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PREMONITORY SEISMICITY BEFORE THE SEPTEMBER 5, 2012, MW 7.6 NICOYA EARTHQUAKE, COSTA RICA: RELATIONSHIP WITH MAINSHOCK RUPTURE AND AFTERSHOCK ZONE
ANTHONY MURILLO GUTIÉRREZ, Universidad Nacional de Costa Rica (UNA)
Research Advisor: Marino Protti

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DUSTIN STEWART, Cal Poly Pomona
Research Advisor: Jeff Marshall

INTRODUCTION

Carbonate-cemented beachrock horizons are a common feature of sand and gravel beaches of the Nicoya Peninsula, Costa Rica (Marshall et al., 2012). These outcrops are much like other beachrock deposits found throughout the tropics (e.g., Turner, 2005; Vousdoukas et al., 2007). They generally consist of seaward-dipping horizons of lithified beach sediments that lie parallel to the beach face and are formed by cementation of sediment grains through precipitation of calcite or aragonite cement within intergranular pore spaces (Bricker, 1971; Scoffin and Stoddart, 1983). Beachrock formation occurs by a number of methods that result in precipitation of carbonate cements, including direct crystallization from sea water, mixing of fresh and saline water, degassing of carbon dioxide by evaporation, and a variety of micro-biological processes (Hanor, 1978; Longman, 1980; Neumeier, 1999; Vousdoukas et al., 2007). Although these deposits typically form beneath unconsolidated sediments on the beachface, they can become exposed at the surface by erosion and changes in relative sea level. Beachrock forms relatively quickly (Vousdoukas et al., 2007) and therefore newer horizons sometimes develop adjacent to older deposits that have been eroded or displaced, resulting in complex beachrock outcrops.

In active tectonic environments such as the Nicoya Peninsula, beachrock horizons provide a potential means of tracking coastal uplift over time (e.g., Marshall, 1991; Marshall and Anderson, 1995; Utick et al., 2006; Marshall et al., 2012). This requires knowing the age of beachrock cementation, the original formation elevation on the beach face, and the modern elevation. At present, Holocene beachrock outcrops have been studied in detail at 17 field sites (Fig. 1) along the length of the Nicoya Peninsula (Marshall et al., 2012). These outcrops have been characterized in the field, topographic profiles surveyed, and samples collected for radiocarbon dating, hand specimen description, and thin section petrography.

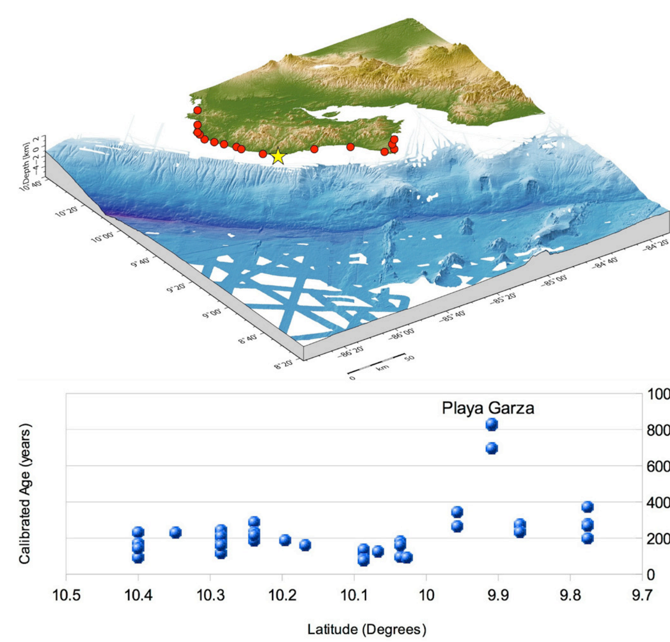

Figure 1. Beachrock study site locations (red dots on DEM) and distribution of radiocarbon ages (blue dots on plot) along the Nicoya Peninsula coastline (Marshall et al., 2012). This research project focuses on the Playa Garza study site (yellow star), which exhibits anomalous ages and complex stratigraphy relative to other sites.

Nicoya beachrock outcrops exhibit substantial variation in lithologic facies, composition, grain size, and cement mineralogy, even on the same beaches (Utick et al., 2006). Sediment grains range from fine sands to coarse gravels, with composition varying from lithic grains to fragments of shell and coral. Cement mineralogy includes acicular circum-granular aragonite fibers and pore-filling calcite crystals typical of saturated zone precipitation, and in some cases meniscus cements typical of vadose zone crystallization (Marshall et al., 2012).

Whole-rock and single-shell radiocarbon ages (42 samples; Fig. 1) range from 700-3800 yrs for deposits on the modern beach, and from 4500-5300 yrs for uplifted deposits located up to 0.5 km inland (Fig. 1; Marshall et al., 2012). One site at Playa Garza, however, exhibits anomalous characteristics and returned much older ages than other Nicoya beachrocks (3 samples, 7000-8300 yrs). The goal of this Keck project was to investigate this anomalous beachrock outcrop in greater detail, to characterize its stratigraphy, provide lithologic descriptions, and examine the petrography of sediment grains and cements in thin sections.

STUDY SITE

The Playa Garza study site (Fig. 2) is located at the most seaward point of the Nicoya Peninsula, a rocky headland known as Punta Guiones that forms an "elbow" where the trend of the coastline bends from NW-SE to E-W (Fig. 1). The majority of the Nicoya Peninsula coastline is comprised of uplifted seafloor basalt of the Cretaceous Nicoya Complex, however the Punta Guiones area is underlain by Paleogene deep marine mudstones, sandstones, and silicic limestones (Baumgartner et al., 1984; Denyer and Alvarado, 2007). These rocks form a broad intertidal platform at the study site (up to 60 m wide) that is exposed at low tide seaward of the Garza beachrock outcrops (Fig. 2). This platform extends up to the beach, which is backed by a small bluff (1-2 m high) cut in uplifted Holocene beach and fluvial deposits.

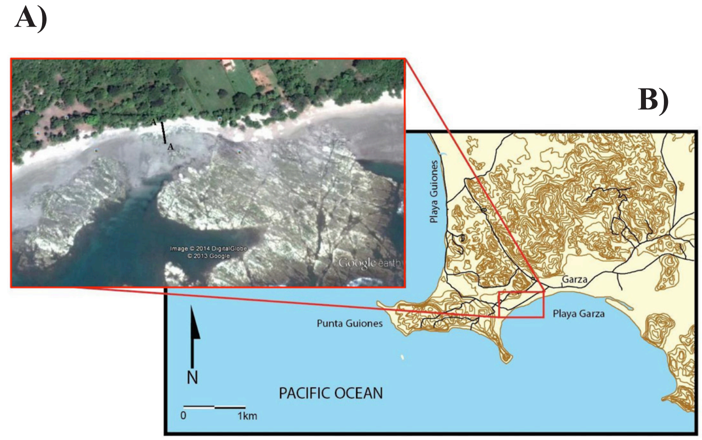

Figure 2. The Playa Garza beachrock study site shown on: A) aerial photograph (from Digital Globe and Google Earth), and B) topographic map (from MINAE-CENIGA, Punta Guiones 1:25,000 scale digital quadrangle). Black line on photo shows location of geologic cross-section (A-A') depicted in Figure 3.

The beachrock itself has multiple outcrops occurring along an area of beach of roughly 20 m x 30 m (Fig. 2). In contrast to other Nicoya beachrock sites, the Garza outcrops are rugged with significant topographic relief (> 2m), exhibiting a complex stratigraphy of multiple layers, with breccias incorporating fragments of local bedrock and older beachrock (Fig. 3). The outcrops also appear more chemically weathered, with orange oxidation and other prominent colors. The beach has a gentle slope (<10^{o}) and consists of locally derived sand and gravel with abundant shell fragments. The beach sediments appear visually different than the framework sediments in the beachrock. Another unique aspect of this site is the presence of multiple small sulfur gas vents (Fig. 4) that bubble up through the beach sediments around the outcrops.

Three samples of Garza beachrock have been dated in prior studies (Marshall et al., 2012). The first two were collected from stratigraphically distinct horizons, yielding calibrated ages of 8250 (+70/-90) ybp for the upper layer (Unit V, Fig. 3) and 8310 (+60/-120) ybp for the lower layer (Unit II, Fig. 3. A third sample was collected at another site within the upper layer (Unit V, Fig. 3), yielding an age of 6960 (+50/-60) ybp. All three of these ages significantly exceed the normal range for other Nicoya samples (500-5500 yrs; Fig. 1), especially for outcrops located directly on the modern beach.

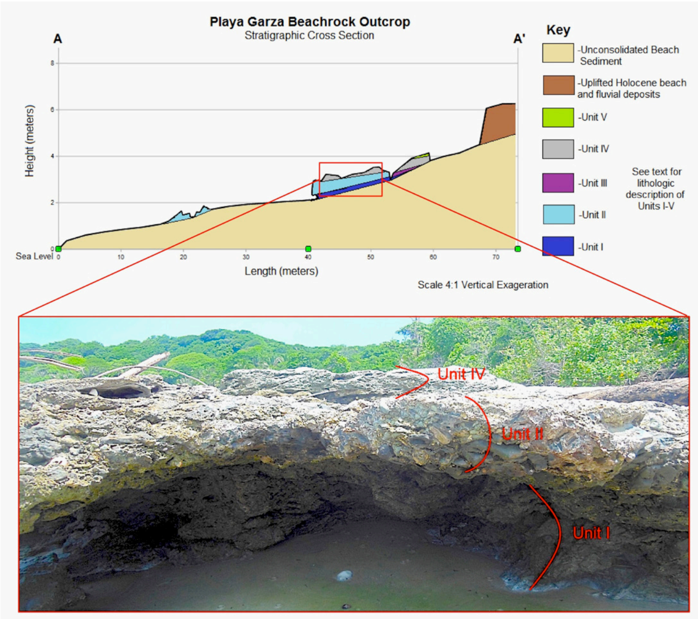

Figure 3. Geologic cross-section and photograph showing the complex stratigraphy (Units I-V) of the Playa Garza beachrock outcrop. Cross-section location shown as line A-A' on Figure 2.

Figure 4. Photograph of small sulfur gas vent in modern beach sand adjacent to Playa Garza beachrock outcrop. Many similar vents occur throughout the area surrounding the outcrop.

METHODOLOGY

This study was conducted as part of a general study of beachrock outcrops in the area of coseismic coastal uplift from the 2012 Mw7.6 Nicoya Earthquake (Marshall et al., 2013; Protti et al., 2014). Beachrock outcrops were visited at multiple sites and geomorphic observations were recorded regarding outcrop dimensions, location on the beach face, and other general features. Hand samples were examined for texture, composition, grain size, shape, sorting, porosity, and cement characteristics. Samples were also collected and catalogued for laboratory thin section analysis and radiometric dating. Topographic profiles were surveyed using a laser range finder, hand levels, and stadia rod. GPS coordinates were recorded for surveys and all samples.

In addition to the basic data recorded at all beachrock sites, a more detailed stratigraphic study was conducted at the Playa Garza site. Topographic maps (1:25,000) and aerial photographs (1:40,000) of the Garza study site (Fig.2) were examined to characterize site geomorphology and to identify any notable geomorphic or structural features related to and he beachrock outcrops. A dense set of topographic profiles was surveyed to create a 3-D grid of the site. Distinct strata were identified and described to create a cross section (Fig. 3).

Representative samples were collected from the five distinct stratigraphic units (Units I-V). The samples were shipped back to Cal Poly Pomona for lab analysis. In the Rock Prep Lab, samples were cut and cleaned using a diamond tipped rock saw, and portions selected for age-dating and thin sections. Cleaned hand samples were inspected with the naked eye and under binocular microscope to improve on the original field lithologic descriptions. These samples were also compared to previous beachrock samples collected from prior field seasons. These ages are still pending at time of publication. Thin sections of previously dated samples (Fig. 5) were analyzed to evaluate grain composition and cement texture.

RESULTS

The primary Playa Garza beachrock outcrop (Fig. 3) encompasses five distinct stratigraphic units (Units I-V):

Figure 5. A) Photograph of Playa Garza beachrock outcrop and sample site CR10-26 within upper horizon (Unit V). This sample yielded a calibrate whole-rock radiocarbon age of 8250 (+70/-90) ybp. B) Thin section photomicrograph (10x polarized) of sample CR10-26 showing shell and lithic fragments cemented by pore-filling blocky high-magnesium calcite typical of saturated zone precipitation.

Unit I: The oldest unit at the base of the outcrop (Unit I, Fig. 3; CR13-DS-03) consists of blue-grey, well-sorted, fine-grained, calcareous arenite. It is poorly consolidated and subject to wave erosion, forming concavities beneath the overlying more resistant beachrock units. The modern beach sediment surrounding the outcrop shows traces of this material, but it does not appear further from the outcrop. Cutting this sample and testing its age proved to be impossible due to its poor durability (about half of the sample was ground into sand during shipping).

Unit II: There are two distinct units that overlie Unit I in different parts of the outcrop. The first of these (Unit II, Fig. 3; CR13-DS-06) occurs on the southern, seaward end of the outcrop. It consists of a blue-grey, well-indurated, fossiliferous calc-arenite breccia with a fine-grained sandy matrix. Prior whole-rock radiocarbon dating (CR10-27) yielded a calibrated age of 8310 (+60/-120) ybp (Marshall et al., 2012). The matrix is similar to Unit I, however this unit is rich in poorly-sorted coral, and shell fragments, as well as rounded pebbles about 5-15 mm in length of varying composition. Most abundant of these pebbles are pale-green, poorly-sorted calc-arenites which also appear further upsection. These pebbles effervesce slightly in reaction to HCL, in contrast to the Unit II matrix which effervesces vigorously. Additional clasts in Unit II include well-rounded, resistant pebbles, and occastional large cobbles and boulders, with the same color and grain texture as the oldest unit (Unit I), but are far more consolidated and resistant to weathering. These resistant clasts have a thin, reddish-brown, fine-grained surface rind that may consist of iron oxide. The largest of these clasts appear concentrated along what may be a paleo-stream channel and some boulders occur on the beach extending inland of the outcrop. Also found in Unit II are occasional fragments of blue and white chert (Moh's hardness of ~7), with conchoidal fractures, and the ability to create a spark when struck together (Klein and Dutrow, 2007).

Unit III: On the northern, landward portion of the outcrop, Unit I is overlain by layered, matrix-supported breccia (Unit III, Fig. 3; CR13-DS-07) with matrix alternating from blue-gray, fine grained calc-arenite (30%) to grey, very-fine grained siltstone (60%). The remaining 10% of this unit is split between white, calcareous fracture-filling veins and the same large resistant arenite cobbles and boulders found in Unit II. Unit III lacks, however, the pale-green, well-rounded clasts, shells, and corals common in Unit II. While Units II and III both overlie Unit I, there is no clear contact within the outcrop between Units II and III.

Unit IV: The previous two units (Units II and III) are both overlain by a blue-grey, fossiliferous breccia (Unit IV, Fig. 3; CR13-DS-04) with a fine-grained, calc-arenite matrix similar to other units. Unit IV, however, is clast-supported, with matrix only filling 50% of the unit. It contains an abundance of shells, corals and the same well-rounded pale-green arenite clasts, which are larger (5-40 mm) than those in underlying units. Unit IV does not contain the large resistant cobbles and boulders found in Units II and III.

Unit V: The youngest unit (Unit V, Fig. 3; CR13-DS-09) is the most typical of other beachrock found along the Nicoya coast. This unit is light-grey and consist of a clast-supported breccia containing abundant shells, coral and pale-green arenite pebbles. Unlike previous units, it has a porous matrix consisting of broken shell and coral fragments, with only trace amounts of the dark-blue calc-arenite in underlying units. This shell and coral matrix gives a far lighter grey color than the dark-blue underlying strata. Two prior whole-rock radiocarbon ages were determined for this unit: CR10-26 yielded a calibrated age of 8250 (+70/-90) ybp, whereas CR12-29 yielded a calibrated age of 6960 (+50/-60) ybp (Marshall et al., 2012).

DISCUSSION AND CONCLUSIONS

The Playa Garza beachrock outcrop exhibits anomalous characteristics in the lower part of its stratigraphic section, but trends up-section toward a lithology that is more typical of other Nicoya beachrocks. Three previous whole-rock ages for samples collected from the lower and upper horizons yield ages (7000-8300 yrs) that far exceed the typical age range for other Nicoya sites (500-5500 yrs) (Marshall et al., 2012) and many beachrock sites worldwide (1000-5000 yrs; Vousdoukas et al., 2007). These anomalous ages are most likely explained by the mixing of shells, cement, and lithic fragments in the whole-rock dating technique (Vousdoukas, et al., 2007). The ages may be skewed toward older values by contamination with older biologic material or carbonate in the local bedrock.

Based on thin section analysis, the Playa Garza beachrock units are mostly cemented by blocky, pore-filling calcite grains (Fig. 5), typical of saturated zone cementation where marine and fresh groundwater mix within the beachface (Vousdoukas et al., 2007). Unlike other Nicoya beachrock deposits which are relatively close to a stream outlet or estuary (source of abundant freshwater), the Playa Garza outcrop is not located near a modern stream. However, the presence of abundant rounded pebbles, cobbles, and boulders in this outcrop suggests fluvial transport. It is possible that a former channel or estuary was present at this site, but has been filled-in by natural or human means (e.g., farmers reclaiming land). The presence of sulfur gas vents and chert in some of the strata also introduce the possibility of diagenetic or geothermal processes affecting beachrock formation.

The results of this study confirm the anomalous nature of the Playa Garza beachrock outcrop, and show that it consists of a complex stratigraphy of calc-arenite breccias and beachrocks that incorporate reworked fragmens of older units, including the bedrock. The mineralogy and texture of both matrix and cements is variable between units. Anomalous whole-rock radiocarbon ages are likely skewed by incorporation of older shell, coral, and lithic fragments. Future dating of these deposits should focus on isolating carbonate cements. Additional study of this outcrop is required to better understand its complex history of deposition, erosion, reworking, and cementation. Geochemical analysis of cements, marine and fresh groundwater, and sulfur gas vents may reveal new insights into the cementation process.

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