NEW SEISMIC ZONATION IN CENTRAL AMERICA: A BASE FOR SEISMIC HAZARD

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Abstract

A new seismic zoning for Central America is proposed in this work, including significant changes in the boundary of zones proposed in previous zonations. The main changes are based on a detailed analysis of: seismotectonic framework, geological context, the update seismic catalogue and other geophysical and geodetic evidences (gravimetric maps, GPS observations). After that, we define the new seismogenic zones based on similar patterns of faulting, seismicity, and rupture mechanism inside each zone. The tectonic environment has required taking into account zones in three particular seismological regimes: a) crustal faulting, including, local faults, major fracture zones of plate boundary limits, and thrust fault deformed belts, b) subduction interplate and c) subduction intraplate or inslab. The seismicity each one has being associated with particular ranges in depth, which are variables taking into account the change in the subduction angle along the Mesoamerica Trench. In fact, the depth for the subduction zones, decrease in the northern Central America (Guatemala, El Salvador and Nicaragua) with respect the southern part (Costa Rica and Panama), and this is also incorporated in the new zonation.

Keywords: seismic zonation, Central America, subduction.

1. Introduction

Different seismic hazard studies in Central America have been generated in the last 25 years, all using different seismic zonations [1, 2]. Also, local studies were done in each of the 7 countries, although most of the local zonations used do not coincide with the zonations of neighbouring countries or the regional ones. Therefore, a regional and an integrated zonation have been here developed, including a homogeneous seismic catalogue of the all isthmus, trying to avoid all the deficiencies previously exposed. The zonation proposed in this paper has as main objective to provide an up-date model which could serve to generate PSHAs (Probabilistic Seismic Hazard Analysis) using a similar zonation criteria for the all isthmus. On the base of this, for the first time, seismologists and seismic-hazard experts from Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Panama, Norway and Spain worked together and by consensus they had proposed this new Central America seismic zonation. The new seismic zonation and the evaluation of seismic hazard for Central America started as part of the cooperation project named RESIS II under the auspices of the Northway Cooperation Agency (NORAD). The first results were already published [1, 3]. but not the basis of the seismic zonation. The present paper is an up-to-day of the seismic zonation, as a base for further seismic hazard studies in the region following the probabilistic seismic hazard assessment (PSHA).

2. Tectonic Framewok

Central America is mostly located on the Caribbean plate, but the northern part is located on the North American plate. The tectonic map of Central America appears on 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 relative plate movements range between 2.0 to 9.0 cm/year [4] and are accompanied by active volcanism, and high shallow to intermediate depth seismicity. 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. The Polochic-Motagua Fault System (PMFS) and the Panama Fracture Zone (PFZ) are the strike slip faults boundaries between the North American-Caribbean plates, and the Cocos-Nazca plates, respectively. The Southern Panama Deformed Belt (SPDB) makes the Caribbean-Nazca plate boundary. The Atrato Suture Zone (ASZ) constitutes part of the Caribbean-South American diffuse plate tectonic boundary.

Panama, the southern part of Costa Rica and northwestern Colombia is considered a block or a microplate (~8 cm/year to the north), as part of the Caribbean plate [5]. The NW limit of the Panama block is defined by a complicate, diffuse, active fault zone system, which across the central and northern part of Costa Rica, named the Central Costa Rica Deformed Belt, CCRDB.

The interaction between these different plates and other regional tectonic features, are the main elements that demarcate, largely, the different seismic sources proposed.

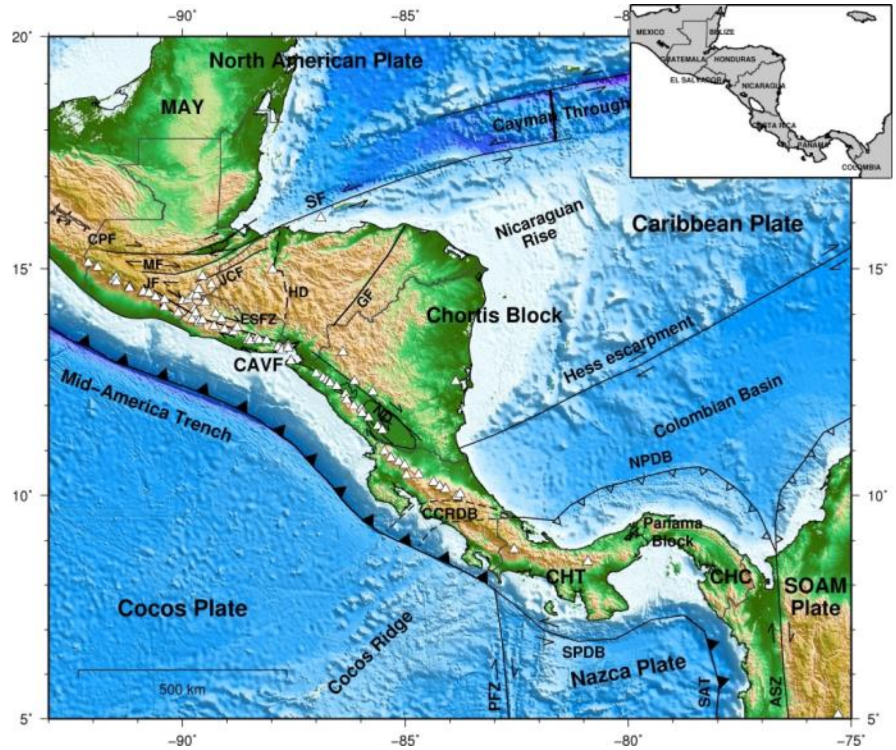

Fig. 1 – Tectonic frame of Central America

3. Methodology for definition of seismic zones

A *seismic zone* is defined as a specific geological feature or group of features, which the style of deformation and tectonic setting are similar, and a relationship between their deformation and historic and potential earthquake can be inferred. For the delineation of seismic source zones it is required the integration of geophysical and geological data to define a seismotectonic structure (fault o fault zone) or seismotectonic zone [6]. 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 concerns of three fundamental elements: i) Identification of significant source of earthquakes, ii) maximum size of these earthquakes and iii) rate at which they occur.

Up today, the state-of-the-art there is not a standard general practice for delineation of the seismic sources zones, the assessment of maximum potential earthquakes, and methodologies employed are, in a several ways, quite subjective in nature. In fact, it is possible for different researches to come up with different seismic source zones delineations using the same data base [6]. It was the case of previous studies in Central America or in individual countries [1]. Therefore, the present study proposed a new regional zonation based on the integration of all Central American available data and researches, in a unique proposal. We integrated all the recent 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 schedule of the maps and kind of data used for definition of the zones model is shown in Fig. 2.

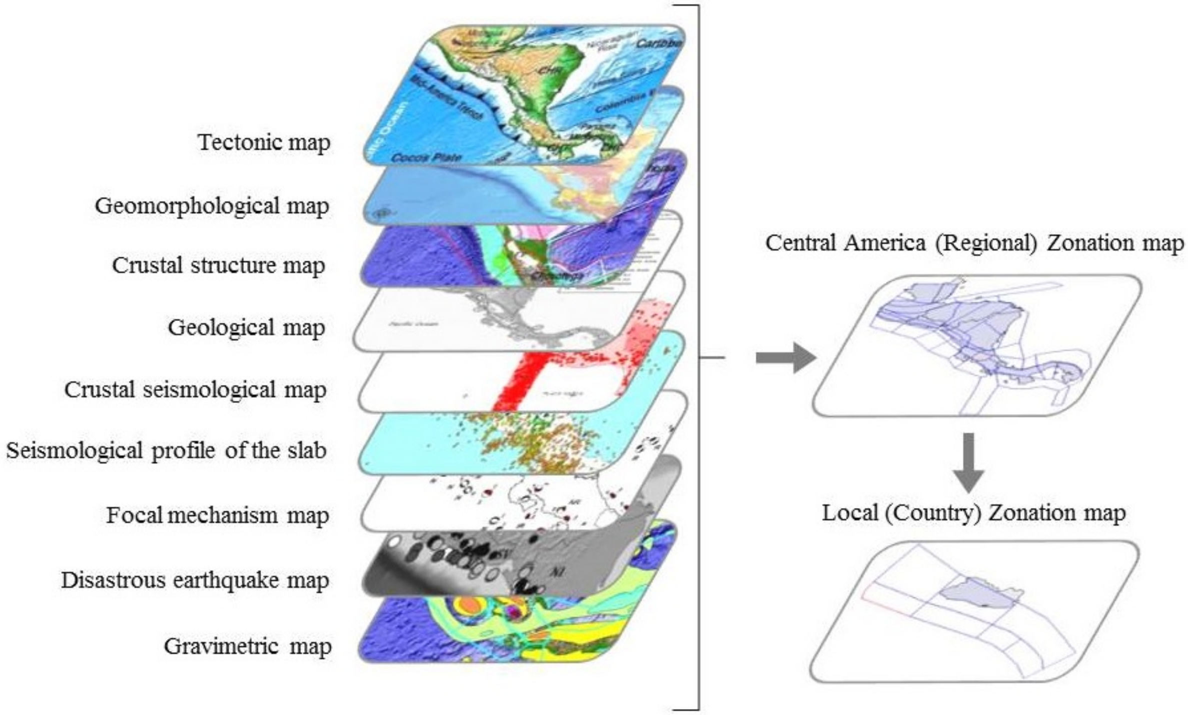

Fig. 2 – Kind of data used for definition of the zones model

For the definition of the regional and local seismic zonation presented here, we evaluated and elaborated separate maps of the major faults, including old and present plate boundaries, the geology, the geomorphology, the gravimetric and crustal structure, the seismicity (shallow, intermediate, deep), focal mechanisms for subduction ($M_w > 5.0$), and local fault ($M_w > 3.0$), and seismic profiles. For each map, we established preliminary "provinces" or zones. Latter, we integrated all the overlapping zones and make a regional consensus in a unique seismic zonation, according the most relevant criteria for the seismic hazard based on the stay of the art of the seismotectonic knowledge. The zonation models proposed by this work include crustal zones, interplate (interfase) and intraplate (inslab) subduction zones, and considering as the main factor for delimitation of the zones, similarities in the patterns of faulting, seismicity, and other parameters above indicated.

The major tectonic features of the region were taken from regional geological and tectonic maps, and on several papers and reviews [e.g. 7]. The major structures were evaluated according to their tectonic style (type of fault, grade of activity, longitude, and maximum estimated magnitude) provide a basis for the selection of seismotectonic zones for hazard estimation. We complemented the geotectonic framework with regional seismological studies and information of the focal mechanisms [8].

For the geophysical studies, we use crustal structure studies [9, 10], including gravimetric maps [11].

Referring at the seismological data base, the first task was to have an uniform earthquake data base, constructing a catalogue with 29,918 events ($M_w \geq 3.5$) from 1522 to 2011, homogenized to a moment magnitude scale (M_w), subtracting the aftershocks events. We identify seismic source zones, delineated on the basis of tectonic deformation style (type of faults), seismicity (rate of activity, historical destructive earthquakes, paleo-events, *a* and *b* values, focal mechanisms, and isoseismal maps). During the last 500 years, several intraplate and interplate destructive earthquakes have occurred, with moderate to high magnitudes ($5.5 < M_w < 8.0$). However, the historical record of earthquakes in Central America is poor in the XV and XVI centuries during the Spanish Conquest because the population kept no records, and the documents during colonial occupation was incomplete prior to the XVIII century. The record improves in the XIX century when the reports notably increased, creating a more complete knowledge of old historical earthquakes for this small region. The current knowledge of historical earthquakes in Central America is based on macroseismic phenomena reported by different people, newspapers and other written accounts that tell us about earthquakes before the installation of seismic stations. 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.

After a careful analysis of the geology, geophysics, seismicity and tectonics, we define the new seismogenic zones. The division were done integrated several geological and seismological information in draft maps, avoiding discontinuities at the national boundaries, and with a consensus among the principal researchers in Central America with foreign scientific collaborators working as a "seismological buffer".

4. Proposed seismic zones

In a first step we proposed a general modelization of the three regimens along the Caribbean plate, including the depth variation in the crustal and slab. Fig. 3 shows the general modelization.

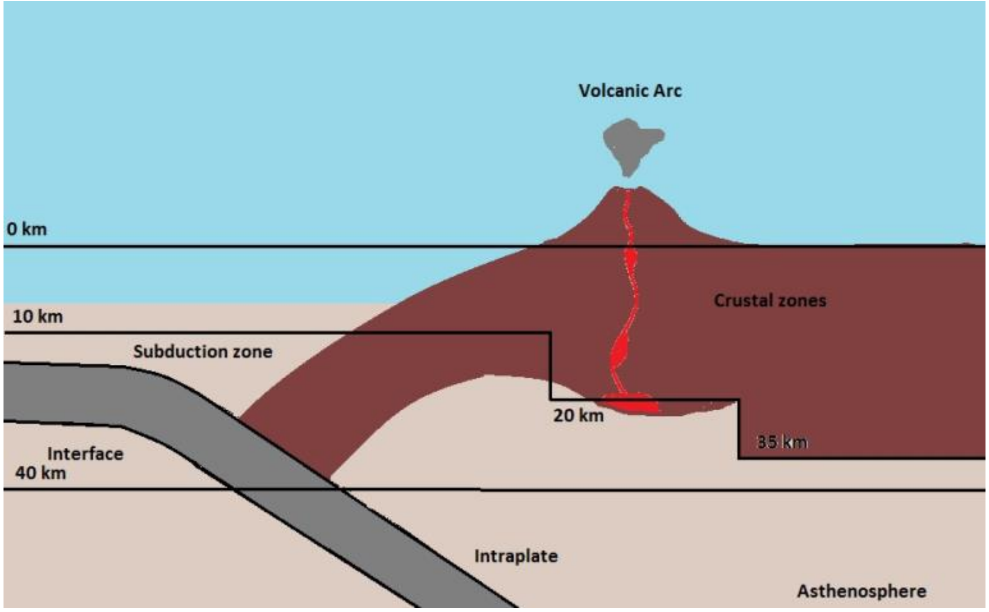

Fig. 3 – General modelization proposed of the three tectonic regimens along the Caribbean plate.

Secondly we defined the seismogenic zones classified in the three main groups: crustal, interplate subduction and intraplate subduction or inslab (Figs. 4, 5 and 6). The surface, intermediate and depth seismicity was associated to the corresponding zones. The maximun expected magnitude M_{max} for each zone was also estimated, taking into account the seismicity and tectonic. To account the maximum magnitude M_{max} of each zone, and its uncertainty, we adopt a truncated Gaussian distribution defined by the parameters: M_1= M*min* maximum historical earthquake (minimum value of M_{max}), $M_2 = M_{max}$ maximum potential magnitude based on tectonic criteria (maximum value of M_{max}), and E(m)= M_{med}, maximum magnitude expected, which corresponds to M_{max} more likely. Similar methods have been used in [12] and [13]. Table 1 includes the name of the zones and the E(m), adopted for each one.

Table 1 - Seismic zones defined in this study within the three tectonic features: crustal, subduction interface and subduction in-slab

Country/Zone name	Code	Depth (km)	E (M)
GT, Pacific	G1	7.5	
GT-ES, Forearc	G2-S2	10	6.7
GT, Volcanic Front W	G3	20	6.8
GT, Volcanic Front E	G4	20	6.8
GT-ES-HD, Central Depression	G5-S5-H1	35	7.5
GT, Polochic-Motagua W	G6	35	7.8
GT, Polochic-Motagua NE	G7	35	7.7
GT, North (Peten-Belice)	G8	35	7
GT, North	G9	35	7
HD, Central Highlands	H2	35	6.7
HD-NI, Guayape fault system	H3-N11	35	6.2
HD, North Coast	H4	35	6.3
ES, Central Pacific	S1	10	5.8
GT-ES, Forearc	G2-S2	10	6.7
ES, Central Volcanic Front	S3	20	6.8
ES-NI, Volcanic Arc (Fonseca Gulf)	S4-N5	20	7
NI, Pacific West	N1	10	7.8
NI, Pacific South- CR, Papagayo Gulf	N2-C1	10	7.3
NI, Forearc West	N3	10	6.8
NI, Forearc East	N4	10	6.5
NI, Volcanic Front W Central	N6-N7	20	7.5
NI, Volcanic Front SE	N8	20	7
NI, Nicaragua Depression	N9-N10	20	6.8
NI, Caribe South	N12	35	6.2
NI, Caribe North	N13-N14	35	6.3
CR, Forearc NW	C2	10	6.5
CR, Forearc Pacific Central	C3	10	7.3
CR-PA, ZFP and Burica peninsula	C4-P1	35	7.7
CR, Guanacaste Volcanic Range	C5	10	6.8
CR, Central Volcanic Range	C6	10	6.7
CR, Talamanca	C7	35	7.2
CR, Backarc North	C9	20	7.5
CR, Central Caribe Parismina	C10	35	6
PA, PDB South	P2	20	7.3
PA, Colombia forearc North	P3	20	6.8
PA, Panama West	P5	20	6.5
PA, Panama Central	P6	20	7.3
PA, Panama East-Darien	P7	35	7.3
PA, NPDB North East	P8	20	8.2
PA, NPDB Central	P9	35	5.3
Panama, NPDB West	P10-C8	35	8
GT, Interface	Gsi9	10-40	7.5
ES, Interface	Ssi5	10-40	8.3
NI, Interface NW	Nsi15	10-40	7

Country/Zone name	Code	Depth (km)	E (M)
NI, Interface SE	Nsi16	10-40	7.5
CR, Inteface Nicoya	Csi11	10-40	8.1
CR, Interface Quepos	Csi12	10-40	7.5
CR, Interface Osa	Csi13	10-40	7.5
PA, Interface South	Psi9	20-40	7.7
PA, Interface San Blas, Darién, Choco	Psi10	20-100	7.5
PA, Panama Southeast	Psi11	20-100	6.8
GA, Guatemala	Gsp10	40-428	8.2
ES, El Salvador	Ssp6	40-346	8
NI, Nicaragua	Nsp17	40-681	7.7
CR, Costa Rica NW	Csp14	40-700	7.3
CR, Costa Rica Central	Csp15	40-239	7.5
CR, Costa Rica SE	Csp16	40-575	7.3
PA, Panama South	Psp11	40-335	7.3

/GT Guatemala, HD Honduras, ES El Salvador, NI Nicaragua, CR Costa Rica, PA Panama

4.1 Crustal zones

Crustal zones include earthquakes with shallow depths, although this depth h increases from the boundary of the subduction zone toward the mainland, with variations between 10 and 35 km. In the volcanic arc a maximum depth of 20 km is established. Three ranges of depth are defined in these zones: (1) up to h = 10 km, cortical zones that cover the subduction zone, along the Middle America Trench MAT (G1, G2-S2, S1, N1, N2-C1, N3, N4, C2, C3, C5 and C6 zones), (2) up to h = 20 km, zones over the volcanic arc and Panama (G3, G4, S3, S4-N5, N6-N7, N8, N9-10, C9, P2, P3, P5, P6 and P8 zones) and (3) up to h = 35 km, zones inland corresponding to Guatemala, Honduras, Nicaragua, Panama fracture zone and east of Panama (G5-S5-H1, G6, G7, G8, G9, H2, H3-N11, H4, N12, N13-N14, N2-C1, C4-P1, C7, P10-C8, C10, P7, P9 and P10-C8 zones).

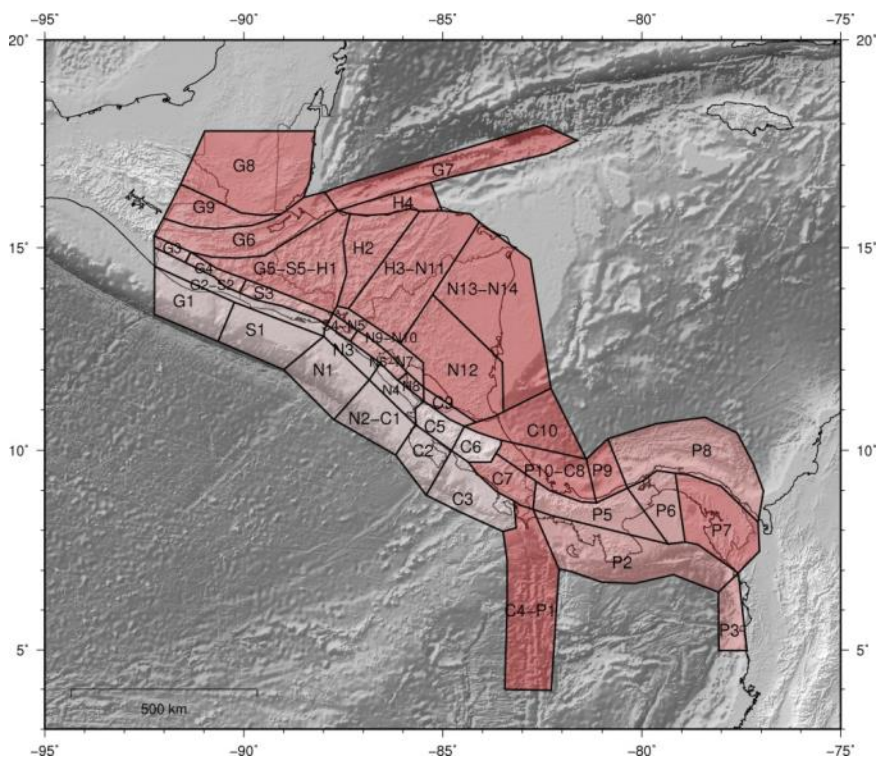

Fig. 4 – Shallow crustal seismic sources

4.2 Subducction zones

The limits of depth and geometry of subduction zones, which vary along the trench, have been defined from the features of subduction slab in Central America. Below, we summarize the main geomorphological and seismic features to describe these limits.

4.2.1 Interfase zones

Normally, the interplate seismogenic zone could extend in deep where the oceanic plate intersects the continental Moho, about 70 km inland from the MAT. However, the observed seismicity related with this zone is restricted between ~10 and ~40 km depth.

The normal and strike-slip focal mechanisms are predominant for the shallow 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.

Three ranges of depth are defined in the interfase zones, shown in Fig. 5: (1) $10 < h \leq 40$ km in the interfase zones of Guatemala, El Salvador, Nicaragua and Costa Rica (Gsi9, Ssi5, Nsi15, Nsi16, Csi11, Csi12 and Csi13 zones), (2) $20 \leq h \leq 40$ 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 convergence between Panama block, Caribbean plate and South American plate (North Andean block). The depth of most seismicity registered in this area in the last 15 years is over 40 km.

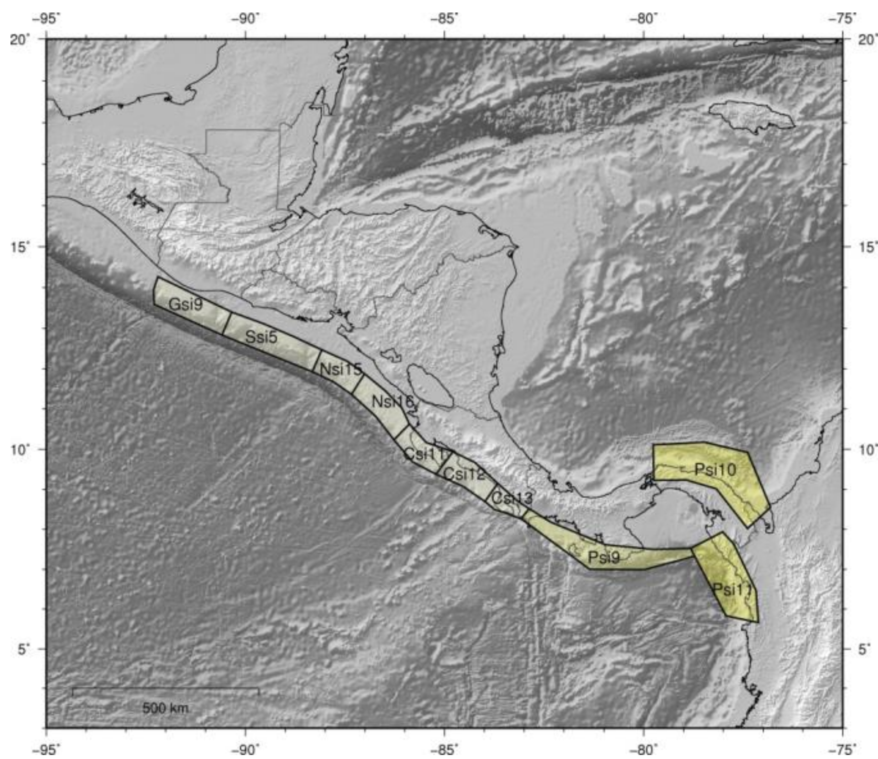

Fig. 5 – Interfase subduction seismic sources

The events of which the hypocenter corresponds with the range of depth and with a thrust mechanism have been assigned to the interfase subduction zones. In the cases where the two conditions were not verified, the focal mechanism has been preference, given the inexactitude in the localization.

In addition, as discussed above, some epicenters are outside of the defined zones; even fulfill the depth and focal mechanism conditions indicated. In these cases, these events have been forcibly included in their respective zone.

4.2.2 Intraplate zones

Most of the seismicity in the subducting slab is deeper than ~40 km. The intraplate zones are defined from the lower boundary of subduction interfase which marks the beginning of the intraplate subduction. Fig. 6 shows the intraplate zones defined with *h* > 40 km (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 intraplate subduction zones.

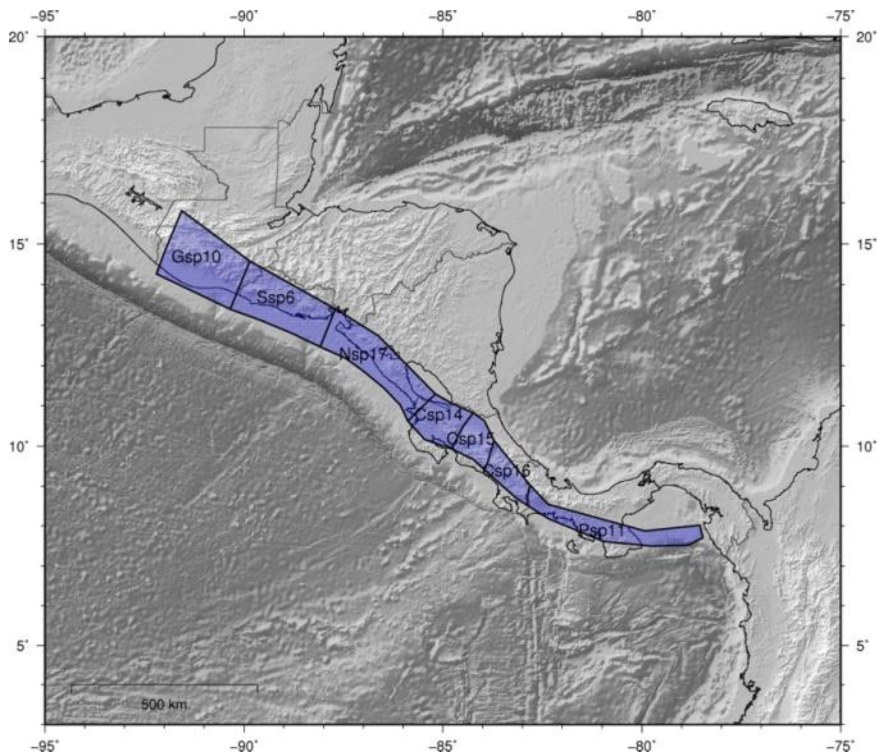

Fig. 6 – Intraple subduction seismic zones

6. Discussion and conclusions

A new regional zonation is proposed in this paper, based on the integration of all Central American available data: geological (tectonic maps, geological maps, geophysical maps, geomorphological maps), geodetic (current crustal deformation from GPS velocities) and seismological information (rate of seismicity, focal mechanisms, seismicity density, depth, magnitude).

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

New 41 Crustal zones have been identified, including earthquakes with shallow depths, this depth *h* increases from the boundary of the subduction zone toward the mainland, with variations between 10 and 35 km. In the volcanic arc a maximum depth of 20 km is established. The M_{max} values have been estimated taking into account the seismicity and tectonic of each zone. The values range between Mw 5.3 and 8.2.

The limits of subduction zones have been drawn taking into account the variation of subduction slab in Central America, in particular the depth and angle along the trench. 10 zones have been defined inside the interfase subduction regime, divided in three ranges of depth: (1) $10 < h \leq 40$ km in the interfase 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 M_{max} for these seismic sources range with values between Mw 6.8 and 8.3 in Psi11 and Nsi15.

In the inslab or intraplate subduction regime 7 zones have been identified, where most of the seismicity is deeper than ~40 km. The intraplate zones are defined from the lower boundary of subduction interfase zones which marks the beginning of the intraplate subduction zones. The deepest subduction is in Guatemala, where earthquakes have occurred as deep as 250 km, and the shallowest in the Southern part of Costa Rica, where the subduction earthquakes reach only 70 km. The values of M_{max} are in the range of 7.3 in zones of Costa Rica and Panama and 8.2 in Guatemala.

In order to improve the proposed zonation, a detailed study of the Panama Fracture Zone is suggested, since the seismicity do not fit well with the tectonic observed. Nevertheless, the zoning model presented and described in this paper may contribute as a base for future seismic hazard assessment in the region.

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