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Original paper

Paleoseismological uncertainty estimation in the Acambay region, Central Mexico

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Resumen

Los estudios paleosismológicos proporcionan información valiosa de los procesos de ruptura de los terremotos como son: las dimensiones de las fallas geológicas, los desplazamien-tos promedios y máximos, así como los tiempos de recurrencia y las magnitudes de eventos ocurridos en el pasado geológico. Esta información se basa en observaciones en los registros geológicos. La interpretación de dichas observaciones geológicas tienen una fuente de incertidumbres inherente al gran número de hipótesis que explican las características geológicas observadas. La información obtenida a partir de estudios paleosísmicos es importante en el análisis del riesgo sísmico y es crucial sobre todo para las regiones de baja actividad sísmica en donde el tiempo de recurrencia de los terremotos mayores alcanzan varios miles de años. Sin embargo, el uso de esta información en el análisis de riesgos requiere un tratamiento sistemático de las incertidumbres. En este estudio, se estimaron las incertidumbres de cuatro estudios paleosismológicos realizados en tres fallas geológicas diferentes en la región del graben de Acambay en el Centro de México. El método usado se basa en el formalismo de los árbo-les lógicos que cuantifica las incertidumbres acumuladas asociadas con las diferentes etapas de los estudios paleosismológicos aunado a una evaluación de la entropía en cada paso y al final del proceso. La incertidumbre final y su importancia relativa en el análisis de riesgo sísmico se expresa como el factor de calidad paleosísmico, el cuál es de 0.14, 0.40-0.50 y 0.41 para las fallas de Acambay-Tixmadeje, Pastores y San Mateo, respectivamente. Estos valores se pueden incorporar en los análisis de riesgo sísmico para la región.

Palabras clave: Eje Neovolcánico, Acambay, Paleosismología, incertidumbres, riesgo sísmi-co, árbol lógico.

Abstract

Paleseismological studies provide valuable information of the earthquake rupture processes such as fault dimensions, average and maximum displacements, as well as recurrence times and magnitudes of events which took place in the geologic past. This information is based on observations of the geological record. Interpretation of geological observa-tions has a source of uncertainties inherent to the large number of hypothesis that explain the observed geological features. Information obtained from paleoseismic studies is im-portant in seismic hazard analyses, and particularly crucial for regions of low seismic activity where the recurrence period of major earthquakes reaches several thousand years. However, using this information in hazard analysis requires the systematic treatment of uncertainties. We estimated uncertainties of four paleoseismological studies conducted at three different faults of the Acambay graben region in Central Mexico. The method used is based on a logic-tree formalism that quantifies the cumulative uncertainties associated with the different stages of the paleoseismic studies together with a quantification of the entropy at each step and at the end of the process. The final uncertainty and its relative importance in seismic hazard analysis is expressed as the paleoseismic quality factor, which indicate 0.14, 0.40-0.50, and 0.41 for the Acambay-Tixmadejé, Pastores and San Mateo faults, respectively. These values can be incorporated in seismic hazard analyses for the region.

Key words: Trans-Mexican Volcanic Belt, Acambay, Paleoseismology, uncertainties, seis-mic risk, logic-tree.

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Introduction

Paleoseismological studies in Mexico are a recent development (e.g. Langridge *et al*., 2000; Norini *et al*., 2010; Garduño-Monroy *et al*., 2009; Langridge *et al*., 2013; Ortuño *et al*., 2015; Sunye-Puchol *et al*., 2015). They were mainly developed due to lack of instrumental data in regions of low strain rate, such as the Trans-Mexican Volcanic Belt (TMVB), notwithstanding the historical occurrence of large events such as the November 19 1912, Acambay earthquake (M_s 6.7/m_b 6.9; Urbina and Camacho, 1913; Abe, 1981), a moderate crustal normal-faulting event that caused widespread destruction and loss of lifes at several towns near its epicenter (Urbina and Camacho, 1913; Singh *et al*., 1984, 2011; Singh and Suárez, 1987). Other relevant shallow crustal events (M > 5) at the TMVB are: the 1567/68 Ameca earthquake (M_w ~ 7.2; Suter, 2015; Suárez *et al*., 1996); the 1887 Pinal (m_b 5.3; Suter, 1996); the 1920 Jalapa (M_s 6.2/m_b 6.5; Abe, 1981); the 1950 Ixmiquilpan (m_b 5.0; Singh *et al*., 1984); the 1976 Cardonal (m_b 5.3; Mexican Seismological Service); and the 1979 Maravatío (m_b 5.5; Astiz, 1980) earthquakes (Figure 1). These intraplate events pose a significant seismic hazard to people and infrastructure in Central Mexico, the most populated region in the country. The importance of the information extracted from paleoseismological studies in seismic hazard analysis highlights the need for systematic treatment of uncertainties. Interpretation of geological observations has a source of uncertainties inherent to large number of hypothesis that may explain the observed geological features. For example, the uncertainties which are related to the spatial observation window (at the scale of the trench) and the preservation of the geological record. In particular, breaking evolved along the fault however, in paleoseismological studies, it can only be observed as deformations preserved in the sedimentary record. Moreover, in Central Mexico, the differential compaction of surface sediments can produce structures that can be

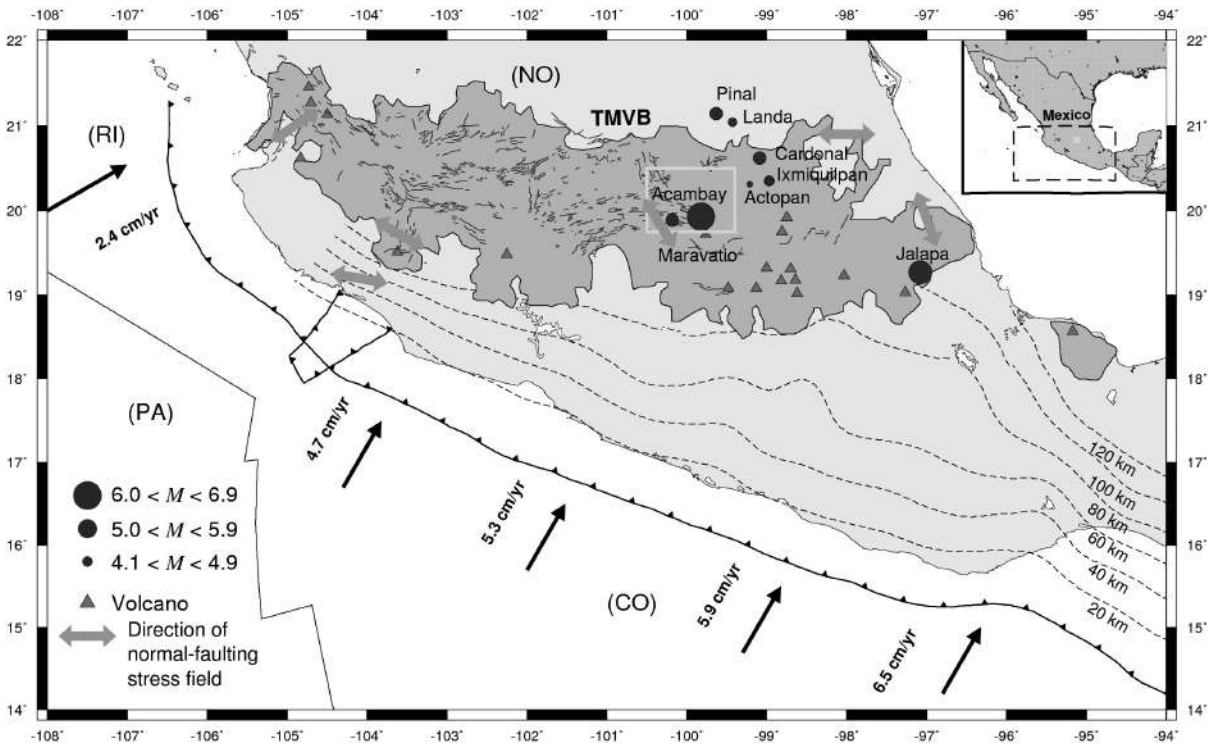


Figure 1. Main tectonic features in Central Mexico. NA is the North American plate, CO is the Cocos plate, PA is the Pacific plate, RI is the Rivera micro plate, and TMVB is the Trans-Mexican Volcanic Belt. Red triangles are volcanoes and the black-bold line delimits the boundary of the TMVB. Dashed lines show contour lines of the subducted slab at 20, 40, 60, 80 and 120 km depth (Hayes *et al*., 2012). Gray circles are shallow crustal earthquakes in the TMVB with M > 4.1 (Orozco and Berra, 1887; Urbina and Camacho, 1913; Astiz, 1980; Suter, 2015; and the Mexican Seismological Service). The size of the circle is proportional to the magnitude. The green rectangle shows the Acambay region. The arrows show the convergence rate relative to North America (DeMets *et al*., 1994). Blue lines are geological faults in the TMVB reported in Ferrari *et al.* (2012). Orange arrows indicate direction of horizontal stress in provinces with a normal fault-type stress field based on Suter (1991).

interpreted, wrongly, as tectonic movements if the study areas are wrongly chosen. Finally, fractures without associated displacement can be wrongly interpreted as being associated with a seismic event on paleoseismological studies. However, without any other structural features described in the trench it can not be discarded that fractures could also be associated to other factors such as a distant earthquake, a period of drought, etc. This makes estimating the uncertainties related to paleoseismological data for their use in seismic hazard analysis a difficult task (Atakan *et al*., 2000). To overcome these pitfalls, a detailed description of the source of paleoseismological data is needed (Atakan *et al*., 2000). None of the paleoseismic studies in Mexico had tried to quantify a total uncertainty in their results. Using paleoseismic data in seismic hazard analysis without any uncertainty quantification may lead to a misinterpretation of the true seismic hazard. In this study, we applied the method proposed by Atakan *et al*. (2000) to estimate uncertainties in paleoseismic studies carried out in the Acambay graben region in Central Mexico. The method is based on logic-tree formalism and it has been applied in paleoseismological and archaeoseismological studies with success (Atakan *et al*., 2000; Grützner *et al*., 2010, respectively). Furthermore, we employ a measure of the information entropy (Shannon, 1948) at each step in the estimation to provide an additional source of validation of the results.

Tectonic setting

The TMVB is an active calc-alkaline volcanic arc that traverses Mexico from the Pacific Ocean to the Gulf of Mexico (1200-km-long, 100-km-wide; Figure 1). The TMVB is associated with the subduction of the Cocos and Rivera plates beneath the North America plate (Suárez and Singh, 1986; Ego and Ansan, 2002; Figure 1). The crustal seismicity of this region is not related to the subduction along the Middle America Trench (MAT) but is due to numerous east-west striking normal faults that are characterized by pronounced scarps and displace Quaternary volcanic rocks (Suter *et al*., 1992; 1995). The Acambay region is located at the central part of the TMVB; it consists of a series of depressions bounded by normal faults, such as the Acambay graben (Figure 2). The Acambay graben is up to 80 km long and 15-38 km wide and has a maximum topographic relief of 500 m (Suter *et al*., 1992; 1995). The graben is delimited by the Epitacio-Huerta and Acambay-Tixmadejé faults to the north and by the, Venta de Bravo and Pastores faults, to the south (Figure 2). The Epitacio-Huerta fault is 30-km-long normal fault with E-W direction and dip to the south but its activity has not been demonstrated. The Acambay-Tixmadejé fault is an approximately 42-km-long, south-dipping normal fault (Suter *et al*., 1992) (Figure 2). The Acambay-Tixmadejé fault forms the master fault of the Acambay graben and was the principal seismogenic source of the 1912 Acambay earthquake (Urbina and Camacho, 1913). The Venta the Bravo is a 45-km-long active normal fault with E-W direction and dip to the north. The Pastores fault is a north-dipping active normal fault about 32-km-long (Suter *et al*., 1992; Langridge *et al*., 2013; Figure 2). The San Mateo fault is a 13 to 25-km-long active normal fault with E-W direction and dip to the south at the center of the graben (Sunye-Puchol *et al*., 2015).

Data and methods

Data

Paleoseismological studies on faults in Mexico concentrate mainly near the epicentral area of the Acambay 1912 earthquake (central segment of the TMVB; Figures 1 and 2), since that was one of the most damaging events occurred in the continental environment of Mexico notwithstanding other faults which have not ruptured in historical times. We used the method proposed by Atakan *et al*. (2000) to estimate uncertainties in paleoseismic studies in the Acambay graben region. We focus our analysis on the studies conducted by Langridge *et al*. (2000) on the Acambay-Tixmadejé fault; Langridge *et al*. (2013) and Ortuño *et al*. (2015) on the Pastores fault; and Sunye-Puchol *et al*. (2015) on the San Mateo fault (Figure 2). All the mentioned studies used trench evidence for identifying paleoearthquakes with a magnitude and time of occurrence, making them suitable for the methodology proposed by Atakan *et al*. (2000). The relevant data employed in the uncertainty estimation will be discussed in a subsequent section.

Uncertainty estimation

Atakan *et al*. (2000) introduced a method to estimate uncertainties in paleoseismic studies using a logic-tree formalism. The method is based on a quantitative description of uncertainties related to paleoseismological data and its interpretation. In this method, the cumulative uncertainties associated with different stages of the study are computed as the combination of the preferred alternative branches of the logic-tree. The total uncertainty and its relative importance in seismic hazard analysis is expressed by a quality factor, known as the paleoseismic quality factor (PQF). This PQF can be directly used in seismic hazard

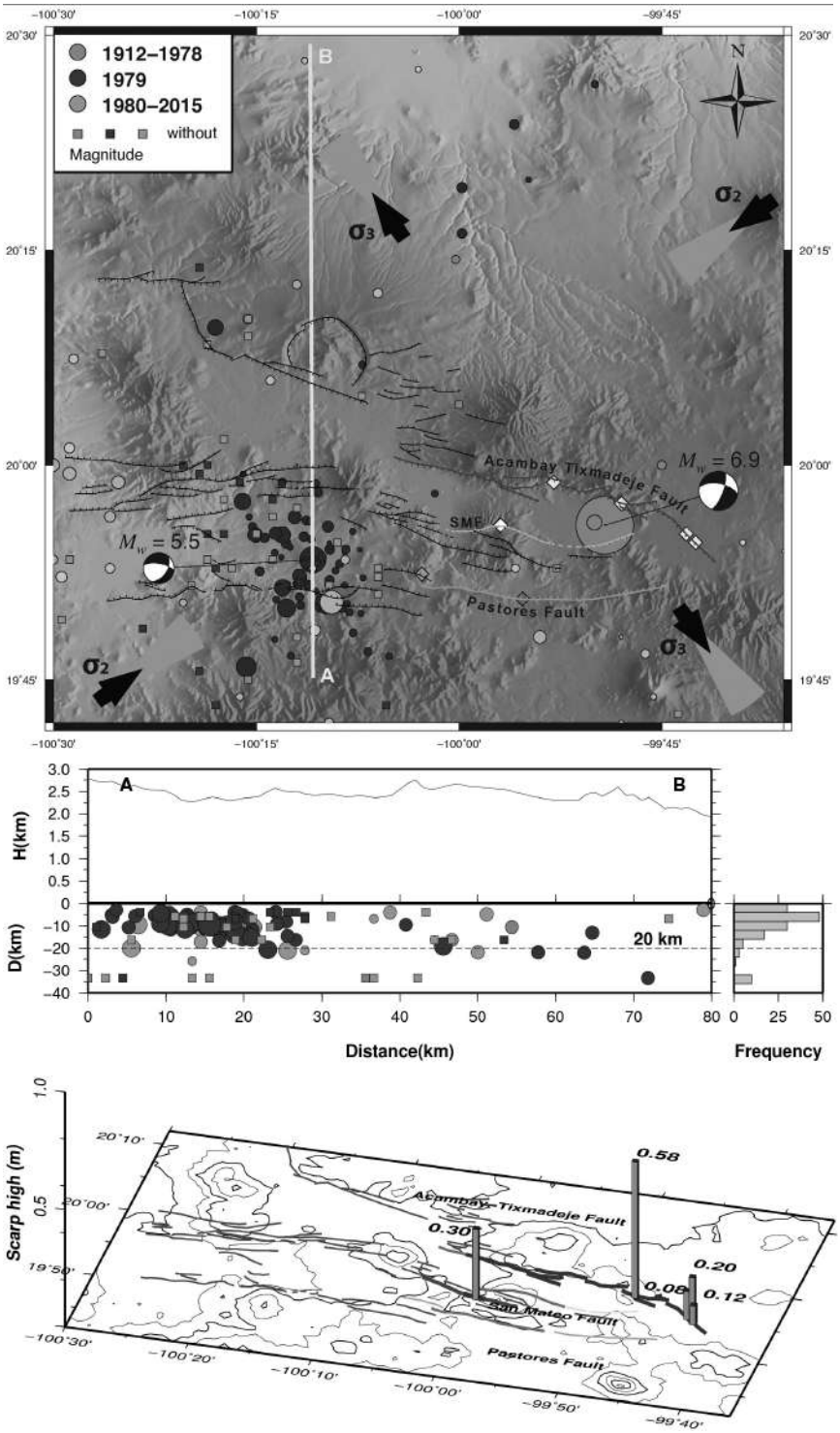


Figure 2. *a*) Main tectonic features in the Acambay region: the Acambay-Tixmadejé fault, the Pastores fault (PF), and the San Mateo fault (SMF). Diamonds are paleoseismological trench sites of Langridge *et al.* (2000) (yellow), Langridge *et al.* (2013) (magenta), Ortuño *et al.* (2015) (green), and Sunye-Puchol *et al.* (2015) (white). Focal mechanisms based on results of Astiz (1980) (Maravatio earthquake, M_w 5.5) and fault orientation reported by Suter *et al.* (1995) and Langridge *et al.* (2000) (Acambay earthquake, M_w 6.9). Thick black arrows indicate the direction of principal stresses with their incertitude cone based on Ego and Ansan (2002). *b*) Most of the events in the region occur at depths less than 20 km (Cross-section AB). *c*) Major surface fault rupture for the 1912 event (blue bold line). Red bold lines show the interpreted extended fault rupture based on descriptions of Urbina and Camacho (1913) in adjacent areas. Vertical bars depict scarp heights reported by Urbina and Camacho (1913) and Langridge *et al.* (2000).

analysis and compared with other studies (Atakan *et al*., 2000). The different study stages are represented as different nodes of the logic-tree. Each node has at least two alternative branches with their respective uncertainties. One branch represents the preferred solution and the other the sum of the remaining alternatives. The uncertainties are expressed in terms of probabilities assigned to each branch of the logic-tree. Eventually, a joint probability of the preferred alternatives will provide a qualitative measure of uncertainty of the paleoseismological analysis. According to Atakan *et al*. (2000), the relevant steps in the paleoseismic analysis are: 1) tectonic setting and strain-rate; 2) site selection criteria: 3) extrapolation of the conclusions drawn from the detailed site analysis to the entire fault; 4) identification of individual paleoearthquakes; 5) dating of paleoearthquakes; 6) paleoearthquake size estimates. In what follows, we summarize the main aspects of each step.

Atakan *et al*. (2000) classified the tectonic settings into three different categories. Each of them with an associated quality weight factor (QWF): plate boundaries (high strain-rate, QWF = 0.8 – 1.0); active plate interiors (intermediate strain-rate, QWF = 0.6 – 0.8); and stable continental regions (low strain-rate, QWF = 0.4 – 0.6). The site selection criteria take into account the methods used to select a site for detailed analysis. The site selection is mainly based on geomorphological information but according to the authors it should be supported by complementary studies. If the geomorphological evidence is supported by at least two or more geodetic and/or geophysical analyses, a QWF of 0.8 – 1.0 is assigned. If the geomorphological evidence is supported by an additional geodetic or geophysical study, a QWF of 0.6 – 0.8 is assigned. If only geomorphological is used, a QWF of 0.4 – 0.6 is assigned. If the selection is based on other indirect evidence, a weight of < 0.4 is assigned.

A criterion to assess the amount of extrapolation of site data to the entire fault is proposed. This criterion is based on the ratio of the total trench area studied to that of the entire fault area (TFR). TFR is defined as (Atakan *et al*., 2000):

$$TRF = \frac{A_{st}}{A_f} = \frac{\sum_{i=1}^{n}\left(T_{l_i} \times T_{d_i}\right)}{F_l \times F_d} \qquad (1)$$

where A_{st} is the total area of the studied trenches, A_f is the total fault area, n is the number of trenches used, T_{li} and T_{di} are the trench length and depth for the i-th trench, respectively, F_l is the fault length and F_d is the fault depth. Depending on the TFR value, a QWF is assigned. If TFR is in the interval of 0.5 – 1.0 (very good classification), QFW is equal to 0.8 – 1.0. If TFR ranges from 0.1 to 0.5 (good classification), QFW is equal to 0.6 – 0.8. If TFR varies from 0.01 to 0.1 (moderate classification), QFW is equal to 0.4 – 0.6. If TFR ranges from 1 $x10^{-6}$ to 0.01 (poor classification), QFW is equal to 0.2 – 0.4. If TFR is < 1 $x10^{-6}$ (very poor classification), QFW has a value of < 0.2. We estimated uncertainties in the TFR by using error propagation rules. Uncertainties in the TFR are mainly due to errors in F_l and F_d. We do not consider errors in the trench dimensions, because they are controlled parameters. We obtained the following expression to estimate the error factor in the TFR (dTFR):

$$dTRF = \frac{1}{F_l \times F_d}\sqrt{\left(\frac{dF_l}{F_l}\right)^2 + \left(\frac{dF_d}{F_d}\right)^2} \qquad (2)$$

where dF_l and dF_d are the uncertainties in the fault length and depth, respectively.

Paleoearthquake identification in the trenches is based on diagnostic criteria. These criteria are used to preclude the possibility of similar structures created by non-tectonic processes. The criteria consider the paleoseismic features defined by McCalpin and Nelson (1996) which focus on three aspects: genesis, location and timing, respectively. Based on the abundance of non-seismic features, a QWF is assigned: few (QWF = 0.8 – 1.0), some (QWF = 0.6 – 0.8), common (QWF = 0.4 – 0.6) and very common (QWF < 0.4) features, respectively. The uncertainties related to the dating of paleoearthquakes depend on the precision and accuracy of the techniques used. Estimating the size of the events is based on either primary or secondary evidence (Atakan *et al*., 2000). Primary evidence includes the following criteria: seismic moment (QWF = 1.0); rupture area (QWF = 0.9); length x displacement, and average displacement (QWF = 0.8); surface-rupture length (QWF = 0.7); maximum displacement (QWF = 0.6). On the contrary, secondary evidence includes the following criteria: the total are afected by liquefaction (QWF = 0.5) and landslides (QWF = 0.4).

The QWFs are expressed in terms of percent probabilities indicating the relative reliability of the chosen (preferred) alternative. This allows

to account for uncertainties systematically. The concept of entropy has been used in information theory to characterize uncertainties in decision trees (Shannon, 1948). The entropy of a probability distribution (H) is defined as (Shannon, 1948):

$$H(p) = -\sum_{i=1}^{n} p_i \log_2(p_i) \qquad (3)$$

where p_i are the probabilities. H ranges from 0 to 1 where high H is associated with high uncertainty and viceversa. We also quantified the conditional entropy in order to estimate uncertainties in tree nodes conditioned on a particular probability value in previous branches (stages in paleoseismology analysis). The conditional entropy is defined as:

$$H(A/B) = -\sum_{i=1}^{n}\sum_{j=1}^{m} p(a,b)\log_2 p(a/b) \qquad (4)$$

where a and b are two random variables.

The cumulative uncertainties provide an end solution (probability) in terms of the paleoseismic quality factor (PQF). PQF is defined as:

$$PQF = P_{es} \cdot C_{ri} \qquad (5)$$

where P_{es} is the probability of the preferred end-solution, in the logic-tree analysis, C_{ri} is a correction term for the relative level of importance of the investigation in the seismic hazard analysis. C_{ri} depends on the aim of the paleoseismic study (see Table 1).

Input parameters for paleoseismological uncertainty analysis

We briefly present the main results of previous studies that were used as input parameters for the uncertainty estimation analysis. Table 2 summarizes the relevant results for the Acambay-Tixmadejé (ATF), San Mateo (SMF) and Pastores (PF) faults.

Case study 1 (Acambay-Tixmadejé fault): The Acambay-Tixmadejé fault is situated in a continental plate interior, where the strain-rate is classified under the intermediate strain-rate category (about 0.17 mm/yr) (Langridge *et al*., 2000). The site selection was based on geomorphological information and on the location of the surface fault rupture (Urbina and Camacho, 1913). Fault length and depth are 42 and 15 km, respectively. Table 2 shows the number of trenches and their dimensions. The diagnostic features observed in the trenches were of primary origin on the fault and co-seismic. The evidence used to identify the events was based on disturbed stratigraphic horizons and colluvial wedges indicating vertical offset. Langridge *et al*. (2000) used ^{14}C to determine the date of the organic material from the sedimentary deposits in the trenches. At least four events of about the same magnitude ($M \sim 7.0$) were recognized by a combination of upward terminating faults, fissure fills, erosionally truncated fissures, colluvial wedges fills, and downward separation of stratigraphic units. These events occurred in the last 34.3 ky cal BP, 11.5 ky cal BP, 7.9 ky cal BP, and 4.7 – 5.2 ky cal BP, respectively. Langridge *et al*. (2000) reported magnitudes in the range of $6.8 < M_w < 7.0$ based on maximum and average displacements and surface rupture length.

Table 1. Correction terms Cri (After Atakan *et al*., 2000).

Correction term Cri	Level of importance	Aim of the study
2	level 1	The results are used for estimating time recurrence and magnitudes in local seismic hazard analysis.
4	level 2	The results are used for estimating time recurrence and magnitudes in regional seismic hazard analysis.
6	level 3	The results reported in an event catalogue and used in the computation of seismic parameters.
8	level 4	To assess the earthquake potential of a fault. The results will not be used directly in the seismic hazard analysis.
10	level 5	To prove that the fault is active.

Case study 2 (Pastores fault): The Pastores fault is also located in a continental plate interior, where the strain-rate is classified under the intermediate strain-rate category (< 0.04 mm/yr in the central fault segment, Suter *et al*., 1995; and 0.23 – 0.37 mm/yr at the western fault tip, Ortuño *et al*., 2015) (Figure 2). The site selection was based on geomorphological evidence supported by a ground penetrating radar (GPR) prospecting (Langridge *et al*., 2013; Ortuño *et al*., 2015). Fault length and depth are 32 and 15 km, respectively. Table 2 shows the number of trenches and their dimensions. The diagnostic features observed in the trenches were of primary origin on the fault and co-seismic. The evidence used to identify the events was based on disturbed stratigraphic horizons and colluvial wedges indicating vertical offset (Langridge *et al*., 2013; Ortuño *et al*., 2015). Both and used ^{14}C to determine the date of the organic material from the sedimentary deposits in the trenches. In the central fault segment, three paleoearthquakes were identified (Langridge *et al*., 2013). The events occurred at 12.2 – 23.9 ky cal BP, 23.9 – 34.6 ky cal BP, and 31.5 – 41.0 ky cal BP, respectively. The average recurrence time is about 10 – 15 ky cal BP (Langridge *et al*., 2013). At the western fault tip, five paleoearthquakes were identified within the past 4 ky (Ortuño *et al*., 2015). A recurrence interval of 1.1 – 2.6 ky cal was inferred (Ortuño *et al*., 2015). Langridge *et al*. (2013) reported magnitudes of $6.4 < M_w < 6.8$ for the paleoearthquakes based on maximum displacement and surface rupture. Ortuño *et al*. (2015) reported magnitudes of 5.8 based on the scaling relationships of Wells and Coppersmith (1994) for average displacement of normal fault events at the western end. The magnitudes were also estimated with the scaling relations of Wesnousky (2008), obtaining magnitudes of about $M_w \sim 6.7$.

Case study 3 (San Mateo fault): The San Mateo fault is located in a continental plate interior as the other cases, and the strain-rate is classified under the intermediate strain-rate category (0.060 – 0.11 mm/yr, Sunye-Puchol *et al*., 2015). The site selection was

Table 2. Input parameters

N	Parameter	ATF	PF	SMF
1	Strain rate (mm/yr)	0.17	< 0.04 central segment 0.23-0.37 western tip	0.06-0.11
2	Site selection	-geomorphic -surface fault rupture	-geomorphic -GPR survey	-geomorphic
3	Fault length (km)	42	32	25
4	Fault depth (km)	15	15	15
5	Number of trenches	4	4	2
6	Trench dimensions (length × depth)(m)	14 × 2 120 × 1.7 30 × 3.75 30 × 4.0	28 × 3 24 × 4 15 × 3 47 × 3	15 × 3 24 × 4
7	Diagnostic features	on-fault coseismic	on-fault coseismic	on-fault coseismic
8	Dating method	numerical 14C	numerical 14C	numerical 14C
9	Earthquake size	6.8 < Mw < 7.0	6.4 < Mw < 6.8	6.4 < Mw < 6.7
10	Magnitude criteria	maximum and average displacement -ruture surface length	-maximum displacement -ruture surface length	-maximum displacement -ruture surface engtth

ATF is the Acambay-Tixmadejé fault; PF is the Pastores fault; SMF is the San Mateo fault.

Table 3. Results

Parameters	QWF interval	Assigned QWF	Observations	Fault
Intermediate strain rate	0.6 – 0.8	0.8	Fault scarp visible along 40 km	ATF
	0.6 – 0.8	0.7	Fault scarp for 5 km/ buried structures	PF
	0.6 – 0.8	0.8	Fault scarp visible over 10 km	SMF
Site selection criteria	0.4 – 0.6	0.8	Geomorphic-fault rupture	ATF
	0.4 – 0.8	0.8	Geomorphic/geophiscial	PF
	0.4 – 0.6	0.6	Geomorphic only	SMF
TFR	< 0.2	0.2	Very poor classification	ATF
	< 0.2	0.2	Very poor classification	PF
	< 0.2	0.2	Very poor classification	SMF
Non-seismic features	0.8 – 1.0	0.9	Few	ATF
	0.8 – 1.0	1.0	Few	PF
	0.8 – 1.0	1.0	Few	SMF
Dating method	0.8 – 1.0	0.8	Isotopic/numerical	ATF
	0.8 – 1.0	0.8	Isotopic/numerical	PF
	0.8 – 1.0	0.8	Isotopic/numerical	SMF
Magnitude estimate	0.6 – 0.8	0.7	Mean/maximum/rupture length	ATF
	0.6 – 0.7	0.7	Maximum/rupture length	PF
	0.6 – 0.7	0.7	Maximum/rupture length	SMF

ATF is the Acambay-Tixmadejé fault; PF is the Pastores fault; SMF is the San Mateo fault.

based only on geomorphological evidence (Sunye-Puchol *et al*., 2015). Fault length and depth are 25 and 15 km, respectively. Table 2 shows the number of trenches and their dimensions. The diagnostic features observed in the trenches were of primary origin on the fault and co-seismic. The evidence used to identify the events was based on disturbed stratigraphic horizons and colluvial wedges indicating vertical offset (Sunye-Puchol *et al*., 2015). Sunye-Puchol *et al*. (2015) used ^{14}C to determine the date of the organic material from sedimentary deposits in the trenches. The dating results indicated that in total, three paleoearthquakes were identified (Sunye-Puchol *et al*., 2015). These events occurred in the last 31 – 29.2 ky cal BP, 19.1 – 6.5 ky cal BP and 6.0 – 4.2 ky cal BP, respectively (Sunye-Puchol *et al*., 2015). A recurrence interval of 11.57 ± 5.32 ky cal BP was inferred (Sunye-Puchol *et al*., 2015). Sunye-Puchol *et al*. (2015) reported magnitudes in the range of $6.4 < M_w < 6.7$ based on maximum displacement and surface rupture length of 13 km.

Results and Discussion

The results are presented for individual faults and then we discuss the advantages and possible drawbacks in the paleoseismology uncertainty method. The assigned QWFs in all the logic tree stages are listed in Table 3. Uncertainties in TFR are estimated with the following assumptions: $F_l = 42 \pm 2$ km and $F_d = 15 \pm 5$ km; $F_l = 32 \pm 4$ km and $F_d = 15 \pm 5$ km; $F_l = 13 \pm 7$ km and $F_d = 15 \pm 5$ km for the Acambay-Tixmadejé, Pastores and San Mateo faults, respectively. Estimations of F_d are based on reported seismicity in the Acambay region (Figure 2b). The calculated *TFR* with uncertainties are: $(7.37 \pm 2.48) \times 10^{-7}$, $(7.62 \pm 2.71) \times 10^{-7}$ and $(3.76 \pm 2.19) \times 10^{-7}$ for the Acambay-Tixmadejé, Pastores and San Mateo faults, respectively. All the results belong to the very poor class according to the classification of Atakan *et al*. (2000). These errors represent 34, 36 and 58% of the TFR value for the ATF, PF and SMF, respectively.

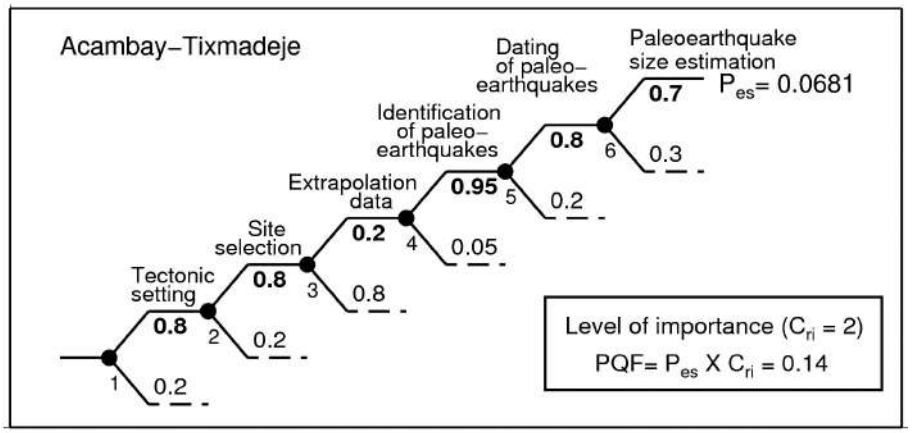
Applying the logic-tree formalism, the probability of the preferred end solution in the analysis is found to be P_{es} = 0.0681 (Figure 3) for the Acambay-Tixmadejé fault. The study conducted by Langridge *et al*. (2000) focused on characterizing typical events in terms of magnitude and time recurrence in the Acambay-Tixmadejé fault, thus a C_{ri} of 2 is assigned (Table 1 and Figure 3). Accordingly, we obtain a PQF of 0.14. For the case of the Pastores fault, we obtained a P_{es} of 0.0502 (Figure 3). Langridge *et al*. (2013) stated that the aim of their study is to assess the earthquake potential of the Pastores fault, thus a C_{ri} of 8 is assigned (Table 1 and Figure 3). This gives a PQF_1 of 0.40. The study conducted by Ortuño *et al*. (2015) focused on the activity of the Pastores fault, thus a C_{ri} of 10 is also assigned (Table 1 and Figure 3). Accordingly, the PQF_2 is 0.50. In the case of the San Mateo fault, the probability of the preferred end solution in the analysis is P_{es} = 0.0511 (Figure 3). Sunye-Puchol *et al*. (2015) stated that the aim of their study is to assess the earthquake potential of the San Mateo fault, thus a C_{ri} of 8 is assigned (Table 1 and Figure 3). For this case, we get a PQF of 0.41.

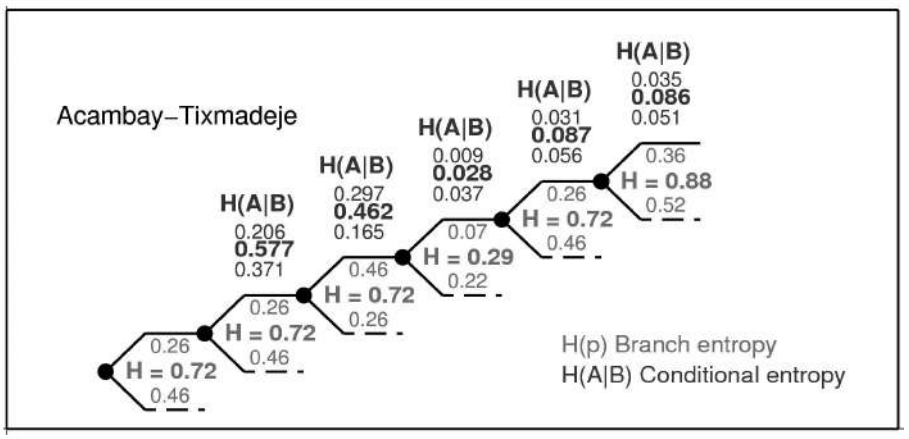
Comparing the entropy, the lowest entropy values are related to the identification of the paleoevents stage (Figure 3a and 3c and Table 4) for the preferred branch and the mean entropy at the ATF and SMF. For these faults the conditional entropy showed a similar behavior throughout the stages (Figure 3a and 3c and Table 4). The correct identification of paleoearthquakes seems to be a key step in estimating uncertainties as is also seen in the Pastores fault case. A QWF of 0.8 in this stage produces significant fluctuations in the entropy of the tree (Table 4). The conditional entropy in the last tree node represents the uncertainty at the end of the paleoseismological study. This final entropy is lower than the conditional entropy in the first two study stages (for example in the site selection and extrapolation data steps) (Figure 3). By incorporating more stages with relative good QWFs, the conditional entropy decreases

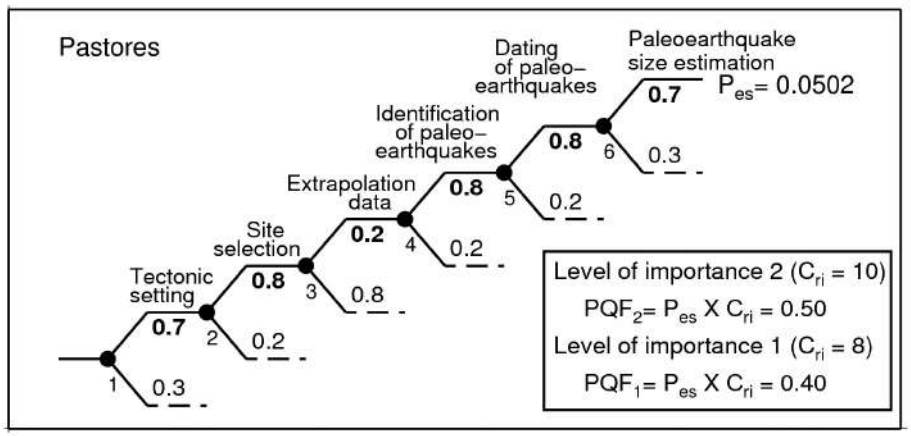
Table 4. Entropy analysis

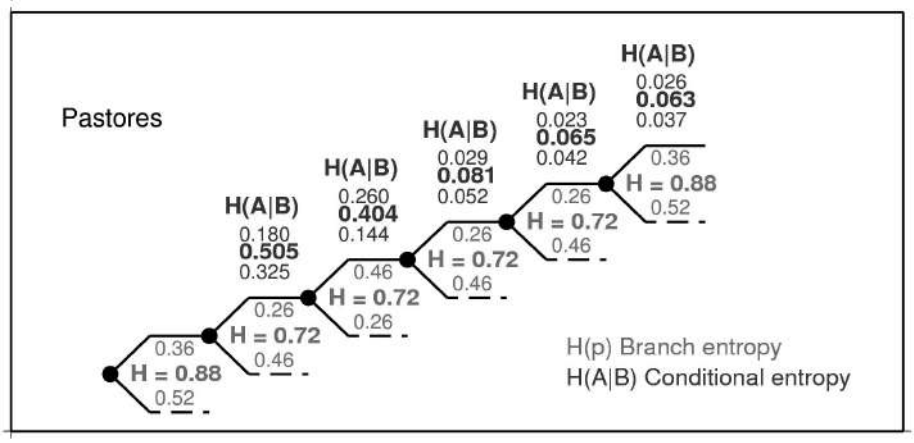
Fault	Stage	Branch 1	Branch 2	H_1	H_2	H	H_1(A|B)	H_2(A|B)	H(A|B)
ATF	1	0.80	0.20	0.26	0.46	0.72			
	2	0.80	0.20	0.26	0.46	0.72	0.206	0.371	0.577 H(2|1)
	3	0.20	0.80	0.46	0.26	0.72	0.297	0.165	0.462 H(3|1,2)
	4	0.95	0.05	0.07	0.22	0.29	0.009	0.028	0.037 H(4|1,2,3)
	5	0.80	0.20	0.26	0.46	0.72	0.031	0.056	0.087 H(5|1,2,3,4)
	6	0.70	0.30	0.36	0.52	0.88	0.035	0.051	0.086 H(6|1,2,3,4,5)
PF	1	0.70	0.30	0.36	0.52	0.88			
	2	0.80	0.20	0.26	0.46	0.72	0.180	0.325	0.505 H(2|1)
	3	0.20	0.80	0.46	0.26	0.72	0.260	0.144	0.404 H(3|1,2)
	4	0.80	0.20	0.26	0.46	0.72	0.029	0.052	0.081 H(4|1,2,3)
	5	0.80	0.20	0.26	0.46	0.72	0.023	0.042	0.065 H(5|1,2,3,4)
	6	0.70	0.30	0.36	0.52	0.88	0.026	0.037	0.063 H(6|1,2,3,4,5)
SMF	1	0.80	0.20	0.26	0.46	0.72			
	2	0.60	0.40	0.44	0.53	0.97	0.354	0.423	0.777 H(2|1)
	3	0.20	0.80	0.46	0.26	0.72	0.223	0.124	0.347 H(3|1,2)
	4	0.95	0.05	0.07	0.22	0.29	0.007	0.021	0.028 H(4|1,2,3)
	5	0.80	0.20	0.26	0.46	0.72	0.023	0.042	0.065 H(5|1,2,3,4)
	6	0.70	0.30	0.36	0.52	0.88	0.026	0.038	0.064 H(6|1,2,3,4,5)

ATF is the Acambay-Tixmadejé fault; PF is the Pastores fault; SMF is the San Mateo fault. H1 and H2 are the entropy in branches 1 and 2, respectively. H is the mean entropy. H1(A|B) and H2(A|B) are the conditional entropies in branches 1 and 2, respectively. H(A|B) is the mean conditional entropy.


Acambay–Tixmadeje
Tectonic setting
Site selection
Extrapolation data
Identification of paleo–earthquakes
Dating of paleo–earthquakes
Paleoearthquake size estimation
0.8
0.2
0.8
0.2
0.95
0.05
0.8
0.2
0.7
0.3
P_{es}= 0.0681
Level of importance (C_{ri} = 2)
PQF= P_{es} X C_{ri} = 0.14


Acambay–Tixmadeje
H(A|B) 0.206 0.577 0.371
H(A|B) 0.297 0.462 0.165
H(A|B) 0.009 0.028 0.037
H(A|B) 0.031 0.087 0.056
H(A|B) 0.035 0.086 0.051
H = 0.72
H = 0.72
H = 0.29
H = 0.72
H = 0.88
H(p) Branch entropy
H(A|B) Conditional entropy


Pastores
Tectonic setting
Site selection
Extrapolation data
Identification of paleo–earthquakes
Dating of paleo–earthquakes
Paleoearthquake size estimation
0.7
0.3
0.8
0.2
0.8
0.2
0.8
0.2
0.7
0.3
P_{es}= 0.0502
Level of importance 2 (C_{ri} = 10)
PQF_2= P_{es} X C_{ri} = 0.50
Level of importance 1 (C_{ri} = 8)
PQF_1= P_{es} X C_{ri} = 0.40


Pastores
H(A|B) 0.180 0.505 0.325
H(A|B) 0.260 0.404 0.144
H(A|B) 0.029 0.081 0.052
H(A|B) 0.023 0.065 0.042
H(A|B) 0.026 0.063 0.037
H = 0.72
H = 0.72
H = 0.72
H = 0.72
H = 0.88
H(p) Branch entropy
H(A|B) Conditional entropy

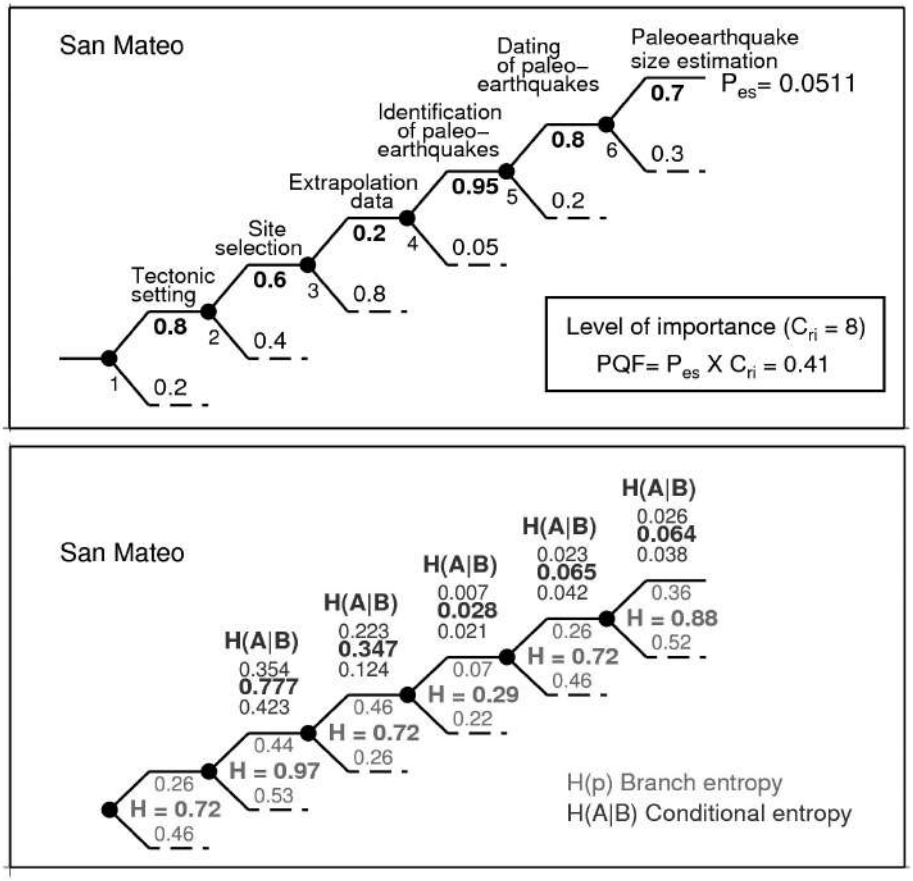


Figure 3. Paleoseismology logic-trees for the Acambay-Tixmadejé, Pastores and San Mateo faults. The logic-trees consist of 12 branches and 6 nodes at which certain probabilities must be defined. The result is the probability of the preferred end solution (P_{es}). In this study, P_{es} is 0.0681, 0.0502 and 0.0511 for the Acambay-Tixmadejé, Pastores and San Mateo faults, respectively. The paleoseismic quality factor (PQF) is P_{es} x C_{ri} (C_{ri} is a correction term depending on the level of importance of the study). PQF is 0.14, 0.40-0.50, and 0.41 for the Acambay-Tixmadejé, Pastores and San Mateo faults, respectively. Estimations of entropy for each branch is shown in the lower panels of *a*), *b*) and *c*) in red colors. Mean entropies are shown bold red color (middle value). Conditional entropy for each branch (upper and lower values) and the average (middle value) are indicated in blue color. Upper values represent the preferred branch.

as shown in Table 4 and Figure 3. This highlights the importance of adding more stages in the paleoseismological studies resulting in more complex logic trees.

Paleoseismology has to deal with many uncertainties caused in particular by limitations in site selection and earthquake identification. Subjective evaluations are inherent in paleoseismic studies, thus the quantification of uncertainty is necessary to address this problem. The logic trees are first attempts to quantify uncertainties that are often hard to express in numbers, and this approach reaches its limits at certain points. Some nodes of the logic trees are based on a number of different criteria, which allow calculations of a wide range of probability values. For example the estimation of QWF for intermediate strain-rate tectonic enviroments (0.6 < QWF < 0.8). Additionally, the paleoseismological logic-tree is mainly designed to investigate faults and related coseismic surface ruptures and hardly incorporates the large variety of secondary earthquake ground effects (e.g. ground failure, liquefaction, landslides). Atakan *et al*. (2000) mentioned that some of the uncertainties that are not considered in their analysis are: 1) those related with the completeness of the paleoseismic records; and 2) aspects concerning the time evolution of different processes involved rupture process. For example, the difficulties in matching the long-term deformation rates with the

co-seismic slip and whether the maximum observed slip at fault is a result of a single or several paleoearthquakes. These aspects can be implemented in the logic-tree analysis but they are difficult to quantify. For future refined studies, these and other aspects would have to be taken into consideration, at least comparatively, to account for the peculiarity of the different studies areas. In the particular case of the Acambay graben, some important factors that are not taken into account by the logic-tree methodology proposed by Atakan *et al*. (2000), are: 1) the data relative to the 1912 earthquake rupture along the Acambay-Tixmadejé fault; 2) the width of the fault zone that may influence the distribution of deformation on unstudied secondary faults; 3) the completeness of the sedimentary record in the trench that directly controls the completeness of the record of paleoseismological events identified.

We now analyze possible sources for the low level of classification of the paleoseismological studies conducted in the Acambay region obtained through the logic tree scheme. One disadvantage of these studies is that few were supported by complementary geodetic and/or geophysical methods. The identification of suitable places for trenching was mostly based on geomorphological evidence. Only one study used a complementary method to the paleoseismic analysis (see Ortuño *et al*., 2015). The advantage of the studies, on the other hand, was that they used numerical dating techniques and they provided a complete description of the diagnostic criteria employed at each trench. A key point in seismic hazard analysis, is the magnitude estimation of the paleoevents. Most of the estimated magnitudes were based on the scaling relationships of Wells and Coppersmith (1994). These relations have been shown to be a poor approximation to magnitudes in certain regions (Stirling *et al*., 2013), such as continental ones. The studies do not specify the valid magnitude range of these relations. For example, Ortuño *et al*. (2015) reported magnitudes of about 5.8 considering average displacement on the Pastores fault using relations developed for events in the magnitude range of $6.0 < M < 7.3$. Another source of low uncertainity of the analyzed studies concerns the extrapolation of site data to the entire fault, since most of them were carried out at single point in the fault, so they fall under the very poor qualitative classification following the rules of Atakan *et al*. (2000) (Table 1). They, nevertheless, provide data of utmost importance since no other source of information was available previous to these studies, which could be used towards a comprehensive evaluation of risk in the region.

Because of the lack of similar studies and the absence of sufficient estimations of PQFs values for different regions, a robust comparison of our results in a logic-tree framework was not possible. We can just state that by incorporating geophysical/geodetic studies, and by analyzing more trenches, a better PQF can be obtained resulting in more reliable results for the Acambay region. For example, under these conditions Atakan *et al*. (2000) obtained better estimates of PQF (PQF = 0.76). More studies are needed to compare different tectonic settings and to prove whether the logic tree approach is suitable method to quantify uncertainties in paleoseismological studies. This comparison could be possible because the logic-tree approach takes into account the tectonic setting and site environment in the probability estimations. A direct comparison of several studies in a certain region may enhance the reliability of the results (Sintubin and Stewart, 2008; Grützner *et al*., 2010). Grützner *et al*. (2010) suggested the incorporation of secondary earthquake ground effects and their relation to ground geotechnical properties and seismic amplification in the logic tree approaches. This will allow to conduct more realistic assessments of non-faulted sites devastated by ground shaking which is the case for most of the severely damaged locations during individual earthquakes (Grützner *et al*., 2010). In the case of the Acambay region, a detailed study of site effects is needed to improve our uncertainty estimates and seismic hazard assessment. Nevertheless, the logic-tree formalism proposed by Atakan *et al*. (2000) is prone to improvement by considering other aspects currently not taken into account, or investigating the effect of different weights on the tree branches.

Conclusions

We estimated uncertainties of paleoseismic studies conducted in the Acambay-Tixmadejé, Pastores, Venta de Bravo and San Mateo faults. We focus on the following steps of the paleoseismic analysis: 1) tectonic setting and strain-rate; 2) site selection; 3) extrapolation of site data to the entire fault; 4) identification of paleoearthquakes; 5) dating of paleoearthquakes and 6) event size estimates. The main results are: 1) In the Acambay region, the probability of the preferred end solution is 0.0681, 0.0502 and 0.0511 for the Acambay-Tixmadejé, Pastores and San Mateo faults, respectively; 2) The paleoseismic quality factor is 0.14, 0.40-0.50, and 0.41 for the Acambay-Tixmadejé, Pastores and San Mateo faults, respectively. These values indicate that the paleoseismic results fall in the very poor to

poor category according to the description of Atakan *et al*. (2000). This implies that better estimates could be attained if complementary studies were carried out at each fault, as well as additional trenching studies. The results, however, do not undermine the importance of all the paleoseismic data collected so far since they are the first steps ever taken in the direction of knowing the seismic potential of faults in Central Mexico, and provide key elements for a correct evaluation of risk in the region. The entropy results showed that the study stage with less uncertainty is associated with the identification of paleoearthquakes. This stage seems to be a key step in estimating uncertainties because QWFs less than 0.8 produce significant fluctuations in the entropy of the logic tree. On the other hand, the entropy conditioned on previous steps is higher at the first two stages (site selection and extrapolation data steps) then it reduces due to the incorporation of more stages (branches) with high QWFs as shown by the results. In the Acambay region, more careful have to be taken in the site selection and extrapolation data stages in order to reduce the entropy and thus the uncertainties in the paleoseisomological studies.

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