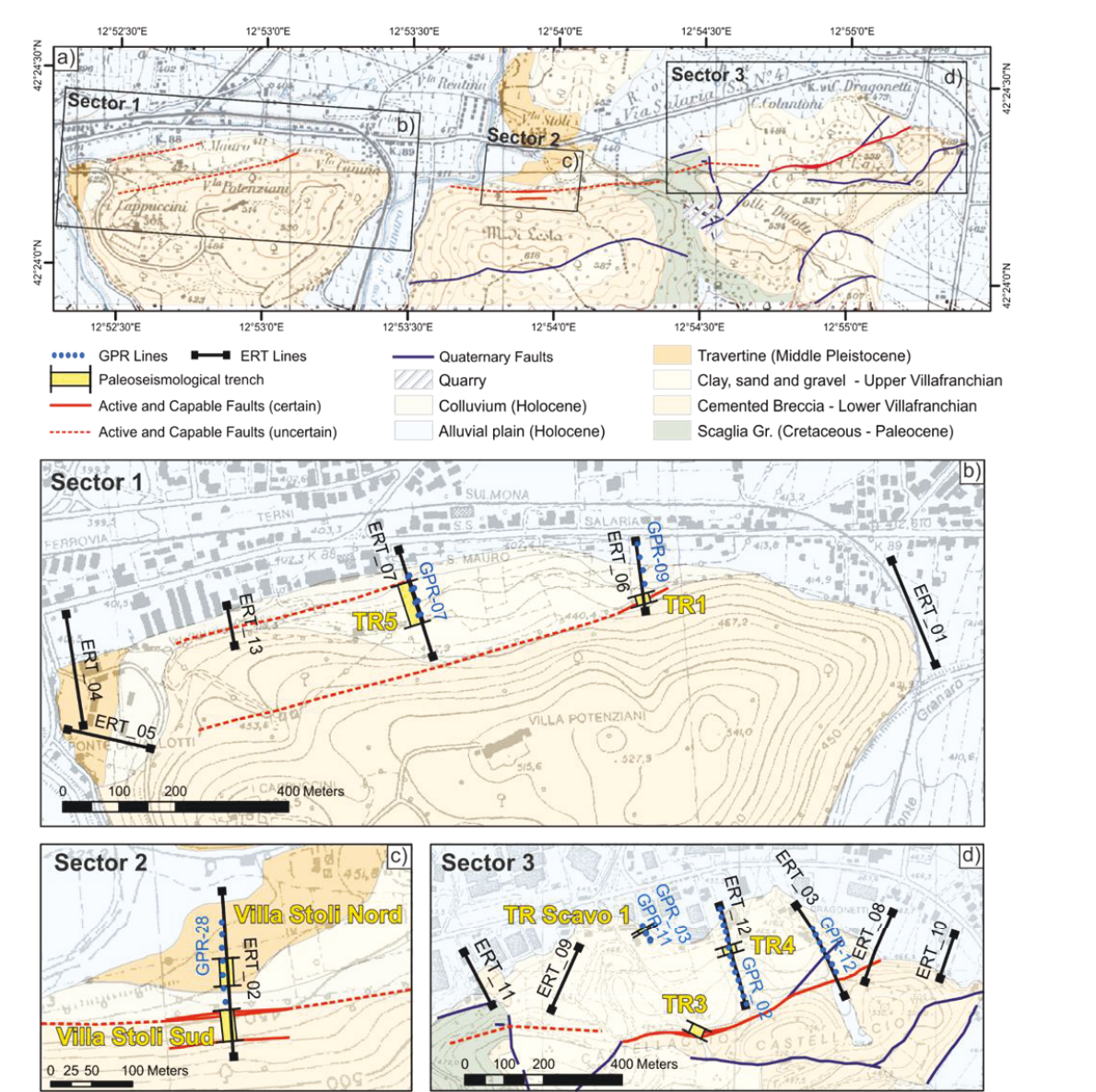


Figure A1. Study Area along the Southern Border Fault: a) simplified geological map; b), c) and d): detailed views on the three studies Sectors (extent is shown in a) with boxes) with the traces of the capable faults and of the geophysical investigations and the footprint of the excavated paleoseismological trenches. (From Livio et al., 2025). Licensed under Creative Commons CC BY 4.0.

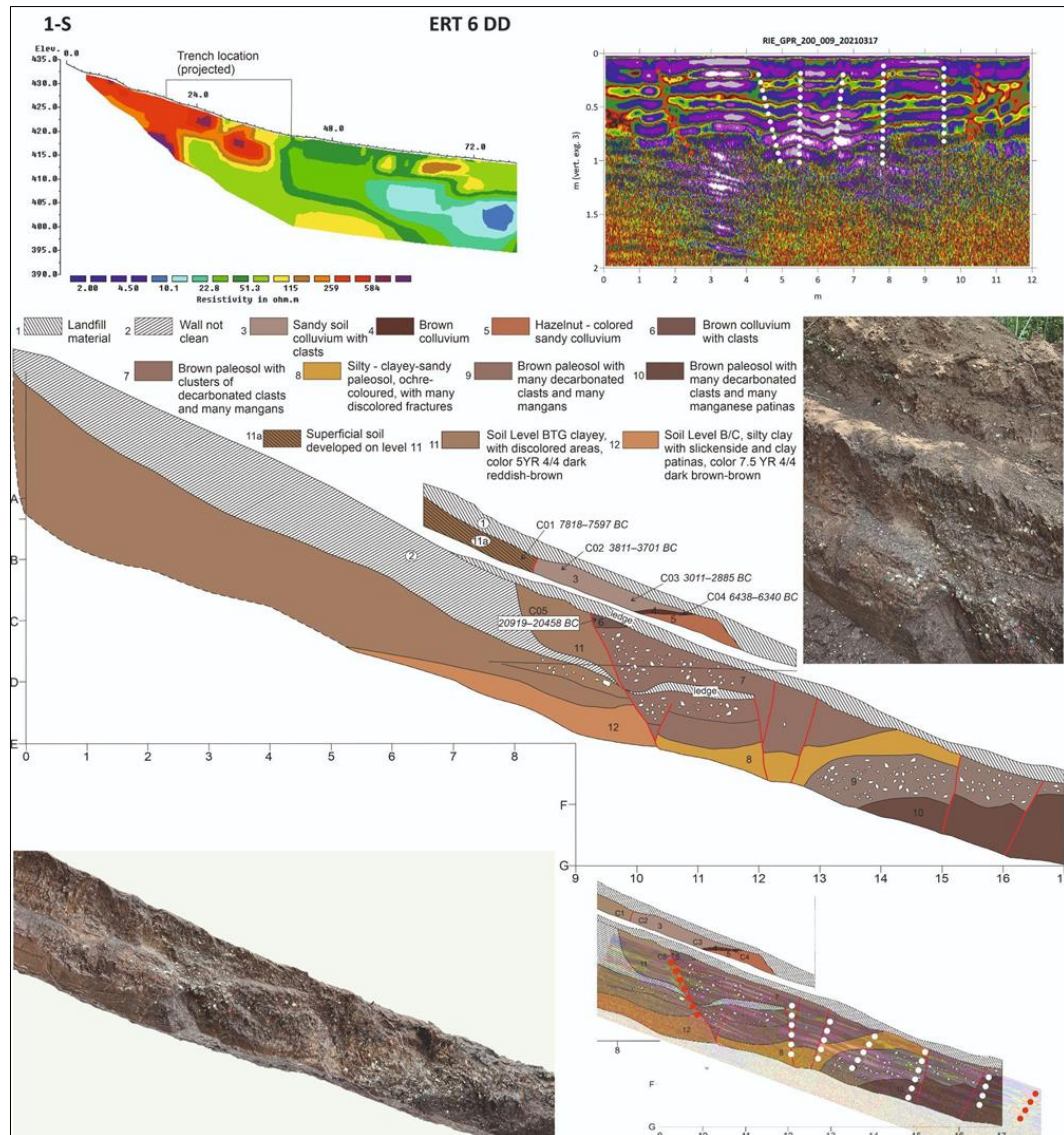


Figure A2. Southern Border Fault, Sector 1: trench documentation and geophysical data from the Trench 1 site. Top: ERT 6 and GPR 09 profiles. Bottom: stratigraphic log of the west trench wall, with a legend describing the various pedogenized deposits of the Monteleone Sabino Synthem and the overlying colluvial units, which are in clear angular discordance. A photomosaic of the lower part of the west wall (stationing 7–17 m) is also included, together with a close-up of the main fault zone between 8 and 11 m. Bottom right: overlay of the stratigraphic log and the GPR profile. (From Livio et al., 2025). Licensed under Creative Commons CC BY 4.0.

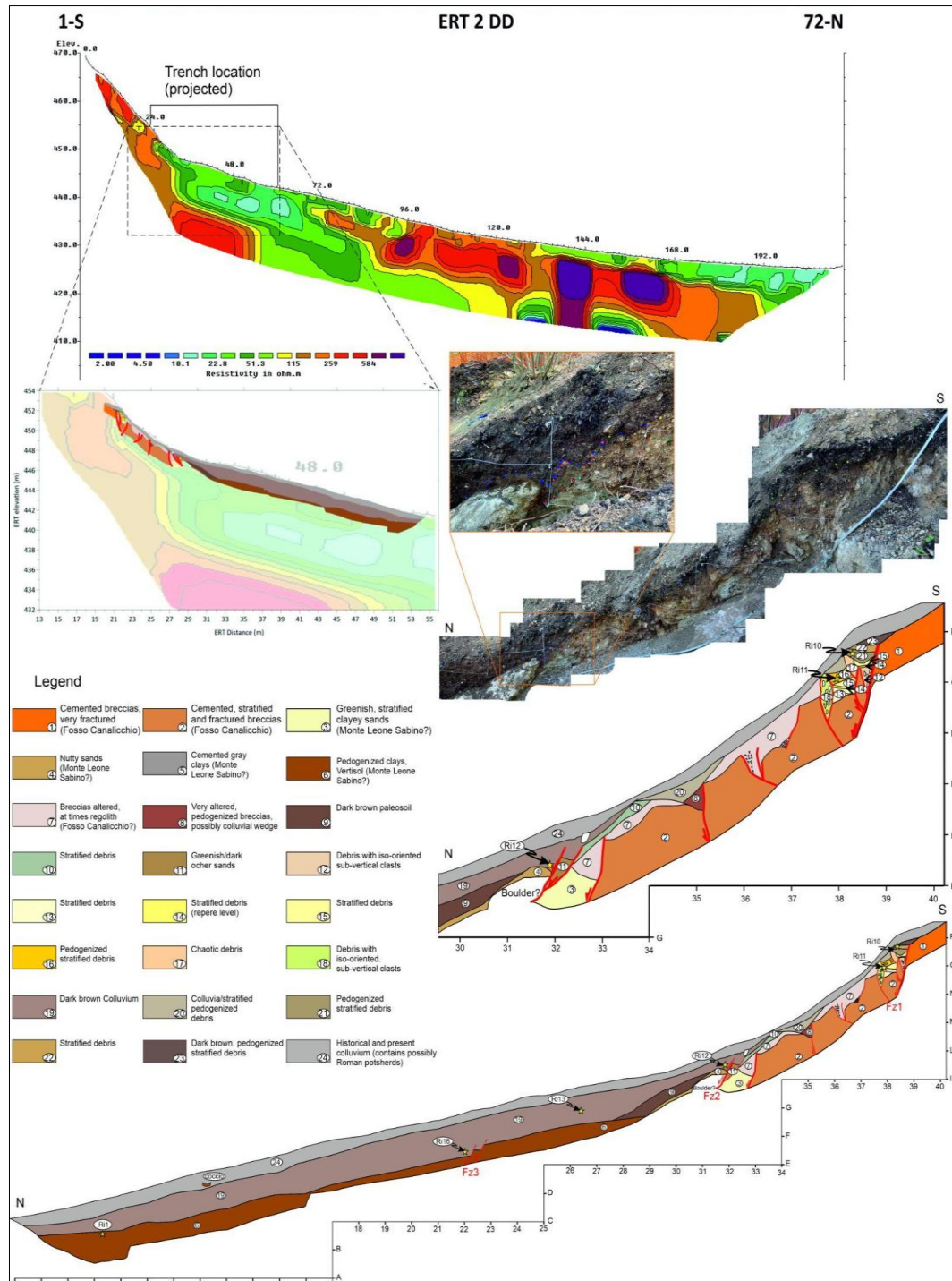


Figure A3. Southern Border Fault, Sector 2 (Villa Stoli): results of investigations at the Villa Stoli site. Top: ERT 02 and GPR 28 profiles. Middle: photomosaic and stratigraphic log of the southern, upper section (first 10 m) of the east wall of the Villa Stoli South trench, showing fault zones Fz1 and Fz2, plus the stratigraphic log overlain on the southern portion of the ERT 02 profile. Bottom: stratigraphic log of the entire east wall of the Villa Stoli South trench. (From Livio et al., 2025). Licensed under Creative Commons CC BY 4.0.

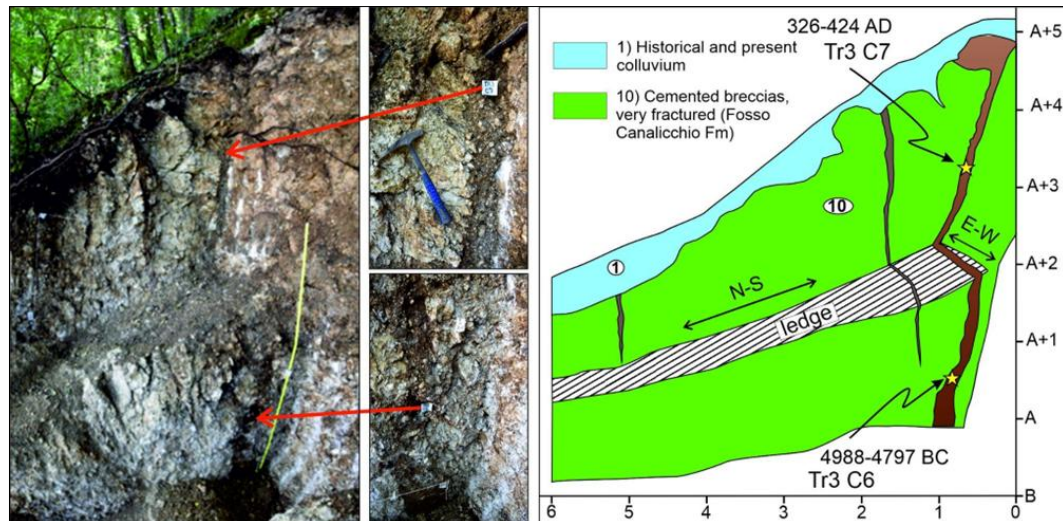


Figure A3. Southern Border Fault, Sector 3. Left: tectonic fracture exposed at the southern end of trench TR3, infilled by colluvial deposits sampled at TR3 C7 (C07) and TR3 C6 (C06). The calibrated ^{14}C ages are 326–424 CE (78.6%) and 4988–4797 BCE (95.4%), respectively. Right: stratigraphic log of the first 6 m of the east trench wall; the “ledge” corresponds to a bench created during backhoe excavation. (From Livio et al., 2025). Licensed under Creative Commons CC BY 4.0.

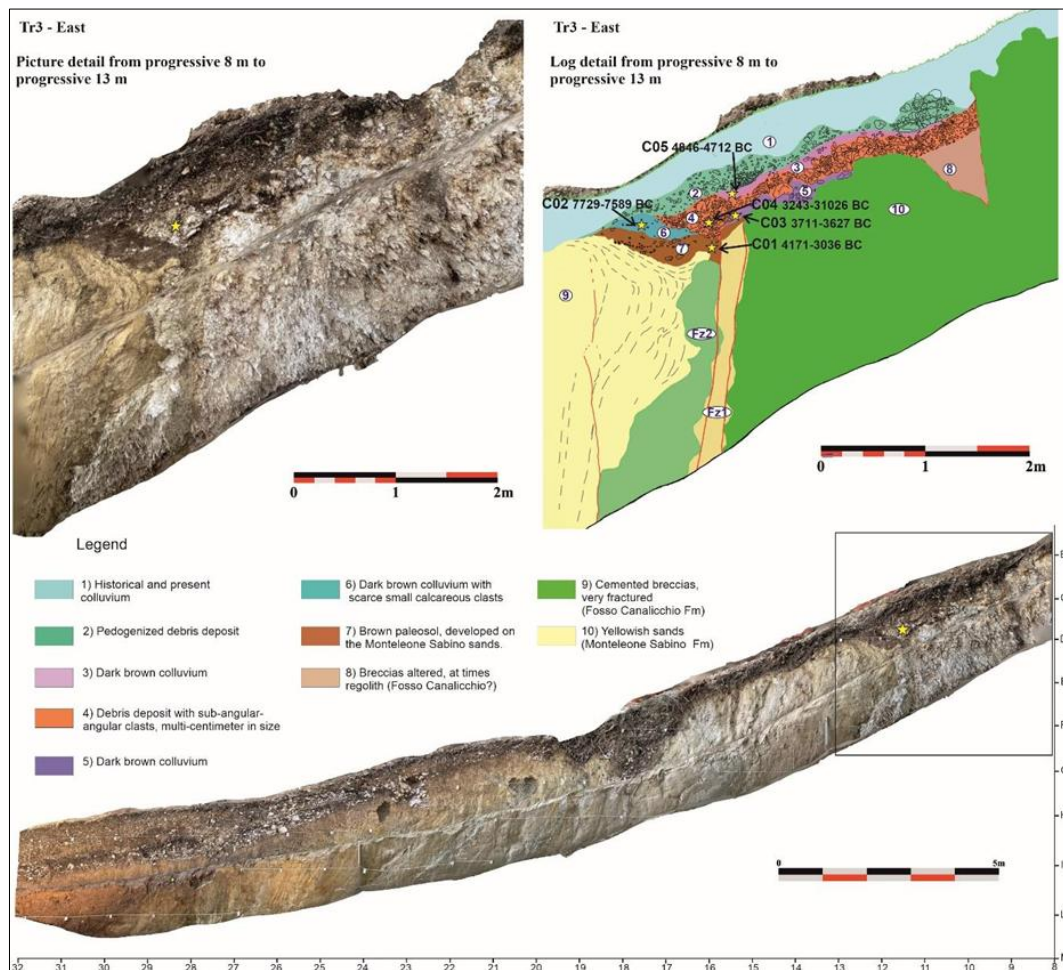


Figure A4. Southern Border Fault, Sector 3. Segment of the east wall of trench TR3 (from progressive 8 m northward to 26 m): close-up and stratigraphic log of the fault zone juxtaposing the Fosso Canalicchio Synthem (Unit 10) against the Monteleone Sabino Synthem (Unit 9). The log depicts the depositional units, AMS dating sampling locations, and fault zones Fz1 and Fz2.