Revista Geológica de América Central, 65, 1-16, 2021
doi: 10.15517/rgac.v0i65.47001
ISSN: 0256-7024

The 22 April 1991 Limón, Costa Rica tsunami field survey

Estudio de campo del tsunami de Costa Rica del 22 de abril de 1991

Stuart Nishenko[1]*, Eduardo Camacho[2], Allan Astorga[3], Luis D. Morales[3] & Jane Preuss[4]

[1]Pacific Gas and Electric Company, San Francisco, CA, USA
[2]University of Panama, Institute of Geosciences, Panama City, Panama
[3]University of Costa Rica (UCR), San Jose, Costa Rica
[4]Urban Regional Research, Seattle WA, USA
*Corresponding author: s_nishenko@msn.com

(Recibido: 12/12/2020; aceptado: 29/03/2021)

ABSTRACT: A small tsunami (tsunami magnitude, m ~ 1) was observed following the 22 April 1991 Mw 7.7 Limón, Costa Rica earthquake along the Caribbean coast of Costa Rica and Panama. This report summarizes eyewitness observations from 26 sites along 150 km of affected coast from Rio Matina, Costa Rica to Bocas del Toro, Northwestern Panama, as well as tide gauge recordings from Panama, Puerto Rico and the Virgin Islands. No emergency warnings were issued before the tsunami occurred. While little or no tsunami-related property damage was reported, two or more drownings were attributed to the tsunami. The maximum runup/wave height was reported to be 2 to 3 m, and inundation and coastal flooding extended up to 100 m inland in some locations. Both coseismic coastal uplift and the presence of fringing offshore reefs appear to have provided protection against major runup effects in some coastal areas. Elsewhere, runup effects were amplified at river mouths due to differential compaction of unconsolidated sediments. Widespread tsunami sand deposition near the Costa Rica-Panama border in 1991 is similar to deposition associated with the 7 May 1822 earthquake and tsunami.
Keywords: Caribbean Tsunamis; 1991 Costa Rica Earthquake and Tsunami; Tsunami Questionnaire; Field Records and Observations; Limón; Bocas del Toro.

RESUMEN: Después del terremoto de Limón, Costa Rica del 22 de abril de 1991 (Mw 7.7) se observó un pequeño tsunami (magnitud, m~ 1) a lo largo de la costa caribeña de Costa Rica y Panamá. Este informe resume las observaciones de testigos oculares de 26 sitios a lo largo de 150 km de costa afectada desde río Matina, Costa Rica hasta Bocas del Toro, noroeste de Panamá, así como mareogramas registrados en Panamá, Puerto Rico y las Islas Vírgenes. No se emitieron advertencias de emergencia antes de que ocurriera el tsunami. Aunque se reportaron pocos o ningún daño a la propiedad relacionada con el tsunami, dos o más ahogamientos fueron atribuidos al tsunami. La altura máxima de las olas fue de 2 a 3 m, y la inundación y las inundaciones costeras se extendieron hasta 200 m tierra adentro en algunos lugares. Tanto la elevación costera cosísmica como la presencia de arrecifes marinos parecen haber proporcionado protección contra los principales efectos del tsunami en algunas zonas costeras. En otros lugares, los efectos de las olas se amplificaron en las desembocaduras de los ríos debido a la compactación diferencial de sedimentos no consolidados. La deposición generalizada de arena de tsunami cerca de la frontera Costa Rica-Panamá en 1991 es similar a la deposición asociada con el terremoto y tsunami del 7 de mayo de 1822.
Palabras clave: tsunamis del Caribe; terremoto y tsunami de Costa Rica de 1991; cuestionario de tsunami; registros y observaciones de campo; Limón; Bocas del Toro.

INTRODUCTION

The 22 April 1991 Mw 7.7 Limón, Costa Rica earthquake is one of the three largest earthquakes to occur in Costa Rica during the last century. In contrast to the 1950 Ms 7.7 and 2012 Ms 7.6 Nicoya Peninsula earthquakes which were located on the seismically active Pacific coast, the 1991 Limón earthquake occurred along the Caribbean coast of southeastern Costa Rica. While the Caribbean coast of Costa Rica and Northwestern Panama is an area of relatively low instrumental seismic activity (Alvarado et al., 2017), it has been affected several times in the past 200 years by large earthquakes associated with back arc thrust faulting (Adamek, Frohlich & Pennington, 1988; Camacho & Víquez,1993; Mendoza and Nishenko, 1989; Plafker & Ward, 1992; Suárez et al., 1995).

The 1991 Limón earthquake occurred on the western part of a southwest dipping fold and thrust belt (North Panama Deformed Belt) that follows the Caribbean coast of Panama and Costa Rica (Plafker & Ward, 1992; Protti & Schwartz, 1994; Silver, Reed, Tagudin & Heil, 1990; Suárez et al., 1995). Field studies by Plafker & Ward (1992) and Denyer, Personius & Arias (1994) indicate a zone of uplift along the inner continental shelf and coast that extended ~ 70 km from north of Limón to the Costa Rica-Panama border. The maximum uplift occurred at Limón (157 cm) and turned sharply westward and inland for an unknown distance. To the southeast, the crest of the uplifted zone is located approximately 3 to 4 km offshore and the amount of uplift gradually decreases towards the Costa Rica-Panama border (Plafker & Ward, 1992).

Researchers from a number of institutions, including the University of Costa Rica, the University of Panama, the Universidad Nacional Autonoma de Mexico (UNAM), the Earthquake Engineering Research Institute (EERI), the University of California Santa Cruz (UCSC) and the U.S. Geological Survey (USGS) conducted field reconnaissance in areas of both Costa Rica and Panama affected by the 1991 Limón earthquake. An area of 15,000 km^2 experienced widespread liquefaction and lateral spreading in places characterized by unconsolidated coastal plain and river deposits (EERI, 1991; Camacho & Víquez, 1994; Denyer et al., 1994; Plafker & Ward, 1992). Estimates of damage to infrastructure and lost revenues are at $500 million in Costa Rica (EERI, 1991) and $75 million in Panama (SINAPROC, Panama Civil Defense, written communication, 1992). This report presents tide gauge records and eyewitness accounts of tsunami activity along the Caribbean coast of Costa Rica and Northwestern Panama following the 1991 Limón earthquake.

TSUNAMI OBSERVATIONS

Tide Gauges

A tsunami or series of waves with heights, h_{max}, of 2 to 3 m were reported by eyewitnesses along the coast from Rio Matina, Costa Rica to Bastimentos Island, Panama following the earthquake (Fig. 1) indicating a tsunami magnitude, m, of ~1 (where $m = \log_2 h_{max}$; Table 1; Iida, Cox & Pararas-Carayannis, 1967; Iida, 1970). The Cristobal tide gauge at Coco Solo, Panama (9.35° N, 79.92° W, 320 km southeast of the source zone) recorded a maximum peak to trough amplitude of 7.6 cm (3 in) 1 hour after the earthquake (Fig. 2). Approximately 3½ hours later, bubbler tide gauges in Magueyes Island, Puerto Rico (18.22° N, 67.16° W) and Limetree Bay, St. Croix, Virgin Islands (17.69° N, 64.75° W) both recorded disturbances of about 7 cm peak to trough (Fig. 2). Appendix 1 in the Electronic Supplement contains copies of the three tide gauge records.

Tsunami Questionnaire

In many cases, little if any systematic data collection occurs for tsunamis that have not been accompanied by extensive damage and loss of life, or where the damage has been limited to the immediate area of generation. As a result, a great deal of perishable information related to the local characteristics and behavior of these smaller tsunamis has been lost. To develop a framework for systematic data collection, a questionnaire was designed to facilitate the analysis of smaller events associated with earthquake generated tsunamis or other unusual wave activity related to submarine landslides or volcanic eruptions (Nishenko, 1987). A prototype tsunami questionnaire was field tested in the Monterey Bay, California region following the 1989 Loma Prieta, California (Ms 6.9) earthquake (Preuss & Nishenko, 1992) and was subsequently revised and simplified.

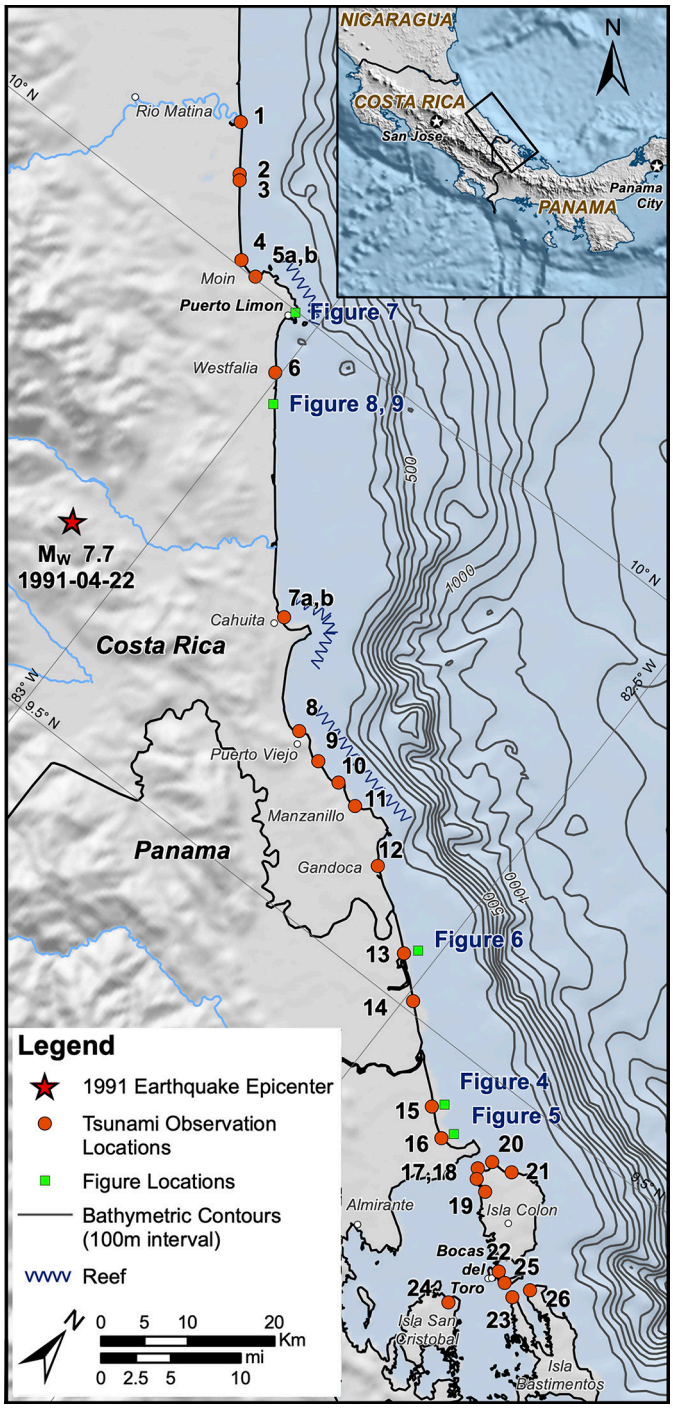

Fig. 1: Map showing locations of photographs (green squares) and questionnaire responses (red circles) collected in Costa Rica (sites 1 – 12) and Panama (sites 13 – 26) following the 22 April 1991 Limón, Costa Rica tsunami. 1991 Mw 7.7 earthquake epicenter is shown as a red star. Coastal coral reefs shown as jagged lines. Background topography and bathymetry from GEBCO Compilation Group (2020).

Table 1

Tsunami Magnitude Scale

Tsunami magnitude, m*	Significance
-1	h_{max} ~ 1/2 m; minor tsunami
0	h_{max} ~ 1 m; no damage
1	h_{max} ~ 2 m; house damage along coastal areas, ships washed ashore
2	h_{max} ~ 4 - 6 m; some destruction of houses, considerable loss of life
3	h_{max} ~ 10 – 20 m; damage area along the coast about 400 km
4	h_{max} greater than 50 m; damage area along the coast more than 500 km

*Tsunami magnitude, $m = \log_2 h_{max}$, where hmax is the maximum height in meters measured at a coast 10-300 km from the tsunami origin (Iida, 1970)

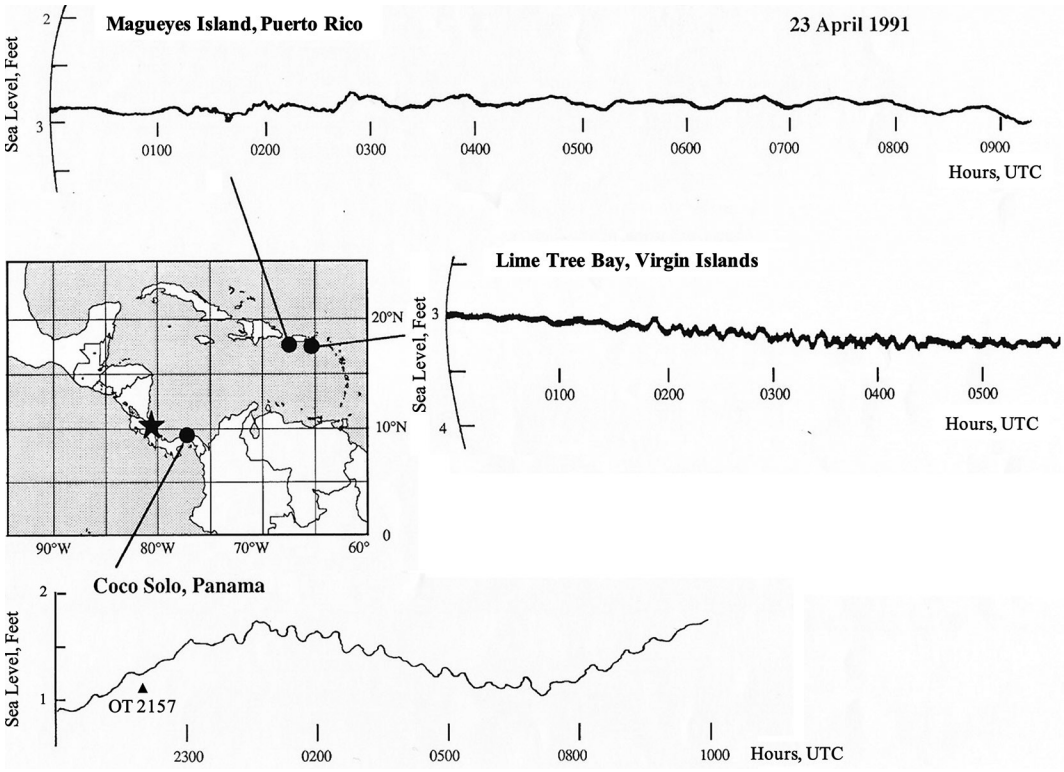

Fig. 2: Tide gauge records of the 1991 Limón, Costa Rica tsunami. Inset map shows the location of the tide gauges with respect to the epicenter (star). Vertical record scale in feet, horizontal scale in hours (Coordinated Universal Time, UTC). **(a)** Coco Solo (Cristobal) Panama [9.35° N, 79.92° W]. Earthquake Origin Time (2157 UTC) shown by arrow. Maximum peak to trough amplitude is approximately 3 in (7.6 cm); both **(b)** Magueyes Island, Puerto Rico [18.22°N, 67.16°W] and **(c)** Limetree Bay, St. Croix, Virgin Islands [17.69°N, 64.75°W] show maximum peak to trough amplitudes of ~ 3 in (7 cm).

Tsunami questionnaires were also distributed following two later tsunamis in which reported damage was slight - the 1992 Petrolia, California (Ms 7.0) and 1992 Nicaragua (Ms 7.2) earthquakes (Preuss, 1994). The results of these surveys demonstrated the utility of a readily available instrument to disseminate immediately after the event.

The prototype tsunami questionnaire was translated into Spanish (Fig. 3) and distributed in Costa Rica with the help of personnel from the University of Costa Rica approximately one week after the 1991 Limón earthquake. Fourteen eyewitness observations were obtained from 12 sites along 90 km of affected coast, from the mouth of the Matina River, north of Limón to Gandoca, north of the Costa Rica-Panama border. Researchers from the University of Panama Institute of Geosciences recorded observations from 14 additional sites in Panama in the fall of 1991 (Camacho, 1994).

The questions asked during the Costa Rica and Panama field surveys (Fig. 3) were organized into three primary categories:

- Data pertaining to the respondent. Questions 1-5 ask the respondents whether they actually witnessed the tsunami or wave, where they were, and what they were doing at the time.
- Data pertaining to the tsunami. Questions 6-9 ask for information about the water activity (the type of disturbance, its effect, and the direction of wave behavior) and the respondent's reaction.
- Data pertaining to damage caused by the tsunami. Question 10 asks for information about building and structural damage caused by the waves and the location of these structures relative to the shoreline.
- Additional Information. Questions 11-13 ask for additional information not covered above as well as information related to injuries, fatalities, and their circumstances; whether the respondent received a community tsunami alert or warning; and any response to the alert or warning.

SUMMARY OF EYEWITNESS OBSERVATIONS

Eyewitness accounts of tsunami activity in Costa Rica and Panama following the 1991 Limón earthquake are summarized below. Figure 1 shows the survey site locations and Table 2 lists a summary of the questionnaire responses at those sites. Tsunami runup and coseismic uplift measurements from Plafker & Ward (1992) are also listed in Table 2 as a reference. This report supersedes an earlier, unpublished version (Nishenko et al., 1994) that has been referenced by O'Loughlin & Lander (2003) and the NGDC/WDS Global Historical Tsunami Database (2021). The survey information is also contained in a Google Earth KMZ file located in Appendix 2 of the Electronic Supplement.

All of the observers in Costa Rica and Panama noted that the sea was calm prior to the earthquake (1557 local; 2157 Coordinated Universal Time, UTC) and that no emergency warnings were issued before the tsunami occurred. Depending on location, the sea initially receded 20 to 500 m from the shoreline. The exposure of recognizable features such as reefs and sandbars provided a basis for a more quantitative estimate of the amount of withdrawal in places.

Following the initial retreat, two principal types of runup behavior were observed. The first consisted of a 2 to 3 m high wave which advanced rapidly to the beach. Runup varied according to location and ranged from 10 to 100+ m inland. This behavior was observed at the mouths of major rivers in the area, including Boca Matina (#1) and Bocas del Pantano (#2). Waves were noted to have overtopped 3 m high dikes at the mouth of the Moin River (#5) and penetrated 1 km upstream at the Estrella River (near #7). Widespread liquefaction along the coast and compaction-induced subsidence of poorly consolidated sediments appear to have locally amplified runup effects at the mouths of large rivers (EERI, 1991; Denyer et al., 1994). Large waves were noted along beaches at Puerto Viejo (#8), Punta Uva (SE sector) (#10), Manzanillo (#11), and Gandoca (#12). While no significant damage resulting from the runup was reported by observers, two drownings are reported to have occurred in the canal near Matina (#1) due to the sudden increase in water height. A third drowning has also been documented near Moin (Chacón-Barrantes, personal communication, 2021). Large waves and fast currents were also noted at sites facing the Caribbean in Bocas del Toro, Northwestern Panama. Onshore flooding was noted at Playa de Julio Abrego (#15, Fig. 4), Tiribibi Point (#16, Fig. 5), and Lime Point (#17). Elsewhere, observers described the water activity as a series of strong currents (West Knapp (#18), Ground Creek (#19) and Nancy Key (#23)). Sand deposition by the tsunami was also noted by the respondents at many locations (12 Millas de Moin (#3), Westfalia (#6), Manzanillo (#11), and Gandoca (#12)). At the San-San Natural Refuge (#13, #14), a layer of sand, approximately 1 m thick was deposited on the beach creating dunes and covering turtle nests (Fig. 6).

El Servicio Geológico de los Estados Unidos y la Universidad de Costa Rica junto con la Comisión Nacional de Emergencia, están interesados en conocer el efecto de ondas del mar, relacionado con el reciente terremoto (22 de abril de 1991). Qué pasó y dónde pasó. Por favor ayúdenos respondiendo unas pocas preguntas.

1. Usted o alguna persona con la cual usted habló, notó alguna actividad inusual en el mar cerca de la fecha y la hora del terremoto? _____ Si _____ No
   Si no, pase a la pregunta 13. Si si pase a la pregunta 2.
2. Si la respuesta es si, acerca de cuando fue esta noticia?
3. Favor diga donde estaba usted cuando la actividad de la onda fue observada?
4. Diga acerca de lo que usted vió, olló o aconteció?
5. En qué capacidad usted observó la onda?
   _____ Mi trabajo _____ Donde vive
   _____ Actividad: pescando, caminando, corriendo, otros. Explique: _____
6. Qué fue lo que usted vió? Turbulencia _____ El agua se salió ____
   Todos los barcos estaban anclados _____
   El mar estaba picado _____ El mar llegó tierra adentro ____
   Otros (Explique) _____
7. Cuál es la dirección de la onda inusual en el mar?
8. Fue esto un peligro? _____ Si _____ No
9. Si responde si, que piensa?
10. Qué tan alta fue la marea donde las construcciones o estructuras estaban dañadas?
    En línea corta____ Entre 15 y 30 metros___Más que 70 metros__
    Menos que 15 metros _____ Entre 30 y 70 metros__
11. Qué dice además de la noticia?
    El mar se mueve por todos lados _____
    Efectos de la vida marina _____
    Otros (Explique) _____
12. Conoce usted algunos peligros o fatalidades asociados con esta onda? _____ Si _____ No
    Si responde si cuántos peligros? _____
    Fatalidades _____
    Circunstancias _____
13. Recibió usted la alerta de un tsunami por medio de un boletín visto, indique la advertencia? ____ Si____ No
    Si responde si, indique el tipo y en qué tiempo (s)? _____
    _____ Alerta _____ Boletín _____ Visto _____ Advertencia
    Si responde afirmativamente, cómo usted recibió la alerta, por medio de advertencia, boletín, visto? Si fue más de una por favor indique el orden? Favor indicar:

    _____ Alarma ___ Televisión ___ Defensa Civil _____ Policía
    _____ Bomberos ____ Otros (Específique)

    Si nosotros necesitamos contactar con usted, favor dar su nombre y número de teléfono:
    Nombre: _____ Teléfono: _____ Localidad: _____

Fig. 3: Tsunami Questionnaire.

The second type of runup consisted of a gradual increase in water level without a large wave. In some locations, the sea returned an hour after the initial retreat. This behavior was noted both in areas that experienced coastal uplift (Moin (#5), Limon (Fig. 7), and Cahuita (#7)) and in areas surrounded by fringing reefs (Limón-Moin, Cahuita, Manzanillo, Puerto Viejo in Costa Rica, and Boca del Drago in Panama) which appear to have acted as natural wave barriers or breakwaters (Fig. 1). One observer in Cahuita noted that the water returned to a level that was lower than before the earthquake. The coseismic coastal uplift reported at Cahuita is 38 cm (Plafker & Ward, 1992). The maximum coseismic uplift offshore Cahuita (#7) and Manzanillo (#11) may be comparable to, or larger than, the uplift north and west of Limon (125-140 cm) based on measured tsunami runup heights (Plafker & Ward, 1992).

DISCUSSION

The 1991 Limón tsunami survey demonstrated the utility of having a readily available questionnaire to distribute immediately after the event to capture perishable information related to the local characteristics and behavior of smaller tsunamis. Eyewitness observations from 26 sites along 150 km of affected coast, from Rio Matina, Costa Rica to Bocas del Toro, Northwestern Panama described a variety of wave and runup behavior. The maximum wave height is estimated to be 2 to 3 m, and the inundation and flooding extended between 10 and 150 m inland depending on local conditions. Coseismic uplift of the coast and the presence of fringing reefs minimized the impact of flooding in a number of coastal areas. Elsewhere, tsunami runup effects were amplified at other locations from the differential compaction of unconsolidated sediments at river mouths.

The 1991 earthquake and tsunami demonstrated the vulnerability of the coastal region to strong ground shaking, coseismic uplift and flooding. Local communities and economies were affected by limited coastal access due to significant bridge and roadway damage (Figures 8 and 9; EERI, 1991). While little tsunami-related property damage was reported, two or more drownings occurred at the canal near Matina and near Moin. No emergency warnings were issued before the tsunami occurred. Preparedness programs can educate residents to run to higher elevations when they feel strong ground shaking along the coast – even in the absence of a siren or other warning.

Information about the behavior of recent smaller tsunamis provides a valuable context for interpreting accounts of earlier Caribbean earthquake-related tsunamis. The deposition of sand near the mouth of the San-San River in 1991 is similar to descriptions of tsunami sand deposited on the coast near Gandoca and Monkey Point, near the Costa Rica-Panama border, during the 7 May 1822 (Ms 7.5+) earthquake and tsunami (Roberts & Irving, 1827). Flooding was also noted to have occurred in bays and the mouths of rivers along the Caribbean coast of Costa Rica (González-Víquez, 1910). Farther east, the 7 September 1882 earthquake (Ms 8.3), located in the North Panama Deformed Belt offshore of the San Blas coast of Northeastern Panama, created a tsunami with 2 to 3 m high waves, great destruction, and nearly 100 deaths on the islands of the San Blas archipelago. The French Panama Canal Company tide gauge near Colon recorded a maximum height of 62 cm (Víquez and Toral, 1986; Mendoza and Nishenko, 1989). The April 26, 1916 (M 6.9) Almirante, Panama earthquake also created a small local tsunami that is reported to have covered the southern tip of Carenero Island in the Bocas del Toro Archipelago minutes after the event (Reid, 1917; Duda, Khattri, Purcaru &Schick, 1990).

Hurricane-related flooding and storm surge occurs more frequently than tsunami flooding along the Caribbean coast of Costa Rica and Panama, yet both can produce comparable flooding and coastal impacts. Addressing these common hazards through identification of coastal flooding and tsunami evacuation areas, the marking of evacuation routes, and implementation of coastal building/land use development guidelines can help local communities to become more resilient in the future.

Table 2

Summary of 22 April 1991 Limón, Costa Rica Tsunami Field Study Observations

Site	Location	N Lat º	W Long º	Description	Runup Height (cm)*	Coseismic Uplift (cm)*	Site Characteristic
	Costa Rica						
1	Boca del Rio Matina	10.12º	83.19 º	The water retreated 400 m followed by large waves that flooded 180 m inland. Two drownings occurred in the canal near Matina. Widespread liquefaction. Dead fish were observed following the tsunami.			Beach/ River Mouth
2	Boca del Pantano	10.07º	83.16º	The water first receded ~100 m and then returned within 3 min without flooding.			Beach
3	12 Millas de Moin	10.07º	83.16º	Two minutes after the earthquake, a 2 m wave flooded 30 to 70 m inland. Sand movement.			Beach
4	6 Millas de Moin	10.00º	83.10º	The water slowly retreated about 20 m	135		Beach
5	Moin	10.00º	83.08º	The water retreated about 200 m. A sea wave overtopped 3 m high dikes in the Moin River.		125-140	Harbor/ River Mouth
6	Westfalia	9.94º	83.00º	The water retreated about 200 m and returned to the shoreline without appreciable runup or flooding. Sand movement.	130	74	Beach
7	Cahuita	9.74º	82.84º	The sea receded 75 m then returned slowly to a level lower than previous. Dead fish were observed.		38	Reefs
8	Puerto Viejo	9.66º	82.76º	The sea receded 100 m followed by a large wave, receded again and was followed by a large wave with 30 -70 m runup. Sand movement and dead fish were also noted.	155	38-45	Reefs
9	Final de Cocles	9.64º	82.72º	The sea receded 20 m then returned slowly over a 5 - 6 min period with no runup.		29-54	Beach and Cliffs
10	Punta Uva	9.64º	82.69º	Water retreats 400–600 m	200	40-45	Beach
11	Manzanillo	9.63º	82.66º	The sea receded 180 m and returned in 5 min to flood 30 to 70 m inland. Sand movement and 1.5 m sand mounds were deposited.	83-130	30-40	Beach
12	Gandoca	9.60º	82.60º	The sea receded 300 m in 5 min and returned to flood about 70 m inland. Sand Movement.	125	30-40	Beach
	Panama						
13	San-San Natural Refuge	9.54º	82.53º	Tsunami waves deposited a great deal of sand on the beach near the mouth of the San-San River, a wildlife refuge near the Costa Rica border, creating dunes which covered numerous turtle nests with approximately 1 m of sand and caused a decrease in the number of newborn turtles (see Fig. 6).			Beach
14		9.51º	82.49º				
15	Playa de Julio Abrego	9.43º	82.41º	A farmer reports that the before the quake occurred, the sea was very quiet. Minutes after the event the sea receded between three and six times. The last wave was the largest and the water penetrated 100 m inland. The NE-SW trend of fallen palm trees and other types of vegetation surrounded by sand and onshore flooding is seen in Fig. 4.			Beach
16	Changuinola River/ Tiribibi Pt.	9.42º	82.38º	Figure 5 shows the onshore flooding in this area and a zone of brown grass and vegetation parallel to the coastline. Sand deposition and fast currents			Beach

Table 2 (Continuation)

Summary of 22 April 1991 Limón, Costa Rica Tsunami Field Study Observations

Site	Location	N Lat º	W Long º	Description	Runup Height (cm)*	Coseismic Uplift (cm)*	Site Characteristic
	Isla Colon						
17	Lime Point (Boca del Drago)	9.41º	82.33º	Every person interviewed at this location reports that the sea was very quiet before the earthquake; but one-half to one hour before the event the sea was unusually warm. The sea receded approximately six times out to the coral reefs (approximately 100 m from shore) which looked like a stone wall. All six times the sea returned with a great roar and noise. The last wave was estimated to be 2 m high and flooded parts of the coastal road. This estimate was verified in the field by one of the authors (E. Camacho). The following day, the Boca del Drago passage had many dead fish floating in the water. Sea recedes 6 times and exposed reefs. Flooded coastal roads			Reef
18	West Knapp Hole	9.41º	82.33º	This site is located in the coast facing Almirante Bay. Before the earthquake, the sea was calm. Minutes after the quake, there was a great turbulence in the sea, similar to rapids of the strong current of a river. The strong current flooded from 5 to 10 m of the beach. Great turbulence with strong currents observed after earthquake. 5-10 m runup			Beach on Almirante Bay
19	Ground Creek	9.40º	82.31º	The sea was quiet before the quake. Water receded several times and returned as a strong river current approximately 0.6 m high, which deposited many fish along the banks of the creek which were flooded in some parts up to 10 m inland. Water receded, returns as strong current 0.6 m high. 10 m runup			Beach on Almirante Bay
20	Punta Cauro	9.43º	82.32º	This site faces the Caribbean Sea. The sea was quiet before the earthquake. The sea receded five times and returned making great noise. One witness left some clothes drying on a rock some 2 m or more above the surface of the water near a cliff. After the high waves ceased, she returned to get her clothes, and discovered they had been taken by the waves. She thinks the last wave was the one that took her clothes. A few days later, she recovered her clothes, which may have been brought back by the strong sea currents which run parallel to the coast in this area. Water receded 5 times and the last wave was ~ 2 m high.			Beach with Cliffs
21	Boket Bay	9.43º	82.30º	This site faces the Caribbean Sea. Ten to fifteen minutes after the earthquake, a 2.5 to 3 m high wave was observed from a house standing on top of a hill.2.5-3.5 m wave 10-15 min after earthquake.			Cove
22	Bocas del Toro	9.34º	82.25º	The sea was quiet before the earthquake. Ten minutes after the event, the sea receded approximately 400 m from the cove facing the town. The sand bar, Las Delicias (Grassy Bank) which is usually covered by 0.6 to 0.7 m of water, emerged and remained subareal from 5-7 minutes. After this period, several 0.6 to 0.7 m high waves started to enter the cove with great force. The water was full of sediment and flooded 100 to 150 m inland, mainly on the north part of town, which is located in an extremely flat area. Water receded 10 min after earthquake and exposed an offshore sandbar usually 0.6 m deep. Wave runup 10-15 m.			Reef

Table 2 (Continuation)

Summary of 22 April 1991 Limón, Costa Rica Tsunami Field Study Observations

Site	Location	N Lat º	W Long º	Description	Runup Height (cm)*	Coseismic Uplift (cm)*	Site Characteristic
23	Nancy Key	9.33º	82.22º	As observed from Hospital Point, 10 to 15 minutes after the earthquake, the sea receded several times and returned as a strong river current from Bocas del Toro passage. Water receded several times and returned as a strong current.			Point
24	Isla San Cristobal	9.29º	82.27º	In the northwest portion of the island, in the mouth of Paloma Creek, the sea receded several meters for approximately 45 minutes. Many fish got trapped in the dry terrain. The water returned as a slow wave recovering the areas that had emerged minutes before. .Sea recedes several meters for 45 min, water returns as a slow wave.			Creek
25	Isla Carenero	9.34º	82.23º	Approximately 15 to 20 minutes after the earthquake, the sea receded, and the usually submerged sand bank Las Delicias could be seen for about 15 minutes. The sea returned with just one very gentle wave and penetrated 100 to 150 m inland crossing the southern tip of the island, which is an extremely flat area. The inhabitants that remained on the island report that the water reached to their knees. The southern portion of the island remained flooded for approximately 20 minutes before the sea receded with great strength back to its original stage. Sea receded 15-20 min after earthquake, remained out for ~ 15 min and returns as gentle wave with 100-150 m run up			Beach
26	Isla Bastimentos	9.35º	82.21º	In the northwest portion of the island, known as Old Bank, the sea receded several meters 10 to 15 minutes after the earthquake. Some submarine vegetation could be seen during this period of time before the sea gently returned 15 minutes later. The sea receded 10-15 min after earthquake and returned gently.			Reef

* Runup heights and coseismic uplifts from Plafker and Ward (1992). Site specific information is provided in Appendix 2 of the Electronic Supplement.

Fig. 4: Near vertical air photograph of an area flooded by the tsunami at Playa de Julio Abrego, Panama (site 15, Fig. 1). Note the onshore flooding and the NE-SW trend of fallen palm trees.

Fig. 5: Near vertical air photograph of an area inundated by the tsunami between the mouth of the Rio Changuinola and Tiribibi Point, Panama (site 16, Fig. 1). Note the onshore flooding in the center of the photograph and zone of brown vegetation in the lower portion of the photograph.

Fig. 6: Tsunami sand deposits on the beach at the San-San Natural Refuge, Panama (site 13, Fig. 1).

Fig. 7: Coseismic coastal uplift near Limón City, Costa Rica.

Fig. 8: Damage to the Vizcaya River bridge, 10 km south of Limón, due to soil liquefaction and lateral spreading.

Fig. 9: Road damage on the Vizcaya River bridge approach due to liquefaction and lateral spreading.

ACKNOWLEDGEMENTS

We thank the United States Geological Survey (USGS) for providing funds to perform the field study in Costa Rica; the Geophysical Commission of the IPGH and CEPREDENAC for providing funds to perform the field work in Bocas del Toro; the Servicio Aereo Nacional (SAN) for logistical support in Bocas del Toro, Panama; J. Espinoza of the Panama Canal Commission and Leonard Hickman of the National Ocean Survey for providing copies of the tide gauge records. Conversations with and help from Silvia Chacón-Barrantes, Serkan Bozkurt, James Dewey, Alvaro Espinosa, Carlos Mendoza, Steve Personius, and George Plafker is gratefully appreciated. Due to the delay in the publication of these survey results, the opinions and conclusions expressed herein may not necessarily represent those of the USGS.

REFERENCES

Adamek, S., Frohlich, C. & Pennington, W.D. (1988). Seismicity of the Caribbean-Nazca Boundary: constraints on microplate tectonics of the Panama region, *Journal of Geophysical Research*, 93, 2053-2075.

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

Camacho, E. (1994). El tsunami del 22 de Abril de 1991 en Bocas del Toro, Pan*ama, Revista Geólogica de América Central, Special Volume: The Limón Earthquake, April 22,* 61-64.

Camacho, E. & Víquez, V. (1994). *Licuefacción y hundimientos costeros en el noroeste de Panamá durante el Terremoto de Limón. Revista Geólogica de América Central, Special Volume: The Limón Earthquake, April 22*, 133-138.

Camacho, E., & Víquez, V. (1993). Historical seismicity of the North Panama deformed belt, *Revista Geólogica de América Central, 15,* 49-64.

Denyer, P., Personius, S. F. & Arias, O. (1994). Generalidades sobre los effectos geologicos del terremoto de Limón, *Revista Geólogica de América Central, Volumen Especial: Terremoto de Limón*, 22, 29-38.

Duda, S. K., Khattri, N., Purcaru, G. & Schick, R. (1990). Weichert seismograms of the Gottingen Observatory – microfilming and reinterpretation, *Gerlands Beitr. Geophysik*, 99, 313-336.

GEBCO Compilation Group 2020 (2020). *The GEBCO_2020 Grid - a continuous terrain model of the global oceans and land*. British Oceanographic Data Centre, National Oceanography Centre, NERC. doi:10/dtg3

González-Víquez, C. (1910). *Temblores, terremotos, inundaciones y erupciones volcánicas en Costa Rica 1608-1910*. Tipografia de Avelino Alsina.

Earthquake Engineering Research Institute [EERI] (1991). Costa Rica earthquake of April 22, 1991 Reconnaissance Report, *Earthquake Spectra, 7* (Suppl. B), 1-127.

Iida, K. (1970). The generation of tsunamis and the focal mechanism of earthquakes. In W. M. Adams (Ed.), *Tsunamis in the Pacific Ocean* (pp. 3-18). East-West Center Press.

Iida, K., Cox, D. C. & Pararas-Carayannis, G. (1967). *Preliminary catalog of tsunamis occurring in the Pacific Ocean, Data Rep. 5, HIG-67-10*. Hawaii Institute of Geophysics, University of Hawaii.

Mendoza, C. & Nishenko, S. (1989). The North Panama earthquake of 7 September 1882: evidence for active underthrusting. *Bulletin of the Seismological Society of America*, 79, 1264-1269.

National Geophysical Data Center / World Data Service (NGDC/WDS) (2021). *Global Historical Tsunami Database*. NOAA National Centers for Environmental Information. doi: 10.7289/V5PN93H7

Nishenko, S. P. (1987). A questionnaire for rapid tsunami damage assessment. In E. N. Bernard (Ed.), *Proceedings of the International Tsunami Symposium, IUGG, August 18 to 19, 1987* (pp. 36-48). NOAA/PMEL Contribution 1041, U.S. Dept. of Commerce.

Nishenko, S. P., Camacho, E., Astorga, A., Morales, L. D. & Preuss, J. (1994). *The 1991 Limon, Costa Rica tsunami.* Unpublished manuscript.

O'Loughlin, K. F. & Lander, J. F. (2003). *Caribbean Tsunamis: A 500-Year History from 1498-1998.* Kluwer Academic Publishers.

Plafker, G. & Ward, S. (1992). Backarc thrust faulting and tectonic uplift along the Caribbean Sea coast during the April 22, 1991 Costa Rica earthquake. *Tectonics*, 11, 709-718.

Preuss, J. (1994). Field Report: Investigation of the September 2, 1992 Nicaragua tsunami. University of Colorado Boulder, Institute of Behavioral Sciences, Natural Hazards Research and Applications Information Center, Quick Response Research Report 66, Boulder, CO 16 pp.

Preuss, J. & Nishenko, S.P. (1992). The National Earthquake Information Center Tsunami Questionnaire. *EOS (Transactions, American Geophysical Union)*, 73, 267.

Protti, M. & Schwartz, S. Y. (1994). Mechanics of back arc deformation in Costa Rica: Evidence from an aftershock study of the April 22, 1991, Valle de la Estrella, Costa Rica, earthquake (Mw=7.7). *Tectonics*, 13(5), 1093–1107. https://doi.org/10.1029/94TC01319

Reid, H. F. (1917). Note on the earthquake at Almirante, Republic of Panama, in April 1916. *Bulletin of the Seismological Society of America*, 7, 27-30.

Roberts, O. W. & Irving, E. (1827). *Narratives of voyages and excursions on the east coast and in the interior of Central America; describing a journey up the river San Juan, and passage across the lake of Nicaragua to the city of Leon: pointing out the advantages of a direct commercial intercourse with the natives*. Constable & Co.

Silver, E. A., Reed, D. L., Tagudin, J. E. & Heil, D. J. (1990). Implications of the North and South Panama Thrust Belt for the origin of the Panama Orocline, *Tectonics*, 9, 261-281.

Suárez, G., Pardo, M., Domínguez, J., Ponce, L., Montero, W., Boschini, I. & Rojas, W. (1995). The Limón, Costa Rica earthquake of April 22, 1991: Back arc thrusting and collisional tectonics in a subduction environment. *Tectonics*, 14, 518-530.

Víquez, V. & Toral, J. (1986). Sismicidad historica sentida en el Istmo de Panama. *Geofisica*, 27, 135-165.

APPENDIX

ELECTRONIC SUPPLIMENT

Electronic Supplement 1: Tide Gauge Records

PDF files of scanned tide gauge records from:

- Coco Solo (Cristobal), Panama [9.35° N, 79.92° W] FILE: 1991_Cristobal.pdf 5.1 MB
- Magueyes Island, Puerto Rico [18.22°N, 67.16°W] FILE: 1991_Magueyes.pdf 5.4 MB
- Limetree Bay, Virgin Islands [17.69°N, 64.75°W] FILE: 1991_Limetree.pdf 5.3 MB

Electronic Supplement 2: Google Earth KMZ

Google Earth .kmz file showing locations of photographs and questionnaire responses collected in Costa Rica (sites 1 – 12) and Panama (sites 13 – 26) following the 22 April 1991 Limón, Costa Rica tsunami, FILE: 1991CR_Site_Locations.kmz 11.6 MB