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Paleoseismology of the North Panamá Deformed Belt from Uplifted Coral Platforms at Moín and Limón, Caribbean Coast of Costa Rica

Gath, Eldon (1), Tania Gonzalez (1), Chris Madugo (1), Walter Montero (2)

(1) Earth Consultants International, 1642 E. 4th St., Santa Ana, CA 92701, USA; gath@earthconsultants.com
(2) Geological Research Center, San Jose, 11501, Costa Rica

Abstract: *In 1991, the Caribbean coastal area between Moín and Limón was coseismically uplifted up to 1.8 m by a M_s7.6 earthquake on the western segment of the North Panamá Deformed Belt (NPDB), resulting in the emergence of a broad coral reef platform. Review of historical accounts showed that multiple large earthquakes have been felt in the region during its ~270 year historical record, with an event in 1822 described somewhat similarly to the 1991 event. Geologic reconnaissance revealed multiple older platforms that provided an opportunity to quantify the timing and rate of 1991-like uplift earthquakes on the Limón section of the NPDB. Mapping and hand surveying identified 7 pre-1991 coral platforms and wave cut notches preserved on the coastal-facing slope beneath a set of higher marine terraces that cap the coast between Moín and Limón. 48 coral samples were obtained but only 12 were suitable for U-series dating due to diagenetic alteration of the original aragonite to calcite. Assuming that these coral die offs were caused by coseismic uplift events, and using additional dated corals from published sources and one radiocarbon-dated shell, we have interpreted and temporally constrained as many as 12 events in the past ~7,000 years. Our preliminary work indicates that the penultimate earthquake did occur in 1822, but was smaller than 1991. We calculate an average slip rate of 3.8±0.3 mm/yr on the NPDB using a geophysically determined fault dip of 27°, and an average earthquake recurrence of ~600 years, but return periods are irregular and clustered, suggesting that the region experiences two types of events: large events with ~1400-year return periods that could reflect multi-segment ruptures of the NPDB, and smaller events with recurrence intervals in the 100s of years.*

Key words*: Paleoseismology, Costa Rica, Panama, corals, PSHA*

INTRODUCTION

As part of a Probabilistic Seismic Hazard Analysis (PSHA) for a new port facility in Moín, Costa Rica, we completed a field reconnaissance of uplifted coral reef platforms of the Caribbean Coast in the Moín-Limón area (ECI, 2012). The purpose of our study was to determine the geologic recurrence of past coseismic uplift events on the offshore North Panama Deformed Belt (NPDB) similar to the M_s7.6 Limon earthquake of April 22, 1991 that resulted in up to 1.8 m of coastal uplift within the project area (Denyer et al., 1994; Plafker and Ward, 1992).

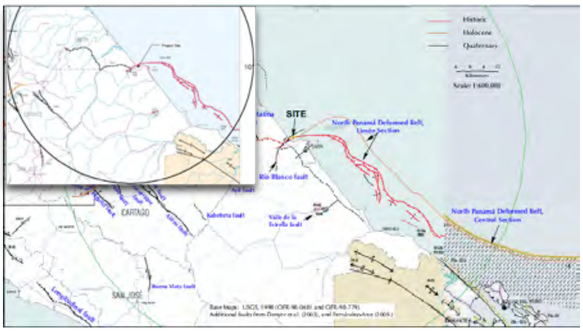

Fig. 1: Fault map of eastern Costa Rica and western Panama showing the North Panama Deformed Belt off their northern Caribbean coasts, and the fault rupture (in red) that occurred in 1991 (inset). Figure modified from (Montero et al. (1998).

The NPDB is a large thrust fault accommodating the northward push of the Cocos-Nazca plates against the Isthmus of Panama. While the majority of the ~90 mm/yr convergence (DeMets, 2001) is consumed by subduction along the Pacific Margin, attempted subduction of the Cocos Ridge and a string of submarine volcanoes (inset in Fig. 2), is acting as a plow, shoving the isthmus onto the Caribbean plate at an estimated 7 mm/yr (Trenkamp et al., 2002). The strain that is partitioned northward forms a large and poorly studied thrust system that reaches from Moín, Costa Rica eastward for 800 km along the entire northern Panama coastline. This fault is assumed to have generated the ~M_s7.9 1882 earthquake off the San Blas Archipelago, Panama (Camacho and Víquez, 1993), but no other confirmed large historical events are known prior to 1991, when the westernmost 80 km of the fault ruptured from Bocas del Toro, Panama to Moin, Costa Rica.

Fig. 2: Map of the Moín and Limón harbor areas, showing the location of the proposed new harbor site, and the topographic uplift associated with the left bend of the NPDB as it turns ashore.

The NPDB steps ashore just west of Moín (Figs. 1 & 2), and continues ~50 km westward as the Siquirres-Matina fault (Montero et al., 1998), forming a prominent escarpment. Where the NPDB steps ashore, it has formed a 7.5 km long left-lateral tear fault, the Río Blanco, that experienced up to 1.4 m of lateral displacement and 0.5 m of vertical surface offset in 1991 (Fig. 1; Denyer et al. 1994). Consistent left-laterally deflected streams along the Río Blanco fault show strong evidence for multiple Holocene events. Between Moín and Limón, an elevated headland has been formed by the leftward bend of the NPDB (Fig. 2). It is this localized uplift that has preserved the coral platforms that formed the basis for our investigation.

Review of historical accounts show that an earthquake reported in 1822 had similar descriptive effects at Moín-Limón as the 1991 event (Ambraseys et al., 2001; Boschini & Montero, 1994); & Camacho & Víquez, 1993), suggesting a recurrence interval of 170 years between uplift events. To confirm this, and to potentially extend this event record paleoseismically for an offshore fault, we mapped and sampled a suite of uplifted coral platforms along about 8 km of the Limón coast (Figures 3, 4 & 5).

Fig. 3: Photo showing the coral platform uplifted by the 1991 earthquake (right), the penultimate platform (grassy area lower left) and pre-penultimate platform (upper left, somewhat obscured in the vegetation).

Fig. 4: Older uplifted coral platforms uphill from Fig. 3.

Seven discrete coral platforms were recognizable on the shoreward-facing coastal slope in the Playa Bonita area between Moín and Limón (Fig. 4). Capping the slope is a marine terrace, with other marine terraces occurring at higher elevations inland. We concentrated on the coral platforms, which could be dated using U-Th dating, and did not map the marine terraces. If they could be dated, or at least correlated to the eustatic marine sea level curve, these uplifted marine terraces would provide an excellent length to the Holocene uplift rate that we determined from the coral platforms.

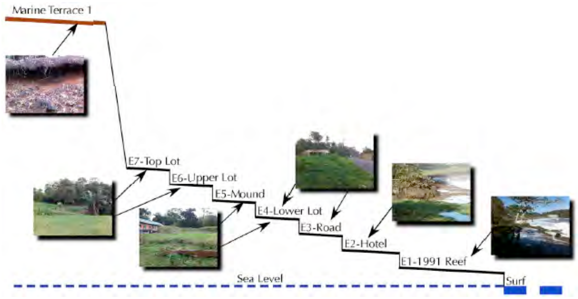

Fig. 5: The suite of seven coral platforms identified during the initial reconnaissance at the Playa Bonita site, capped by the marine terrace platform from Punta Portete (Fig. 2). Because each bench was vertically separated by 1-2 meters, our preliminary working hypothesis was that each bench recorded an earthquake. Diagram not to scale.

INVESTIGATION

Because of the urban environment, and the short duration of the project, we did not prepare a comprehensive map of all of the coral platforms, but concentrated our efforts at three locations where they were particularly well expressed and preserved. To measure lateral distances we used a hand-held 100-meter tape, and to measure the vertical separation between platforms, we used a hand-made stadia rod and an iPhone-based "Theodolite" application (Theodolite© by Hunter Research & Technology LLC) (Fig. 6). We estimate that our vertical error could be as much as 0.5 meters for long traverses, but less than 0.2 meters for most measurements.

Fig. 6: Example shot of the theodolite surveying of the relative vertical separation between the coral platforms.

To provide age control, we obtained 48 coral samples from a wide range of vertical and spatial locations for U-Th age dating. We sampled some obvious 1991-killed corals to check the accuracy of the dating technique (Fig. 6). We then sampled at least one coral from each identified platform at each location along the coast. Unfortunately, 75% of our coral samples were not suitable for U-series dating due to diagenetic alteration of the original aragonite to calcite.

In addition to the corals, we also collected two shells, one from its growth position at the base of a bench. These corals were dated using 14C.

Fig. 7: One of the corals uplifted by the 1991 earthquake.

Fig. 8: Sampling drill used for the older coral platforms.

RESULTS

Despite the difficulties with the U-Th dating of the corals, the study did generate important results concerning the paleoseismic history of the NPDB that were useful to the PSHA for the project. Before those results could be understood however, the coral ages needed to be put into context of their vertical positioning with respect to the many mapped platforms (Fig. 9). Not all paleo-events might be preserved everywhere along the coast due to dissolution or erosional removal.

In Fig. 9 we correlate the various sea level indicators and platforms that we mapped at the three principal study locations (vertical transects) from west to east along the coast. Within the error limits of our mapping results, there are definite correlations of platform elevations across the 5 km coastline. But there are also platforms that are recognizable at only one or two locations. Additional mapping along the coastline between the three principal locations should result in better resolution of the platform correlations.

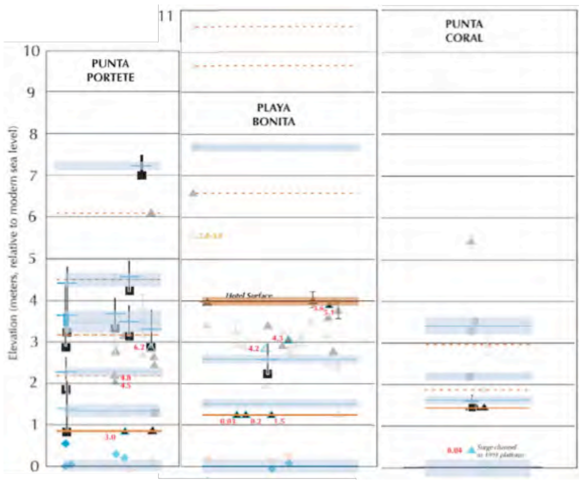

Fig. 9: Composite plot of the coral platform (brown) and notch (light blue) elevations that were mapped at three principal localities, west to east (left to right) along the Limón coast. Elevation in meters on the left; horizontal distance is about 5 km. The line widths represent the uncertainties in the elevation measurements.

After correlating the coral samples across the various platforms, we needed to correct their current elevations with the sea level elevation that was present at their determined age (Fig. 10). The 6.2 ka coral sample was obtained from the fourth highest platform on Punta Portete (Fig. 9) at a modern elevation +2.9 m. Absent better information on coral water depth ranges, we assumed an original water depth of 2 m for all stony coral samples and 0.5 m for others. As illustrated on Fig. 9, at 6.2 kya the sea level was at -6 m, resulting in an uplift of 10.9 m (2.9+2+6) in 6.2 ka (uplift rate = 1.8 mm/yr). Similar results were calculated for all of the other datable samples and they were placed into context on Fig. 11 to show their true positioning with both age and lateral correlation.

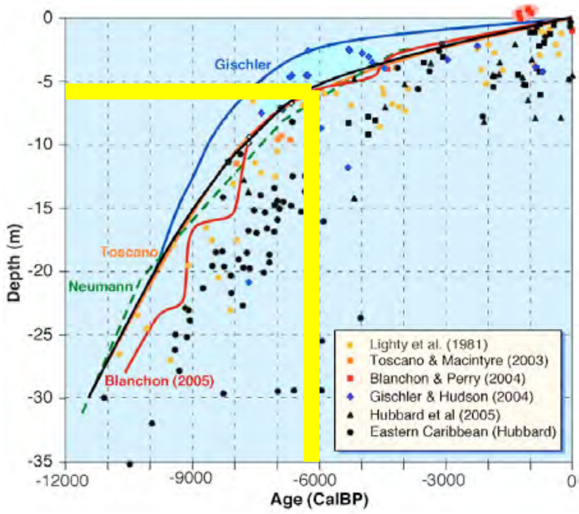

Fig. 10: Composite plot of the various Caribbean sea level results developed by six different researchers. The black line from Hubbard et al. (2005) represents an approximate mean value that we used in our analysis to correct for paleo sea level elevation. The yellow bars illustrate that the 6.2 ka coral sample corresponds to a -6 m sea level.

Fig. 11 shows how the various events were counted across the study area, and how often they correlate to other dated locations laterally, west to east. Unless we are missing events, which is possible, the pattern of earthquakes strongly indicates that they are irregular, with several events clustered between longer quiescent intervals.

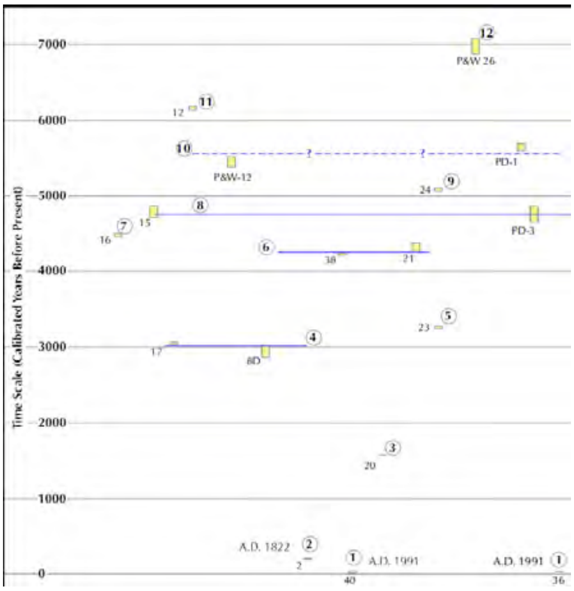

Fig. 11: A twelve event earthquake chronology that was determined after correcting and correlating the dated coral sample elevations for the 7.5 m sea level rise in the last 7 ka, as measured from Fig. 10. The interpreted event number is circled, starting with 1991 and 1882 AD near the bottom. Age in years on the left, distance west to east (left to right) across the bottom (Fig. 9), but not to scale.

Our limited data set allows only speculation about event magnitude, but the two most recent events (1822 and 1991) resulted in ~1 m and 1.8 m uplift events respectively, clearly implying that they were of different magnitudes. From Fig. 11, before the 1822-1991 cluster, it was almost 1500 years to the pre-penultimate event (#3), and another 1500 years to the one before that (#4), closely preceded by an event (#5). Then it was over 1000 years before a series of temporally clustered events (#6-11) followed by an 800 year hiatus to event #12.

With 12 events recognized in 7 ka, the average recurrence interval would be ~600 years. But based on events 2, 5 & 7, we conclude that the recurrence between uplift events can be as short as ~200 years, while the recurrence between larger events can be as long as 1400 years. These rates are in good agreement with those determined by Plafker and Ward (1992) but provide a much higher degree of resolution to be able to interpret the temporal variability.

To calculate the uplift rate we calculated each dated sample's uplift rate (1.6–2.7 mm/yr, strongly clustered between 1.6 and 2.1 mm/yr, and averaged them. To calculate the fault's slip rate, we used the geophysically-imaged 27° of the offshore fault (Brandes et al., 2008) and resolved the rate trigonometrically from the uplift rate, resulting in 3.8±0.3 mm/yr, or about 50% of the Trenkamp et al. (2002) rate for Caribbean convergence.

CONCLUSIONS

- 75% of the coral samples were too degraded to date (aragonite to calcite transformation).
- Those samples dated ranged from 1991 to ~7,000 years BP.
- Interpreted 12 events on the NPDB, assuming the coral deaths were all earthquake-induced.
- Holocene uplift rate of 1.9 ± 0.2 mm/yr.
- Slip rate on NPDB of 3.8 ± 0.3 mm/yr.
- Irregular earthquake recurrence with larger events ~1400 years and smaller events ~200+ years.
- Most recent event was April 22, 1991 (M_s7.6).
- Penultimate event was in 1822, while the pre-penultimate event was 1.6 ka.
- There is a huge opportunity for more work.

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