Responses to referee #2

The manuscript is well written and supported with informative figures. The methods employed are applicable, appropriately applied and adequately described. I have only some minor/moderate suggestions prior to publication.

Author's response (AR): We sincerely thank the reviewer for the time and effort dedicated to revising our manuscript.

The manuscript states that 100 sub-catalogues of 1 kyr duration are randomly extracted from a 1 Myr synthetic catalogue and used for PSHA. However, I would like to suggest clarifying more explicitly that each sub-catalogue represents only one possible realization of earthquake occurrence over a limited time window, and not the long-term "true" seismic hazard of the system. As currently written, the text may give the misleading impression that each sub-catalogue is equally representative of the long-term hazard, whereas they should instead be interpreted as stochastic realizations sampling different portions of the seismic cycle.

AR: We extracted 1-kyr sub-catalogues to match the duration of our historical catalogue (which spans from 1050 AD and is therefore approximately 1 kyr long). As the reviewer correctly notes, each sub-catalogue represents just one possible realization of the long-term hazard. This is precisely what we aim to compare: the hazard estimated from 100 stochastic 1-kyr realizations against the hazard derived from the actual historical catalogue—which we also consider, in fact, as one possible realization. We will clarify this point in paragraph 1 of the Materials and Methods section and again in the Discussion.

Slip-rate input and data origin.

The mean slip rate of the fault system (1.5 ± 0.3 mm/yr; Echeverría et al., 2013) is a key input of the synthetic model and therefore strongly controls the long-term seismic moment release and earthquake productivity. However, its origin is not discussed. I would like to suggest clarifying how these slip rates were derived (e.g., paleoseismological trenching, geomorphology, geodesy) and over which temporal window they are averaged. This information would be important for assessing the consistency between the geological input and the simulated seismicity.

AR: We sincerely thank the reviewer for this comment. We agree that the origin and temporal representativeness of the slip-rate estimates are essential to properly assess the consistency between the geological input parameters and the simulated seismicity. To address this point, we have now included a new table compiling the slip-rate values assigned to each fault segment, together with the corresponding references and a brief description of the methods used to derive them (e.g., geomorphological analysis, paleoseismological data, and/or geodetic constraints, where applicable).

Additional details on the geological characterization of the fault system can be found in the supplementary material of Herrero-Barbero et al. 2021.

Table X: Model input parameters for fault sections in the EBSZ obtained from Herrero-Barbero et al., 2021.

Fault name	Fault section name	Rake	Deviation	Slip rate	Deviation	References
Alhama de Murcia Fault (AMF)	Góñar–Lorca	20	0–40	1.1	0.50–1.70	R from slickenlines measured by Martínez-Díaz (1998). SR based on trenches (Ferrater et al., 2017; Ortuño et al., 2012)
	Lorca–Totana	39	19–59	0.9	0.80–1.00	R from 2011 Lorca eq.(Martínez-Díaz, Bejar-Pizarro, et al., 2012) and structural analysis by Alonso-Henar et al. (2020). SR from trenching and morphotectonic analysis (Ferrater et al., 2016; Ferrater et al., 2017)
	Totana–Alhama de Murcia	42	25–58	0.2	0.07–0.32	Data inferred from AMF-4
	Alhama de Murcia–Alcantarilla	42	25–58	0.2	0.07–0.32	SR and R from cross-section restorations (Herrero-Barbero et al., 2020). Min.SR from Silva et al. (2003).
Carboneras Fault (CF)	Southern Carboneras (offshore)	10	0–20	1.2	1.10–1.30	Data from deflected submarine channels in CF-1 (Moreno, 2011) and onshore fluvial channels in CF-2 (Moreno et al., 2015). Max. SR based on GPS data of Echeverria et al. (2015)
	Northern Carboneras (offshore-onshore)	10	0–20	1.2	1.10–1.30	
Palomares Fault (PF)	Southern Palomares–Arteal Faults	−5 (0)	(-25) - 15	0.04	0.01–0.08	Data measured by Booth-Rea et al. (2004), comparing fluvial deposits and paleochannels in PF-1. R in PF-2 is consistent with the moment tensor of a recent M_w3.6 event (IGN, 2019)
	Northern Palomares (S[a] Almenara)	15	0–35	0.04	0.01–0.08	
	Northern Palomares–Hinojar Faults	15	0–35	0.1	0.04–0.16	R is inferred from PF-2 and SR is based on comparison between PF-3 and LTF-1
Los Tollos Fault (LTF)	Los Tollos Fault	15	0–35	0.16	0.06–0.25	R and SR obtained through trenching by Insua-Arévalo et al. (2015).
Carrascoy Fault (CAF)	SW Carrascoy–Algezares–Casas Nuevas	90	75–90	0.37	0.29–0.45	R and SR estimated from trenches by Martín-Banda et al. (2016). R is referred to the younger reverse branch (see Table S1).
	NE Carrascoy Fault	15	5–25	0.85	0.50–1.20	Data from structural analysis (Martín-Banda, 2020; Sanz de Galdeano et al., 1998; Silva, 1994).
Bajo Segura Fault (BSF)	Hurchillo	90	70–110	0.4	0.29–0.51(0.6)	SR estimations from Alfaro et al. (2012) using stratigraphic markers and assuming pure reverse. Note that GPS data from Borque et al. (2019) show 0.6 ± 0.2 mm/yr of shortening for the entire BSF zone
	Benejúzar	90	70–110	0.27	0.20–0.34	
	Guardamar	90	70–110	0.2	0.15–0.25	
	Bajo Segura Offshore	90	70–110	0.2	0.15–0.25	For R, see seismic profiles from Alfaro et al. (2012) and Perea et al. (2012). SR is inferred from BSF-3

Herrero-Barbero, P., Álvarez-Gómez, J. A., Williams, C., Villamor, P., Insua-Arévalo, J. M., Alonso-Henar, J., & Martínez-Díaz, J. J. (2021). Physics-based earthquake simulations in slow-moving faults: A case study from the Eastern Betic Shear Zone (SE Iberian Peninsula). *Journal of Geophysical Research: Solid Earth*, *126*(5), e2020JB021133.

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Magnitude–frequency distributions of sub-catalogues

It may be useful to include a figure showing the variability of the magnitude–frequency distributions (MFDs) of the individual sub-catalogues compared with those derived from the historical/instrumental catalogue and from the ZESIS database. This would help the reader to visually assess how representative the synthetic sub-catalogues are with respect to observed seismicity and to the long-term model.

AR: We sincerely thank the reviewer for this helpful suggestion. We agree that a visual comparison of the variability of the magnitude–frequency distributions (MFDs) significantly enhances the assessment of how representative the synthetic sub-catalogues are with respect to the observed seismicity and the long-term model. In response, we have prepared and incorporated a new figure showing the MFDs of the individual synthetic sub-catalogues together with the one derived from the historical/instrumental catalogue. We believe this addition improves the clarity of the comparison and allows the reader to more readily evaluate the consistency between the simulated and observed seismicity.

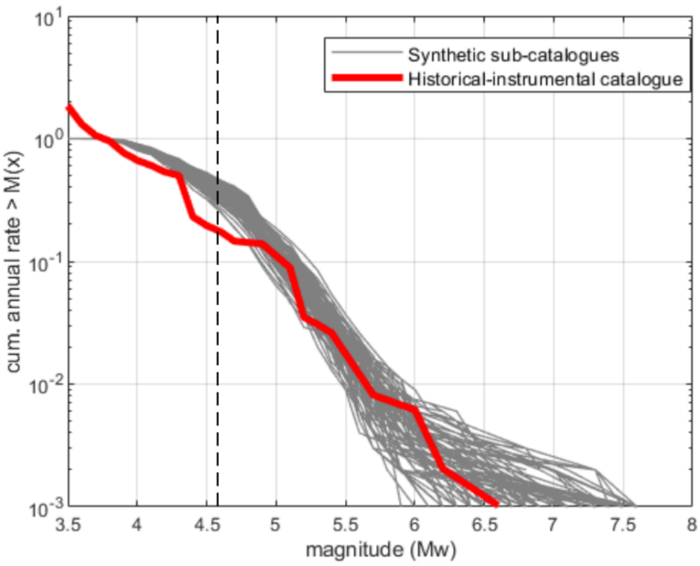
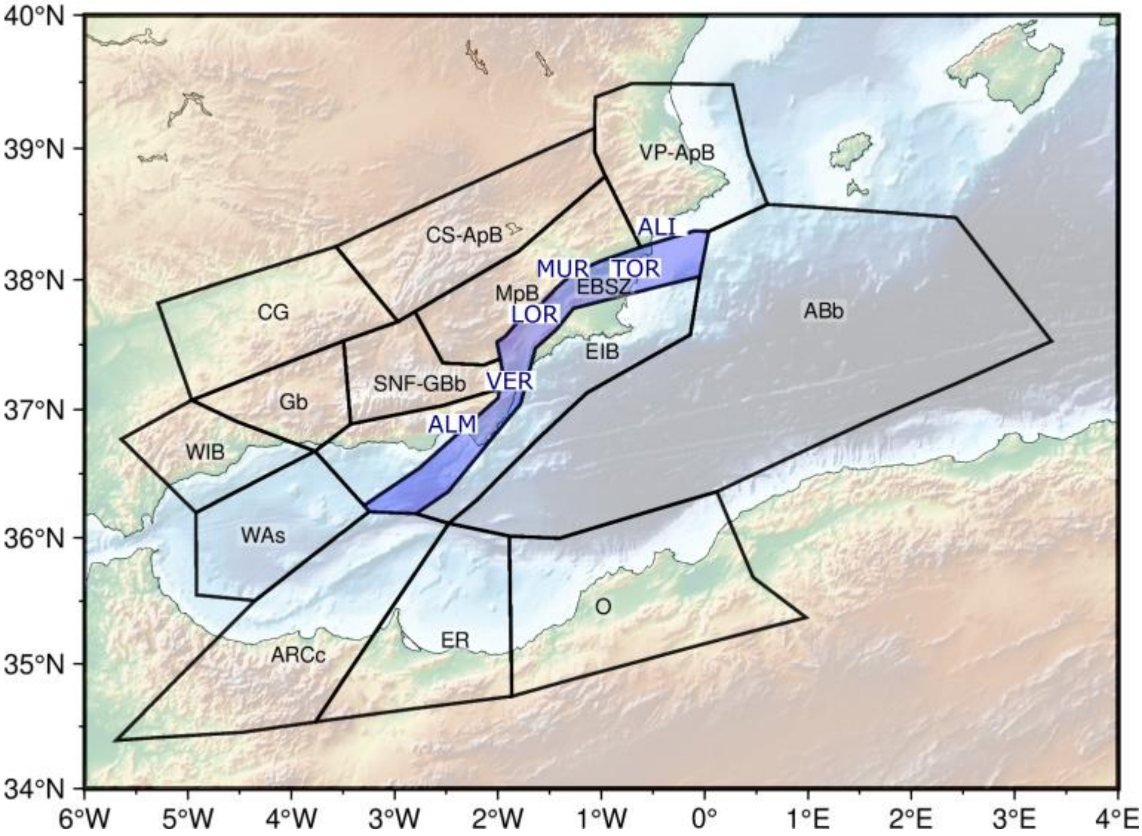


Figure X. Frequency magnitude distribution for the 100 synthetic catalogues (grey lines) and the historical-instrumental catalogue (red line). The dashed line represents the magnitude of completeness for the full length of synthetic catalogues according to Herrero-Barbero et al., 2021. The magnitude of completeness for the historical-instrumental catalogue is M_W 3.5 (IGN-UPM, 2013).

Spatial variability of hazard curves

In Figures 8 and 9, the hazard curves and return periods differ significantly between cities. It is not clear why such variability is expected if all sites belong to the same tectonic domain (same seismogenic area). If the cities are located within the same source zone, the observed differences may simply reflect source discretization effects (e.g., edge vs. central locations). I would like to suggest discussing this point more explicitly. Alternatively, if some cities are located outside the main study area, it may be worth questioning whether including peripheral sites is necessary.

AR: We understand the reviewer's point; however, the hazard at each city is also influenced by the contribution of the seismogenic zones surrounding zone 55 (the EBSZ), which explains the hazard differences among them. We apologize for any confusion. To clarify this, we will also plot the cities in Figure 2 so that readers can clearly see their spatial relationship to the seismogenic zone layout.



Interpretation of epistemic vs aleatory uncertainty

The manuscript states that the use of multiple sub-catalogues allows the evaluation of epistemic uncertainty. However, since all sub-catalogues are generated from the same synthetic model with identical fault geometry and slip-rate inputs, epistemic uncertainty is common to all of them. I would like to suggest that the variability observed among sub-catalogues mainly reflects aleatory variability associated with earthquake occurrence. In practice, the study is quantifying the dispersion of hazard estimates around the long-term mean due to temporal sampling effects.

AR: We fully agree with the reviewer's observation that, since all sub-catalogues are generated from the same synthetic model, the epistemic uncertainty is common to all of them. In fact, as we state in line 250 and the following lines:

[250] The main objective of this research is to study the variability between sub-catalogues with similar characteristics from the same synthetic catalogue. In this way, the epistemic uncertainties derived from their use are common to all the synthetic sub-catalogues used in the comparison, and the results obtained are independent of these epistemic uncertainties.

We believe that the use of the term "independent" may be the cause for this confusion, so we would change it in the revised version of the manuscript:

The main objective of this research is to study the variability between sub-catalogues with similar characteristics from the same synthetic catalogue. In this way, the epistemic uncertainties derived from their use are common to all the synthetic sub-catalogues used in the comparison. Therefore, any differences in the resulting hazard are solely due to the aleatory variability in earthquake occurrence inherent to each individual sub-catalogue.

A thorough study on the influence of epistemic uncertainties in the EBSZ can be found in Gómez-Novell et al 2021 and Herrero-Barbero et al 2021:

Gómez-Novell O, García-Mayordomo J, Ortuño M, Masana E and Chartier T (2020) Fault System-Based Probabilistic Seismic Hazard Assessment of a Moderate Seismicity Region: The Eastern Betics Shear Zone (SE Spain). Front. Earth Sci. 8:579398.

Herrero-Barbero, P., Álvarez-Gómez, J. A., Williams, C., Villamor, P., Insua-Arévalo, J. M., Alonso-Henar, J., & Martínez-Díaz, J. J. (2021) Physics-based earthquake simulations in slow-moving faults: a case study from the Eastern Betic Shear Zone (SE Iberian Peninsula). Journal of Geophysical Research: Solid Earth, 126(5), e2020JB021133.

Complex ruptures and maximum magnitudes

The manuscript suggests that complex ruptures are more common than previously thought and associates the largest magnitudes (Mw ≈ 7.2) with such events. However, it is not entirely clear from the figures whether "complex" refers to multi-segment/multi-fault ruptures or simply to large slip values on individual faults. I would like to suggest clarifying this distinction. Moreover, it may be useful to explore whether the large magnitudes are controlled primarily by rupture geometry or by slip distribution, and whether this can be verified within the simulation framework.

AR: We agree with the reviewer that the term "complex" may be ambiguous to readers. Indeed, we were referring to multi-segment and multi-fault ruptures, as the reviewer correctly guessed. To improve clarity, in the revised version of the manuscript we will replace the term "complex ruptures" with the more precise "multi-fault ruptures."

Regarding the reviewer's suggestion to explore rupture geometry or slip distribution as controlling factors in the occurrence of large-magnitude events, we agree that this is a very interesting topic. For example, recent work by Gómez-Novell et al. (2026) shows that maximum magnitude is directly proportional to fault connectivity at depth and inversely proportional to fault sinuosity. However, addressing this question for our EBSZ fault model (from Herrero-Barbero et al. 2021) falls beyond the scope of the present manuscript.

Herrero-Barbero, P., Álvarez-Gómez, J. A., Williams, C., Villamor, P., Insua-Arévalo, J. M., Alonso-Henar, J., & Martínez-Díaz, J. J.: Physics-based earthquake simulations in slow-moving faults: a case study from the Eastern Betic Shear Zone (SE Iberian Peninsula). Journal of Geophysical Research: Solid Earth, 126(5), e2020JB021133, https://doi.org/10.1029/2020JB021133, 2021.

Gómez-Novell, O., Visini, F., Álvarez-Gómez, J. A., Pace, B., & García-Mayordomo, J. (2026). "Coseismic surface rupture probabilities from earthquake cycle simulations: influence of fault geometry." Natural Hazards and Earth System Sciences (NHESS), 26, 651–673.https://doi.org/10.5194/nhess-26-651-2026

Interpretation of Table 3 and justification of the ensemble size

The justification of the use of 100 sub-catalogues based on the similarity of the Gutenberg–Richter parameters in Table 3 is not entirely clear. I would like to suggest explaining more explicitly how this comparison demonstrates that the ensemble provides a statistically stable

AR: We agree with the reviewer that maybe the data from table 3 is not enough to demonstrate the equivalence between samples. We have added the distribution of parameters in Figure 4 to compare with the 10000 catalogue and added the following in line 227:

The parameter distributions obtained from the 100 sub-catalogues reproduce the central tendency and dispersion of the reference set of 10 000 sub-catalogs (Figure 4). No systematic bias is observed in the distributions of the a, b, and maximum magnitude values; therefore, the sample of 100 sub-catalogues is statistically representative of the variability of the dataset. The differences are thus attributable to expected fluctuations in finite samples.

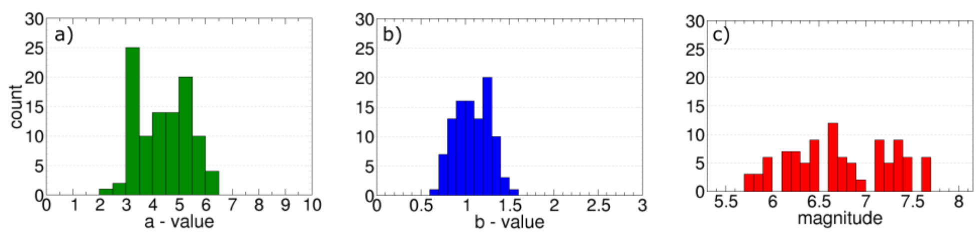


Figure X: Statistical variability of a) a - parameter (Gutenberg-Richter relationship), b) b - parameter (Gutenberg-Richter relationship) and c) Mmax for 100 synthetic sub-catalogues used in PSHA calculation.

Synthetic vs observed hazard levels

The manuscript concludes that hazard derived from historical and instrumental catalogues is less conservative than that obtained from synthetic seismicity and attributes this to the limited sampling of large earthquakes. While this is a plausible interpretation, it implicitly assumes that the synthetic model represents the "true" long-term hazard. I would like to suggest treating this assumption more cautiously. Historical catalogues do not necessarily always underestimate hazard: the sampling of a rare large event on a long-recurrence fault could also lead to an overestimation (assuming the average recurrence represents the "true" hazard). Alternative explanations could be discussed, including catalogue incompleteness, uncertainties in slip-rate estimates or fault coupling in the synthetic model, and the possible absence of secondary faults or aseismic deformation.

AR: We understand the reviewer's concern that calculating hazard from a historical catalogue does not necessarily lead to less conservative results, and we fully agree. In the paper, we state that this is what we observe in our particular case study, and that a major reason for it is the fact that, because we are sampling 1-kyr-long sub-catalogues in a slow-moving fault region with long seismic cycles, there is a significant chance of extracting catalogues that capture larger magnitudes (M > 5.5) and higher activity rates than those present in the available historical catalogue. As a consequence, using synthetic seismicity catalogues yields higher hazard values compared to the historical one.

Of course, we do not claim that this result can be straightforwardly extrapolated to every slow-moving fault region worldwide. As the reviewer points out, in some areas the historical record may indeed include a large event (e.g., central Australia), which could lead to somewhat overestimated hazard results.

To clarify this point, in the revised version of the manuscript we are adding a new figure comparing the cumulative rates of the synthetic and historical catalogues (find the figure at the beginning of the document).

Additionally, we will modify line 38 at the beginning of Section 6 (Conclusions), which will now read:

When the source model characterization relies entirely on the historical earthquake catalogue, the incompleteness of the data becomes a major limitation, as fault seismic cycles are usually longer.

Finally, following the reviewer's suggestions, the last line of the paper (line 355) will now read:

To better understand the models and their impact on seismic hazard, further investigations should focus on issues such as fault segmentation, structural development, frictional properties, and degree of coupling (aseismic deformation and secondary faulting).

Role of very large magnitudes in hazard

The manuscript highlights a significant contribution of magnitudes larger than Mw 7.2. However, in my experience (mainly in Italy, so this may not be fully transferable), such events are not expected to dominate hazard at return periods of 500–2000 years and may be more relevant for risk analysis than for classical PSHA. I would like to suggest further discussing this point.

AR: We agree that, in many tectonic settings and classical PSHA applications, earthquakes with magnitudes larger than Mw ~7 do not necessarily dominate seismic hazard at return periods of 500–2000 years, and may instead play a stronger role in risk-oriented analyses or in very long return periods. We appreciate the opportunity to clarify this point in the manuscript.

In our study, events with Mw > 7.2, although infrequent, have noticeable influence on the magnitude-frequency distributions of the EBSZ when long synthetic catalogues are considered. Their occurrence is model-dependent and linked to ruptures involving the full fault length or multi-fault ruptures affecting the fault sources with highest slip rates within the fault system. This observation is relevant in terms of seismogenic behaviour, which is the context in which these large magnitudes are discussed in Section 5.1. However, our intention is not to claim that large magnitudes systematically control hazard at engineering return periods, but rather to demonstrate how the inferred hazard depends on the observation time window used to characterize seismicity. In slow-deforming systems, the intermittent occurrence of rare large earthquakes may strongly affect the statistical characterization of seismicity and therefore the resulting hazard variability.

We acknowledge that, from a hazard and PSHA perspective, this distinction requires clarification. Accordingly, the manuscript has been revised to better distinguish between (i) the description of seismogenic behaviour derived from the synthetic catalogues, (ii) the sensitivity of hazard estimates to rare large events, and (iii) their role within classical PSHA applications. Section 5.1 has been revised to clarify this point, including the statement: *"Although these large events do not necessarily dominate hazard at engineering return periods in classical PSHA frameworks, their intermittent occurrence strongly influences the variability of hazard estimates when different observation time windows are considered".*

Additionally, lines 347–349 of the Conclusions have been revised to better contextualize the role of large-magnitude events: *"The evaluation of a statistically representative set of 10,000 sub-catalogues reveals the recurrent appearance of large-magnitude events (Mw > 7.2) associated with multi-fault ruptures. Although infrequent, these events reflect the long-term seismogenic behaviour emerging from the synthetic fault system, typically nucleating on the AMF and CF, which exhibit the highest slip rates within the EBSZ. Rather than implying a systematic dominance of large earthquakes in seismic hazard at engineering return periods, their presence highlights how rare events may significantly influence hazard variability when different observation time windows sample the seismic cycle unevenly."*

Finally, the caption of Figure 5 has been modified to avoid possible confusion and now reads: *"The count represents the number of times the 10,000 sub-catalogues show the corresponding magnitude as the maximum magnitude on the indicated fault."*

Validation/comparison with observations of the synthetic catalogue

The manuscript states that the synthetic catalogue reproduces the main features of observed seismicity, but quantitative validation is limited. I would like to suggest discussing whether synthetic and historical catalogues are comparable in terms of rates, magnitude distributions, and cumulative moment release. The cumulative seismic moment analysis is useful, but I would encourage integrating it with a direct MFD comparison.

AR: We sincerely thank the reviewer for this constructive comment, which we consider highly pertinent and helpful for improving the manuscript. We would like to clarify that a detailed qualitative validation of the synthetic catalogue was already carried out in Herrero-Barbero et al., 2021., where its ability to reproduce the main characteristics of the observed seismicity was thoroughly assessed. In response to the present suggestion, we have now incorporated an additional comparative figure showing the frequency–magnitude distributions (FMDs) of the 100 synthetic catalogues used in the hazard assessment. We believe this addition strengthens the quantitative comparison between the synthetic and historical datasets and improves the overall clarity and robustness of the validation presented in this study.

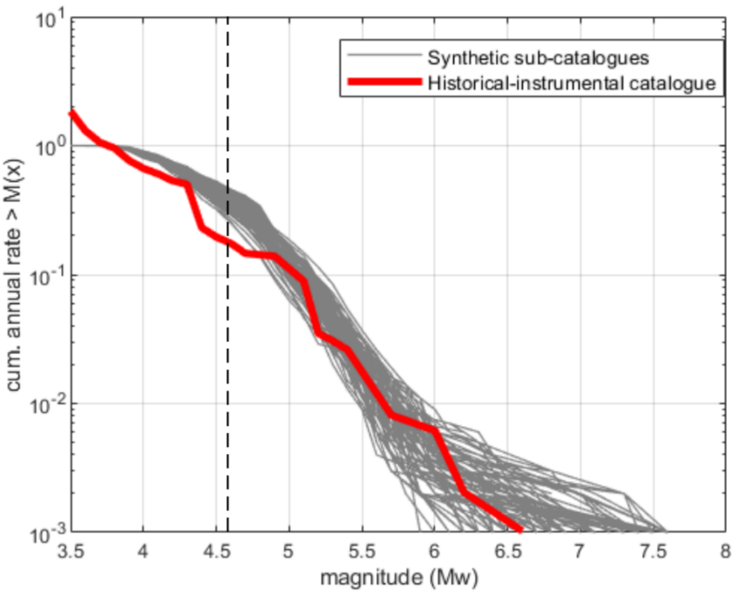


Figure X. Frequency magnitude distribution for the 100 synthetic catalogues (grey lines) and the historical-instrumental catalogue (red line). The dashed line represents the magnitude of completeness for the full length of synthetic catalogues according to Herrero-Barbero et al., 2021. The magnitude of completeness for the historical-instrumental catalogue is M_W 3.5 (IGN-UPM, 2013).