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# Historic-prehistoric earthquakes, seismic hazards, and Tertiary and Quaternary geology of the Gandoca-Manzanillo National Wildlife Refuge, Limón, Costa Rica

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**Abstract:** The Gandoca-Manzanillo region is part of the Limón Basin, located in southeastern Costa Rica. The depositional environment of Tertiary sedimentary rocks shows a progressive shallowing through geologic time, from deep marine (Miocene-Pliocene) to deltaic-fluvial and coral reef environments (Quaternary). The most dramatic geologic effect of the Limón-1991 earthquake was coseismic uplift of the shoreline, which ranged from 0.3 to 0.6 m in the Gandoca- Manzanillo region. This event caused liquefaction of thick deposits of young, fine-grained fluvial sediments in the region, and produced a tsunami affecting the vicinity of Manzanillo and Punta Uva, but the heaviest damage was reported in northwestern Panamá. The effects of the tsunami may have been diminished in Costa Rica because of the presence of fringing reefs, and the fact that this part of the coast had been coseismically uplifted by the time tsunamis arrived at the coast. Two platform levels were dated using radiocarbon method on coral samples. The platform level at 1.5-2.0 m had radiocarbon ages of 5 220±50 years B.P. and 4 540±50 years B.P., and the 8.0-10.0 m terrace level was dated at 27 145±290 years B.P., yielding a 1.8 mm/year long-term coseismic uplift rate. Variations in the heights of individual platforms reflect a very irregular coseismic uplift behavior, and probably also an irregular earthquake time recurrence period. However, similarities between the 1991 and 1822 events suggest 150 to 200 years as the earthquake recurrence time.

Key words: Paleo-seismology. co-seismic uplifting, Quaternary geology, Caribbean-Costa Rica. Gandoca wildlife refuge.

Gandoca-Manzanillo is located in the Limón Basin, a thick sequence of Cenozoic sedimentary rocks which constitute the substrate to an ecological reserve. The age of its outcroping geologic units ranges from Miocene to the present. The depositional environment ranges from relatively deep marine waters during the Miocene to coral reefs and fluvial conditions in the Quaternary. A tendency to progressive shallowing is observable through geologic time. In this paper I focus on the Quaternary geology, providing an account of preliminary field observations (May and June, 1991) of coastal phenomena that occurred, in part, during the 1991-Limón earthquake. This study was performed in order to determine recurrence times and prevent damage for similar earthquakes.

## GEOLOGY

The southeastern Costa Rica region belongs to the North Panamá Deformed Belt, a seismically active fold and thrust belt that extends from southeastern Costa Rica to Colombia (Case & Holcombe 1980, Adamek *et al.* 1988, Bowland & Rosencrantz 1988). The North Panamá Deformed Belt has been the subject of much discussion in the geologic literature, most of which focuses on its role in the com-

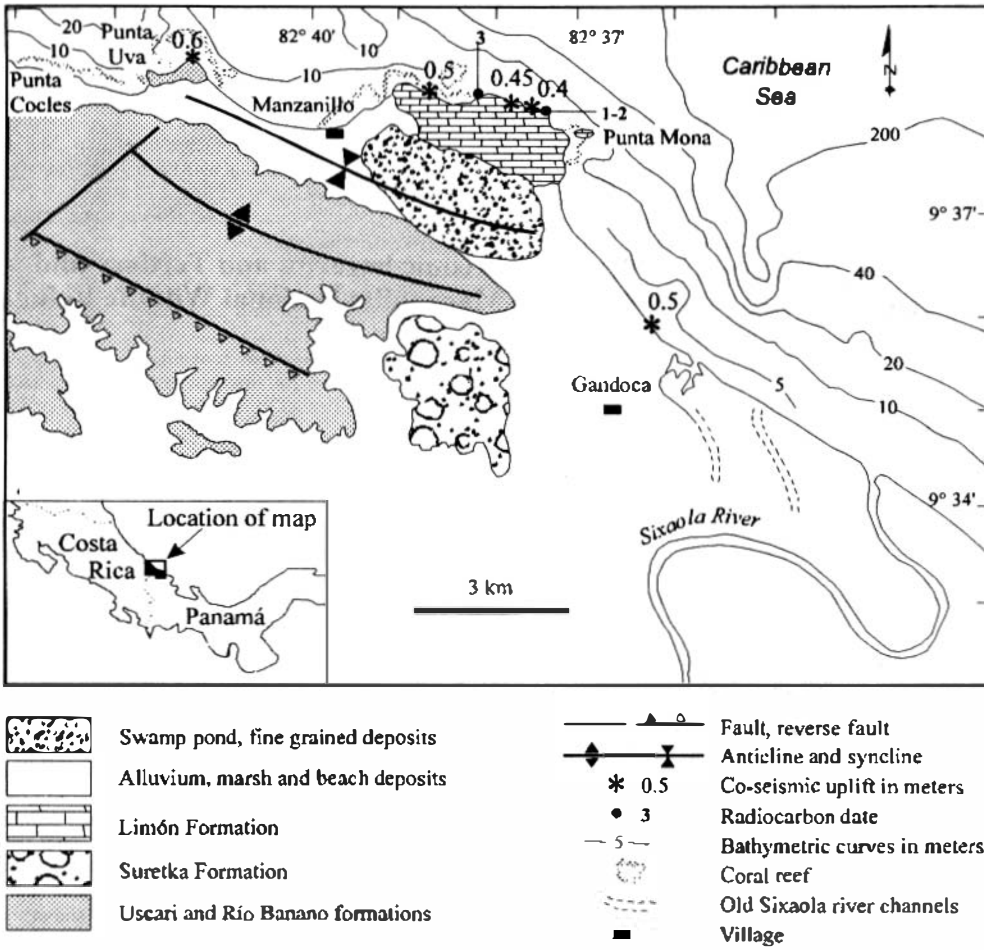


Fig. 1. Geology of the Gandoca-Manzanillo region. After Anonymous (1976), Sáenz (1982), Compañia Petrolera and RECOPE (*in* Bolaños 1983). Geodetic based on the Sixaola quadrangle of the Instituto Geográfico Nacional.

plex and poorly understood interaction between the Caribbean, Nazca, and Cocos plates (Adamek *et al.* 1988, Muñoz 1988, Mann & Corrigan 1990, Silver *et al.* 1990).

The main Neogene tectonic events of the region occurred at the end of Miocene and during the Pliocene, involving west and northwest-trending folds, and north and northwest-trending thrust faults (Anonymous 1976, Sáenz 1982, Bolaños 1983, Malavassi 1985, Rivier 1985, Campos 1987, Denyer *et al.* 1987, Astorga *et al.* 1991, Denyer *et al.* 1994 a). During the same period, the Talamanca Range was uplifted rapidly, leading to deposition of very coarse-grained conglomerates (Suretka Formation) in the Limón Basin during the Pliocene and Pleistocene.

The geologic map of the Gandoca-Manzanillo region (Fig. 1) was interpretated from my own observations and from a compilation map from Compañía Petrolera and RECOPE, which is shown by Bolaños (1983). The Holocene coral-algae reef is dipping 10° SSW in Punta Mona. The mapped defonnation is a result, at least in part, of late Quaternary compressive compressive-stress, which caused folding and reverse faulting. Such deformation could be related to a regional stress regime in the North Panamá Thrust Belt.

**Stratigraphy**: The geologic history recorded in the Gandoca-Manzanillo Region began in the Miocene, as a progressive shallowing from relatively deep marine waters to deltaic-fluvial and coral reef environments. The formal geological units are (Fig. 2) the Uscari and Río Banano Formations (Miocene and Pliocene), and the Suretka Formation, (Pliocene and Pleistocene). The Holocene Limón Formation of fossil algal reef, and informal units of alluvium, marsh, beach and lagoon deposits.

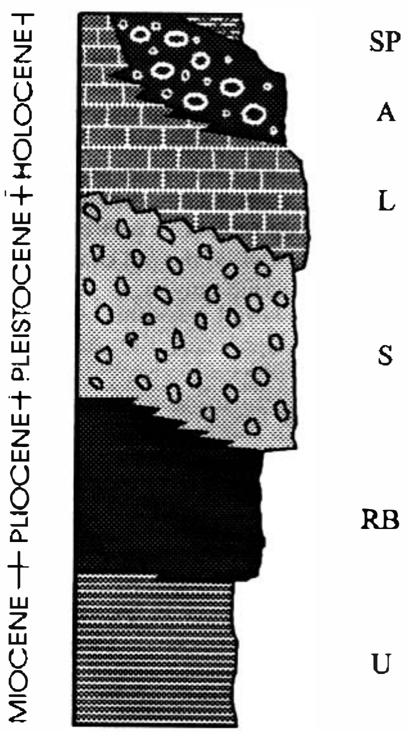


Fig. 2. Stratigraphic column of the Gandoca-Manzanillo region. U: Uscari Formation, RB: Río Banano Formation, S: Suretka Formation, L: Limón Formation, A: Aluvium, marsh and old beach deposits, SP: Swamp pond, fine grained deposits.

The Rio Banano and Uscari Formations are not differentiated on the geologic map (Fig. 1). A more detailed study is required to map the contact between these formations, which crop out to the west of the studied area. Coates *et al.* (1992) considered both formations as part of the so-called Limón Group. Each of these formations represents a further stage of progressive marine shallowing, as has been observed in many localities across the Limón Basin (Escalante 1990).

The Uscari Formation (Fig. 2) consists of 500-2 000 m of well-bedded soft and dark-colored shales, which range in age from lower to upper Miocene (Olsson 1922, Taylor 1975, Pizarro 1985), the diachronism is suggested by A. Aguilar (*in* Sprechmann 1984) and Fernández *et al.* 1994. According to Taylor (1975), these rocks were deposited in a low energy environment, and a warm climate, in the outer neritic or upper continental slope environment, at dephts of 400 to 600 m.

The Río Banano Formation (Fig. 2) was described by Olsson (1922) as the Gatún Formation in Panamá. This geologic unit overlies the Uscari Formation. The Río Banano Formation is upper Miocene to Pliocene in age (Aguilar *in* Sprechmann 1984, Campos 1987, Denyer *et al.* 1987), and becomes younger towards to the North (Coates *et al.* 1992). It attains a thickness of up to 1 500 m (Bolaños 1983, Fernández 1987, Campos 1987). In the study area, this unit consists of fine-grained, gray to blue sandstones, that were deposited in shallow marine water, on the inner to middle continental shelf, although the conditions were quite variable (Taylor 1975). Deposition occurred at a depth of about 20 m (Cassell & Sen Gupta 1989).

The shoaling marine units are followed by fluvial conglomerates and sandstones of the Suretka Formation, derived from erosion of the uplifting intrusive rocks of Talamanca Range. The Suretka overlies and also is interstratified with Río Banano Formation (Fig. 2). This conglomerate contains blocks up to 1 m in diameter, is composed of volçanic and plutonic rocks, and reaches a thickness of 1000 m in cores of Telire (Bolaños 1983), with 2000 m maximum (Fernández *et al.* 1994). The Suretka Formation was deposited during the Pliocene and Pleistocene to Holocene (Taylor 1975, Fernández 1987) as molassic fan delta deposits (Campos 1987). The outcrops shown in the geologic map (Fig. 1) are those of the Compañía Petrolera y RECOPE (Bolaños 1983).

The fossil coral-algal reef (Figs. 1 and 2) may be equivalent to the unnamed reef limestone described by Coates *et al.* (1992), and the Limón Formation used by geologists of the oil companies in 50's decade (Campos 1987). It is probably late Pleistocene to Holocene, and forms the headland of Punta Manzanillo and Punta Mona about 20 m above sea level.

The alluvium, marsh and old beach deposits (Fig. 1 and 2) were deposited mainly by the Sixaola River. They consist of soft silty, sandy and coarse grained sediments. The old beaches and marshes correspond with ancient locations of the shoreline.

The swamp deposits (Figs. 1 and 2) consit of very fine grained deposits accumulated within the lagoon behind the fossil coral-algae reef.

## QUATERNARY PROCESSES

**Litoral sediments budget**: Historical information about the coastal changes indicate that erosion had caused migration of the beach inland at Cahuita and Puerto Viejo (location in Fig. 3), at least during this century (Palmer 1986). These localities are a few tens of kilometers northward of Gandoca-Manzanillo. The same phenomenon was reported by inhabitants of Manzanillo, Punta Mona and Gandoca. For example, on Manzanillo beach there are remains of a mango tree trunk that grew to a back yard 20 years ago. It was exposed to sea water and wave action in the foreshore before the co-seismic earthquake uplift, and now forms part of the beach. In the shallow water, it was possible to recognize palm roots on the sandy sea floor.

Another evidence of a predominant erosional regime is the amount of palms falling seaward and the existence of rip currents in the Gandoca sand beach. I interviewed several inhabitants, most of whom have lived more than twenty years on the coast. They all agree, in general, that the amount of landward transgression of the shoreline is about 30-50 m in the last 10 years.

The erosion of the beach might have increased during the last decades due to damage to the reef barrier as a result of siltation associated with deforestation of the highlands and banana plantations in the lowlands (Cortés & Risk 1985).

These phenomena could also be related to the transgression of 1.6 mm/year, reported in Puerto Limón by Aubrey *et al.* (1988), from 1948-1969 tide-gauge records.

**Quaternary changes of the Sixaola river**: Sixaola River has apparently changed its channel during the Holocene. Two abandoned channels shown in the geologic map (Fig. 1) were recognized from the aerial photographs indicating that the mouth of the river has changed since the last glacial period.

The bathymetric curves of the Sixaola quadrangle of the Instituto Geográfico Nacional (scale 1:50 000) indicate a depression 1.5 km offshore. I interprete this feature as a submarine canyon, which might funnel sand offshore as has been described in Southern California (Komar 1976).

The origin of the submarine canyon may be related to the ancient river channels of the Sixaola River in the Late Wisconsin Regression around 20 000 years ago. During this epoch the position of the mean sea level was probably more than 100 m lower, and this canyon could then have been part of the Sixaola River valley. One of the old channels lines up with the submarine canyon.

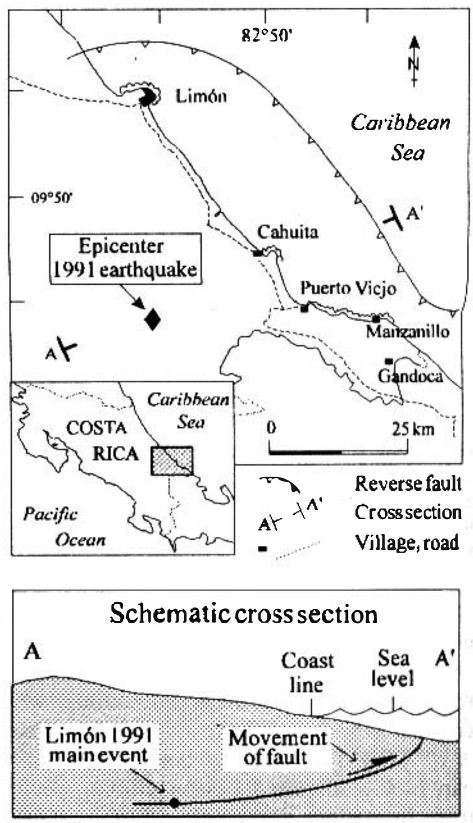


Fig. 3. Limón 1991 epicenter, showing the probably fault trace offshore, and the tectonic model associated to this event (after Suárez *et al.* 1995).

## HAZARDS ASSOCIATED WITH THE APRIL 22nd, 1991 EARTHQUAKE

The controlling structure involved in the April-1991 earthquake is best interpreted as a reverse fault, striking roughly parallel to the coast and dipping southwest (Fig. 3). This seismic event was 7.6 in magnitude (Ms) using the Ritcher scale and the resulting focal depth is 9 km (Montero *et al.* 1994, Suárez *et al.* 1995). The occurrence of a small tsunami, the uplift patterns described above and the focal mechanism indicate that most of the surficial trace of this fault zone lies offshore (Plafker *et al.* 1991, Plafker & Ward 1992, Montero *et al.* 1994, Suárez *et al.* 1995). The rupture occurred as four subevents lasted over 25 second period, and had a rupture area of 3 200 to 4 500 km$^2$ (Goes & Schwartz 1991, Montero *et al.* 1991-1994).

**Earthquake-induced liquefaction and related ground failures:** Liquefaction of thick deposits of young, fine-grained fluvial sediments during the April earthquake (Mora & Yasuda 1994) affected part of the Manzanillo-Gandoca area. Liquefaction phenomena included: a) sand boils and fissures, and forceful ejection of subsurface sand layers, b) cracking and flowage related to lateral spreading of coherent deposits over liquefied subsurface sediments, and c) subsurface compaction of sediments and subsequent subsidence of the overlying land surface. In many places, all three types of ground failure occurred during the earthquake.

The severity of earthquake-induced liquefaction features is more clearlly related to the consistency of sediments underlying the region than to proximity to the earthquake epicenter (Denyer *et al.* 1994 c). Extensive liquefaction occurred primarily in areas of thick, water-saturated sequences of Quaternary fine-grained fluvial and beach sediments (Fig. 1), particularly where sandy shoreline and levee deposits were interbedded with finer grained swamp, lagoon, and mud flat sediments (for example Gandoca lagoon and surroundings). The area affected by extensive liquefaction is larger than the area of fault rupture (Montero *et al.* 1991), probably because of seismic-wave accelerations and the influence of dynamic amplification in the less cohesive sediments (Matti & Carson 1991).

Numerous houses and other structures in the region were severely damaged by a combination of liquefaction and oscillatory ground motion. In most cases, liquefaction caused more destruction than the shaking movements, even in areas with competent subsurface sediments.

a) Damage related to sand venting: The most spectacular phenomenon related to earthquake-induced liquefaction was the extrusion of sand through individual vents (sand "boils" or "volcanoes") and elongated fissures. In many localities near the coast, and close to the Sixaola River, salty or brackish, fetid, warm water with sand and mud was vigorously ejected to heights of more than 5 m. I observed some residues (piles of sand) of this effect 8 days after the earthquake, near Daytonia, about 10 km southwest of Gandoca.

b) Damage related to lateral spreading and flowage: Numerous cracks and fissures were formed in the land surface during the earthquake. Many of the apparently randomly oriented fractures were caused by shaking but those that parallel geological features such as sand bars, river levees, and shorelines were caused by lateral spreading and flowage. The fracturing and flowage at the toes of the lateral spreads was very common and caused the most severe damage of all liquefaction-related phenomena.

Lateral-spread fracturing caused extensive damage to manmade structures, including drainage channels in banana plantations. Particularly affected were the Sixaola Valley and northwestern Panamá. Banana companies have developed complex drainage systems of natural and artificial channels that are used for draining low-lying areas. These channels were narrowed and often blocked by lateral spreading similar to that seen along the larger rivers and canals.

c) Subsidence and differential compaction: Several examples of compaction-induced subsidence were observed in the area affected by the earthquake. Most sites of compaction-induced subsidence are located in swampy areas near the coast and at the mouths of large rivers where there were thick deposits of poorly consolidated, water-saturated fluvial and deltaic sediments. I consider areas of subsidence are not directly related to tectonic displacement.

**Collapse features:** In several areas along the coast, I observed fractures in the exposed reef platforms that were caused by the collapse of caves and undermined parts of the reef during earthquake shaking; similar underwater examples of collapsed reefs were reported (Cortés *et al.* 1992). Collapse features were observed on rocky headlands from Manzanillo to Punta Mona. In some areas these features caused an apparent tilting of the reef platform and beach rock in the offshore direction that could be confused with tectonic tilting, but these areas are very localized and are easily recognized as non-tectonic collapse features.

**Tsunami hazards:** I interviewed several inhabitants about the tsunamis following the 1991-Limón earthquake, and received generally consistent responses. Where tsunami effects were reported, the inhabitants reported a calm sea before the earthquake, a sudden drop in sea level during or immediately following the earthquake, and then the occurrence of a tsunami 0-2.5 m in height. 5-15 min after the earthquake. In some localities, a series of tsunamis occurred over time periods of 15-60 min.

In Costa Rica, most reports of tsunamis were recorded along the southeastern coast in the vicinity of Manzanillo and Punta Uva. The heaviest damage from tsunamis was reported in northwestern Panamá, particularly at Bocas del Toro, one hour after the main shock (Camacho 1994). This region was previously affected by tsunamis at May 7$^{th}$, 1822, September 7$^{th}$, 1882, and at April 26$^{th}$, 1916 (Camacho 1994).

The effects of tsunamis may have been diminished along most of the Costa Rican coast because of the presence of fringing reefs, and the fact that this part of the coast had been coseismically uplifted by the time the tsunamis arrived.

**Groundwater hazards:** After the earthquake, water tables rose 1.0-1.5 m and in some areas are now at the surface. This phenomenon is probably related to compaction and reduction in porosity of sedimentary aquifers in these areas. In Olivia, located about 15 km west of Manzanillo, a small hot spring was activated for about 8 days following the earthquake. Such a phenomenon is a common effect of strong earthquakes, and I interpret them to be venting through fractures formed by the earthquake. The hot water could be the result of organic decomposition in recent alluvial and marsh deposits or geothermal gradient.

**Coseismic uplift:** The most dramatic geologic effect of the April earthquake was the coseismic uplift of the southeastern Caribbean coast of Costa Rica. Widespread coseismic uplift has been commonly associated with historic thrust earthquakes elsewhere in the world (for example: Plafker 1972), and is best observed in coastal regions where sea level can be used as a widespread datum.

In the Gandoca-Manzanillo region I made 5 measurements of coastal uplift (Fig. 1, Table 1) with hand levels, stadia rods, and measu ring tapes. More precise instruments were not used be cause of large errors associated with determining preearthquake sea levels and estimating the tidal range. A tidal range of 0.3 m was used in our analysis, and was based on

TABLE 1

*Measurements of changes in elevation along the Sixaola Quadrangle of the southern Caribbean coast of Costa Rica, as a co-seismic effect of April-91 earthquake*

| Locality | Location (Lat./long.) | Land-level uplift | Comment |
|---|---|---|---|
| Punta Cocles | 09°38'50"N/82°43'20"W | 0.50 m | Rocky coast |
| Punta Uva | 09°38'40"N/82°41'10"W | 0.60 m | Rocky coast |
| Punta Manzanillo | 09°38'30"N/82°38'50"W | 0.50 m | Rocky coast |
| Punta Manzanillo | 09°38'18"N/82°37'50"W | 0.45 m | Cliff |
| Punta Mona | 09°38'10"N/82°37'23"W | 0.40 m | Cliff |
| Gandoca | 09°36'10"N/82°36'25"W | 0.50 m | Sandy beach |

Fig. 4. Terrace of old reef limestone that forms the head lands of the Gandoca-Manzanillo region. Punta Manzanillo (9°38'30"N, 82°39'W)

preliminary data from JAPDEVA (Junta de Administración Portuaria de la Vertiente Atlántica; Julio Sarmiento pers. comm. 1991). I estimate our measurement errors to be about ±0.2 m on rocky headlands, and ± 0.3 m on sandy beaches. Our coastal-uplift data grossly correspond with Plafker and Ward (1992) measurenments.

The coast of Gandoca-Manzanillo is characterized by isolated headlands of uplifted Quaternary limestones (Fig. 4) and intervening sandy beaches. On the rocky headlands, such as in Punta Manzanillo, pre-earthquake sea levels were observed as erosional V-shape notches (Fig. 5) and exposed shore platforms.

The uppermost extent of killed organisms as coral, calcareous algae and barnacles, could be distinguished as drawn lines in manmade structures and back edge platforms.

Uplift was much more difficult to measure in sandy coastal regions. I used the following criteria to quantify uplift in these areas: the difference in elevation between pre-and post-earthquake storm-beach accumulations of driftwood; and interviews with fisherman and other inhabitants familiar with changes in sea level caused by the earthquake.

In the Gandoca-Manzanillo region, the

Fig. 5. The pre-earthquake mean sea level is expressed as notches in the islet (10°38'10"N, 82°37'20" W).

coastline was uniformly uplifted 0.3-0.6 m; no uplift was reported in Panamá. Coastal uplift dies out rapidly along the coast south of the Sixaola River, a low swampy region that contrasts sharply with the rocky, uplifted coastline north of the Sixaola River. Subsidence has been reported in Panamá, but such a phenomenon is probably related to differential compaction of young sediments, rather than to tectonic subsidence.

Uplift of the coast caused severe damage to the fringing reefs surrounding rocky headlands along the Costa Rican coast (Cortés *et al.* 1992). However, the coseismic uplifting recovered only 10 years of the previous shoreline erosion, discussed above. Tectonic uplift represents a process of compensation, but erosion is still greater than the uplifting compensation.

Uplift has modified the longitudinal profiles of rivers by reducing the gradient across the coastal plain. During the first rainy period, about three months after the earthquake, serious flooding occurred along the flood plains of many coastal rivers, perhaps due, in part, to reduction in stream gradient.

## HISTORIC AND PREHISTORIC SISMICITY

**Historic earthquakes:** Historical seismicity on the North Panamá Deformed Belt has been compiled by Camacho & Víquez (1993). The major earthquakes (Table 2) occurred in the western edge of this large tectonic feature. The most interesting is the 1822 earthquake, because the similarities to 1991-Limón earthquake (Montero *et al.* 1991). The 1822 seismic event has been known as the San Estanislao earthquake, and was recently studied by Montero (1986).

TABLE 2

*Main larger historic earthquakes occurring in the North Panamá Deformed Belt*

| Date | Latitude | Longitude | Ms |
|---|---|---|---|
| 21-02-1798 | 10.2° | 82.9° | ? |
| 07-05-1822 | 9.5° | 83.0° | 7.5 |
| 25-04-1916 | 10.0° | 82.0° | 7.3 |
| 22-04-1991 | 9.63° | 83.16° | 7.6 |

Based on Camacho & Víquez (1993) and Montero *et al.* (1994)
Magnitude (Ms) in Ritcher scale.

Roberts (1827) stayed at Monkey Point (Punta Mona, Fig. I), in the 1822, the night of this event, and he described the phenomena as a "tremendous earthquake". He wrote: "I observed such a scene as will never to the last hour of my existence be erased from my memory. The ground under our feet seemed to heave convulsievely, as if ready to open and swallow us, producing a low terrific sound; the trees, within a short distance of the huts, where so violently shaken from their upright position, that their branches were crashing, and their trunks grinding against each other, with a groaning sound; the domestic fowls, the parrots, macaws, pigeons, and other birds, were flying about and against each other, in amazement, screaming in their loudest and harshest tones..."

A more suggestive paragraph by Roberts (1827), from the geologic point of view, is an evidence of dramatic uplifting of the shoreline: "... No lives were lost here, or at the other Indian settlements, in the neighborhood, but the ground appeared rent in various places, the sand on the beach was either raised in ridges, or depressed in furrows; a place, which in the evening had been a small lagoon, or pond, in which several canoés were floating, was now become quite dry; ...". This seismic event also caused another geologic effects, as in 1991, a tsunami. Landslides in the highlands and liquefaction in the Caribbean lowlands occurred in both 1822 (Montero 1986) and 1991. Also remarkable are the very similar magnitudes of 1991 and 1822 events, 7.6 and 7.5 respectively (Table 2) (Montero *et al.* 1994, Montero 1986).

**Evidence of prehistoric earthquakes:** Although no earthquake prior to April 1991 has been well recorded in this region, and historically only the 1822 San Estanislao earthquake seems to be similar than Limón earthquake, I have observed evidence of large prehistoric earthquakes along the Manzanillo-Gandoca headlands (Denyer *et al.* 1994 b). This evidence is most noticeable in the trail between Manzanillo and Gandoca, where the cliff consists of old coral-algal reefs, that originally formed below sea level. Some hills built up by this reef rock are presently as much as 20 m

TABLE 3

*Accelerator Mass Spectrometry (AMS) radiocarbon dates for tectonically uplifted coral samples*

| Figure 1 location | $^{14}C$ age yr. B.P. | Coral specie | Elevation a.m.s.l. | Corrected elevation | Field number | Lab. Number | Location lat./long. |
|---|---|---|---|---|---|---|---|
| 1 | 5 220±50 | *Diploria* | 1.5 m | 5.7 m | 6-27-2-92 | AA10593 | 82°37.5'/9°38.2' |
| 2 | 27 145±290 | *Millepora* | 8.8 m | 48.3 m | 7-27-2-92 | AA10594 | 82°37.5'/9°38.2' |
| 3 | 4 540±50 | *Dichocoenia* | 1.6 m | 4.2 m | 4-27-2-92 | AA10591 | 82°38.2/9°38.3' |

The $^{14}C$ results were normalized for $^{13}C/^{12}C$ of 0 per mil for carbonates. The glacio-eustatic correction of elevation is based on Pinter & Gardner (1989) curves.

above sea level. While some small component of this height may be related to eustatic changes in sea level, or isostatic changes of land, most of the relative emergence must be related to tectonic uplift during earthquakes similar to the April event.

I measured several profiles, showing three platforms levels, along the rocky coast between Manzanillo and Gandoca that I interpret as witness of previous seismic events. Evidence of at least two previous events was indicated both by the presence of uplifted shore platforms and by physical and biological features such as paleo-barnacle lines and notches or steps in the uplifted reef limestone. A fossil brain coral (*Colpophyllia natans*) in growth position on a terrace about 1 m above the pre-April 1991 sea level is identical to those exposed in the shore platform uplifted during the 1991-event. The profiles between Manzanillo and Gandoca show a lower platform of about 0.5-1.0 meter a.m.s.l. (above mean sea level); another one at 1.5-2.0 m a.m.s.l., and a higher platform at about 8.0-10.0 m a.m.s.l. These platforms can be correlated over several kilometers in this region and they are the result of regional coseismic uplift events, as was observed in 1991, and probably in 1822.

**Uplift rates as a paleoseismic approach:** The presence of several platform levels can be interpreted as abrupt emergence events, similar to the coseismic shoreline uplift in 1991. Assuming this hypothesis, three coral samples, croping out on these platforms were radiocarbon dated. Good samples, with no evidences of contamination or diagenesis were not easy to obtain, because these platforms consist of calcareous material which could be older than the age of the platforms. The coral samples that I took were croping out on the surface of the platforms, and they seemed to be younger, probably killed by the aereal exposure after the coseismic uplifting.

The ages of these coral samples confirm an Holocene tectonic uplifting in this region (Table 3). Otherwise all of this coral samples would be under several meters of sea water, because the glacio-eustatic rise of the mean sea level; but now they are croping out at the top of the 1.5-2.0 m and 8.0-10.0 m platforms.

The calculation of the radiocarbon age of the sample assumes that the specific activity of the $^{14}C$ in the atmospheric $CO_2$ has been constant. However, the $^{14}C$ activity in the atmosphere and other reservoirs has varied over time (Stuiver & Braziunas 1993). A calibration of the conventional radiocarbon ages was done to the samples 1 and 3 (Table 3) into calibrated years using the computer program CALIB 3.03 (Stuiver & Brazinuas 1993, Stuiver & Reimer, 1993, Stuiver & Pearson 1993). Therefore, the calibrated ages for sample 1 is 5 577 years B.P. and for sample 3 is 4 783 years B.P. Fig. 6 shows statistical parameters of probability, one sigma (68%) and two sigma (95%), for the calibrated ages. The sample 2 could not be corrected because the absence of marine calibration data of ocean carbon exchange, for ages older than 21 950 years. For these reason, in the rest of this paper, I will use the non corrected radiocarbon ages, considering that in this way is more valid to relate the three radiocarbon dated samples.

The 700 years difference in age of two samples, collected from similar heights, 1.6 and 1.5 m a.m.s.l. (samples 1 and 3 on Table 3), can be explained by irregularities in the uplifting event, as have been described during

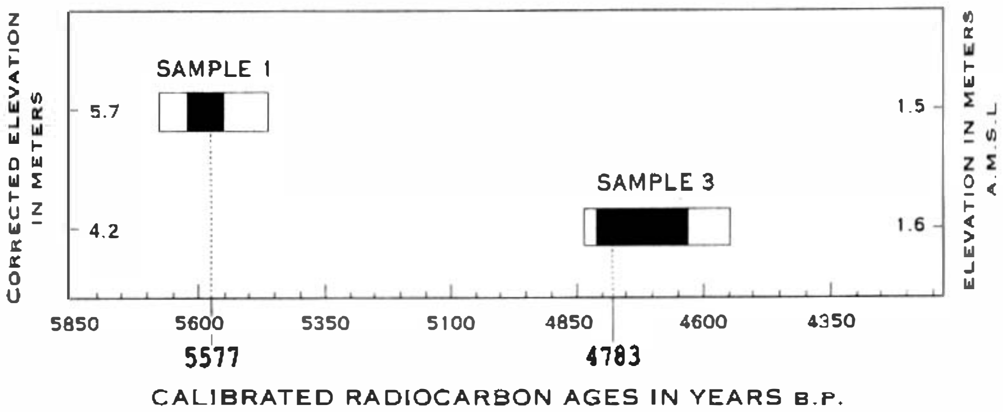


Fig. 6. Radiocarbon calibrated ages, using the method of intercepts with curves, in the computer program CALIB, version 3.03 (Sluiver and Reiner, 1993). The elevation measured at field and the glacio-eustatic corrected are included for each sample. The age in years before present: (B.P.) showed in bars the combined standard deviation, 1 sigma (68 % probability) and 2 sigma (95% probability). Used variables. $^{13}C/^{12}C=0$, lab mult.=1.

the 1991-Limón earthquake (Denyer *et al.* 1994 b). Althought, this discrepancy can be also a result of diagenesis or post-death contamination of the sample material.

With the age of the two dated platforms, the tectonic elevation of each one of these terraces was recalculated, using the Caribbean regional curves of glacio-eustatic fluctuation (Pinter & Gardner 1989) (Table 3, Fig. 6 and 7). It was possible to obtain a gross estimation of the long-term uplift rate of 1.8 mm/year, using the oldest age of 27 145 ± 290 and the eustatic corrected elevation of 48.3 m a.m.s.l.

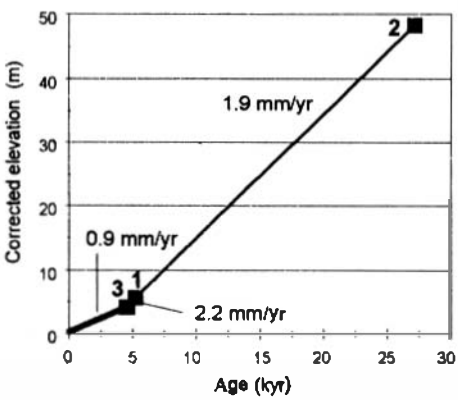


Fig. 7. Relationship of radiocarbon ages and the elevation, previously corrected for the eustatic mean sea level fluctuation (Table 3). The numbers correspond to the samples indicated in Fig. 1 and Table 3.

Changes in the sea level are responsible, at least in part, for the apparent differences in height of the platforms. The climatic variation during the end of the last glacial epoch could be responsible for sedimentological changes and the consequence differences in coral growth. However, the differences in height, age, and apparent uplift of the platforms described above can be explained in several ways: 1) the magnitude of uplift that exposed the higher platforms was actually greater, which implies that uplift was related to larger magnitude earthquakes, 2) evidence of uplift events of intermediate age has been removed by erosion, perhaps due to longer recurrence times between events, or 3) uplift that occurs during subsequent earthquakes at individual sites may not be uniform through time. Perhaps the height differences can be better explained by changes in the recurrence time between events, which may have allowed more extensive erosion of intermediateaged platforms. The estimate of the coseismic uplift ra-te was done separately for each pair of samples with radiocarbon age data (Fig. 7). They show a variation between 0.9 to 2.2 mm/year. The evolution of the coseismic uplift could be improved finding more datable material in heights between 1.5 to 9.0 m a.m.s.l., which must have ages between 5 000 to 27 000 $^{14}C$ years B.P.

**Seismic recurrence, an educated guess:** To understand the neotectonics of the western edge of the North Panamá Deformed Belt means, solving the puzzle that relates the 1991 Limón earthquake, the 1822 San Estanislao earthquake, the evidence of prehistoric and paleoseismic events, and the height of the different dated platforms and their ages.

Considering that the 1991 and 1822 earthquakes were similar in magnitude (Montero *et al.* 1994, Montero 1986). Assuming also, that recurrence time period of this kind of events is linear, we would have similar earthquakes every 170 years, very grossly. considering also that equal magnitude events produce equal coseismic uplift, an uplifting of 0.40 m (1991 measured coseismic uplift closer to dated samples 1 and 2, Fig. 1) would ocurr successively with a rate of 2.4 mm/ year. On the other hand, Aubrey *et al.* (1988) reported a transgression slope of 1.6 mm/year in Limón, calculated using tide-gauge records between 1948 and 1969; part of it was due to the rising of the ocean level (1 mm/year, could be assumed in the past half century (Aubrey *et al.* 1988) (Perhaps, Miyamura (1975) gave a more irregular behavior of Limón coast during 1948-1969, using levelling surveys). Doing the numbers, using Aubrey, Emery & Uchupi (1988) data, the tectonic subsidence measured during 1948-1969 was around 0.6 mm per year. If we assumed this was due to interseismic subsidence occurred between larger events, the coseismic uplift rate would be 2.4-0.6=1.8 mm/year, which is the same long-term rate of coseismic uplift, obtained from the oldest sample radiocarbon dated.

Considering the 170 years as a valid recurrence period of time for this kind of events, it would be necessary to look for it in the past. Peraldo & Montero (1994) have comppiled references of several strong earthquakes from 1622 to 1670. However, they could not locate epicenters or collect sound information about their magnitude; the written history of this epoch is so scarce. For example, several changes in the course of the Reventazón river (one of the largest rivers in the Caribbean of Costa Rica), occurred during the decade 1650-1660, but the reason of these changes have not been established, they could be the consequence of a seismic event in the region (G. Peraldo, pers. comm. 1998).

These numbers are based on many assumptions, but they show an amazing correspondence, and the 1.8 mm/year long term uplift is also in the range of 1-2 mm/ year estimated by Miyamura (1975) for the tectonic uplifting of the central mountains of Costa Rica.

## CONCLUSIONS

The field studies after the April 22, 1991 earthquake, about the coseismic uplift showed that from northwestern edge of the studied region (lat. 9°40') and the mouth of the Sixaola River at the Panamá border (lat. 9°35'), the coastline was uplifted 0.3-0.6 m. The amount of uplift diminishes a very short distance south of the Sixaola River, and thus the southern boundary of uplift may be controlled by projection of surface faulting. Although spectacular, tectonic uplift of the Caribbean coast caused much less damage to manmade structures than liquefaction.

Damage related to tsunami during Limón earthquake occurred mostly in Panamá; relatively little tsunami damage was observed in Costa Rica, probably because of uplift of the coast that reduced the effect of higher-than-normal sea waves, althought, the whole region is very susceptible to tsunami hazards, as can be historically interpreted.

The 1822 San Estanislao earthquake had similarities to the 1991 earthquake, having both coseismic uplift, intensive landslides, tsunami effect, and liquefaction.

Evidence of prior seismic events is preserved in several places as shore platforms of reef limestone, and as erosion features etched into sea cliffs. Two platform levels were dated using radiocarbon method on coral reef samples, the platform level of 1.5-2.0 m reported radiocarbon ages of 5 220±50 years B.P. and 4 540±50 years B.P., and the 8.0-10.0 m terrace level was dated in 27 145±290 years B.P. The variation of the heights of these individual platforms, and the absence of intermediate levels and ages, some appear to reflect uplift events of similar size to the 1991 uplift, and others appear to have been much larger, showing this region have had a very irregular coseismic uplift behavior, and probably also an irregular earthquake time recurrence period. From this point of view, the seismic events recurrence do not seem to have a ciclic and linear behavior.

Although the geologic evidences of irregular seismic behavior, the 1.8 mm/year long-term coseismic uplift calculated from radiocarbon dates fits into a very confidence and predictable range, and therefore it can be used in predictions in a more datailed paleoseismologic work.

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## RESUMEN

La región de Gandoca-Manzanillo es parte de la cuenca de Limón, localizada en el sureste de Costa Rica. En esta cuenca se nota una somerización progresiva con el tiempo geológico, desde sedimentación marina profunda en el Mioceno-Plioceno, hasta fluvio-deltáica y ambientes marino arrecifales en el Cuaternario. El efecto más sobresaliente del terremoto de Limón de 1991, fue el levantamiento co-sísmico de la línea de costa, que varió entre 0.3 a 0.6 m en la región que incluye este artículo. Este evento causó también la licuefacción de los espesos sedimentos fluviales de la región. Un tsunami afectó Manzanillo y Punta Uva, reportándose los mayores daños en el noroeste de Panamá. Los efectos del tsunami fueron menores en Costa Rica, a causa de la presencia de barras arrecifales y que en el momento en que llegó la ola, la tierra habla tenido un levantamiento. Se hicieron dataciones radiométricas de corales de plataformas de dos niveles, el nivel de 1.5-2.0 m reportó una edad de 5 220±50 y 4 540±50 años B.P. Otro nivel de una altura de 8.0-10.0 m fue datado en 27 145±290 años B.P., dando una tasa de levantamiento de 1.8 mm/año. Las variaciones en las alturas de las plataformas indican un comportamiento irregular del levantamiento co-sísmico, que podría indicar un periodo de recurrencia irregular de este tipo de evento sísmico. Sin embargo, la similitud de este evento y el de 1822 sugiere que este tipo de terremoto podría tener una recurrencia entre 150 y 200 años.

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