Taylor & Francis
Taylor & Francis Group

Journal of Maps

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjom20

The pattern of brittle deformation in Central America for an assessment of the seismo-tectonic framework

Mauro Agate, Francesco Caldareri, Luis Castillo, Amalia Garcia, Giuseppe Giunta, Luis Mixco, Jaime Requena, Carlos Rubi Tellez, Maynor Ruiz, Attilio Sulli, Abel Alexei Argueta-Platero, Heyddy Calderon, Julio Luna & Lidia Elizabeth Torres Bernhard

To cite this article: Mauro Agate, Francesco Caldareri, Luis Castillo, Amalia Garcia, Giuseppe Giunta, Luis Mixco, Jaime Requena, Carlos Rubi Tellez, Maynor Ruiz, Attilio Sulli, Abel Alexei Argueta-Platero, Heyddy Calderon, Julio Luna & Lidia Elizabeth Torres Bernhard (2024) The pattern of brittle deformation in Central America for an assessment of the seismo-tectonic framework, Journal of Maps, 20:1, 2285479, DOI: 10.1080/17445647.2023.2285479

To link to this article: https://doi.org/10.1080/17445647.2023.2285479

Published online: 17 Dec 2023.

JOURNAL OF MAPS
2024, VOL. 20, NO. 1, 2285479
https://doi.org/10.1080/17445647.2023.2285479

The pattern of brittle deformation in Central America for an assessment of the seismo-tectonic framework

Mauro Agate [a], Francesco Caldareri [a], Luis Castillo[b], Amalia Garcia[c], Giuseppe Giunta[a], Luis Mixco[c], Jaime Requena[d], Carlos Rubi Tellez[e], Maynor Ruiz[f], Attilio Sulli [a], Abel Alexei Argueta-Platero[b], Heyddy Calderon[e], Julio Luna[d] and Lidia Elizabeth Torres Bernhard[f]

[a]DISTEM, Department of Earth and Marine Sciences, University of Palermo, Palermo, Italy; [b]UES, Universidad de El Salvador, San Salvador, El Salvador; [c]MARN, Ministerio de Medio Ambiente y Recursos Naturales de El Salvador, San Salvador, El Salvador; [d]USAC, Universidad de San Carlos de Guatemala, Guatemala City, Guatemala; [e]UNAN, Universidad Nacional Autónoma de Nicaragua, Managua, Nicaragua; [f]UNAH, Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras

ABSTRACT
A seismo-tectonic map depicting the principal structural elements of the northern Central American region has been meticulously crafted to characterize the tectonic setting and the individual seismo-tectonic structures of this area. This region is subject to heightened seismic activity, with a large number of medium-high Magnitude occurrences transpiring annually. This map is presented alongside an informative dataset wherein fault trace locations, geometry and kinematics descriptors and other available metadata have been stored. Therefore, the map offers a detailed and up-to-date depiction of the brittle deformation across the region, serving as a valuable resource for a comprehensive assessment of the seismo-tectonic framework. Moreover, the map and its accompanying database summarize fault characteristics for seismic hazard analysts and for civil protection workers, proving to be useful instruments in pinpointing areas where urgent fault research should be conducted from a seismic risk standpoint.

ARTICLE HISTORY
Received 31 January 2023
Revised 30 October 2023
Accepted 14 November 2023

KEYWORDS
Tectonics; seismicity; seismic hazard; Central America

1. Introduction

Central America is characterized by an exceedingly vigorous tectonic and volcanic activity, resulting in repeatedly natural disasters (earthquakes, volcanic eruptions, landslides, tsunamis) that have frequently led to substantial loss of life and extensive damages to civil habitation and infrastructure.

These catastrophic occurrences are the product of a fervent and widespread tectonic deformation, stemming from the intricate interplay amongst five lithospheric plates: the Caribbean plate, the North American plate, the Cocos plate, the Nazca plate and the South American plate (Figure 1A).

The interaction between these plates is of the transcurrent type along the boundary connecting the North American and Caribbean plates, as well as along a segment of the boundary separating the latter from the South American plate. Additionally, these displacements take on the convergent form ('B' subduction) along the boundary between the Cocos plate and the Caribbean and North American plates (Figure 1A). The relative movements and subsequent interactions between these three plates continuously accumulate tectonic stresses along the boundaries, giving rise to an intense seismic activity (Figure 2) that renders Central America as one of the most seismically active regions worldwide.

The regional seismicity can be divided into three different types (Benito et al., 2012): (i) earthquakes of strong energy and high hypocentral depth (h > 60 km), closely connected to the subduction motion of the Cocos Plate beneath the Caribbean Plate; (ii) earthquakes of intense energy and comparatively shallower hypocentres (25 < h < 60 km), still associated with the subduction zone, but more specifically, with the interface between the plates; (iii) earthquakes of moderate energy and superficial hypocentres (h < 25 km), predominantly resulting from upper crustal tectonic or volcanic activity (Figure 2; Benito et al., 2012).

Notably, the most powerful earthquakes, with a magnitude close to 8 and hypocentres reaching depths of approximately 200 km, are situated along the subduction plane that extends beneath the Central American Trench (CAT; Figures 1C and 2). On the other hand, the intraplate regions are characterized by widespread seismicity, with an average magnitude < 6.5 and medium-low hypocentre depth (Figure 2; Benito

CONTACT F. Caldareri francesco.caldareri@unipa.it DISTEM, Department of Earth and Marine Sciences, University of Palermo, Palermo 90123, Italy
Supplemental map for this article is available online at https://doi.org/10.1080/17445647.2023.2285479.

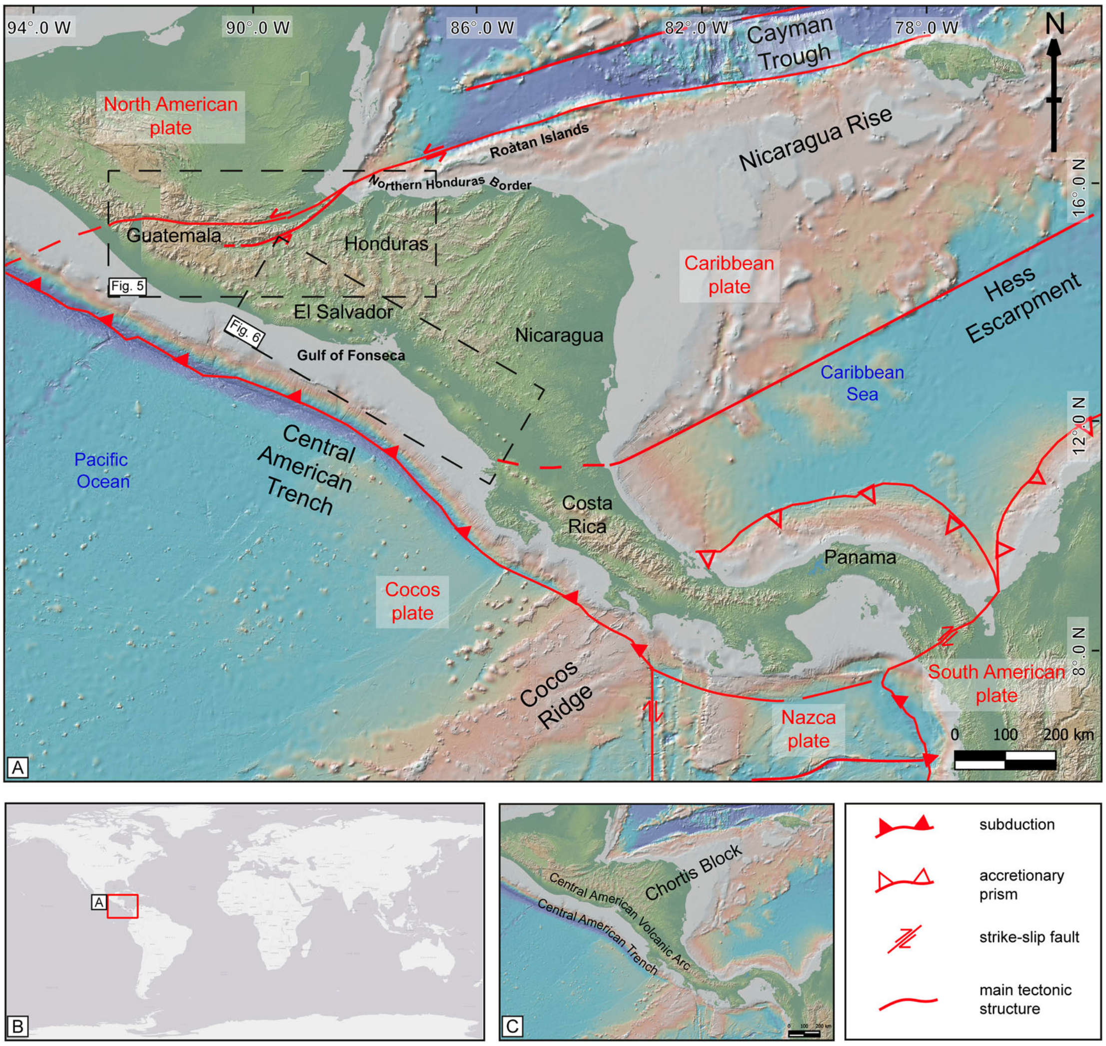

Figure 1. (A) Simplified structural map showing the main tectonic features related to the current plate tectonic setting of the Caribbean area (Central America region). The dashed rectangles represent the areas illustrated in Figures 5 and 6. (B) Study area geographical framework. (C) Location of the Chortis Block, Central American Volcanic Arc (CAVA) and Central American Trench (CAT) within the study area.

et al., 2010); nevertheless, even small magnitude seismicity can generate considerable damage of social impact. In fact, the most destructive earthquakes known to us were primarily caused by the shallow hypocentral depths (<10 km), compounded by the susceptibility of the civil structures.

In recent decades, the crustal seismicity has given rise to the most devastating occurrences: the earthquake linked to the Motagua fault (Mw = 7.6), which resulted in 22,000 deaths in Guatemala in 1976; in 1972, an earthquake measuring magnitude Mw 6.2 struck Managua city (Nicaragua), claiming the lives of 10,000 individuals; in 2001, El Salvador experienced two separate events, measuring magnitude Mw 7.7 and 6 respectively, within a month's time, resulting in the loss of 1200 lives. Conversely, seismic events with epicentres in the subduction zone, characterized by significant magnitude and depth, have often caused minimal damage.

Moreover, these upper crustal earthquakes frequently triggered extensive and catastrophic landslides near the epicentral areas, exacerbated by the lithology of rocks composed of volcanic sediments, tephra and weak ignimbrites. Furthermore, documented evidence (e.g. Cox et al., 2008) reveals that large-scale earthquakes occurring in offshore areas generated intense shaking along the coastlines and gave rise to destructive tsunamis.

In-depth analysis of the geological hazard in the Central American region constituted one of the primary objectives of the 'Escenarios de Riesgo en Centro America' (RIESCA Project; https://www.youtube.com/watch?v=RCNJdmLNZQY). This collaborative endeavour, spanning from 2016 to 2021, was undertaken through the cooperation among various academic and research institutions from Italy and Central American countries, including El Salvador, Guatemala, Honduras and Nicaragua. The Project facilitated and advanced scholarly and investigative endeavours in the field of seismic, volcanic, and hydrogeological hazard. The research activity illustrated in this paper was aimed at mapping and

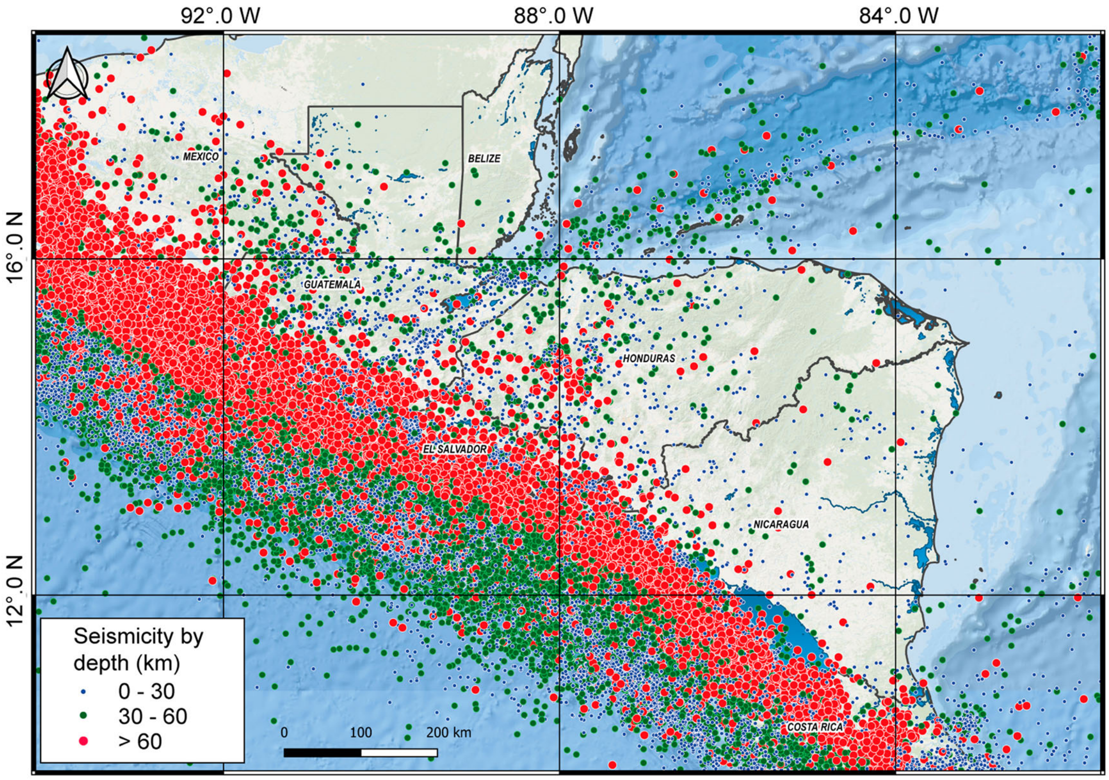

Figure 2. Depth distribution pattern of seismic hypocentres across the Central America region related to the hypocentre depth.

characterizing the main seismo-tectonic structures of the northern Central American region, with the purpose of offering a more dependable evaluation of seismic sources and associated hazard. The main achieved outcome is the regional-scale seismo-tectonic map showing the pattern of the brittle deformation.

2. Regional tectonic setting

The Central American region is situated within the Caribbean Plate, composed of both continental and oceanic lithosphere. Presently, it is superimposing the Pacific (to the West) and Atlantic (to the East) oceanic lithosphere, thereby generating the arc-trench systems of the Central American Isthmus and Lesser Antilles, respectively (Figure 1). Since the Early Cretaceous period, the northern and southern boundaries of the Caribbean plate have corresponded to two extensive shear zones, hosting as sites for large-scale strike-slip faults that remain active and act as sources of seismic activity.

Within this regional geodynamic framework, the study area, encompassing the states of Guatemala, El Salvador, Honduras and Nicaragua, predominantly corresponds to the Chortis Block (Figure 1C), a roughly triangular-shaped continental mass. This block is comprised of a Palaeozoic basement, overlain by Mesozoic marine sediments and volcanic materials generated from the subduction process associated with the CAT. Along the exposed portion of the Chortis Block, the thickness of the crust progressively increases from 22 to 26 km along the coasts of the Caribbean Sea and Pacific Ocean, to approximately 40 km in two distinct depocentres situated in the states of Guatemala and Honduras, respectively (Figure 3).

Moreover, the Chortis Block is bounded by deformed marginal belts resulting from interactions with the adjacent Nazca, Cocos and American plates during the Late Jurassic up to the Quaternary periods (Figure 1; Giunta & Orioli, 2011).

Since the Late Cretaceous period, the convergence process between the Caribbean plate and the Cocos and Nazca plates gave rise to an extensive arc-trench system characterized by highly vigorous tectonic and volcanic activity. Stretching over a distance exceeding 1200 km along the active Pacific boundary from Costa Rica to Guatemala, the Central America Volcanic Arc (CAVA; Figure 1C) abruptly terminates at the Polochic fault, within a region where the triple junction of the Cocos, the Caribbean, and the North American plates occurs (Guzmán-Speziale et al., 1989; Lyon-Caen et al., 2006; Plafker, 1976).

The CAVA, which demarcates the boundary between the Central America fore-arc and the Caribbean continental crust, is distinguished by the presence of 75 closely spaced basaltic to dacitic volcanoes that have remained active during both the Holocene and historic epochs. As inferred from earthquake focal mechanisms and geodetic data, the predominant type of tectonic deformation along the arc is primarily strike-slip motion (Burkart and Self, 1985).

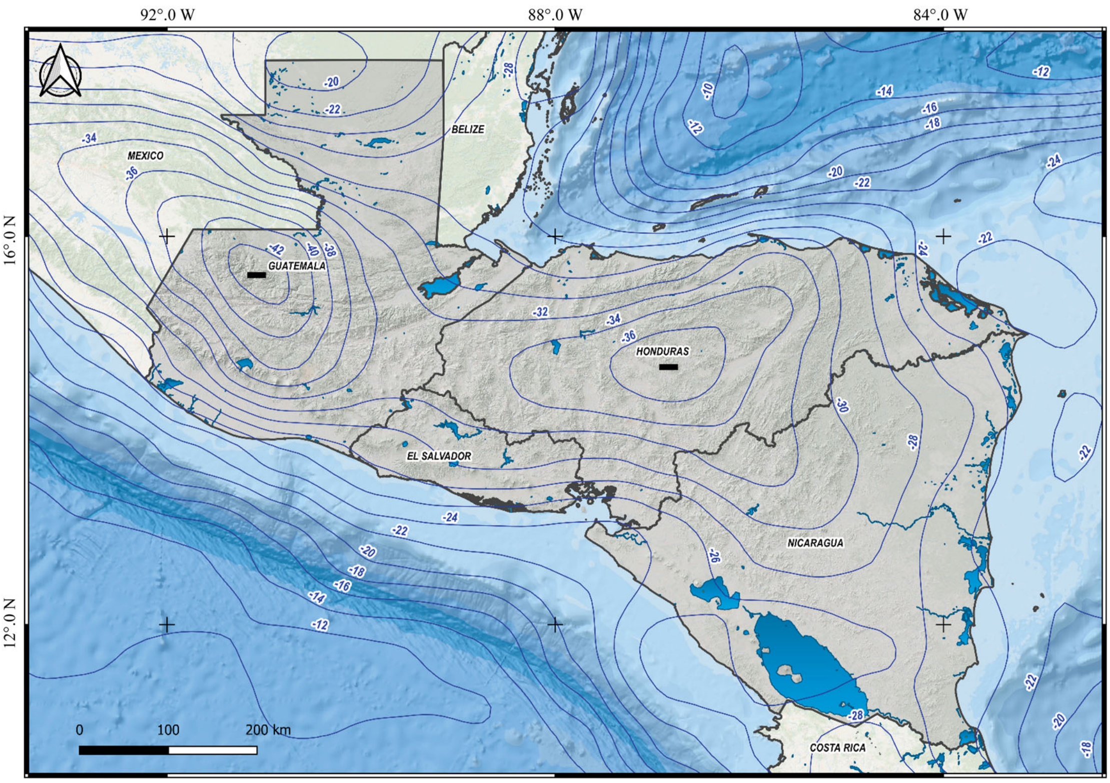

Figure 3. Isobaths of Mohorovicic discontinuity in Central America region. The crustal thickness values were generated using the 'GEMMA Crustal Model' illustrated in Sampietro et al. (2014).

The boundary separating the North American and Caribbean plates is regarded as a left-lateral shear zone since the Late Jurassic-Early Cretaceous period, presently exhibiting a displacement rate of 15–21 mm/y (Mann et al., 1990; Dixon et al., 1998), accompanied by high seismic activity. This shear zone corresponds to the Motagua-Polochic fault zone (Figure 4), which exhibits a clear association with the Cayman Trough located in the eastern offshore region (Figure 1).

Overall, the prevailing structural trends across Central America encompass both NW and NE orientations. One of the more prominent features is the Guayape fault, which runs along a N35°E direction and significantly affects the entirety of the Chortis block across Honduras. Another noteworthy tectonic characteristic at a regional scale is a series of structural lows trending approximately NNW-SSE, situated in the Central America Highlands between the Motagua-Polochic fault zone and the CAVA (Figure 4). The most prominent structures within this system include the Guatemala City Graben and the Ipala Graben in Guatemala, and the Honduras Depression, which encompasses the Sula and Comayagua grabens in Honduras (Figure 4).

3. Data and methods

Between 2016 and 2021, researchers from various countries gathered geological and seismological data on tectonic structures within their respective countries, drawing up on the scientific literature available. Regular joint meetings were conducted to discuss fault-finding criteria and data entry methodologies for the GIS project, ensuring a consistent representation of the study area. These meetings also included seminars by experts on different geological hazard topics in the Central American region. Civil protection representatives collaborated to determine the most relevant information for inclusion in the GIS Project. Additionally, field observations were conducted to gather detailed geological and kinematic parameters for select tectonic structures.

As part of the RIESCA Project, a georeferenced dataset was compiled to identify the main tectonic fault structures in the Central American region. This dataset was used to create a structural map at a scale of 1:1,200,000 (see Main Map), encompassing the countries involved in the project: Guatemala, El Salvador, Honduras, and Nicaragua.

The map provides a concise representation of the brittle deformation framework in the region. The dataset includes 986 fault trace locations and attributes for 86 selected structures, such as fault geometry, kinematics, slip rates, seismological parameters, and bibliographic references. QGIS, a free open-source GIS software, was utilized to map the faults based on a Digital Elevation Model (DEM) with a spatial resolution of 30 m. The DEM was generated using photogrammetric, LIDAR, or regular classic topographic data.

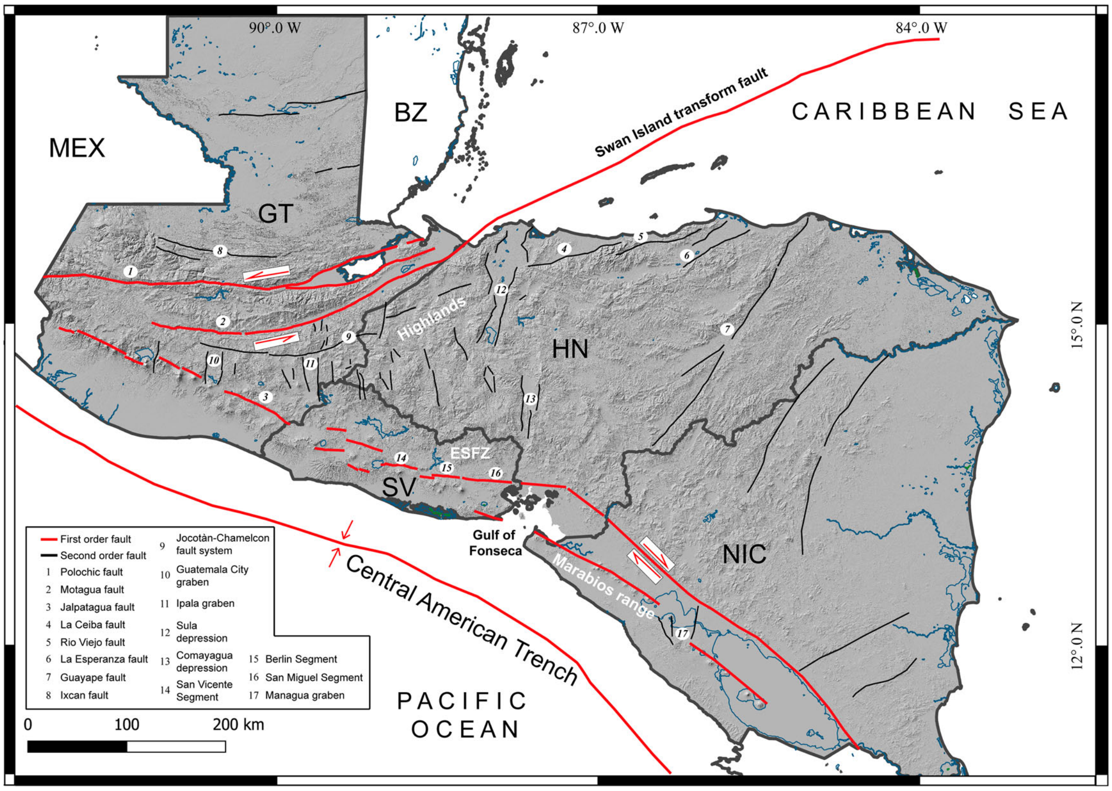

Figure 4. First and second order tectonic structures defining the brittle deformation pattern of northern Central America region (first order highlighted in red; second order highlighted in black). The figure also shows the tectonic structures, numbered from 1 to 17, mentioned in the text.

The Main Map in the RIESCA Project showcases fault traces obtained from geological and morpho-structural surveys, paleo-seismology investigations and tele-detection observations illustrated in scientific literature over the past few decades. The fault lines on the map are drawn by considering the topography of the field surface.

The map aims to represent all major, active and non-active faults, providing an overall setting of the brittle deformation pattern in the region, in order to understand the geological framework in which specific tectonic structures can generate crustal earthquakes. In this paper we define as *seismogenic*, faults with tectonic activity associated with documented seismicity by instrumental data or paleoseismological investigations or macroseismic studies, and *active*, faults that have experienced displacement within the past million years, aligning with the existing strain field. Our approach is heavily influenced by the technical guide IAEA TECDOC 1767 (https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1767_web.pdf).
The kinematics of active and seismogenic faults has been stored in the GIS project from paleosismological, geodetic and morphostructural analyses carried out by many researchers during the last decades (Alonso-Henar et al., 2014; Canora et al., 2012; Corti et al., 2005; Garibaldi et al., 2016; Staller et al., 2016 among others). In the related WEB-GIS dataset, one can find the attributes and references associated with each fault (https://giovannacilluffo.github.io/geomap/#7/14.195/-88.473). For the extensively studied and significant faults in the study area, we have also compiled a detailed and up-to-date attribute table (Table 1A,B). This table summarizes the geometric, kinematic, and seismological indicators necessary for assessing seismic hazard.

4. Results: overview of main seismotectonic structures

In the framework of the brittle deformation affecting the mainland Caribbean region, the structures can be classified into two categories: main (first order) tectonic structures, which are directly influenced by the displacements along the lithospheric plate boundaries, and secondary (second order) tectonic structures, which result from the distributed deformation occurring within the Chortis Block (Figure 1C). In the upcoming paragraphs, we will discuss the most significant and seismically relevant first and second order tectonic structures, starting from the North.

4.1. The Caribbean – North America plate boundary

The Motagua-Polochic fault system, spanning over 300 km (White, 1984), represents the primary segment of the North American-Caribbean plate boundary in

Table 1. A–B: the table shows the geometric, kinematic and seismological values of the main faults identified in the study area. The faults are numbered from 1 to 86 (id column); for their location, refer to the figures available as supplementary material.

Fault name	Fault system	Country	Strike	DIP	Length (km)	Fault type	Lateral slip rate	Activity	MW (max)	Last recorded earthquake	References	Note	ID
(A)													
Ahuachapan E	ESFZ Western segment	SV	22	70	7.369	Normal		Seismogenic	6		Alonso Henar et al., 2013		1
Ahuachapan W	ESFZ Western segment	SV	30	70	10.8			Seismogenic	6.22		Alonso Henar et al., 2013		2
Apaneca	ESFZ	SV	311	90	11.501	Normal	1.5 mm/y	Active			Alonso Henar et al., 2013, 2018		3
Ayagualo	ESFZ Western segment	SV	299	80	9.447	Strike-Slip		Seismogenic	6.2		Alonso Henar et al., 2013		4
Berlin	ESFZ Berlin segment	SV	278	80	12.579	Strike-Slip		Active	6.4		Alonso-Henar et al., 2018		5
Boqueron N	ESFZ	SV	140		7.229			Active			This paper		6
Charanga	ESFZ	SV	184	70	5.191	Normal	0.5 mm/y	Active	5.08		Alonso Henar et al., 2013		7
Chilanguera	ESFZ	SV	300	80	6.156		0.5 mm/y	Seismogenic	5.9		Alonso Henar et al., 2018		8
Coatepeque W	ESFZ	SV	18	70	4.972	Normal		Active			This paper		9
Comecayo	ESFZ Western segment	SV	96	70	17.45	Strike-Slip	3 mm/y	Seismogenic	6.6		Alonso Henar et al., 2013, 2018		10
Conchagua	ESFZ	SV	189	70	12.85	Normal	0.5 mm/y	Seismogenic	6.3		Alonso Henar et al., 2013, 2018		11
El Caracol	ESFZ Lempa segment	SV	271	90	6.269		1 mm/y	Active			Alonso Henar et al., 2013, 2018		12
El Espino	ESFZ	SV	288	70	10.893	Strike-Slip	1 mm/y	Seismogenic	6.6		Alonso Henar et al., 2013, 2018		13
El Pulguero	ESFZ Lempa segment	SV	106	70	12.645		3 mm/y	Active			Alonso Henar et al., 2013, 2018		14
El Tecomatal	ESFZ Lempa segment	SV	132	70	14.719	Normal	1 mm/y	Seismogenic	6.5		Alonso Henar et al., 2013		15
El Tigre	ESFZ Western segment	SV	31	70	10.31	Normal		Seismogenic	6.2		Alonso Henar et al., 2013		16
El Tigre E		SV	190	65	7.494	Strike-Slip		Active			This paper		17
El Tigre W		SV	283	86	7.304	Strike-Slip		Active			This paper		18
El Triunfo		SV	94	70	25.928	Strike-Slip		Seismogenic	6.7		Alonso-Henar et al., 2018		19
El Zacamil		SV	359	70	13.262	Normal		Active			Alonso Henar et al., 2013, 2018		20
El Zapote		SV	185	70	14.988	Normal		Seismogenic	6.4		Alonso Henar et al., 2018		21
Guachipilín	ESFZ	SV	116	70	21.269	Normal		Seismogenic			Alonso Henar et al., 2018		22
Guaycume		SV	108	80	35.789	Right-lateral strike-slip	9 + - 3 mm/y	Seismogenic	6.9		Alonso-Henar et al., 2018		23
Ilopango S	ESFZ	SV	302	65	10.298	Strike-Slip		Active			This paper		24
Intipucá		SV	288	70	27.627	Strike-Slip		Seismogenic			Alonso Henar et al. 2018		25
Jucuarán		SV	322	70	9.473	Normal		Seismogenic			Alonso Henar et al., 2013		26
La Joya	ESFZ Lempa segment	SV	315	70	5.877	Normal	1 mm/y	Active			Alonso Henar et al., 2013		27
Laguna del Llano	ESFZ Western segment	SV	18	70	14.135	Normal		Active			Alonso Henar et al., 2013		28
Las Brisas		SV	7	70	2.959	Normal		Active			Alonso Henar et al., 2013		29
Lempa S		SV	277	80	12.386	Strike-Slip	1 mm/y	Active					30

	ESFZ Berlin segment										Alonso Henar et al., 2013, 2018		
Olomega		SV	318	70	13.236	Normal	0.5 mm/y	Active			Alonso Henar et al. 2013, 2018		31
Opico	ESFZ Western segment	SV	138	80	6.164	Normal		Active			Alonso Henar et al., 2013		32
Pacayal		SV	102	80	8.742	Normal		Active			This paper		33
Palo Pique	ESFZ Western segment	SV	10	70	9.479	Normal		Active			Alonso Henar et al., 2013		34
Panchimalco	ESFZ Western segment	SV	287	80	8.345	Strike-Slip	1.5 mm/y	Active			Alonso Henar et al., 2013		35
Río Grande		SV	309	70	15.877	Strike-Slip		Active			Alonso Henar et al. 2013, 2018		36
San Miguel	ESFZ	SV	94	85	47.644	Strike-Slip		Seismogenic			Alonso Henar et al. 2013, 2018		37
San Salvador E		SV	105	84	8.209	Strike-Slip		Active			This paper		38
San Salvador W		SV	2	89	5.572	Strike-Slip		Active			This paper		39
San Vicente	ESFZ	SV	88	70	18.683	Strike-Slip	7+-1 mm/y (1) 4 mm/y	Seismogenic	6.6	February 2001	Alonso Henar et al., 2018		40
Santa Ana E	ESFZ	SV	163	70	10.91	Normal		Seismogenic	6.2		Alonso Henar et al., 2018		41
Santa Ana W	ESFZ	SV	344	70	15.417	Normal		Seismogenic	6.4		Alonso Henar et al., 2018		42
Sensuntepeque E		SV	193	60	10.85	Normal	0.5 mm/y	Active			Alonso Henar et al. 2013, 2018		43
Sensuntepeque W		SV	177	60	11.887	Normal	0.5 mm/y	Active			Alonso Henar et al. 2013, 2018		44
Teotepeque	ESFZ Western segment	SV	275	90	5.443	Strike-Slip	1.5 mm/y	Active			Alonso Henar et al., 2013, 2018		45
Victoria		SV	193	90	7.02	Normal	0.5 mm/y	Active			Alonso Henar et al. 2013, 2018		46
Zapotitan	ESFZ Western segment	SV	94	80	27.321	Strike-Slip	1 mm/y	Active			Alonso Henar et al., 2013		47
(B)													
Aeropuerto W	Managua Graben	NI	180		9.927		<5 mm/y	Seismogenic		1650–1810	Cowan et al., 2002	vertical slip rate 0.3–0.9 mm/	48
Ciudad Dario W		NI	170		7.494	Normal		Active			This paper		49
Cofradia	Managua Graben	NI	4–13		33.641	Normal	0–5 mm/y	Seismogenic			Cowan et al., 2002	age of most recent movement <5	50
Estadio		NI	220–180		4.1	Left-lateral strike-slip		Seismogenic			This paper		51
Las Nubes		NI	25		17.717	Normal		Active			This paper		52
Marabios		NI	125		144.342	Strike Slip-dx		Active			Turner et al., 2007		53
Mateare		NI	165		31.787	Normal		Active			This paper		54
Nejapa		NI	180		19.816	Normal		Seismogenic			This paper		55
Nicaragua Depression Boundary		NI	160		345.709	Normal		Active			This paper		56
San Rafael		NI	160		56.268	Normal		Active			This paper		57
Sebaco E		NI	180–190		16.691	Normal		Active			This paper		58
Sebaco W		NI	180–210		41.307	Normal		Active			This paper		59
Segmento Sur Este CV		NI	125		97.208	Strike Slip-dx		Active			This paper		60

(*Continued*)

Table 1. Continued.

Fault name	Fault system	Country	Strike	DIP	Length (km)	Fault type	Lateral slip rate	Activity	MW (max)	Last recorded earthquake	References	Note	ID
Tiscapa	Managua Graben	NI	35	80–90	6.635	Left-lateral strike-slip	<5 mm/y	Seismogenic	5.6 (6.2)	23 December 1972	Ward et. al., 1974		61
Valle de Jalapa NW		NI	190		37.347	Normal		Active			This paper		62
Guayape N		HN	30	90	48.088			Active (?)			Gordon & Muehlberger, 1994		63
Guayape S		HN	30	90	80.802			Active (?)			This paper		64
La Ceiba		HN	85	90	96.425			Seismogenic		2009	Rogers & Mann, 2007		65
La Esperanza		HN	70	90	76.339	Normal		Active			Rogers & Mann, 2007		66
Atitlàn		GT	0		16.077			Active			This paper		67
Ayatza		GT	0		14.027			Active			This paper		68
Graben de Guatemala (Mixco)		GT	180		32.213	Normal		Seismogenic		February 1976 (1)	Plafker, 1976; Guzmán-Speziale, 2001	(1) linked to Motagua event	69
Graben de Guatemala (Pinula)		GT	180		11.529	Normal		Active			Guzman-Speziale, 2010; Franco et al., 2012		70
Ipala		GT	175		22.56	Normal		Active			Styron et. al 2020; Guzmán-Speziale, 2001		71
Ixcan E	Motagua-Polochic	GT	90		36.436	Strike-slip		Seismogenic		12 October 1971 (1)	Guzman-Speziale, 2010	(1) M = 5.7	72
Ixcan West	Motagua-Polochic	GT	95		49.474	Strike-slip		Seismogenic		12 October 1971 (1)	Guzman-Speziale, 2010	(1) M = 5.7	73
Jalpatagua		GT	110		72.289	Right-lateral strike-slip (1)	1.4–7.6 mm/y	Active			Authemayou et al., 2011; Garnier et al., 2020	(1) Ellis et al., 2019	74
Jilotepeque		GT	175		36.42	Normal		Active			Styron et. al 2019; Guzmán-Speziale, 2001		75
Jocotàn	Motagua-Polochic	GT	85–90		95.093	Left-lateral strike-slip		Active			Gordon & Muehlberger, 1994		76
Laj Chimel – El Chol		GT	90		28.408	Left-lateral strike-slip		Active			This paper		77
Motagua Central	Motagua-Polochic	GT	75		122.405	Left-lateral strike-slip	0.45–1.88 cm/y (3)	Seismogenic	7.5	4 February 1976	Plafker, 1976; Guzman-Speziale, 2010		78
Motagua E	Motagua-Polochic	GT	80		60.553	Left-lateral strike-slip	0.45–1.88 cm/y (3)	Seismogenic	7.5	4 February 1976	Plafker, 1976; Guzman-Speziale, 2010		79
Motagua N	Motagua-Polochic	GT	80		184.397	Left-lateral strike-slip	0.45–1.88 cm/y (3)	Active	7.5	4 February 1976	Plafker, 1976; Guzman-Speziale, 2010		80
Motagua S	Motagua-Polochic	GT	90		46.253	Left-lateral strike-slip	0.45–1.88 cm/y (3)	Active	7.5	4 February 1976	Plafker, 1976; Guzman-Speziale, 2010		81
Motagua W	Motagua-Polochic	GT	95		89.517	Left-lateral strike-slip	0.45–1.88 cm/y (3)	Seismogenic	7.5	4 February 1976	Plafker, 1976; Guzman-Speziale, 2010		82
Polochic E (a)	Motagua-Polochic	GT	75		14.269	Left-lateral strike-slip		Seismogenic			This paper		83
Polochic E (b)	Motagua-Polochic	GT	75		15.358	Left-lateral strike-slip		Seismogenic			This paper		84
Polochic N	Motagua-Polochic	GT	90–75		272.328	Left-lateral strike-slip	4.8+-2.2 mm/y – 2–4	Seismogenic	7.5–7.7	22 July 1816	White, 1984, 1985; Authemayou et al., 2012		85
Polochic S	Motagua-Polochic	GT	90–75		163.001	Left-lateral strike-slip		Active			Guzman-Speziale & Molina, 2022		86

the continental crust. It extends across almost all of the Central American isthmus and connects to the Swan Island transform faults in the oceanic crust to the east (Figures 1A and 4). Both the Motagua and Polochic faults are several hundred kilometres long and exhibit a slightly northward concave, east–west orientation on the map. Between these faults a mountainous territory (Sierra de las Minas) lies, except for the eastern sector, towards the Caribbean Sea, which features a flat area hosting Lake Izabal, interpreted as a pull-apart basin (Lyon-Caen et al., 2006).

The Motagua-Polochic fault system, which encompasses parallel sinistral faults like the Los Amates fault and the Ixcan fault, plays a significant role in the region. The Los Amates fault is situated south of the Motagua fault near the border with Honduras, while the 190 km long Ixcan fault stretches about 80 km northward from the Polochic fault (Figure 4).

Geodetic investigations have measured a slip rate of approximately 20 mm/y for the central segment of the Motagua fault (Franco et al., 2012; Lyon-Caen et al., 2006), which closely matches the total North American – Caribbean relative plate velocity (DeMets et al., 2010). This highlights the regional importance of this large-scale crustal structure. The Polochic Fault, located around 45 km north of the Motagua Fault, exhibits a similar direction and extends over a hundred km further west. Its estimated slip rate is about 4–5 mm/y (Authemayou et al., 2012; Franco et al., 2012; Lyon-Caen et al., 2006).

Both structural geology and seismological investigations have extensively studied and documented the tectonic activity of the faults in Guatemala (Guzman-Speziale & Molina, 2022; Plafker, 1976). These faults have been responsible for at least 25 destructive earthquakes since 1530. The Motagua fault, in particular, was the main fault along which the devastating Guatemala earthquake of 1976 occurred. This earthquake, with a magnitude Mw = 7.5 (Bucknam et al., 1978; Plafker, 1976) claiming the lives of 23,000 individuals (Husid et al., 1976; Olcese et al., 1977), resulted in a maximum horizontal displacement of 325 cm along the Motagua fault (Bucknam et al., 1978) and the reactivation of numerous secondary faults (Plafker, 1976). Both the Motagua and Polochic faults exhibit left-lateral strike-slip kinematics, as indicated by earthquake fault plane solutions (Figure 5; Guzmán-Speziale et al., 1989; Cáceres et al., 2005; Lyon-Caen et al., 2006). Based on focal mechanisms (Guzman-Speziale, 2010), the Ixcan fault also shows a left-lateral strike-slip kinematics, and to the east of it, there is an 80 km long fault trending ENE-WSW near the village Las Conchas that has experienced earthquake activity in recent decades (Styron et al., 2020).

To the south of the Motagua fault, the Jocotàn-Chamelecon fault system (Figure 4) is another important regional structure. Studies by Schwartz et al. (1979), Ferrari et al. (1994), and Ellis et al. (2018, 2019) have not found any field or geodetic evidence of recent displacement along this fault system. However, it is possible that during the Miocene, the Jocotàn-Chamelecon fault system was part of the broader Motagua-Polochic fault zone, as suggested by Gordon and Muehlberger (1994).

4.1.1. Northern Honduras and its borderland

The northern coastal belt of Honduras is influenced by additional tectonic structures associated with the Caribbean – North America plate boundary. Within the Nombre de Dios range and the Aguan Valley, there is widespread oblique-slip faulting, characterized by active left-lateral river offsets and uplift of stream reaches (Rogers & Mann, 2007). Among the numerous faults in this dense grid, the most prominent and laterally continuous ones include the La Cieba fault, La

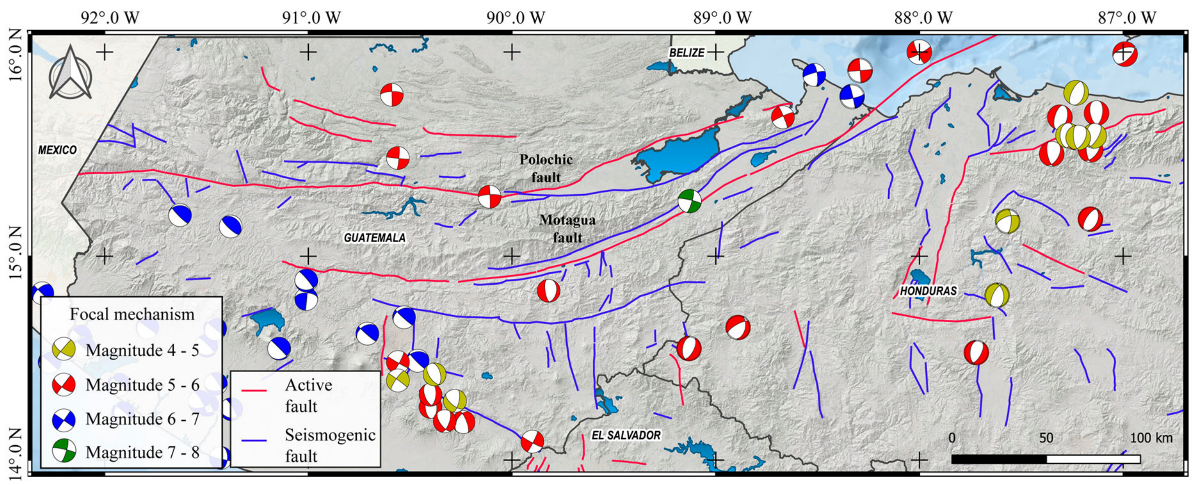

Figure 5. Seismo-tectonic setting of the Highlands and the northern Honduras border with focal mechanism coloured according to the different magnitude for the main earthquakes.

Esperanza fault, and Rio Vejo fault (Figure 4). These features trend ENE and exhibit a combination of normal and left-lateral transtensional offset mechanisms (Figure 5; Rogers & Mann, 2007).

Off the coast of the western Caribbean Sea, there is a wide area spanning over 100 km known as the Honduran borderlands (Figure 1A); it is characterized by active submarine faults that impact the shelf-to-slope region (Case and Holcombe, 1980; Mann et al., 1991). The primary tectonic structure in this area is the Swan Islands fault zone (Figure 4), which was the site of a tsunami event in August 1956. Additionally, there are currently active normal faults with a north–south orientation in the Roatàn Islands (Figure 1A; AvéLallemant and Gordon, 1999). These faults have caused recent uplift and tilting of coastal features in that area (Cox et al., 2008).

4.2. The CAVA fault system

The CAVA (Figure 1C), home to 18 active volcanoes, separates the central American forearc from the Caribbean continental crust. This region exhibits significant transcurrent tectonic activity along an extensive fault system that runs parallel to the volcanic arc. The faults in close proximity to the volcanic arc experience dextral shear of up to 10–15 mm/year (Canora et al., 2010, 2012; Martínez-Díaz et al., 2004), while there are also conjugate faults with left-lateral offset (Carr, 1976).

Starting from the North, the main component of this regional fault system is the Jalpatagua fault (Figure 4), which stretches for about 70–80 km and exhibits right-lateral strike-slip movement. The displacement rate along this fault ranges from 1.4 to 7.6 mm/y (Ellis et al., 2019), increasing as it moves southeast across Guatemala towards the El Salvador border.

To the southeast of this border lies a very relevant seismo-tectonic structure, known as the El Salvador Fault Zone (ESFZ; Figure 4). It spans 150 km in length and 20 km in width, comprising a series of disconnected faults with dextral strike-slip to transtensional characteristics (Figure 6). These faults affect deposits from the upper Pleistocene to the Holocene, with a fault trace trending at approximately N90°−100° (Canora et al., 2012).

The ESFZ exhibits several distinct segments, particularly noticeable to the east of San Salvador: the San Vicente segment, the Berlin segment, and the San Miguel segment (Figure 4). The ESFZ features E-W strike-slip faults, accompanied by smaller structures that show varying orientations, such as WNW-ESE, NW-SE, and NNW-SSE to N-S. The overall arrangement of major and minor structures within the ESFZ can be attributed to an E-W dextral shear couple, along with the presence of Riedel fractures (Corti et al., 2005).

In the main segments of the ESFZ, slip rate values have been estimated to be as high as 11–12 mm/year (Corti et al., 2005; Staller et al., 2016). Overall, the deformation related to trench-parallel strike-slip displacement in the upper crust is estimated to be at least 8 mm/year (DeMets et al., 2007), resulting in high seismic activity. The faults within the ESFZ are significant sources of upper crustal seismic activity and have been responsible for numerous M-6 earthquakes in El Salvador during the twentieth century, including events in 1917, 1919, 1951, 1986, and 2001 (Alonso-Henar et al., 2018; Martínez-Díaz et al., 2004; White & Harlow, 1993).

Moving southward to the Gulf of Fonseca area (Figure 1A), seismo-tectonic activity is more partitioned, with strike-slip focal mechanisms characterizing seismic events occurring throughout the gulf (Figure 6; Funk et al., 2009; Alvarado et al., 2011). The Nicaraguan depression is a graben that stretches over 500 km in length and approximately 60 km in width. It is bounded by WNW-ESE trending faults and extends from the Gulf of Fonseca to the Caribbean coast of Costa Rica (see Main Map).

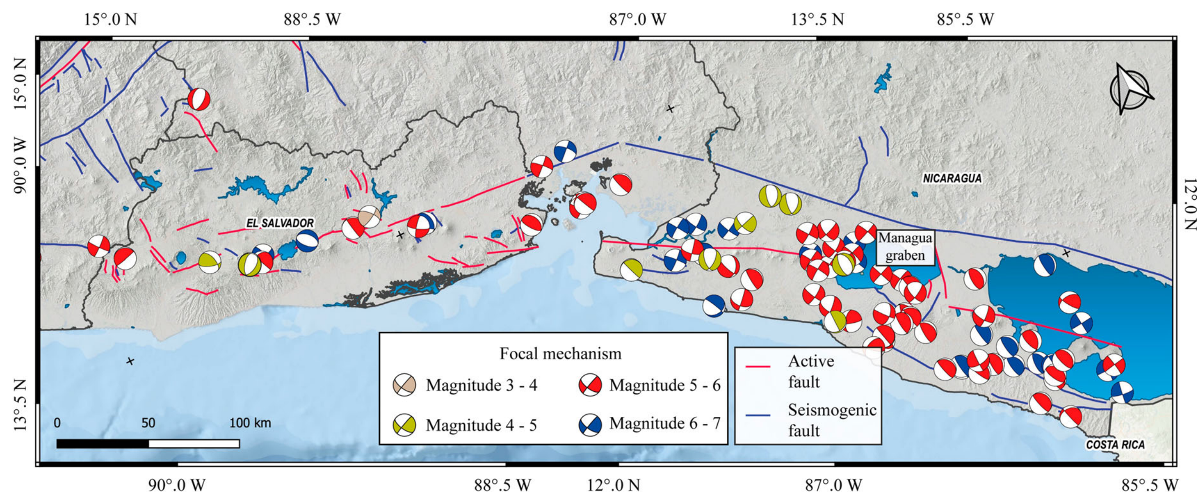

Figure 6. Seismo-tectonic setting of the Volcanic Arc fault system with focal mechanism coloured according to the different magnitude for the main earthquake.

In this sector, the Managua Graben (Figure 4) is a significant feature characterized by a disruption in the alignment of the volcanic chain. Various hypotheses have been proposed regarding the kinematic relationship between the graben and the driving plate-boundary forces (see Cowan et al., 2002 with references therein). The graben area is affected by north to north-east oriented strike-slip and oblique-normal faults (Figure 6), with the Tiscapa, Aeropuerto, Cofradia, and Estadio faults being the most notable (Cowan et al., 2002). Morpho-structural investigations have documented Holocene tectonic activity along these faults (Woodward-Clyde Associates, 1975). In Nicaragua, the focal mechanism (Figure 6) from 1972 Managua earthquake (Ms 6.2) originated along the Tiscapa fault with a sinistral slip (Brown et al., 1972) and, in 1931, an M 6.0 earthquake originated from a rupture along the Estadio fault, located 1.5 km west of the Tiscapa fault (White & Harlow, 1993).

To the south, there is a zone of dextral strike-slip deformation across Lake Nicaragua, where normal faults have been reactivated as strike-slip faults, according to Funk et al. (2009).

The CAVA spans across Guatemala, El Salvador, and Nicaragua, and serves as a boundary between the Central America forearc sliver and the Caribbean plate (Styron et al., 2020). This extensive fault system experiences strain and seismicity, primarily localized on E-W dextral strike-slip faults (Figure 6), as well as on transtensional zones where the fault system forms releasing bends.

The Marabios Range is also affected by seismic activity, with focal mechanisms (Figure 6) indicating dextral slip (La Femina et al., 2002), which is further supported by geodetic data (Styron, 2008).

4.3. The fault system in the Highlands

A region called The Highlands (Figure 4) is situated between the Motagua fault and the volcanic arc fault system. This elevated, wedge-shaped area is characterized by a series of more than 10 N-S trending grabens. These grabens are defined by steep, fault-controlled escarpments and are filled with deposits ranging from the Late Miocene to the Quaternary. (Gordon & Muehlberger, 1994). The Guatemala City graben, located in the western part of the region, is considered one of the most active structures, with an estimated extension rate of 5 mm/y based on GPS data (Franco et al., 2012). However, the slip rate on specific structures in this area has not been determined yet. Moving eastward from the Guatemala City graben, another significant feature is the Ipala Graben (Figure 4). Further east, the large Honduras Depression comprises the Sula Graben, the Comayagua Graben, and the transtensional Gulf of Fonseca to the south (Figure 4), making it the most tectonically active system in the region.

The current tectonic activity in the graben system is associated with distributed extension. This strain allows for approximately 10 mm/year of E-W extension (Caceres et al., 2005; Lyon-Caen et al., 2006; Rodriguez et al., 2009; Franco et al., 2012). This activity is believed to be responsible for the intraplate deformation of the western sector of the Caribbean plate (Guzmán-Speziale, 2001). Over the past five centuries, numerous historical and instrumental earthquakes have occurred in Central America, with magnitudes ranging between 5.0 and 7.5, which can be attributed to tectonic activity affecting grabens (Guzmán-Speziale, 2001).

5. Conclusive remarks

Central America is currently experiencing intense and widespread tectonic activity due to its unique geodynamic setting and evolution, characterized by high relative motions at the plate boundaries. This has resulted in the formation of major (first order) tectonic structures along the boundaries of the Caribbean and North American plates, as well as along the Central American Volcanic Arc (CAVA).

The Motagua-Polochic fault zone, located to the north, represents the mainland segment of the Caribbean-North American plate boundary. The fast, left-lateral strike-slip-rate along this fault zone has led to the occurrence of frequent high-magnitude earthquakes. Along this active fault system, an average recurrence interval of 225 ± 50 years between major fault ruptures has been estimated (Alvarado et al., 2017) for events with magnitude Mw > 7.3.

In the western region, the CAVA area is characterized by the Jalpatagua – El Salvador fault zone, a right-lateral strike-slip fault system that runs in an east–west direction. This fault zone has been responsible for earthquakes which are almost always devastating, because they occur at shallow depths and near population centres. The historic recurrence time for these shallow earthquakes is of 30 years (Alvarado et al., 2017) for El Salvador where, according to Canora et al. (2014), earthquakes up to M 7.2 could happen.

Additionally, there are some minor (second order) fault systems in Central America, that equally pose a considerable seismic hazard; (i) the system of north–south graben-bounding normal faults located between the Motagua-Polochic fault zone and the northern end of the Jalpatagua-El Salvador fault zone, in the wedge-shaped Highland sector. Extensive normal faulting in this sector can be attributed to regional extension occurring in response to eastward shift of the Caribbean plate South of the Motagua-Polochic fault-zone; (ii) the ENE transtensional fault system along the border of Honduras, adjacent to the Caribbean Sea; (iii) the system of mostly north–south and NNW-SSE oriented strike-slip and oblique-normal faults observed in the Nicaragua depression. The origin of these seismotectonic structures affecting the interior of the Caribbean plate could be local stress fields that are generated by differential displacement caused by the interplate interaction of the North American and the Caribbean plates. These fault systems, although minor, are equally dangerous in terms of seismic activity.

After analyzing seismological instrumental data and conducting macroseismic and paleoseismology investigations, numerous active seismo-tectonic structures have been identified in the Central American region. To provide a comprehensive overview, we have summarized the structural and kinematic characteristics of these structures and created a georeferenced queryable Web-GIS map at a scale of 1:1,200,000.

This map, along with the GIS data-set, is the result of a collaborative effort among researchers from four Central American countries. The objective was to establish a consistent representation of the brittle deformation patterns in the region. The database serves as a valuable resource for accessing information on known seismogenic structures, aiding in seismic risk assessment and facilitating future updates.

A deeper understanding of the regional seismotectonic setting, as well as the kinematic and seismological characteristics (e.g. slip-rate value, rupture surface extension) of individual seismogenetic structures, can significantly enhance the definition of seismic zonation in the Central America region. This knowledge also improves the reliability of results obtained from probabilistic seismic hazard analysis (PSHA), which are crucial for studying and mitigating seismic risk. These activities play a vital role in preventing and reducing the impact of earthquakes.

Software

The fault mapping was conducted using QGIS 3.22, a free open-source and cross-platform GIS software. The analysis was made on a Digital Elevation Model (DEM) with a 30 m resolution, compiled from the national DEMs provided by the various countries.

For the main map layout, we employed Adobe Illustrator CC 2020. We integrated the 30 m resolution DEM exported from QGIS, which contained a comprehensive set of 986 fault vectors, into an A0-sized canvas.

Acknowledgements

Critical reviews by Jiří Pánek, Jorge Arzate and Carlos César Uchôa de Lima helped us to improve the paper. The researchers of the University of Palermo warmly thank the colleagues of the Universities of Central America, the MARN of El Salvador and the INSIVUMEH of Guatemala for the generous welcome and hospitality during the periods of activities carried out in collaboration on the Central American region. The expenses incurred for this research were financed within the RIESCA project.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The costs incurred for carrying out the research illustrated in this paper were funded by the RIESCA Project, that was funded by the Italian Agency for Development Cooperation (AICS) of the Italian Ministry for Foreign Affairs, and coordinated by the University of Palermo.

Data availability statement

The data presented in this study are available from the corresponding author, upon reasonable request.

ORCID

M. Agate http://orcid.org/0000-0002-9861-7601
F. Caldareri http://orcid.org/0000-0002-8735-9408
A. Sulli http://orcid.org/0000-0002-7705-3632

References

Alonso-Henar, J., Álvarez-Gómez, J. A., & Martínez-Díaz, J. J. (2014). Constraints for the recent tectonics of the El Salvador fault zone, central America volcanic arc, from morphotectonic analysis. *Tectonophysics*, *623*, 1–13. https://doi.org/10.1016/j.tecto.2014.03.012

Alonso-Henar, J., Benito, M. B., Staller, A., Álvarez-Gómez, J. A., Martínez-Díaz, J. J., & Canora, C. (2018). Main Crustal Seismic Sources in El Salvador. *Data in Brief*, *20*, 1085–1089. https://doi.org/10.1016/j.enggeo.2018.06.015

Alonso-Henar, J., Martinez-Diaz, J. J., Benito, B., Alvarez-Gomez, J. A., Staller, A., Canora, C., & Capote, R. (2013). Seismic sources in El Salvador. A geological and geodetic contribution. *Meeting of Americas, AGU, Cancun, Mexico, 14–17 May 2013*.

Alvarado, D., DeMets, C., Tikoff, B., Hernández, D., Wawrzyniec, T. F., Pullinger, C., Mattioli, G., Turner, H. L., Rodriguez, M., & Correa-Mora, F. (2011). Forearc motion and deformation between El Salvador and Nicaragua: GPS, seismic, structural, and paleomagnetic observations. *Lithosphere*, *3*(*1*), 3–21. http://doi.org/10.1130/L108.1

Alvarado, G. E., Benito, B., Staller, A., Climent, Á., Camacho, E., Rojas, W., Marroquín, G., Molina, E., Talavera, J. E., Martínez-Cuevas, S., & Lindholm, C. (2017). The new Central American seismic hazard zonation: Mutual consensus based on up to day seismotectonic framework. *Tectonophysics*, *721*, 462–476. https://doi.org/10.1016/j.tecto.2017.10.013

Authemayou, C., Brocard, G., Teyssier, C., Simon-Labric, T., Guttiérrez, A., Chiquín, E. N., & Morán, S. (2011). The Caribbean–North America–Cocos Triple Junction and the dynamics of the Polochic–Motagua fault systems:

Pull-up and zipper models. *Tectonics*, *30*(*3*). http://doi.org/10.1029/2010TC002814

Authemayou, C., Brocard, G., Teyssier, C., Suski, B., Cosenza, B., Morán-Ical, S., González-Véliz, C. W., Aguilar-Hengstenberg, M. A., & Holliger, K. (2012). Quaternary seismo-tectonic activity of the Polochic fault, Guatemala. *Journal of Geophysical Research: Solid Earth*, *117*, B07403. https://doi.org/10.1029/2012JB009444

Avélallemant, H. G., & Gordon, M. B. (1999). Chapter 8 Deformation history of Roatán Island: Implications for the origin of the tela basin (Honduras). In *Sedimentary Basins of the World* (Vol. 4, pp. 197–218). Elsevier. https://doi.org/10.1016/S1874-5997(99)80042-2.

Benito, B., Lindholm, C., Camacho, E., Climent, Á, Marroquín, G., Molina, E., Rojas, W., Talavera, E., Escobar, J. J., Alvarado, G., Torres, Y., & Perez-Escalante, M. (2010). Amenaza sísmica en América Central. In B. Oterino, M. B. and Y, & T. Fernández (Eds.), (pp. 371). Entimema.

Benito, M. B., Lindholm, C., Camacho, E., Climent, A., Marroquín, G., Molina, E., Rojas, W., Escobar, J. J., Talavera, E., Alvarado, G., & Torres, Y. (2012). A new evaluation of seismic hazard for the central America region. *Bulletin of the Seismological Society of America*, *102*(2), 504–523. https://doi.org/10.1785/0120110015

Brown, R. D., Jr, Ward, P. L., & Plafker, G. (1972). Geologic and seismologic aspects of the Managua, Nicaragua, earthquakes of December 23, 1972. *Geological Survey Professional Paper*, *838*, 34.

Bucknam, R. C., Plafker, G., & Sharp, V. (1978). Fault movement (afterslip) following the Guatemala earthquake of February 4, 1976. *Geology*, *6*(3), 170–173. https://doi.org/10.1130/0091-7613(1978)6<170:FMAFTG>2.0.CO;2

Burkart, B., & Self, S. (1985). Extension and rotation of crustal blocks in northern Central America and effect on the volcanic arc. *Geology*, *13*, 22–26. https://doi.org/10.1130/0091-7613(1985)132.0.CO;2.

Cáceres, D., Monterroso, D., & Tavakoli, B. (2005). Crustal deformation in northern Central America. *Tectonophysics*, *404*(*1-2*), 119–131. http://doi.org/10.1016/j.tecto.2005.05.008

Canora, C., Martínez-Díaz, J. J., Villamor, P., Berryman, K., Álvarez-Gómez, J. A., Pullinger, C., & Capote, R. (2010). Geological and seismological analysis of the 13 February 2001 Mw 6.6 El Salvador earthquake: Evidence for surface rupture and implications for seismic hazard. *Bulletin of the Seismological Society of America*, *100*(6), 2873–2890. https://doi.org/10.1785/0120090377

Canora, C., Martínez-Díaz, J. J., Villamor, P., Staller, A., Berryman, K., Álvarez-Gómez, J. A., Capote, R., & Diaz, M. (2014). Structural evolution of the El Salvador Fault Zone: an evolving fault system within a volcanic arc. *Journal of Iberian Geology*, *40*(*3*), 471–488. http://doi.org/10.5209/rev_JIGE.2014.v40.n3.43559.

Canora, C., Villamor, P., Martínez-Díaz, J. J., Berryman, K., Álvarez-Gómez, J. A., Capote, R., & Hernández, W. (2012). Paleoseismic analysis of the San Vicente segment of the El Salvador Fault Zone, El Salvador, Central America. *Geologica Acta*, *10(2)*, 103–123. https://doi.org/10.1344/105.000001700

Carr, M. J. (1976). Underthrusting and Quaternary faulting in northern Central America. *Bulletin of the Seismological Society of America*, *87*, 825–829.

Case, J. E., & Holcombe, T. L. (1980). *Geologic-tectonic map of the Caribbean region (No. 1100)*.

Corti, G., Carminati, E., Mazzarini, F., & Garcia, M. O. (2005). Active strike-slip faulting in El Salvador, Central America. *Geology*, *33*(12), 989–992. https://doi.org/10.1130/G21992.1

Cowan, H., Prentice, C., Pantosti, D., de Martini, P., Strauch, W., & Workshop Participants. (2002). Late Holocene Earthquakes on the Aeropuerto Fault, Managua Nicaragua. *Bulletin of the Seismological Society of America*, *92*(5), 1694–1170. https://doi.org/10.1785/0120010100

Cox, R. T., Lumsden, D. N., Gough, K., Lyod, R., & Talnagi, J. (2008). Investigation of late Quaternary fault block uplift along the Motagua/Swan Islands fault system: Implications for seismic/tsunami hazard for the Bay of Honduras. *Tectonophysics*, *457*(1-2), 30–41. https://doi.org/10.1016/j.tecto.2008.05.014

DeMets, C., Gordon, R. G., & Argus, D. F. (2010). Geologically current plate motions. *Geophysical Journal International*, *181*(1), 1–80. https://doi.org/10.1111/j.1365-246X.2009.04491.x

DeMets, C., Mattioli, G., Jansma, P., Rogers, R., Tenorio, C., & Turner, H. L. (2007). Present motion and deformation of the Caribbean plate: Constraints from new GPS geodetic measurements from Honduras and Nicaragua, in Geologic and Tectonic Development of the Caribbean Plate in Northern Central America, Geol. Soc. Am. Spec. Paper, ed. Mann P., 428, 21–36. The Geological Society of America, Boulder. https://doi.org/10.1130/2007.2428(02)

Dixon, T. H., Farina, F., DeMets, C., Jansma, P., Mann, P., & Calais, E. (1998). Relative motion between the Caribbean and North American plates and related boundary zone deformation from a decade of GPS observations. *Journal of Geophysical Research*, *103*(B7), 15157–15182. https://doi.org/10.1029/97JB03575

Ellis, A., DeMets, C., Briole, P., Cosenza, B., Flores, O., Graham, S. E., Guzmán-Speziale, M., Hernández, D., Kostoglodov, V., LaFemina, P., Lord, N., Lasserre, C., Lyon-Caen, H., Rodriguez Maradiaga, M., McCaffrey, R., Molina, E., Rivera, J., Rogers, R., & Staller, A. (2018). GPS constraints on deformation in northern Central America from 1999 to 2017, Part 1 - Time-dependent modelling of large regional earthquakes and their post-seismic effects. *Geophysical Journal International*, *214*(3), 2177–2194. https://doi.org/10.1093/gji/ggy249

Ellis, A., DeMets, C., McCaffrey, R., Briole, P., Cosenza Muralles, B., Flores, O., Guzmán-Speziale, M., Hernández, D., Kostoglodov, V., LaFemina, P., Lord, N., Lasserre, C., Lyon-Caen, H., Rodriguez Maradiaga, M., Molina, E., Rivera, J., Rogers, R., Staller, A., & Tikoff, B. (2019). GPS constraints on deformation in northern Central America from 1999 to 2017, Part 2: Block rotations and fault slip rates, fault locking and distributed deformation. *Geophysical Journal International*, *218*(2), 729–754. https://doi.org/10.1093/gji/ggz173

Ferrari, L., Pasquare, G., & Zilioli, E. (1994). Kinematics and seismotectonics of a segment of the North America-Caribbean plate boundary: a remote sensing and field study of the Jocot´an fault system in Guatemala. *Proceedings SPIE 2320, Geology from Space*. https://doi.org/10.1117/12.197300.

Franco, A., Lasserre, C., Lyon-Caen, H., Kostoglodov, V., Molina, E., Guzman-Speziale, M., Monterosso, D., Robles, V., Figueroa, C., Amaya, W., Barrier, E., Chiquin, L., Moran, S., Flores, O., Romero, J., Santiago, J. A., Manea, M., & Manea, V. C. (2012). Fault kinematics in northern Central America and coupling along the subduction interface of the Cocos Plate, from GPS data in Chiapas (Mexico), Guatemala and El Salvador:

Kinematics in northern Central America. *Geophysical Journal International*, *189*(3), 1223–1236. https://doi.org/10.1111/j.1365-246X.2012.05390.x
Funk, J., Mann, P., McIntosh, K., & Stephens, J. (2009). Cenozoic tectonics of the Nicaraguan depression, Nicaragua, and Median trough, El Salvador, based on seismic reflection profiling and remote sensing data. *Geological Society of America Bulletin*, *212*(11-12), 1491–1521. https://doi.org/10.1130/B26428.1.
Garibaldi, N., Tikoff, B., & Hernandez, W. (2016). Neotectonic deformation within an extensional stepover in El Salvador magmatic arc, Central America: Implication for the interaction of arc magmatism and deformation. *Tectonophysics*, *693*, 327–339. https://doi.org/10.1016/j.tecto.2016.05.015.
Garnier, B., Tikoff, B., Flores, O., Jicha, B., DeMets, C., Cosenza-Muralles, B., Hernandez, D., Marroquin, G., Mixco, L., & Hernandez, W. (2021). An integrated structural and GPS study of the Jalpatagua fault, southeastern Guatemala. *Geosphere*, *17*(1), 201–225. https://doi.org/10.1130/GES02243.1.
Giunta, G., & Orioli, S. (2011). The Caribbean plate evolution: Trying to resolve a very complicated tectonic puzzle. In E. Sharkov (Ed.), *New Frontiers in Tectonic Research - General Problems, Sedimentary Basins and Island Arcs*. InTech. https://doi.org/10.5772/18723
Gordon, M. B., & Muehlberger, W. R. (1994). Rotation of the Chortis block caused dextral slip on the Guayape fault. *Tectonics*, *13*(4), 858–872. https://doi.org/10.1029/94TC00923
Guzmán-Speziale, M. (2001). Active seismic deformation in the grabens of northern Central America and its relationship to the relative motion of the North America-Caribbean plate boundary. *Tectonophysics*, *337*(1-2), 39–51. https://doi.org/10.1016/S0040-1951(01)00110-X
Guzman-Speziale, M. (2010). - Beyond the Motagua and Polochic faults: Active strike-slip faulting along the Western North America–Caribbean plate boundary zone. *Tectonophysics*, *496*(1-4), 17–27. https://doi.org/10.1016/j.tecto.2010.10.002
Guzman-Speziale, M., & Molina, E. (2022). - Seismicity and seismically active faulting of Guatemala: A review. *Journal of South American Earth Sciences*, *115*, 103740. https://doi.org/10.1016/j.jsames.2022.103740
Guzmán-Speziale, M., Pennington, W. D., & Matumoto, T. (1989). The triple junction of the North America, Cocos, and Caribbean plates: Seismicity and tectonics. *Tectonics*, *8*(5), 981–997. https://doi.org/10.1029/TC008i005p00981
Husid, R., Espinosa, A. F., & Quesada, A. (1976). Damage and engineering implications. In A. Espinosa (Ed.), *The Guatemala Earthquake of February 4, 1976, a Preliminary Report, Vol. 1002*. United States Geological Survey Professional Paper, p. 90
La Femina, P. C., Dixon, T. H., & Strauch, W. (2002). Bookshelf faulting in Nicaragua. *Geology*, *30*(8), 751–754. https://doi.org/10.1130/0091-7613(2002)030
Lyon-Caen, H., Barrier, E., Lasserre, C., Franco, A., Arzu, I., Chiquin, L., Chiquin, M., Duquesnoy, T., Flores, O., Galicia, O., Luna, J., Molina, E., Porras, O., Requena, J., Robles, V., Romero, J., & Wolf, R. (2006). Kinematics of the North American–Caribbean-Cocos plates in Central America from new GPS measurements across the Polochic-Motagua fault system. *Geophysical Research Letters*, *33*(19), L19309. https://doi.org/10.1029/2006GL027694
Mann, P., Draper, G., & Lewis, J. F. (1991). An overview of the geologic and tectonic development of Hispaniola, in Geologic and Tectonic Development of the North America – Caribbean Plate Boundary in Hispaniola, edited by P. Mann, G. Draper, and J. F. Lewis, Spec. Pap. Geol. Soc. Am., 262, 1–28.
Mann, P, Schubert, C, Burke, K, Dengo, G, & Case, J E. (1990). The Caribbean Region. In *Review of Caribbean neotectonics* (pp. 307–338). Boulder, CO: The Geological Society of America.
Martínez-Díaz, J. J., Álvarez-Gómez, J. A., Benito, B., & Hernández, D. (2004). Triggering of destructive earthquakes in El Salvador. *Geology*, *32*(1), 65–68. https://doi.org/10.1130/G20089.1
Olcese, O., Moreno, R., & Ibarra, F. (1977). The Guatemala Earthquake Disaster of 1976: A review of its effects and of the Contribution of the United Nation family. United Nations Development Programme, Guatemala, p. 24.
Plafker, G. (1976). Tectonic aspects of the Guatemala earthquake of 4 February 1976. *Science*, *193*(4259), 1201–1208. https://doi.org/10.1126/science.193.4259.1201
Rodriguez, M., DeMets, C., Rogers, R., Tenorio, C., & Hernandez, D. (2009). A GPS and modelling study of deformation in northern Central America. *Geophysical Journal International*, *178*(3), 1733–1754. https://doi.org/10.1111/j.1365-246X.2009.04251.x
Rogers, R. D., & Mann, P. (2007). Transtensional deformation of the western Caribbean-North America plate boundary zone, in Geologic and Tectonic Development of the Caribbean Plate Boundary in Northern Central America, pp. 37–64, ed. Mann P. Geol. Soc. Am. Spec. Paper 428, The Geological Society of America, Boulder, doi:10.1130/2007.2428(02).
Sampietro, D., Reguzzoni, M., & Negretti, M. (2014). The GEMMA crustal model: First validation and data distribution. Proc. "ESA Living Planet Symposium 2013", Edinburgh, UK, 9-13 September.
Schwartz, D. P., Cluff, L. S., & Donnelly, T. W. (1979). Quaternary faulting along the Caribbean-North American plate boundary in Central America. *Tectonophysics*, *52*(1-4), 432–445. https://doi.org/10.1016/0040-1951(79)90258-0
Staller, A., Martínez-Díaz, J. J., Benito, B., Alonso-Henar, J., Hernández, D., Hernández- Rey, R., & Díaz, M. (2016). Present-day crustal deformation along the El Salvador fault zone from ZFESNet GPS network. *Tectonophysics*, *670*, 66–81. https://doi.org/10.1016/j.tecto.2015.12.017
Styron, R. (2008). *Kinematics of the Western Margin of Nicaragua from GPS Geodesy* [Master's thesis]. University of Arkansas, Fayetteville.
Styron, R., García-Pelaez, J., & Pagani, M. (2020). CCAF-DB: the Caribbean and Central American active fault database. *Natural Hazards and Earth System Sciences*, *20*(3), 831–857. http://doi.org/10.5194/nhess-20-831-2020
Turner, H. L., LaFemina, P., Saballos, A., Mattioli, G. S., Jansma, P. E., & Dixon, T. (2007). Kinematics of the Nicaraguan forearc from GPS geodesy. *Geophysical Research Letters*, *34*(2), 302. http://doi.org/10.1029/2006GL027586.
Ward, P. L., Gibbs, J., Harlow, D., Aburto, A. (1974). Aftershocks of the Managua, Nicaragua, earthquake and the tectonic significance of the Tiscapa Fault. *Bulletin of the Seismological Society of America*, *64*, 1017–1030.
White, R. A. (1984). Catalog of historic seismicity in the vicinity of the Chixoy–Polochic and Motagua

faults, Guatemala. U. S. Geol. Surv. Open–File Rep. 84–88. 34 pp.
White, R. A. (1985). The Guatemala earthquake of 1816 on the Chixoy-Polochic fault. *Bulletin of the Seismological Society of America*, *75*, 455–473.
White, R. A., & Harlow, D. H. (1993). Destructive upper-crustal earthquakes in Central America since 1900. *Bulletin of the Seismological Society of America*, *83*(4), 1115–1142. https://doi.org/10.1785/BSSA0830041115
Woodward-Clyde Associates. (1975). Investigation of active faulting in Managua, Nicaragua, and vicinity. Final report to Vice Ministerio de Planificacion Urbana, Gobierno de la Republica de Nicaragua.