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Tsunamis and Tsunami Hazards in Central America

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Abstract. A tsunami catalogue for Central America is compiled containing 49 tsunamis for the period 1539–1996, thirty seven of them are in the Pacific and twelve in the Caribbean. The number of known tsunamis increased dramatically after the middle of the nineteenth century, since 43 events occurred between 1850 and 1996. This is probably a consequence of the lack of population living near the coast in earlier times.

The preliminary regionalization of the earthquakes sources related to reported tsunamis shows that, in the Pacific, most events were generated by the Cocos-Caribbean Subduction Zone (CO-CA). At the Caribbean side, 5 events are related with the North American-Caribbean Plate Boundary (NA-CA) and 7 with the North Panama Deformed Belt (NPDB).

There are ten local tsunamis with a specific damage report, seven in the Pacific and the rest in the Caribbean. The total number of casualties due to local tsunamis is less than 455 but this number could be higher. The damages reported range from coastal and ship damage to destruction of small towns, and there does not exist a quantification of them.

A preliminary empirical estimation of tsunami hazard indicates that 43% of the large earthquakes ($Ms \geqslant 7.0$) along the Pacific Coast of Central America and 100% along the Caribbean, generate tsunamis. On the Pacific, the Guatemala–Nicaragua coastal segment has a 32% probability of generating tsunamis after large earthquakes while the probability is 67% for the Costa Rica–Panama segment. Sixty population centers on the Pacific Coast and 44 on the Caribbean are exposed to the impact of tsunamis. This estimation also suggests that areas with higher tsunami potential in the Pacific are the coasts from Nicaragua to Guatemala and Central Costa Rica; on the Caribbean side, Golfo de Honduras Zone and the coasts of Panama and Costa Rica have major hazard. Earthquakes of magnitude larger than 7 with epicenters offshore or onshore (close to the coastline) could trigger tsunamis that would impact those zones.

Key words: tsunamis, earthquakes, tsunami hazard, wave.

1. Introduction

Over 51,000 coastal residents have been killed by 94 destructive tsunamis in the past century (El-Sabh, 1995). In recent times, the large earthquake in the Moro Gulf in Philippines (August, 1976) killed over 8,000 people and the last big tsunami in Papua Guinea in 1998 killed over 2,000 people (Kawata *et al.*, 1999). These data clearly indicate that tsunamis, like volcanic eruptions, earthquakes, landslides and hurricanes, are still provoking great disasters and killing human beings.

Tsunamis are classified into three categories, distant (> 750 km from the source), regionals (100–750 km from the source), and local (< 100 km from the source). The Central American Coasts, as some other areas in the world, are exposed to the three types of tsunamis, but mainly to the local ones. The last tsunami in the area, in Nicaragua (Kanamori and Kikuchi, 1993), is real evidence of the tsunami hazard in this very active seismic zone. Even though the Central American Coast have been hit by 34 well documented tsunamis, there was no consciousness about tsunami-hazard before the Nicaragua case. It was just after that event, that people seriously considered the destructive effects of tsunamis and some ideas came out to protect coastal residents. Sponsored by CEPREDENAC (Centro para la Prevención de Desastres Naturales en América Central), an exhaustive investigation on Central America's tsunamis was started in 1997 and a tsunami catalogue, containing historical tsunami data that were scattered in different sources, was compiled (Molina, 1997). This catalogue is the most complete document concerning tsunamis in the Central American Region, as it has more data than any other previous work.

The results presented in this study are largely based on Molina (1997) and summarize tsunami occurrences and hazard in Central America. The spatial and temporal distribution of the catalogue are: 6-18N and 93-77W, and from 1539 to 1996, respectively. Most of the entries were compiled from previous earthquake and tsunami catalogues, both regional and local. Macroseismic information is included in the catalogue in order to relate it with the tsunami phenomenon. The quality of the reports for the tsunamis in the region is variable, but as a general rule we include all the events reported as tsunami in the previous catalogues or in specific studies. Based on this catalogue, a preliminary empirical estimation of tsunamic hazard was done. This is the first step in establishing a reliable Tsunami Warning System in Central America.

2. Tectonic Setting

The tectonic setting of Central America is given by the interaction of the Cocos, Caribbean and Nazca plates (Figure 1). The Cocos Plate subducts under the Caribbean Plate along the Middle American Trench; from Mexico to Central Costa Rica, the subduction process is normal and the Wadatti-Bennioff zone is well defined by intermediate and deep earthquakes. But in southern Costa Rica, subduction becomes more shallow due to the presence of Cocos Ridge. This ridge collided with the Caribbean Plate ca 5 Ma (de Boer *et al.*, 1995), generating a bouyant effect that makes it difficult to penetrate under the Caribbean Plate. That effect is responsible for the lack of deep seismicity there as well as for the inhibiting of volcanism and uplift of the Talamanca Range, Costa Rica (Montero *et al.*, 1992).

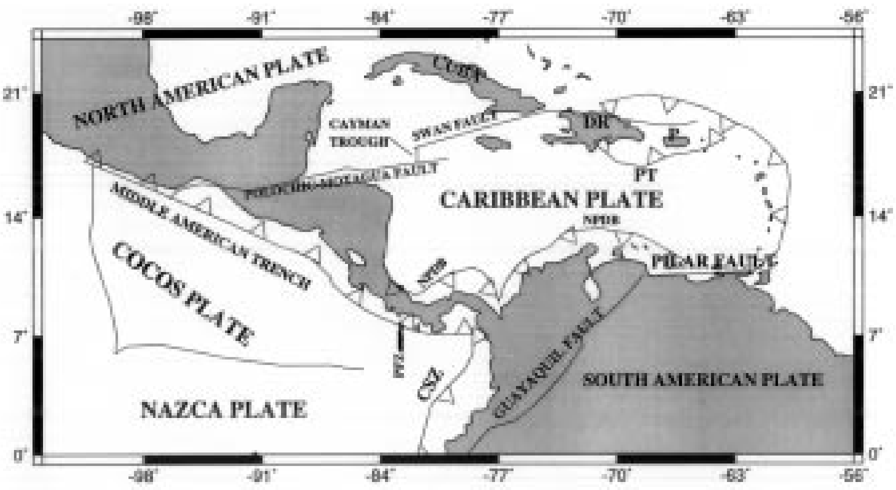

Figure 1. Tectonic setting. NPDB: North Panama Deformed Belt, PFZ: Panama Fracture Zone, CSZ: Colombia Subduction Zone, PT: Puerto Rico Trench. DR: Dominican Republic, P: Puerto Rico. Based on Calais *et al.*, 1992.

The limit between Cocos and Nazca plates is the Panama Fracture Zone (PFZ). The PFZ is composed of north-south trending faults located in front of the Pacific Coast of Costa Rica and Panama. The boundary between the Caribbean Plate and Nazca Plate is still ambiguous, some authors consider it as a subduction zone (Di Marco *et al.*, 1995; Kolarsky and Mann, 1995) and others as a strike-slip fault (Kellogg and Vega, 1995; Westbrook *et al.*, 1995). The Panama Deformed Belt lies towards the Caribbean coast of Costa Rica (Bowin, 1976) and it is a convergent margin.

The Northern boundary of the Caribbean Plate is a strike-slip fault system that include the Polochic–Motagua–Chamalecon faults and the Swan Fault, both separated by Cayman Trough. The system crosses southern Cuba and ends in the eastern Dominican Republic where frontal subduction of the Lesser Antilles begins. This subduction zone is the eastern limit of Caribbean Plate. Toward the South, the Caribbean Plate is bounded by South American Plate along the Pilar Fault Zone.

3. Seismicity and Large Earthquakes of Central America

The data used in this section are from the seismological database of the Central America Seimological Center (CASC, Alvarenga et al.,1998). This database contains the source parameters of more than one hundred thousand earthquakes which occurred within the Central American Region from 1500 to the present. In this study only earthquakes with magnitude larger than 5 are used.

The epicentral distribution of earthquakes (Figure 2) clearly shows a high level of seismic activity along the whole Middle American Trench. Also the Panama Fracture Zone (PFZ) has intense seismic activity; the earthquakes in this zone

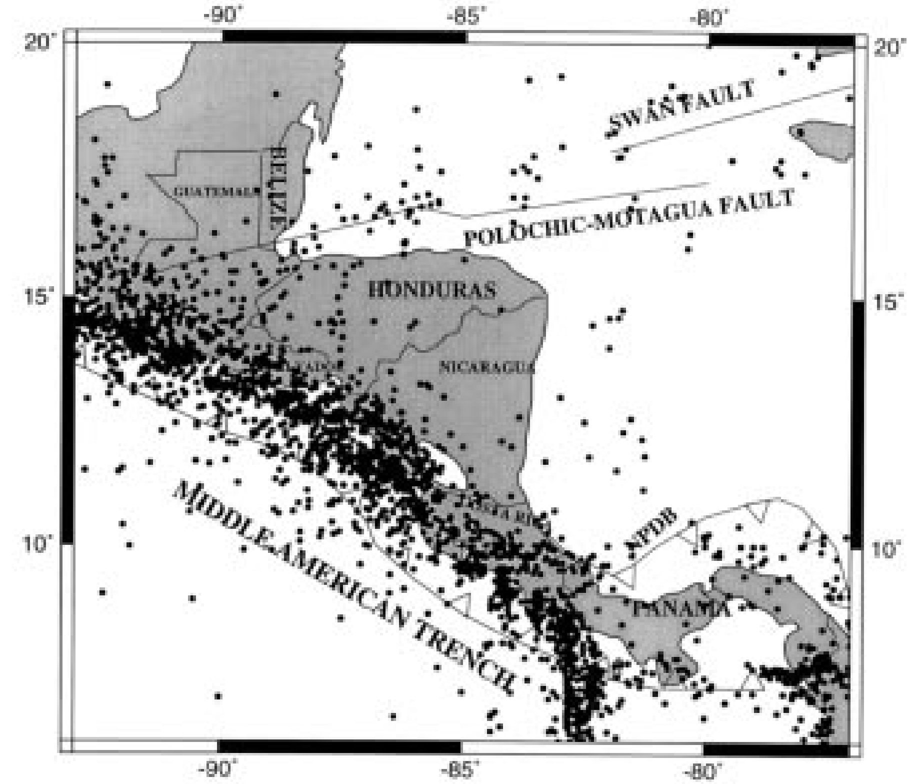

Figure 2. Seismicity of Central America. Only earthquakes of magnitude (M_S) larger 5.0 were included in this figure. NPDB: North Panama Deformed Belt.

reflect very well the tectonic activity along the north-south faults that compose the PFZ. The tectonic boundary between the Caribbean and North American Plate, the Polochic-Motagua Fault System, is also delineated by the seismicity; both inland and onshore segments of this system have important seismicity. The North Panama Deformed Belt (NPDB) is the tectonic environment with the lowest rate of earthquake occurrence with respect to other areas in Central America, nevertheless large earthquakes have originated there in the last two centuries.

Large earthquakes of Central America have been studied by several authors (Chael and Stewart, 1982; Cruz and Wyss, 1983; Rojas *et al.*, 1993a, and Ambraseys and Adams, 1996). The main findings are that most earthquakes are shallow and related to the Cocos-Caribbean Subduction Zone. Ambraseys and Adams (1996), studying large earthquakes of Central America for the period 1898–1994, found that the total moment release in the whole region is 917×10^{26} dyn cm and 93 per cent of this total moment was released along the Middle American Trench, which shows how much more active this part of the region is.

Regarding the depth of the earthquakes, they can be separated in two populations shallow (0–30 km) and intermediate (40–200 km) depth earthquakes (Rojas *et* *al.*, 1993b). There are not earthquakes deeper than 200 km. The deepest seismicity is in the Central part of MAT (Guatemala–Nicaragua). In the north (Mexico) the seismic activity suggests a more shallow mode of subduction (Chael and Stewart, 1982) and similarly in the South where there is no seismicity under 50 km (Protti *et al.*, 1994).

4. Tsunamis

Several previous works have information about tsunamis of Central America. The most important ones are Iida *et al.* (1967), Sutch (1981), Cruz and Wyss (1983), Soloviev and Go (1984), Fernandez *et al.* (1993), and Ambraseys and Adams (1996). Four of these studies deal with tsunami catalogues (two about world-wide tsunamis and two are related to tsunamis of the Central American Region) and the other two are investigations concerning large earthquakes in Central America. Of these surveys, Soloviev and Go (1984) and Ambraseys and Adams (1996) have more tsunamis than any other, 19 and 15 respectively which is about 1/3 of the known in the region. The remaining information about Central America's tsunamis are scattered in specific studies, many of which are not usually available. Due to this problem, we have compiled the whole data set of known tsunamis, giving the most complete information available and creating a good empirical base for evaluating tsunami hazard in Central America.

4.1. TSUNAMIS ON THE CARIBBEAN COAST OF CENTRAL AMERICA

It is well known that the seismicity on the Caribbean Coast of Central America is low. If the probability of tsunami occurrence is proportional to the rate of seismicity, the possibility of finding tsunamis should be lower. Surprisingly, after having investigated all sources of information available, it was found that the area has have been hit by tsunamis which have caused severe damage and loss of life. The total number of tsunamis is 12 (Table 1). It is important to note that because the tsunamigenic earthquakes are the largest in the region, few of them could be grossly mislocated except the oldest earthquakes. Anyway, the most accurate hypocentral determinations are used in this work in order to avoid mislocations, especially those of Ambraseys and Adams (1996), the most recent study about large earthquakes in the area.

Four earthquakes corresponding to tsunamis that hit Honduras Gulf Coasts do not have location and are therefore not included in Figure 3. In spite of this, their origin is attributed to the interaction between the North American and Caribbean plates. This is quite probable because all those events were strongly felt in or near Honduras (Sutch, 1981). Most recent earthquakes generating tsunamis that hit Caribbean coasts of Central America originated at NOAM-CA or at NPDB and their focus are therefore shallow (Table 1).

Table I. Earthquakes and tsunamis at the Caribbean coast of Central America

No.	Time	Earthquake					Tsunami			Tect. Env.
		Lat	Lon	D	M_s	LS	Location	R-u(m)	tm	
1	1539 – 1124						Honduras Gulf			NOAM-CA
2	1798 – 0222	10.2	82.9			CV	Matina, CR		−1	MATINA NEST
3	1822 – 0507	09.5	83.0		7.6	CV	Matina, CR		−1	NPDB
4	1825 – 02..				5–5.5		Honduras Gulf			NOAM-CA
5	1855 – 0925				6–6.5		Honduras Gulf			NOAM-CA
6	1856 – 0804				7–8.0		Honduras Gulf	5	2	NOAM- CA
7	1873 – 1014	10.2	80.0			CV	Colon Harbor, PAN			NPDB
8	1882 – 0907	10.0	79.0		7.9	CV	San Blas, PAN	3	1	NPDB
9	1904 – 1220	09.2	82.8	25	7.3	AA	Bocas Toro, PAN			NPDB or CO-CA
10	1916 – 0426	09.2	83.1	S	6.9	AA	Bocas Toro, PAN	1.3	0	NPDB
11	1976 – 0204	15.2	89.2	5	7.5	AA	Honduras Gulf	0.45	−0.5	NOAM-CA
12	1991 – 0422	09.6	83.2	20	7.6	AA	Bocas Toro, PAN	3	1	NPDB

Lat: Latitude, Lon: Longitude, D: Depth (km) M_s, LS: Source of the earthquake location data, R-u: Run-up, m: meters, tm: tsunami magnitude, and Tect. Env: the tectonic enviroment where the earthquake took place, CV: Camacho and Viquez (1993a), AA: Ambraseys and Adams (1996). NOAM-CA means North America-Caribbean plate boundary and NPDB North Panama Deformed Belt. Matina Nest is a small cluster of epicenters located in front of Caribbean Coast of Costa Rica.

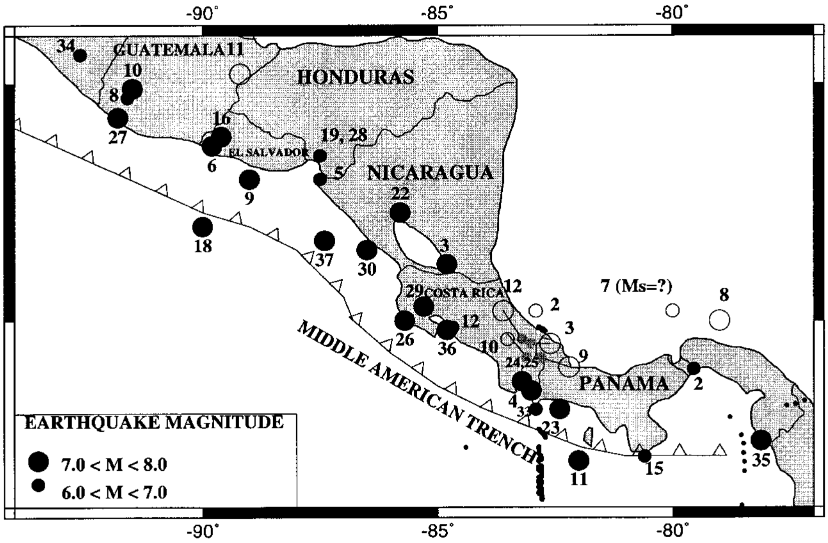

Figure 3. Epicenters of tsunamigenic earthquakes on the Caribbean (open circles) and Pacific (black circles) coast of Central America. The number attached is the number of the earthquake in Tables 1 and 2.

Figure 3 shows epicenters of 8 earthquakes (gray circles) that caused tsunamis in Caribbean coasts of Central America. Only one event from NOAM-CA is shown, which is the 7.5 magnitude earthquake that destroyed Guatemala City in 1976. Seven earthquakes occurred close to NPDB, most of them in the thrust faulting inland Caribbean side of Costa Rica (cluster close to Costa Rica-Panama border). One of these earthquakes is the Limon (Costa Rica) Earthquake (M_s 7.6) that hit strongly several localities of Costa Rica and Panama, killing almost one hundred people. That event produced a tsunami whose maximum amplitude was 3 meters.

Note that most of these tsunamigenic earthquakes originated inland. Guatemala (no. 11) and Limon (no. 12) are good examples of inland tsunamigenic earthquakes. Most of the largest earthquakes of the Caribbean coast of Central America have only generated small tsunamis, since epicenters were inland.

4.2. DAMAGE, EFFECTS AND COMMENTS ABOUT CARIBBEAN TSUNAMIS

Details of the tsunamis as well as the references are described in Table 2. Tsunami magnitudes are based on the effects as described in Table 2. The definition of the tsunami magnitude scale is given in Appendix 1.

Most of these tsunamis are small and they caused little damage. Nevertheless, three of them had sea waves larger than 3 m and one a sea wave higher than 5 m. Entire localities have been destroyed by tsunamis on the Atlantic coast of Central America. Only reports about the San Blas tsunami (1882) mention dead people,

Table II. Damage, effects, comments and references of Caribbean Tsunamis

No.	Date	Damage, effects, comments and references
1	1539 – 1124	A violent seaquake was felt by people on a ship (Montessus de Ballore, 1888; Sutch, 1981).
2	1798 – 0222	After the earthquake the sea became more agitated being possible an inundation (Gonzalez, 1910; Peraldo and Montero, 1994).
3	1822 – 0507	Rivers and bays grew and caused floods. In Bocas del Toro, a resident mentioned the existence of a report about a Tsunami that happened in this region between 1820 and 1830 (Roberts, 1829; Montessus de Ballore, 1888; Gonzalez, 1910; Montero, 1986; Camacho and Viquez, 1993a; Boschini and Montero, 1994).
4	1825 – 02..?	A shock was reported by passangers on a boat. A rumbling noise was heard (Mallet and Mallet, 1858; Montessus de Ballore, 1888; Rockstroch, 1902; Sieberg, 1932; Sutch, 1981).
5	1855 – 0925	The ship Simpronius was suddenly lifted up and brusquely dropped , creating a wave (Kluge, 1863; Montessus de Ballore, 1888; Sucth, 1981).
6	1856 – 0804	At Omoa, the sea fell and rose to a height of 5 m in still weather. Damage in towns like Cortez, Atlantida, Trujillo and Criba Lagoon. There are accounts of the complete ruin of Omoa, destruction of entire villages and rivers changing directions. The sea retreated and then returned increasing damage. The sea was elevated 5 meters at the base of the port. (Montessus de Ballore, 1888; Boscowitz, 1885; Milne, 1912; Sieberg, 1932; Heck, 1947; Montandon, 1962; Iida *et al.*, 1967; Sutch, 1981; Cruz and Wyss, 1983; Soloviev and Go, 1984).
7	1873 – 1014	A shock was strongly felt on board the ships in the harbour. In Aspinwal the people were much frightened and fear of the tidal wave added to the excitement (Camacho and Viquez, 1993a)
8	1882 – 0907	The earthquake caused a tsunami which affected the San Blas coast, northeastern Panama, with waves 3.0 m high or more. These waves washed most of the islands of the San Blas Archipelago out. Between seventy five and one hundred natives were drowned. More than 50 dead most of them drowned A large tsunami associated with the earthquake swept the San Blas Islands in northern Panama on 7 September 1882, killing about 65 people. The tide ran out a great distance, and on its return, swept away the villages built on the beaches of different islands of the archipelago and on the mainland. The vessel Honduras felt a seaquake, preceded by a rumbling. The sea began to move rapidly and the vessel also began to move (Bulletin du Canal Interoceanique, 1882; Montessus de Ballore, 1888, Nelson, 1889; Milne, 1912; Sieberg, 1932; Tabor, 1967; Iida *et al.*, 1967; Grases, 1974; Soloviev and Go, 1984; Mendoza and Nishenko, 1989; Grases, 1990; Camacho and Viquez, 1993b).
9	1904 – 1220	The shock was strongly felt on a ship. Part of the islet Sapodilla subsided. The Crew of the United States Warship DIXIE (at anchor) severely felt the shock and were alarmed. (Oddone, 1907; Gonzalez, 1910; Camacho and Viquez, 1993a; Ambraseys and Adams, 1996).

Table II. Continued

No.	Date	Damage, effects, comments and references
10	1916 – 0426	The sea wave carried canoes and debris 200 m inland and destroyed storage tanks. The wave flooded Bastimentos, Isla de Carenero and others part of the coast A small tsunami throw litter and canoes some two hundred meters ashore. Sea flowed over knee deep into the land. A tsunami which affected Caranero and Colon Islands was reported, the wave was 50 cm high. A 4 feet high wave flooded Isla Caranero. The shock was severely felt on a ship. (Kirkpatrick, 1920; Reid, 1917; Feldman, 1984; Guendel, 1986; Viquez and Toral, 1987; Camacho and Viquez, 1992; Camacho and Viquez, 1993a; Ambraseys and Adams, 1996).
11	1976 – 0204	A tsunami with a maximum amplitude of 45 cm was recorded on the Puerto Cortes tide gauge (Espinosa, 1976; Buckman *et al.*, 1978; Kanamori and Stewart, 1978, Young *et al.*, 1989; Ambraseys and Adams, 1996.
12	1991 – 0422	A seismic sea wave with 2.0 m high was recorded at San Cristobal. This wave affected the whole coast from north of Limon to Panama. The maximum amplitude of the wave at the gauge of Coco Solo was 76 cm. A tsunami with wave heights of 2 to 3 m was observed along the coast from Cahuita (Costa Rica) to Bastimentos Island (Panama). This wave flooded from 10 to 200 m inland and was also recorded in Puerto Rico and Virgin islands (Plafker and Ward, 1992; Denyer *et al.*, 1992, Barquero and Rojas, 1994; Camacho, 1994; Ambraseys and Adams, 1996.

75–100 in that case. It is amazing that in spite of the complete destruction of Omoa by the tsunami of 1856, nobody was reported dead.

4.3. TSUNAMIS ON THE PACIFIC COAST OF CENTRAL AMERICA

The largest tsunamis of Central America have taken place at the Pacific Coast. This is normal considering that the most active margin of Caribbean Plate is the Middle American Trench that is located in front of the Pacific Coast of Central America. According to Molina (1997), 37 tsunamis have hit those coasts. In Table 3 we summarize both earthquake and tsunami parameters.

In summary, there are 37 reports of tsunamis of the Pacific Coast of Central America, where 23 originated from subduction earthquakes due to the interaction between Cocos and Caribbean plates, one from Panama Fracture Zone, two from shallow faults, one at the interaction between North American and South American plates and six remain without identification of their tectonic environment. Based on this data set, it seems that CO-CA is the most important tectonic environment to generate tsunamigenic earthquakes on the Pacific Coast of Central America.

Only 17 of these have tsunami magnitudes (tm) reported. The magnitudes of these events are in the range (-3)–(2.5). The largest tsunamis of this area were the Guatemala-Salvador Tsunami (1902) with magnitude 2 and The Nicaragua

Table III. Parameters of earthquakes and tsunamis of the Pacific Coast

No.	Time	Earthquake					Tsunami			Tect. Env.
		Lat	Lon	D	M_s	LS	Location	R-u(m)	tm	
1	1579 – 0316						Isla de Cano, CR			CO-CA
2	1621 – 0502	08.97	79.55			VC	Panama, la Vieja			Canal Discont.
3	1844 – 05..	11.20	84.80	130	7.4	R	Nicaragua Lake			CO- CA
4	1854 – 0805	08.50	83.00	33	7.3	R	Golfo Dulce, CR		1.5	CO-CA
5	1859 – 0826	13.00	87.50		6.2	M	Fonseca Gulf, HON		1.5	CO-CA
6	1859 – 1209	13.75	89.75	40	7.0	SG	Acajutla Bay, SAL		1.5	CO-CA
7	1884 – 1105	40.00	76.00	100	7.5	R	Acandi, Colombia			NPDB
8	1902 – 0118	14.70	91.60	> 40	6.3	A	Ocos, Guatemala			CO-CA
9	1902 – 0226	13.00	89.50	30	7.0	R	P. Coast GUA/SAL		2	CO-CA
10	1902 – 0419	14.90	91.50	< 60	7.5	AA	Ocos, Guatemala		−1	CO-CA
11	1904 – 0120	07.00	82.00	S	7.0	AA				CO-CA
12	1905 – 0120	09.85	84.68	45	6.8	R	Coco island, CR			CO- CA
13	1906 – 0131	01.00	81.30		8.1	PS	ECUA, PAN, CR	2–5		NA-SU
14	1906 – ..						S. Coast, SAL			
15	1913 – 1002	07.10	80.60	S	6.7	AA	Azuero, PAN		−1	Azuero Fault
16	1915 – 0907	13.90	89.60	60	7.7	AA	S. Coast, SAL		0.5	CO-CA
17	1916 – 0131						Pan. Canal, PAN			
18	1916 – 0525	12.00	90.00		7.5	H	El Salvador			
19	1919 – 0629	13.50	87.50	> 40	6.7	AA	Corinto, NIC			CO- CA
20	1919 – 1212						El Ostial, NIC			CO-CA
21	1920 – 1206						Fonseca Gulf, HON			
22	1926 – 1105	12.30	85.80	135	7.0	AA	Offshore NIC			CO- CA
23	1934 – 0718	08.10	82.60	S	7.5	AA	Chiriqui Gulf, PAN	0.60	1.5	PFZ
24	1941 – 1205	08.70	83.20	S	7.6	AA	Dominical, CR	0.22	−1	CO-CA
25	1941 – 1206	08.76	83.48		6.9	R	Nicoya Gulf, CR	0.08	−2	CO-CA
26	1950 – 1005	10.00	85.70	< 60	7.7	AA	CR, NIC, SAL		−1	CO-CA
27	1950 – 1023	14.30	91.80	S	7.3	AA	Coast GUA/SAL		−1	CO-CA
28	1951 – 0803	13.00	87.50	100	6.0	L	Fonseca Gulf, HON			CO-CA
29	1952 – 0513	10.30	85.30	32	7.0	CW	Puntarenas, CR	0.10	−3	CO-CA
30	1956 – 1024	11.50	86.50	S	7.2	AA	S. Juan Sur, NIC			CO- CA
31	1957 – 0310	51.63	171.4		8.1	PS	Acajutla, SAL	> 2		PA- NO
32	1960 – 0522	38.20	73.50	32	8.5	PS	GUA, SAL			NA-SU
33	1962 – 0312	08.10	82.90	30	6.7	CW	Chiriqui Gulf, PAN	0.30	−1	CO-CA
34	1968 – 0925	15.60	92.60	138	6.0	BSSA	Pacific Coast	1.9		
35	1976 – 0711	07.4	78.12	3	7.0	G	Darien, PAN		−1	
36	1990 – 0325	09.80	84.80	S	7.0	AA	Puntarenas, CR	1	0	CO-CA
37	1992 – 0902	11.70	87.40	S	7.2	AA	Nicaragua Coasts	9.5	2.5	CO-CA

S: Shallow earthquake with macroseismic or instrumental evidence for a focus in the upper crust, VC: Viquez and Camacho (1994), R: Rojas *et al.* (1993a), SG: Soloviev and Go (1984), A: Ambraseys (1995), AA: Ambraseys and Adams (1996), Pacheco and Sykes (1992), Hatori (1995), L: Leeds (1974), CW: Cruz and Wyss (1983), BSSA: Bulletin Seismological Society of America, 59, Grases, 1990.

Tsunami (1992) with magnitude 2.5. There are 26 earthquakes with reported depth, 14 of these events have shallow focus (0–30 km) and the rest are intermediate depth earthquakes.

Epicentral location of tsunamigenic earthquakes (black circles) at the Pacific side of Central America are plotted in Figure 3. As it can be see, all countries of the area have been hit by tsunamis. Fortunately, most of these tsunamis were small, causing little damage. Along the Pacific Coast, many tsunamigenic events are inland or close to the coast, which might have reduced the height of the sea waves.

Regional tsunamis from elsewhere in the Pacific have also hit the coasts of Central America. In 1957 an earthquake from the Aleutian Islands generated a tsunami that reached the coasts of El Salvador and caused extensive damage to coastal villages and killed people. The 8.5 magnitude Chile Earthquake in 1960 hit some coasts of Guatemala and Salvador, but neither damage nor deaths were reported at that occasion. Also the Tumaco (Ecuador) Tsunami was observed along the entire coast of Central America. One interesting tsunami affected the Fonseca Gulf, Honduras, in 1951, and historical reports pointed at Cosiguina Volcano (Nicaragua) as the trigger for this tsunami.

These tsunamis flooded villages, washed out houses, and produced great damage to property. Regarding the total number of casualties, only 355 were reported. However this might be a minimum because three tsunamis (Golfo Dulce Costa Rica, 1854; Pedasi Village, Panama, 1913 and Acajutla, El Salvador, 1957) caused large damage but no casualties were reported. The most tragic tsunamis in the Pacific Coast were the Guatemala-Salvador one in 1902 that killed 185 people and the Nicaraguan Tsunami in 1992 which killed 170 people.

The Nicaraguan event (1992) was a tsunami earthquake (Kanamori, 1972), an earthquake with a great disparity between the magnitude and the generated tsunami and also between M_s and M_w (Kanamori and Kikuchi, 1993). Because the energy of these earthquakes takes a long time to build up (Okal, 1994), they can be weekly felt. That was the case in Nicaragua, where many people did not feel the shock but were washed out by the sea waves. The horizontal inundation caused by this tsunami was of the order of few hundred meters. The tsunami earthquakes represent a serious problem for issuing a tsunami warning and remain a challenge for the all tsunami warning systems in the world because the tsunami potential can not be inferred from the seismic information. The latest approach regarding the identification of tsunami earthquakes was proposed by Shapiro *et al.*, 1998. They indicate that tsunami earthquakes have large total energy to high-frequency energy ratio (ER) and the disparity M_s–M_w is similar to M_E-ER disparity for these earthquakes. This finding might be very useful to identify tsunamigenic earthquakes and avoid false alarms.

It can be seen in Figure 3, that 16 of the earthquakes which triggered tsunamis on the Pacific Coast have epicenters inland and only 12 are located offshore. The first caused only very small damage and the maximum reported height for them

Table IV. Damage, effects, comments and references of tsunamis from the Pacific Coast

No.	Date	Damage, Effects, Comments and References
1	1579 – 0316	A ship was shaken and did quiver as if it had been laid on dry land (Gonzalez, 1910; Peraldo and Montero, 1994)
2	1621 – 0502	Tides almost flood La Calle de las Carreras (Salcedo, 1640; Viquez and Camacho, 1994).
3	1844 – 05..	Two rivers were reopened and Lake Nicaragua cascaded through the rapids causing damage. Seiches (?) in Lake Nicaragua. Water got out of Lake Nicaragua (Montessus de Ballore, 1888; Montessus de Ballore, 1884; Crawford, 1902; Milne, 1912; Montandon, 1962; Jorgensen, 1966; Leeds, 1974; Carr and Stoiber, 1977; Rojas *et al.*, 1993a).
4	1854 – 0805	The village of Golfo Dulce was flooded by the sea and destroyed (Perry, 1855, Montessus de Ballore, 1888; Soloviev and Go, 1984).
5	1859 – 0826	The houses suffered a great deal. Two vessels and a brigantine sank from the tsunami following the shock at La Union, El Salvador. Horrible situation in the sea, two canoes damaged. (Montessus de Ballore, 1888; Milne, 1912; Heck, 1947; Larde, 1960; Iida *et al.*, 1967; Sutch, 1981; Soloviev and Go, 1984.
6	1859 – 1209	The sea became very agitated at Acajutla port. High seawave and terrible noise. Sea retreated far from the shore; the docks and the river boat yards dried up almost to the breakwater. Cave and grottos collapsed. State warehouses were destroyed. The breakwater and the customhouse were flooded. Fish floundered on the beach and terraces (Perry, 1862; Montessus de Ballore, 1888; Milne, 1912; Larde, 1916; Heck, 1947; Montandon, 1962; Iida *et al.*, 1967; Soloviec and Go, 1984).
7	1884 – 1105	A seismic wave (this wave could be an earthquake or a tsunami) destroyed churches, state buildings and private homes (Milne, 1912; Sieberg, 1932; Iida *et al.*, 1969; Soloviev and Go, 1984).
8	1902 – 0108	Three sand ridges about 2 km long formed at Ocos. The visible ground waves were 25–30 m long and 25–30 cm high (Sapper, 1902, 1905; Montessus de Ballore, 1906; Anderson, 1908; Larde, 1916; Sieberg, 1932; Iida *et al.*, 1967; Soloviev and Go, 1984).
9	1902 – 0226	The coast of Ahuachapan in El Salvador from Garita Pamera to Barra del Paz and beyond (a distance of about 120 km) was flooded. Damage to the property. A loud rumble like cannon shots were heard. The sea water retreated and the sea bottom was exposed for a considerable distance. A large wave arose from the sea and reached the coast killing 100 persons in Barra de Santiago and 85 more in Barra del Paz. Homes and trees were washed out to sea. Three waves were observed. (Sapper, 1902, 1905; List, 1903; Montessus de Ballore, 1906; Anderson, 1908; Larde, 1916; Sieberg, 1932; Iida *et al.*, 1967; Soloviev and Go, 1984; Ambraseys and Adams, 1996).
10	1902 – 0419	Standing waves in Lake San Cristobal. The coast in the Ocos region subsided 1 m. (Rockstroch, 1902; Sapper, 1902, 1905; Montessus de Ballore, 1906; Anderson, 1908; Larde, 1916; Sieberg, 1932; Iida *et al.*, 1967; Soloviev and Go, 1984).

Table IV. Continued

No.	Date	Damage, Effects, Comments and References
11	1904 – 0120	On 21 January, the ship "City of Panama" encountered floating tree-trunks and bodies of dead animals floating on the Ocean Water. This could be the result of the earthquake which occurred the day before. (Oddone, 1907, Gonzales, 1910; Soloviev and Go, 1984; Ambraseys and Adams, 1996).
12	1905 – 0120	Sea retreated and transgressed. Flooded areas. Trees tumbled down (Guido, 1905; Weston, 1992; Alvarado, 2000).
13	1906 – 0131	A tidal wave of 2.5–5 m high. Parts of Tumaco City submerged by the wave. Several moorages and homes washed away. The tsunami was observed along the entire coast of Central America, in Mexico and California. A beach 2 km long dried up in Potrero Bay, then the water rushed onshore, tossing up boats (Sieberg, 1932; Gutenberg and Richter, 1954; Shepard *et al.*, 1950; Iida *et al.*, 1967; Soloviev and Go, 1984).
14	1906 –	High waves invaded Los Negritos Beach. A tsunami was observed on the beach at Los Negros (Larde, 1960; Soloviev and Go, 1984).
15	1913 – 1002	Strange behaviour of the sea resembling boiling water. Sudden elevation of the sea level. Rivers rose up flooding areas inland. Pedasi Village disappeared (MacDonald and Johnston, 1913; Feldman, 1984; Viquez and Camacho, 1993a; Ambraseys and Adams, 1996).
16	1915 – 0 907	There are unreliable reports about a disturbance at sea (Soloviev and Go, 1984).
17	1916 – 0131	Change of sea level in the Panama Canal Zone (Kirkpatrick, 1920; Soloviev and Go, 1984).
18	1916 – 0525	Both earthquake and tsunami are not reliable (Hatori, 1995).
19	1919 – 0629	Flooded area in Golfo de Fonseca and Corinto (INETER, 1993).
20	1919 – 1212	Flooded areas in Ostial Village (Morales, Unpublished).
21	1920 – 1206	Tsunami and/or macro seismic report (INETER, 1993).
22	1926 – 1105	The earthquake was reported as destructive in Nicaragua. The shock was felt at sea on two ships (Seismological Notes-BSSA,1926; Richter 1958; Leeds, 1974; Ambraseys and Adams, 1996).
23	1934 – 0718	A sea wave flooded the west coast of Gulf of Chiriqui. Houses washed out completely in Armuelles. The tsunami caused minor damage along the western shores of the gulf. A strong seaquake was felt on several ships. Two large anchored buoys were displaced 300 m from the moorage out to sea. The main street of an Indian village at Puerto Armuelles was covered with water several times and homes were completely washed out (Soloviev and Go, 1984; Camacho, 1991; Ambraseys and Adams, 1996).
24	1941 – 1205	The shock was felt on board a vessel. The oscillations in sea level was 23 cm high at a tide gauge located in Puntarenas, Costa Rica. Fluctuations of the sea level observed in Dominical and recorded in Puntarenas (Soloviev and Go, 1984; Montero, 1990; Ambraseys and Adams, 1996).
25	1941 – 1206	Oscillations of the sea level recorded in Puntarenas (Soloviev and Go, 1984).

Table IV. Continued

No.	Date	Damage, Effects, Comments and References
26	1950 – 1005	Small oscillations of the sea level were recorded at San Juan del Sur, Nicaragua and at La Union, El Salvador. The tide gauge at Puerto Armuelles was destroyed and those at Puntarenas (Costa Rica), La Union (Salvador), San Juan del Sur (Nicaragua) and Hilo (Hawaii), recorded a sea wave of 10 cm.. (Seismological Notes-BSSA, 1951; Murphy and Ulrich, 1952; Iida *et al.*, 1967; Cruz and Wyss, 1983; Ambraseys and Adams, 1996).
27	1950 – 1023	A wave of about 30 cm high at San Jose, Guatemala . A wave of 10 cm was also reported at La Union and Hilo (Seismological Notes-BSSA,1951, Murphy and Ulrich, 1952; Iida *et al.*, 1967; Ambraseys and Adams, 1996).
28	1951 – 0803	It was possible a lahar from Cosiguina Volcano (Seismological Notes-BSSA, 1951; Leeds, 1974).
29	1952 – 0513	Sea waves of 10 cm recorded at Puntarenas (Iida et al., 1967; Soloviev and Go, 1984).
30	1956 – 1024	Reliable earthquake information but not reliable tsunami information (Rothe, 1957; Hansen, 1972; Leeds, 1974; INETER, 1993; Ambraseys and Adams, 1996).
31	1957 – 0310	A sea wave several meter high damaged Acajutla Village. Loss of lives. The earthquake took place in Aleutians Islands (Alvares, 1979, Guinea *et al.*, 1995).
32	1960 – 0522	Tsunami from Chile (R. Torres, 1997, personal communication).
33	1962 – 0312	A seawave of 30 cm was recorded at Puerto Armuelles and Islas Galapagos. A small tsunami recorded at San Cristobal, Galapagos (Lander and Cloud, 1964; Iida *et al.*, 1967; Soloviev and Go, 1984; Viquez and Toral, 1987).
34	1968 – 0925	The Pacific Coast road of Guatemala was reported awash by 1.9 meters tsunami (Seismological Notes-BSSA, 1969).
35	1976 – 0711	Moderate damage in the province of Darien, especially in the coastal villages of Jaque and La Palma. In Jaque people died (Grases, 1990).
36	1990 – 0325	Oscillations of the sea level (Gutierrez and Soley, 1991; Barquero and Rojas, 1994; Ambraseys and Adams, 1996).
37	1992 – 0902	A sea wave 9.5 m high. Wave run-up to 1 km was reported at Masachapa. The horizontal extent of the inundation was of the order of few hundred meters. About 170 casualties. The largest run-up occurred in the central part of the Nicaragua coast. Sea wave of 2-4 m high in Costa Rica. Damage to small harbours and boats (Baptista *et al.*, 1993; Ide *et al.* 1993; Imamura *et al.*, 1993; Fernandez *et al.*, 1993; Sakate, 1994; Camacho, 1994; Ambraseys and Adams, 1996).

is 0.6 m (Table 4). On the contrary, tsunamis triggered by earthquakes offshore have been the most destructive and have reached heights larger than 9 m. The only tsunami with epicenter inland that could have killed people is No. 4, which destroyed the Village of Golfo Dulce. However, the epicenter of that earthquake is located close to the coastline.

5. Probability that $M_s \geqslant 7$ Earthquakes Generate a Tsunami

Figure 4 shows the distribution of magnitude 7 or larger earthquakes along the Pacific Coast of Central America for events which took place during the last century and that have epicenters offshore or close to the coastline. The coastal segments with the highest rates of large earthquake occurrence are A and C which are located in the Mexico–Guatemala and Salvador–Honduras territory, respectively. Based on data from A, B, and D, it can be said that the segment of the Middle American Trench extending from Nicaragua to Mexico generates more and larger earthquakes than the Costa Rica-Panama segment; the only exception is segment B which might be a seismic gap. The Costa Rica-Panama segment is characterized by having a low rate of large magnitude earthquakes, probably because the subduction of Cocos Plate becomes shallow at that part of the trench.

The total number of large earthquakes ($M_s \geqslant 7.0$) and the number of large tsunamigenic earthquakes were plotted in Figure 5 to estimate the rate between them and determine the areas at higher danger. The results indicate that 20% of the large earthquakes at A generate tsunamis, 50% for C and 50% in D. In general, 32% of the large earthquakes for the segment Nicaragua–Guatemala which have occurred during last century have triggered tsunamis. In the Costa Rica-Panama segment the situation is quite different; large earthquakes are not so abundant there but 67% of them trigger tsunamis. According to the results in this work, Nicoya (F), Osa (H), Chiriqui Gulf (I) and Panama Gulf (J) seismic zones have 60, 100, 67 and 50% of probability to generate a tsunami when a large earthquake occur. This means that earthquakes from this segment, although fewer, are more effective to generate tsunamis than those from the segment Nicaragua-Guatemala. In conclusion, 45% of the large earthquakes located offshore or close to the Pacific Central American coastline trigger tsunamis in this tsunamigenic region.

On the Caribbean Coast there were only three large earthquakes during the last century but all them generated small tsunamis. In consequence, there are 100% of probability that large earthquakes trigger tsunamis on the Caribbean side of Central America. However, these tsunamis might not be dangerous if the earthquake source is inland.

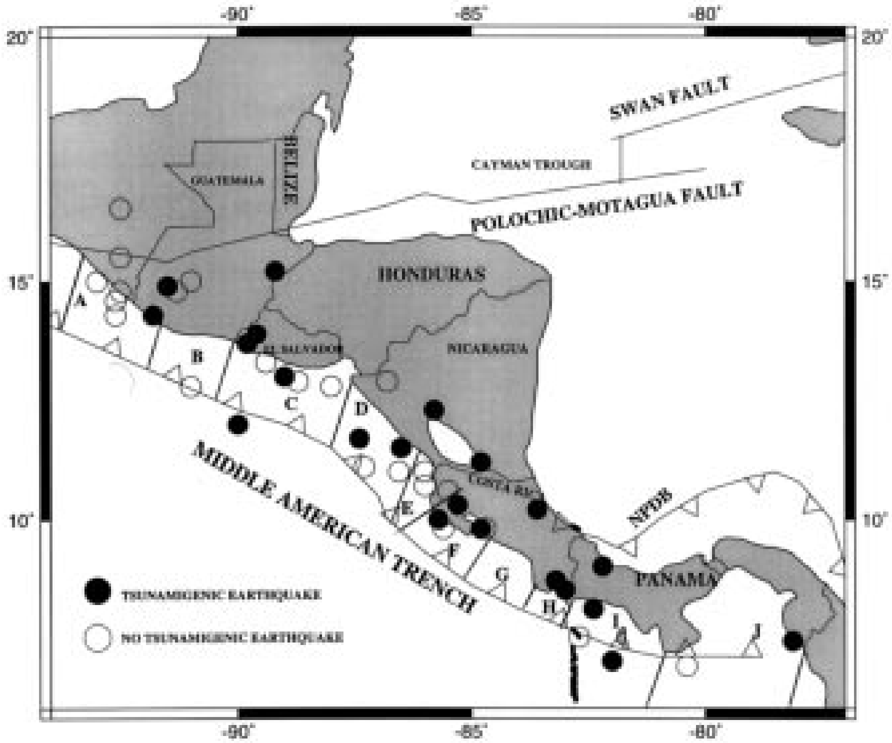

Figure 4. Distribution of $M_S \geqslant 7$ earthquakes, which occurred during the current century, along both the Pacific and Caribbean coasts of Central America. Letters represent coastal segments.

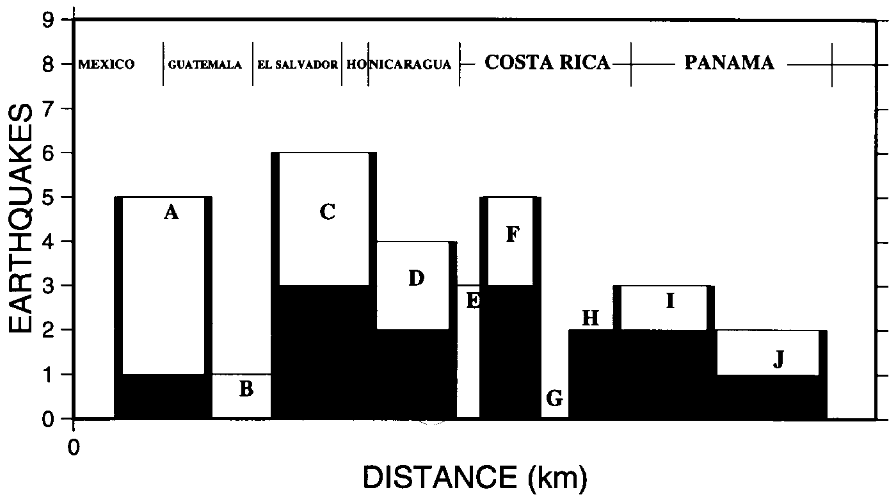

Figure 5. Frequency of $M_S > 7$ earthquakes along the Pacific Coast of Central America. The bars correspond to the coastal segments indicated in Figure 4. Black areas represent the frequency of tsunamis. HO: Honduras. 1 cm = 139 km.

6. Preliminary Empirical Tsunami Hazard Estimation

First of all, there are three basic problems in estimating tsunami hazard for Central America: Location of historical earthquakes, demographic growth, and the recurrence interval of past tsunamis. Because there is no instrumental location for some historical earthquakes, they can be mislocated and this could have a marked effect on relation to tsunami hazard (Ambraseys and Adams, 1996). The study of tsunamis is further complicated by demographic problems (Lander, 1995); with no villages along the coast, no tsunamis can be reported. To mitigate damage from future tsunamis it is useful to know the run-up and recurrence interval of past tsunamis but even documentation of some historical tsunamis is insufficient (Nakata and Kawana, 1995). In addition, the estimation of tsunami hazard identification of at-risk populations and possible areas of inundation (Bernard, 1997). In this work, an empirical tsunami hazard analysis is carried out using data from earlier tsunamis.

The first fact concerning tsunami hazard in Central America is that both coasts have been hit by tsunamis and on both coasts there are reports of extensive destruction and loss of lives. However, the Pacific Coast has a higher hazard than the Caribbean. This is supported not only by the number of tsunamis but by the distribution of them and their corresponding earthquakes epicenters. There are 37 tsunamigenic earthquakes well distributed along this coast, in contrast to 12 on the Caribbean which, in addition, are concentrated near Honduras Gulf and Caribbean coasts of Panama and Costa Rica. So, the most critical hazard is related to local earthquakes within Central America and to the subduction (MAT).

Based on a map of Central America (Escuela Para Todos, 1993), on the Caribbean Coast there are 44 population centers exposed to tsunamis (Figure 6), 16 in Panama, 4 in Costa Rica, 7 in Nicaragua, 9 in Honduras, 1 in Guatemala and 6 in Belice. The most important ports of this coast are: Colon, Limon, Blufields, Puerto Cabezas, Puerto Lempira, Trujillo, La Ceiba, Puerto Cortes and Belize. As shown in Figure 6 tsunamis on this coast are concentrated in two distinct areas (i) near Costa Rica-Panama coasts and (ii) Belice–Guatemala–Honduras coasts. Earthquakes that trigger tsunamis in those areas come from NA-CA and NPDB tectonic environments. Because the Caribbean coast of Nicaragua is far away from NA-CA and NPDB it has probably not been hit by any tsunami in the past. Villages most seriously affected by tsunamis at this coast are Omoa, Puerto Cortes, Trujillo, and San Blas Islands (Panama). Both Costa Rica-Panama and Belice-Guatemala-Honduras coasts have been hit by at least three tsunamis. One of these events had a sea wave of 5 m height and two of 3 m. They devastated villages and, according to the reports, killed 65 people. Considering 6 tsunamis from the last century and 4 from the current, the recurrence of these events is 20 years.

On the Pacific there are 60 population centers in danger due to the effect of tsunamis (Figure 7); 14 in Panama, 19 in Costa Rica, 9 in Nicaragua, 3 in Honduras, 6 in El Salvador, and 8 in Guatemala. Eleven of those localities are important ports (Balboa, Puerto Armuelles, Golfito, Quepos, Caldera, Puntarenas, Corinto,

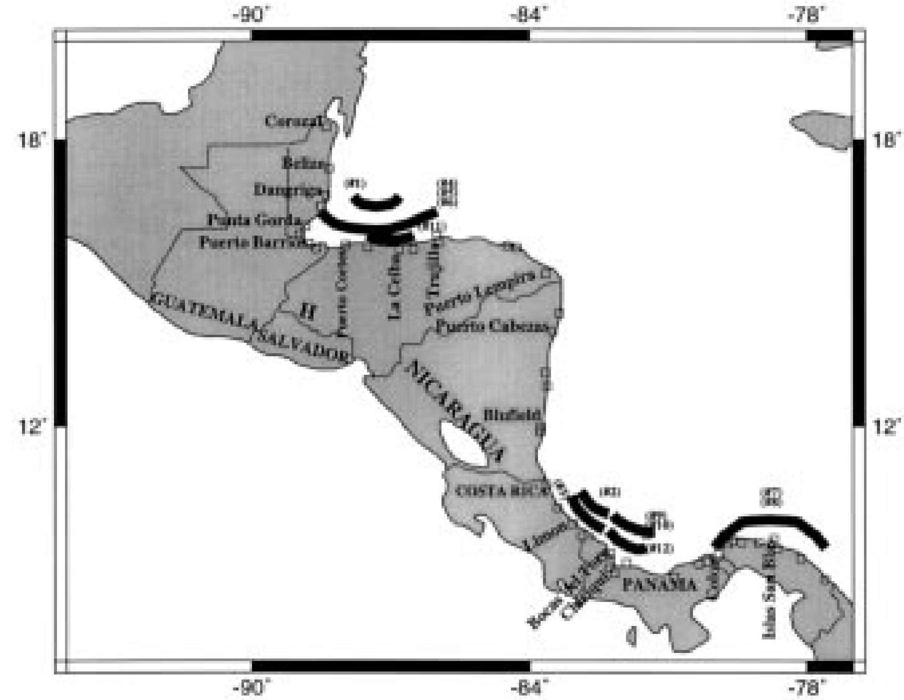

Figure 6. Map of tsunami affected areas on the Caribbean Coast of Central America. White squares are localities and solid heavy lines are tsunami reported area. The number of the tsunami in Table 3 have been attached. H: Honduras.

La Libertad, Acajutla, San Jose, and Champerico) where more than one thousand people live. The most affected localities by tsunamis are Golfito (Golfo Dulce) destroyed by the tsunami of 1854, Acajutla flooded during the tsunamis of 1859 and 1957, Pedasi that disappeared as a consequence of the tsunami in 1913, and El Transito, completely destroyed by the Nicaragua Tsunami in 1992. In Figure 7 we show the tsunami affected area for 25 tsunamis of our catalog, the rest were not plotted because the report is doubtful. The most conspicuous fact on the figure is that almost the entire Pacific Coast of Central America have experienced the effect of a tsunami, except parts of Guatemala, Salvador, Costa Rica and Panama. Most of the localities along Central American Coast have been hit by local tsunamis (Figure 7) and some of them, located between El Coco (Costa Rica) and Las Lisas (Guatemala), have experienced at least 3 tsunamis. This area seems to be the most dangerous tsunamigenic zone on the Pacific Coast of Central America not only by the number of tsunamis but also the destruction they have caused. Tsunamis in Costa Rica and Panama are scarce, nevertheless one of them in Costa Rica and another in Panama destroyed small villages, suggesting that the hazard should not be underestimated. The total number of tsunamigenic earthquakes on this coast during the current century is 37 with an average recurrence of 3.7 years.

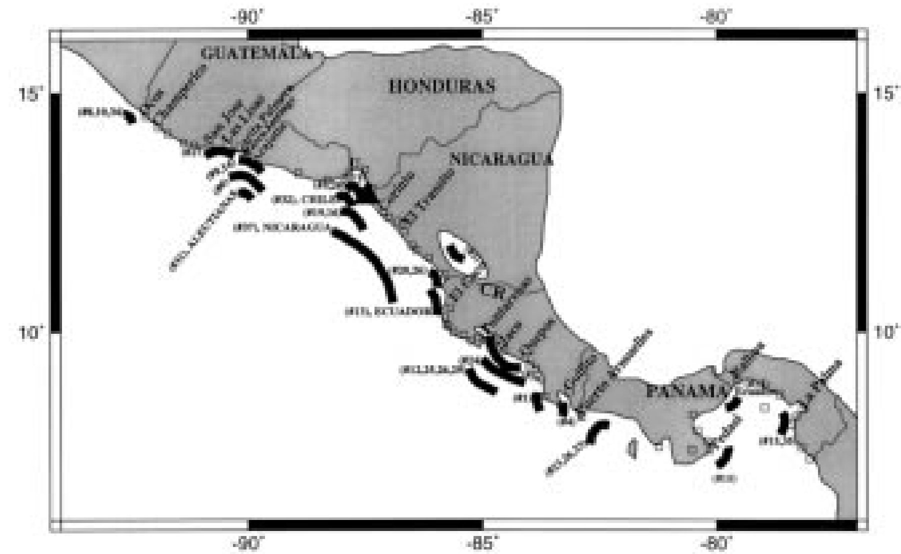

Figure 7. Map of tsunami affected areas on the Pacific Coast. White squares are localities and solid lines tsunami reported area. The black triangle close to Corinto is Cosiguina Volcano. The number of the tsunami in Table 4 have been attached. U: La Union Port.

Regarding the earthquake magnitudes it is important to note that even earthquakes with magnitude 6 have triggered tsunamis both in the Caribbean and Pacific Coast. One magnitude 6 earthquake caused a tsunami in 1913 that destroyed Pedasi Village on the Pacific Coast of Panama (Tables 3 and 4) and another rose a sea wave higher than 1 m on the Caribbean Coast. However, the largest and most destructive local tsunamis were associated with magnitude 7 or larger earthquakes. Regional earthquakes of magnitude larger than 8 produced tsunamis that reached the coasts of Central America. A total of 36 tsunamis have earthquake magnitudes reported; one has magnitude five, 14 magnitude six and 22 magnitude seven or larger. In Figure 8, we plotted the 23 tsunami magnitudes data against earthquake magnitudes. The result shows scattered points that do not define a linear dependence between those variables. This is probably due to the fact that most earthquakes are inland. The Nicaraguan Tsunami (1992) does not fit very well in this comparison because such tsunamis are themselves an anomaly, where the tsunami magnitude is very high with respect to the earthquake magnitude (Kanamori and Kikuchi, 1993).

The Nicaraguan Tsunami was the largest in Central America, and was associated with a slow earthquake (Kanamori and Kikuchi, 1993). From this event two lessons were learned: (i) A slow earthquake can trigger a destructive tsunami and (ii) the lack of historical large tsunamis does not necessarily mean that they will not occur some time in the future. Considering the latter, it is possible that a large tsunami can take place in other areas where no previous tsunamis have been recorded. This possibility represents a potential hazard, especially taking into account the expansion of tourism along the Central American Coasts.

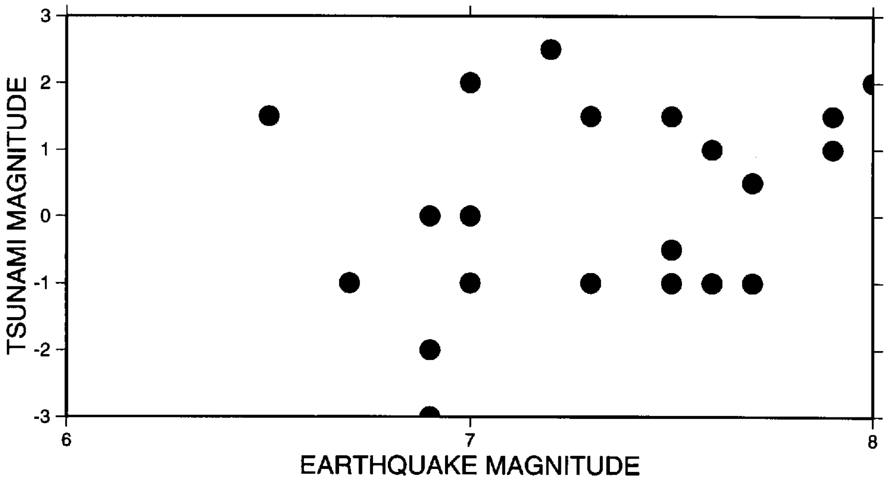

Figure 8. Tsunami magnitude vs earthquake magnitude for some tsunamis in Central America.

7. Conclusions

There are reports of 49 tsunamis along the coasts of Central America, where 12 are in the Caribbean and 37 in the Pacific. Among all tsunamis, 34 are well documented. These have destroyed villages and killed 455 people. Along both Pacific and Caribbean coasts there have been several sea waves higher than 3 m and two higher than 5 m. The highest one corresponds to Nicaraguan Tsunami (9.5 m) in 1992.

On the Caribbean Coasts, tsunamis are concentrated near Honduras Gulf that include coasts of Belice, Guatemala and Honduras and at the Costa Rica-Panama Coasts. They are related to seismic activity in NA-CA and NPDB tectonic environments respectively. On the Pacific side, they are distributed along all the coast from Guatemala until Panama and are associated to the CO-CA tectonic margin. The coastal segment of Nicaragua-Guatemala is the section with highest probability of being hit by the largest large tsunamis.

The most dangerous tsunamigenic earthquakes are those of magnitude seven or higher, with epicenters offshore. From 31 of these earthquakes which occurred during the last century in the Pacific 14 (45%) generated tsunamis; at the Caribbean there were only 3 events but all them (100%) generated tsunamis. Other earthquakes from elsewhere in the Pacific need to have $M_s \geqslant 8$ to generate tsunamis that affect coasts of Central America.

Considering the historical and recent tsunamis in Central America and taking into account the growth in coastal villages due to tourism, an effective Tsunami Warning System is required.

8. Recommendations

Reports of tsunamis in Central America increased considerably in the last century probably because more settlements were established there in that century. This indicates that coastal villages are growing fast in Central America, increasing the vulnerability to the impact of tsunamis. Because of this we recommend the evaluation of the growth of settlements and population along Central American Coasts in order to estimate the tsunami risk in the region. We also recommend further studies of bathymetry and the geological conditions of the Central American Coast to better define the tsunamigenic zone along it. It is also necessary to make inundation maps in order to establish an efficient tsunami warning system in the region.

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Appendix 1: Qualitative Imamura-Iida Tsunami Magnitude (Tm) Scale (Molina, 1997)

Tm	Tsunami height(m)	Damage
4	30	Considerable damage along more than 500 km of coastline
3	10–20	Considerable damage along more than 400 km of coastline
2	4–6	Damage and lives lost in certain landward areas
1	2	Coastal and ship damage
0	1	Very small damage
−1	0.5	None

m: meters

References

Alvarado, G.: 2000, Los volcanes de Costa Rica: su geología, historia y riqueza natural, Editorial UNED, 301 pp.

Alvarenga, E., Barquero, R., Boschini, I., Escobar, J., Fernandez, M., Mayol, P., Havskov, J., Galvez, N., Hernandez, Z., Ottomoller, L., Pacheco, J., Redondo, C., Rojas, W., Vega, F., Talavera, E., Taylor, W., Tapia, A., Tenorio, C., and Toral, J.: 1998, Central American Seismic Center (CASC), *Seism. Res. Lett.* **59**(5): 394–399.

Alvarez, S.: 1979, Apuntes de Sismologia General y normas de prevencion de terremotos, Centro de Investigaciones Geotecnicas, El Salvador.

Ambraseys, N.: 1995, Magnitudes of Central America Earthquakes, 1898–1930, *Geophys. J. Int.* **121**, 545–546.

Ambraseys, N. and Adams, R.: 1996, Large Magnitude Central America Earthquakes, 1898–1994, *G. J. Int.* **121**, 545–556.

Anderson, T.: 1908, The volcanoes of Guatemala, *Geogr. J.* **31**, 473–489.

Baptista, A., Priest, G., and Murty, T.: 1993, Field Survey of the 1992 Nicaragua Tsunami, *Marine Geodessy* **16**, 169–203.

Barquero, R. and Rojas, W.: 1994, Sismicidad inducida por el terremoto de Limon, *Revista Geol. Amer. Central*, v. Especial, San Jose, pp. 111–120.

Bernard, E.: 1997, Reducing Tsunami Hazard Along U.S. Coastlines, In: G. Hebenstreit, G., *Perspectives on Tsunami Hazard Reduction, Observations, Theory and Planning*, Kluwer Academic Publishers, Dordrecht, Boston, London.

de Boer, J., Drummond, M., Bordelon, M., Defant, M., Bellon, H., and Maury, R.: 1995, Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca), In: P. Mann (ed.), *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, Boulder, Colorado, Geological Society of U.S.A., Special Paper 295.

Boschini, I. and Montero, W.: 1994, Sismicidad historica e instrumental del Caribe de Costa Rica, *Rev. Geol. Amer. Central*, v. especial: *terremoto de Limon*, pp. 65–72.

Boscowitz, A.: 1885, *Les Tremblements de terre*, Paris, pp. 135- -155.

Bowin, C.: 1976, The Caribbean gravity field and plate tectonics, *Geol. Soc. Amer.*, Special Paper 169.

Buckman, R., Plafker, G., and Sharp, R.: 1978, Fault movement following the Guatemala earthquake of February 4, 1976, *Geology* **6**, 170–173.

Bulletin du Canal Interoceanique: 1882, Issues 76–78 (October– December), Troisieme annee, pp. 647–648, 663–664, Imprimerie de la Societe de Publications Periodiques, Paris, France.

Calais, E., Bethoux, N., and Mercier de Lepinay, B.: 1992, From transcurrent faulting to frontal subduction: A seismotectonic study of the northern caribbean plate boundary from Cuba to Puerto Rico, *Tectonics* **11**(1), 114–123.

Camacho, E.: 1991. The Puerto Armuelles earthquake (Southwestern Panama) of July 18, 1934, *Rev. Geol. Amer. Central* **13**, 1–14.

Camacho, E.: 1994, El tsunami del 22 de abril de 1991 en Bocas del Toro, Panama, *Rev. Geol. Amer. Central*, v. especial: *terremoto de Limon*.

Camacho, E, and Viquez, V.: 1992, Historical seismicity of the North Panama Deformed Belt, Instituto de Geociencias, University of Panama.

Camacho, E. and Viquez, V.: 1993a, Historical seismicity of the North Panama Deformed Belt, *Rev. Geol. Amer. Central* **15**, 49–64.

Camacho, E., and Viquez, V.: 1993b, El terremoto de San Blas del 7 de Septiembre de 1882, Rev. Humanidades, Abril 1994, tercera epoca, N 2 Panama.

Carr, M. and Stoiber, R.: 1977, Geological setting of some destructive earthquakes in Central America, Appendix I: Destructive earthquakes in Central America, *Bull. Geol. Soc. Am.* **88**, 151–156.

Chael, E. and Stewart, G.: 1982, Recent Large Earthquakes Along the Middle American Trench and their Implication for the Subduction Process, *J. Geophys. Res.* **87**, 329–338.

Crawford, J.: 1902, Earthquakes in Nicaragua, *Am. Geologist* **29**, 323.

Cruz, G. and Wyss, M.: 1983, Large earthquakes, mean sea level, and tsunami along the Pacific Coast of Mexico and Central America, *Bull. Soc. Seis. Am.* **73**, 553–570.

Denyer, P., Arias, O., and Personius, S.: 1992, Generalidades sobre los efectos geologicos del terremoto de Limon, *Rev. Geol. Amer. Central*, Special Volumen, 29–38.

Di Marco, G., Baumgartner, P., and Channell, J.: 1995, Late Cretaceous-Early Tertiary Paleomagnetic Data and a Revised Tectonostratigraphic Subdivision of Costa Rica and Western Panama, In: P. Mann (ed.), *Geologic and Tectonic Development of the CaribbeanPlate Boundary in Southern Central America*, Geological Society of America, Special Paper 295.

El-Sabh, M.: 1995, The role of public education and a awareness in tsunami hazard management, In: Y. Tsuchiya and N. Shuto, 1995: *Tsunami: Progress in Prediction, Disaster Prevention and Warning*, Kluwer Academic Publishers, London.

Escuela para Todos: 1993, *Mapa de Centroamerica.*

Espinosa, F. (ed.): 1976, The Guatemalan earthquake of February 4, 1976, a preliminary report, USGS Prof. paper 1002, Washington, D.C.

Feldman, L.: 1984, A catalogue of historical documents pertaining to the earthquake damage in Panama and Costa Rica, Unpublished.

Fernandez, M., Peraldo, G., Rojas, W., and Flores, R.: 1993, Tsunamis en Centroamerica, *Tecnologia en Marcha* **12**(2), 17–10, Costa Rica.

Gonzalez, C.: 1910, Temblores, terremotos, inundaciones y erupciones volcanicas en Costa Rica, 1606–1916, *Tipografia de Avelino Alsira*, San Jose, Costa Rica.

Grases, J.: 1974, *Relacion cronologica de sismos destructores de America Central, lapso 1526–1900*, Vol. 2, UCV, Caracas.

Grases, J.: 1990, *Terremotos destructores del Caribe 1502– 1990*, UNESCO-RELACIS, Caracas, Agosto de 1990.

Guendel, F.: 1986, Seismotectonic of Costa Rica: An analytical view of the southern terminus of the Middle America Trench, PhD Thesis, University of California, St. Cruz.

Guido, A.: 1905, *Expedición a la Isla del Coco, por Agustin Guido, Febrero de 1905*, diario de un viaje, Imp. El Pacífico, Puntarenas.

Guinea, R., Manzano, A., Pineda, A., and Torres, I.: 1995, Metodologias para la evaluacion del riesgo sismico en El Salvador, con aplicacion a las instituciones educativas, Tesis, lic., Fac. Ing. Univ. Simeon Canas, abril 1995, San Salvador, El Salvador.

Gutenberg, B. and Richter, C.: 1954, *Seismicity of the Earth and Associated Phenomena*, Princeton University Press, Trenton, New Jersey.

Gutierrez, A. and Soley, J.: 1991, Analisis de los registros de nivel del mar correspondientes al terremoto de Cobano de 23-3-90, *Geofisica*, N 35, IPGH.

Hansen, F.: 1972, Origen de los sismos – Historia sismica de Nicaragua, Managua.

Hatori: 1995, Magnitude scale for the Central America tsunamis, *PAGEOPH* **144**(3/4), 471–479.

Heck, N.: 1947, List of seimic waves, *Bull. Seism. Soc. Am.* **37**, 269–285.

Ide, S., Imamura, F., Yoshida, Y., and Abe, K.: 1993, Source characteristics of the Nicaragua tsunamiearthquake of September 2, 1992, *Geophys. Res. Lett.* **20**, 863–866.

Iida, D., Cox, C., and Pararas-Carayannis, G.: 1967, Preliminary catologue of tsunamis occurring in the Pacific Ocean, Hawaii Inst. Geophys. Univ. Hawaii, Data report No. 5.

Imamura, F., Shuto, N., Ide, S., Yoshida, Y., and Abe, K.: 1993, Estimate of the tsunami source of the 1992 Nicaragua earthquake from tsunami data, *Geophys. Res. Lett.* **20**, 1515–1518.

INETER: 1993, Tsunami 1 de septiembre de 1992, Min. de Construccion y Transporte, Agosto 1993, Managua, Nicaragua.

Jorgensen, M.: 1966, Seismological history of the Canal Zone and Panama, Panama Canal Company, Canal Zone, IOCS Memorandum, PCC-3, February 1966.

Kanamori, H.: 1972, Mechanism of tsunami earthquakes, *Phys. Earth Planet. Inter.* **6**, 346–359.

Kanamori, H. and Kikuchi, M.: 1993, The 1992 Nicaragua Earthquake: a slow earthquake associated with subducted sediments, *Nature* **361**, 714– 716.

Kanamori, H. and Stewart, G.: 1978, Seismological aspects of the Guatemala Earthquake of February 4, 1976, *J. Geophys. Res.* **83**, 3427–3434.

Kawata, Y., Benson, B., Borrero, J. C., Borrero, J. L., Davies, H., de Lange, W., Imamura, F., Letz, H., Nott, Jonathan, and Synolakis, C.: 1999, Tsunami in Papua, New Guinea Was as Intense as First Thought, Eos, Transactions, *Am. Geophys. Union* **80**(9), 104–105.

Kellogg, J. and Vega, V.: 1995, Tectonic Development of Panama, Costa Rica, and the Colombian Andes: Constraints from Global Positioning System Geodetic Studies and Gravity, In: P. Mann (ed.), *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, Geological Society of America, Special Paper 295.

Kirkpatrick, Z.: 1920, Earthquakes in Panama up to January 1, 1920, *Bull. Soc. Seis. Am.* **10**(3), 120–128.

Kluge, E.: 1863, *Ueber Synchronismus und Antagonismus von Vulkanischen Eruptionen*, Leipzig

Kolarsky, R. and Mann, P.: 1995, Structure and neotectonics of an oblique-subduction margin, Southwestern Panama, In: P. Mann (ed.), *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, Geological Society of America, Special Paper, 295.

Lander, J.: Alaskan tsunamis revisited, In: Tsuchiya, Y., and Shuto, N.: 1995, *Tsunami: Progress in Prediction, Disaster Prevention and Warning*, Kluwer Academic Publisher, Dordrecht, Boston, London.

Lander, J. and Cloud, W.: 1964, *U.S. Earthquakes 1962*, U.S Department of Commerce, Coast and Geodetic Survey, Washington D.C., pp. 1–114.

Larde, J.: 1916, *El terremoto del 6 de setiembre de 1915*, Revista de la Ensenanza, San Salvador.

Larde, J.: 1960, *Historia sismica y erupciones volcanicas de El Salvador*, Documentacion historica, critica y conclusiones, Obras completas, Tomo I. Min Cultura, Depto. Ed,. El Salvador, pp. 441–576.

Leeds, J.: 1974, Catalog of Nicaragua earthquakes, *Bull. Soc. Seis. Am.* **64**, 1135–1158.

List, K.: 1903, Erdbeben an der Kuste Guatemalas im Jahre 1902 und deren Folgeerscheinungen, *Ann Hydrograph. und Marit. Meteorolog.*, Feb. 1903, 52- -54 and Beilag.: ii–iv, Hamburg.

Mallet, R. and Mallet, J.: 1858, The earthquake catalogue of the British association, *Brit. Assoc. Adv. Sci. London*.

McDonald, F. and Johnston, C.: 1913, Isthmian earthquakes, *Canal Record* **7**, 144–149.

Mendoza, C. and Nishenko, S.: 1989, The North Panama Earthquake of 7 September 1882: evidence for active underthrusting, *Bull. Seismol. Soc. Am.* **79**, 1264–1269.

Milne: 1912, Catalogue of Destructive Earthquakes A.D. 7–1899, Report 81st Meeting, Br. Assoc. Adv. Sci. Portsmouth 1911.

Molina, E.: 1997, Tsunami catalogue for Central America 1539–1996, Technical Report No. II 1-04, Reduction of natural disasters in Central America. Earthquakes Preparedness and Hazard Mitigation, Phase II, Institute of Solid Earth Physics, University of Bergen, Norway.

Montandon, F.: 1962, Les Megaseismes en Amerique: Revue pour l'Etude des Calamites, *Bull. de l'Union Internationale de Secours* **38**, 57– 97.

Morales, A.: (unpublished), Catalogo de terremotos, erupciones y otros fenomenos (1877 a la fecha), Depto de Sismologia, INETER, Managua, Nicaragua.

Montero, W.: 1986, Periodos de recurrencia y tipos de secuencia sismica de los temblores intraplaca en la region de Costa Rica, *Rev. Geol. Amer. Central* **5**, 35–72.

Montero, W.: 1990, *Tsunamis en Costa Rica*, Boletin del Colegio de Geologos de Costa Rica.

Montero, W., Paniagua, S., Kussmaul, S., and Rivier, F.: 1992, Geodinámica interna de Costa Rica, *Rev. Geol. Amer. Central* **14**, 1–12.

Montessus de Ballore, F.: 1884, *Temblores y erupciones volcanicas en Centroamerica, San Salvador, El Salvador*.

Montessus de Ballore, F.: 1888, *Tremblements de terre et eruptions volcaniques on Centre Amerique depuis la coquete espagnole fusqu'a nos jours*, Societe Sciences Naturelles de Saore-et-Loire, Dijon, p. 293, et suivants.

Montessus de Ballore, F.: 1906, *Les tremblements de Terre: Geographie Seismologique*, Librairie Armand Colin, Paris, pp. 384–392.

Murphy, L. and Ulrich, F.: 1952, *U.S. Earthquakes, 1950*, U.S. Department of Commerce, Coast and Geodetic Survey, Washington D.C., Ser. 755, pp. 1–47.

Nakata, T. and Kawana, T., Historical and prehistorical large tsunamis in the Southern Ryukyus Japan, In: Y. Tsuchiya and N. Shuto, 1995, *Tsunami: Progress in Prediction, Disaster Prevention and Warning*, Kluwer Academic Publisher, Dordrecht, Boston, London.

Nelson, W.: 1889, *Five years at Panama, The Trans-Isthmian Canal*, Belford Co., New York.

Oddone, E.: 1907, *Tremblements de terre Ressentis pendant l'anne 1904*, Publ. Bureau Centr. Assoc. Intern. Sism., Ser. B., Strassburg.

Okal, E.,: 1994, Tsunami Warning: beating the waves to death and destruction, *Endeavour*, New Series, **18**(1).

Pacheco, J. and Sykes, L.: 1992, Seismic moment catalog of large, shallow earthquakes, 1900–1989, *Bull. Seism. Soc. Am.* **82**, 1306–1349.

Peraldo, G. and Montero, W.: 1994, *Los temblores del periodo colonial de Costa Rica, 1538–1821*, Editorial Tecnologica de Costa Rica, Cartago.

Perry, M.: 1855–1856, 1861–1862), *Bibliographie Seismique*, Academie de Dijon, iv–v (1855–1856) and ix–x (1861–1862), Dijon, France.

Plafker, G. and Ward, S.: 1992, Backarc thrust faulting and tectonic uplift along the Caribbean Sea Coast during April 22, 1991 Costa Rica Earthquake, *Tectonics* **11**, 709–718.

Protti, M., Guendel, F., and Mcnally, K.: 1994, The geometry of the Wadati-Bennioff zone under southern Central America and its tectonic significance: result from a high-resolution local seismographic network, *Phys. Earth Planet. Int.* **84**, 271–287.

Reid, F.: 1917, Note on the earthquake at Almirante, *Bull. Seism. Soc. Am.* **7**, 27–30.

Richter, C.: 1958, *Elementary Seismology*, W. H. Freeman and Co., San Francisco, pp. 650–651.

Roberts, W.: 1829, *Narrative of Voyages and Excursions on the coast and the interior of Central America*, Collection Montemont and Maussion de Conde.

Rockstroch, E.: 1902, Earthquake in Guatemala, *Nature* **66**, 150.

Rojas, W., Bungun, H., and Lindholm, C.: 1993a, *A Catalog of Historical and Recent Earthquakes in Central America*, NORSAR, Oslo, Norway, technical report.

Rojas W, Cowan H, Lindholm C, Dahle A, and Bungum H.,: 1993b, Regional seismic zonation for Central America: A preliminar model. Technical Report, NORSAR, PO Box 51, N-2007 kjeller, Norway 1993b; 40.

Rothe, J.: 1957, Chronique Seismologique, Revue por l'Etude des Calamites, *Geneva* **36**, 2–27

Satake, K.: 1994, Mechanism of the 1992 Nicaragua tsunami earthquake, *Geophys. Res. Lett.* **21**(23), 2519–2552.

Sapper, K.: 1902, Das Erdbeben in Guatemala vom 18 April 1898 und die Maribios-Vulkane, *Globus* **75**, 201–208; 222–227, Braunschweig.

Sapper, K.: 1095, In den Vulcangebieten Mittelamerikas und Westindies. Reisechildernngen und Studien uber die Vulkanausbruche der Jahre 1902 bis 1903, ihre geologischen, wirtschaftlichen und socialen Folgen, E. Schweizerbartsche Verlagsbuchandlung, Stuttgart.

Salcedo, R.: 1640, *Historical and Geographical Report of the Province of Panama*, 1947 translation by Alice E. Wetman, Panama Canal Collection.

Seismological Society of America: 1926, Seismological Notes – Nicaragua August 3–6, 1951, *Bull. Seis. Soc. Am.* **41**(4), 399.

Seismological Society of America: 1951, Seismological Notes – Nicaragua August 3–6, 1951, *Bull. Seis. Soc. Am.* **41**(4), 399.

Seismological Society of America: 1969, Seismological Notes - Mexico–Guatemala border, April 9–10, 1968, *Bull. Seis. Soc. Am.* **59**(2), 1028.

Shepard, F., McDonald, G., and Cox: 1950, The tsunami of April, 1946, *Bull. Scripps Inst. Oceanog.* **5**, 391–528.

Shapiro, N., Singh, S., and Pacheco, J.: 1998, A fast and simple diagnostic method for identifying tsunamigenic earthquakes, *Geophy. Res. Letters* **25**(20), 3911–3914.

Sieberg, A.: 1932, Erdbebengeographie: Mittelamerika samt Westindien, In: B. Gutenberg (ed.), *Handbuch der Geophysik*, Band IV, Berlin, pp. 948–960.

Soloviev, L. and Go, N.: 1984, A catalogue of tsunamis on the eastern shore of the Pacific Ocean (1513–1968), *Can. Transl., Fish. Aquat. Sci.* 5078, Nauka Publishing House, Moscow.

Sutch, L.: 1981, Estimated intensities and probable tectonic sources for the historic (pre-1898) earthquakes, *Bull. Soc. Seism. Am.* 71, 865–881.

Tabor, L.: 1967, Compilation on seismic data: Panama and adjoining sea area, NVO-99-22, J. A. Blume, Research Division, San Francisco, December.

Viquez, V. and Toral, J.: 1987, Sismicidad historica sentida en el itsmo de Panama, *Geofisica* **27**, 135–165.

Viquez, V. and Camacho, E.: 1994, El terremoto de Panama La Vieja del 2 de mayo de 1621: un sismo intraplaca, Boletin de Vulcanologia, OVSICORI-UNA.

Westbrook, G., Hardy, N., and Heath, R.: 1995, Structure and Tectonics of the Panama-Nazca Plate Boundary, In: P. Mann (ed.), *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, Geological Society of America, Special Paper 295.

Weston, C.: 1992, *La Isla del Coco-Cocos Island*, Trejos.

Young, C., Lay, T., and Lynnes, C.: 1989, Rupture of the 4 February 1976 Guatemalan earthquake, *Bull. Seis. Soc. Am.* **79**, 670–689.