The 1991 Limon, Costa Rica Tsunami

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Abstract

A small tsunami (tsunami magnitude 1) was observed following the 22 April 1991, M_S 7.6, Limon, Costa Rica earthquake along the Caribbean coast of Costa Rica and Panama, as well as on tide gauges in Puerto Rico and the Virgin Islands. This study summarizes eyewitness observations from 26 sites along 150 km of affected coast, from Rio Matina, Costa Rica to Bocas del Toro, Panama. While little or no direct tsunami related property damage was reported, 2 drownings were attributed to the tsunami. No emergency warnings were issued before the tsunami occurred. The maximum runup height was 2 m, and inundation and coastal flooding extended up to 200 m inland in some locations. Coseismic uplift and the presence of fringing reefs 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 sand deposition near the Costa Rica-Panama border was similar to deposition associated with a tsunami caused by a large local earthquake that occurred on 7 May 1822, suggesting that the return time for tsunamigenic events of this size may be less than a few hundreds of years in this region.

Key Words: Caribbean tsunamis, 1991 Costa Rica earthquake, tsunami questionnaire, tsunami hazard mitigation

Introduction

The National Earthquake Information Center (NEIC) of the U.S. Geological Survey has developed a questionnaire to document unusual wave activity in coastal areas related to earthquakes (Nishenko, 1987, 1990). Unusual wave activity (including tsunamis, tidal waves, seiches, etc) may be primarily caused by submarine landslides and tectonic displacement. Along coastal areas, lateral spreading, compaction, and tectonic subsidence which can occur in conjunction with earthquakes may serve to locally amplify the impact of tsunamis. In contrast, coastal uplift may serve to decrease these effects. Recent coastal earthquakes have resulted in the realization that when tsunamis have not been accompanied by extensive devastation, or when the damage has been limited to the immediate epicentral area, little systematic collection of tsunami characteristics have been undertaken. A great deal of data pertaining to tsunami characteristics and behavior has therefore been lost. Data obtained through distribution of a tsunami questionnaire can contribute to a balanced description of earthquake effects at the land-water interface and can result in improved hazard mitigation strategies along coastal areas.

Approximately one week after the occurrence of the 22 April 1991, M_S 7.6 Limon, Costa Rica earthquake, the NEIC tsunami questionnaire was translated into Spanish and distributed in Costa Rica with the help of personnel from the University of Costa Rica. Observations were obtained from 12 sites along 90 km of affected coast, from the mouth of the Matina River, north of the port of Limon, to Gandoca, north of the Costa Rica-Panama border. Observations from 14 additional sites in Panama were recorded by researchers from the University of Panama in the fall of 1991. This report summarizes the results of these field surveys, and attempts to correlate eyewitness observations of water activity with the pattern of coastal uplift and subsidence associated with the 22 April earthquake. Finally, we discuss strategies for tsunami hazard mitigation along the Caribbean coast of Costa Rica and Panama.

The NEIC Tsunami Questionnaire

The NEIC Tsunami Questionnaire (Appendix 1) was developed for distribution following earthquake generated tsunamis, and other tsunami or unusual wave activity that may be associated with volcanic eruptions and landslides. The structure of the NEIC Tsunami Questionnaire is based, in part, on the U. S. Geological Survey's Earthquake Report which is a postage-paid questionnaire that is distributed to local officials (i.e., postmasters, police and fire departments, civil defense personnel) and volunteers in communities that have been affected by earthquakes. Answers to questions in the Earthquake Report are assigned intensity values according to the Modified Mercalli scale. These intensity values are then plotted and contoured to produce isoseismal maps which show the geographic distribution of felt effects, structural damage, and levels of ground shaking in the affected area (Stover, 1989). Other derivative products based on the intensity data collected by these questionnaires include seismic risk and economic loss studies and projections, lifeline performance evaluations, microzonation studies and comparisons of qualitative observations with instrumental data.

Questions in the Tsunami Questionnaire cover four basic categories:-, 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; questions 6-7 ask for information about the water activity (the type of disturbance, its effect, and the direction of the wave behavior); and questions 8-10 are intended to provide information on building and structural damage caused by waves and the location of these structures relative to the shoreline. Here it is important to be able to distinguish wave-related damage from damage induced by strong ground motion related to the earthquake. Questions 11-13 ask for information about injuries, fatalities, and their circumstances; whether the respondent received a tsunami alert or warning in their community, and their response to the alert or warning.

A prototype tsunami questionnaire was field tested in the Monterey Bay, California region following the 1989 Loma Prieta earthquake (Preuss and Nishenko, 1992) and was subsiquently revised and simplified. To date, tsunami questionnaires have been distributed following the 1989 Loma Prieta, California (M_S 7.1) [Preuss and Nishenko, 1992] , the 1991 Limon, Costa Rica (M_S 7.6) [Preuss and Nishenko, 1992 and this report], the 1992 Petrolia, California (M_S 7.0), and the 1992 Nicaragua (M_S 7.2) [Preuss, 1994] earthquakes.

Western Caribbean tsunamis- a historic perspective

The Caribbean coast of Costa Rica and Panama has been affected several times by tsunamigenic earthquakes. The first known tsunami occurred on 7 May 1822 in association with what is considered the largest known earthquake in northwestern Panama and eastern Costa Rica. Water waves induced by this event caused floods in the bays and mouths of rivers along the Caribbean coast of Costa Rica (Gonzalez-Viquez, 1910). This tsunami also deposited so much sand on the coast near Gandoca and Monkey Point, near the Costa Rica - Panama border, that it created dunes on the beach (Roberts, 1827). A similar pattern of sand deposition occurred during the tsunami of 22 April 1991 near the mouth of the San-San river. On September 7, 1882, a large earthquake located offshore the San Blas coast of eastern Panama created a tsunami with 2 - 3 m high waves, great destruction, and nearly 100 deaths on the islands of the San Blas archipelago. The Panama Canal Company tide gauge near Colon recorded a maximum height of 62 cm (Viquez and Toral, 1986; Mendoza and Nishenko, 1989). The April 26, 1916 Almirante, Panama earthquake (M 6.9, Duda et al., 1990) caused a local tsunami which covered the southern tip of Carenero Island and carried canoes and debris 200 m inland on Bocas del Toro island (Reid, 1917, Viquez and Toral, 1986). Additional information about the seismicity of this region can be found in Camacho and Viquez (1993).

The 1991 Limon, Costa Rica tsunami

The 22 April 1991 Limon earthquake occurred along the Caribbean coast of southeastern Costa Rica and northwestern Panama. An area of 15,000 square km experienced widespread liquefaction and lateral spreading in the regions characterized by unconsolidated coastal plain and river deposits (Plafker and 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).

Following the earthquake a tsunami with wave heights of 2 to 3 m was was reported by eyewitnesses along the coast from Cahuita, Costa Rica, to Bastimentos Island, Panama (see Figure 1). These reports indicate a tsunami magnitude, m, of about 1 (where $m = \log_2 h_{max}$, and h_{max} is the waveheight in meters measured at a point 10 to 300 km from the source zone [Iida, 1970]). The tide gauge in Coco Solo, Panama (8.37° N, 79.88° W, the closest gauge to the epicenter, approximately 320 km east of the source zone) recorded a maximum peak to peak amplitude of 7.5 cm approximately 1 hour after the earthquake (see Figure 2). Approximately three and a half hours later, tide gauges at Magueyes Island, Puerto Rico (17.97° N, 67.05° W) and Limetree, St. Croix, Virgin Islands (17.75° N, 64.60° W) recorded disturbances of about 7 cm peak to peak (Figure 2).

Following the 22 April earthquake, researchers from a number of institutions and governmental agencies, including the University of Costa Rica, the University of Panama, the Earthquake Engineering Research Institute, and the U.S. Geological Survey conducted field reconnaissance along the affected coastlines of Costa Rica and Panama. The following sections summarize the tsunami questionnaire responses from the field investigations. These sites and a summary of the observed effects are listed in Table 1. The observation sites are mapped in Figure 1. The responses from the individual sites in Costa Rica and Panama can be found in Appendix 2.

All of the observers in Costa Rica and Panama noted that the sea was calm before the earthquake and that no emergency warnings were issued before the tsunami occurred. In Costa Rica, the sea receded 20 to 500 m from the shoreline immediately following the earthquake. To the southeast in Panama, the initial recession began approximately 10 to 15 minutes later. In both areas, the amount of the retreat varied from 100 to 400 m and lasted from 5 to 45 min in places. The exposure of recognizable features (reefs, sand banks, etc.) provided a basis for quantitative estimates of the amount of withdrawal in some places.

Following the initial retreat, two principal types of runup behavior were observed. The first type consisted of a wave 2 to 3 meters high which advanced rapidly onshore and flooded from 10 to 100 m inland. No damage resulting from the runup was reported by observers. This type of behavior was observed at mouths of major rivers in the area, including Boca Matina, Bocas del Pantano, Boca Moin (waves were noted to have overtopped 3 m high dikes at the mouth of the Moin river), and the Estrella River (where the wave penetrated 1 km upstream). Two drownings occurred in the canal near Matina due to the sudden high water level. 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 (Denyer et al., 1994).

Sand deposition by the tsunami was also noted by the respondents at many locations (12 Millas, Westfalia, Manzanillo, and Gandoca). At the San-San Natural Refuge, a layer of sand, approximately 1 meter thick was deposited on the beach (see Figure 3). Large waves were also noted along beaches including sites at Puerto Viejo, Punta Uva (SE sector), Manzanillo, and Gandoca. Large waves and high energy current structures were also noted at sites facing the Caribbean in Panama - Julio Abrego Beach, Tiribibi Point (Figure 4), Lime Point, and Boket Bay.

The second type of runup behavior consisted of a retreat followed by a gradual increase in water level without the formation of a large wave. In some locations this occurred an hour after the initial retreat. This behavior was noted at Seis Millas de Moin, Limon, Cahuita, Punta Uva (western sector), Bocas del Toro, and Carenero. Reefs which surround the Limon-Moin, Cahuita, Manzanillo, Puerto Viejo and Boca del Drago areas acted as natural wave barriers or breakwaters (see Figure 1). One observer in Cahuita noted that the water returned to a level that was lower than before the earthquake. Coseismic uplift at Cahuita had occurred before the tsunami arrived (Denyer et al., this vol.). Observers at sites facing Almirante Bay in the Bocas del Toro region of Panama described the water activity as a series of strong currents (West Knapp, Ground Creek, and Nancy Key).

Following the tsunami, many respondents noted the presence of dead fish.

Reconnaissance studies by Plafker and Ward (1992) and Denyer et al. (1994) indicate a zone of uplift, with axis roughly parallel to the coast, that extends from Limon to the Costa Rica-Panama border. Maximum uplift occurred at Limon (157 cm) and turns sharply westward and inland for an unknown distance. To the southeast, the amount of coastal uplift gradually decreases towards the Costa Rica-Panama border. The approximate offshore distance to the tsunami source was estimated by Plafker and Ward (1992) using eyewitness observations of the tsunami arrival time and is shown in Figure 2. Runup heights were also estimated by Plafker and Ward (1992) using the heights of tsunami deposited driftwood on the beaches. These runup heights are included in Appendix 2 for the sites were questionnaire responses were obtained.

Summary and Conclusions

A small tsunami (tsunami magnitude 1) was observed following the 1991 Limon, Costa Rica earthquake along the Caribbean coast of Costa Rica and Panama well as on tide gauges in Puerto Rico and the Virgin Islands. Eyewitness observations from 26 sites along 150 km of affected coast, from Rio Matina, Costa Rica to Bocas del Toro, Panama indicated a variety of wave and runup behavior along the coast. The maximum runup height is estimated to be about 2 meters, and the inundation or flooding extended up to 200 m inland. Along some coastal areas, fringing reefs provided protection against runup effects by damping tsunami waves. Coseismic coastal uplift also locally helped minimize the impact of flooding. Tsunami runup effects were amplified at other locations from the differential compaction of unconsolidated sediments at river mouths. Widespread liquefaction along the coast also served to increase the inland extent of flooding.

Both the earthquake and tsunami are associated with backarc thrusting along the north Panama deformed belt (Plafker and Ward, 1992). The deposition of sand near the Costa Rica-Panama border is similar to descriptions associated with a tsunami that occurred on 7 May 1822. Hence, the return period for large thrust earthquakes along the eastern coast of Costa Rica and Panama may be less than a few hundreds of years (e.g., 1822 to 1991). The large 7 September 1882 earthquake in the San Blas Islands region of Panama (Mendoza and Nishenko, 1989) may reflect similar backarc deformation along the eastern extension of the north Panama deformed belt. This sequence of events points to the apparent segmentation of the north Panama deformed belt into at least three primary segments. The central portion of the deformed belt, southeast of Bocas del Toro, last ruptured during the 1916 M 6.9 Almirante, Panama event. The potential for this central segment to rupture in an even larger tsunamigenic earthquake (i.e., comparable to the 1882 or 1991 events) is not known at this time.

The 1991 earthquake demonstrated the vulnerability of this region to both earthquake and tsunami damage. Awareness of this vulnerability can be used by communities for future damage mitigation, preparedness, and evacuation planning. In 1991, some coastal areas experienced significant damage to bridges and roadways and access was limited. No emergency warnings were issued before the tsunami occurred. While little or no tsunami related property damage was reported, 2 drownings occurred at the canal near Matina. Preparedness efforts should educate residents to run inland to higher elevations when they feel strong shaking. A tsunami "experience area" of approximately 300 to 400 m inland should be defined. Along the Costa Rica-Panama border these efforts are especially critical at rivermouths and areas not protected by coral reefs. While large earthquakes have been relatively infrequent in this area, the observed tsunami runups are comparable to those associated with more frequent meteorological phenomena (e.g., storm surges, hurricanes, etc.). An example of one type of common risk is the storage of flammable and toxic materials in port areas prone to possible flooding. Damage to fertilizer storage facilities or moorage of fishing boats, by either tsunamis or hurricanes, could have resulted in contamination of ground waters, as well as the pounding, capsizing or sinking of vessels. The rupture of gas tanks and resulting fires are particularly severe since water lines necessary for fire fighting would, in all likelihood, also have been damaged.

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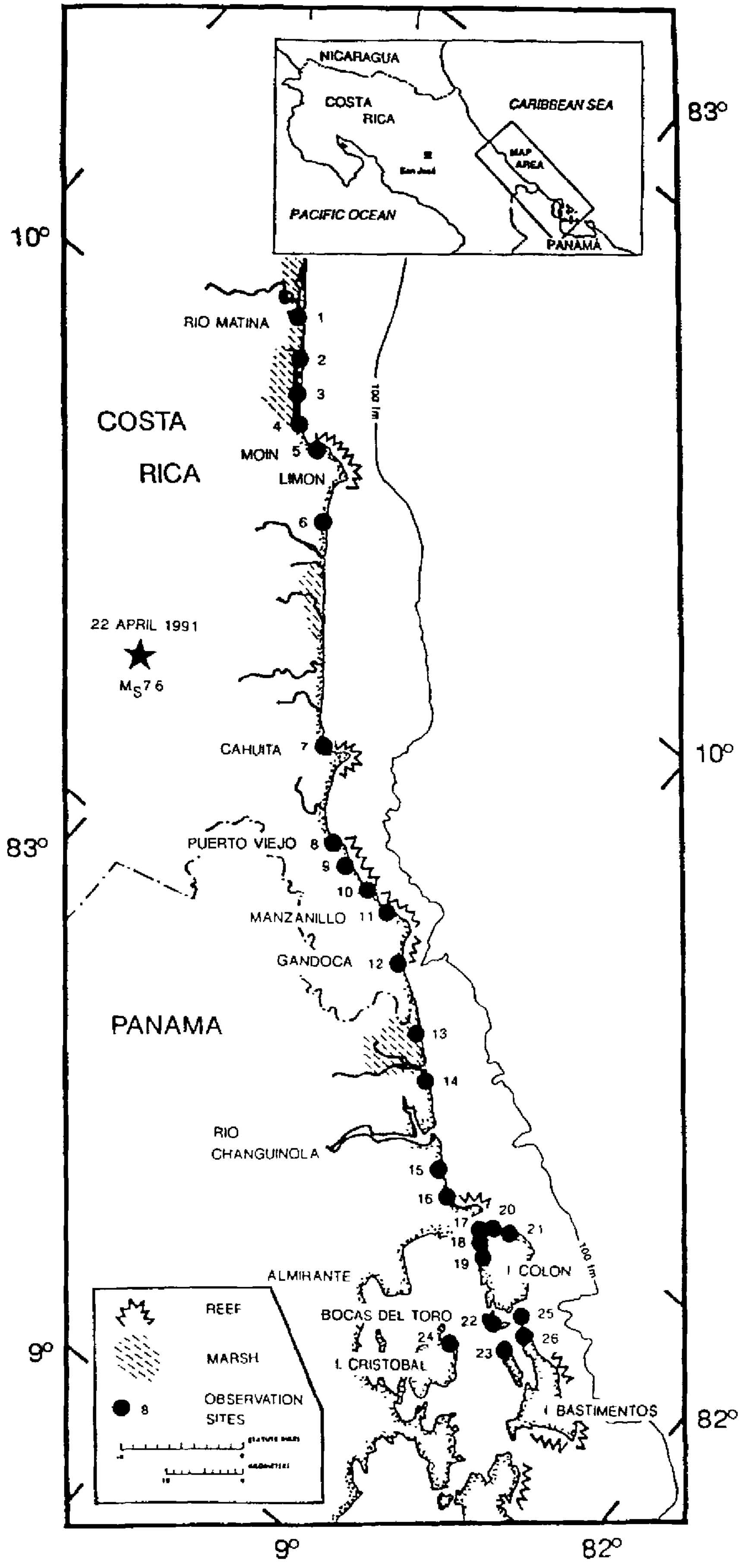
Figure Captions

Figure 1. Map showing locations of tsunami reports along the Panama- Costa Rica coast. Star is the epicenter of the 22 April 1991 earthquake. Numbered points refer to sites discussed in the text, Table 1, and Appendix 2.

Figure 2. Tide gauge records of the 22 April tsunami. Inset maps shows location of tide gauge stations with respect to the epicenter. (a) Coco Solo (Cristobal) Panama [8.37°N, 79.88°W, vertical record scale in feet Maximum peak to trough amplitude is approximately 15 cm. Horizontal scale is hours, UTC], (b) Magueyes Island, Puerto Rico [17.97°N 67.05°W, record scale in feet], and (c) Limetree Bay, St. Croix, Virgin Islands [17.75°N 64.60°W, record scale in feet].

Figure 3 Oblique air photograph of an area flooded by the tsunami in the San-San region, Panama [sites 13 and 14, Figure 1]. Note the sand deposits (light colored areas) in the lower portion of the photograph.

Figure 4 Near vertical air photograph of an area inundated by a tsunami between the mouth of the Rio Changuinola and Tiribibi Point, Panama [site 16, Figure 1]. Note the NE-SW trend of fallen palm trees.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RIO MATINA
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22 APRIL 1991
M_S 7.6
CAHUITA
PUERTO VIEJO
MANZANILLO
GANDOCA
PANAMA
RIO
CHANGUINOLA
ALMIRANTE
I. COLON
BOCAS DEL TORO
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I. BASTIMENTOS
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Fig. 1

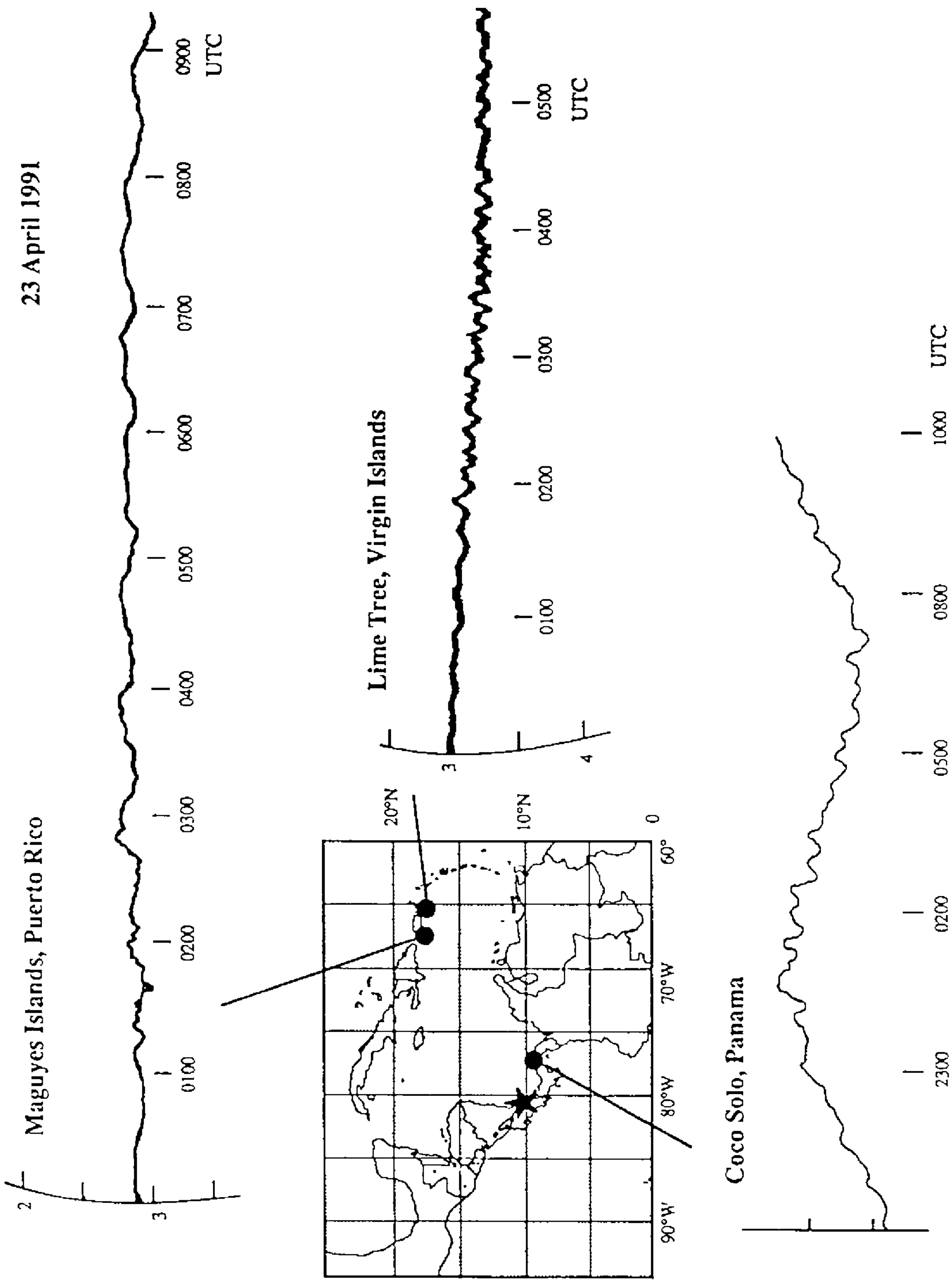
23 April 1991
Maguyes Islands, Puerto Rico
Lime Tree, Virgin Islands
Coco Solo, Panama
UTC
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Fig. 2

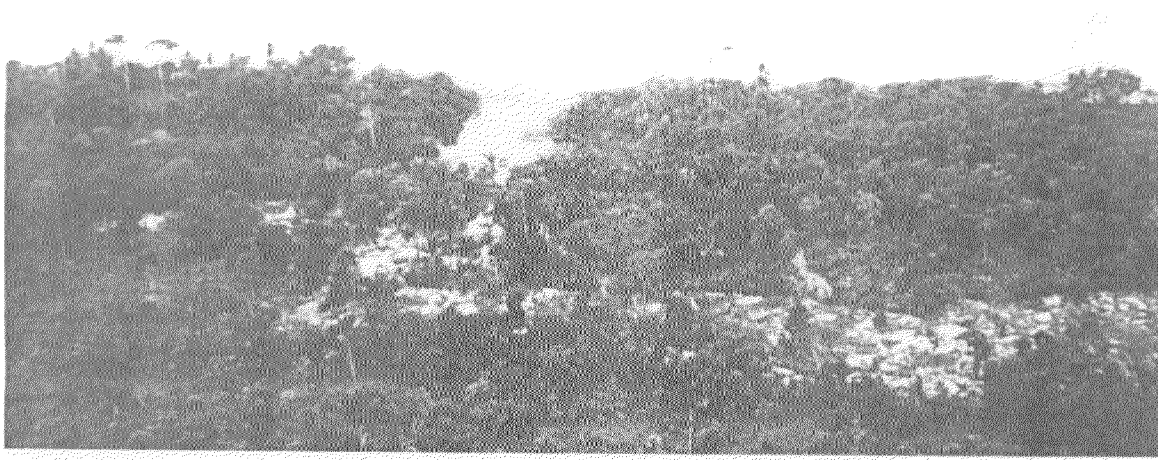

Fig 3.