The new Central American seismic hazard zonation: Mutual consensus based on up to day seismotectonic framework

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The new Central American seismic hazard zonation: Mutual consensus based on up to day seismotectonic framework

Guillermo E. Alvarado[a], Belén Benito[b,*], Alejandra Staller[b,*], Álvaro Climent[a], Eduardo Camacho[c], Wilfredo Rojas[d], Griselda Marroquín[e], Enrique Molina[f], J. Emilio Talavera[g], Sandra Martínez-Cuevas[b], Conrad Lindholm[h]

[a] *Instituto Costarricense de Electricidad, Sismología y Vulcanología, Apdo., 10032-1000, Costa Rica*
[b] *Dpto. de Ingeniería Topográfica y Cartografía, Universidad Politécnica de Madrid, 28031 Madrid, Spain*
[c] *Instituto de Geociencias, Universidad de Panamá, Panama City, Panama*
[d] *Red Sismológica Nacional (RSN), Universidad de Costa Rica, Costa Rica*
[e] *Gerencia de Geología, Dirección General del Observatorio Ambiental, Ministerio de Medio Ambiente y Recursos Naturales, El Salvador*
[f] *Universidad Mariano Gálvez, Ciudad de Guatemala, Guatemala*
[g] *Instituto Nicaragüense de Estudios Territoriales (INETER), Managua, Nicaragua*
[h] *Norwegian Seismic, NORSAR, Kjeller, Norway*

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ABSTRACT

Central America is one of the most active seismic zones in the World, due to the interaction of five tectonic plates (North America, Caribbean, Coco, Nazca and South America), and its internal deformation, which generates almost one destructive earthquakes ($5.4 \leq Mw \leq 8.1$) every year. A new seismological zonation for Central America is proposed based on seismotectonic framework, a geological context (tectonic and geological maps), geophysical and geodetic evidence (gravimetric maps, magnetometric, GPS observations), and previous works. As a main source of data a depurated earthquake catalog was collected covering the period from 1522 to 2015. This catalog was homogenized to a moment magnitude scale (Mw). After a careful analysis of all the integrated geological and seismological information, the seismogenic zones were established into seismic areas defined by similar patterns of faulting, seismicity, and rupture mechanism. The tectonic environment has required considering seismic zones in two particular seismological regimes: a) crustal faulting (including local faults, major fracture zones of plate boundary limits, and thrust fault of deformed belts) and b) subduction, taking into account the change in the subduction angle along the trench, and the type and location of the rupture. The seismicity in the subduction zone is divided into interplate and intraplate inslab seismicity. The regional seismic zonation proposed for the whole of Central America, include local seismic zonations, avoiding discontinuities at the national boundaries, because of a consensus between the 7 countries, based on the cooperative work of specialists on Central American seismotectonics and related topics.

1. Introduction

Central America, although a small land bridge (1400 km long, 80–400 km wide; 523,412 km^2) between the Americas, is home to about 50 million inhabitants, which live in a very active geological area, with many earthquakes, volcanic eruptions, landslides, floods, hurricanes, and other hazards. In the last centuries, about 40,000 people died due to intermediate earthquakes ($5.4 \leq Mw \leq 8.1$) at a rate of one destructive earthquake approximately every one or two years. For that reason, different seismic hazard studies in Central America have been generated in the last 25 years, all using different seismic zonations (Lindholm et al., 2007; Benito et al., 2009, 2012; and references therein). Local seismological studies have been done in each of the 7 countries. The local seismic zonations used do not coincide with the zonation of neighbouring countries at the boundaries or the regional seismic zonations. We analysed the geological framework and the char-

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* Corresponding author at: Dpto. de Ingeniería Topográfica y Cartografía, Universidad Politécnica de Madrid, Campus Sur, Autovía de Valencia km. 7, 28031 Madrid, Spain.
Email addresses: mariabelen.benito@upm.es (B. Benito); a.staller@upm.es (A. Staller)

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acteristics of the plate boundaries, seismotectonic and seismic sources, in order to provide the geometry, and seismic parameters of the regional and local seismic zones, a fundamental base for seismic hazard studies. The zonation proposed in this paper has as its main objective to provide an up-date model, which could serve to generate Probabilistic Seismic Hazard Analysis (PSHA) using a similar zonation criterion for the entire isthmus. We applied a simple method based in the integration of the different layers of information (seismic, tectonic and GPS measurements) and the relation between them in order to develop criteria for delineation of the seismic zones boundaries. Each seismic zone is later characterized by seismic parameters (parameters a and b, maximum magnitude and recurrence).

The new zoning takes as its starting point the previous model defined in the framework of the RESIS II project sponsored by the Norwegian Cooperation Agency (NORAD) aimed at the study of regional seismic hazard of Central America (Benito et al., 2009, 2012). The zones proposed now are based on additional information collected from 2012 to 2017 in which we include the subduction angle variations along the Central American trench, and new additional information on the Panama microplate, southern Mexico and northwestern Colombia.

The process followed the definition of the new zonation and characterization of the seismic parameters of the zone is described in this paper. In the next section, we present the tectonic framework of the CA region; the methodology for definition of the zones, the geometry and description of the new zones classified by tectonic regime in subduction interface, subduction inslab and crustal; and the seismic parameters of each zone.

2. Tectonic framework and crustal structure

Central America is mostly located on the Caribbean plate, but the northern part of Guatemala is located on the North American plate (Fig. 1). The Caribbean plate is surrounded by four major tectonic plates: The Coco plate to the southwest, the Nazca plate to the south, and the North American and South American plates to the north and southeast, respectively. The complex crustal deformation in Central America is due to the relative motion of the different plates and microplates. The plate velocities derived from GPS measurements are shown in Fig. 1 (Fig. S1 in Supplementary material show GPS velocities relative to the stable Caribbean plate from Franco et al., 2012; Kobayashi et al., 2014; Rodriguez et al., 2009 and Staller et al.,

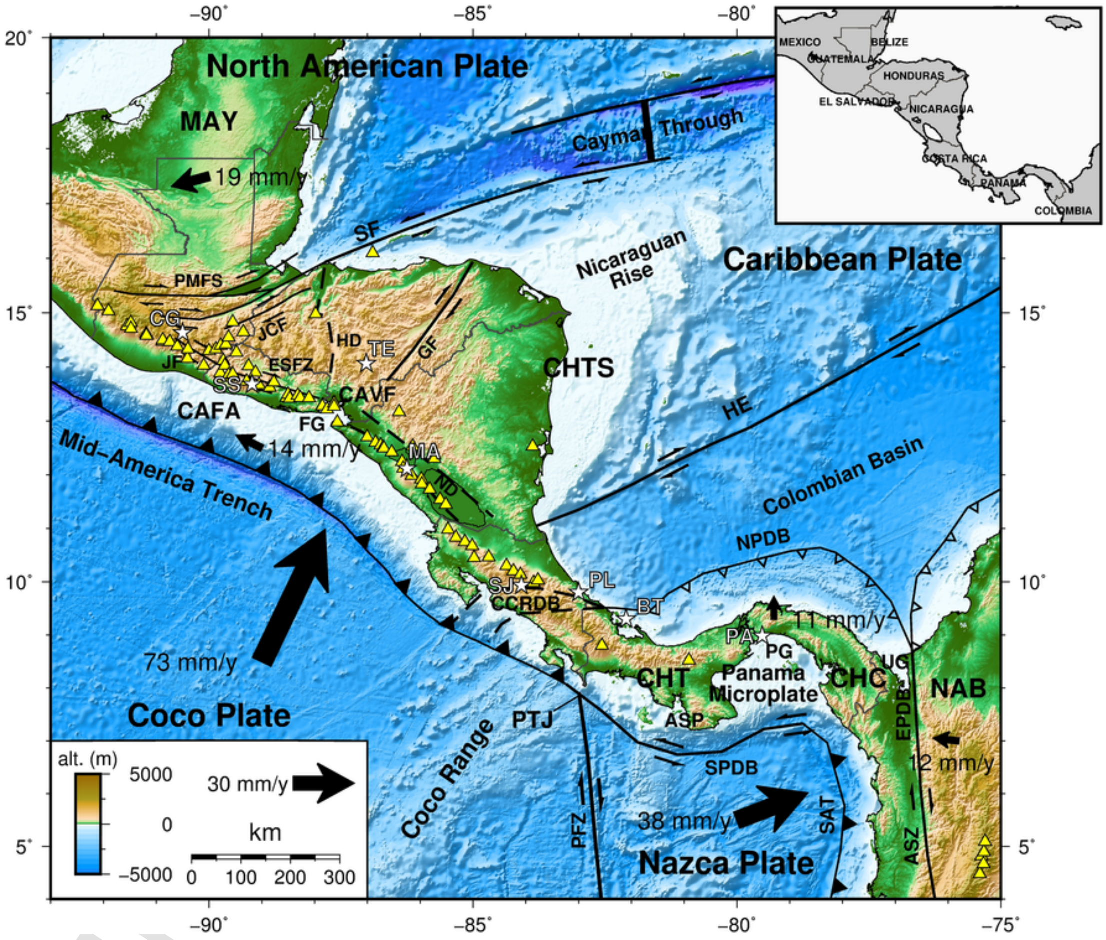

Fig. 1. Topographic and bathymetric map of Central America with the main tectonic elements, related plates and structural elements. Plate boundaries and main tectonic structures, heavy black lines. National boundaries, grey lines. Yellow triangles are Holocene volcanoes from the Smithsonian Global Program. White stars show the location of the capitals of each country and city of interest. Black vectors show the motion of the Plates, microplates and blocks relative to the Caribbean Plate (DeMets et al., 2010). MAY – Maya block, CHT – Chorotega block, CHC – Choco block, NAB – North Andean Block, PMFS – Polochic-Motagua Fault System, CAVF – Central America Volcanic Front, CAFA – Central America Forearc block, JCF – Jocotan-Chamelocon fault, SF – Swan fault, JF – Jalpatagua fault, ESFZ – El Salvador fault zone, HD – Honduras depression, GF – Guayape fault, ND – Nicaraguan depression, CCRDB – Central Costa Rica deformed belt, PFZ – Panama Fracture zone, NPDB – North Panama deformed belt, SPDB – South Panama deformed belt, EPDB – East Panama deformed belt, SAT – South America Trench, ASZ – Atratos' suture zone, PTJ – Panama Triple Junction, CG – Ciudad de Guatemala, SS – San Salvador, TE – Tegucigalpa, MA – Managua, SJ – San José, PA – Panama City, PL – Puerto Limón (Costa Rica), BT – Bocas del Toro. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2016). The relative plate movements range between 2.0 and 9.0 cm/yr (DeMets et al., 2010; Protti et al., 2012), although the kinematical characterization in a small scale is still subject of considerable debate.

The Coco-Caribbean margin is a subduction zone whose tectonic boundary is the Middle America Trench (MAT). The MAT and the active Central America Volcanic Front (CAVF) reflect subduction of the Coco plate beneath Central America (Fig. 1). The Southern Panama Deformed Belt (SPDB) makes the Caribbean-Nazca plate boundary; the Polochic-Motagua Faults System (PMFS) marks the Caribbean-North American plate boundary. The Atrato Suture Zone (ASZ) constitutes part of the Caribbean-South American boundary, although other authors do not consider it a plate boundary (i.e. Vargas and Mann, 2013). The relative movement between the plates and the internal deformation result in the major tectonic features in the Caribbean plate.

Panama, southern Costa Rica and northwestern Colombia are part of the Panama microplate which converges ~ 8–9 cm/year to the northeast (Fig. 1) (Kellogg and Vega, 1995; Trenkamp et al., 2002; Vargas and Mann, 2013). The NW limit of the Panama microplate is defined by a complicate, diffuse, active fault zone system, which cross the central and northern part of Costa Rica, named the Central Costa Rica Deformed Belt, CCRDB (Fig. 1) (Montero, 1999a, 2001; Marshall et al., 2000).

The Coco volcanic range (1200 km long by 100–350 km wide) is a submarine volcanic ridge that is a hotspot trace (N43°E) of the Galápagos hotspot, which stands 2 to 2.5 km higher than the surrounding seafloor, and it is being subducted beneath southern Costa Rica (Rojas and Alvarado, 2012). The subduction of the Coco volcanic range produced an indentation in the margin, which together with the North Panama Deformed Belt (NPDB), generated a compressional regime of collisional margin that is reflected in thrust and strike-slip faults in the Costa Rica - Panamá region (Kolarsky et al., 1995; Marshall et al., 2000).

In Central America, the knowledge of crustal structure is still limited despite that some wide-angle seismic experiments were done during the past decades in its southern region. Crustal structure was largely inferred prior to 1990 from geologic maps, sparse gravity studies, potential field data, and seismic and seismological observations. Fundamental questions, still debated by geoscientists are the location of boundaries between the continental Paleozoic basement of North America, and the oceanic igneous crust or "island arc" crust of Costa Rica, where seismic velocities are similar to the continental crust (Flueh and von Huene, 2007).

The Maya (MAY) and Chortis blocks (CHTS) (Fig. 1) are recognized as continental blocks with Precambrian and Paleozoic crystalline sialic basement regarded as the Precambrian-Paleozoic continental nucleus of northern Central America, covered by Mesozoic-Cenozoic red beds, carbonates, clastics sedimentary rocks, volcanic and volcaniclastic rocks. Accreted/obducted oceanic/volcanic arc rocks are also present. While MAY is seen as part of North America, CHTS, Chorotega (CHT) and Panama-Chocó (CHC) lie on the western margin of the Caribbean plate. The CHT and CHC are characterized by troughs of marine Cenozoic deposits with volcanic and plutonic rocks, above Mesozoic oceanic rocks. No high temperature and pressure metamorphic rocks are known, and the blocks are regarded as having intra-oceanic origins. Neogene volcanic rocks are abundant in CHT, rare in CHC. Accreted oceanic terranes are present on CHT and CHC. The Southern limit of CHC is a major break in the Occidental cordillera of Colombia at 5°S, welded to northwestern South America but the plate boundary is diffuse (Dengo, 1985; Escalante, 1990; Bundschuh and Alvarado, 2007).

3. Methodology and definition of seismic zones

A seismic zone is defined as a specific geological feature, or group of features, in which the nature of deformation and seismotectonic setting are similar and a relationship between their deformation and historic or earthquake potential can be inferred. The delineation of seismic source zones requires the integration of geophysical and geological data in order to define a seismotectonic structure (fault o fault zone) or seismotectonic zone (Erdik et al., 1985). A seismic source zone may be isolated, but typically they are contiguous to, or completely surrounded by other source zones characterized by different seismological parameters. The characterization of seismic sources considers three fundamental elements: i) identification of significant source of earthquakes, ii) maximum size of these earthquakes, and iii) rate at which they occur (Wong et al., 2004).

Despite the degree of knowledge in state-of-the-art of global seismic hazards studies, there is not a standard for delineation of the seismic sources zones and assessment of maximum potential earthquakes Mmax, employed are, in a several ways, quite subjective in nature. Different researchers come up with different seismic source zones delineations using the same database (Erdik et al., 1985). This was the case in previous studies in Central America and in individual countries (Rojas et al., 1993a,b,c; Güendel and Protti, 1998; Montero, 1999b; Fernández and Rojas, 2000; Fernández et al., 2007). For this reason, we integrated all recent geological (tectonic, geological, geophysical and geomorphological maps), geodetic (current crustal deformation from GPS velocities (Fig. S1)) and seismological information (rate of seismicity, focal mechanisms, seismicity density, depth, magnitude), trying to avoid the deficiencies previously exposed. The flowchart of the maps and kind of data used for definition of the zones model is shown in Fig. 2. National and regional geologic maps of Central America were used, in order to delimit the major tectonic blocks (different tectonic origin, age, composition, crystalline terrains). A geomorphologic map was used to identify the major physiographic regions (volcanic ranges, alluvial plains, coastal ranges, drainage patterns, etc.). Clearly, the geologic provinces no necessary coincide with the seismic provinces, but the idea was to integrate and weighted the different maps, and provide a better model that fit all the recognized provinces in a final seismic zonation.

On this basis, for the first time, seismologists and seismic-hazard professionals from Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Panama, Norway and Spain have worked together and by consensus to propose this new Central American seismic zonation. The final result is a new regional zonation based on the integration of all Central American available data and research, in an unique proposal.

Based on the regional and local seismic zonation presented here, we evaluated and elaborated separate maps for major faults, including old and present plate boundaries, the geology, geomorphology, gravimetric and crustal structure, seismicity (shallow, intermediate, deep), focal mechanisms for subduction (Mw > 5.0), local fault (Mw > 3.0), and seismic profiles. For each map, we established preliminary "provinces" or zones. Then, we integrated all the overlapping zones and reached regional consensus for a unique seismic zonation.

The major tectonic features of the region were taken from regional geologic and tectonic maps (Case and Holcombe, 1980; French and Schenk, 2004), and on several papers and reviews (e.g. Burkart, 1990; Mann et al., 2007; James, 2007). The major structures were evaluated according to their tectonic characteristics (type of fault, grade of activity, longitude, and maximum estimated magnitude) and provide a basis for the delineation of seismotectonic zones for hazard estimation. However, the velocities of the major faults are still under research. We complemented the geotectonic framework with regional seismological stud-

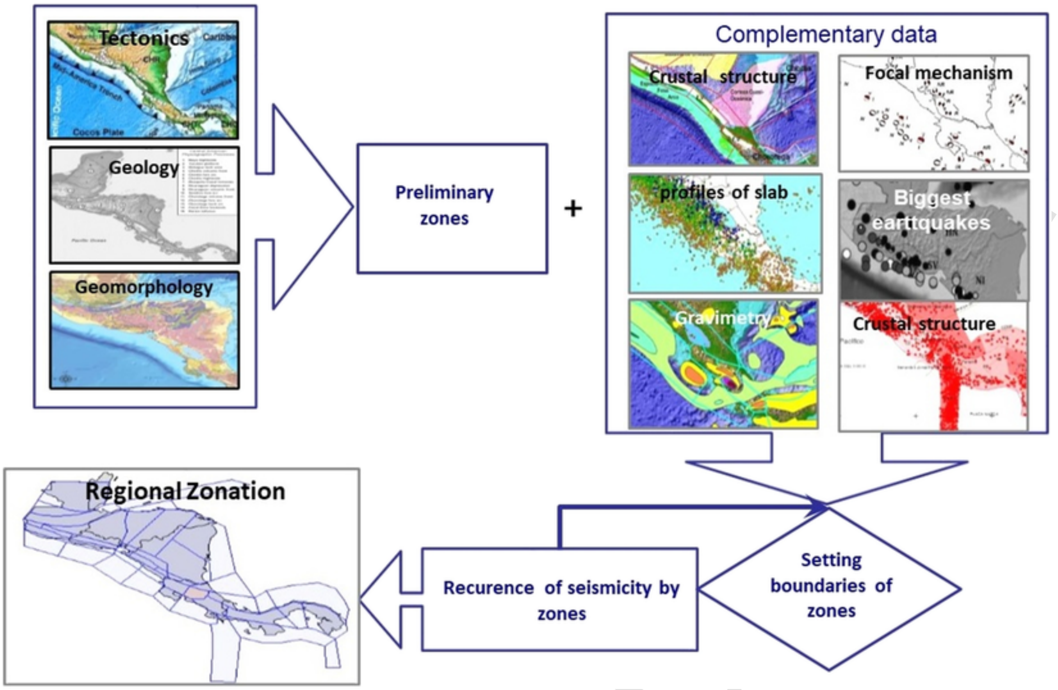

Fig. 2. Flowchart of the maps and kind of data used for definition of the zones model.

ies (e.g. Rojas et al., 1993a,b,c; Güendel and Protti, 1998; Montero, 1999b; Fernández et al., 2007), and focal mechanisms (Dziewonski et al., 1981; Güendel and Protti, 1998; Montero, 1999b; Fernández et al., 2007; Mann et al., 2007; Camacho et al., 2010). For the geophysical studies, we use crustal structure studies (Flueh and von Huene, 2007; Mann et al., 2007; MacKenzie et al., 2008; Dzierma et al., 2010; Linkimer et al., 2010; Hayes et al., 2013), including gravimetric maps (Weyl, 1980; Cuevas et al., 2003; Lücke et al., 2010).

The seismicity of Central America has been studied, by several researchers, by Molnar and Sykes (1969), Burbach et al. (1984), White and Harlow (1993), Protti et al. (1994), Rojas et al. (1993a), Ambraseys and Adams (2001), LaFemina et al. (2002), Camacho et al. (2010), among several others. The installation of seismic digital networks in all the countries of Central America, during the last three decades, has greatly improved the quality of the seismic catalogs and focal mechanisms estimations (Fernández et al., 2004). Earthquake distribution of the events with Mw > 5.0 are shown in Fig. 3a. Fig. 3b, c and d show the focal mechanisms with depths $h \leq 20$ km, 20 km $< h \leq 40$ km and $h \geq 40$ km, respectively. As a Supplementary material, Fig. S2 shows the focal mechanisms of events with Mw > 5.0 separated by type: strike-slip, reverse and normal.

During the last 500 years, several crustal, and subduction (interplate and inslab) destructive earthquakes have occurred, with moderate to high magnitudes (5.5 < Mw < 8.1) in Central America. However, the historic record of earthquakes is poor and incomplete prior to the 18th century. The record notably improves in the 19th century when the reports increased, creating a more complete knowledge of historic earthquakes for this small region (Peraldo and Montero, 1999; Fernández et al., 2007).

A new seismic zonation proposed for Central America is described in next section, including the general modelling of the three major seismic regimens along the Caribbean plate and its plate boundaries, including the depth variation in the crust and slabs (Fig. 4).

4. The proposed new seismic zones

A careful analysis of the seismotectonic features and seismicity linked to the plate boundaries, in particular the Caribbean plate, has been done in order to generate criteria for the definition of the new seismic zonation model, besides the others consideration indicated above. The tectonic and seismologic framework has been fundamental for this seismic zonation. Taking these elements into account a regional area sources zonation is proposed from which, each country can be divided into subzones within major seismic zone boundaries. In several cases, there are overlaps between different geotectonic features.

The seismic zones were classified in the two main seismological groups: a) Zones associated with crustal faulting, including local faults, major fracture zones of plate boundary limits, and thrust fault of deformed belts, mostly occurring in the broad area around and in the volcanic front, but in general in the continental crust, or at shallow seismicity in the incoming oceanic plate. b) Zones associated with subduction seismic sources, including interplate and intraplate (inslab). Interplate seismicity is associated to the seismogenic zone of the slab interface, and inslab seismicity occurs into the subducted oceanic plate, at intermediate-depth.

4.1. The subduction seismic zones

The interaction of the Coco plate with the continental plates of North America and Caribbean generated a subduction megathrust fault, which is seismically defined by the Wadati-Benioff zone. The MAT is an oceanic depression in the eastern Pacific Ocean (2750 km long and 6669 m at its deepest point), which marks the beginning of the subduction zone, extending from western Mexico to the Panama fracture zone (Fisher, 1961).

The historic seismicity at the Central American subduction zone has been well documented. In the 20th Century, about 51 large earthquakes (6.0–7.8 Mw) originated in this zone (White et al., 2004; Ambraseys and Adams, 2001; Benito et al., 2009). The subduction zone has been the main source (93%) of the total moment release for

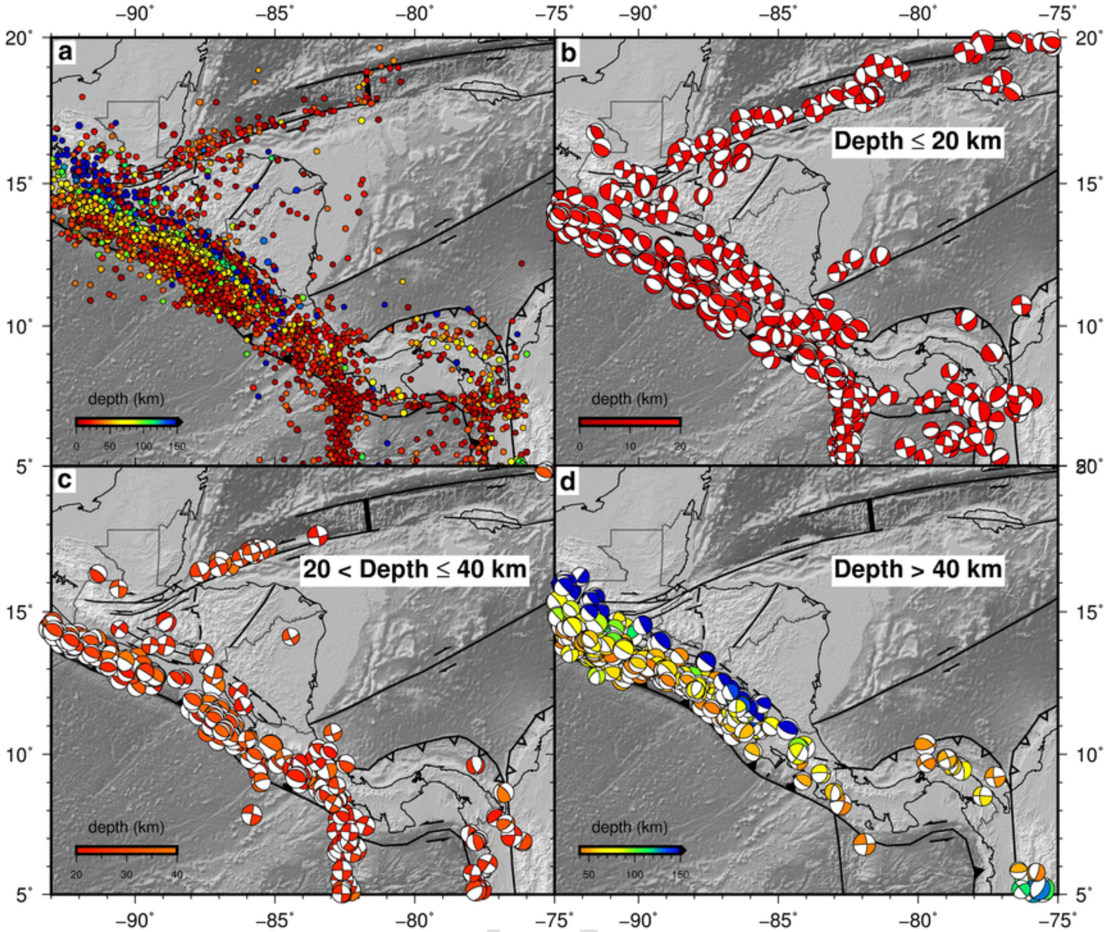

Fig. 3. a) Earthquakes distribution Mw > 5 in Central America for 1522–2011 period (Benito et al., 2012). b) Focal mechanisms of Central America events with Mw > 5.0 and depth ≤ 20 km from 1976 to 2011 (Global CMT). c) Focal mechanisms of Central America events with Mw > 5.0 and 20 ≤ depth ≤ 40 km from 1976 to 2011 (Global CMT). d) Focal mechanisms of Central America events with Mw > 5.0 and depth > 40 km from 1976 to 2011 (Global CMT). Dark lines indicate plate tectonic boundaries and main tectonics structures.

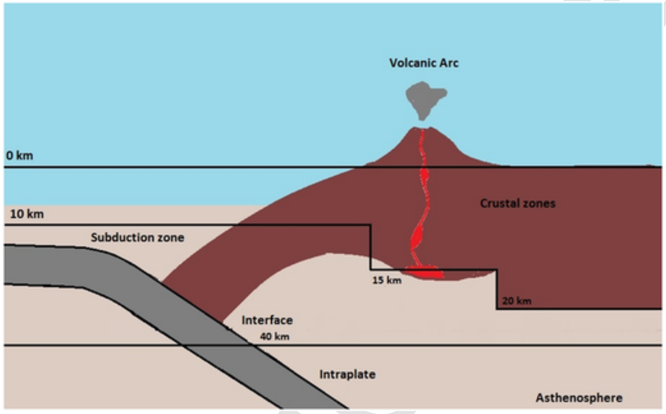

Fig. 4. Scheme of tectonic regimes in Central America.

Mw > 7.0 shallow earthquakes in Central America during the period 1895–1995 (Ambraseys and Adams, 2001). Data suggest that earthquakes no greater than Mw 8.1 occur in this region, however, 500 years is not long enough to rule out the occurrence of such events in the region. The relative lower level of destructive earthquakes in Central America is probably due to poor coupling, and to the segmentation of the subduction zone. However, Schellart and Rawlinson (2013) proposed the probability of a giant earthquake (Mw > 8.5) with an epicenter in southeast Costa Rica, where the Coco Range subducts (deviatoric compression), with unilateral rupture propagation towards the Nicaragua subduction segment in the northwest with low or tensional deviatoric normal stresses on the interface. Something similar is proposed by Rong et al. (2014).

The subducted plate could be subdivided into subzones based on seismicity, focal mechanisms, geophysics studies, strike variations on the MAT line, depth geometry of the Wadati- Benioff zone, and undersea morphology of the Coco oceanic plate. Fig. 5a, b and c shows the morphology and depth distribution of the subduction, based on Hayes et al. (2012). Thus, the MAT could be divided in segments of 100–300 km in length, which have different strike variations, morphology and seismicity, but also different recurrence periods (Burbach et al., 1984; Güendel and Protti, 1998; White et al., 2004). The seismicity related to the subduction is deepest in Guatemala, where earthquakes have occurred as deep as 250 km, and shallow earthquakes that only reach depth of 70 km in the southern part of Costa Rica, because the subduction of the Coco volcanic range (Rojas et al., 1993a,b,c; Protti et al., 1994; Sallarès et al., 2000; Lücke and Arroyo, 2015).

The seismicity of the subducted slab into the mantle, can be divided into three major segments: a) the aseismic front or aseismic stable zone, b) the seismogenic zone of the interplate region, also known as interfase seismogenic zone, and c) the subducting slab (inslab).

Although the aseismic front is considered stable for large earthquakes (Dixon and Moore, 2007), as in other regions, there is shallow complex seismicity (thrust, normal and strike-slip faults) before and after the oceanic plate arrives to the trench (Fig. S2). Some thrust earth-

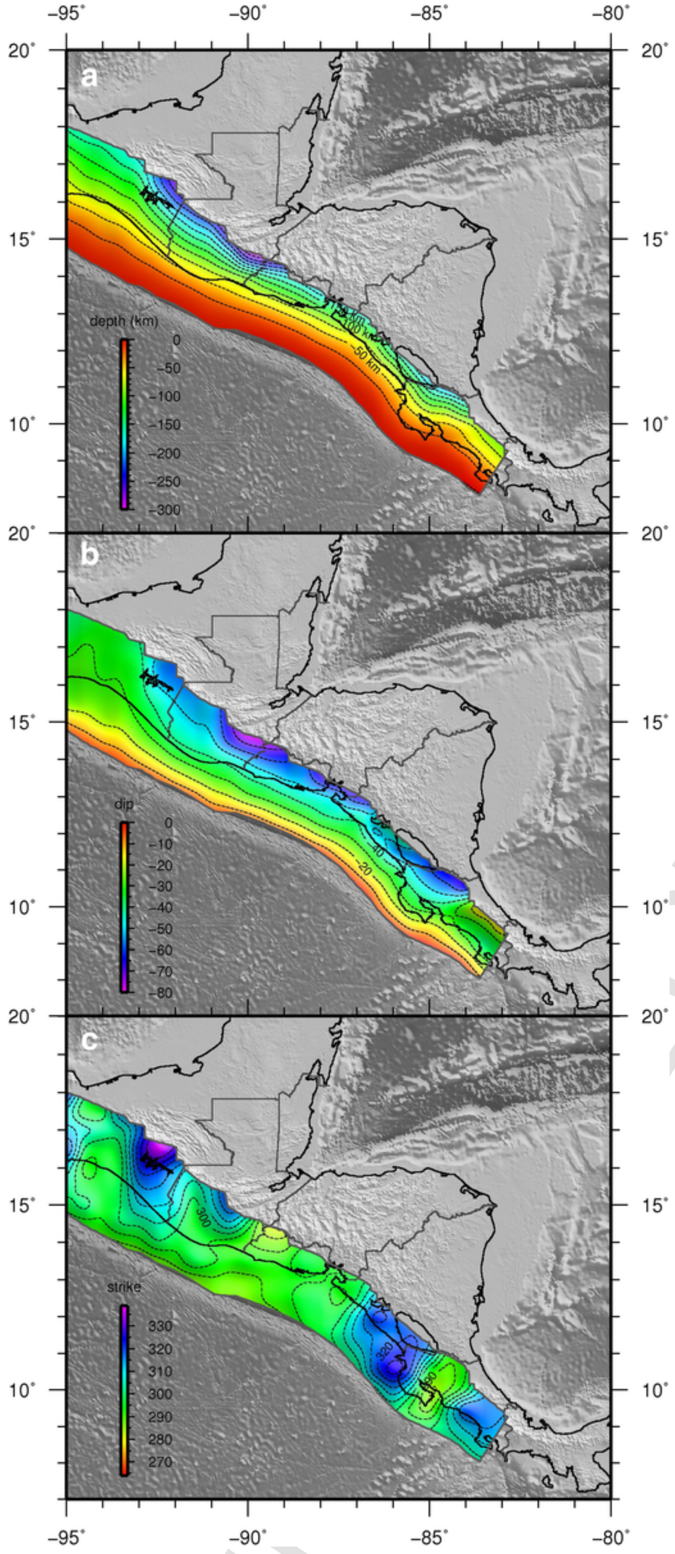

Fig. 5. Morphology and depth distribution of the Central America subduction slab (Hayes et al., 2012). a) Depth distribution along the subduction. b) Dip distribution. c) Strike distribution.

quakes are related to oceanic plate bending and, in the first 10 km from the trench in a landward direction, there are horst and grabens structures in the outer rise (De Shon et al., 2003; Hansen et al., 2006; Bird et al., 2009). The random seismicity in this zone has been exclude from the Wadatti-Benioff zone and included in the crustal zonation.

The shallow, and intermediate depth seismicity was associated to the corresponding zones in order to obtain the recurrence laws and the seismic parameters of each one. However, taking into account the change of subduction angle along the MAT (Fig. 5b), the depth ranges related with the two tectonic regimes vary. In addition, the seismicity has been adjusted, particularly in subduction zones, because some earthquakes with depth and focal mechanism consistent with the interplate or inslab zones project their epicenters outside of the boundaries of these zones. These earthquakes have been included in the respective zones for calculations, considering the present errors in the epicenter location.

4.1.1. The seismic zones related to the subduction seismogenic zone of the interplate region

The subduction seismogenic zone can be defined as the seismic active portion of the subduction thrust fault interface, between subducting and overriding lithospheric plates. The interplate seismogenic zone has been very well define in Costa Rica, and part of South Nicaragua, though several local marine studies (OBS: ocean bottom seismic stations), and terrestrial seismic networks, which generated very high quality data. Normally, the interplate seismogenic zone could extend in depth, where the oceanic plate intersects the continental Moho, about 70 km inland from the MAT. Most of seismicity is restricted to a depth between 10 and 50 km (De Shon et al., 2003, 2006; Husen et al., 2003; Schwartz and De Shon, 2007; Arroyo et al., 2009). Nevertheless, we noticed that the seismologic precision of the interplate seismicity is not the same in the Central America catalog.

From 1898 to 2015, 35 Mw ≥ 7.0 earthquakes occurred off the Pacific coast of Central America (Fig. 6). Some of these: 1942 (MW 7.7) in Guatemala, 1915 (Mw 7.7) in El Salvador, 1992 (Mw 7.6) in Nicaragua, 2012 (Mw 7.6) in Costa Rica earthquakes (Fig. 6). White et al. (2004) have proposed that for the Chiapas-Guatemala-El Salvador subduction zone segment recurrence periods for events 7.5 < Mw < 8.0 are 155–169 ± 10 years in Chiapas, 94 ± 54 years for Guatemala and 71 ± 17 years in El Salvador. A recurrence time for large events (Mw ≥ 7.0) in Costa Rica is of about 40–50 years (Montero, 1986; Adamek et al., 1987). The normal and strike-slip focal mechanisms are predominant for the shallow earthquakes (< 50 km depth). From the trench towards land, the focal mechanisms are generally normal in the first ~ 10 km, while thrust events are more frequent between depths of ~ 15 and ~ 50 km (Güendel and Protti, 1998; Warren et al., 2008).

The area sources defined for this seismic zone have been identified as Gsi9, Ssi5, Nsi15, Nsi16, Csi11, Csi12, Csi13, Psi9, Psi10 y Psi11 and showed in Fig. 7a.

The criteria for selection included the depth range and the thrust type focal mechanism for each of the interface zones. In the cases where these two conditions were not satisfied, the focal mechanism was preferred. Three depth ranges are defined in the interface zones (Fig. 7a): (1) $10 < h \leq 40$ km in the interface zones of Guatemala, El Salvador, Nicaragua and Costa Rica (Gsi9, Ssi5, Nsi15, Nsi16, Csi11, Csi12 and Csi13 zones), (2) $20 \leq h \leq 40$ km in the SPDB (south of Panama) where the Nazca plate converges in an oblique sense and with a very shallow dip angle below the Panama block (Psi9 zone), and (3) $20 < h \leq 100$ km, corresponding with northeast of Panama and northwest of Colombia (Psi10 and Psi11 zones). In this zone, the seismicity is part of the subduction associated with the Panama microplate convergence with Caribbean plate and South American plate (North Andean block). Most of the events in this zone have depths > 40 km (Camacho et al., 2010).

Fig. 7b show the seismicity associated to the interface zones, the limits of the interface zones (bold lines) and the limits of extended

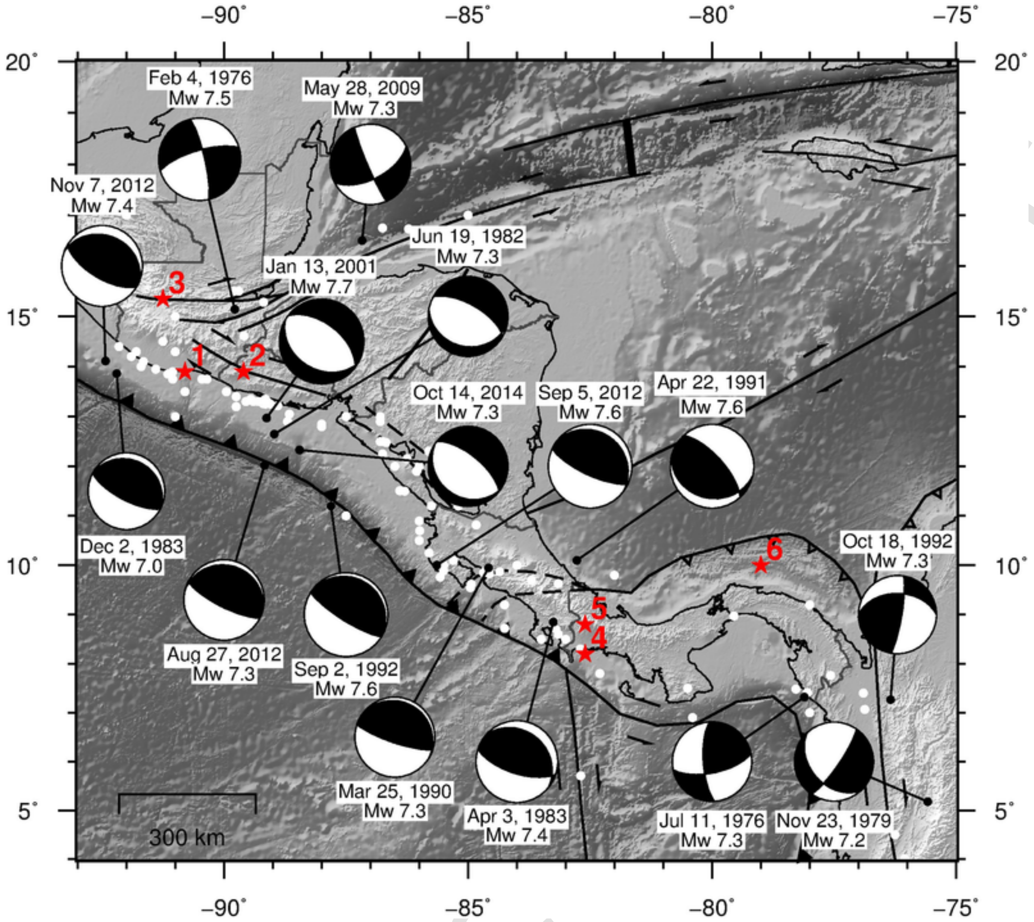

Fig. 6. Earthquakes distribution (white dots) and focal mechanism of Mw ≥ 7 events in Central America for 1522–2014 period. Red stars show the epicenters of main historical earthquakes cited in the text: 1 – Guatemala 1942 Mw 7.7 earthquake, 2 – El Salvador 1915 Mw 7.7 earthquake, 3 – Guatemala 1816 Mw 7.5 earthquake, 4 – Panama (Gulf of Chiriquí) 1934 Mw 7.5 earthquake, 5 – Western Panama 1945 Mw 7.1 earthquake, 6 – Northern Panama 1882 Mw 7.9 earthquake. Dark lines indicate plate tectonic boundaries and main tectonics structures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

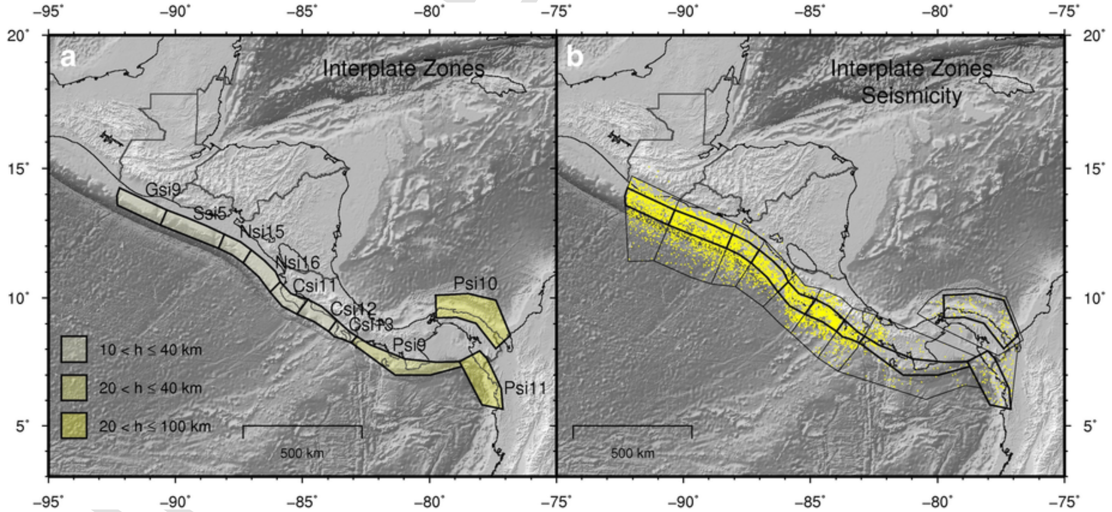

Fig. 7. Interplate seismogenic zones. a) Interplate zones with the depth ranges: (1) 10 < h ≤ 40 km in the interfase zones of Guatemala, El Salvador, Nicaragua and Costa Rica (Gsi9, Ssi5, Nsi15, Nsi16, Csi11, Csi12 and Csi13 zones), (2) 20 ≤ h ≤ 40 km in the SPDB (south of Panama) where the Nazca plate converges in an oblique sense and with a very shallow dip angle below the Panama block (Psi9 zone) and (3) 20 < h ≤ 100 km, corresponding with northeast of Panama and northwest of Colombia (Psi10 and Psi11 zones). b) Seismicity associated to the interplate zones, with limits of the interplate zones (in bold line) and limits of the extended zones (thin line).

zones (thin lines) considered to covering the irregular or poorly localized seismicity.

4.1.2. The subducting slab (inslab)

Most of the seismicity in the subducting slab is deeper than 40 km and < 280 km, where the slab subducts with an angle of 60–65°. Between 35 and 85 km depth, Warren et al. (2008) observed both subhorizontal and subvertical fault planes. The subvertical fault planes are consistent with the reactivation of outer rise faults, whereas the subhorizontal fault planes suggest the formation of new faults. Deeper than 85 km, only subhorizontal faults are present, indicating that the outer rise faults are no longer being reactivated. Between 35 and 100 km depth the focal mechanisms are both, normal and thrust fault movement (Güendel and Protti, 1998; Warren et al., 2008). The 2001 (Mw 7.7), 2012 and 2014 (Mw 7.3) earthquakes off the coast of El Salvador (Fig. 6), show similar normal faulting in the subduction zone (Vallée et al., 2003; Geirsson et al., 2015).

The seismicity gets deeper, particularly in Nicaragua. In the north part of Costa Rica, the intermediate seismicity ranges between 50 and 200 km with the slab dipping at 65° to the NE. There is no record of a major earthquake in this zone, but from its dimensions, the maximum event could be Mw 7.5. In the central part of Costa Rica, the inslab earthquakes are between 50 and 125 km in depth. In the southern part, the Coco Cordillera subducts below the Panama microplate, seismically active no deeper than 70 km depth (Lücke and Arroyo, 2015). Due to the characteristics of this zone it could generate an event on the order of Mw 7.4.

The seismic zones are defined from the lower boundary of subduction interface which marks the beginning of the inslab subduction. The inslab zones are defined with h > 40 km (Fig. 8a): Gsp10, Ssp6, Nsp17, Csp14, Csp15, Csp16 and Psp11 zones. In this case, the events with a depth larger than 40 km, as well as with a normal focal mechanism have been assigned to the inslab subduction zones. Fig. 8b shows the seismicity associated with these zones. As in the case of interplate subduction, the boundaries of the inslab zones (bold line) are extended (thin line) to cover the events which do not satisfy the depth and focal mechanism requirements.

4.2. The shallow crustal seismic zones related with plate boundaries

Shallow seismic zones are related to plate boundaries. Some are defined in or near the boundary plates of North American and Caribbean, Coco and Nazca, Caribbean and Nazca and Caribbean and South American, but mainly related with the shallow seismicity in the Caribbean plate itself, as those that were defined in the space between the MAT and the Central America Volcanic Front (CAVF), the CAVF, the back of the CAVF or in the Panama Microplate.

The traditional division of the tectonic boundaries of a convergent arc (Dickinson, 1974), does not completely fit in Central America. For example, the active volcanic range and the back-arc in Costa Rica are a "textbook" example, but the back-arc basin in Costa Rica is an extension of the Nicaraguan graben, where the volcanic front grows inside the graben. This makes it difficult to define the seismic zones. In any case, both regions present a shallow crustal seismicity.

Crustal zones include earthquakes with shallow depths (h ≤ 20 km). In the volcanic arc a maximum depth of 15 km is established. Three depth ranges are defined (Fig. 9a): (1) up to h = 10 km, cortical zones that cover the subduction zone, along the MAT and south of Panama (G1, S1, N1, N2-C1, C2, C3, C4, P2 and P3 zones), (2) up to h = 15 km, zones over the volcanic arc, forearc and Panama (G3, G2-S2, G4, S3, N3, N4, S4-N5, N6-N7, N8, N9–10, P5, P6 and P7 zones) and (3) up to h = 20 km, zones inland corresponding to Guatemala, Honduras, Nicaragua, Panama fracture zone and north of Panama (G5-S5-H1, G6, G7, G8, G9, H2, H3-N11, H4, N12, N13-N14, C5, C6, C7, C9, C10, P1, P10-C8, and P8 zones). The seismicity associated with these seismic sources is shown in Fig. 9b.

A brief description of the main tectonic features and geological zones are included in the area sources defined is presented below.

4.2.1. The North American-Caribbean plate boundary

The Maya and Chortis blocks meet onshore along the E-W strike, Chixoy-Polochic, Motagua and Jocotán-Chamalecón system, which are sub-parallel, left-lateral strike-slip faults that form the principal elements of the Caribbean-North America plate boundary, called the Polochic-Motogua Faults System (PMFS). PMFS extends offshore in the Caribbean Sea by the Swan Fault (SF) and the Cayman Trough (Fig. 1).

Onshore, faults in this plate boundary are more commonly exposed in Cretaceous and older rocks than the Neogene volcanic rocks, suggesting that slip mostly occurred before 30 Ma (Plafker, 1976; Mann et al., 1990). However, the western extension of PMFS in Chiapas, Mexico forms the triple junction (Caribbean-North American-Coco), but seems to divide in two branches, which are latter parallel to the pacific coast. It becomes diffuse and propagates to the northwest into the strike slip

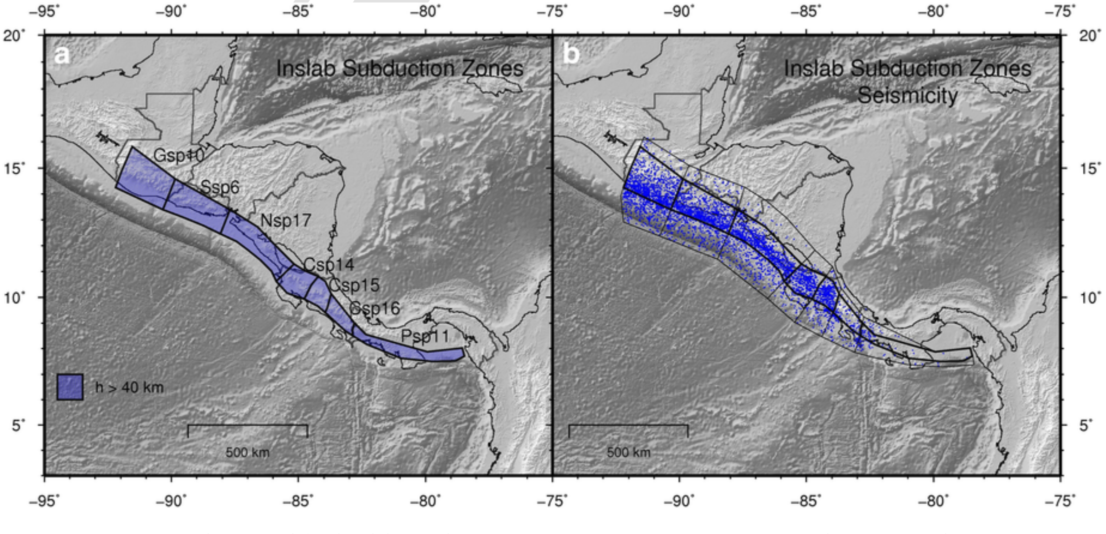

Fig. 8. Intraplate seismogenic zones. a) Intraplate zones defined with h > 40 km (Gsp10, Ssp6, Nsp17, Csp14, Csp15, Csp16 and Psp11 zones). b) Seismicity associated to the intraplate zones, with limits of the intraplate zones (in bold line) and limits of the extended zones (thin line).

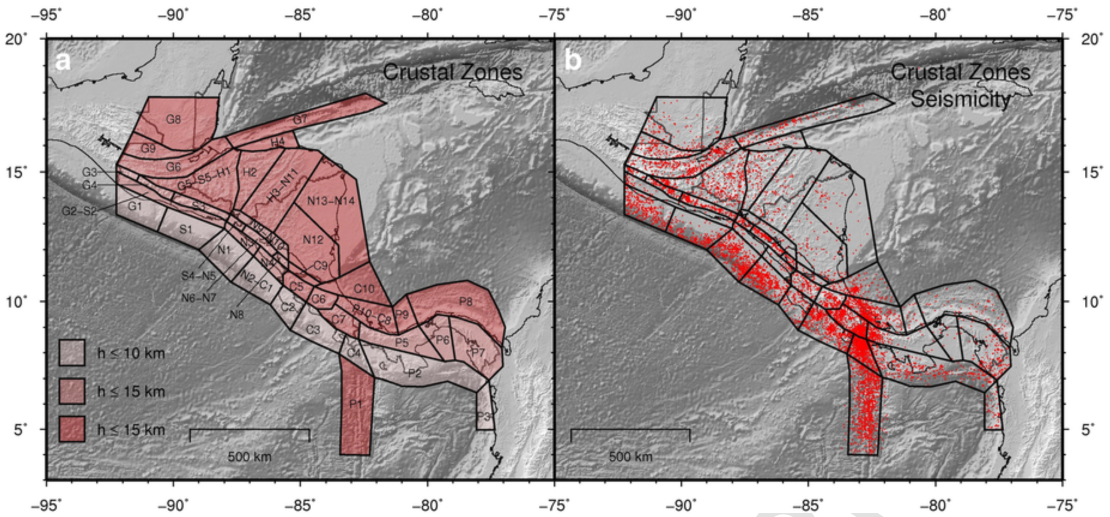

Fig. 9. Crustal seismogenic zones. a) Crustal zones (in bold line) with the depth ranges: (1) h = 10 km, cortical zones that cover the subduction zone, along the MAT (G1, S1, N1, N2-C1, C2, C3, C4, P2 and P3 zones); (2) up to h = 15 km, zones over the volcanic arc, forearc and Panama (G3, G2-S2, G4, S3, N3, N4, S4-N5, N6-N7, N8, N9–10, P5, P6 and P7 zones) and (3) up to h = 20 km, zones inland corresponding to Guatemala, Honduras, Nicaragua, Panama fracture zone and north of Panama (G5-S5-H1, G6, G7, G8, G9, H2, H3-N11, H4, N12, N13-N14, C5, C6, C7, C9, C10, P1, P10-C8, and P8 zones). b) Seismicity associated to the crustal zones (in bold line).

faults and fold belt of the Sierra de Chiapas (Burkart, 1978; Manea et al., 2013).

An earthquake in 1816 (White, 1985; Peraldo and Montero, 1999), which seriously damaged buildings in many towns, has been suggested to have occurred in the western end of the PMFS (Fig. 6). Reconstructions of isoseismic patterns have been used to infer a probable rupture length of 340 km and Mw 7.5–7.75. This fault ruptured during the 1976 (Mw 7.5) Guatemala earthquake (Fig. 6), with an average horizontal offset of 1 m left-lateral strike (Espinosa, 1976; Plafker, 1976; White, 1991). In Guatemala, the PMFS shows evidence of late Quaternary activity with slip-rate estimates ranging from > 7 mm/yr in eastern Guatemala, and 6–20 mm/yr during the last 6 ka in Central Guatemala (Schwartz et al., 1979; White, 1991). This data suggested an average recurrence interval of 225 ± 50 years between major fault ruptures within the Caribbean-North American plate boundary intervals for events with magnitude Mw > 7.3. GPS measurements along this fault system show that the relative displacement between the North American and the Caribbean plate is 1.7 cm/yr in its eastern segment (Lyon-Caen et al., 2006; Franco et al., 2012).

4.2.2. *The Coco and Nazca plate boundary*

The Panama Fracture Zone (PFZ) (Fig. 1), is a dextral slip N—S striking oceanic transform fault zone and constitutes the plate boundary between the Coco and Nazca plates. The PFZ is located between 82° and 83°W and extends from near the equator up to 6° N, where it splits into a series of parallel north-west trending dextral strike slip faults (comprising the Panama, Balboa and Coiba faults). which subduct near 7.3°N, at the Panama trench, obliquely with a 20° angle. The Panama Triple Junction (Coco-Nazca-Caribbean) (PTJ Fig. 1) is the point that abruptly separates the thick and rapidly subducting Coco plate to the northwest from the thin and obliquely subducting Nazca plate to the southeast along the Central American convergent margin. The Coco volcanic range is cut on its eastern edge by the PFZ; this configuration results in a ~ 2 km bathymetric step between the two plates (Adamek et al., 1988; Silver et al., 1990; Camacho, 1991).

The seismicity in this zone is shallow (< 20 km depths) with right lateral focal mechanism (Pennington, 1981; Wolters, 1986; Adamek et al., 1988; Camacho, 1991). At the northern terminus of the PFZ there have been large earthquakes (Mw > 7.0) in 1879, 1927, 1934 y 1962. The 1934 (Mw 7.5) earthquake, with epicenter in the Gulf of Chiriquí (Fig. 6), is the largest Panamanian event recorded instrumentally. Between June 2002 and January 2005, this region was shaken by four shallow depth earthquakes (< 15 km) with Mw > 6.0, located in the Caribbean plate along north-south strike-slip faulting, which caused destruction along the Panama-Costa Rica border region. Fault-plane solutions reveal right lateral strike-slip movement, but some earthquakes depths are shallow and could be associated with local faulting.

4.2.3. *The Caribbean-Nazca plate boundary*

The Caribbean-Nazca plate boundary extends south of the Isthmus of Panama bordering its Pacific continental margin, along the Panama trench. It defines a complex system called the Southern Panama Deformed Belt (SPDB) (Fig. 1). The Nazca plate converges in an oblique manner (N71°E) with a very shallow dip angle of 20° below the Panama microblock reaching a depth of 20 km. Two thrust type events (Mw > 6.0) occurred in the Gulf of Chiriquí, East of Burica peninsula, in December 2014. In Western Panama the inslab earthquakes occur between 20 and 80 km (Pennington, 1981; Moore et al., 1985; Heil and Silver, 1987; Silver et al., 1990; Camacho and Víquez, 1993). A Mw 7.1 and 80 km deep event occurred near David, western Panama on 1945 (Fig. 6) (Cowan et al., 1997; Camacho et al., 1997). The largest earthquakes ever recorded in this zone occurred in 1904 and 1941 (both Mw 7.4), south of the Gulf of Panama, and have a thrust type focal mechanism (Selva and Marzocchi, 2004). North and parallel to the Panama trench, the Southern Panama fault zone extends offshore as a left strike slip fault, which south of Azuero peninsula splays into to two branches; one continues parallel to the coast and the other continues onshore with a NW-SE strike, traversing the Azuero and Soná peninsulas (ASP Fig. 1) as a wide left lateral deformation zone (Hardy et al., 1990). The largest event in the Soná-Azuero fault zone occurred in 1913 (Mw 7.0) and caused widespread damage in the Azuero peninsula (Víquez and Camacho, 1993b). Due to the length of these faults and their characteristics, this zone could generate events on the order of Mw 7.5.

4.2.4. *The Caribbean-South American plate boundary*

The eastern portion of Panama and northwestern portion of Colombia comprises a diffuse zone, called the Atrato Suture Zone (ASZ), associated to the convergence of the Panama microplate and the South American plate (SOAM Plate) (Fig. 1). In this zone, E-W compression has caused diffuse and complex faulting along NW-SE trending strike slip faults (Pennington, 1981; Adamek et al., 1988). A main feature is the left lateral Atrato fault, which extends along the western flank of the Colombian Western Andes to the Uraba Gulf (UG) in the Caribbean. This fault is considered as the boundary between the Panama microplate and the North Andean block (Duque-Caro, 1990) and for some authors the Caribbean-South American plate boundary (i.e. Vargas and Mann, 2013).

In eastern Panama and northwestern Colombia, earthquakes are deeper than 33 km and are related to the diffuse convergence between the Panama microplate and the South American plate. The 1992 Murindo earthquake (Mw 7.3) (Fig. 2), with a right lateral focal mechanism with a strong thrust component and a thrust foreshock, appears to be related to this diffuse boundary. A strong event originated in this fault zone in 1883 (Toussaint et al., 1987).

4.3. The intraplate seismicity in the Caribbean plate

The Caribbean plate is limited in the north by the PMFS, in the western portion by the MAT, and in the eastern part by the South American plate. The shallow seismicity (< 40 km) seems to be related to intracrustal source processes and takes place in some spots of activity located in the upper crust related to active faults. The western part of the Caribbean plate is affected by internal tectonic deformation (faulting, folding) including E-W extension through the grabens and strike slip faults in the Central American Volcanic Front (CAVF). Several tectonic models have been proposed to explain the structures at the interior of the Caribbean plate (Mann et al., 2007; Álvarez-Gómez et al., 2008; DeMets et al., 2010). All of them assume that the local stress fields are the product of differential displacement cause by the interplate interaction of the North American and Caribbean plates (Guzmán-Speziale et al., 2005; Cáceres et al., 2005; Lyon-Caen et al., 2006; Franco et al., 2012; Staller et al., 2016).

4.3.1. The space between the Middle America Trench and the Central America Volcanic Front

Between the MAT and the CAVF exist offshore basins and tectonic depressions on the continent, which shows faulting subparallel to the trench and defines the fore-arc basins. There are no records of a significant earthquake in historical times from Nicaragua to Guatemala, but some evidence of recent faulting has been detected. In Costa Rica, however, there are some events that appear to be related to major active faults that generated earthquakes of Mw 6.5 to 7.0 (Adamek et al., 1987; Cowan et al., 1997; Montero and Denyer, 2011).

On the Nicaraguan part of the CAVF exists a series of NW-SE elongated grabens and faults subparallel to the trend of the MAT, called the Nicaraguan depression (ND), which extends for approximately 600 km from the northern of Fonseca Gulf (FG) in El Salvador to the Caribbean coast of Costa Rica. This tectonic feature continues in El Salvador as a series of en-echelon Plio–Pleistocene basins. The trough widens from 35 to 40 km in El Salvador to about 75 km in southern Nicaragua. This is an atypical backarc basin in that the depression commonly encompasses the entire active volcanic chain rather than occurring only in a back-arc position (Mann et al., 2007). Molnar and Sykes (1969) and White and Harlow (1993) interpreted earthquake focal mechanisms as dextral slip on trench-parallel faults such as those along the depression. This region also contains important strike-slip faults perpendicular to the graben as Tizcapa and perpendicular ones as Mateare. The NE-SW Tizcapa fault caused the very destructive 1972, Managua earthquake (Mw 6.5) event that killed thousands of people (Mann et al., 1990).

Geodetic studies (e.g. Correa-Mora et al., 2009; LaFemina et al., 2009; Franco et al., 2012; Kobayashi et al., 2014; Staller et al., 2016) indicate northwest motion of the CAFA at 11–17 mm/yr (Fig. 1), which is accommodated by shallow destructive earthquakes along the Central America volcanic arc.

4.3.2. The Central America Volcanic Front

The CAVF extends from the Tacaná volcano in the Mexico-Guatemala border to Irazú-Turrialba volcano system in Costa Rica. In Central America, the population, economic activities, and facilities are concentrated along the CAVF, where the seismic risk is the highest of the region. Between 1900 and 2011, 35 destructive earthquakes have occurred in this region with a magnitude range between Mw 5.7 and Mw 6.9 (White and Harlow, 1993). In spite of their relatively low magnitude, the strong earthquakes that happen at the CAVF are almost always disastrous, because they occur at shallow depths and near population centers. The largest cities of the region are located along this volcanic axis, in valleys covered by volcanic deposits and cut by active faults. Several faults cross the capital cities of San Salvador, Managua, and surround San José and Panamá City. .

The faults of the CAVF strike in three major directions (NE-SW, NW-SE, and N-S) with most of the active faults with relatively short lengths (≤ 30 km). Focal mechanisms in the highlands of western Panama are left lateral slip, striking ENE-WSW and right lateral slip, striking NW-SE. Focal mechanisms in central Costa Rica indicate strike-slip faulting on steeply dipping nodal planes, either ENE-WSW left-lateral or NW-SE right-lateral, similar to mechanisms described from the volcanic chain in El Salvador. Earthquakes as low as Mw 5.7, have been felt with maximum intensities of VIII MM. In Guatemala, during the XX century, at least five events generated intensities MM $\geq$ VII; the largest (Mw 6.9), occurred in 1930, but the ones that caused the most damage were five earthquakes ($5.1 \leq$ Mw ≤ 6.2), between December 1917 and January 1918 (White and Harlow, 1993; Ambraseys and Adams, 2001). The historic recurrence time for these very shallow earthquakes is of 30 years for El Salvador, with the largest (Mw 6.8) occurred in 1854 (Harlow et al., 1993). The most recent destructive earthquake in this region was a shallow right lateral strike-slip event on February 13, 2001 (Mw 6.6), 30 km east of San Salvador (Bommer et al., 2002).

In Nicaragua, the style of faulting associated with historic earthquakes is similar to that of El Salvador. Destructive earthquakes near Managua occurred in 1931, two in 1951 (Mw 5.8) and the most destructive one in 1972 (Mw 6.0) (Brown et al., 1974).

The cities of San José and Cartago in Costa Rica have suffered moderate crustal earthquakes in 1841 and twice in 1910. Other towns in the Central Valley have suffered similar events in 1852, 1988, 1911, 1912, 1952, 1955 and 2009. A Mw 6.3 earthquake occurred in northwestern Costa Rica in 1973, but the historic catalog since the 1600′s indicates relatively low seismicity in northern Costa Rica.

4.3.3. The back of the Central America Volcanic Front

Behind the CAVF there are a series of lowlands (old rocks and alluvial plains) with relatively low seismicity. Rifting across the western Chortis block is attributed to regional extension in response to eastward movement of the Caribbean plate south of the arcuate PMFS (Dengo, 1985; Manton, 1987; Mann et al., 2007). Within the Honduras Depression (HD) most of the earthquakes are moderate (Mw 5–6.5). These include the earthquakes of 1774, 1809, 1820 and two closely spaced events in September and November of 1851, the latter being the largest of the Honduran events, and an event in 1982 (Osiecki, 1981; Peraldo and Montero, 1999).

Another important feature is the Guayape fault system (GF), in Honduras, which comprises a 2–20 km wide zone along 290 km long of predominantly left-lateral strike-slip faults that trend N30°E. The GF shows evidence of Holocene displacement near its northeastern end close to the Caribbean coast (Finch and Ritchie, 1991). The seismicity is a very low, but suggests that the July 27, 1990 earthquake (Mw 5.4) originated in this fault (Kozuch, 1991).

The flatlands of northern Costa Rica and the southern part of the Nicaraguan depression have sparse and sporadic seismicity, and the type of faulting is not well known. Some historical earthquakes are reported here in 1648, 1651 y 1663 (Peraldo and Montero, 1994). The maximum magnitude assigned to this zone is Mw 7.0. Earthquake nest east of the mouth of the Parismina River have depths between 15 and 30 km, a maximum magnitude of 5.1, but normally events below 4.2. The epicenters are roughly NE aligned, and composed focal mechanism suggested a sinistral strike slip fault (Brenes, 1992).

A very important "dormant" feature is the Hess escarpment, which is a prominent bathymetric NE-striking fault within the Colombian basin (Caribbean plate), which separates a region of extensional tectonics to the north from contraction tectonics to the south. It extends for > 1000 km from the Caribbean border of Nicaragua – Costa Rica to southern Cuba. Bowland (1993) suggested that the Hess escarpment is a Late Cretaceous to Early Paleogene strike-slip margin separating the Chortis block from the Caribbean oceanic plateau and inland Chorotega block to the south, and the major tectonic activity had largely ceased by Paleogene time. Although the Hess escarpment has been seismically quiet compared to other tectonic features, however, moderate activity has occurred near Nicaragua with sinistral fault-plane solutions and normal component. The contrasting pattern of active tectonic structure across this feature may therefore indicate a potential for infrequent but large earthquakes (Fernández et al., 2004).

4.3.4. The Panama microplate

The Panama microplate is limited in both oceans by the North and South Panamá deformed belt, but the continental portion of Panama seismic zone, from the point of view of the seismic zonation, no correspond exactly to the tectonic limits of the Panama microplate. It is limited to the north along the Caribbean coast with the North Panama Deformed Belt (NPDB), to the east with the Eastern Panama Deformed Belt (EPDB), to the South along the Pacific coast with the diffuse subduction zone in Panamá and the South Panama Deformed Belt (SPDB) (Case and Holcombe, 1980; Ponce and Case, 1987; Adamek et al., 1988; Silver et al., 1990; Camacho and Víquez, 1993; Morell, 2016). The western part coincides with a NE-SW gravimetric lineament and a diffuse faulting zone which traverses northern and central Costa Rica from the Caribbean to the Pacific (Montero, 2001; Marshall et al., 2000).

The NPDB extends offshore the Caribbean coast of Panama with an arcuate shape from the Panama-Colombia border northwestward to the shore northwest of Puerto Limón in Costa Rica. This overthrust fault system is originated from convergence between the Caribbean plate and the Panama microplate. Destructive earthquakes in Panama are less frequent than in most of Central America (Rojas et al., 1993a,b,c; Güendel and Protti, 1998), so it could be included in a single block for regional zonification, but for local zonation, it should be divided in several subzones. The seismicity at the eastern segment of the NPDB reaches depth of up to 80 km with a SW-dipping, based on local networks data and teleseismic waveforms of onshore and offshore earthquakes, suggested the existence of a Wadati-Benioff zone (Adamek et al., 1988; Camacho et al., 2010). On 1882 occurred the largest known earthquake in northern Panama (Fig. 6), 150–200 km northwest of Panama City. This earthquake, referred to as the San Blas earthquake, was located in a relatively active region of the NPDB. It had a calculated magnitude of Mw 7.9, a depth of 29 km, and approximately 100 people drowned in a tsunami generated by this offshore earthquake (Mendoza and Nishenko, 1989; Camacho and Víquez, 1993). The seismicity has been low during the instrumental period in the northwestern part of the NPDB, along the Caribbean coast of Costa Rica and western Panama. However, near a dozen of large earthquakes (Mw ~ 6.1–7.9) have occurred between 1798 and the most recently in 1991 (Camacho and Víquez, 1993). The 1991 Limón earthquake (Fig. 6) was shallow (ca. 14 km) and accompanied by thrust faulting on a 40 × 80 km fault dipping land award at about 30°. Uplift occurred along 70 km of the coastline between Puerto Limón (PL) and Bocas del Toro (BT) near the Panama-Costa Rica border. Analysis of older uplifted shorelines suggests a recurrence interval of 200–1100 years between similar events (Plafker and Ward, 1992). There is a tectonic gradation from a shallow subdution zone in the NPDB in the Caribbean site of Panama (Camacho et al., 2010) to a typical thrust fault system (thrust and fold beld) on the Caribbean site of Costa Rica, suggesting an incipient subduction zone in that area (Alvarado, 2016).

The western volcanic range of Panama is the continuation of the Central American volcanic arc, which is interrupted by the Cordillera de Talamanca. It extends from the Barú volcano, close of the Panama-Costa Rica border up to the El Valle volcano near the Panama Canal. Faulting in this zone and in Central Panama is predominantly NNW-SSE and SW-NE strike slip, running parallel and perpendicular to the volcanic arc. > 98% of the focal mechanisms in this zone are left lateral or right lateral strike slip, but some with normal and thrust components (Cowan et al., 1997; Rockwell et al., 2010). Seismicity in this zone is relatively low and historically has been shaken by an event in 1621, which caused building collapses and serious damages in Panama (Víquez and Camacho, 1993a). Based on the length of the Pedro Miguel-Limón fault system, a maximum magnitude for this zone is around Mw 7.2 (Rockwell et al., 2010).

The SPDB extends along the Panama trench up to the entrance of the Gulf of Panama. Here the Nazca plate subducts obliquely with a very low angle (< 20°) (Heil and Silver, 1987; Silver et al., 1990; McKay and Moore, 1990). Historically, this zone has been shaken by some strong thrust events (Mw > 6.5), as the 1904 and the 2014 earthquakes. In southern Panama, the Gulf of Chiriquí, offshore, and the Azuero and Soná peninsulas (ASP), onshore are crossed by a series of NNW-SSE parallel left lateral strike slip faults, and some of the focal mechanism of this region show normal or thrust components (Okaya and Ben-Avraham, 1987; Corrigan et al., 1990).

5. Seismic parameters of the zones

The geometry of the seismic zones were selected according to similar patterns of faulting, seismicity, and rupture mechanism inside each zone. For obtaining the recurrence law of each zone, a double truncated Gutenberg- Richter model has been adopted, for which the seismicity has been fit to the expression $\log N = a - b \bullet M_w$.

The seismic parameters for each zone were calculated from the seismic catalog of the RESIS II project (Benito et al., 2012). This catalog, homogenized to Mw and declustered of fore- and after-shocks and swarm seismic activity, is finally composed by 21,485 events in the magnitude range Mw 3.5 to 8.1, and focal depth up to 280 km. Later, the catalog was subdivided in three sub-catalogs, according to the depth ranges previously established (Fig. 4). The seismicity of the zones was modeled using a Poisson model. The completeness analysis was made according to the reference years showed in Table 1, year since we considered complete the catalog for each magnitud range or interval. We estimated the annual rate of events with $m \geq m_0$, $N(m_0)$, and the a and b parameters, using the maximum likelihood estimation (MLE) for characterizing the recurrence of each zone (Table 2). The minimum magnitude was set at 3.5 for the parameters adjustment, while a value of m0 = 4.5 was considering for the annual rate $N(m_0)$.

To account for the uncertainty in the maximum magnitude Mmax of each zone, we used a truncated Gaussian distribution defined as follows: M1 maximum historical earthquake (minimum value of Mmax),

Table 1
Reference years for different magnitude intervals derived from the completeness analysis.

Magnitude (M_w)	Reference year $h \leq 25$ km*	Reference year $h > 25$ km*
3.5–3.9	1984	1984
4.0–4.4	1976	1980
4.5–4.9	1971	1972
5.0–5.4	1957	1965
5.5–5.9	1932	1959
6.0–6.4	1865	1953
6.5–6.9	1745	1850
7.0–7.4	1732	1825
7.5–7.9	1522	1522
> 8.0	1522	1522

* h is the depth of the hypocenters.

M2 maximum potential magnitude based on tectonic criteria (maximum value of Mmax), and E(m), maximum magnitude expected, which corresponds to Mmax more likely.

Resulting parameters characterize the seismicity patron of each zone for each regime interface, inslab and crustal. These parameters are given in Table 2.

6. Discussion

We propose a new regional seismic zonation, based on the integration of all Central American available data: geological (tectonic, geological, geophysical and geomorphological maps), geodetic (current crustal deformation from GPS velocities) and seismological information (rate of seismicity, focal mechanisms, seismicity density, depth, magnitude). The limits between zones were drawn avoiding discontinuities at the national boundaries.

The zonation model proposed include crustal zones, interplate (interface) and intraplate (inslab) subduction zones, and considers similarities in the patterns of faulting, seismicity, and other parameters above indicated as the main factor for delimitation of the zones.

The crustal zones are related with the boundaries between North America, Caribe, Coco and Nazca plates, and the shallow seismicity in the Caribbean plate itself ($h < 20$ km).

The limits of subduction zones have been drawn considering the variation depth and angle along the trench. The subduction zone has been the main source (93%) of the total moment release for $Mw > 7.0$ earthquakes in Central America from 1895 to 1995 (Ambraseys and Adams, 2001). During the 500 years covered by the seismic catalog, there were no earthquakes with $Mw > 8.1$ in the region. The maximum historical earthquake is the event that happened on El Salvador in 1862 at depth of 40 km with Mw 8.1. However, this observation period is not long enough to rule out the occurrence of bigger events in the future. In fact, Schellart and Rawlinson (2013) and Rong et al. (2014) proposed the probability of a giant earthquake ($Mw > 8.5$) with an epicenter in southeast Costa Rica, where the Coco Range subducts.

In addition, recurrence models for each zone have been obtained (Table 2) using a seismic catalog unified to moment magnitude Mw compose by 21,485 events in the ranges of magnitude Mw 3.5 to 8.1 and focal depth up to 280 km; however, earthquakes with greater depth are considered. The seismicity of each zone was fit to a Gutenberg-Richter model truncated to a minimum magnitude m_0 4.5 (Mw) for establishing the annual rate of events with $m \geq m_0$, and the parameters a and b have been estimated together with the expected maximum magnitude Mmax. The range of variation for the b values obtained (Table 2) is coherent with the typical values found in other regions with similar tectonic regimes and previous studies (Benito et al., 2012).

7. Conclusions

As a global conclusion derived from the analysis of different kind of data described in this paper, a new zonation model for Central America has been proposed, considering the three tectonic regimes in the region. According this model, 41 zones have been identified for active crustal, 10 zones for interphase subduction and 7 zones for inslab subduction. The new zonation avoids discontinuities at the national boundaries and joins a consensus between the 7 countries of Central America, based on the cooperative work of specialists on seismology, seismic engineering and seismotectonics.

The Crustal zones have been identified including earthquakes with shallow depths, although this depth increases from the boundary of the subduction zone towards the mainland, with variations between 10 and 20 km. In the volcanic arc a maximum depth of 15 km is established. The seismicity parameters in this zones have a quite heterogeneous distribution, taking b-values in the ranges of 0.60 to 0.80 in Nicaragua and Guatemala volcanic arc to 1.35 in a crustal zone of El Salvador and Honduras, close to the boundary with Guatemala; and activity rate $N(m > 4.5)$ from 0.13 in Guatemala volcanic arc to 6.14 in the Panama fracture zone. The Mmax values are usually in the range 6.5–7, with some extreme cases where Mmax is 5.3 in the North Deformed Belt Central zone (P9) and 8.2 in the North Panama Deformed Belt North East (P8) both in Panama. For definition of the subduction zones, special attention was paid in the change of the dip angle along the Middle America Trench, which is bigger in Guatemala and minor in Costa Rica, arriving the depth of the earthquakes to 250 km in the first case and only to 70 km in the second. This fact involves variations in the depth of the zones along the trench.

The zones defined inside the interface subduction regime, were classified in three ranges of depth: (1) $10 < h \leq 40$ km in the interplate zones of Guatemala, El Salvador, Nicaragua and Costa Rica (2) $20 \leq h \leq 40$ km in the SPDB (south of Panama) where the Nazca plate converges in an oblique sense and with a very shallow dip angle below the Panama block and (3) $20 < h \leq 100$ km, corresponding with northeast of Panama and northwest of Colombia. The normal and strike-slip focal mechanisms are predominant for the shallower earthquakes (< 50 km depth). From the trench in a landward direction, the focal mechanisms are in general normal in the first ~ 10 km, while thrust events are more frequent between depths of ~ 15 and ~ 50 km. The seismicity parameters in interface take b-values in the ranges of b from 1.02 in Costa Rica (Csi12) to 0.41 in NW of Nicaragua; and N(4.5) from 1.28 in Psi10 zone of Panama to 12.24 in El Salvador, which presents the maximum value of Mmax, with 8.3.

The subduction intraplate or inslab zones are defined from the lower boundary of subduction interface. Most of the seismicity of these zones is deeper than ~ 40 km. The deepest subduction is in Guatemala, where earthquakes have occurred as deep as 250 km, but in the Southern part of Costa Rica, the MAT earthquakes reach only 70 km. The earthquakes are less destructive on the Central segment, probably due to poor coupling and weak continental crust, as is suggested by several researchers. The seismicity parameters in this group of zones have a quite heterogeneous distribution, taking values in the ranges of b from 0.65 in the intraplate of Guatemala and El Salvador to 1.1 in Costa Rica Central intraplate zone (Csp15); and N(4.5) from 0.63 in Panama South zone (Psp11) and 10.63 in Nicaragua (Nsp17). The values of Mmax are in the range of 7.3–7.7 in Nicaragua, Panama and several zones of Costa Rica, and 8.0–8.2 in Guatemala and El Salvador. The zonation proposed in this paper provides an up-date model which could serve to generate Probabilistic Seismic Hazard Analysis (PSHA)

Table 2
Seismic parameters for the seismogenic zones defined in this study within the three tectonic features: crustal, subduction interfase and subduction in-slab.

Country/Zone name	Code	Depth (km)	Maximum magnitude			Seismic parameters		
			E(M)[a]	M1[b]	M2[c]	a[d]	b[d]	N(Mmin)[e]
Crustal Seismicity								
Guatemala Pacific	G1	10	7.5	7.2	7.7	6.17	0.80	1.31
Guatemala-El Salvador forearc	G2_S2	15	6.7	6.4	6.9	4.68	0.69	0.27
Guatemala, Volcanic Arc W	G3	15	6.8	6.6	7.1	5.02	0.78	0.13
Guatemala, Volcanic Arc E	G4	15	6.8	6.5	7.0	5.79	0.81	0.52
Guatemala-El Salvador-Honduras, Central Depression	G5_S5_H1	20	7.5	7.2	7.7	6.51	0.87	1.35
Guatemala, Polochic-Motagua W	G6	20	7.8	7.5	8.0	6.41	0.79	1.49
Guatemala, Polochic-Motagua NE	G7	20	7.7	7.4	7.9	4.48	0.46	0.96
Guatemala, North (Peten-Belice)	G8	20	7.0	6.7	7.2	5.09	0.64	0.60
Guatemala North	G9	20	7.0	6.8	7.3	5.42	0.71	0.66
Honduras, Central Highlands	H2	20	6.7	6.4	6.9	4.86	0.64	0.68
Honduras-Nicaragua, Guayape fault system	H3_N11	20	6.2	5.9	6.4	4.09	0.53	0.65
North Coast Honduras	H4	20	6.3	6.0	6.5	2.57	0.14	0.58
El Salvador, Central Pacific	S1	10	5.8	5.6	6.1	4.18	0.44	2.10
El Salvador, Central Volcanic Arc	S3	15	6.8	6.6	7.1	6.21	0.85	0.91
El Salvador-Nicaragua, Volcanic Arc (Fonseca Gulf)	S4_N5	15	6.7	6.4	6.9	0.40	0.51	0.33
Nicaragua, Pacific West	N1	10	7.8	7.6	8.1	5.93	0.61	3.02
Nicaragua, Pacific South- Costa Rica, Papagayo Gulf	N2_C1	10	7.3	7.0	7.5	5.41	0.54	3.34
Nicaragua, forearc West	N3	15	6.8	6.5	7.0	3.21	0.32	0.23
Nicaragua, forearc East	N4	15	6.5	6.2	6.7	2.41	0.10	0.63
Nicaragua, Volcanic Arc West-Central	N6_N7	15	7.5	7.3	7.8	5.19	0.59	1.20
Nicaragua, Volcanic Arc SE	N8	15	7.0	6.7	7.2	3.85	0.49	0.17
Nicaragua Depression	N9_N10	15	5.8	6.6	7.1	3.80	0.45	0.22
Nicaragua, Caribe South	N12	20	6.2	5.9	6.4	4.07	0.54	0.54
Nicaragua, Caribe North	N13_N14	20	6.3	6.0	6.5	3.43	0.34	0.55
Costa Rica, forearc NW	C2	10	6.5	6.2	6.7	5.77	0.87	0.49
Costa Rica, forearc Pacific Central	C3	10	7.3	7.0	7.5	7.54	1.10	1.37
Panama-Costa, Burica peninsula	C4	10	7.3	7.0	7.5	6.18	0.74	2.52
Costa Rica, Guanacaste Volcanic Arc	C5	20	6.8	6.5	7.0	6.06	0.88	0.50
Costa Rica, Central Volcanic Range	C6	20	6.7	6.4	6.9	6.05	0.88	0.89
Costa Rica-Talamanca	C7	20	7.2	6.9	7.4	7.47	1.06	1.84
Costa Rica, Backarc North	C9	20	7.5	7.3	7.8	4.00	0.46	0.31
Costa Rica, Central Caribe Parismina	C10	20	6.0	5.8	6.3	6.38	1.05	0.58
Panama Fracture Zone	P1	20	7.3	7.0	7.5	5.41	0.48	6.14
Panama, Deformed Belt South of Panama	P2	10	7.3	7.0	7.5	5.45	0.62	1.68
Panama, Colombia forearc North	P3	10	6.8	6.5	7.0	3.25	0.26	0.45
Panama, West	P5	15	6.5	6.3	6.8	5.93	0.88	0.66
Panama, Central	P6	15	7.3	7.0	7.5	3.37	0.42	0.11
Panama, East-Darien	P7	15	7.3	7.1	7.6	4.90	0.61	0.51
Panama, North Panama Deformed Belt North East	P8	20	8.2	7.9	8.4	5.24	0.65	0.44
Panama- North Panama Deformed Belt Central	P9	20	5.3	5.1	5.6	2.00	0.15	0.41
Panama, North Panama Deformed Belt West	P10_C8	20	7.8	7.6	8.1	7.48	1.02	1.66
Interplate Seismicity								
Guatemala, Interface	Gsi9	10–40	7.5	7.2	7.7	6.54	0.77	6.20
El Salvador, Interface	Ssi5	10–40	8.3	8.1	8.6	6.92	0.70	12.24
Nicaragua, Interface NW	Nsi15	10–40	7.0	6.7	7.2	4.89	0.41	6.98
Nicaragua, Interface SE	Nsi16	10–40	7.5	7.3	7.8	5.14	0.47	5.65
Costa Rica, Interface Nicoya	Csi11	10–40	8.1	7.8	8.3	6.83	0.81	3.18
Costa Rica, Interface Quepos	Csi12	10–40	7.5	7.3	7.8	7.42	1.02	3.57
Costa Rica, Interface Osa	Csi13	10–40	7.7	7.4	7.9	6.72	0.91	2.33
Panama, Interface South	Psi9	20–40	7.7	7.4	7.9	6.41	0.79	3.85
Panama, Interface San Blas, Darién, Choco	Psi10	20–100	7.5	7.2	7.7	4.85	0.55	1.28
Panama Southeast	Psi11	20–100	7.3	7.0	7.5	4.56	0.48	1.31
Intraplate Seismicity								
Guatemala	Gsp10	40-	8.2	7.9	8.4	6.58	0.65	9.42
El Salvador	Ssp6	40-	8.0	7.7	8.2	6.58	0.65	9.05
Nicaragua	Nsp17	40-	7.7	7.4	7.9	5.43	0.47	10.63
Costa Rica NW	Csp14	40-	7.3	7.0	7.5	6.67	0.92	1.77
Costa Rica Central	Csp15	40-	7.5	7.3	7.8	7.17	1.05	1.55
Costa Rica SE	Csp16	40-	8.0	7.7	8.2	6.61	0.91	0.70
Panama South	Psp11	40-	7.3	7.0	7.5	4.95	0.64	0.63

[a] E(M) expected value of M_{max} defined by expert criteria.
[b] M_1 is the minimum value of M_{max} defined from the historical catalog.
[c] M_2 is the maximum value of M_{max} defined from geologic criteria.
[d] a and b are the parameters of the Gutemberg-Richter relationship.
[e] $N(M_{min})$ is anual number of events with $M_w \geq m_0$; $m_0 = 4.5$.

using a similar zonation criterion for the whole isthmus, with possible application to the revision of the hazard maps for the seismic codes.

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Appendix A. Supplementary data

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