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An Earthquake Catalogue for El Salvador and Neighboring Central American Countries (1528-2009) and Its Implication in the Seismic Hazard Assessment

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Abstract: Merging all available databases, a comprehensive and updated earthquake catalogue for El Salvador and surrounding areas has been compiled, containing a total of 2,584 events for the period 1528-2009, covering the geographic window delimited by the coordinates 11.0°-16.5° N and 85.5°-92.0° W, focal depths of 0.0 to 304 km, and the moment magnitudes in the interval $5.0 \leq M_W \leq 8.1$. Events in the catalogue are distributed into six seismogenic sources taking into consideration the tectonic regime affecting El Salvador, the interplay and complexities between shallow crustal, intraplate and interface subduction seismicity has been thoroughly investigated, primarily with the aim of developing detail criteria to delimit the seismogenic sources in order to perform a consistent seismic hazard assessment. A uniform hazard spectrum for San Salvador and seismic hazard maps and their uncertainty have been calculated for the horizontal component of ground motion for rock site conditions using zone and zone free methods. The references cited in the article constitute a comprehensive list of sources of information on the tectonics and seismicity of El Salvador and neighboring Central American countries.

Key words: Earthquake catalogue, tectonics, seismogenic sources, Gutenberg-Richter relationships, seismic hazard.

1. Introduction

In countries affected by earthquakes, the compilation of an accurate seismic catalogue turns into an inevitable part of the seismological investigations. Once compiled, the seismological catalogue serves a whole variety of purposes, including the evaluation of the seismic hazard inherent to the region under consideration. Cataloguing of El Salvador seismicity has been attempted before, Martínez [1] published the first comprehensive catalogue for El Salvador including historical seismicity since 1520 sizing the earthquakes and then assigning a modified Mercalli intensity, this work was the main reference for future special studies in the region which later re-calculate the origin parameters of the destructive events. Algermissen et al. [2] made the first probabilistic seismic hazard assessment for the country, however, their seismological data base is not accessible from the article. Alfaro et al. [3] compiled an earthquake catalogue including historical events covering the period 1538-1986 based on the work of White [4] for the Guatemalan seismicity in the boundary of the North American plate and the Caribbean Plate and some publications in process by the same author at that time with updated works listed in Table 1 for both, the subduction zone and the volcanic chain in Central America (Section 4). To homogenize the catalogue, they employed the surface wave magnitude M_S (magnitude scale) incorporating mainly the ISC (International Seismological Centre) and the PDE

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Table 1 List of references employed to compile the earthquake catalogue for El Salvador and surrounding areas.

Code	Reference
	Historical seismicity (1500-1900)
U	Muñoz and Udias (2006) [7]
G	Guzmán-Speziale et al. (2005) [8]
W	White et al. (2004) [9]
W	White (1984) [4]
E	Leeds (1974) [10]
N	NOAA (National Oceanic and Atmospheric Administration) significant earthquakes of the world [11]
	Special studies (1900-1994)
A	Ambraseys and Adams(1996) [12]
M	Ambraseys (1995) [13]
W	White and Harlow (1993) [14]
S	Molnar and Sykes (1969) [15]
	World standard catalogues (1900-2009)
I	ISC (International Seismological Centre), 2010, England [16]
P	Program of PDE (preliminary determinations of epicenters), from NEIC (National Earthquake Information Center) [17]
D	DNA (Decade of North America) Geology—NGDC [18]
H	IPGH (Instituto Panamericano de la Geografía y la Historia) [19]
C	Global CMT (centroid moment tensor) catalogue [20]
	Local and regional catalogues (1984-2009)
L	Local earthquake catalogue for El Salvador: Geological Survey/General Directorate of Environmental Observatory (DGOA), El Salvador (1984-2009)
R	Regional earthquake catalogue for Central America: CASC (Central American Seismic Center) (1994-2009)

(Preliminary Determination of Epicenters) catalogues.

Singh et al. [5] compiled an earthquake catalogue based also on world standard catalogues and retrieved the historical information presented in Ref. [3]. This catalogue was used to perform the seismic hazard assessment for the building code regulations of El Salvador [6]. However, to evaluate the seismicity and the seismic hazard in the region, Singh et al. [5] did not homogenize the magnitude to a single scale, they adopted the maximum reported value of magnitude amongst different available determinations. A common feature of the works of Alfaro et al. [3] and Singh et al. [5] are historical events prior to 1900 with magnitudes up to 7.9 in the volcanic chain of Central America (its location shown in Fig. 1). According to White et al. [14] and the notorious macro-seismic compilation of Feldman [21], earthquakes in this source are moderate in size with maximum magnitudes reaching up to 6.9 due to the high degree of fragility of the crust in Central America, which is reflected with the presence of many faults of short lengths along the volcanic belt.

Lindholm et al. [22] performed a seismic hazard assessment based on the catalogue of Rojas et al. [23] for the Central American Isthmus using the M_S for the period 1500-1990. More recently Benito et al. [24] updated the catalogue of Rojas et al. [23] to perform a new seismic hazard assessment for the Central American region in terms of M_W magnitude, but the whole catalogue itself is not accessible yet for the general public (personal communication with Eng. Alvaro Climent, Trinidad 2011). Grases [25] presented useful macro-seismic information and instrumental determinations for destructive earthquakes in the Caribbean and the Central American region for the period 1502-1990 listing magnitudes m_b and M_S.

Salazar et al. [26] compiled an instrumental seismic catalogue for the period 1898-1994 compiling new seismological information that were not included in the previous works, this catalogue and the correspondent geometrical delimitations for the seismic sources were employed in the seismic hazard assessment presented by Bommer et al. [27] in terms of the magnitude M_S.

They performed the seismic hazard assessment employing normalized values of peak ground acceleration discussing the spatial distribution of the hazard in the country using both zone and zone-free methods. Later Salazar [28] updated the work of Salazar et al. [26] extending the period of observation covering the years 1898-2001 including the burst of seismicity related with the earthquake disasters of January 13 and February 13, 2001 [37], employing *Ms* as the homogenized magnitude as well and incorporating for the first time in the region as local and regional network information.

In keeping with modern requirements of cataloguing seismicity, this article presents an updated catalogue based on Salazar [28] including new historical, instrumental, geological and tectonic information that has been analyzed and published in the last decades. Attempts have been made to ensure that the final catalogue is as homogeneous as possible in terms of magnitudes originally reported on five different

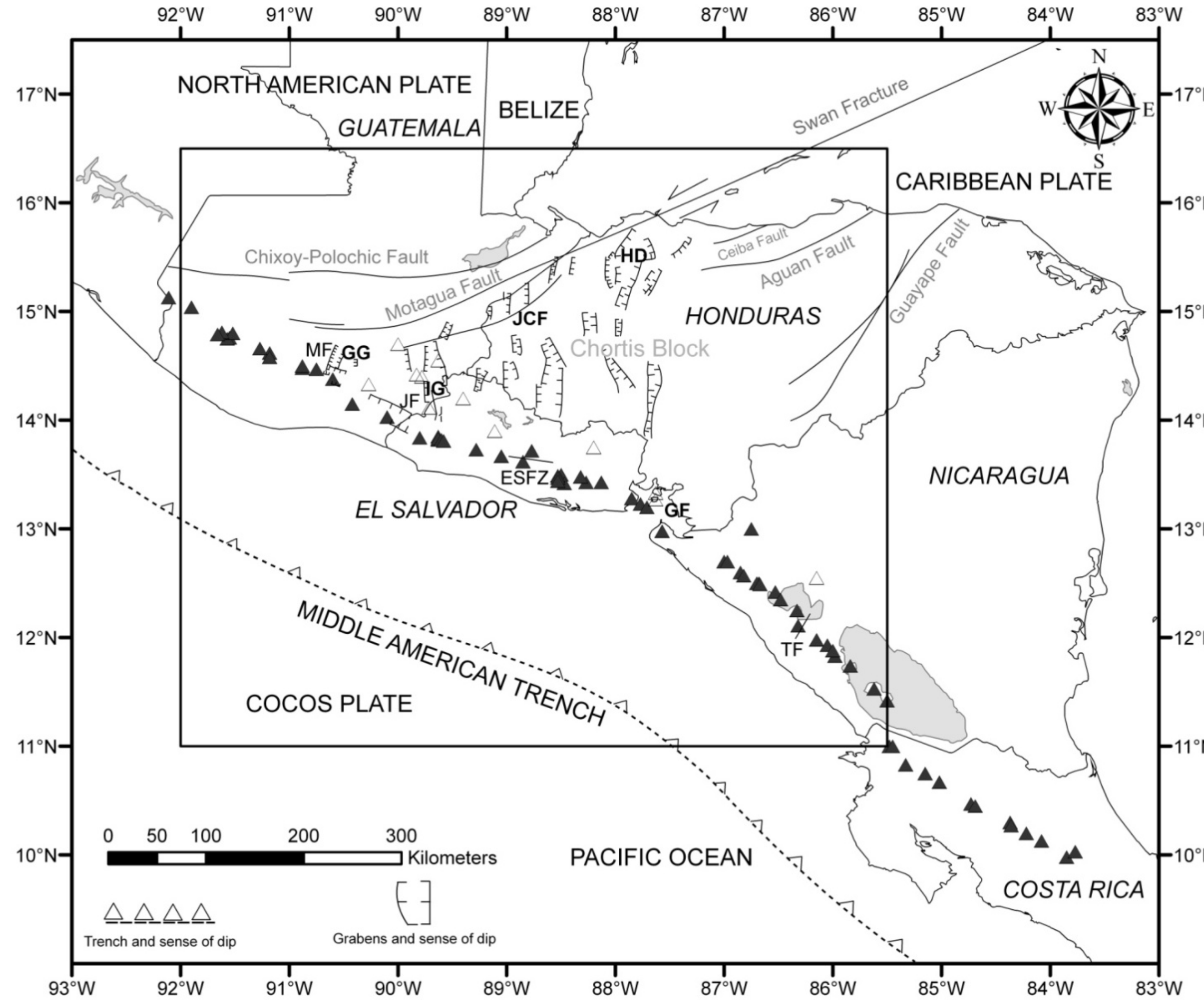


Fig. 1 Tectonic map of El Salvador and neighboring Central American countries, solid and open triangles indicate the DVF (dominant volcanic front) and the BVF (behind volcanic front), respectively [29, 30], MF: Mixco Fault; GG: Guatemalan Graben; IG: Ipala Graben; HD: Honduran Depression; JCF: Jocotán-Chamelecón Fault; JF: Jalpatagua Fault; GF: Gulf of Fonseca; ESFZ: El Salvador Fault Zone; TF: Tiscapa Fault [30-36]; position of the Middle American trench [12]. The inner rectangle delimitates the geographical window employed for the seismic catalogue (11.0°-16.5° N and 85.5°-92.0° W), the lakes are represented by the gray color areas.

magnitude scales, namely M_W, M_S, m_b, M_D and M_L. A new empirical relationship amongst magnitudes M_W-M_S, M_W-m_b and M_W-M_D have been calibrated specifically for El Salvador.

The catalogue includes the solutions of the local and regional seismological networks in El Salvador and Central America. Events were also separated as subduction events in interface and intraplate shocks in order to keep with actual requirements in seismic hazard estimations. An ASCII (American Standard Code for Information Interchange) format version of the catalogue is available that also lists whether or not other natural phenomena such as volcanic eruptions, tsunamis or eclipses coincided with the occurrence of the earthquakes (as shown in Appendix).

2. Data Sources

The source of the information used to compile the catalogue is presented in Table 1. Events within this geographic window are delimited by the coordinates 11.0°-16.5° N and 85.5°-92.0° W which cover inland events of El Salvador, Guatemala, Honduras and Nicaragua and offshore earthquakes in the Central American Isthmus (Fig. 1).

To extend the catalogue back in time (1500-1900), the six studies were used, listed in Table 1 (from Code U to N in this order of priority) which based the determinations on macro-seismic data, public reports and early historical records. The authors choose the origin parameters listed in Ref. [9] for the Santa Marta earthquakes in Guatemala of July 29, 1773 (*M* 7.6) and its aftershock on December 12, macro-seismic information [25, 38] confirm that the main shock were felt in western El Salvador and Mexico suggesting that this earthquake is related with the subduction zone, while Guzmán-Speziale et al. [8] located the events in the Guatemalan Grabens with moderate magnitudes of 6.0 and 5.7, respectively (as shown in Fig. 1 and Section 4). Leeds [10] also assigned magnitude values for volcanic eruptions in Nicaragua, however, in this study, only the events for which there is an evidence of strong shaking and damage of infrastructure are included. Similarly, only subduction events listed in Ref. [9] which has a seismogenic source classification, namely, interface or intraplate subduction origin are included in this catalogue. For the historical seismicity related with the boundary of North American and the Caribbean Plate in the Guatemalan Faults (Fig. 1) the earthquake epicenter was adopted as the centroid of the isoseismal maps as presented by White [4]. Leeds [10] listed historical subduction earthquakes with magnitudes above 7.0, only the earthquakes were included for which depth range estimation is available classifying them as either inter and intraplate shocks (as shown in the earthquakes classification scheme in the Section 4).

For the instrumental period, in most cases several hypocentral determinations for one earthquake were available constituting a initial merge catalogue of about 50,000 solutions, each set of apparent duplicates was examined visually and a decision was taken as to which event should be included as primary in the depurated catalogue: as a first, priority the special studies were chosen which recalculate the origin parameters for destructive earthquakes (Code A to S) and as a second priority, the standard world catalogues (Code I to C) following the hierarchy listed in the Table 1 from top to bottom. Local and regional catalogues determination (code L and R) were used to include the shallow-crustal earthquakes in the volcanic chain in Central America that are not listed in the special studies covering the years 1984-2009, using these catalogues aftershocks sequences were included with the destructive earthquakes for events located inside the volcanic belt in Central America.

It is noted that the CASC solutions are also included in the ISC catalogue.

3. Estimating Moment Magnitude

To homogenize the catalogue, a unique and consistent magnitude is used for each event, the moment magnitude M_W was taken directly when it was listed in the CMT catalogue.

In the cases in which M_W was not available, the value of M_W was obtained from the surface wave magnitude M_S making use of the empirical relationships suggested by Ambraseys and Adams [12] between M_S and the seismic moment M_o calibrated for Central America, later the value of M_W was obtained using the classical relation of Hanks et al. [39] between M_W and M_o (Table 2). For the case of historical earthquakes, only the minimum reported values (usually M_S) were

Table 2 Empirical magnitude relations employed to homogenize the earthquake catalogue to the moment magnitude M_W.

Empirical relation	Reference
$M_W = 4.363 - 0.155\ M_S + 0.077\ M_S^2$	This work
$M_W = 0.050 + 1.089\ m_b$	This work
$M_W = 2.189 + 0.660\ M_D$	This work
$M_W = 3.518 + 0.371\ M_L$	This work
$\log M_o = 24.578 - 0.903\ M_S + 0.17\ M_S^2 + 0.0043\ (h - 40)\ p$, $p = 0$, $h < 40$ km, and $p = 1$, $h > 40$ km	Ambraseys and Adams [12]
$M_W = 2/3 \log M_o - 10.7$	Hanks and Kanamori [39]
$\text{Log}\ M_o = 17.53 + 0.63\ M_L + 0.10\ M_L^2$	Hanks and Boore [40]

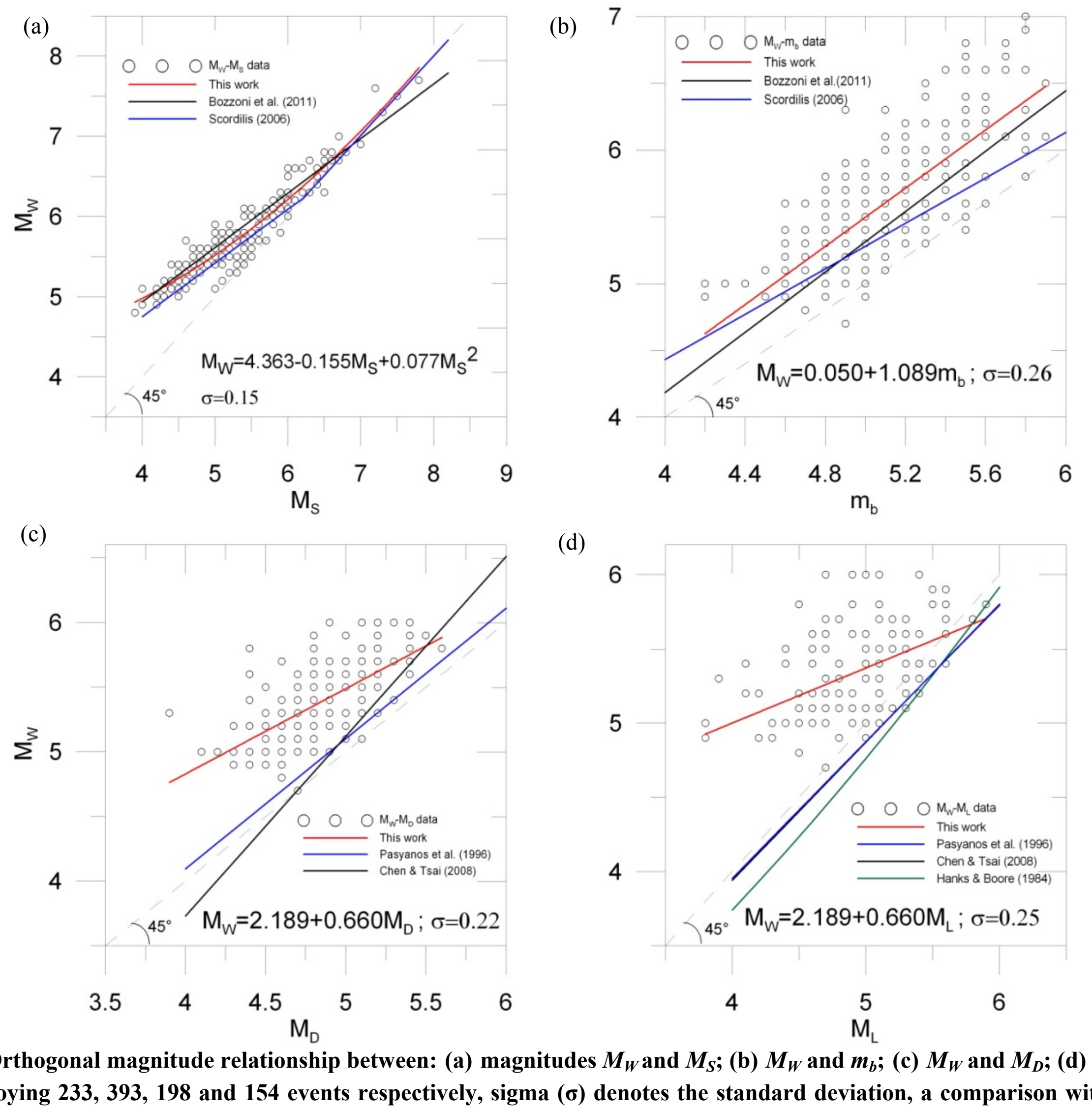


Fig. 2 Orthogonal magnitude relationship between: (a) magnitudes M_W and M_S; (b) M_W and m_b; (c) M_W and M_D; (d) M_W and M_L employing 233, 393, 198 and 154 events respectively, sigma (σ) denotes the standard deviation, a comparison with other empirical relations in the world is presented [40-44].

selected because the assessment of higher intensities later converted to magnitudes could be have been the influence from a diet of exaggeration of the local press reports, conquerors and clerical authorities letters asking for financial recovery support to political governors in Spain. Since a specific depth value is required in the empirical relationships of Ambraseys et al. [12] between M_o and M_S, earthquakes listed in the standard world catalogues with a fixed depth value of 33 km can not be incorporated directly in this scheme, in this case, a empirical magnitude relationship was employed developing in this work by applying a orthogonal regression between 233 magnitude pairs of M_S and M_W for all depths of the catalogue (Fig. 2 and Table 2). Some historical destructive earthquakes prior to 1900 lack of a depth value determination, if the earthquake is located in the volcanic chain or in the interface subduction zone according to the seismogenic source delimitations developed in this work, a $p = 0$ was assigned based on the Ref. [12] relations. There is one historical earthquake dated on December 19, 1862 with $Ms = 8.10$ cited by White et al. [9] that occurred in the intraplate subduction zone based on the analyzed macro-seismic information. The reported M_S value was adopted as a good approximation of M_W for these events.

When M_S was not given, the body wave magnitude m_b was selected in order to calculate M_W employing the empirical relation developed in this work for 393 pairs of magnitudes m_b-M_W via application of an orthogonal regression scheme (Fig. 2 and Table 2). When M_W, M_S, and m_b were not available, the duration M_D was used as listed in the solutions of the local DGOA and regional CASC catalogues (Table 1) employing the empirical relation developed in this work using 198 pairs of M_D and M_W (Table 2). Similarly, when the local magnitude M_L was only available, the empirical relation between M_L and M_o proposed by Hanks and Boore [40] was employed and later obtain the M_W by using the cited relation by Hanks and Kanamori [39]. The authors did not employ the relation between M_L and M_W developed in this work employing 154 pairs of magnitude due to the high dispersion observed in the M_L data and the high deviation from relations of other parts of the world [40-42].

The final depurated catalogue contains 2,584 events for the period 1528-2009 covering focal depths of 0-304 km and in a magnitude range $5.0 \leq M_W \leq 8.1$ (Fig. 1). In Tables 3 and 4, the contributions are presented for each sub-catalogue as listed in Table 1 and basic statistics of magnitudes conversions.

4. Tectonic Setting and Definition of Seismogenic Sources Delimitation

Once the catalogue has been compiled, each event must be associated to a seismogenic source in the region and make the geometrical delimitations of each of them. The six seismogenic sources established that affect the study area based on tectonics and geological features that have been already studied by different authors [14, 15, 45-52]. From their studies, the following sources are detected in El Salvador and surrounding areas (Fig. 1):

Zone 1: volcanic chain: The seismicity of this source is concentrated mainly in the upper part of the crust in the Caribbean Plate (depth ≤ 25 km), and within a nearly continuous belt of 20-30 km width along the axis of the principal quaternary volcanoes. The earthquakes in the volcanic chain frequently appear in clusters with no discernible main shock (swarms). Their location lays parallel to the subduction Middle American Trench (Figs. 1, 3 and 4). Destructive earthquakes in Central America are located in the DVF (dominant volcanic front) composed by major stratovolcanoes and calderas, located not more than 200 km from the subduction trench. More distant to the north, an irregular zone of volcanic edifices formed in the BVF (behind volcanic front) characterized by the presence of small, basaltic volcanic, mostly monogenic cinder cones and associated lava fields [30] where the lowest level of seismicity is observed in the area.

Table 3 Number of events for each source of information regarding with epicenter location (see the Code in Table 1).

Code	U	G	W	E	N	A	M	S	I	P	D	H	C	L	R	Total
Number	1	44	44	12	2	21	86	104	1,773	407	5	26	2	24	33	2,584

Table 4 Magnitude contribution, the star (*) denotes magnitude conversion to moment magnitude M_W from the original values of M_S, m_b, M_D and M_L using the empirical relations listed in Table 2.

Magnitude	M_W	$^*M_S$	$^*m_b$	$^*M_D$	$^*M_L$	Total
Number	388	1,020	1,156	8	12	2,584

White et al. [14] and more recently Corti et al. [34] suggested that the seismicity in the volcanic chain could be interpreted as the result of a right-lateral shear zone, driving an oblique component of convergence between the Caribbean and the Cocos Plates. However, recent research suggests that the strain field along the Central America Arc Volcanic Front is the result of a slight compression along the convergent Cocos-Caribbean margin, and the extension in the back-arc region, along the Guatemalan-Honduras Grabens of northern Central America (Zone 3 shown in this section). This field is resolved a strike-slip faulting along the volcanic belt [13, 53].

Faults with left lateral and right lateral mechanisms are located perpendicular and parallel to the volcanic chain axis, respectively. The last destructive earthquake in El Salvador of February 13, 2001 (M_S = 6.5) had a right lateral fault mechanism in the E-W fault segment of San Vicente with evidence of surface rupture [54]. The destructive earthquake in San Salvador City on October 10, 1986 (M_S = 5.4) had a left lateral mechanism with N-E striking plane. The increase of coulomb failure stress also enhances the possibility of infrequent fault slip on arc-faults that are

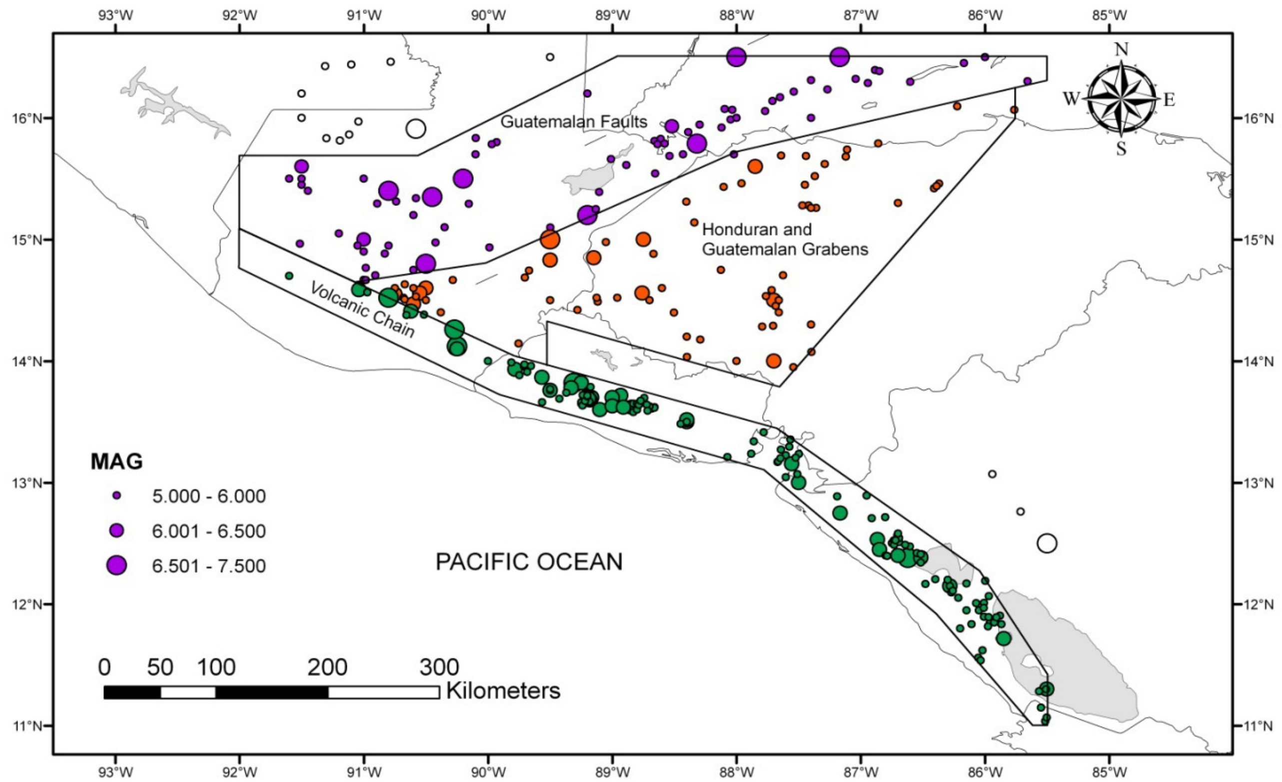


Fig. 3 Epicenters (solid circles) and geometrical delimitations of the seismogenic Zone 1: volcanic chain, Zone 2: Guatemalan faults and Zone 3: Honduran-Guatemalan grabens, the epicenters in the background seismicity are denoted by the open circles.

located between the volcanic centers [55] as the case of the destructive earthquake in Nicaragua on December 23, 1972 (M 6.3) along the Tiscapa Fault [49, 56]. Strike slip earthquakes also take place in this area of the Volcanic Chain in Guatemala (e.g, September 18, 1991 M 6.2). In El Salvador, Corti et al. [34] suggest a late Pleistocene-Holocene slip rate of about 11 mm/yr along Berlin City, while Lyon-Caen et al. [57] proposed a similar value of 10 mm/yr of dextral slip across the Mid-American Volcanic Arc. More recently [58] suggested a slip rate of 4 mm/yr for the modern volcanic zone in El Salvador. Fig. 3 shows the geometrical delimitation and related epicenters for the volcanic zone in the study area. A tsunami was reported for the upper crustal earthquake of August 3, 1951 with a M 6.15 located in the Golf of Fonseca.

Salazar et al. [59] employing strong motion data for El Salvador confirmed that the source spectra match those obtained from the point source model after setting the stress drop of 75 bars for upper-crustal inland earthquakes in the volcanic chain, and that the seismic waves attenuate rapidly in the volcanic zone with a faster rate of 10 times in comparison of the subduction zone earthquakes. From this, the authors confirm the source and path characteristics via inspection of the isoseismal maps for destructive inland-earthquakes in the country;

Zone 2: Guatemalan faults: These constitute the boundary between North America Plate and the Caribbean plate. Most of the events that have their

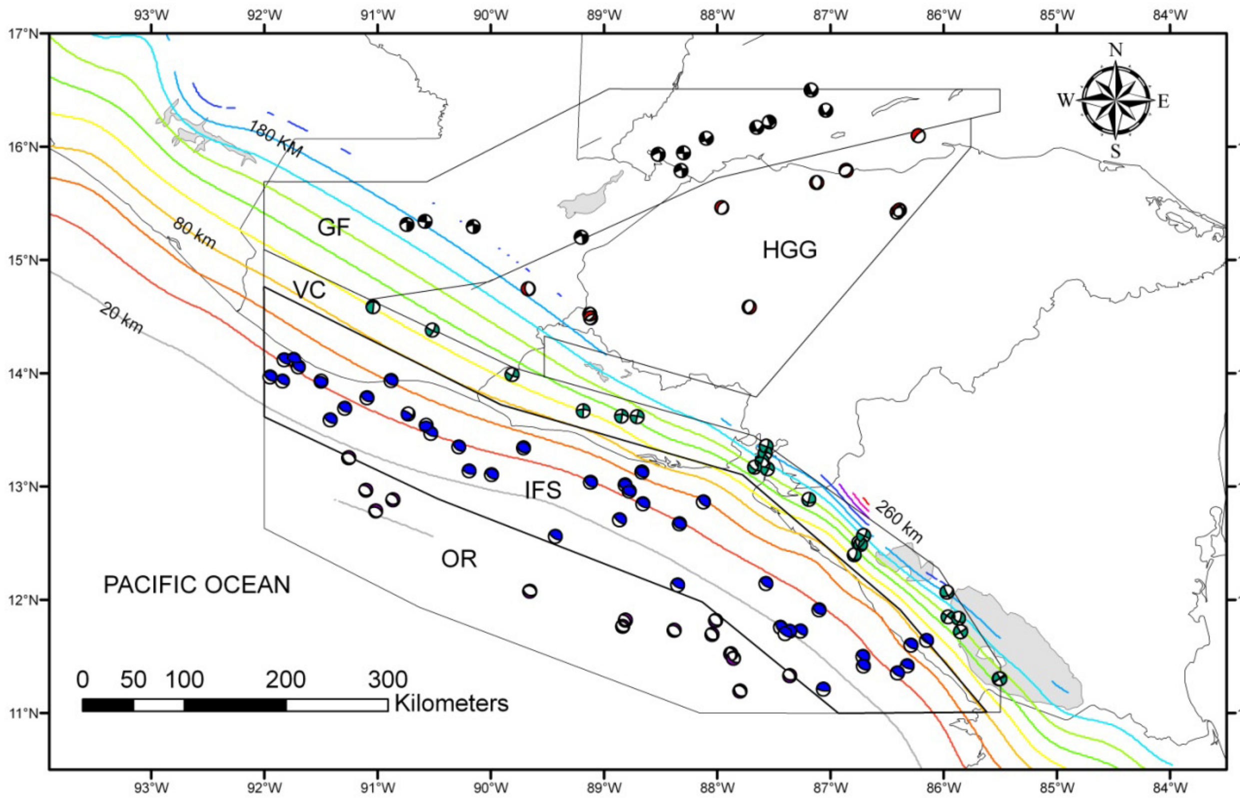


Fig. 4 Geometrical delimitation and focal mechanisms for shallow earthquakes, GF: Guatemalan faults (Zone 2), HGG: Honduras and Guatemalan grabens (Zone 3), VC: volcanic chain (Zone 1), IFS: interface subduction (Zone 4), OR: outerise earthquakes (Zone 6). The blue focal mechanism inside IFS: earthquakes with an inverse focal mechanism (T1) with slip vector between 45° and 135° within ±20° azimuth of the Central American Trench, purple focal mechanism inside OR: earthquakes with an normal focal mechanism (N1) with slip vector between -45° and -135° within ±20° azimuth of the Central American Trench. Other focal mechanism belongs to strike slip faults (in VC and GF), and normal faults (HGG), the depth contours of the upper part of the Cocos plate are presented based on SLAB 1 [60].

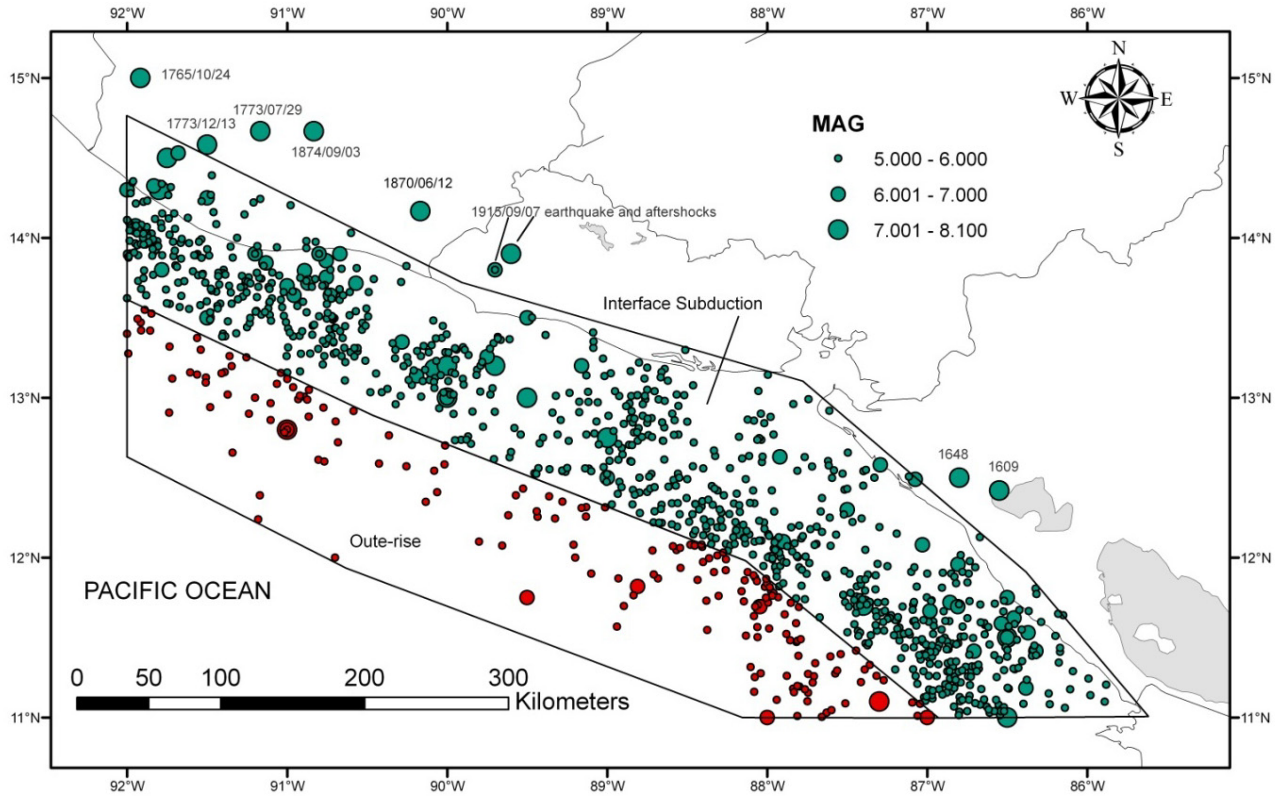


Fig. 5 Epicenters (solid circles) and geometrical delimitations for the Zone 4: interface subduction and Zone 6: outer rise earthquakes, epicenters that lay outside the geometrical delimitation correspond to the center of the maximum isoseismal contours for historical earthquakes.

origin in the faults are shallow (less that 35 km). They are characterized by left lateral strike slip mechanism. The Motagua and Polochic faults cross Central Guatemala in an arc concave to the north (Figs. 1, 3 and 4) and it extends in the Caribbean Sea to the north east in the area known as the Swan Fracture [30, 61]. The maximum magnitudes listed in catalogue dated on July 22, 1816, August 4, 1856 and April 19, 1902 all with magnitude 7.8 and 7.6, respectively. The largest reported destructive earthquake in the last hundred years in this boundary had a magnitude 7.5 on February 4, 1976, producing a surface rupture along 230 km of the Motagua Fault. Franco et al. and De Mets et al. [62, 63] estimated the North American-Caribbean plate relative motion to 18-20 mm/yr. Plate boundary deformation may have been localized further south along the inactive Jocotán-Chamelecón fault zone in northwestern Honduras, which has been fragmented by the east-west extension of the Honduran-Guatemalan north trending Grabens. Two tsunamis are reported in the catalogue corresponding to this source dated on August 4, 1856 (M 7.8) and another one on February 4, 1976 both hit the Gulf of Honduras [12, 64]. Fig. 3 shows the geometrical delimitation and related epicenters for the Guatemalan earthquakes;

Zone 3: The Honduran-Guatemalan grabens: This zone extends approximately from the Guatemalan Graben to the Honduras Depression [31] where infrequent shallow earthquakes (less than 35 km) occurred in the Chortis Block (Figs. 1, 3 and 4), this zone is characterized by extensional deformation reporting normal focal mechanism. This seismogenic source is delimited by the Motagua-Polochic fault system to the west, the Swan Fracture zone to the north, the Guayape Fault to the east and the volcanic chain to the south, conforming the western rifted highlands according to physiographic provinces suggested by Marshall [35]. The largest reported earthquake in this zone occurred in October 15, 1743 and had an estimated magnitude of 6.7. According to Ref. [36], the Graben is bounded by en-echelon oblique-normal faults which form part of the northwest-trending zone of early Tertiary faults.

The most prominent extensional structure is the Ipala Graben, situated in southeastern Guatemala and northwestern El Salvador [30, 51, 52]. Three main volcanoes are located in this Graben, namely, Ipala, Suchitán and Chingo, there are also almost hundredth of monogenetic volcanoes cinder cones with associated basaltic and andesite basaltic lavas. The age of this cones mostly are Holocenic to Pleistocene cluster chiefly in domains of extensional tectonic regime perpendicular to the DVF (dominant volcanic front) [30]. Other important feature is the existing of a rhyolitic domes in the center of the Ipala Graben, which converts it in a bimodal volcanism [51, 52]. The Ipala Graben is by far the largest of several areas and with more volcanic cluster behind the volcanic front of Central America, maybe because it is located in the higher inflection of the Jocotán-Chamelecón fault curvature. A shallow earthquake (depth 5 km) with M_L 4.6 ($\approx M_w$ 4.3) occurred on December 20, 2006 in this source producing severe damage in adobe houses and engineering structures. This event occurred during a swarm from Dec. 17, 2006 to January 8, 2007 with a total of 157 felt earthquakes and a total of 1,119 events. Casualties were not reported [65, 66]. Preliminary analysis [66] indicates a normal focal mechamism for the main event.

This seismogenic source also includes a zone of infrequent earthquakes in an extensional tectonics in an area bounded by the Guatemala faults to the north and north-west (with its bo undary in the Jocotán Chamelecón Fault [67]), the volcanic chain to the southeast and the Honduras Depression on the east, near the Trifinio forest in the junction of Guatemala, Honduras and El Salvador in the western part of the Ipala Graben.

Guzmán-Speziale et al. [8] has calculated a rate of approximately of 8 mm/year E-W opening while Rodríguez et al. [68] employed GPS measurements at 37 stations in Honduras and El Salvador suggesting 3.3 mm/year in Central Honduras, 4.1 in western Honduras and 11-12 mm/year in southern Guatemala, Álvarez-Gómez et al. [53] suggested that the state of the extensional stress of this wide Graben area is a result of: (1) the drift direction of the eastern part of the Chortis Block toward the east-northeast; (2) the curvature of the Guatemalan Faults and a low degree of coupling in the subduction Middle American Trench. Fig. 3 shows the geometrical delimitation and related epicenters for this seismogenic source.

The earthquakes in the Chortis Block also appear in clusters with no discernible mainshocks. Normal-faults earthquakes are reported in the Guatemala Graben and the Mixco Fault to the West of Guatemala City in the aftershock sequence of the destructive earthquake on February 4, 1976 in the Motagua Fault [67];

Zone 4-5: Subduction: The Middle American trench that runs about 150 km and almost parallel to the coast (Figs. 1 and 5), where the Cocos plate submerges itself underneath the Caribbean plate, reaching depths of 300 km below the Central America Isthmus [15, 45, 47, 48]. Convergence of these two plates takes place at a rate of 7-8 cm/year reaching maximum magnitudes of about 8.1. The shallow focus earthquakes along the inclined seismic zone yield underthrust focal mechanisms (Fig. 4) with depth less than 60 km [12], Zone 4 is declared as an interface subduction. The focal mechanisms of intermediate events (60 km < depth ≤ 120 km) with its origin beneath the trench axis indicate that there is occurrence of normal faulting resulting from initial flexure of the down going Cocos plate with a steeply NE-dipping of an average of 45° (Fig. 6). However, mixed-motions earthquakes with thrust and strike slip indicate bending of the subducting slab at deeper depths as such Zone 5 is declared as the intraplate subduction zone (Fig. 7).

Large intraplate shocks occurred in El Salvador offshore on December 12, 1862 and on January 13, 2001 with magnitudes 8.10 and 7.70, respectively. Panagiotopouls [69] suggested the occurrence of a large earthquake of M 7.5 in El Salvador with the highest probability magnitude value among all the seismogenic sources in the Central American and Caribbean Sea based on the time- and magnitude-predictable model during the decade 1993-2002, the January 13, 2001 confirmed his analysis. The largest interface event in the catalogue offshore El Salvador is dated on September 7, 1915 with a magnitude 7.8 [25]. Sometimes the thrust earthquakes are accompanied by destructive tsunamis, as the case of the recent event in the coast of Nicaragua on September 2, 1992 with M 7.60 [64] with an abundant foreshock activity. The subduction earthquake on March 5, 1719 with M 7.2 occurred during a lunar eclipse with an abundant foreshock activity producing severe damage in the towns of San Vicente, San Salvador and Cojutepeque [38]. Contrary to the subduction zone, the magnitudes of the earthquakes in the volcanic chain are moderate. The maximum magnitude observed in the last century in the volcanic region was 6.9 on July 14, 1930 in Guatemala, geographically associated with the E-W Jalpatagua right lateral strike-slip fault. However, Canora et al. [58] suggested a maximum magnitude of 7.6 in El Salvador Front Zone (ESFZ in Fig. 1) with a recurrence interval of about 750-800 years based on paleoseismological investigations.

To delimit geometrically the interface and intraplate zones, the depth determinations listed in this catalogue, the focal mechanism listed in the CMT catalogue and

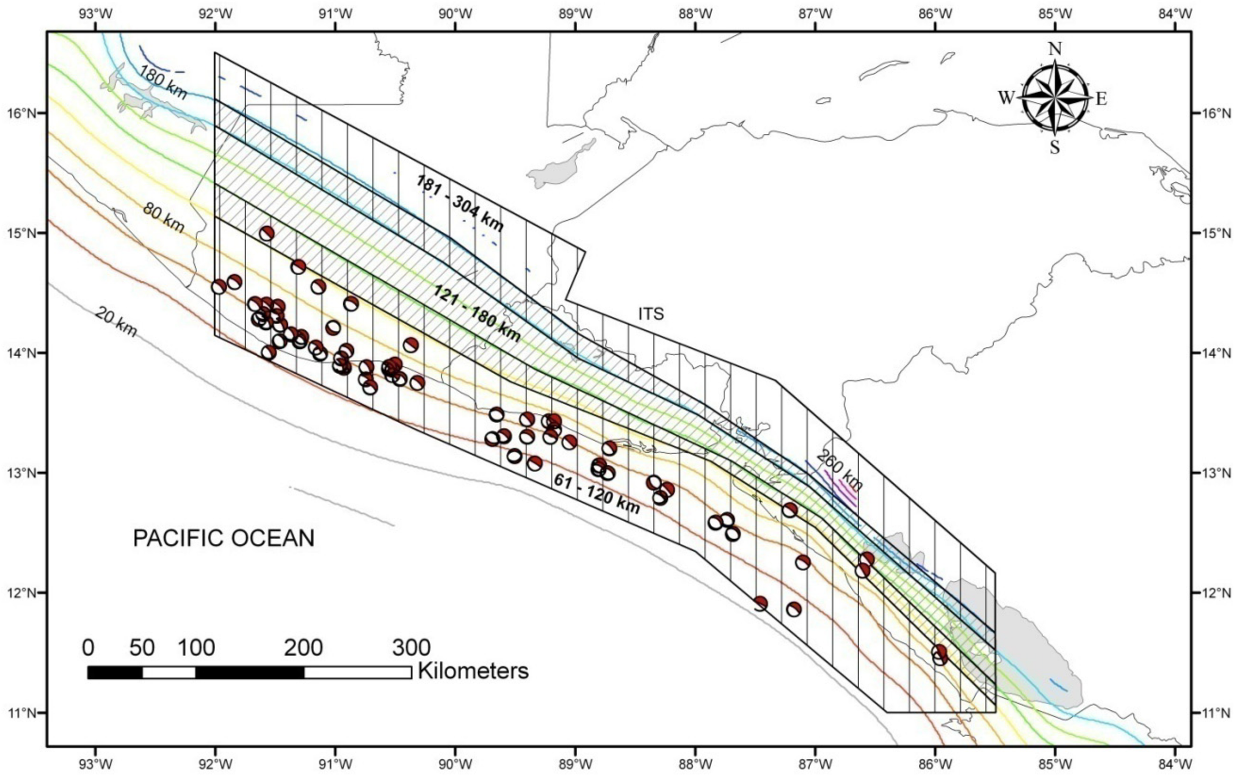


Fig. 6 Geometrical delimitation and focal mechanisms for ITS (intraplate subduction) Zone 5: normal focal mechanism (N1) with slip vector between -45° and -135° within ±20° azimuth of the Central American Trench, the depth contours of upper part of the Cocos plate are presented based on SLAB 1 [60], the intraplate subduction zone is divided in three sub sources according to the depth range of the subducted slab, namely (1) Zone 5a: 61-120 km (vertical stripes); (2) Zone 5b: 121-180 km (inclined stripes); (3) Zone 5c: 181-304 km (vertical stripes).

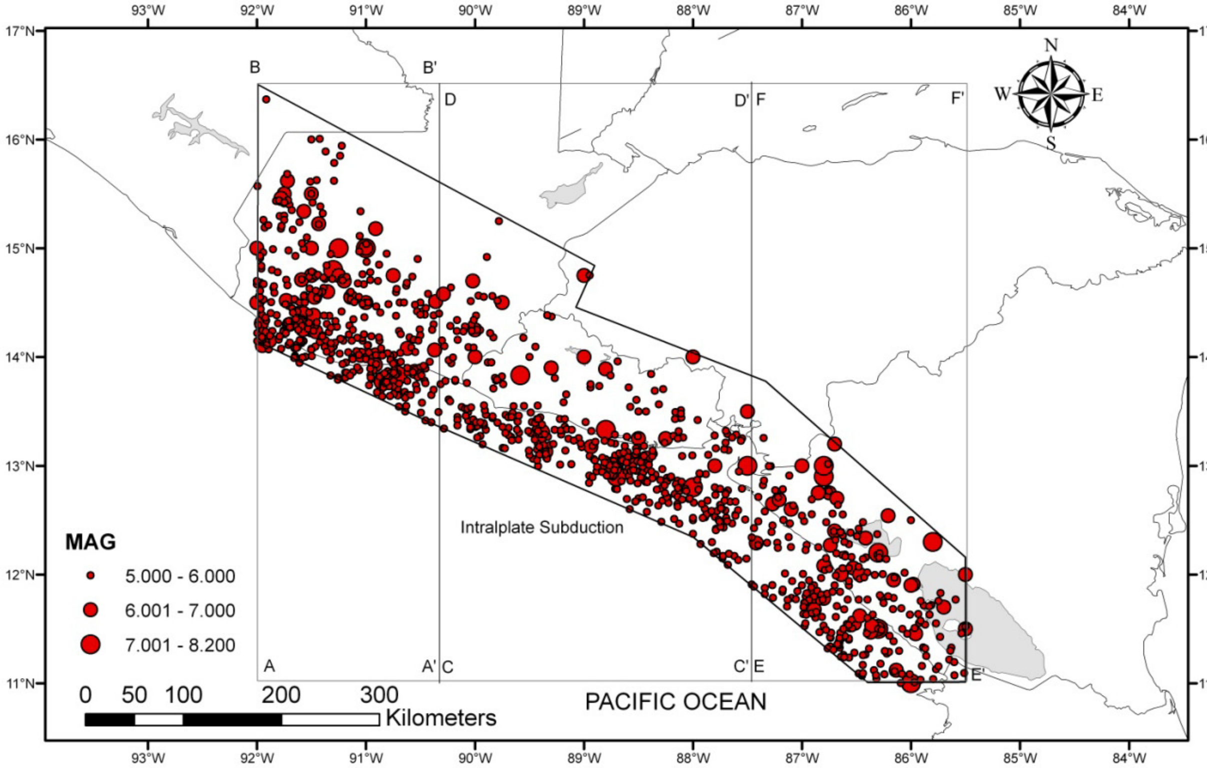


Fig. 7 Epicenters (solid circles) and geometrical delimitation of seismogenic Zone 5: intra-plate subduction (see cross sections AB-A'B', CD-C'D' and EF-E'F' in Fig. 8).

the geometrical features of the subduction trench and the depth to the subducted slab (SLAB 1.0 model [60]) was employed simultaneously. The interface subduction source is declared as an area geographically delimited by the Middle American Trench to the south [12] and the Central American Coast to the north which incorporates the epicenters of events with a component of thrust faulting with depth less than 60 km. Employing the definition of Hauksson [70], a reverse-slip vectors is identified as having rakes of 45° to 135° and within ±20° of the strike of the Middle America Trench [71]. The northern limit of the interface subduction zone coincides with the southern limit of the Volcanic Chain (Figs. 3 and 5). Some historical earthquakes epicenter are located outside the geometrical delimitation that occurred on 1648, 1609, 1765/10/24, 1773/07/29 and 1773/12/13 (Santa Marta earthquakes in Guatemala), 1870/06/12, 1874/09/03 and 1915/09/07 and its aftershocks. The epicenter location is assumed to be the center of the isoseismal maps presented by the authors or where the maximum intensity was reported amongst different observations [9, 10].

On the other hand, the intra-plate source is delimited geographically as an area that incorporates the epicenters of events with a component of normal faulting with depth greater than 60 km to the south and the bottom of the subducted slab to the north [45] (Fig. 7). Following the definition of Hauksson [70], a normal-slip vectors is established as having rakes of -45° to -135° and within ±20° of the strike of the Middle America Trench. When the earthquakes are located in the overlapped inter-intraplate zone and have a lack of focal mechanisms, these are classified as the interface and intraplate earthquakes based on the depth value. Interface earthquakes were considered with depth less or equal than 60 km and intraplate events with depth greater than 60 km. The overlapped zone is the result of the inclination of the subducted slab. The rest of the events are separated into the interface and intraplate sources using the correspondent geometrical delimitations based on epicentral determinations. A depth of 33 km is fixed by the world standard catalogues when the depth is indeterminate based on only on the first-arriving P-waves, the events are assigned to the intra-plate subduction zone when the epicenter lies in the overlapped inter-intraplate zone. In order to have a realistic tectonic model for the intraplate earthquake source, three sub sources have been assigned according to the depth range of the subducted inclined slab (Fig. 6), namely, (1) Zone 5a: 61-120 km; (2) Zone 5b: 121-180 km; (3) Zone 5c: 181-304 km.

Salazar et al. [59] employing strong motion data for El Salvador confirmed that the source spectra match those obtained from the point source model after setting the stress drop of 300 bars for intra-plate earthquakes and that the geometrical spreading factor accounts for most of the attenuation. The source and path characteristics can be defined via inspection of the isoseismal maps for destructive subudction earthquakes in the country;

Zone 6: Outer-rise: These earthquakes occurred south of the subduction trench in front of the Central America coast at shallow depth less than 50 km. Outer-rise earthquakes are caused by stresses in the subducting oceanic plate induced by bending as the plate enters the trench, flexure of the plate elevates the sea floor, creating an oceanic feature that dips parallels to the oceanic trench. The tensional stresses in the oceanic crust can create large normal faults (Figs. 4 and 5). Crustal stresses caused by earthquakes on the interplate thrust fault in subduction zones can also be transferred to the outer rise, triggering earthquakes on normal faults that are already close to failure.

Besides the interface subduction zone, this seismogenic zone is identified as a potential source of tsunamis, these earthquakes are infrequent but their damage can be devastated as the cases of the earthquakes of 1933 in Sanriku with a M 8.6 (3,000 victims) and significance damage in the Hawai Island. An earthquake in 1977 in Sumba with a M 8.3 produced 189 deaths in Indonesia. On September 29, 2009, an earthquake occurred in front of Samoa Island next to the Tonga Trench with M 8.1 with a considerable amount of victims.

The background seismicity is located at the north of Guatemala with a very low level of disperse earthquake locations and also located in Central west Nicaragua, characterized by earthquakes with relative low magnitude and shallow depth (Fig. 3).

The 2,584 events in the earthquake catalogue were separated into the six seismogenic sources and background seismicity as explained before, yielding 2,071 for the subduction zone (974 for the interface and 1,097 for the intraplate zones), 155 events for the Volcanic Chain, 78 for the Guatemalan faults, 79 for the Honduran-Guatemalan Grabens, 187 for the outer-rise and 14 for the background seismicity. Figs. 3-7 illustrate the geometrical delimitation for both shallow and deep zones covering the subduction, the upper-crustal volcanic zone, transform and intra-plate faulting and extensional graben zones. This configuration comprises the subduction trench to the south and the deepest part of the Cocos Plate to the north. The geometrical delimitation for upper-crustal seismicity comprises related epicenters and main geological structures such as volcanoes and seismic faults. The background seismicity is introduced in order to keep shallow events that could not be associated with a specific seismic source. Typical cross section showing the subduction and volcanic chain events are presented in Fig. 8 and the focal mechanisms for each seismogenic sources are presented in Figs. 4 and 6.

5. Seismicity Evaluation

5.1 The Catalogue Completeness and Recurrence Relationships

In this section, one specific aspect of quality control for the catalogue is addressed, namely the assessment of the magnitude of completeness M_c which is defined as the lowest magnitude at which 100% of the

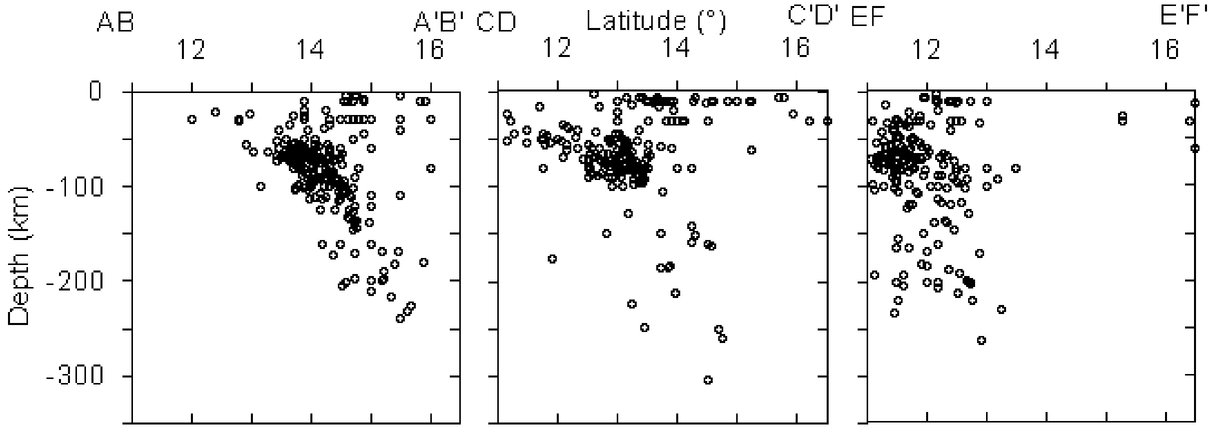


Fig. 8 Hypocenter cross sections AB-A'B', CD-C'D' and EF-E'F' (Fig. 7) in the Central American Isthmus (1898-2009).

earthquakes in a space-time volume are detected [72]. A number of methods have been applied to test the completeness of the catalogues, based on the assumption that earthquakes of magnitude greater than a stated value follow a Poisson probability distribution suggesting de-clustering of the catalogue before computing the completeness method, in this regard, the foreshocks and aftershocks were removed from the catalogue. The method of Gardner et al. [73] was applied to decluster the catalogue. After applying the algorithm, the final catalogue contains 894 independent events with magnitude M_w between 5.0 and 8.1 covering the years 1528-2009. To compute the completeness period, it was suitable to apply the visual method of Tinti et al. [74] for each seismogenic source, suggesting that the earthquakes within a magnitude interval (i.e., 5.0-5.5, 5.5-6.0, 6.0+, etc.) are complete back to a specific year if the cumulative annual numbers of events for this magnitude range are approximately linear back to that date (Fig. 9). A magnitude bin size of 0.5 units has been used for all zones except for the volcanic chain, for which a magnitude bin size of 0.25 was used to revise the non-linear trend in the G-R (Gutenberg-Richter) recurrence relationship [3, 27, 28, 75]. In Table 5, the estimated period of completeness is presented with the correspondent magnitude M_c for each seismogenic source of this catalogue.

In the attainment of a G-R recurrence relationship, the regional seismicity is characterized by adopting the expression:

$$\log_{10}(N) = A - BM \qquad (1)$$

where, N represents the accumulative number of earthquakes per year above magnitude M, and A and B set two constants derived from regression analysis. It is worth mentioning that the computation of the N values must be consistent with the completeness period for each magnitude bin. Constant B is the measure of the relative abundance of large to small shocks and characterizes the degree of fracture of the crust and it could be related with the thermal gradient constituting the seismogenic source or the degree of coupling between two plates. Figs. 10 and 11 illustrate the Gutenberg-Richter recurrence relationships after applying the completeness analysis and Table 6 shows the A and B recurrence values. It is noted that the two options are presented for the G-R recurrence relationships based on the clustered and declustered catalogue (Fig. 10).

When using the declustered catalogue, a B value yields 0.84 and 0.94 for the intraplate subduction zone for the range depth of 60-120 km and 121-180 km, respectively, confirming the results of the work [76] for Central America employing data for the years 1964-1994. In the case of the interface zone the high B value of 1.01 coincides with the results of Ghosh [77] for the subduction zone, in Costa Rica and Benito et al. [24] in Central America suggesting a moderate seismic coupling between the Cocos-Plate and the Caribbean plate confirming also the previous analysis of Álvarez-Gómez et al. [53] who affirm a slight compression between the two plates. What is not clear at this time, if such slight compression yields maximum magnitudes below 8.0 in the interface and what would be the possibility of having a megathrust event in the Central American trench of M 9.0 as the recent cases in Japan in 2011 and Sumatra earthquakes in 2004. During the preparation of this article, two earthquakes occurred offshore El Salvador and Guatemala; both inside of our geographical window of study in the interface subduction zone with M 7.3 and M 7.4 on August 27 and November 7, 2012, respectively. Employing the recurrence relationship with the correspondent standard deviation, the recurrence interval for a magnitude M 7.3 and above yields 21 years. Taking the last century as the most reliable set of data, three earthquakes with M 7.3 and above are registered in our catalogue for the period 1915-1992. By extending the period from 1915 to 2012 (98 years) to incorporate the last earthquakes on Aug. 2012 and Nov. 2012, it will obtain a recurrence interval of almost 20 years (98 yr over 5 earthquakes), nearly the recurrence value employing the G-R relationships for this zone.

The tri-linear G-R relationships in the volcanic chain reflects for the first part (B_1 = 1.02) a large number of small earthquakes related to destructive ones, the middle part with very low B_2 value reflects the effects of clusters or the abundance of intermediate size earthquakes (for the declustered catalogue B_2 = 0.42) and the third part suggests small number of moderate to big shocks related to the clusters and the small shocks (B_3 = 1.46). It is worth mentioning that same tri-linear trend is obtained when using a 0.5 magnitude bin size (Fig. 10). These results for crustal seismicity differ greatly with the linear trends in the G-R relationships obtained by Benito et al. [24] for the volcanic chain in Guatemala, El Salvador and Nicaragua with *B* values

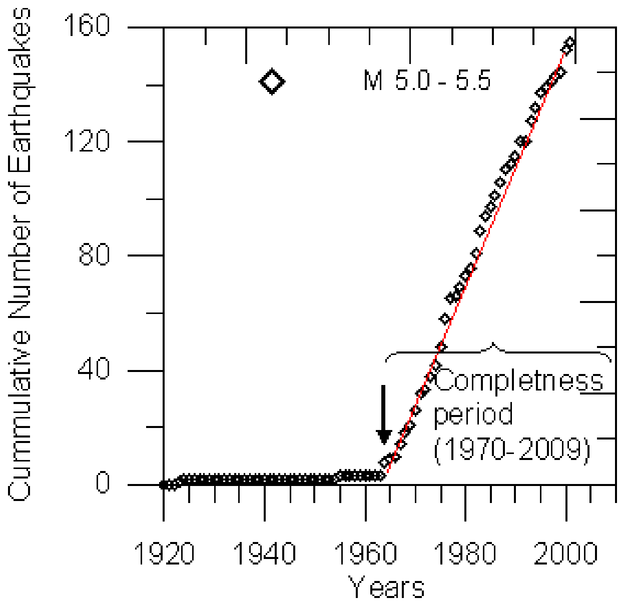


Fig. 9 Illustrative example of the method of Tinti et al. [74] to compute the completeness period for the whole intraplate subduction zone, the method suggests that the earthquakes within a magnitude interval (i.e., 5.0-5.5) are complete back to a specific year if the cumulative annual numbers of events for this magnitude range are approximately linear back to that date, the number of earthquakes in this magnitude range is utilized to obtain the Gutenberg-Richter relations presented in Fig. 10 and Table 6.

Table 5 Estimation of completeness period employing the visual cumulative method for all the seismogenic sources employing 0.25 and 0.5 of magnitude bin size for the seismogenic sources (1) and (2-6), respectively.

Zone	M_W														
	5.13	5.38	5.63	5.88	6.13	6.38	6.63	6.88	5.25	5.75	6.25	6.75	7.25	7.75	8.25
1	1984	1991	1838	1856	1839	1847	1717	1930	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	1978	1928	1750	1907	1785	1816	-
3	-	-	-	-	-	-	-	-	1961	1918	1689	1743	-	-	-
4	-	-	-	-	-	-	-	-	1980	1975	1964	1867	1776	1765	-
5	-	-	-	-	-	-	-	-	1970	1960	1930	1898	1916	1907	1862
6	-	-	-	-	-	-	-	-	1975	1978	1918	1911	1907	-	-
All sources	-	-	-	-	-	-	-	-	1961	1838	1689	1717	1776	1765	1862

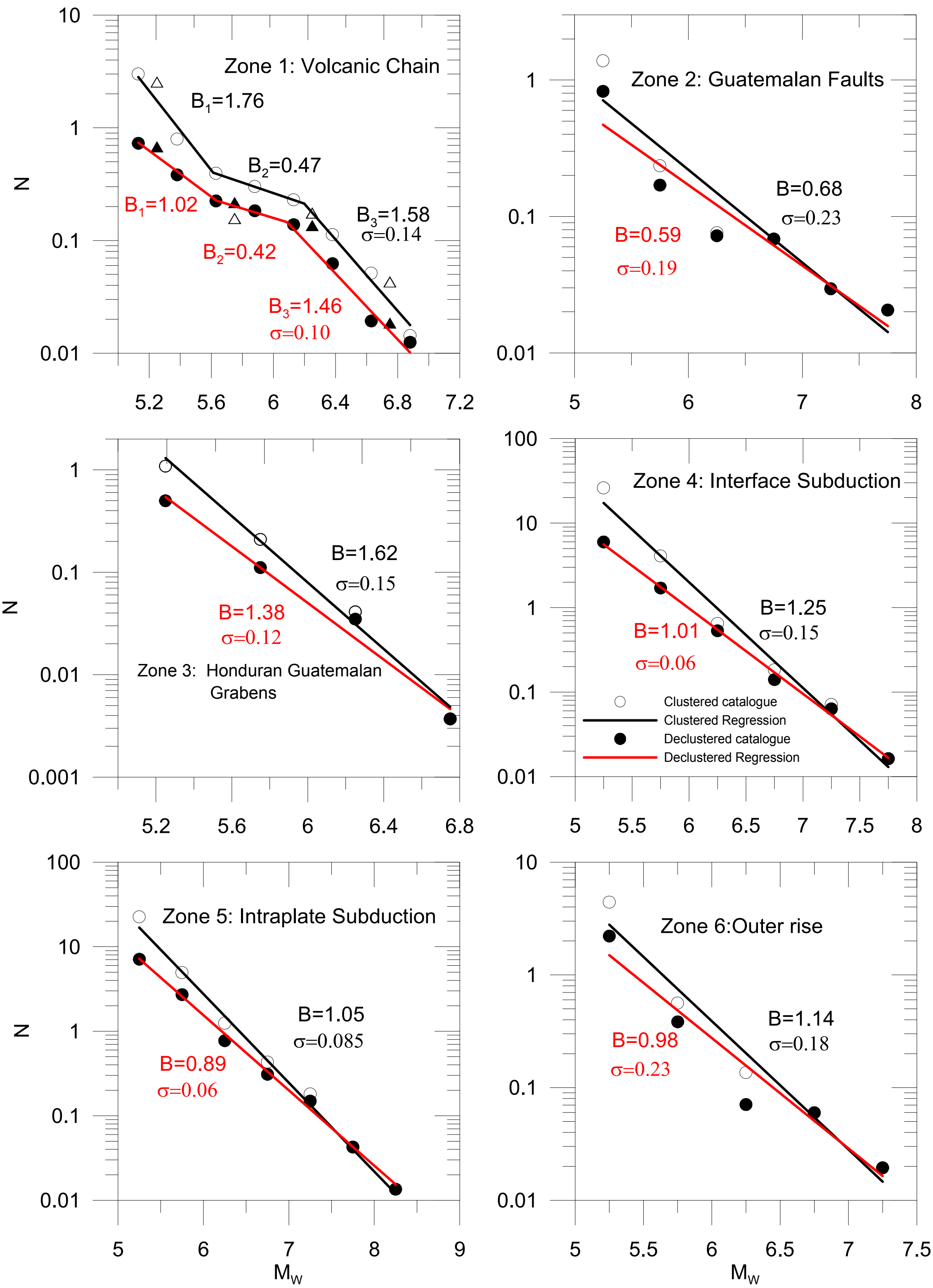


Fig. 10 **Gutenberg-Richter (G-R) recurrence relationships (Table 6), in the case of the volcanic chain (Zone 1), the triangles correspond to magnitudes bin size of 0.5 and the circles to magnitudes bin size of 0.25 for which the G-R relationships was obtained, σ denotes the standard deviation in the regression. N denotes the number of earthquakes per year ad M_w the moment magnitude. The G-R relationships are presented for both the clustered (with foreshocks and aftershocks) and the declustered catalogue (removing the foreshocks and aftershocks), see the correspondent legend in Zone 4 graph.**

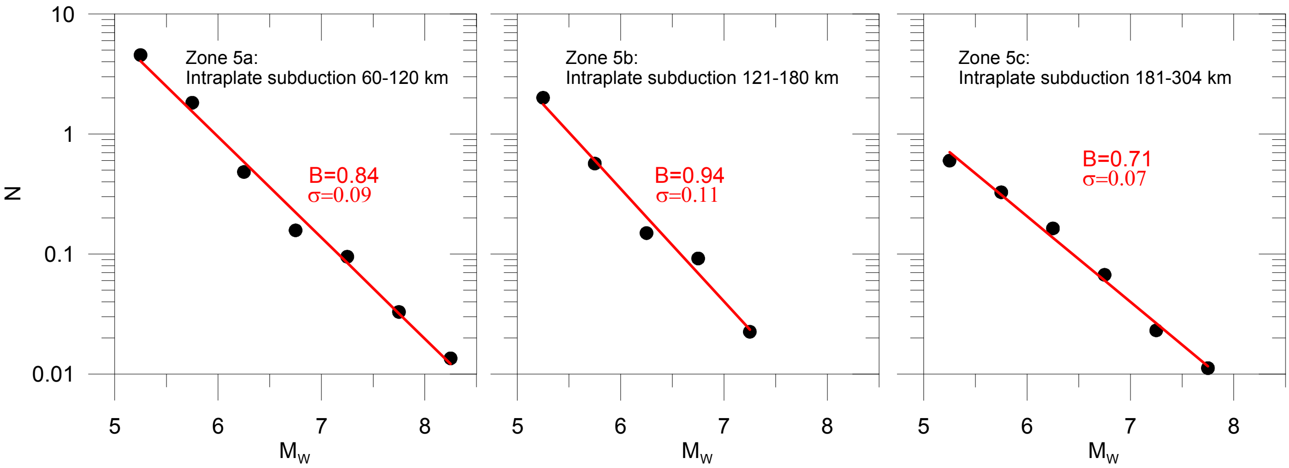


Fig. 11 Gutenberg-Richter (G-R) recurrence relationships for subsources in the intraplate subduction (Zone 5) zone for the declustered catalogue (Table 6).

Table 6 Constants *A* and *B* for the Gutenberg and Richter (G-R) relationships (log *N* = *A* – *BM*), M_{min}: minimum magnitude, M_{max1}: maximum magnitude listed in the catalogue; M_{max2}: maximum magnitude based on paleoseismological investigations [56] for Zone 1 (volcanic chain*) or M_{max1} + an increment Δ of 0.5 units for zones 2-6; ν_{min}: activity rate (number of earthquakes per year) above M_{min}. Noted that for the intraplate subduction Zone 5, the G-R relationships is presented for the whole intraplate zone (5) and the intraplate subsources, namely, Zone 5a: 61-120 km; Zone 5b: 121-180 km and Zone 5c: 181-304 km depth (Fig. 6).

Zone	Variable											
	A_1	B_1	A_2	B_2	A_3	B_3	M_{min}	M_{max1}	M_{max2}	ν_{min}	A	B
1	5.10	1.02	1.72	0.42	8.05	1.46	5.0	6.9	7.6*	1.0	-	-
2	-	-	-	-	-	-	5.0	7.6	8.1	0.66	2.77	0.59
3	-	-	-	-	-	-	5.0	6.7	7.2	1.20	6.98	1.38
4	-	-	-	-	-	-	5.0	7.8	8.3	10.00	6.05	1.01
5	-	-	-	-	-	-	5.0	8.1	8.6	12.02	5.53	0.89
5a	-	-	-	-	-	-	5.0	8.1	8.6	6.61	5.02	0.84
5b	-	-	-	-	-	-	5.0	7.5	8.0	2.95	5.17	0.94
5c	-	-	-	-	-	-	5.0	7.8	8.3	1.12	3.59	0.71
6	-	-	-	-	-	-	5.0	7.1	7.6	2.57	5.31	0.98

between 0.67-0.97. It is noted that non-linear trends in the G-R for the volcanic chain have been obtained before [3, 27, 28, 75]. In order to use the catalogue in the calculation of the seismic hazard, the catalogue must be declustered (Section 5.1) by employing a Poisson probability function. However, applying the de-cluster algorithm [73] to the whole catalogue eliminates destructive earthquakes in the volcanic chain as an interpretation of aftershock of offshore subduction earthquakes (i.e., September 1915-June 1917, January 2001-February 2001). However, a low *B* value for intermediate earthquakes is obtained even applying the descluster scheme in the volcanic chain (Fig. 10), the G-R trilinear trend is observed for both the clustered and declustered catalogue suggesting the same seismicity pattern but with a decrease in the activity rate of earthquakes after the declustering process for the whole range of magnitudes. Note that the decluster scheme affects the activity rate for only small and moderate magnitudes for the rest of seismogenic sources.

Employing the G-R relationship for the volcanic chain using the clustered catalogue, results yield log *N* = 9.12 – 1.58 *M* for *M* > 6.2, and for a *M* 7.6 the recurrence interval results in 773 years, nearly the 750-800 years suggested by Canora et al. [54] for this maximum magnitude based on paleoseismological investigations. When employing the G-R relationships for the declustered catalogue the recurrence interval of this earthquake yields 1,000 yr. A similar high *B* value of 1.38 is obtained for the Honduran Guatemalan Grabens and coincides with the short length of the geological faults in the broad area of extensional tectonics.

The lowest *B* value of 0.59 yields in the Guatemalan Faults suggests a low degree of fragility represented by faults with hundreds of kilometers in length in northern Central America, however, there is a lack of events in the 6.0-6.5 magnitude bin in this source including just two earthquakes for the whole period of the catalogue suggesting a similar tri-linear trend for strike slips earthquake regimes in Central America. While the tri-linear trend in the volcanic chain is caused by the abundance of moderate earthquakes in clusters, the tri-linear trend in the Guatemalan faults is caused by the lack of seismicity of medium size events. The same suspicious tri-linear trend is observed for the outer-rise Zone 6 and yields the largest standard deviation in the G-R relationships amongst all the seismogenic sources (Fig. 10).

5.2 Earthquake Interactions

The catalogue can be used to identify possible earthquake interactions among the seismogenic sources that affected the region. For example, in 1982 the Honduran Grabens, the Subduction Zone and the Volcanic Chain produced earthquakes of M 5.3-5.6 (April 27 and September 29), M 7.3 (June 19) and M 6.1 (December 1), respectively. Besides, after all large subduction earthquakes in the twentieth and the current century, destructive volcanic chain events have occurred within less than four years [37] as the cases of the subduction earthquake in 1915 and the subsequent earthquakes in 1917 in San Salvador and the Guatemala Graben, the sequence of volcanic chain earthquakes in Jucuapa-Chinameca and Gulf of Fonseca in 1951 were preceded by the interface earthquake in Guatemala offshore on October 23, 1950. Martínez-Díaz et al. [33] investigate the existence of a mechanism of static stress triggering driven by the interaction of normal faults in the Cocos Plate and strike-slips faults inside the volcanic arc of El Salvador. The results suggested causative relationships between both kinds of earthquakes as the destructive ones occurred in January-February 2001. Earthquake interactions are reported also for the Guatemalan earthquake of February 4, 1976 and the aftershock sequences located in the Guatemalan Grabens [67]. Also in Managua Nicaragua, the January 8, 1968 earthquake of M 5.0 precedes the destructive earthquake on December 23, 1972. It is not clear how to incorporate the earthquake interactions in future seismic hazard assessment for El Salvador and neighboring countries.

6. Seismic Hazard Implications

In order to test the reliability of this catalogue, the authors performed a preliminary seismic hazard in terms of hazard maps and uniform hazard spectral accelerations for the horizontal component of motion.

Two different computation methodologies have been adopted: the standard and classical Cornell-McGuire approach based on the definition of appropriate seismogenic sources and the Poisson probability distribution [78, 79] and the zone-free Kernel approach developed by Woo [80], which overcomes the ambiguities related with the definition of the seismic sources employing directly the location and size of the earthquakes listed in our catalogue. Since the zone-free method is not based on a Poissonian model of earthquake recurrence, the entire catalogue which includes foreshocks, aftershocks and clusters may be used in the hazard computation. In this sense, the use of the free-zone probabilistic approaches is needed as an alternative method. As a first instance, the inclusion of aftershocks in the hazard assessment can be justified due to catastrophic consequences after the main shock. Just for citing some examples, in the case of the destructive earthquake of October 10, 1986 in San Salvador City, an aftershock on October 13 produced the collapse of a children hospital and other buildings in the city. The aftershock sequence of January 13, 2001 produced the collapse of many residential houses along El Salvador [37], such situation has been observed in several parts of the world as in the recent earthquakes in Haiti (2010), Chile (2010) and New Zealand (2010, 2011).

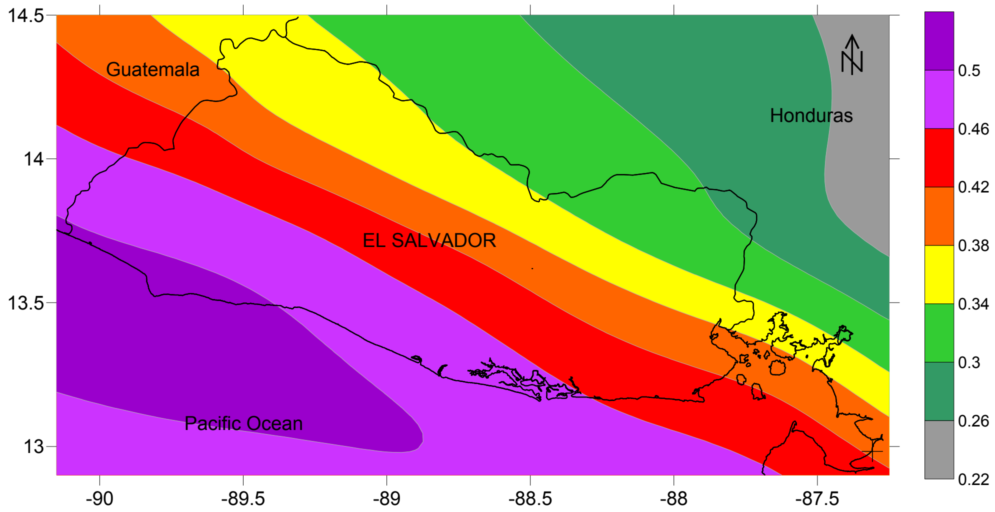
Seismic hazard calculations for the Cornell method have been performed using EZ-FRISK 7.62 code. The Kernel method has been applied using a modified version of the original numerical FORTRAN code KERFRACT developed by Woo [80].

The seismic loads are calculated for: (1) stiff ground conditions (NEHRP site classification B) and flat topographic surface representing outcropping ground conditions; (2) 5% structural damping of the critical; (3) two return periods RP = 475 and 2,475; (4) three spectral periods (PGA, 0.2 s and 1.0 s); (5) 1,947 computational points corresponding to a resolution of a spatial grid of 0.050 degrees with an average spacing of the nodes of about 5.5 km; and (6) a truncation value of 3 sigma (3σ) in the GMPE's (ground motion prediction equations). The attenuation relationships of Kanno et al. [81] was used to compute the hazard and made use of the seismogenic zone delimitations and the G-R relationships developed in the previous sections. The number of earthquakes within different magnitude ranges expected in each seismogenic zone has been obtained using the bounded G-R relationships [82]. For the case of the free zone method, the catalogue is divided in two sub catalogues, namely: (1) crustal events; (2) subduction zone events that are separated in interface and intra plate events. This subdivision was necessary because the depths of the shallow and deep zones can not be averaged because this would result in an intermediate unrealistic depth. The uncertainties in epicenter location and magnitude are taken from Ref. [44] and the completeness periods were adopted for all the sources listed in Table 5. The results of the two probabilistic methods are averaged with equal weights employing the maximum magnitudes M_{max1} and M_{max2} listed in Table 6.

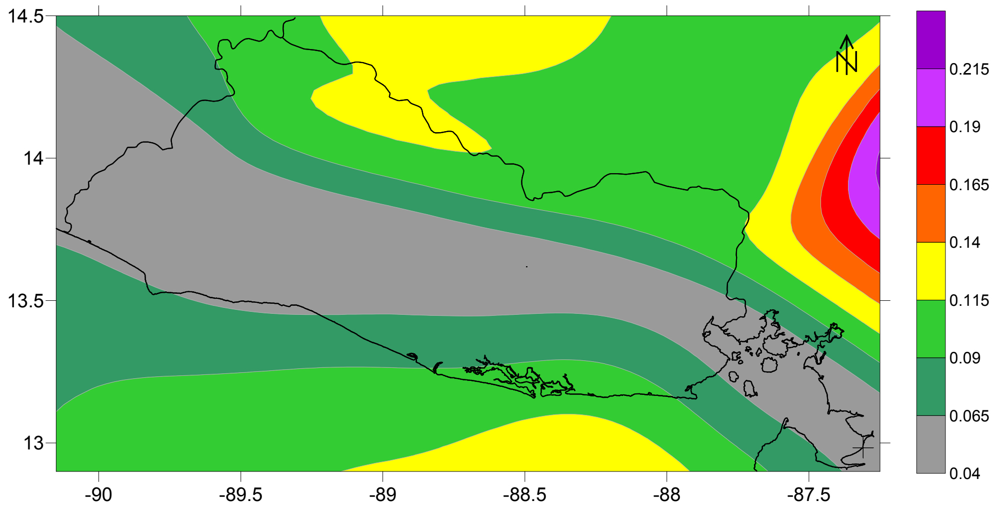
Figs. 12-14 show the seismic hazard contour maps developed for El Salvador in terms of PGA with 10% probability of exceedance in 50 years (RP = 475 years), SA at 0.2 s and 1.0 s with 2% probability of exceedance in 50 years (RP = 2,475). PGA with RP = 475 years has been considered since it is the widely used parameter to express the results of the PSHA (probabilistic seismic hazard assessment), while the computing of the spectral acceleration at periods of 0.2 s and 1.0 s and RP = 2,475 years is consistent with International Building Codes [83, 84]. The covariance COV is the standard deviation of the estimated PGA (or spectral ordinate) at each point divided by the mean value at that point (COV = σ/χ) and tells you the relative breath of the Gaussian distribution used to represent the variability for the two probabilistic methods and correspondent maximum magnitudes used in the hazard assessment [85].

The covariance for the PGA and the period of 0.2 s varies from 0.04 to 0.14 inland El Salvador, yielding a high level of reliabiltiy in our hazard calculations and also for our catalogue. For the period of 1.0 s, a level of covariances 0.14 to 0.24 (Table 7) was observed.

A comparison between the UHS (uniform hazard spectrum) computed for San Salvador Metropolitan Area for RP = 475 and 2,475 years and the design response spectrum recommended by the North American Building Codes [83, 84] for rock site conditions, "site class B", is provided in Fig. 15. It is noticed that both probabilistic methods yield almost the same spectral values (Fig. 15) as expected according to the calculated covariance in the maps, it is worth nothing that the three linear trends in the G-R relationship for the volcanic chain were weighted according to the probability of magnitude occurrence yielding a total of 1.0 when summing all magnitudes bin contributions employed in the Cornell hazard analysis computation (e.g., for the B_1, B_2 and B_3 parts the weights were calculated as 0.75, 0.09 and 0.16, respectively). The United States spectral shape has

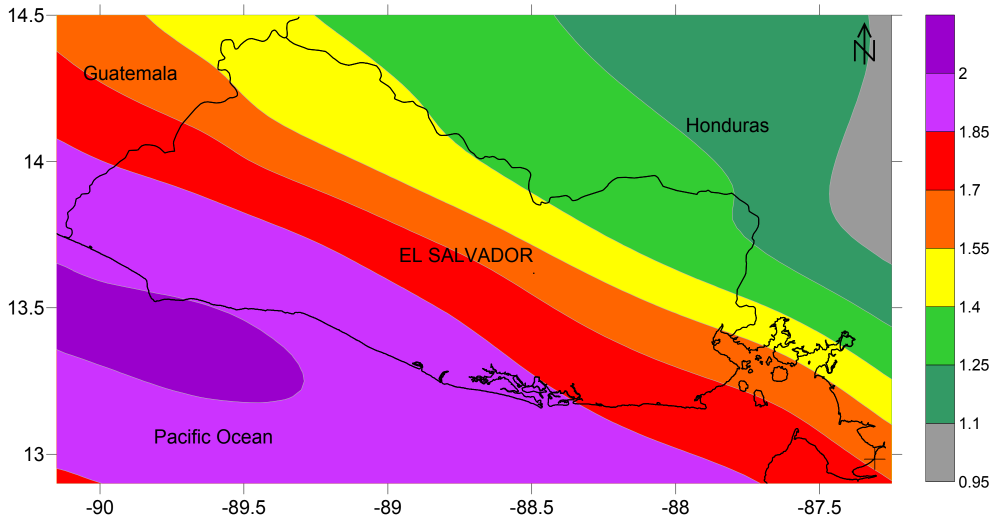


(a)

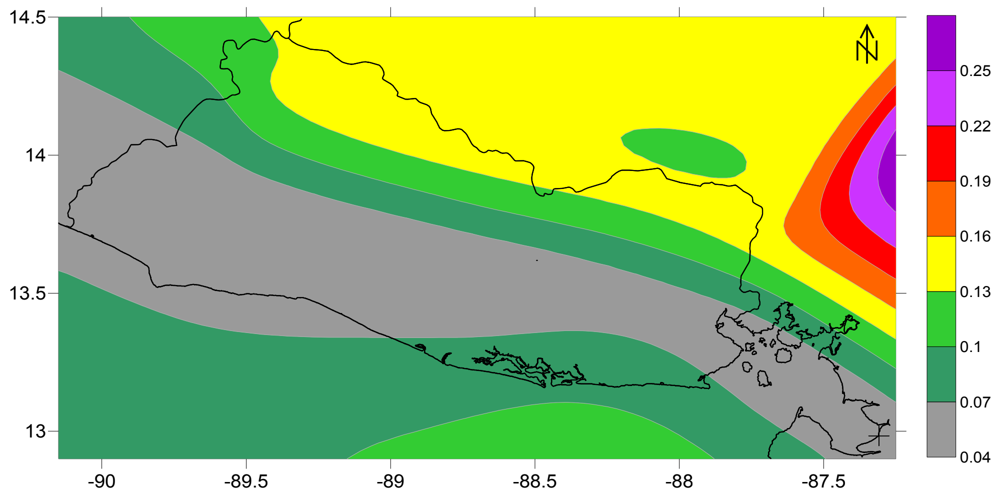


(b)

Fig. 12 The seismic hazard contour map and its uncertainty: (a) seismic hazard map for the peak ground acceleration (g) and 475 years return period; (b) acceleration uncertainties in terms of covariance (COV).

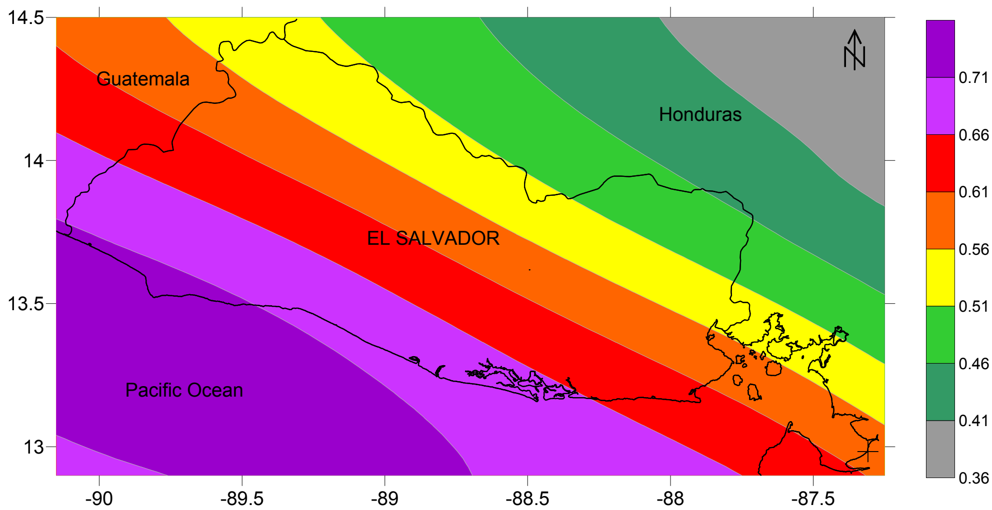


(a)



(b)

Fig. 13 The seismic hazard contour map and its uncertainty: (a) seismic hazard map for spectral acceleration (g) at the period of 0.2 s and 2,475 years return period; (b) acceleration uncertainties in terms of covariance (COV).



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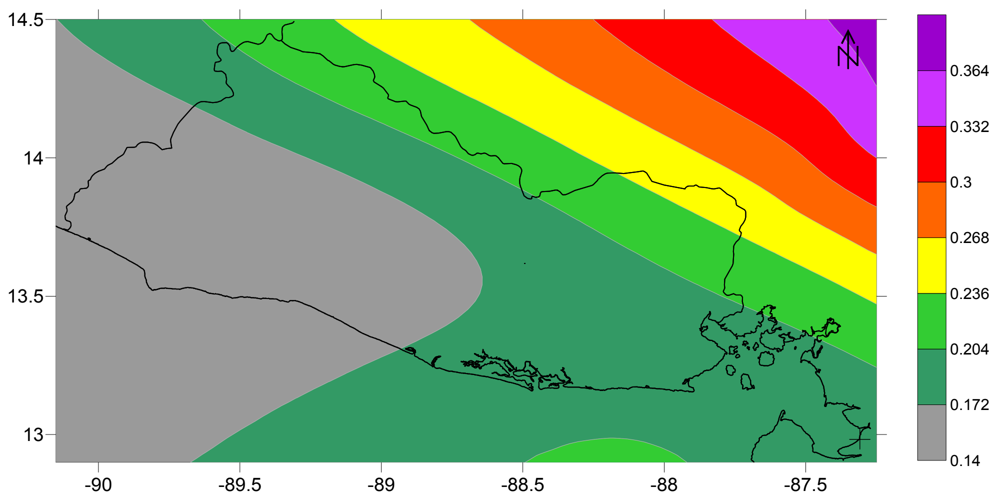

(b)

Fig. 14 The seismic hazard contour map and its uncertainty: (a) seismic hazard map for spectral acceleration (g) at the period of 1.0 s and 2,475 years return period; (b) acceleration uncertainties in terms of covariance (COV).

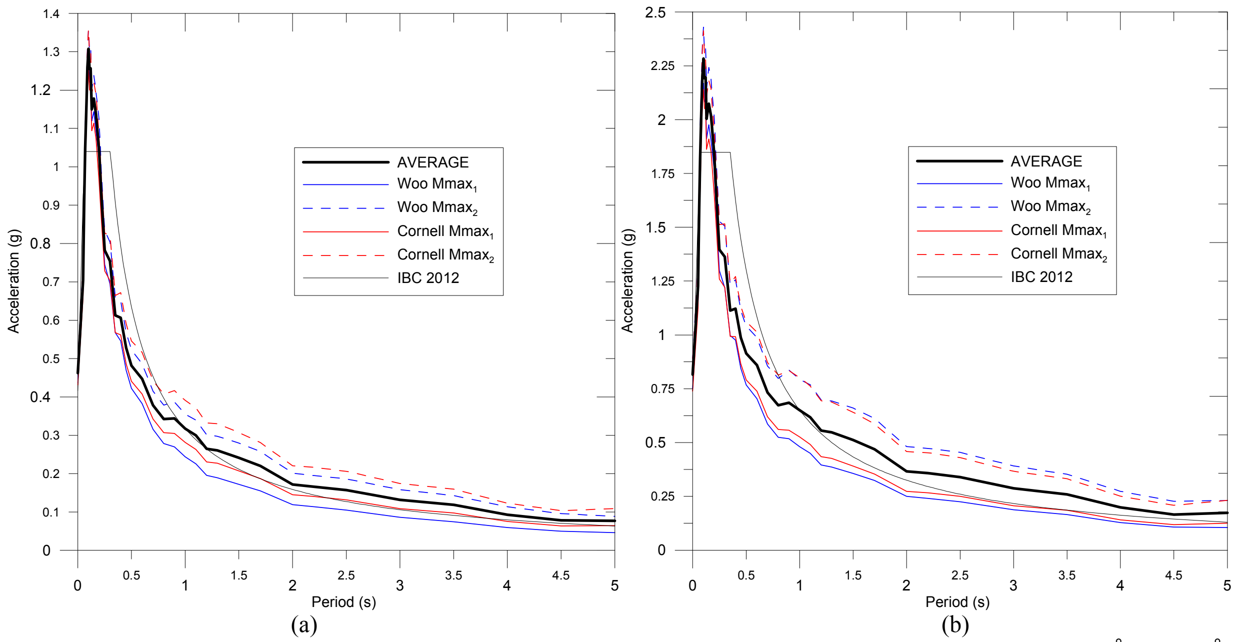

Fig. 15 Design elastic response spectra for 5% of critical damping for San Salvador Metropolitan Area (13.70° N, 89.21° W) for (a) 475 years return period; (b) 2,475 years return period.

Table 7 Degree of reliability for different values of covariance COV.

Covariance	Degree of reliability
0 ≤ COV < 10%	Very high
10% ≤ COV< 20%	High
20% ≤ COV< 30%	Medium
30% ≤ COV < 40%	Low
COV ≥ 40%	Very low

been scaled to the spectral acceleration at 0.2 s and 1.0 s computed in this study for San Salvador employing IBC formulas.

It is of practical interest to see that the spectrum calculated in this study is not totally in good agreement with the elastic response spectrum [83, 84], especially for short period components less than 0.3 s. The differences are attributed due to the abundance of earthquakes in the volcanic chain for moderate shallow magnitudes yielding an underestimation of seismic loads when applying IBC spectral shapes factors. It is suggested that such differences are the consequences of employing spectral shapes calibrated for California seismicity in areas of subduction and volcanic environments. The level of uncertainty increases at longer periods and the correspondent maximum magnitudes in the analysis.

7. Conclusions

El Salvador and surrounding areas are characterized with a high seismic activity yielding about 40 earthquakes per year with magnitude 5.0 or above that generates in six seismogenic sources in the region with a whole variety of focal depth, fault plane solutions and expected maximum magnitudes. In this regard, the most critical aspect in the upper-crustal seismicity generated in the volcanic chain is the possibility of a M_{max} of 7.6 every 750-800 years according to the new paleoseismological information and its coincidence with the recurrence time for these events employing our G-R recurrence relationships. Long return periods of earthquake ground motion (e.g., 4,975 years that corresponds to 1% of probability of exceedance in 50 years life time of the structure) might be considered the maximum possible earthquake and future critical facilities in the country.

Despite large interface thrust earthquakes have not been reported in El Salvador and neighboring Central American countries since historic times, the worldwide seismic activity trend suggests that large megathrust events of magnitude 8.0-9.0 are possible in subduction trenches worldwide (e.g., recent Sumatra and Japan

Earthquakes in 2004 and 2011, respectively). In this regard, it is recommended to introduce a characteristic models for this seismogenic source based on slip rates and the inclined geometry of the slab beneath Central America in the future hazard calculations.

This research suggests that either the interface subduction Trench, the outer-rise zone offshore or the Guatemalan faults constitutes clear sources for triggering tsunamis. However, tsunamis have been also reported due to upper crustal earthquakes located in the Gulf of Fonseca in El Salvador.

The earthquake catalogue could be used to calibrate time-space empirical formulas for main-aftershock sequences for El Salvador and the surrounding areas. The local magnitude calculations for Central America deserve further revision at the monitoring centers in the Isthmus (Fig. 2) observing a high dispersion in the actual data and a very high deviation when comparing with other parts of world.

The horizontal peak ground acceleration expected on stiff ground, with a 10% probability of exceedance in 50 years, which corresponds to 475 years return period, ranges between 0.26 g and 0.55 g. The highest hazard is observed at the western coast of the country presumably by the effects of the close megathrust interface zone, the effects of the 1915 earthquake interface subduction zone with M 7.8 in the free zone method yields a high influence in the hazard results. The low values of covariance obtained in the seismic hazard maps employing zone and free-zone methods for 475 and 2,475 years return period suggest an acceptable degree of reliability for both the seismogenic source delimitations and the earthquake catalogue itself employing appropriate weights for the tri linear G-R relationships in the volcanic chain. At the same time the low error observed suggests that both methods can be used for the hazard calculation in the country respecting their assumption and limitations for the earthquake probability of occurrence.

When using the free-zone method, special caution must be taken into account regarding with the epicenters errors of historical earthquakes for the subduction zone, since the epicenters sometimes correspond to the center of the isoseismal curves inland instead being offshore Central America (e.g., epicentral error of 30 km were used for interface earthquakes prior 1900), instead, a recalculation of the epicentral locations for subduction historical earthquakes offshore is needed.

Employing the IBC formulas scaling the spectral values for 0.2 s and 1.0 s in the maps must be doing with caution for El Salvador and Central American countries. The authors propose that the seismic coefficients must be calibrated for the volcanic and subduction conditions inherent to the region if the future codes would anchor the spectral shapes using control periods and its correspondent spectral acceleration level.

The complete catalogue is available in ASCII format upon request to the correspondent author and its format is listed in the Appendix. An advantage of the catalogue is that for each earthquake it is possible to identify the original source of information where the data was taken according to the code listed in the left column in Table 1, making this easy to use, revise and update.

The authors expect that the catalogue can be used, updated and corrected according to the suggestions presented in this report as new information become available, for both historical and instrumental seismicity. Salazar et al. [86] also compiled macro-seismic information from the newspapers of the National Library of El Salvador and the Indian Sevilla Archives in Spain that could help to complement previous historical earthquake research in the region. As a parallel research work to the seismicity evaluation, new GMPE's (ground motion prediction equations) must be developed for El Salvador and neighboring Central American countries taking into account the effects of surface geology on the seismic motion.

It is expected that this information will contribute to the mitigation of the seismic risk in the country if new and proper seismic hazard methodologies sustain the tectonics features and the seismicity patterns observed in the catalogue.

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Appendix: Format and Catalogue Excerpt.

The format of the earthquake catalogue is as follows:

Column	Description
1-4	Year
5	Blank space
6-7	Month
8	Blank space
9-10	Day
11	Blank space
12-13	Hour
14	Blank space
15-16	Minutes
17	Blank space
18-21	Seconds
22	Blank space
23-29	Epicentral coordinate in west longitude (degrees)
30	Blank space
31-36	Epicentral coordinate in north latitude (degrees)
37	Blank space
38	Source information code for the origin time and epicentral coordinates determinations (Table 1)

39	Blank space
40-42	Focal depth (km)
43	Blank space
44	Source information code for the depth determination (Table 1)
45	Blank space
46-49	Magnitude M_W
50	Blank space
51	Source information code for the magnitude determination (Table 1)
52	Blank space
53-55	Magnitude used to convert to M_W: **Ms*: from surface wave magnitude; **mb*: from body wave magnitude; **MD*: from Coda—duration magnitude. *Mw* without a star means that the original value of moment magnitude was taken directly when available
56	Blank space
57-61	Focal mechanism classification according to the slip λ, LL: left lateral ($-44^o \le \lambda \le 44^o$); RL: right lateral ($136^\circ \le \lambda \le -136^\circ$); T1: thrust ($45^\circ \le \lambda \le 135^\circ$) and $\pm 20^\circ$ within the strike of the Middle American Trench N1: normal ($-135^\circ \le \lambda \le -45^\circ$) and $\pm 20^\circ$ within the strike of the Middle American Trench T: thrust ($45^\circ \le \lambda \le 135^\circ$), N: normal ($-135^\circ \le \lambda \le -45^\circ$)
62	Blank space
63	Related phenomena: V: volcanic eruption; T: tsunami; E: eclipse

Excerpt of Earthquake Catalogue for Zone 1: Volcanic Chain

```
         1         2         3         4         5         6
123456789012345678901234567890123456789012345678901234567890123

1917 06 08 00 51 51.0 -89.310 13.820 M  10 M 6.69 M *Ms       V
1917 06 08 02 54  0.0 -89.500 13.770 M  10 M 5.73 M *Ms       V
…..
2001 01 14 16 22 21.7 -89.565 13.662 R  16 R 5.01 I *Ms
2001 01 14 18 17 31.8 -89.425 13.690 I   5 I 5.06 I *Ms
2001 01 16 11 53 22.9 -89.655 13.960 I   1 I 5.09 I *Ms
2001 01 17 06 51 10.1 -86.400 12.205 R   3 R 5.12 I *Ms
2001 02 13 14 22  5.6 -88.845 13.620 L   7 L 6.50 C  Mw LL RL
2001 02 17 20 25 15.7 -89.249 13.661 L   5 L 5.56 L *Ms
2001 02 23 16 22  8.0 -89.200 13.715 I  12 I 5.01 I *Ms
2001 02 25 08 28 15.5 -89.200 13.708 I  13 I 5.03 I *Ms
2001 03 08 06 17 32.8 -87.861 13.339 R   5 R 5.03 I *Ms
2001 04 10 21 46 58.9 -88.722 13.641 L   8 L 5.12 I *Ms
2001 05 08 18 02 17.3 -88.706 13.615 L   9 L 5.70 C  Mw LL RL
2001 05 08 18 15 47.0 -88.682 13.608 L  11 L 5.52 I *mb
2001 05 08 18 40 21.4 -88.662 13.616 L   7 L 5.31 I *Ms
2001 05 08 19 52 12.0 -88.715 13.592 L   3 L 5.09 I *Ms
```

Excerpt of Earthquake Catalogue for Zone 4: Interface Subduction

```
         1         2         3         4         5         6
123456789012345678901234567890123456789012345678901234567890123

1609 00 00 00 00  0.0 -86.550 12.420 E   0   7.19 E *ML T
1648 00 00 00 00  0.0 -86.800 12.500 E   0   7.19 E *ML T
1663 00 00 00 00  0.0 -86.550 12.420 E   0   7.19 E *ML T
1719 03 05 00 00  0.0 -89.500 13.000 G   0   7.23 G *Ms T     E
1752 05 07 00 00  0.0 -87.500 12.300 G   0   6.74 G *Ms T
1765 10 24 00 00  0.0 -91.917 15.000 B   0   7.66 W *Ms T
1773 07 29 00 00  0.0 -91.167 14.667 B   0   7.55 W *Ms T
1773 12 13 00 00  0.0 -91.500 14.583 B   0   7.12 W *Ms T
1776 05 30 00 00  0.0 -90.080 13.180 G   0   7.23 G *Ms T
1815 08 20 00 00  0.0 -89.000 12.750 G   0   7.23 G *Ms T
1831 02 07 00 00  0.0 -89.700 13.200 G   0   7.02 G *Ms T
1859 12 08 00 00  0.0 -90.000 13.200 G   0   7.02 G *Ms T     T
1867 06 30 00 00  0.0 -89.160 13.200 G   0   6.56 G *Ms T
1869 03 01 00 00  0.0 -90.000 13.000 G   0   7.02 G *Ms T
1870 06 12 00 00  0.0 -90.167 14.167 B   0   7.23 W *Ms T
1874 09 03 00 00  0.0 -90.833 14.667 B   0   7.12 W *Ms T
1885 10 12 00 00  0.0 -87.030 12.080 G   0   6.74 G *Ms T
1900 11 09 16 08  0.0 -90.000 13.000 A  30 A 6.93 A *Ms
1901 10 08 02 16  0.0 -86.500 11.000 A  30 A 7.02 A *Ms       T
1915 09 07 01 20  0.0 -89.600 13.900 A  60 A 7.83 A *Ms T     T
```