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Discussions

Active Faults sources of the Morelia-Acambay Fault System, Mexico based on Paleoseismology and the estimation of magnitude Mw from fault dimensions

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Abstract. The Morelia-Acambay fault System (MAFS), located in the central part of the Trans-Mexican Volcanic Belt (TMVB) is delimited by an active transtensive deformation zone associated with the oblique subduction zone between the Cocos and North American plates, with a convergence velocity of 55 $\mathrm{mm/yr}$ at the latitude of the state of Michoacán, México. Part of the oblique convergence is transferred to the central TMVB, just in the MAFS zone, where the slip rates range from 0.009 to 2.78 $\mathrm{mm/year}$. The occurrence of great earthquakes like the Acambay earthquake ($M_s = 6.7$) on November 19, 1912 with a surface rupture, and in Maravatío, 1979 with $M_b = 5.3$ are located into the MAFS. The zone is seismically active but with large periods of recurrence, as revealed by the seismic sequence (2.5 < M_w <3.0) occurred near the city of Morelia in October 2007, with focal mechanisms corresponding to normal faulting with left-lateral components. Moreover, there are some paleoseismic analyses showing quaternary movements of some faults with magnitudes between 6.0 – 7.1M_w. The purpose of this work is to probe an intrinsic definition of Active Faults for the MAFS as well as the estimation of possible maximum earthquake magnitudes, in order to understand the dynamic of seismic activity along the MAFS. For the new fault dimensions and using three empirical relationships, we found a maximum magnitude of $M_w = 7$. Additionally, a slip-rates series were compiled and analyzed, the results show a temporal strong persistence behavior and a high value of fractal dimension ($D_b = 1.86$) related with a less concentration of small slip-rates. In other words, there is not an excess of the deformation in the MAFS in a single or restricted range of scales, and furthermore, this represents a migration of the ruptures to larger scales (3 ≤ length ≤ 38 km).

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1 Introduction

The state of Michoacán in Mexico is one of the zones with major seismic hazard in all the country. This high seismic activity is mainly due to the oblique collision between the tectonic plates in the pacific coast (Cocos and North American plates), and to the existence of crustal faults in the interior of the state. Furthermore, there are records of earthquakes that have affected populations such as Pátzcuaro and Araró (in 1845 and 1858), Zinapécuaro and Tlalpujahua (in the XIXth century), Acambay (in 1912) and Maravatío (in 1979). More recently, in 2007, a set of earthquakes occurred in the vicinity of the city of Morelia as a consequence of the movement of the active fault named “La Paloma”.

The goal of this study is to understand the seismic activity from Pátzcuaro to Acambay sector. For this purpose, we analyze the geometry and faults distribution, the paleoseismic data and evaluate the instrumental record of few intraplate earthquakes. In particular, this system is a fractal network of faults, that keep a persistence behavior of the slip-rates trend and its fractal dimension is related to the existence of a high concentration of larger earthquake-generating faults (5.4 $\leq M_w \leq$ 7.1).

1.1 Seismotectonic Setting in the Central TMVB

The Trans-Mexican Volcanic Belt (TMVB) is an active continental volcanic arc that crosses Mexico with an approximate E-W orientation. The TMVB is developed within an extensional tectonics setting as a result of the subduction of the Rivera and Cocos plates beneath the North American plate. From the point of view of tectonics, the TMVB is divided in three geographic zones with different types of volcanism and structural features (Figure 1) (Pasquaré et al., 1987; Aguirre-Díaz et al., 1998; García-Palomo et al., 2002; Ortuño et al., 2015).

Especially, we will focus in the central portion of the Tula-Chapala Fault Zone, comprising the cities from Pátzcuaro to Acambay (Johnson and Harrison, 1990), where the kinematics is extensional and transtensional since the Miocene (Johnson and Harrison, 1989; Martínez-Reyes and Nieto-Samaniego, 1990; Garduño-Monroy et al., 2009a) with a left-lateral component (Suter et al., 1992, 1995, 2001; Ego and Ansan 2002; Norini et al., 2006). Suter et al. (1995, 2001) and Ego and Ansan (2002) confirm that this region has been dominated by transtensive stresses since mid-Quaternary with $\sigma 3$ at NW-SE orientation. Additionally, this portion also includes the Taxco-San Miguel de Allende Fault System with a NW trending (Demant, 1978; Aguirre-Díaz et al., 2005; Alaniz-Alvarez and Nieto-Samaniego, 2005), which coincides with a change in the cortical thickness (Ortuño et al., 2015). The eastern zone of the central TMVB is active with a micro seismicity documented in the literature (Ego and Ansan, 2002; Campos et al., 2015; Ortuño et al., 2015) and is characterized by a left-lateral transtensive deformation with NW-SE to NNW-SSE orientation.

According to Mennella (2011) there are three major fault sets in the study area, the first one and oldest is the NNW-SSE that is expressed by the Tzitzio-Valle de Santiago fault. The other two systems configured lake areas and have morphology of seismically active faults with E-W and ENE-WSW strike. The kinematics of them shows clear evidence that begins in the Miocene (17Ma) with left lateral faulting, that later becomes a normal faults with a left lateral component. This stress field generates, in the NNW-SSE faults, a reactivation as oblique faults (normal-right). This deformation always keeps the $\sigma 3$ moving from N360° to N340°.

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Inside the Morelia-Acambay Fault System (SFMA; Suter et al., 1991, 1995 and 2001; Garduño-Monroy et al., 2009b), the Acambay earthquake ($M_s = 6.7$) occurred on November 19, 1912 (Suter et al., 1996) and is the only earthquake recorded in the TMVB with a surface rupture (Ortuño et al., 2015). During this earthquake, at least three faults showed surface rupture (Urbina and Camacho, 1913): the Acambay-Tixmadejé fault ($D_{max} = 50$ cm), Temascalcingo fault ($D_{max} = 30$ cm) and The Pastores fault (Ortuño et al., 2015). Subsequently, another earthquake in 1979 caused major damage in Maravatío, with a magnitude of $M_b = 5.3$ and a depth of 8.2 km (Astiz-Delgado, 1980).

Nowadays, in the MAFS and very close at the city of Morelia, a sequence of seven earthquakes occurred ($2.5 < M_w < 3.0$) with focal mechanisms corresponding to normal faulting with left-lateral components. This set of tremors occurred in a 33-hour interval in October 2007 and were recorded by two local stations located within the city (Krishna-Sing et al., 2012). It is very probable that this sequence of earthquakes is related to the La Paloma fault of 13 km of length that is considered active from the Holocene (Garduño-Monroy et al., 2009). The rupture of a small segment of this fault can generate earthquakes with magnitudes up to $5M_w$ (Krishna-Sing et al., 2012).

Although the seismotectonic context of the MAFS is summarized as a left-lateral transtensional system in several works (Ego and Ansan, 2002; Suter et al., 2001), seismic risk studies are still considered as partials. This is due to the scarcity of data regarding the slip rates and recurrence periods of the prehistoric and historical activity of the fault segments in the system.

Before the Paleoseismology studies in Mexico, these parameters were calculated by the accumulated displacements in the escarpment for each segment and the age of the displaced lithological units. In this sense, for some of the main faults of the system were considered displacement rates of 0.04 mm/year, 0.05 mm/year and 0.18 mm/year (Pastores, Morelia and Cuitzeo faults, respectively; Suter et al., 1992; 2001). Currently, the paleoseismic analyzes of these and other structures in the MAFS have allowed to refine the estimates.

The first faults studied with a paleoseismological approach were the (1) Acambay-Tixmadejé fault (Urbina and Camacho, 1913; Suter et al., 1995a; 1996), where the record of at least five rupture events allowed to calculate a recurrence interval of 3,600 years, mean slip rates of 0.17 mm/year and potential magnitudes of 6.8 to $7M_w$. (2) Pastores fault, with a recurrence interval of 10,000 - 15,000 years and 1,100 - 2,600 years (short and long time span), slip rates of 0.03 to 0.23 - 0.37 mm/year and potential magnitudes of 6.6 to $6.8M_w$ (Suter et al., 1992; Langridge et al., 2013; Ortuño et al., 2015). (3) Temascalcingo and San Mateo faults (Urbina and Camacho, 1913; Roldan-Quintana et al., 2011; Langridge et al., 2013; Sunye-Puchol et al., 2015) found a recurrence interval of 11,000 - 12,000 years, a slip rate of 0.085 mm/year and potential magnitudes of 6.4 to $7M_w$. Other studies using soft-sediment deformations related to seismic activity (seismites) have been carried out also in the basins of Estado of Mexico, such as Tierras Blancas (Rodríguez-Pascua et al., 2010) and Ixtlahuaca controlled by the Perales fault (Benente, 2005; Velázquez-Bucio et al., 2013; 2015), allowed to estimate the potentiality of the near faults, obtaining magnitudes $\geq 6M_w$.

In Michoacán, the work has been concentrated in Pátzcuaro, Morelia and Cuitzeo, where almost a dozen faults have been studied in detail (Garduño-Monroy et al., 2001; 2009; Suter, 2016). For these structures, slip-rates have been obtained in a range of 0.009 - 2.78 mm/year (long and short time span, respectively), recurrence intervals of 1,200 - 100,000 years (long and short time span, respectively) and potential magnitudes of 5.8 - $7.1M_w$.

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Above all, these studies highlight the need to define the intracontinental structures that are susceptible to generate moderate and strong seismic events, as well as the affected area that can produce such events, especially in the center of Mexico where they coexist with highly populated areas.

2 Methods

2.1 Active Fault definition

First, this work contributes with the definition of active fault within the MAFS. Faults are those that can rupture the ground surface in a single maximum magnitude earthquake (Christophersen et al., 2015). Subsequently, an active fault, is defined here as a plane that ground-rupturing with speeds of approximately 0.001 $\mathrm{mm/year}$, with seismic activity associated, at least, in the last 10,000 years and is oriented in favor of the current stress field. The active fault planes must be related to earthquakes of magnitude $M_w \geq$5.4 or capable of generating rupture lengths greater than or equal to 3 km. If the active fault present seismicity with these characteristics will be considered as a seismogenetic fault.

2.2 Mapping the Morelia-Acambay Fault System

For the construction of the database belong at the MAFS, we used the imagery from the Instituto Nacional de Estadística y Geografía (INEGI, acronym in Spanish) and a digital elevation model of the Mexican continental territory with a resolution of 15×15 meters. On a Geographic Information System (GIS) we identified and defined fault segments with morphological evidences. Also, we used information of the faults digitalized around the Cuitzeo basin by the group of the proyect 17 of the Centro Mexicano de Innovación en Energía Geotérmica (CeMIEGeo, acronym in Spanish), based in Morelia, Mexico.

The fault sources database obtained is show in Figure 2. The new fault data consists of a total of 316 segments with length $\geq$ 3 km and comprises the following characteristics:

a) Fault name

b) Length (meters)

c) Scarp (meters)

d) Start coordinates (X1, Y1)

e) Final coordinates (X2, Y2)

f) Intermediate point coordinates (Xm, Ym)

g) Near locality name

h) Distance to fault (meters)

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i) M_w(Wells and Coppersmith, 1994)

j) M_w (Anderson et al., 1996)

k) M_w (Wesnousky. 2008)

2.3 Estimation of the maximum magnitudes

Maximum earthquake magnitudes are calculated from magnitude-scaling relationships. We assess fault relationships by the surface rupture length (SRL) for faults using the empirical regression model of Wells and Coppersmith (1994) for normal faults ($M_w = 4.86 + 1.32\log_{10}(SRL)$); as well as, the equivalent regression model proposed by Wesnousky (2008; $M_w = 6.12+0.47\log_{10}(SRL)$); finally, we also include the model proposed by Anderson et al. (1996; $M_w = 5.12+1.16\log(SRL)-0.2\log(S)$), where S is the slip-rate.

The Wesnousky (2008) relationship represents another way to estimate the maximum expected magnitude and is based on the total fault length for normal faults and crust thicker than 10 km. The relationship of Wesnousky was used previously in the MAFS for the complete fault Jaripeo-Morelia-Cerrito (JMC) and for the Cointzio fault (Suter, 2016).

2.4 Fractal analysis

2.4.1 The Hurst Exponent

We use the Hurst exponent (H) as the measure of roughness of the slip-rates distribution, because of its ability to express the asymptotic statistical properties of a random process (Denisov, 1998), and because it merges local and global features of space/time anisotropy inside the unique variable called roughness. In time-series the Hurst exponent measures the growth of the standardized range of the partial sum of deviations of a data set from its mean (Ellis, 2007). The Hurst exponent is especially suitable to characterize stochastic processes (Mandelbrot and Van Ness, 1968) and there are basic differences between persistent ($H > 0.5$) and antipersistent ($H < 0.5$) processes, while the white noise is characterized by $H = 0.5$ (Torres-Argüelles et al., 2010). For estimating the Hurst Exponent we use the Wavelet transform (Rehman and Siddiqi, 2009), where the characteristic measure of wavelet variance analysis is the wavelet exponent, H_w (Malamud and Turcotte, 1999). Indeed, the time series of interest was the slip-rates distribution belongs to the MAFS.

Consider n wavelet transforms, all of them with a different scaling coefficient; i.e., let $S_1, S_2, ..., S_n$ be their standard deviations from zero. Define the ratios $G_1, G_2, ..., G_{n-1}$ of the standard deviations as $G_1 = \frac{S_1}{S_2}, G_2 = \frac{S_2}{S_3}, ..., G_{n-1} = \frac{S_{n-1}}{S_n}$, and compute the average value of G_i as (TruSoft, 1999):

$$G_{avg} = \frac{\sum_{i=1}^{n-1} G_i}{(n-1)}. \tag{1}$$

The Hurst exponent is $H = f(G_{avg})$, where f is a heuristic function which describes H by G_{avg} for stochastic self-affine traces (TruSoft, 1999).

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2.4.2 Devil´s staircase slip-rate distribution

In order to characterize the persistence of the slip-rates distribution for faults in the MAFS, we construct the Devil's staircase of the cumulative slip-rates distribution organized from East to West, due the fact that the 1956-2016 instrumental locations in the central TMVB show that most of the microseismicity is concentrated in the eastern part of the MAFS, near to the Acambay Graben with a maximum depth of 15 km (Lacan et al., 2017). In order to obtain the fractal dimension for the slip-rates distribution (capacity dimension or box-dimension) for active faults, we use the Box counting 2D algorithm (Walsh and Watterson, 1993), to obtain the exponent D_b in the relationship:

$$N(e) \approx \frac{1}{e^{D_b}}, \tag{2}$$

for the cumulative slip-rates distribution for active faults in MAFS with paleoseismology studies. In equation (**??**), $N(e)$ is the number of boxes of linear size e, necessary to cover a data set of points distributed in a two-dimensional plane. The basis of this method is that, for objects that are Euclidean, equation (**??**) defines their dimension. The range of values of this fractal dimension lies between one (Euclidean dimension of a line) and three (Euclidean dimension of a volume). If the fractal dimension ranges between one and two, the earthquakes or faults are distributed on the interface between a line (Euclidean dimension equal to one) and a plane (Euclidean dimension equal to two) (Pascua et al., 2003).

A number of boxes proportional to $\frac{1}{e}$ is necessary to cover a set of points lying on a smooth line, proportional to $\frac{1}{e^2}$ to cover a set of points evenly distributed on a plane, and so on. To measure D_b we counts the number of boxes of linear size e necessary to cover the set for a range of values of e; and plot the logarithm of $N(e)$ on the vertical axis versus the logarithm of e on the horizontal axis. If the set is indeed fractal, this plot will follow a straight line with a negative slope that equals $-D_b$. The "box counting" technique is the classic way to test fractal behavior because it allows calculate the capacity dimension. For the box dimension calculation, we use the Benoit 1.3 Software (Trusoft, 1999).

3 Results and Discussion

The active faults map is presented in Figure 2, defined previously as a fault planes that ground-rupturing with speeds of approximately 0.001 $\mathrm{mm/year}$, with seismic activity, at least, in the last 10,000 years, oriented in favor of the current stress field, and with fault planes related to earthquakes of magnitude $M_w \geq 5.2$ or related to rupture lengths greater than or equal to 3 km. In this figure, all the active fault sources are represented with solid lines; the faults that are shown in red color represent those that had have studies of paleoseismology. The seismicity, represented by circles, was taken from the catalog of the Mexican Seismological Survey (SSN), focal mechanism from Krishna-Sing et al (2012), Ego and Ansan (2002) and Pacheco et al (1999) the magnitude homogeneous catalog including historical events presented by Magaña-García (2017) and Zúñiga et al. (2017), wich includes earthquakes since 1912 to 2016.

The results of the maximum magnitudes for the active faults, in order to characterizing the seismic potential for the MAFS, are summarized as: (1) The model proposed by Anderson et al. (1996) (Figure 3a) is always lower in comparison with others

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relationships. However, (2) the highest magnitudes are obtained with the relationship of Wesnousky (2008), up to $\Delta M_w \approx 1.04$ as we can see in Figure 3b. It is important to mention that segments of faults at the southern boundary of the Acambay graben (i.e., the VEBF:Venta de Bravo and PASF:Pastores faults), have been found to rupture at intervals ranging from 600 to 10,000 years, depending on whether each fault breaks as a single unit or in separate segments (Langridge et al. 2013; Ortuño et al. 2015). Taken together, a significant earthquake can be expected in the region every 300 to 600 years (Zúñiga et al. 2012). In a particular study of the seismicity in the MAFS, Magaña-García (2017) presents a recurrence periods in the order of 9,000 to 11,000 years base on the b-value stability which is consistent with previous paleoseismological studies (Garduño-Monroy et al. 2009a; Sunye-Puchol et al., 2015).

The fault name, length, scarp and slip-rate for faults with paleoseismological studies in the MAFS are presented in Table 1. Furthermore, the M_w estimated (Wesnousky, 2008) and the intensity scale (ESI 07) are presented, as well as the corresponding affected area (km^2). In the last column, we present the cumulative form of the slip-rates ($\mathrm{mm/yr}$) too. And the resulting cumulative plot for the slip-rates and the fractal box dimension analysis is presented in Figure 4.

According to the Environmental Seismic Intensity scale (ESI 07) used for measuring the effects of an earthquake on the natural environment, all the faults in the MAFS with paleoseismological studies are capable to generate Class B events, with affected areas ranging from 1000 to 5000 km^2 where geomorphological and geological evidences are frequent and characteristic. The size of the affected areas for any of the faults revised in this work cover some of the most populated cities of Mexico, such as Ecatepec, Mexico City, Toluca, Morelia, among others.

The predictability of time series begins with the original work of Hurst (1951), who focused on the analysis of fluctuating fluvial time series, by analyzing the standard deviation of the accumulated water flow. Thus, Hurst established the wet and dry cycles in the Nile Valley. In our case the Hurst Exponent has a value of $H = 0.949$ and shows a strong persistent process for the slip-rates ($\mathrm{mm/yr}$) distribution. This temporary memory, related to a non-linear dynamic, and in turn, with cycles or periods with different seismic activity (the probability to change in the trend of the series is less than the probability to continue in it) is important in seismotectonic. In fact, the slip-rates along the MAFS, in the cumulate form, has the structure of a well-known fractal called the Devil's staircase (Figure 4.Left).

The box dimension for our Devil's staircase result ($D_b = 1.86$) is consistent with values obtained by Nieto-Samaniego et al., (2005; $D_b = 1.87$ upper limit), who proved that box dimension is in inverse relation with fracture concentration and in direct relation with fracture density. The high value of the fractal dimension may indicate the possibility for generation of a major earthquake (Aviles et al., 1987) in the faults of the MAFS, which could crack in an irregular rupture.

The fracture concentration is an estimate for the mean distance between centres of fractures divides by the average fracture lengths, which characterizes the interactions between adjacent fractures (Nieto-Samaniego et al., 2005), then our data supports the idea that a high value of D_b represents the loss of stability for the slip-rates for the faults in the MAFS, it is an indicative that we have a critical state of earthquake-generating (Smirnov and Zaviyalov, 1997) in the entire fault system, so this correspond to larger slip-rates (i.e. large scale). In other words, the critical state in the MAFS corresponds to a smaller values of the rupture concentration parameters (high D_b value), based on the stability of the faults within the MAFS in the stress field throughout time. The stability was lost when small fractures grew and joined to form big faults, consequently there is a high concentration

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of the latter, which are capable to generating earthquakes up to magnitudes $7.0M_w$ in the MAFS (Soria-Caballero et al., in prep).

4 Conclusions

The temporal slip-rates distribution for the faults in the MAFS has a fractal behaviour, with strong persistent characteristics ($H = 0.949$). In this context, we have a statistical measure of the memory of the slip-rates series, so, we can infer the predictability of this temporal series and conclude that the entire fault system is active.

The fractal dimension of the faults distribution, D_b, is a high value ($D_b = 1.86$), that indicates less concentration of small slip-rates, and therefore there is not an excess of the deformation in the MAFS in a single or restricted range of scales. Consequently, this fractal dimension represents a migration of the ruptures to larger scales (earthquake-generating faults with lengths ≥ 3 km).

The estimation of maximum and minimum earthquake magnitudes, obtained by means of empirical relationships, which the system can generate, is similar to generate moderate to strong ($5.4 \leq M_w \leq 7.1$) shallow earthquakes ($h < 20$ km), as well as great area of influence of affectation ($1000 \leq \mathrm{km}^2 \leq 5000$) in the center of Mexico, where there are many cities with high population density.

The mathematical behaviour observed for the entire MAFS contribute to define areas under seismic risk and the improvement of the vulnerability studies in Mexico.

Data availability. The datasets generated during the current study are available from the corresponding author on reasonable request.

Author contributions. AMP built the GIS-based database of active faults and was supervised by VGM and DSC. AMP and AFS performed the fractal analysis and the estimations of the maximum magnitudes, as well as the discussion of the results. AFS took the lead in writing the manuscript. DCS contributed with the Intensity Scale values for the active faults in the MAFS and together with VGM helped shape the research. VGM also performed the review of the tectonics in the MAFS and helped supervise the project. All authors discussed the results and contributed to the final manuscript

Competing interests. The author declares no competing financial interests

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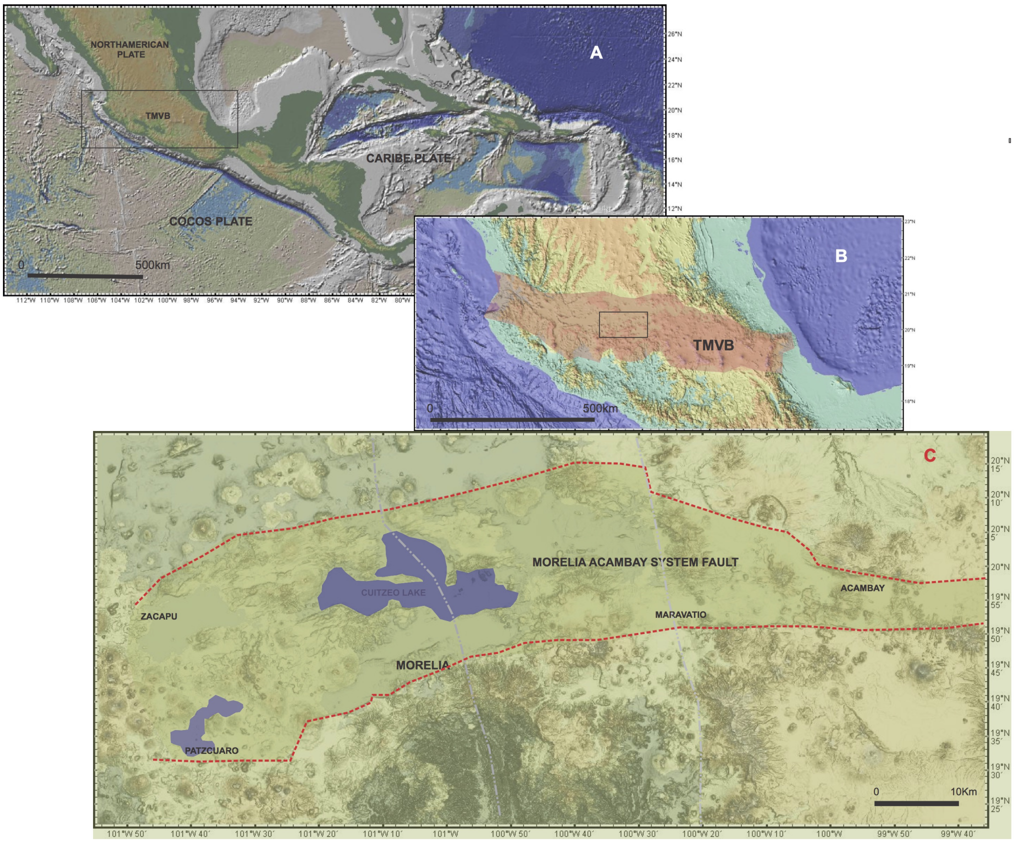

Figure 1. (A) Geodynamic setting along the Middle America Trench. TMVB: Transmexican Volcanic Belt. **(B)** Tectonic setting in the Transmexican Volcanic Belt (red zone). **(C)** Seismotectonic setting in the Morelia-Acambay Fault System within the TMVB.

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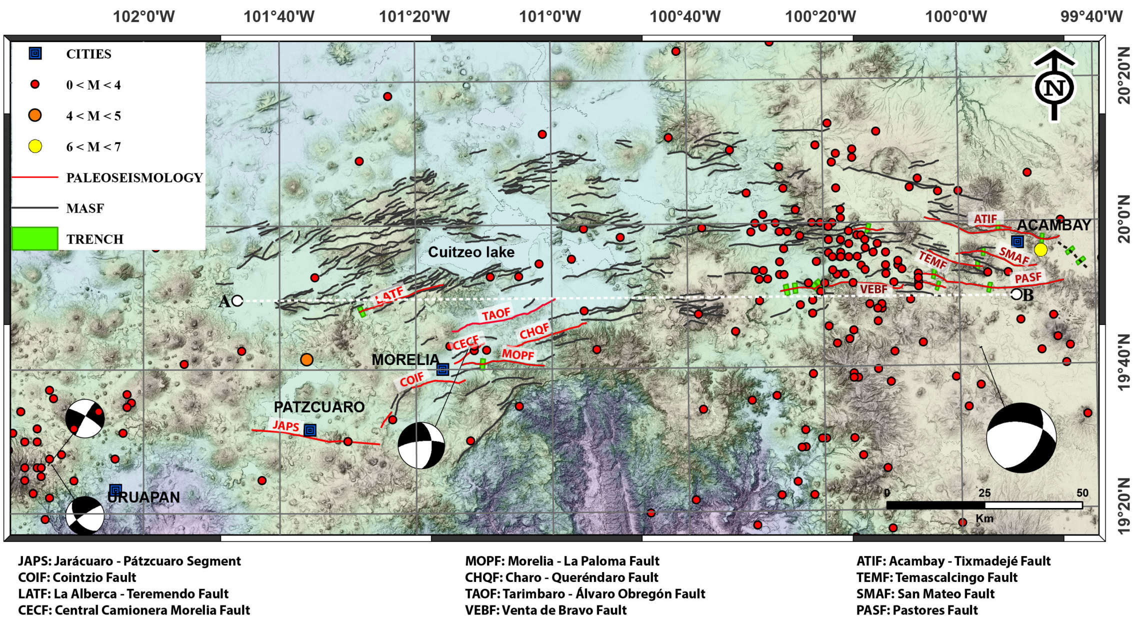

Figure 2. Active Faults in the MAFS. Circles represents the seismicity based on a homogeneous catalog from Magaña-García (2017) and Zúñiga et al. (2017) between 1912 to 2016 based on the seismicity reported by de National Seismological Service of Mexico (SSN). Focal Mechanisms were reported by Krishna-Sing et al (2012), Ego and Ansan (2002) and Pacheco et al (1999).

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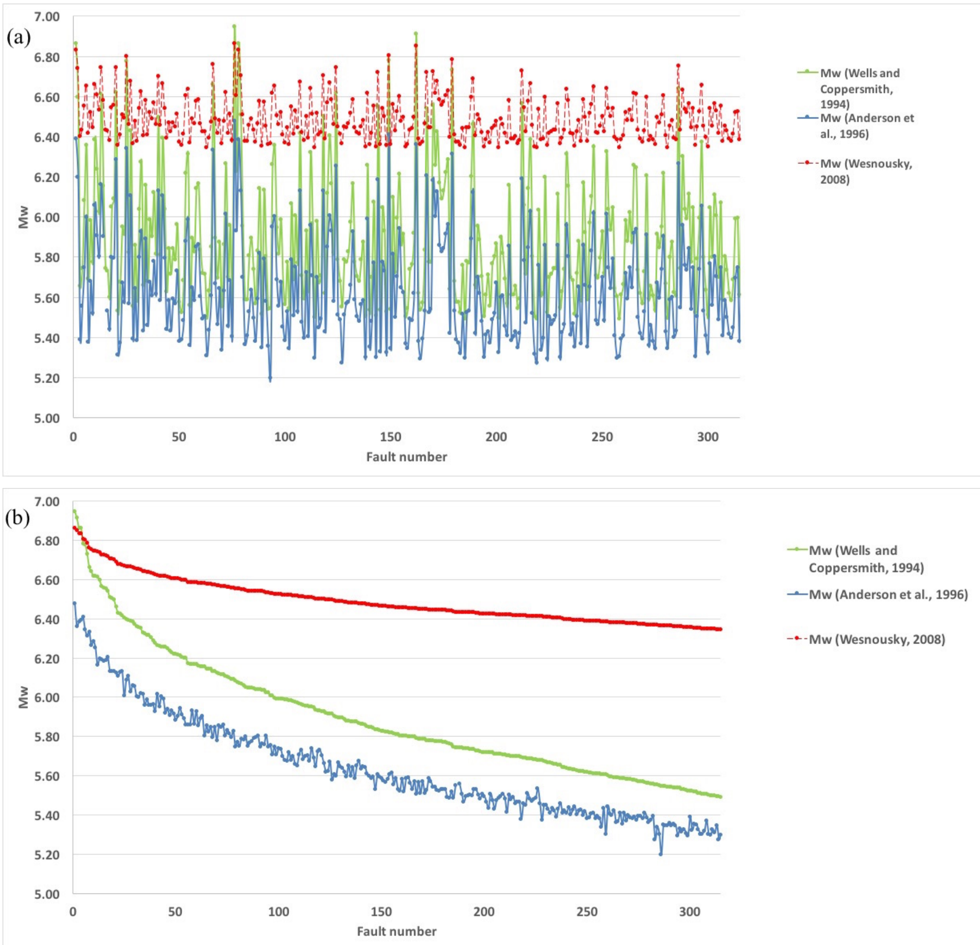

Figure 3. (a) Comparison between the estimations of the earthquake sizes for the active faults in the MAFS. **(b)** Magnitudes organized in descendent order based on the maximum value of the magnitude obtained by the relationships of Wesnousky (2008).

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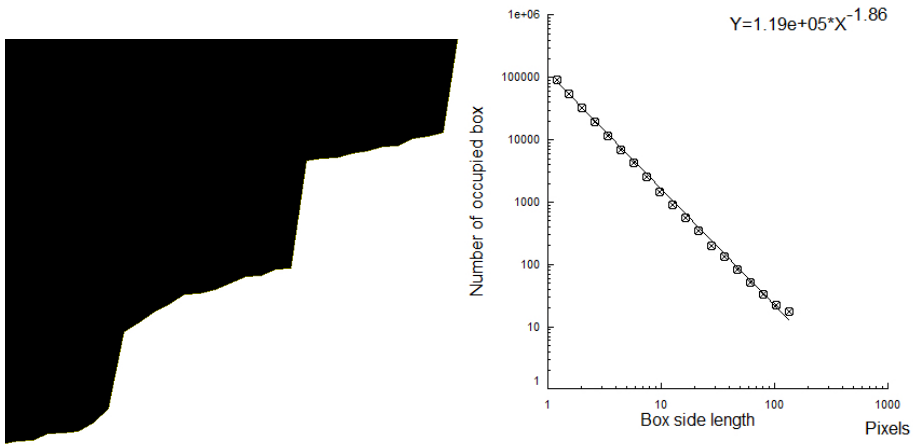

Figure 4. (Left) Fractal model for the cumulative slip-rates $(\mathrm{mm/yr})$ distribution of active faults in the MAFS. **(Right)** Analysis of the capacity dimension or box-dimension with a fractal dimension of D_b = 1.86 and a Hurst Exponent H = 0.949.

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Table 1. Faults with slip-rate information along different faults in the MAFS.

Fault name	Length (km)	Scarp (m)	Slip-rate (mm/yr)	Slip-rate cumulative-form	References	M_w estimated (Wesnousky, 2008)	ESI 07 scale	Affected area (km^2)
Colluvium 60*(ATIF)			0.17		Suter et al., 2001			
Acambay-Tixmadejé	36	650	0.17	0.34	Langridge et al., 2000	6.85	X	5000
San Mateo	21	115	0.085	0.43	Sunye-Puchol et al., 2015	6.75	IX	1000
San Pedro Alto	6	136	0.0159	0.44	Velazquez-Bucio (in process)	6.48	IX	1000
Temascalcingo	15	230	0.17	0.61	Ortuño et al., 2018	6.67	IX	1000
Temascalcingo	15	230	0.0173	0.63	Velazquez-Bucio (in process)	6.67	IX	1000
Unnamed Basalt 59*(PASF)	15		0.04	0.67	Suter et al., 2001			
Pastores	38	243	0.23	0.90	Ortuño et al., 2015	6.86	X	5000
			0.37	1.27				
Venta de Bravo	33	300	2	3.27	Suter et al, 1995	6.83	X	5000
Venta de Bravo	32	300	0.24	3.51	Ortuño et al., 2018	6.83	X	5000
			0.26	3.77				
Venta de Bravo	47	50-300	0.22	3.99	Lacan et al., 2017	6.91	X	5000
			0.24	4.23				
Ciudad Hidalgo Basalt 65*		20	0.03	4.26	Suter et al., 2001			
Ciudad Hidalgo Basalt 47*		70	0.09	4.35	Suter et al., 2001			
San Andrés Dacite 50*		60	0.18	4.53	Suter et al., 2001			
Cuitzeo Basalt 37*		120	0.16	4.69	Suter et al., 2001			
Cuitzeo Basalt 39*		20	0.03	4.72	Suter et al., 2001			
Charo-Queréndaro	21	80	0.17	4.89	Garduño-Monroy V.H. et al., 2009	6.75	IX	1000
Tarimbaro y Álvaro Obregón	28	200	0.025	4.91	Garduño-Monroy V.H. et al., 2009	6.80	X	5000
			2.78	7.69				
Quinceo Basalt 41*		40	0.07	7.76	Suter et al., 2001			
Quinceo Basalt 44*		10	0.02	7.78	Suter et al., 2001			
Morelia Central Camionera	10	60	0.12	7.90	Garduño-Monroy et al., 2009	6.58	IX	1000
Morelia La Paloma	21	300	0.057	7.96	Garduño-Monroy et al., 2009	6.74	IX	1000
Teremendo	23	70	0.11	8.07	Soria-Caballero (in process)	6.76	IX	1000
Morelos	8	50	0.009	8.08	Garduño-Monroy et al., 2009	6.53	IX	1000
Cointzio	14	100	0.2	8.28	Garduño-Monroy et al., 2009	6.66	IX	1000
C. El Aguila lava 42*		40	0.05	8.33	Suter et al., 2001			
Huiramba	5	50	0.1	8.43	Garduño-Monroy et al., 2009	6.43	IX	1000
Jarácuaro-Pátzcuaro	33	277	2.5	10.93	Garduño-Monroy et al., 2009	6.83	X	5000

*Scarp refer to the top of the faulted rock unit.