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PSHA APPLIED IN CENTRAL AMERICA USING SOURCE HYBRID MODELS. SENSITIVITY ANALYSIS OF RESULTS

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Abstract: *In Probabilistic Seismic Hazard Assessments (PSHA), the introduction of faults as independent seismic sources in hazard assessment has a great impact on the results, with respect to those obtained with classical zoning methods (CZM). Some approaches for hybrid models (HM) composed of zone-type sources and fault-type sources, reveal that expected ground motion values in the surroundings of the faults may double those obtained by CZM. We apply and compare two methods that address two key aspects: how to quantify the geological information and transfer it to recurrence models and how to distribute the seismic potential between the two types of sources. These methos are: Hybrid method (MHP) developed by* Rivas-Medina et al. (2018) *and SHERIFS by* Chartier et al. (2019)*. The two methods have been tested in Guatemala containing important system faults (e.g. Motagua-Chixoy fault system, Ixcan fault, Jalpatagua, among others). Finally, we analyzed the sensitivity of the results with the different methods and draw conclusions about the advantages and disadvantages of each method, proposing some criteria for its optimization.*

1 Introduction

The classical zonified methods (CZM) for probabilistic seismic hazard assessment (PSHA) allow us to calculate the level of inherent threat in the region due to the occurrence of seismic events through seismic zones that divide and generally describe the seismic activity in different areas of the region. However, these methods do not fully consider the latent seismic danger on the site, as they do not take into account the incorporation of active geological faults that are responsible for the most significant damage to cities and the region as a whole. Therefore, it is necessary apply methods that incorporate geological faults into seismic hazard calculations by combining zone-type sources and fault-type sources. These methods are known as hybrid methods.

Evaluations of seismic hazard through hybrid methods have been carried out in various countries (Chartier et al. (2017); Rivas-Medina et al. (2018); Gómez-Novell et al. (2020); Fernández Campos & Benito (2022)), and the results have shown new insights into the level of seismic danger near faults and their influence on final calculations due to the proximity of the seismic source. This study presents a sensitivity analysis of how these hybrid methods impact seismic hazard calculations compared to using classical zonified methods (CZM) and deterministic methods on faults. The case study was conducted in Guatemala, where four important faults interact in the region. These faults are of great significance in seismic hazard calculations due to their moderate to high slip rates, and they have been responsible for major disasters in the populations located nearby.

2 Study Case: Guatemala

2.1 Seismotectonic frame

Guatemala is a highly seismic country, where the convergence of three tectonic plates (Cocos, Caribbean and North America) generates intense activity with frequent vibratory ground motion. The capital, Guatemala City, is one of the country´s population centres at greatest seismic risk, due to the impending threat to the city and its exposure and vulnerability. Some fault systems lie in the city's environs, dictating the danger to it: Polochic-Chixoy and Motagua to the north; Ixcan fault to the north; and Jalpatagua to the south-east (Authemayou et al. (2012); Garnier et al. (2021); (Garnier et al., 2022)) (Fig. 1).

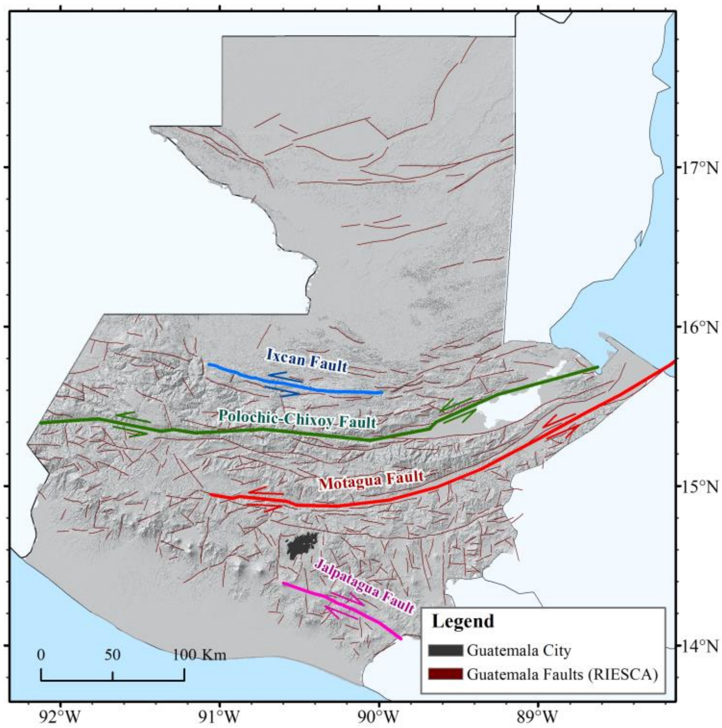

Figure 1. Regional seismotectonic frame of Guatemala.

The study focuses on these four faults because they have been investigated due to their significance and impact on seismic hazard in Guatemala. These faults, with their extensive lengths and the significant impact they have had with their recent earthquakes in the region, have been examined using geophysical, geomatic, and geotechnical methods. This has resulted in accurate data regarding their geometry and slip rates, which are essential for the purposes of this work (Franco et al. (2009); Authemayou et al. (2012); Garnier et al. (2021); (Garnier et al., 2022)). Table 1 summarizes the geometric and kinematic properties of the studied faults.

Table 1. Parameters of the faults of Guatemala modelized as independent sources.

Code	Segment	Fault type	Dip – Rake°	Longitude (Km)	Width (Km)	L/W	Slip rate (mm/yr)
M01	E-W segment Motagua	Sinestral strike-slip	(90°, 0°)	239.68	18.0	13.32	12.0 ± 1.9
M02	NE – SW segment Motagua	Sinestral strike-slip	(90°, 0°)	160.08	18.0	8.89	14.0 ± 1.9

P01	E-W segment Polochic-Chixoy	Sinestral strike-slip	(90°, 0°)	232.02	18.0	12.89	3.7 ± 1.2
P02	NE – SW segment Polochic-Chixoy	Sinestral strike-slip	(90°, 0°)	168.08	18.0	9.34	3.7 ± 1.2
IXC	Ixcan Fault	Sinestral strike-slip	(90°, 0°)	125.0	18.0	6.94	1.0 ± 0.9
JLP	Jalpatagua Fault	Dextral strike-slip	(90°, 0°)	73.08	15.0	4.87	7.1 ± 1.8

2.2 Seismic catalog

The new regional seismic catalog for Central America (Gamboa-Canté et al. (2024) was generated from 14 databases of local and regional seismic networks. This seismic catalog comprises 260,548 seismic events ranging from magnitude Mw 1.0 to Mw 7.9, with depths of up to 300 km. This database was created as part of the results of the first phase of the KUK-AHPÁN project (Fig. 2).

In general, seismic activity rates in Guatemala are high in the southern coastal region due to the subduction of the Cocos Plate beneath the Caribbean Plate. Additionally, there are low seismic activity rates in the transverse strip of the country. However, the interaction between the North American Plate and the Caribbean Plate results in earthquakes with magnitudes of Mw ≥ 6.0.

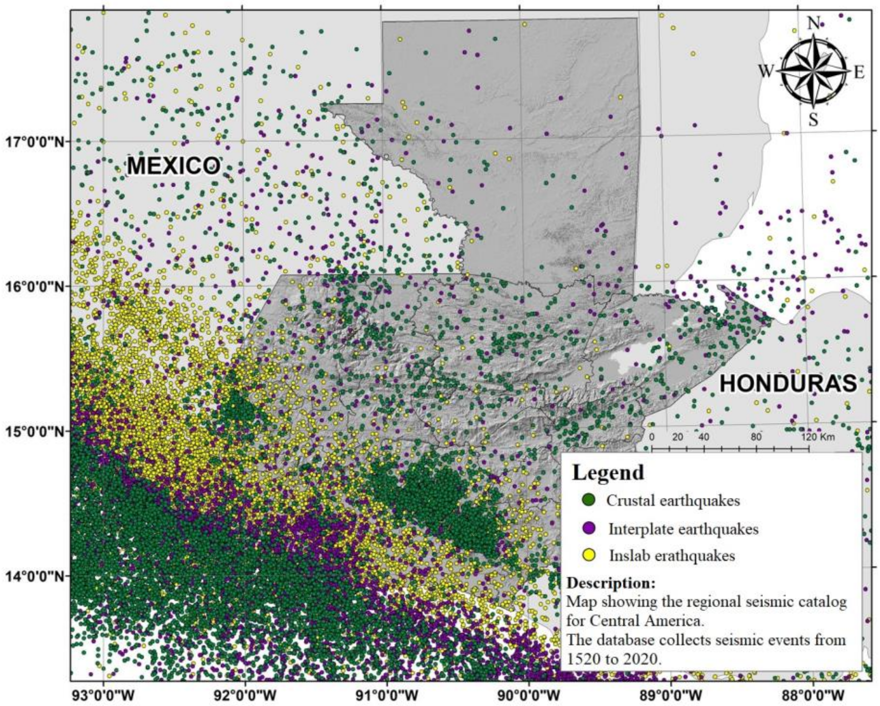

Figure 2. Seismic activity in the Republic of Guatemala across the period 1520–2020. The map shows the epicentres of the earthquakes listed in the catalogue created for this study.

2.3 Seismic zones

The seismogenic zones included in this study are those proposed by Benito et al. (2012) and improved by Alvarado et al. (2017). Specifically, the following were considered and analysed for study purposes: ten zones for the crustal regime, associated with superficial seismicity occurring at a depth of 0 to 20 kilometres (Fig. 3a); one zone for the interplate regime, associated with seismicity occurring at a depth of 20 to 60 kilometres (Fig. 3b); and two zones for the inslab regime, associated with deep seismicity occurring at depths below 60 kilometres (Fig. 3c).

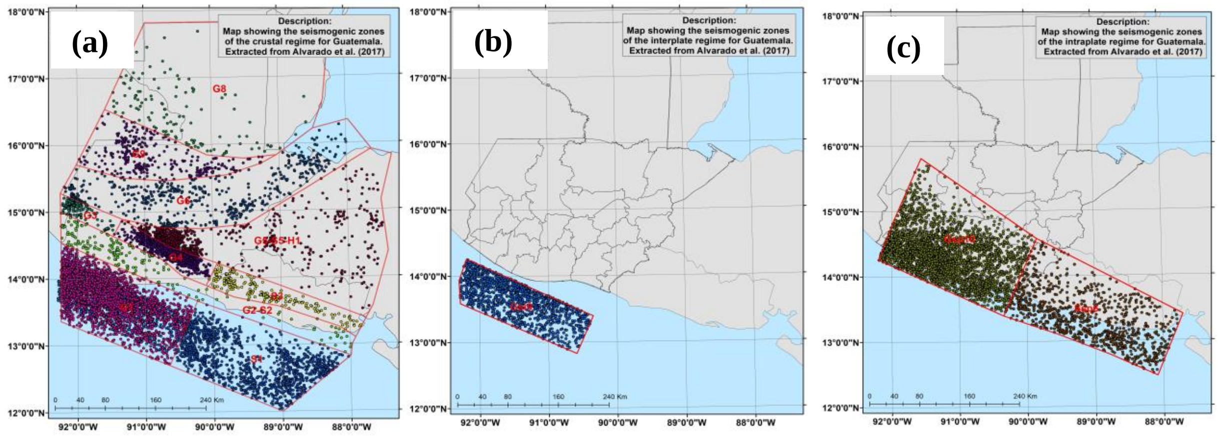

Figure 3. Seismic zones considered in the study for Guatemala, drawn from Alvarado et al. (2017), superimposed with seismicity: (a) crustal regime; (b) interplate regime; and (c) inslab regime.

Furthermore, for the purposes of this study, the focus was on the interaction of geological faults with the cortical zones G4, G6, and G9, respectively. Figure 4 show these three seismic zones along with the associated seismicity and the studied geological faults.

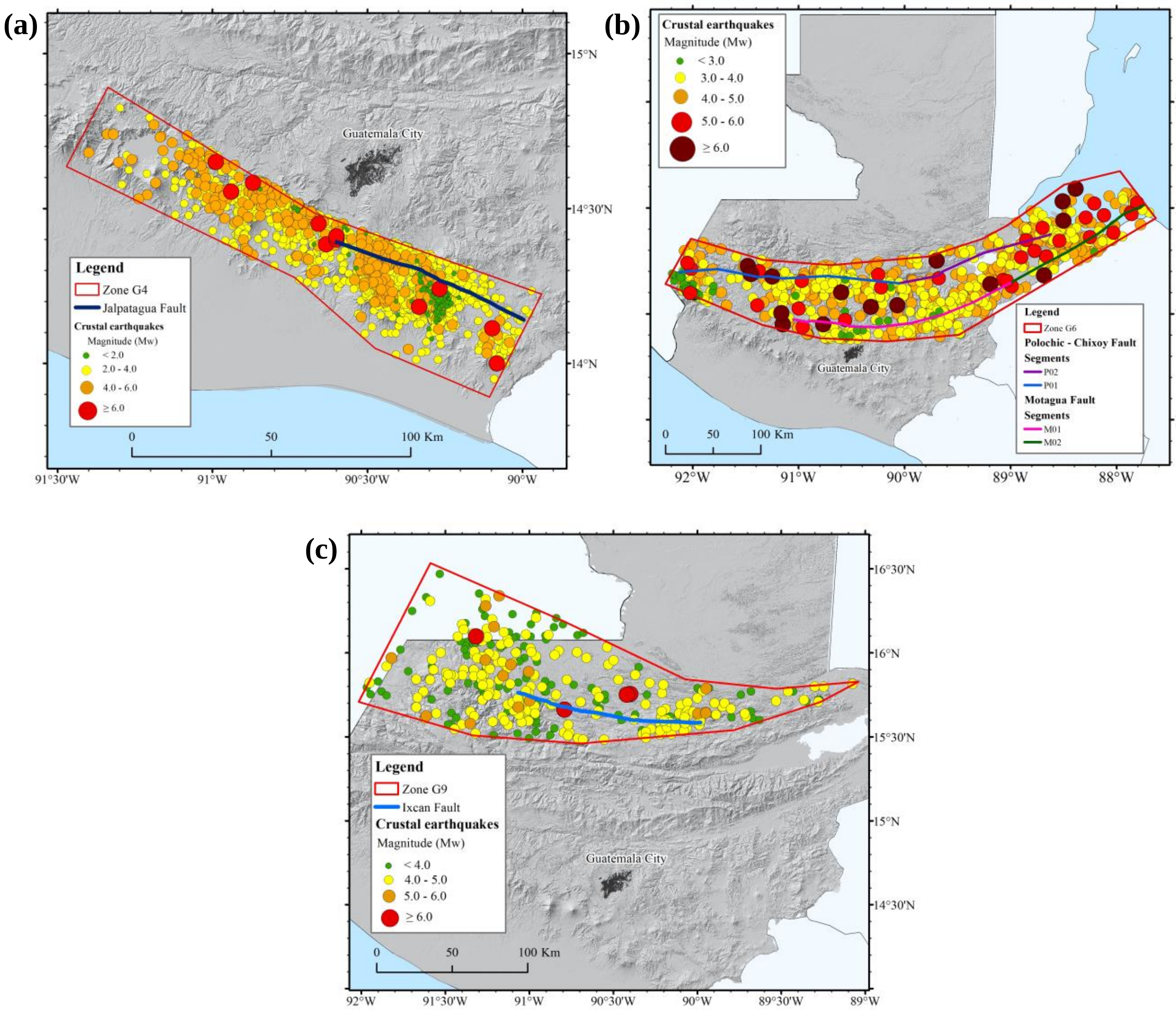

Figure 3. Seismic zones considered in the analysis of hybrid methods for Guatemala. (a) Zone G4 with Jalpatagua fault, (b) zone G6 with Motagua fault and Polochic-Chixoy fault and (c) zone G9 with Ixcan fault.

3 Methods

3.1 MHP method

Rivas-Medina et al. (2018) proposed a hybrid method that combines seismic zones and faults for seismic hazard assessment. The method involves distributing a portion of the seismic potential recorded in the seismic catalog in a complete manner, and then extrapolating it to the entire analysis period. To consider this distribution, a minimum magnitude (Mmin) is defined as the lower limit, and a maximum magnitude of completeness (MMC) is defined as the upper limit. All possible solutions are calculated to ensure that the distribution of seismic potential is balanced for the fault based on its slip rate.

3.2 SHERIFS method

Chartier et al. (2019) defined a hybrid method using simulations and iterative processes to distribute the seismic potential of both the fault and the seismic zone, considering the uncertainties in the calculation. The iteration process involves defining small increments in slip rate (dsr) that will be "spent" until the entire slip rate of the fault is exhausted. This process continues until the seismic potential of the zone, as determined by the user's distribution between the zone and the fault for each magnitude bin, is completely covered.

4 Results

Various seismic hazard maps were generated for the spectral ordinate PGA with a return period of 475 years to analyse the variability of accelerations using hybrid, deterministic, and classical zonified methods.

4.1 Seismic recurrence parameters

Table 2 displays the results of the parameters for fault-type and zone-type sources for the various methods. Additionally, it shows the percentage of seismic moment distributed. Also, Table 3 presents the parameters used for deterministic scenarios.

Table 2. Recurrence parameters for the seismic sources used in this study.

Method	Code	Mmin	Mmax	a	b	$\dot{N}(M_{min})$	% Mo
Classic zoned method	G4	4.5	7.4	4.60	0.98	1.48	100.0
	G6	4.5	8.0	5.29	1.08	2.86	100.0
	G9	4.5	7.3	6.05	1.29	1.81	100.0
MHP Method Rivas-Medina et al. (2018)	JLP	4.5	6.9	2.52	0.65	0.39	21.9
	G4	4.5	5.4	4.44	0.96	1.39	78.1
	M01	4.5	7.7	1.85	0.53	0.31	10.5
	M02	4.5	7.3	2.15	0.53	0.58	19.6
	P01	4.5	7.5	1.54	0.53	0.14	4.7
	P02	4.5	7.4	1.50	0.53	0.13	4.4
	G6	4.5	5.0	3.22	0.66	1.80	60.8
	IXC	4.5	7.2	3.38	0.91	0.19	9.2
	G9	4.5	5.1	3.40	0.70	1.88	90.8
SHERIFS Method Chartier et al. (2019)	JLP	4.5	7.0	4.87	1.09	0.67	67.7
	G4	4.5	6.4	7.78	1.79	0.32	32.3
	M01	4.5	7.6	3.58	0.97	0.14	10.1
	M02	4.5	7.4	4.43	1.04	0.27	19.6
	P01	4.5	7.5	3.73	1.02	0.17	12.3
	P02	4.5	7.4	4.03	1.08	0.25	18.1

	G6	4.5	6.9	6.30	1.44	0.55	39.0
	IXC	4.5	7.2	5.60	1.31	0.41	27.7
	G9	4.5	6.8	7.93	1.73	1.07	72.3

4.2 Acceleration maps for sources fault type

Figure 4 presents the results obtained for the Ixcan fault, Figure 5 for the Polochic-Chixoy and Motagua faults, respectively, and finally, Figure 6 illustrates the results for the Jalpatagua fault.

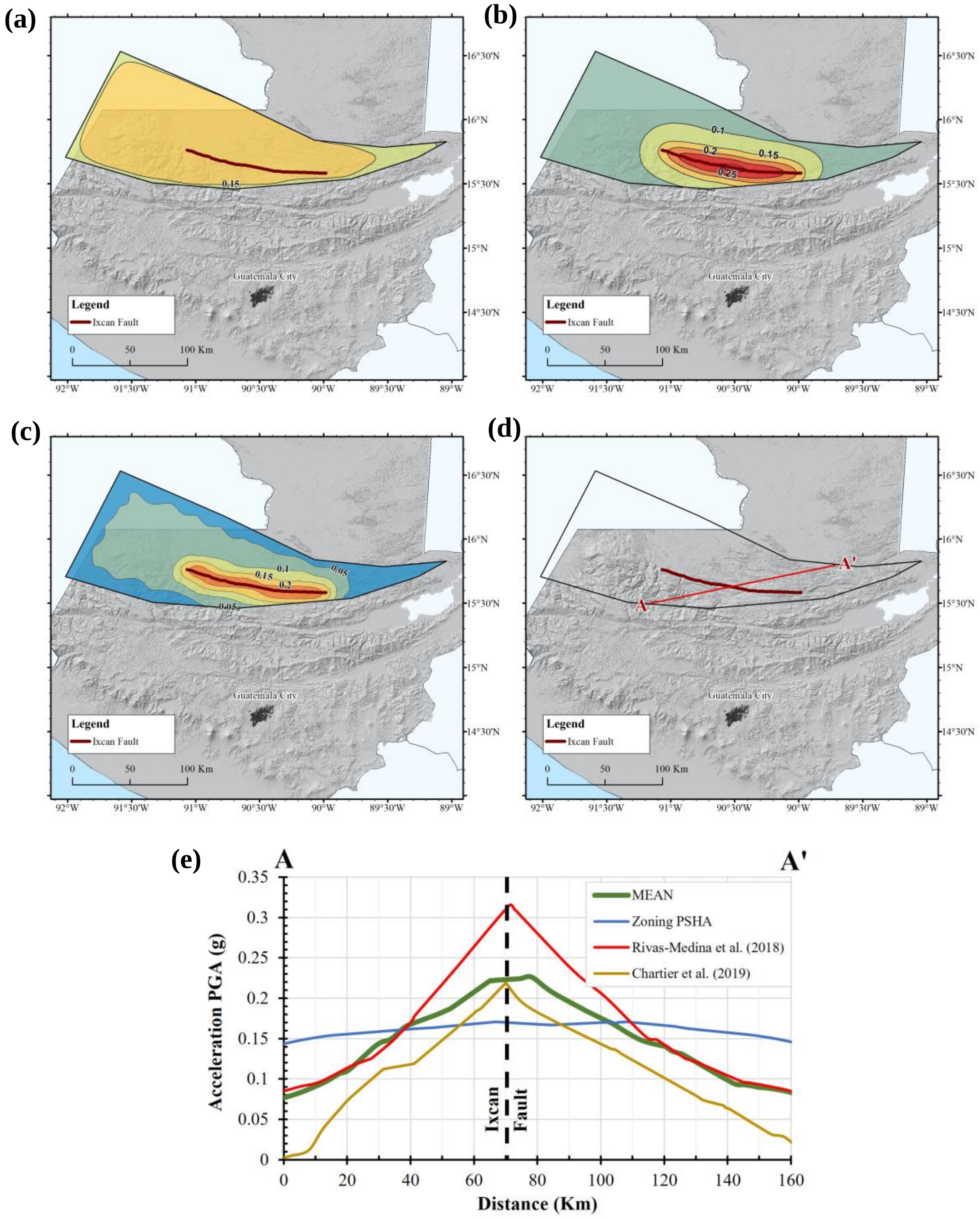

Figure 4. Acceleration map in g of Ixcán fault for PGA and return period of 475 years using (a) classical zone method, (b) MHP hybrid method, (c) SHERIFS hybrid method. Also, (d) a profile that cut the segment fault with (e) the corresponding acceleration in each method.

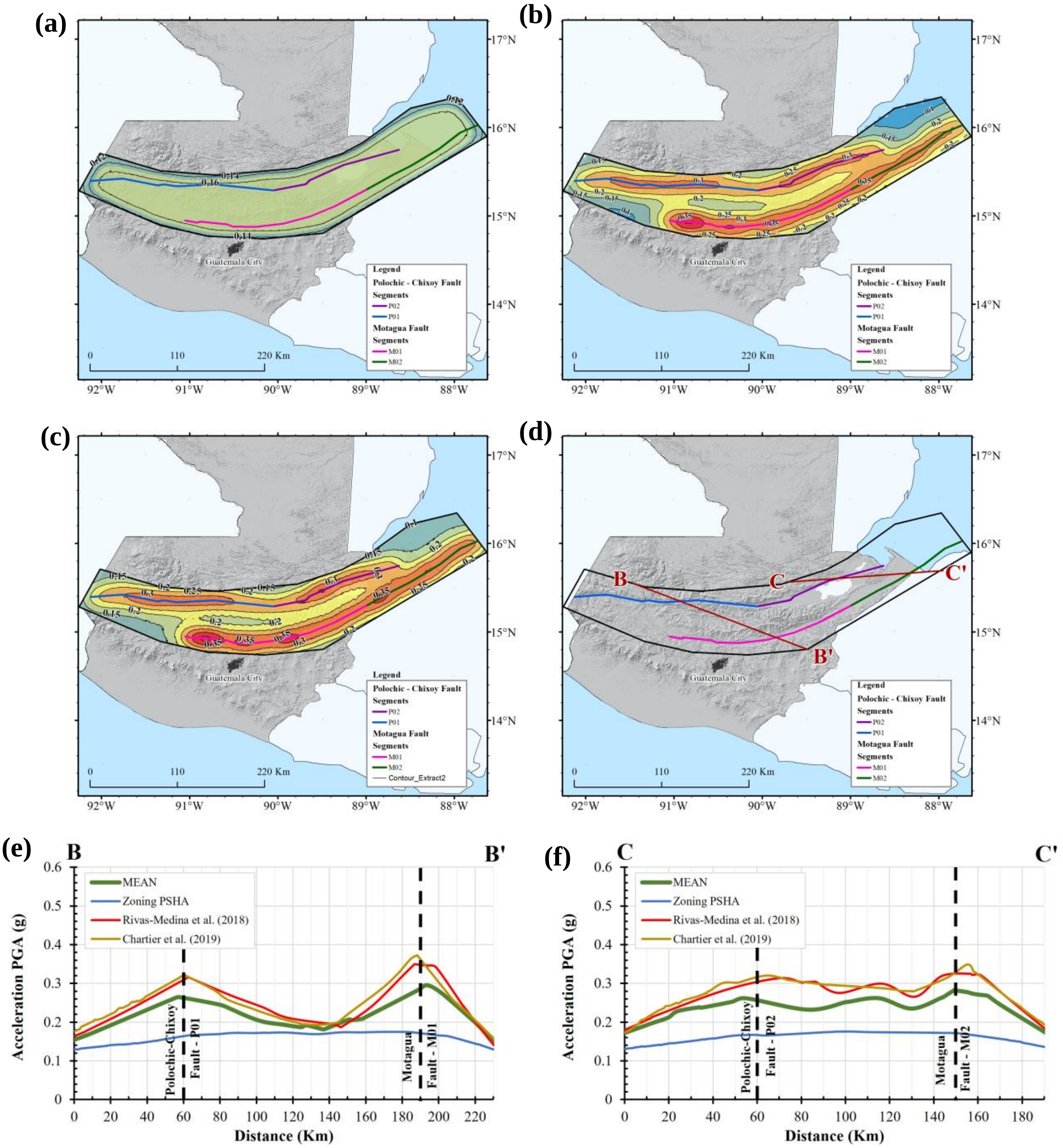

Figure 5. Acceleration map in g of Polochic-Chixoy and Motagua fault for PGA and return period of 475 years using (a) classical zone method, (b) MHP hybrid method, (c) SHERIFS hybrid method. Also, (d) a profile that cut the segments (e) P01 - M01 and (f) P02 – M02 with the corresponding acceleration in each method.

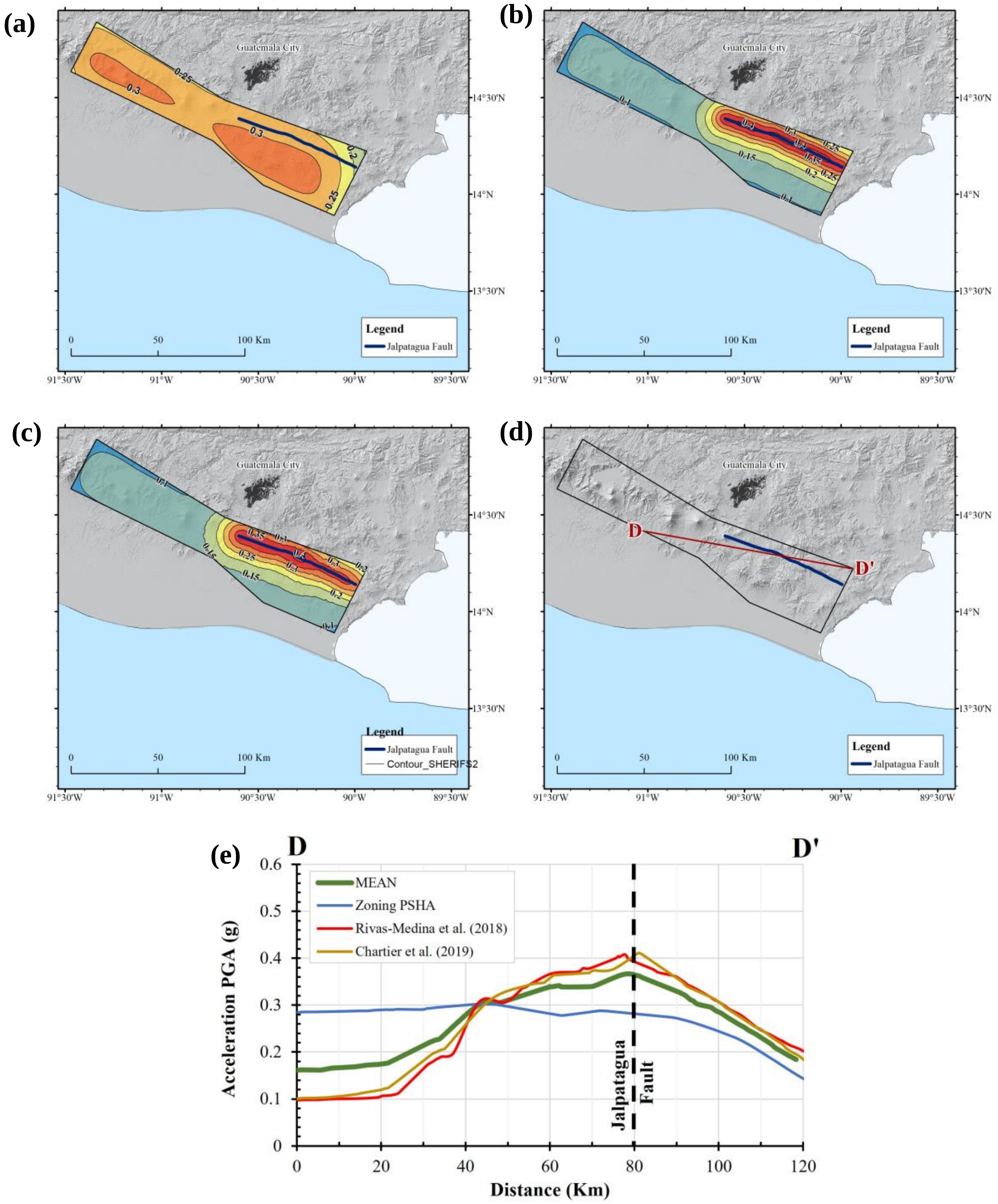

Figure 6. Acceleration map in g of Jalpatagua fault for PGA and return period of 475 years using (a) classical zone method, (b) MHP hybrid method, (c) SHERIFS hybrid method. Also, (d) a profile that cut the segment fault with (e) the corresponding acceleration in each method.

4.3 COV maps

The variability was evaluated using the coefficient of variation (COV), where a COV greater than 0.3 indicates data heterogeneity in relation to the average acceleration value. Conversely, a COV less than 0.3 suggests that the accelerations calculated by the different methods are homogeneous with respect to the average acceleration value. To assess the variability among the results of each method, coefficient of variation (COV) maps were created, and the results indicate that this variability is significant when comparing the deterministic method to the use of probabilistic hybrid methods. Figure 7 displays the COV maps obtained for each of the faults, respectively.

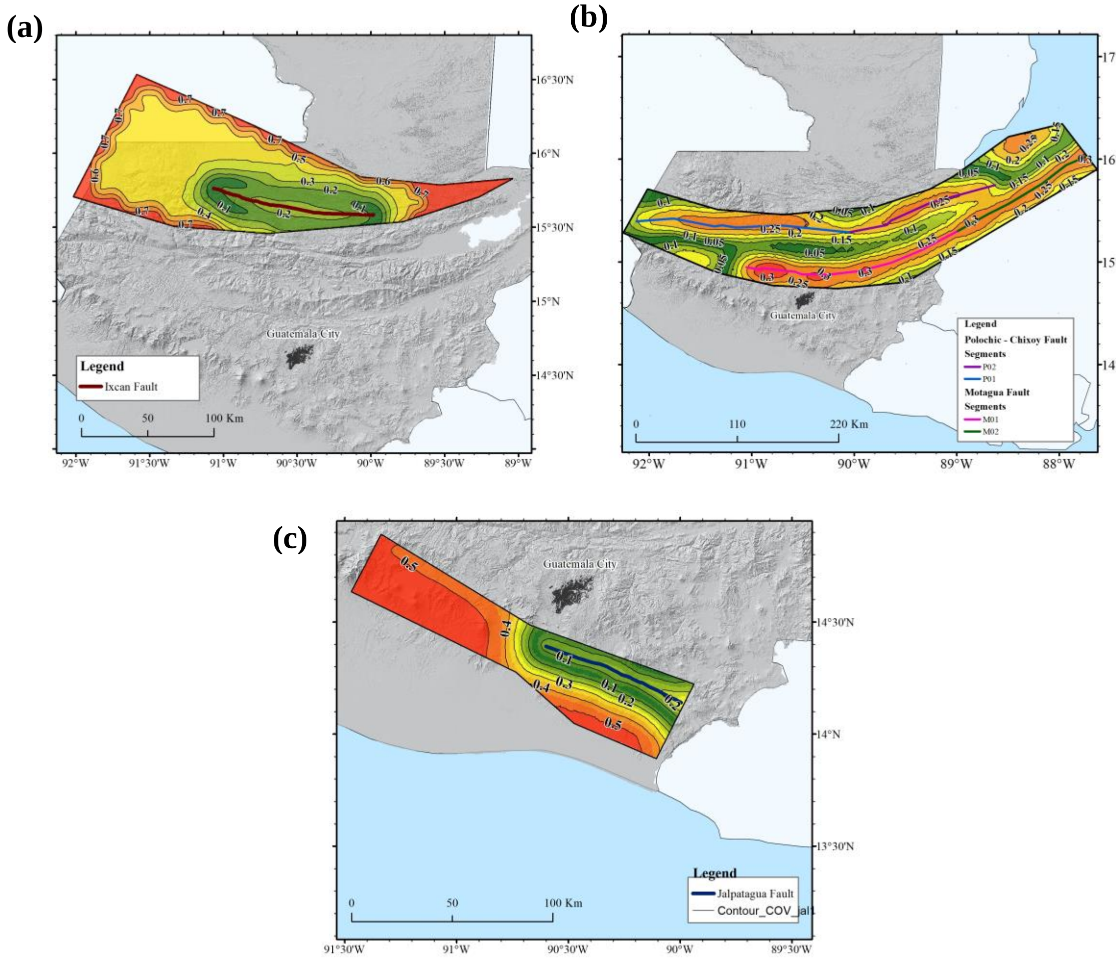

Figure 7. COV maps comparing results of deterministic method, MHP method and SHERIFS method. For (a) Ixcan fault, (b) Polochic-Chixoy and Motagua fault and (c) Jalpatagua fault.

5 Discussion

The Table 2 presents the results of the seismic potential distribution from the analyzed seismic sources using different hybrid methods and the zoned PSHA method. It can be observed that there is a significant variation in the recurrence parameters (*b-value, a-value*) of fault-type sources depending on the applied hybrid method. This is due to the way the method distributes the seismic moment among different faults. The MHP method distributes the seismic potential of the fault based on observed data from the seismic catalog within a magnitude interval considered complete in the catalog (Rivas-Medina et al., 2018), while SHERIFS iteratively distributes the budget of the MFD considering each fault source until it has covered the global seismic potential of the region (Chartier et al., 2019). Another notable difference is the value of maximum earthquake (M_{max}) for faults and zones, which is due to the scaling laws used by each method to assign to fault segments. In the MHP method, the M_{max} value of the fault is assigned based on expert input, whereas in SHERIFS, different pre-established scaling laws can be chosen by the user to assign to fault-type sources. Specifically, for the MHP method, the scaling laws of Arroyo-Solórzano et al. (2024) specific to Central America were used, while for SHERIFS, the scaling laws defined by Leonard (2010) were used as they best suited the tectonic context of Central America.

When applying hybrid methods to the Ixcan fault (Fig. 4), it can be observed that the variation in accelerations is relatively small between one method and another. By plotting an acceleration profile across the fault segment, it is noted that the MHP method increases the acceleration on the fault by 0.1 g compared to the SHERIFS method (Fig. 4e). Moreover, it is noticeable how the accelerations calculated by the zoned PSHA method are lower than those calculated by the hybrid method around the fault, which may imply an underestimation of the true accelerations in this region (Fig. 4e).

Analyzing fault segments in the Polochic-Chixoy and Motagua fault systems, no apparent variation is observed when using different hybrid methods (Fig. 5). When analyzing the acceleration profile for segments P01 and M01, accelerations with hybrid methods reach up to 0.3 g and 0.35 g, respectively, while the zoned PSHA method still significantly underestimates these calculated accelerations (Fig. 5e). Similarly, for segment P02 and M02, there is no apparent variation between the use of different hybrid methods, where accelerations remain up to 0.3 g, while accelerations in zoned PSHA do not exceed 0.18 g (Fig. 5f).

Lastly, in the Jalpatagua fault, the same trend as in the Polochic-Chixoy and Motagua fault systems is observed, where the variation in accelerations with each applied hybrid method is insignificant (Fig. 6). When analyzing the acceleration profile for the Jalpatagua fault, accelerations reach up to 0.4 g using hybrid methods and up to 0.3 g using the zoned PSHA method (Fig. 6e). This highlights the importance of using hybrid methods in fault-type sources in seismic hazard calculations, necessitating further calculations by varying source parameters to fully understand the variation between using one hybrid method or another and to establish control over epistemic uncertainties in the logical tree.

In the calculated COV maps, it is observed that the greatest variability (COV > 0.3) exists in sectors where fault-type sources do not interact, i.e., in areas with only background seismicity (Fig. 7). This is because most of the seismic potential migrates towards fault-type sources, causing accelerations calculated with hybrid methods to decrease compared to accelerations with the zoned PSHA method, as clearly observed in the Ixcan fault (Fig. 7a) and Jalpatagua fault (Fig. 7c).This migration of seismic potential from the zone to the fault indicates the importance of considering the proximity of the fault in seismic hazard calculations. To demonstrate this effect, a seismic hazard map was generated using the classical zonified method (CZM) (Fig. 8), and another map was generated using the hybrid methods employed (Fig. 9). Subsequently, a map of the ratio between the accelerations obtained by the hybrid methods and those obtained by the classical zonified method (CZM) was created to determine at what distance the effects of fault-type sources are perceived in the region (Fig. 10).

In general, it can be observed that the influence of the fault becomes noticeable at a distance of approximately 25 km. For the Motagua fault, this trend is more evident, but this is because the Motagua fault has the highest slip rate, so it is reasonable to assume that its influence is more significant compared to the other faults (Fig. 10). Additionally, there are areas where the accelerations obtained from the hybrid method are higher than those from the classical zonified method (CZM). This demonstrates the migration of seismic potential from the zone towards the faults, as previously shown in the acceleration maps for each of the fault-type sources.

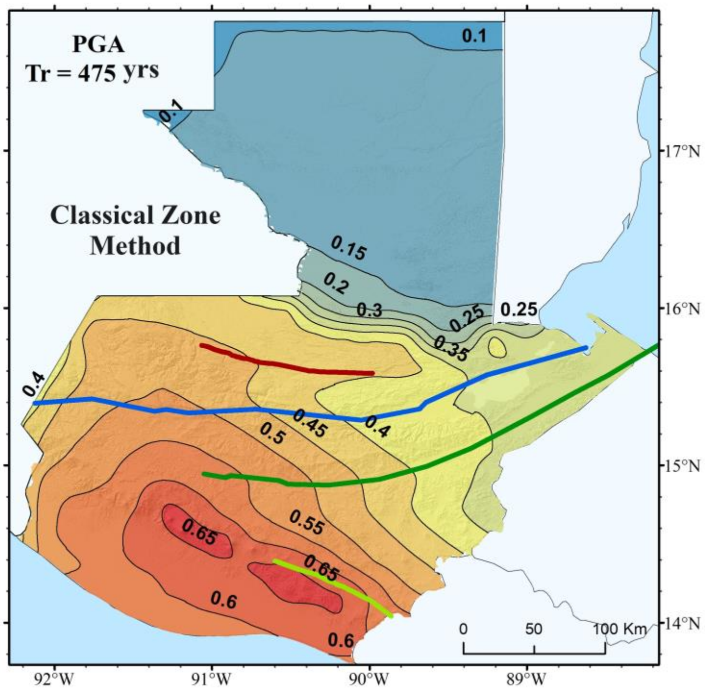

Figure 8. Classical Zone Method (CZM) map for PGA and return period of 475 yrs in Guatemala.

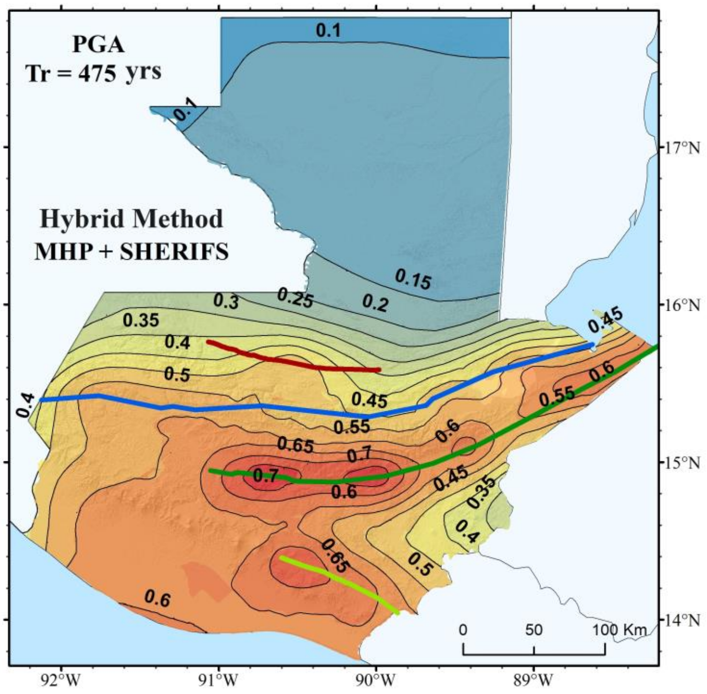

Figure 9. Hybrid method map for PGA and return period of 475 yrs in Guatemala.

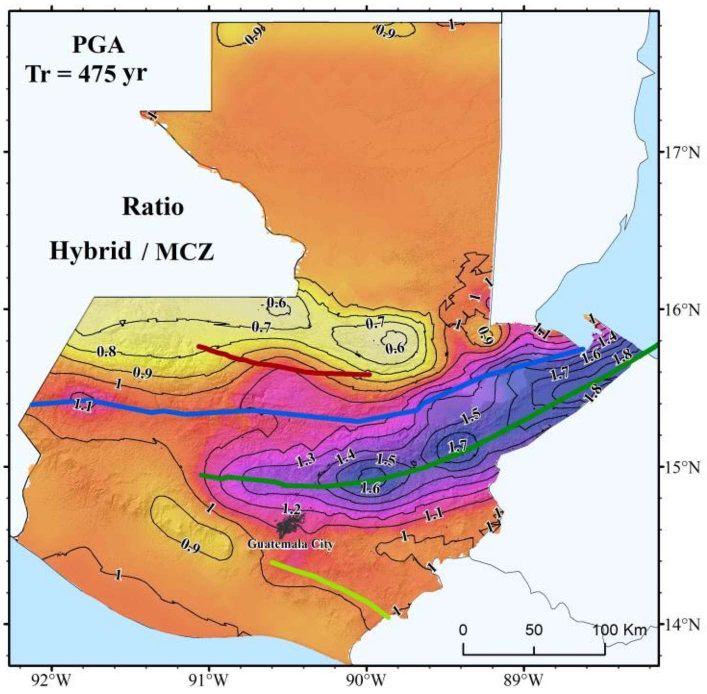

Figure 10. Ratio map comparing hybrid methods and classical zone method (CZM).

6 Conclusions

Among the most important findings highlighted by these preliminary results using hybrid methods are:

1) Fault-type sources can produce accelerations that may be twice as high as those produced by zone-type sources.

2) The influence of fault-type sources becomes noticeable at a distance of approximately 25 km, and this influence becomes more pronounced when the fault's slip rate is high.

3) Accelerations calculated by hybrid methods are highly dependent on the fault's slip rate and geometry, making their representation more realistic for site-specific conditions.

4) The classical zonified method is a good approximation for obtaining a general understanding of seismic threat in a region, but the accelerations it produces are lower compared to what can be obtained with fault-type sources.

5) Different hybrid methods should continue to be analyzed to integrate fault-type sources in seismic hazard calculations, with the objective of controlling epistemic uncertainties in the logical tree and establishing appropriate weights for each hybrid method.

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