Author's response

We thank the Editor and the Reviewers for their constructive comments, which helped improve the clarity and robustness of the manuscript. In addition to the revisions detailed below, we addressed the remarks from the preceding review file validation; we also ensured consistency in section titles and by adding geographic coordinates to the location maps. Following RC3-7, we implemented a minor correction in the definition of rupture configurations, updating the models and corresponding figures accordingly in both the manuscript and the Zenodo repository (new version released). These adjustments do not affect the overall interpretation of the results nor the main conclusions of the study.

Responses to Referee #1

RC1-1 The introduction is very well written and no changes are suggested regarding writing quality. However, indeed the target study area is Italy, however recent earthquakes such as the 2023 Türkiye–Syria earthquake sequence represent a highly relevant example of multi-fault rupture behavior. Including this event and related studies in the references particularly in the context of multi-fault rupture scenarios discussed in the introduction would strengthen the relevance of the manuscript. Several studies addressing such rupture complexity should now be available.

Author's response (AR): We agree that the 2023 Türkiye–Syria earthquake sequence represents a highly relevant and recent example of complex multi-fault rupture behaviour. We will include this event and the related recent literature in the Introduction to further strengthen the motivation for considering multi-fault rupture scenarios in fault-based PSHA.

RC1-2 The introduction provides a solid overview of fault-based PSHA approaches; however, the scope would benefit from a clearer conceptual distinction between traditional (area-source-based) PSHA and fault-based PSHA. For example, are there specific uncertainties that are better addressed by one approach compared to the other? It would be useful to include quantitative examples or clearly stated metrics (e.g. rates) illustrating the benefits and limitations of fault-based PSHA relative to traditional approaches.

AR: We agree that a more quantitative distinction between traditional area-source-based PSHA and fault-based PSHA would strengthen the Introduction. In the revised manuscript, we will support this discussion by referring to published studies showing quantitative differences between the two approaches, for example in terms of long-term ground-motion estimates and spatial variability of hazard (e.g., Williams et al., 2023).

RC1-3 Typos and minor issues: Line 115: Its probably meant to be "coseismic"; Table 3: In the title: should be "background" (check spelling); Figures 7–12: Figure resolution is poor. The resolution limits readability even with a bit of zooming into the document.

AR: All typographical errors have been corrected, the table title has been revised, and the resolution of Figures 7–12 has been improved in the revised manuscript to enhance readability.

REFERENCES:

Williams, J. N., Werner, M. J., Goda, K., Wedmore, L. N., De Risi, R., Biggs, J., ... & Chindandali, P. (2023). Fault-based probabilistic seismic hazard analysis in regions with low strain rates and a thick seismogenic layer: a case study from Malawi. Geophysical Journal International, 233(3), 2172-2207.

Responses to Referee #2

RC2–1 The Introduction outlines well-known limitations of catalogue-based PSHA and motivates the use of fault-based and multi-fault rupture approaches. However, the Discussion does not clearly close the loop by explicitly demonstrating how the presented results resolve, reduce, or reframe the issues raised in the Introduction. Yet, the manuscript stops short of articulating what new insight this study provides for that debate, beyond confirming that multi-fault ruptures perform better in this case study.

Author's response (AR): The main challenges in fault-based PSHA applications adopting "relaxed segmentation" frameworks are: (1) the explicit definition of possible earthquake rupture scenarios and (2) the estimation of their associated rates of occurrence. While the approach employed in our application does not tackle or "solve" the physical questions behind the plausibility of multi-fault ruptures in the southern Apennines (that would be the role of physics-based investigations; see next comment), it does provide a systematic framework to structure and explore uncertainties related to their definition (earthquake rupture configurations) and rates within a PSHA context. In this framework, the approach does allow to narrow some of these uncertainties through consistency analyses with available observational data (instrumental seismicity and paleoseismic rates). At the same time, our hypothesis-based setup allows preserving the probabilistic nature of PSHA, as the results are intended to be implemented within a logic-tree scheme. In the revised version of the manuscript, we will place emphasis on discussing how our approach might help to address uncertainties arising from arbitrary decisions on earthquake rupture scenarios and earthquake rate estimates for PSHA.

RC2–2 The Discussion correctly acknowledges that SHERIFS is not a physics-based model and therefore cannot assess rupture compatibility or stress interactions. While this caution is appropriate, it also weakens the strength of the conclusions regarding the feasibility of large multi-fault events (e.g., Mw 7.6). The manuscript would benefit from a clearer distinction between statistical consistency with observations and physical plausibility of rupture scenarios. At present, these two concepts are sometimes conflated, which may lead readers to overinterpret the robustness of the conclusions.

AR: We agree with the reviewer that the distinction between physical plausibility and statistical consistency should be more clearly stated to avoid potential misinterpretations. In the revised manuscript, we will systematically differentiate references to "feasibility" from those referring to "statistical consistency" where appropriate.

RC2–3 Section 4.5 proposes explicit weighting of rupture sets and modelling branches for PSHA logic trees. While this is one of the most practically relevant outcomes of the study, the Discussion does not sufficiently address: the transferability of these weights beyond the study area, whether the proposed weighting scheme is meant as a general methodological template or as a region-specific recommendation. This ambiguity reduces the impact of what could otherwise be a key contribution to hazard modelling practice.

AR: The modelling framework we propose follows a logic-tree structure that can be directly implemented within PSHA engines (e.g., OpenQuake). This is due to the nature of SHERIFS, whose workflow is explicitly designed to explore epistemic uncertainties in data and transfer them to PSHA. However, the weighting of rupture sets and branches in the study remains inherently site- and region-specific because they result from consistency checks with regional benchmarks that are not transferrable (seismicity, paleoseismic data). In the revised manuscript, we will better clarify that the proposed weighting scheme is intended as an application-specific implementation within a general methodological framework.

RC2–4 The distinction between SubArea 1 and SubArea 2 is well motivated and clearly described. However, the underperformance in SubArea 2 is largely attributed to data limitations and simplified fault representations, which raises the question of whether the poorer model performance reflects tectonic behaviour or model-input inadequacy. This distinction should be more explicitly discussed to avoid misinterpretation of the results.

AR: We agree that the interpretation of the lower model performance in SubArea 2 requires careful discussion. While the observed lower seismic activity in SubArea 2 raises the question of whether tectonic behaviour may play a role, the modelling framework adopted in this study is not targeted towards unveiling tectonic behaviour and controls on seismicity. Instead, the model evaluates the statistical consistency of different assumptions with regional observations, which are largely affected by input data. The amount and quality of geological fault data available in Subarea 2 is considerably lower than Subarea 1. That is, most estimates of critical parameters like slip rates are based on rough estimates from long-term geodynamical constraints, while in Subarea 1 these are usually based on reliable fault-specific studies. The underperformance of SubArea 2 is likely highlighting poorly constrained fault parameters in this region. This is evidenced by the consistent misfit between model and seismicity rates for SubArea 2, regardless of model setup. Such issues are common in many fault-based studies and reflect heterogeneities in the state of the art of the region, a topic that is beyond the scope of our work. We will better clarify this point in the discussion of the revised manuscript to avoid misinterpretation of the results.

RC2–5 The conclusion that background seismicity has a limited impact is well supported for the chosen buffer configuration. However, the Discussion itself acknowledges that this result is sensitive to buffer size and expert judgment. As written, the conclusions regarding background seismicity risk are interpreted as more general than justified by the tested configurations.

AR: We tested additional buffer sizes (5, 10 and 15 km; respectively Fig. 1, Fig. 2 and Fig. 3) for the background analysis and the conclusions we extract are the same. A 5-km buffer from fault traces is not optimal because it does not always capture the whole surface projection area of the faults and, as such, might exclude some seismicity related to the faults at study. Conversely, 10 and 15 km buffers show the same result, being the 10-km configuration the preferred one, as it is more constrained to the faults. In terms of background ratios, the broad range of background ratios already explored suggests that such variations are unlikely to substantially affect the main conclusions. These points will be more clearly discussed in the revised manuscript (Sections 2.2.4 and 4.4), where we will further emphasize that our conclusions are valid across buffer size values and ratios tested. Also, the buffer-size test figures, together with a map showing the three buffer configurations (5 km, 10 km, and 15 km) superimposed on the fault system (displayed in Fig. 4), will be included in the Supplement.

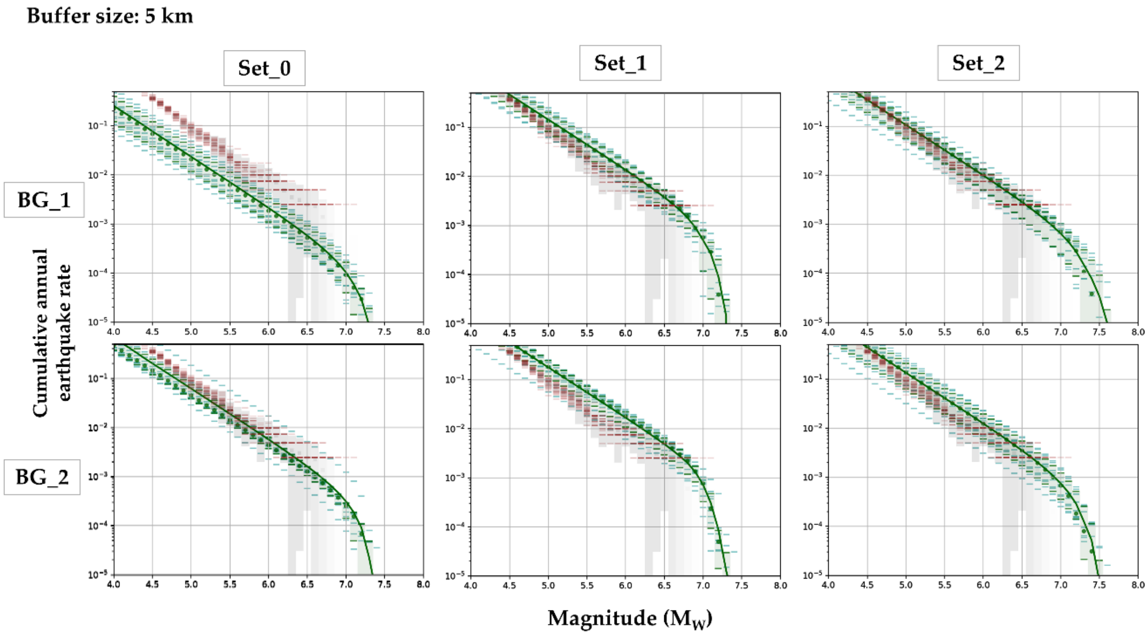

Fig. 1 Buffer size of 5 km from the modelled faults. Columns show the comparison between modelled magnitude-frequency distributions (MFDs; green) and seismicity rates derived from the historical and instrumental regional catalogues within the study area (red), for the three rupture scenarios. Rows correspond to different background seismicity ratio scenarios.

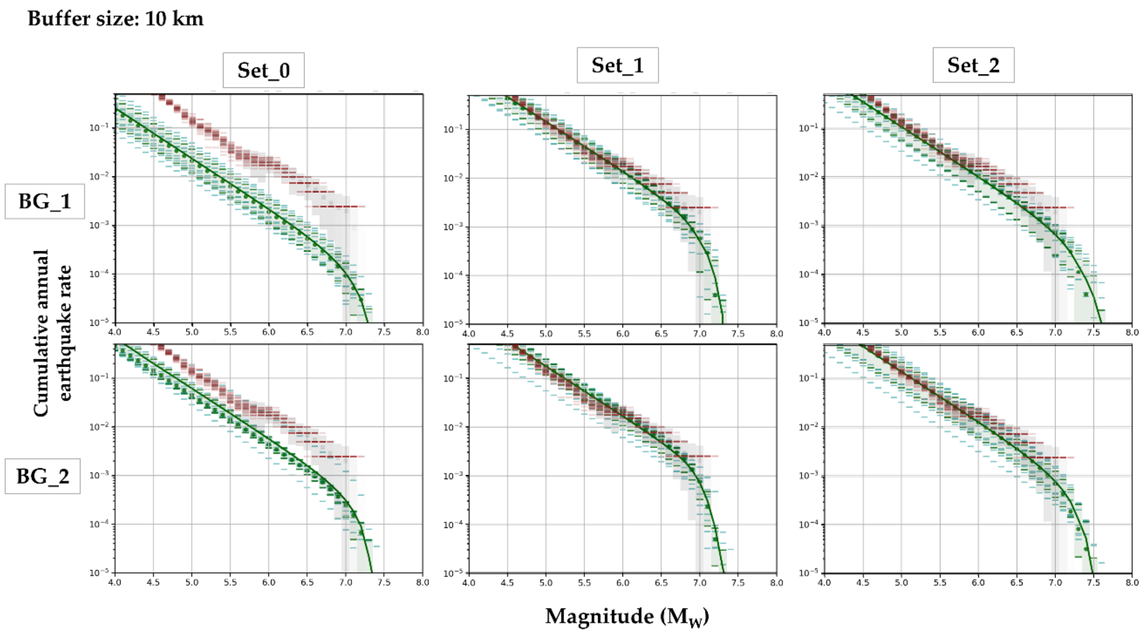

Fig. 2 Buffer size of 10 km from the modelled faults. Columns show the comparison between modelled magnitude-frequency distributions (MFDs; green) and seismicity rates derived from the historical and instrumental regional catalogues within the study area (red), for the three rupture scenarios. Rows correspond to different background seismicity ratio scenario.

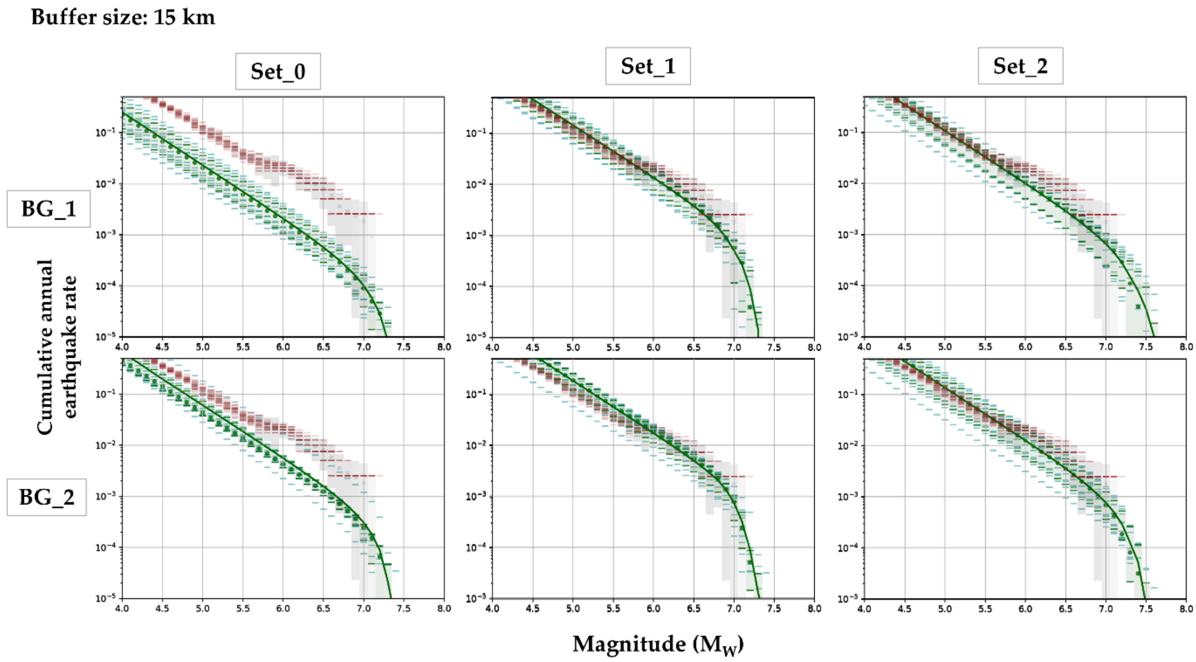

Fig. 3 Buffer size of 15 km from the modelled faults. Columns show the comparison between modelled magnitude-frequency distributions (MFDs; green) and seismicity rates derived from the historical and instrumental regional catalogues within the study area (red), for the three rupture scenarios. Rows correspond to different background seismicity ratio scenario.

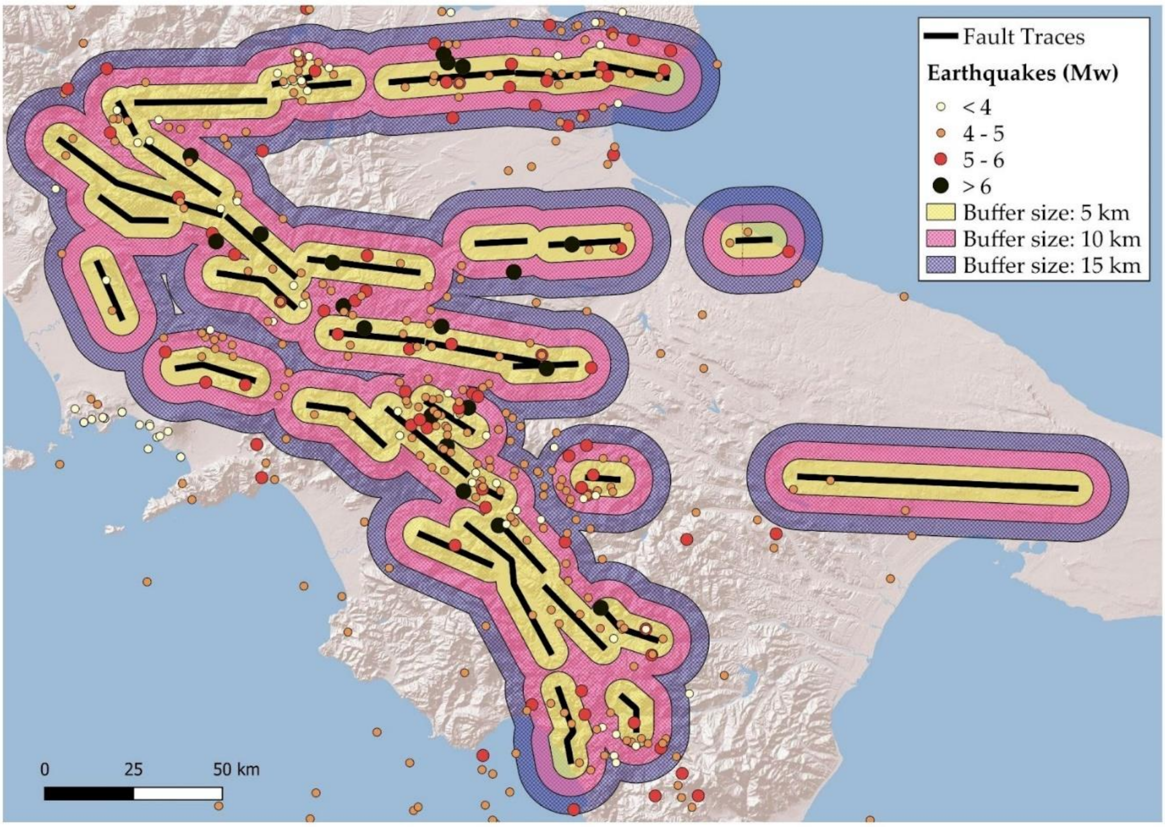

Fig. 4 Geometry of the three buffer configurations (5 km, 10 km, and 15 km) around the faults used to define the background seismicity and to extract the seismic catalogue for the consistency checks. Earthquakes from the CPTI15 v4.0 catalogue (Rovida et al., 2022) are shown for reference.

Responses to Referee #3

RC3-1 The study adopts a relaxed segmentation framework for multi-fault rupture modeling, but the explicit criteria for defining fault segment boundaries (e.g., based on geometric discontinuities, kinematic differences, or tectonic domain divisions) are not clearly stated. Could you elaborate on the segmentation principles and provide quantitative justifications for the division of the 35 seismogenic faults?

Author's response (AR): Fault segmentation criteria are not defined within this study, as fault geometries and segment boundaries are directly adopted from literature and published datasets (DISS Working Group, 2025; Valentini et al., 2017). These datasets use geological, geophysical and seismotectonic criteria for defining fault segments. For instance, Basili et al. (2008) defines individual seismogenic sources in the DISS database - i.e., the fault segments we use - from various sources. These include published geological maps, seismicity, geological, geomorphic and geodetic deformation evidence, among others, to define fault location, fault geometry and parameters. The segmentation we use reflects the state of the art on active faults for seismic hazard applications in the region. We will better clarify this in section 2.2.1 in the revised version of the manuscript.

RC3-2 For the slip rate parameters assigned to each fault (derived from DISS 3.3.1 and Valentini et al., 2017), there is a lack of analysis on the consistency between slip rates of adjacent faults in the same tectonic domain. Please clarify how slip rate variations across the fault system are reconciled with regional geodynamic constraints.

AR: The consistency of slip rates across adjacent faults is addressed in the original studies from which we extract the fault data (DISS Working Group, 2025; Valentini et al., 2017). A re-evaluation and discussion of slip rate consistency with regional constraints is beyond the scope of this study. Having said that, slip rate variability is natural within fault systems even within a same strain field or geodynamic context. Faults accommodate strain rates differently depending on orientation, geometry and frictional parameters. This behaviour has been recognized in many fault systems, including the Central Apennines, and is reflected in other databases (e.g., Faure Walker et al., 2021).

RC3-3 The introduction lacks detailed information on the regional tectonic background, which is essential to justify the strike-slip and normal faulting characteristics of the fault system in the southern Apennines.

AR: We will expand the tectonic background explaining the coexistence of extensional and strike-slip regimes.

RC3-4 For Figure 1 in Page 3, the slip rates of strike-slip faults lack consistency or continuity. Areas without mapped fault traces may correspond to segments where blind faults are developed. I suggest the authors either incorporate this consideration into the segmentation model or discuss it in detail in the Discussion section.

AR: The lack of continuity between fault traces in the strike-slip systems may reflect the potential presence of blind unmapped faults. However, our scope is not to speculate on the potential incompleteness of existing fault databases, but rather to use them for an applicative purpose. As such, the mere presence of an active fault is not a sufficient condition for its inclusion into a fault-based application for PSHA. For instance, additional faults are identified in the ITHACA (ITaly HAzards from CApable faults, available at https://sgi.isprambiente.it/ithaca/viewer/) catalogue beyond those depicted in the DISS database. However, these faults are not considered suitable for our assessment, as they generally lack key parameters required for earthquake rate modelling, such as slip rates and seismogenic depths. For this reason, only faults with sufficiently constrained parameters should be included in the modelling, which is the criterion we follow. In the revised manuscript (section 2.2.1) we will clarify this point more explicitly.

RC3-5 The three rupture scenarios (Set_0, Set_1, Set_2) are defined using different distance thresholds (5 km and 10 km) for rupture propagation, but the rationale for selecting these specific thresholds is not sufficiently justified. Could you provide references or quantitative analysis to support the choice of distance criteria for multi-fault rupture connectivity?

AR: The distance criterion adopted for Set_1 is supported by the definition of multi-fault rupture distances in previous studies, as already discussed in the manuscript. One of the most important references is the UCERF-3 definition (Milner et al., 2013; Field et al., 2014), which allows multi-fault ruptures with a maximum inter-fault jump distance of 5 km. Set_2 is intentionally more speculative and was introduced to explore an upper-bound behaviour. This choice is motivated by historical evidence of complex multi-fault ruptures in the study area, such as the 1980 Mw 6.9 Irpinia earthquake, which involved multiple adjacent fault segments separated by distances exceeding 5 km (faults 21–22–23). We will further clarify this rationale in Section 2.2.2 and 4.1 of the revised manuscript.

RC3-6 The study uses Wells & Coppersmith (1994), Leonard (2010), and Thingbaijam et al. (2017) scaling relationships for magnitude estimation, but it does not address whether these global or broad-scale models are fully applicable to the tectonic setting of the southern Apennines. Please supplement a discussion on the regional adaptability of the selected scaling laws, including potential adjustments for local tectonic characteristics.

AR: All the scaling relationships adopted in this study are widely used in PSHA applications and have broad applicability. Leonard (2010) has already been employed in regional studies in Italy and is used for the parametrization of the databases (e.g., DISS, 2025), supporting its suitability for the study area. Wells and Coppersmith (1994) provide a robust and widely adopted model that does not require specific adjustments between continental extensional and compressional regimes. In addition, Thingbaijam et al. (2017) explicitly provides coefficients for normal faults, which represent the dominant faulting style in the Apennines, allowing a better representation of this tectonic regime. We will clarify this motivation in the revised manuscript.

RC3-7 Line 155, for the multi-fault ruptures, the difficulty in this area is not only the rupture combinations of the segments with the same rupture characters, but the rupture combinations of the segments with strike-slip and the ones with normal-slip. These combinations are hard to judge for multi-segment ruptures. For instance, the multi-fault rupture scenario involving Faults 18, 19, and 20 is likely to be geologically feasible. I suggest the authors to add these rupture combinations. For instance, the multi-fault rupture scenario involving Faults 18, 19, and 20 is likely to be geologically feasible. Such rupture combinations are fully mechanically explicable (Oglesby, 2005) and have been observed in numerous regions worldwide (e.g., the 1995 *M*2 Multi-Segment Nuweiba Earthquake), as stated by Oglesby (2005), and are also incorporated into the multi-segment rupture scenarios for the SHERIFS modeling framework (e.g., Cheng et al., 2025, NHESS).

AR: While it is true that earthquake ruptures involving faults with different kinematics have been observed in several earthquakes in nature, the extrapolation of such phenomena - which represent exceptional rather than typical behaviour - is not straightforward for the southern Apennines. The linkage between extensional and strike-slip systems in this region is not sufficiently studied and, as such, the consideration of joint ruptures across these systems remains highly speculative from our perspective. Incorporating such scenarios would propagate this level of speculation into the modelling results, which are already based on a number of important assumptions in terms of fault model parametrization.

Having said that, we conducted an additional test explicitly including the F18-F19-F20 multi-fault rupture in both Set_1 and Set_2 (Fig. 5; Fig. 6). We observe that the inclusion of this scenario does not significantly change the modelled earthquake rates across rupture sets. This indicates that the kinematic rule adopted in our modelling is likely not a driving factor in controlling the earthquake rates.

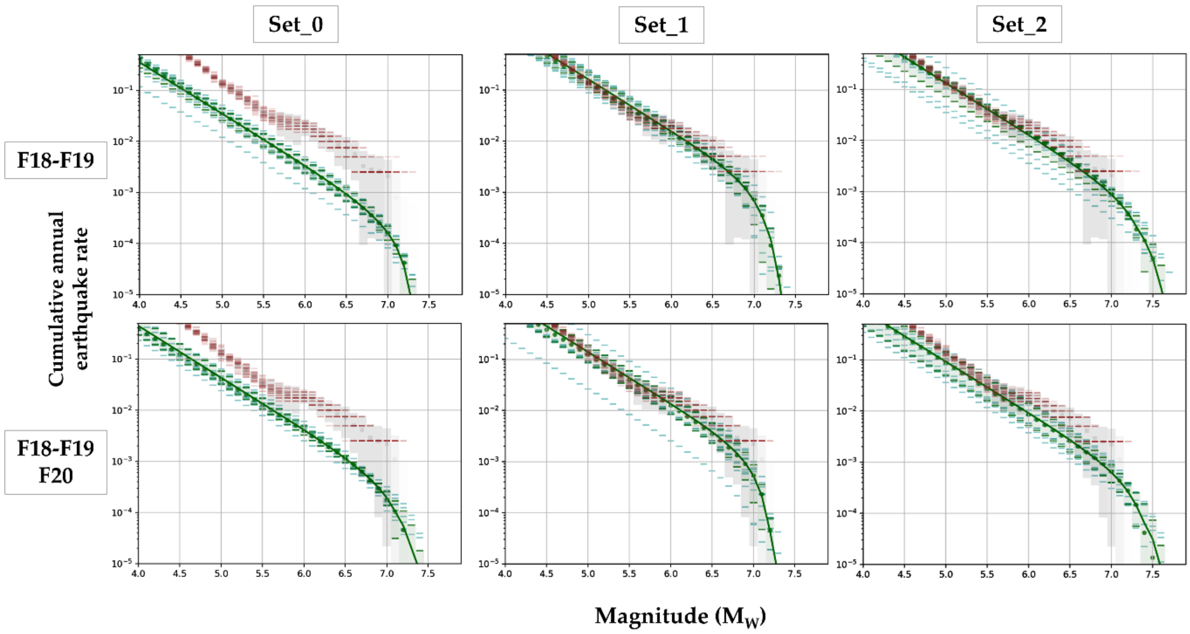

Fig. 5 Comparison between the original model configuration (above) and the model including the additional F18-F19-F20 multi-fault rupture (below). Columns show the comparison between modelled magnitude-frequency distributions (MFDs; green) and seismicity rates derived from the historical and instrumental regional catalogues within the study area (red), for the three rupture scenarios.

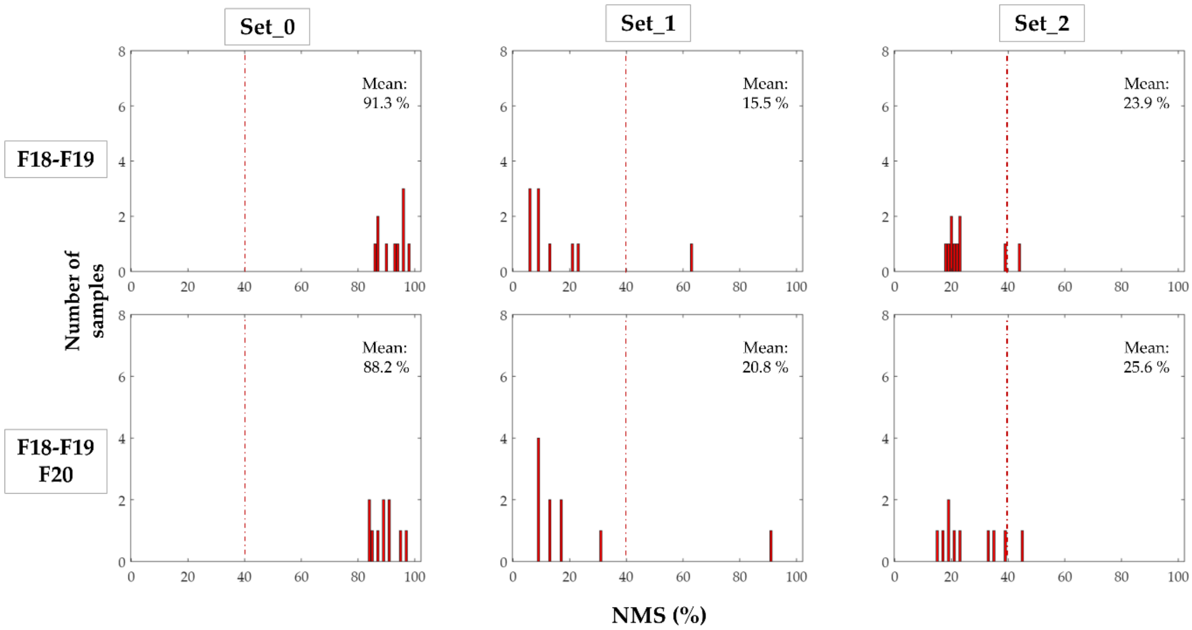

Fig. 6 Comparison between the original model configuration (above) and the model including the additional F18-F19-F20 multi-fault rupture (below). Columns show the non-mainshock slip (NMS, expressed as a percentage) for each random sample explored in the model, for the three rupture scenarios.

Two main reasons explain this limited impact. First, the strike-slip fault system in the southern Apennines generally shows lower slip rates than the extensional system, which means that these faults have a smaller contribution to the overall seismicity rates. Second, the distances between the extensional and strike-slip fault systems are, in most cases, larger than even our least restrictive connectivity threshold (10 km), meaning that the ability of both systems to participate in a multi-fault rupture is limited.

To preserve internal consistency and reproducibility, we therefore adopt uniform rupture-definition criteria based on tectonic domain and distance thresholds, avoiding case-specific exceptions. This choice is consistent with our objective of defining general rules for seismicity-rate estimation in PSHA, rather than enumerating individual geologically plausible rupture scenarios. The comparison between the original model configuration and the configuration including the F18-F19-F20 rupture is shown in Fig. 5, and does not change our conclusions, nor the model performance in terms of NMS (Fig. 6).

In the process of addressing this comment, the revision of the rupture configurations also allowed us to identify and correct two minor inconsistencies in the rupture scenario definitions. This led to a slight re-configuration of the rupture sets compared to the original manuscript version. While this results in minor differences in the absolute values of some metrics (e.g., MFDs and NMS), these adjustments do not affect any of the scientific interpretations or conclusions of the study. If anything, the revised configuration improves the internal consistency and overall modelling performance. The figures presented here therefore refer to the updated model configuration, which will be reflected in the revised manuscript.

RC3-8 The non-mainshock slip (NMS) ratio is employed as an indicator of model quality, yet this study fails to discuss how the NMS ratio varies with fault kinematics (i.e., strike-slip vs. normal faults) across the two tectonic sub-areas. The NMS ratios of normal fault systems tend to be higher than those of strike-slip fault systems, because the extensional stress environment can activate a greater number of small-scale faults compared with the shear stress environment. It is recommended that an analysis of NMS differences between different fault types, as well as their corresponding geological interpretations, be supplemented.

AR: The non-mainshock slip (NMS) is primarily a metric to evaluate model performance and consistency with observed seismicity, rather than as a direct indicator of tectonic behaviour. That is, it is an indicator of how the model configuration is able to allocate slip rate budget seismically within the fault system. As the original SHERIFS paper suggests, small NMS proportions can be linked to aseismic processes because geological slip rates include both seismic and aseismic processes; hence it is reasonable to expect a certain amount of the slip to be aseismic. However, large NMS indicate inability of the model set up to spend slip rate seismically. Differences in NMS values between SubArea 1 and SubArea 2 mainly reflect features of the fault data coverage and rupture-scenario configuration. In this context, we would rather not do geological interpretations from NMS because the metric was not designed to be an indicator or reproduction of any natural behaviour in fault systems.

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