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TSUNAMIS AND TSUNAMI PREPARDNESS IN COSTA RICA, CENTRAL AMERICA

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ABSTRACT

The Costa Rican coasts are at risk of local tsunamis. On both Pacific and Atlantic sides of Costa Rica there are coastal segments characterised by a flat relief, which increases the vulnerability of the coastal communities. In addition to tsunamis originating in the Middle American Trench (MAT), Costa Rican communities are at risk of a local tsunami generated by an earthquake in an undersea thrust fault system that runs along the Caribbean coasts of Costa Rica and Panama (NPDB). Furthermore, recent bathymetric studies reveal evidence of prehistorical submarine landslides in the Pacific Ocean capable of generating large tsunamis. The Golfo Dulce tsunami in 1854 in the Pacific and the Bocas del Toro tsunami in 1991 in the Caribbean are the real evidence of the hazard in the country. The University of Costa Rica is working on the implementation of the Tsunami Hazard Mitigation Program.

KEYWORDS: Tsunamis, Tsunami Hazard, Vulnerability, Tsunami Mitigation Program

INTRODUCTION

The tsunami hazard in Central America was little known and completely underestimated before 1992. The catastrophic 1992 Nicaraguan Tsunami demonstrated that the local seismic sources have potential to generate large tsunamis. Because of this reality, Nicaragua took actions to protect coastal residents from the attack of tsunamis. Later, the Centro de Coordinacion para la Prevencion de los Desastres Naturales en America Central (CEPREDENAC) supported the study of tsunamis in the region. The investigations indicated that 49 tsunamis have reached the Central American coasts since 1539 (Fernandez et al., 1999; Fernandez et al., 2000). Eight of these tsunamis have been destructive (Table 1).

Table 1: Destructive Tsunamis in Central America

Date	Country	Height (m)	Deaths	Comments
1854-08-05	Costa Rica	ND*	ND*	Destruction of a Village
1856-08-04	Honduras	5	ND*	The Ruin of a Coastal Community
1882-09-07	Panama	3	75-100	Several Islands Struck by the Waves
1902-02-26	El Salvador	> 5	185	Waves as High as the Coconut Trees
1913-10-02	Panama	ND*	ND*	A Village Disappeared
1957-03-10	El Salvador	> 2	ND*	The Tsunami Killed People in El Salvador
1976-07-11	Panama	ND*	ND*	People Died in Panama
1992-09-02	Nicaragua	9.5	170	The Largest Known Tsunami in the Region

*ND: No Data

The reported tsunamis might not represent the complete tsunami history of Central America. Other historical tsunamis were probably not documented because the coastal areas were sparsely populated when they occurred. The 49 documented tsunamis in the region since 1539 indicate that most tsunamis might have been prehistorical tsunamis. It has been observed by von Huene et al. (2004) that prehistorical landslides could have generated tsunamis in Costa Rica.

The historical tsunamis strongly suggest that Central America needs preparation to treat the phenomenon. Efforts to establish a Tsunami Warning System in the region began in 1998. However, the establishment of a Tsunami Warning System is still incipient. The seismic and mareographic networks are not well-integrated. People and authorities are not prepared to respond in case of tsunami, and the determination of areas at risk, which is useful information to establish the warning system, is just starting.

In this paper, we address the problem of the tsunami hazard in Costa Rica. We briefly describe the characteristics of the coasts and the tsunami sources, giving examples of tsunamis that have originated on the Costa Rican coasts. Plans and actions to mitigate the tsunami disaster in the country are mentioned in this work.

TECTONIC SETTING

Central America is located in the western end of the Caribbean plate, a medium-size plate that moves eastward at a speed of 2 cm/yr. This plate is bordered by four other plates: North American, South American, Nazca and Cocos (Figure 1). The tectonic boundaries between these plates are the Middle American Trench (MAT), the Polochic-Swan Fault System, the North Panama Deformed Belt (NPDB), and the Panama Fracture Zone (PFZ). MAT is located at the junction of Cocos and Caribbean plates. At this trench the Cocos plate subducts under the Caribbean plate causing a collision and high tectonic stress. Hypocenters indicate that the maximum depth of the subducting slab is 250 km and the minimum depth is 70 km.

A set of parallel approximately east-west trending strike-slip faults (the principal movement is horizontal and therefore parallel to the strike of the faults) is the main expression of the North America-Caribbean plate boundary in northern Central America. Its continental section is a series of faults (PMCHFS, see Figure 1) whose activity and sense of movement have been documented by geologic, geomorphic, and seismic evidence. This system continues into the Caribbean Sea as a single fault called Swan. The slip rates on this plate boundary range from 1.3 to 20 mm/yr over the past years, using geologic and geomorphic data, and from 9 to 34 mm/yr, using global tectonic models (Guzman-Speziale, 2001; Heubeck and Mann, 1991).

The Panama Fracture Zone (PFZ), a dextral north-south striking oceanic transform fault zone, constitutes the plate boundary between the Cocos and Nazca plates. This fracture zone is located between 82° and 83°W. It extends from 3°N up to 6°N (Adamek et al., 1988; Camacho, 1991).

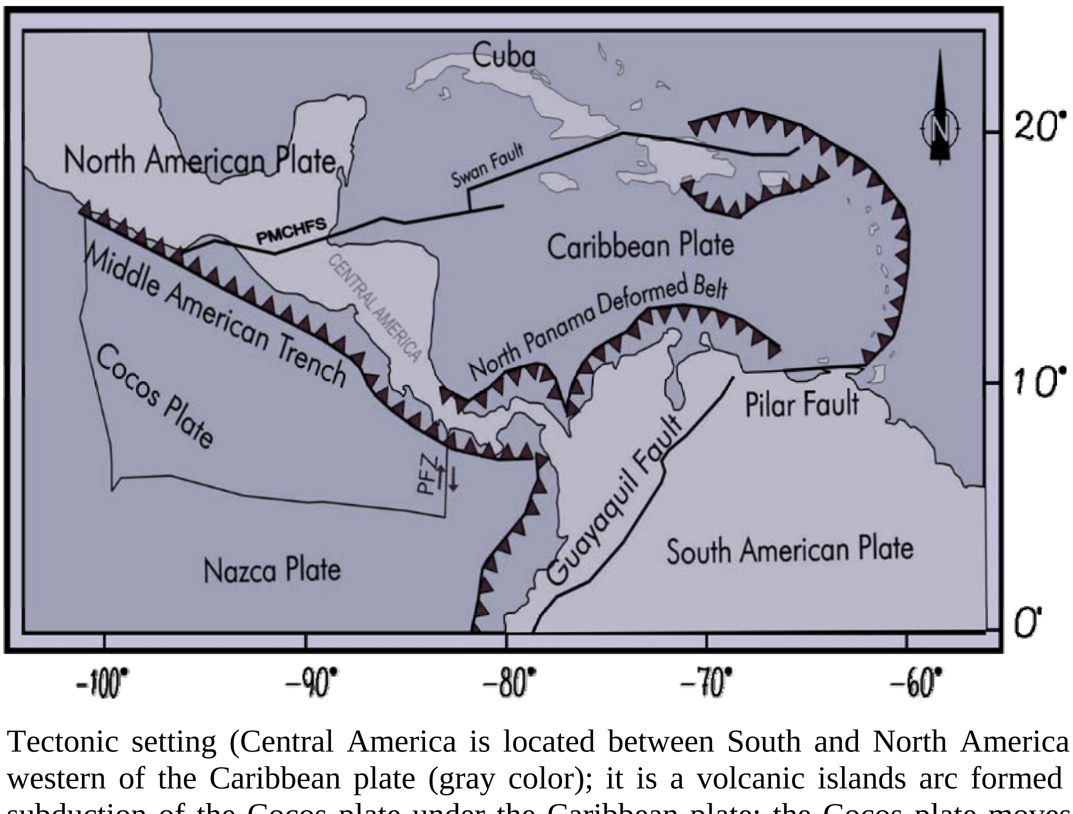

Fig. 1 Tectonic setting (Central America is located between South and North America in the western of the Caribbean plate (gray color); it is a volcanic islands arc formed by the subduction of the Cocos plate under the Caribbean plate; the Cocos plate moves to the north-east; PMCHFS: Polochic-Motagua-Chamalecon Fault System, PFZ: Panama Fracture Zone)

NPDB extends offshore from Pilar fault in the east to Central Costa Rica in the west. This overthrust boundary, which originates from convergence between the Caribbean plate and the Panama block, is not a mature subduction zone. Deformation of the Panama block has caused this wide belt of folds and thrusts north of Panama. This belt is not associated with a Benioff zone or an active volcanic arc (Adamek et al., 1988; Silver et al., 1990). Its existence can be explained by the movement of blocks in the Caribbean plate.

These tectonic boundaries are responsible for the seismicity of Central America. MAT generates most of the earthquakes in the region. The level of seismicity is also high at the Panama Fracture Zone. On the contrary, the seismicity of the PMCHFS-Swan Fault System and the North Panama Deformed Belt is low. More importantly, underwater earthquakes capable of generating tsunamis occur in all the tectonic boundaries of Central America.

THE COSTA RICAN COASTS

Costa Rica has coasts on both Pacific and Caribbean sides. The Pacific coast is geometrically and topographically very irregular. Large segments of this coast are highlands that have made them safer and less vulnerable to the threat of tsunamis. However, flat topography like the Parrita plain (Figure 2) is more vulnerable. In consequence, the risk is higher in this zone where there are important population centers like Quepos and Esterrillos. Other populated communities at this coast are Jacó and Puntarenas.

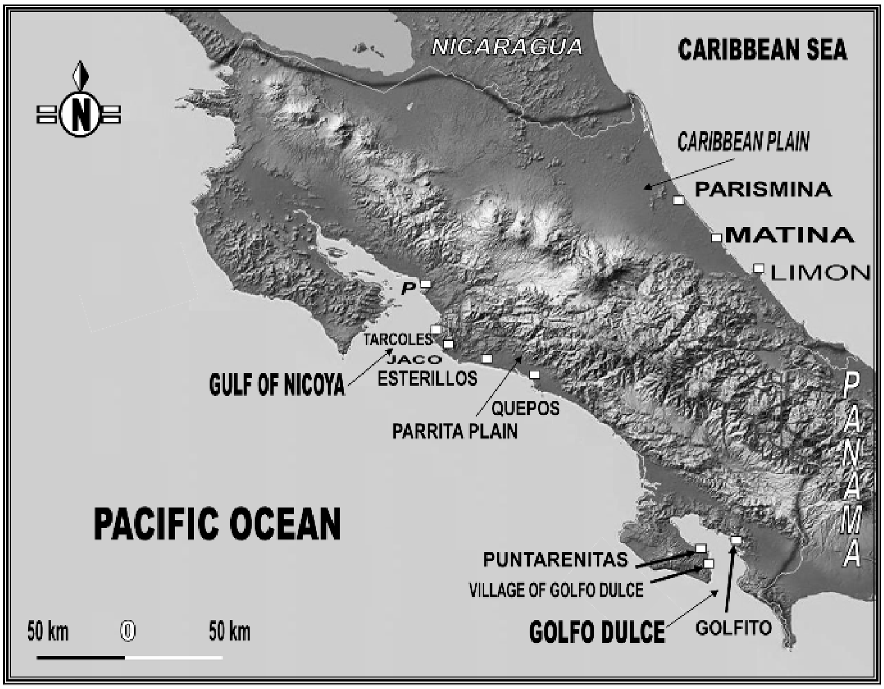

Fig. 2 Relief map of Costa Rica showing flat and abrupt topography (almost the entire Caribbean coast is part of a large alluvial plain; on the contrary, the topography of the Pacific is abrupt and high, offering safer locations to the coastal residents and visitors; P: Puntarenas; the elevation model is courtesy of Javier Bonatti)

Jacó is a 3 km long beach with more than 5000 residents. Puntarenas is a harbour city of 36000 inhabitants situated on a low, strikingly flat, sandbar within the Gulf of Nicoya (Figure 3). In the first two kilometers from the shore the bar broadens westward, attaining a width of 400 m near its end. From the mean tide level, this plain rises gradually to a nearly uniform height of 2 m above the tide**.** These natural conditions expose the city to the impact of tsunamis. Just as an example, the 1998 Papua New Guinea Tsunami destroyed communities located on the Sisano sandbar killing more than 2000 people (Kawata et al., 1999).

In vulnerable areas like Sisano and Puntarenas, the tsunami threat can be assessed by means of tsunami inundation maps and community education. However, escaping from a tsunami in Puntarenas is really difficult. Reaching a safe location above the sea level is impossible and there is only one way available to escape (Figure 3). Thousands of people will have to use that way to evacuate within 20 or 30 minutes after the earthquake. In this case, the best option could be vertical evacuation.

Fig. 3 Puntarenas, Costa Rica (this city is the main harbour on the Pacific coast of Costa Rica; many tourists visit this place every year; the interaction between the ocean and the local rivers formed this sandbar; this is an example of high vulnerability to tsunamis; courtesy: Jean Mercier)

Offshore of Costa Rica, the Cocos Ridge and its seamounts (Figure 4) interrupt an otherwise monotonous Pacific Ocean Basin. This rise supports a chain of seamounts that extends from the present Fisher Mount to the end of the studied area. The Cocos Ridge is an aseismic and volcanic bathymetric high region, which reaches more than 4 km above the surrounding ocean floor and is being subducted beneath southern Costa Rica. The intersection of Cocos Ridge with the Middle American Trench creates a shallowing of both the subduction zone and the trench. Other prominent features on the subducting Cocos plate are large volcanoes and lava flows like the Eves volcanoes and the Quepos Plateau. This plateau is about 2 km high and 100 km long.

The Caribbean coast is shorter, more rectilinear and flatter than the Pacific. These characteristics result from the large plains that occupy the Caribbean side of the country. Interesting localities of this coast are Limon and Parismina. Limon, a city of 61200 people and the main harbour in the Caribbean, is approximately in the middle of this coast. Parismina is a small coastal town whose streets are covered by sand. This could be the result of the interaction between the sea and the Parismina River but the effect of an historical or prehistorical tsunami cannot be ruled out. The nearby area was hit by tsunamis in 1798 and 1882.

TSUNAMI POTENTIAL

The potential for destructive tsunamis in both, the Caribbean and Pacific coasts, is real. However, the Pacific coast has the greatest tsunami potential in the country. This is due to the existence of a subduction zone in front of the Pacific coast and unstable slopes at the end of the continental platform. Hence, the best mechanisms to trigger tsunamis in Costa Rica are underwater earthquakes and landslides.

1. Underwater Earthquakes

All the tectonic environments of Central America have generated moderate magnitude earthquakes in the past. However, the subduction zone (Middle American Trench) has been their main source. In fact, 93% of the total moment release (for M_s > 7.0 earthquakes) in Central America during 1898-1994 period was released along MAT (Ambraseys and Adams, 1996). Therefore, this margin is the main source of tsunamigenic earthquakes in Central America. Just as an example, 37 of the 49 tsunamigenic earthquakes of Central America were generated along MAT. Eleven of the sixteen tsunamis that have reached the Costa Rican coasts occurred in the Pacific (Table 2) and were related to the subduction process.

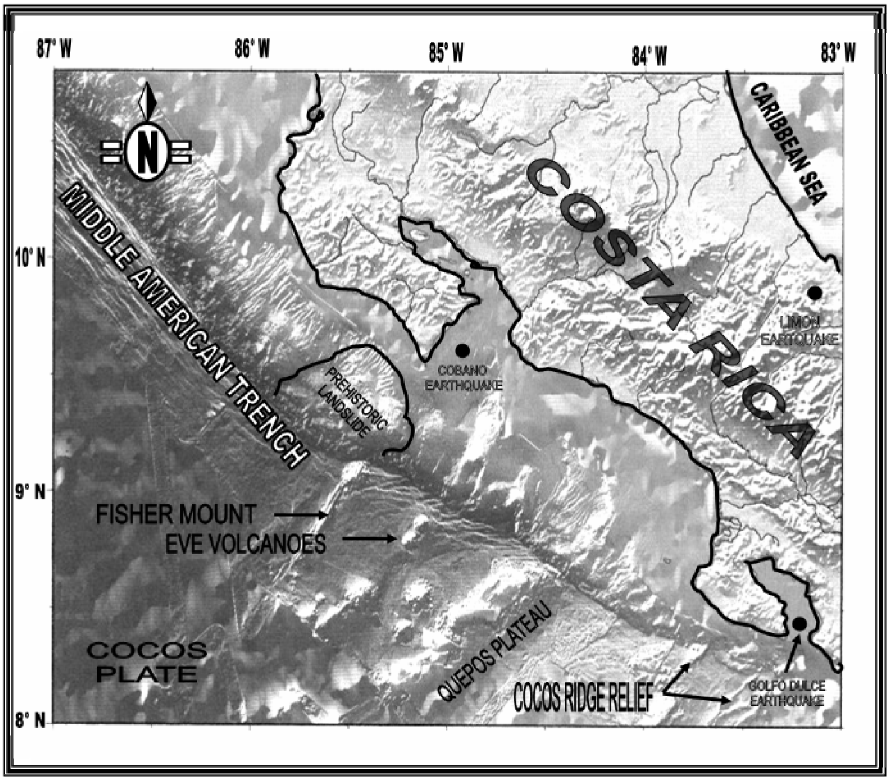

Fig. 4 Morphology of the Cocos-Caribbean convergent margin showing the Middle American Trench, seamounts, a prehistoric slump scar and the epicenter of three earthquakes mentioned in the text (the relief of the Cocos Ridge is also shown; adapted from Ranero and von Huene, 2000)

Table 2: Tsunamis in Costa Rica

Date	Coast	Height (m)	Type	Tectonic Environment
1579-03-16	Pacific	ND*	Local	Middle American Trench
1798-02-22	Caribbean	ND*	Local	North Panama Deformed Belt
1822-05-07	Caribbean	ND*	Local	North Panama Deformed Belt
1854-08-05	Pacific	ND*	Local	Middle American Trench
1904-12-20	Caribbean	ND*	Local	North Panama Deformed Belt
1905-01-20	Pacific	ND*	Local	Middle American Trench
1906-01-31	Pacific	ND*	Regional	Colombia Subduction Zone
1916-04-26	Caribbean	1.30	Local	North Panama Deformed Belt
1934-07-18	Pacific	0.60	Local	Nazca-Caribbean Margin
1941-12-05	Pacific	0.22	Local	Middle American Trench
1941-12-06	Pacific	0.08	Local	Middle American Trench
1950-10-05	Pacific	ND*	Local	Middle American Trench
1952-05-13	Pacific	0.10	Local	Middle American Trench
1962-03-12	Pacific	0.30	Local	Panama Fracture Zone
1990-03-25	Pacific	0.01	Local	Middle American Trench
1991-04-22	Caribbean	3.00	Local	North Panama Deformed Belt

*ND: No Data

2. Underwater Landslides

Cocos plate relief clearly influences tectonism of the margin where it subducts beneath the Caribbean plate at the latitude of Costa Rica. The first-order effects of the subducting lower plate on the upper one involve entry of seamounts into the trench, uplifting of the continental platform and deformation of the continental crust. The seamounts on the descending plate form asperities that result in earthquake nucleation. Fernandez et al. (2006) relate the high seismicity of Central Costa Rica to the intense tectonism associated with the subduction of ocean floor relief under the Caribbean plate.

Aseismic ridges and seamount chains that are being subducted cause significant compressional deformation of the forearc. Data suggest that subduction of seamounts has significantly altered the structure of the forearc of Costa Rica, creating steeper, unstable slopes that are more susceptible to uplifting, fracturing, slumping and erosion. Mass wasting is evidenced by slump scars in the steep continental slope. It is argued by von Huene et al. (2004) that the steepening of the continental slope above underthrust relief on the Cocos plate causes slope failure along the convergent margin, which may result in tsunamis. They found a 50-km-wide prehistoric slump (landslide) in the continental slope in front of the Nicoya Peninsula (Figure 4). According to them, that slump could generate a tsunami 27 m high.

As mentioned before, the tsunami and earthquake production of the Caribbean coast is low compared to the Pacific coast. The North Panama Deformed Belt generates relatively few earthquakes and consequently, the occurrence of tsunami is low too. However, all the large Caribbean earthquakes ($M >$ 7.0) of the last 100 years have generated tsunamis. Until the present, five tsunamis of this coast have been documented (Table 2).

THE REAL EVIDENCE OF TSUNAMIS IN COSTA RICA

Most of time, the risk of natural hazards is overlooked and underestimated by the population and the local governments. They tend to ignore the danger instead of getting to know about it. According to our investigation, Costa Rica is a tsunami prone area and therefore, the phenomenon cannot be ignored. The following descriptions illustrate the occurrence of tsunamis in Costa Rica.

1. The Destructive Tsunami of 1854

On 5 August 1854 a 7.3 magnitude earthquake hit Golfo Dulce in southern Costa Rica. The event was located 33 km deep in the same gulf. The earthquake caused only slight damage to man-made structures, mainly because of the sparse and scarce population in the epicentral area. According to Lewis (1984), 200 hundred people lived in the village of Golfo Dulce in 1885 and 200 more around Golfo Dulce. The extent of the area that experienced damaging earth motion was estimated to be the whole country. However, shaking that was strong enough to alarm the general population occurred over the area of Golfo Dulce. The earthquake magnitude was estimated from isoseismal maps.

The region most seriously affected was characterized by sunken lands. Along the west coast of Golfo Dulce, the land subsided in some places. A notable area of subsidence was Puntarenitas just north of the village of Golfo Dulce (currently Puerto Jimenez). Part of that bar sank and was covered with water. The village of Golfo Dulce was flooded by the sea and destroyed.

Despite several publications having mentioned the tsunami (Montessus de Ballore, 1888; Soloviev and Go, 1984; Lewis, 1984) the cause of the reported damage is not clear yet. The best documented effect was the subsidence and disappearance of the village Puntarenitas (Montessus de Ballore, 1888; Peralta, 1911; Hoffmann, 1947; Soloviev and Go, 1984) but there are no reports of any death. This effect could be originated by the following causes: (i) strong waves that eroded the coast, and (ii) an earthquake-triggered landslide. Although doubts persist, the tsunami should have existed because the second scenario favours the water oscillations too.

Few people lived in Golfo Dulce and Puntarenitas by 1854. The French failed in colonizing that region and therefore left it in 1850. Thus, the absence of people could be the reason for the lack of death reports.

2. The Cobano-Earthquake Tsunami

On 25 March 1990, the Cobano earthquake struck the Golf of Nicoya where a small tsunami was generated. Gutiérrez and Lizano (1991) reported, based on eyewitness reports, waves of at least 1 m on the beach of Puntarenas. However, this would be improbable if the earthquakes source was a north-south fault (the tsunami energy flow is perpendicular to the earthquake source) as was proposed by the Red Sismologica Nacional (Barquero and Boschini, 1990). The tsunami was recorded by a tide gauge in Quepos, and its amplitude was 1 cm.

3. The Limon-Earthquake Tsunami

At 1557 hours GMT on 22 April 1991, the Caribbean coast of Costa Rica experienced a devastating 7.7 magnitude earthquake. The event was located 36 km southwest of Limon 20 km deep. The most severe damage was concentrated in the Caribbean side of Costa Rica and Panama where 98 people were killed. A co-seismic uplift occurred during the earthquake due to vertical movement of an underlying active thrust fault. As a result, the marine abrasion platforms were elevated up to 1.0 m above the active shoreline. The maximum coseismic uplift recorded was as much as 1.85 m near Limon harbor (Denyer et al., 1994a).

Tsunami waves were confirmed along a 160-km segment of coastline, from Matina, Costa Rica, to Bocas del Toro, Panama (Figure 5). They struck the coast within 5-15 minutes of the earthquake (Denyer et al., 1994b). The first sign of the tsunami was a recession of the sea water before the first wave reached the shoreline. Soon after that, a succession of small waves hit the coastal areas during an hour. At a greater distance, the tsunami was documented on Colon, Panama, where a tidal gauge recorded a wave of 7.62 cm one hour after the earthquake and many others in the following 5 hours (Camacho, 1994).

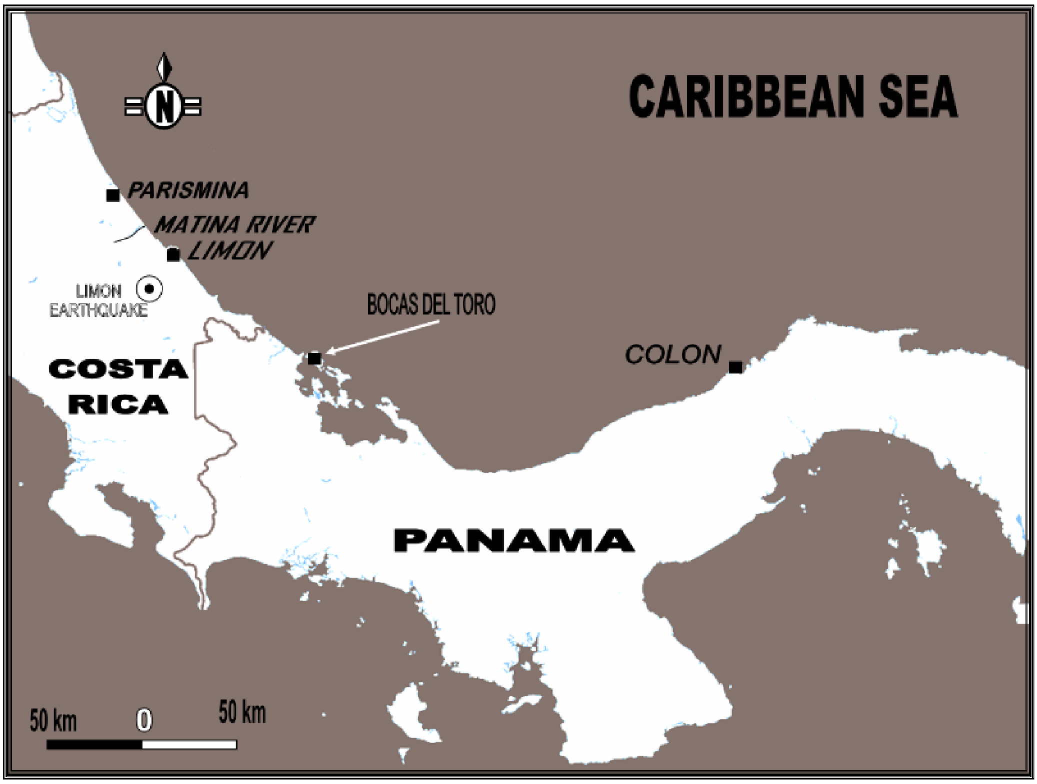

Fig. 5 Area affected by the tsunami generated by the 1991 Limón earthquake (the inland epicenter is shown; the tsunami was recorded by a tidal gauge in Colon, Panama)

Most of the tsunami energy was focused on a 60-km strip of the Panama coastline in the south. This is consistent with eyewitness observations indicating that waves traveled from north to south. Such waves produced maximum height and landward penetration in Panama of 3 m and 150 m respectively. The inundation decreased rapidly about 25 km northwest of the Panama-Costa Rica border. Regarding the damage, the tsunami left sand layer and accumulations of debris behind on ground with favorable circumstances and dead fish floating along the coast in some places. Some of the coastal residents were frightened and ran to higher ground.

The tsunami was local and small. It is quite probable that its waves were not higher because the earthquake epicenter was located inland. Otherwise, the vertical deformation of the sea bottom would have generated a higher initial wave. Depending on the distance to the coast, the wave would have grown by refraction and shoaling.

Panama was more affected by the tsunami than Costa Rica despite the epicenter of the earthquake being located in Costa Rica. This could be explained by the co-seismic uplift along the Costa Rican coast and the associated inclination of the sea bottom southward. Both facts could have led to propagating waves from north to south. Consequently, the Panama coast experienced major flooding and the highest waves.

LESSONS AND PREVENTION

The tsunami hazard of Central America was underestimated until 2 September 1992 when a catastrophic tsunami struck Nicaragua. This event raised public awareness that large earthquakes in the region can generate destructive tsunamis. The largest of its waves was more than 9 m high. It inundated low-lying coastal areas by as much as 1 km. The tsunami was responsible for 170 deaths. Waves ranging from 2-4 m reached Costa Rica and damaged small harbors and boats. This event proved that Central America is a tsunamigenic zone. The lesson from recent tsunamis (the 1991 Costa Rica tsunami in the Caribbean Sea, and the 1992 Nicaragua tsunami in the Pacific) is that locally generated tsunamis in Central America may cause loss of lives and damage to property. In addition, regional tsunamis can also strike the Central American coasts.

1. Public Education

The challenge for University of Costa Rica (UCR), the Red Sismologica Nacional (RSN), and the Central American Seismological Center (CASC) is to provide a public education program that may change attitudes and influence behaviors with respect to the threat of tsunamis. The development of an effective community program in tsunamis will enhance this role and enable people to realise that they can protect themselves from fearsome tsunamis. The message should reach not only those who visit the beach but the whole of society. A real need is to take education out into the community to reach those who would not normally become involved. Through outreach programmes and projects we can also raise awareness of the tsunami hazard.

The UCR, RSN and CASC are trying to implement an education program on tsunamis in Costa Rica. A pilot plan started in the region of Garabito located in the central segment of the Pacific coast of Costa Rica (a coastal region between Tarcoles and Esterillos, see Figure 2). Seismologist and education managers worked with a number of local groups to disseminate basic information about tsunamis, including the rules to face them. Among its efforts to raise awareness of the hazard, the UCR-team holds workshops on community education. Workshop activities include oral presentations on tsunamis, videos, evacuation practices and installation of signs at the beaches.

A working group, consisting of appointed experts from the University of Costa Rica and the Ministry of Education of Costa Rica, was formed to facilitate the education process on tsunamis. The objectives of this group include the discussion and development of educative material on tsunamis. Particular emphasis will be placed on disseminating the educational products among many national and cross-sector education communities. The group is currently preparing a text whose publication is planned for November 2005. This material will be distributed to approximately 5000 elementary schools and 3000 high schools of the country.

The first workshop on community education was held in Herradura beach, Garabito on 26-27 July 2005. During this activity, tsunami educative signs were installed at the aforementioned beach (Figure 6). Those signs are the first in Costa Rica and Central America. The community of Garabito plans to expand the number of signs along its beaches. This improves the ability of local emergency respondents to protect the coastal residents and tourists against the tsunamis. Hopefully, the Garabito pilot plan will be taken to all the coastal communities of Costa Rica and Central America.

Fig. 6 Educative tsunami signs installed on Herradura beach, Costa Rica in July 2005 (these are the first signs of its kind installed in Costa Rica and Central America; despite the official language of Costa Rica being Spanish, the sign were also written in English with consideration for the tourists; courtesy Press Department, University of Costa Rica)

CONCLUSIONS

Coastal communities of the Pacific and Caribbean coasts of Costa Rica are susceptible to inundation by tsunamis. The probability of inundation by local and regional tsunamis is higher in the Pacific coast due to two important tsunami sources: the Cocos-Caribbean Subduction Zone and the unstable continental slope. The subduction zone generates many underwater earthquakes capable of triggering tsunamis. In fact, most of the tsunamis of Costa Rica and Central America have been produced by this process. The subducting seamounts on the Cocos plate have significantly altered the structure of the forearc of Costa Rica, creating steeper, unstable slopes, which are more susceptible to slumping that can provoke large tsunamis.

Tsunamis cannot be ignored in Costa Rica. Therefore, the University of Costa Rica has started a tsunami mitigation program which includes public education on tsunamis. The first tsunami signs were installed on Herradura beach in July 2005.

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