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Short Contributions— Earthquake Geomorphology, Costa Rica Project

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RELATIONSHIP BETWEEN BEACH MORPHOLOGY AND COSEISMIC COASTAL UPLIFT, NICOYA PENINSULA, COSTA RICA

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INTRODUCTION

Subduction zones and associated megathrust earthquakes are of interest to both the public and to scientists. Within the past ten years, large earthquakes in Sumatra (M9.3, 2004), Chile (M8.8, 2010), and Japan (M9.0, 2011) have drawn attention because of their large magnitudes and resultant destruction and loss of life. Studying the geomorphic signature of coseismic uplift or subsidence offers a means of understanding the influence of crustal motions on coastal topography (Atwater, 1987; Ferranti et al., 2007; Scheffers et al., 2012). In addition, geomorphic markers of vertical tectonic motion can be used to confirm or support measured uplift in some regions of the world. Our project focused on the coast of the Nicoya Peninsula, Costa Rica and examined the morphotectonic footprint of coseismic uplift associated with a M7.6 earthquake that took place on September 5, 2012 (Yue et al., 2013; Protti et al., 2014). Our overarching goal was to add to existing post-earthquake geomorphic and geodetic data on coseismic uplift (Marshall et al., 2013; Protti et al., 2014), and to contribute to ongoing investigations on the net effect of repeated earthquake events on Nicoya Peninsula deformation and topography (e.g., Hare and Gardner, 1985; Marshall and Anderson, 1995; Gardner et al., 2001; Marshall et al., 2001; Sak et al., 2009; Marshall et al., 2012).

Beach morphology is controlled by a multitude of geomorphic, oceanographic, and tectonic processes (e.g., Gujar et al., 2011; Komar, 1992; Nolan et al., 1999; Dail et al., 2000; Ferranti et al., 2007). The western beaches of the Nicoya Peninsula, located along the Pacific coast of Costa Rica, are nestled between rocky headlands (Marshall, 2007). We surmise the magnitude and direction of wave energy incident on a beach, tidal fluctuations, and existing sediment grain size exert the strongest daily control on beach morphology, with sea level changes spurred by tectonic uplift exerting a secondary long-term control on coastal morphology.

Repeated coseismic uplift throughout the Quaternary has resulted in emergence of the western coast of the Nicoya Peninsula (Marshall and Anderson, 1995), indicated geomorphically by the uplift of paleo-shorelines and ongoing migration of the extent of high tide. This study hypothesizes that the pre-earthquake geomorphic high tide markers were abandoned after coseismic uplift, and the vertical difference between these old markers and those being deposited after the earthquake represents the magnitude of uplift. On a majority of the ~25 beach topographic profiles examined at four study beaches, a stacked two berm signature was evident, and occasionally a relict debris line could be found at the same elevation as the higher of the two berms. At beaches fed by estuaries, the two berm signature was not present proximal to the estuary outflow. Offset measured between the two beach berms increases from the northernmost study site (San Juanillo) to the southernmost site (Playa Carrillo), consistent with post-earthquake geomorphic field measurements (Marshall et al., 2013) and GPS geodetic data (Protti et al., 2014).. In general, the magnitude of measured uplift based on beach geomorphology surpasses that of reported GPS values, suggesting local geomorphic forcing plays a role in the development and spacing of beach berms and tidal debris lines.

STUDY AREA

The Nicoya Peninsula, along the Pacific coast of Costa Rica, is located directly above the seismogenic zone caused by subduction of the Cocos oceanic plate beneath the overriding Caribbean plate at the Middle America Trench (MAT). This subduction occurs at a rate of 8.5 cm/year (DeMets, 2010) and has caused repeated large historic earthquakes (>M7.5) over the past few centuries. The recent record shows earthquakes happening in 1853 (M≥7.5), 1900 (M≥7.5), 1950 (Ms=7.7), and 2012 (Mw=7.6) (Protti et al., 2001). While the 2012 M7.6 earthquake was felt throughout Central America, no lives were lost and fewer than 200 injuries were incurred as a result of public awareness efforts by geoscientists and government officials. For 62 years following the 1950 earthquake, seismic, geodetic, and geomorphic data showed the Nicoya Peninsula seismic gap to be maturing (Protti et al., 1995 and 2001; Marshall and Anderson, 1995; Feng et al., 2012) up to its rupture in 2012.

Because it is just 65 kilometers landward of the MAT, the Nicoya Peninsula is particularly sensitive to vertical displacements incurred by recurring earthquakes. Along the western coast of the Peninsula, raised terraces denote a history of coastal uplift, while on the eastern, landward facing coast subsidence is marked by the presence of drowned rivers and broad mangrove estuaries (Hare and Gardner, 1985; Marshall and Anderson, 1995; Gardner et al., 2001; Marshall et al, 2001; Sak et al., 2009; Marshall et al., 2012). Four beaches along the western coast in the fifty kilometer stretch between San Juanillo and Puerto Carrillo (Figure 1) were characterized in terms of their morphology in an effort to record the coastal response to coseismic uplift.

Playa San Juanillo (Fig. 1A) has west, north, and south facing beaches with wave energy partially obstructed by bedrock platforms. Waves reaching the beach are funneled between these platforms. Sediment retained by these platforms has formed a tombolo with both north and south facing beaches. In contrast to the other sites, the sediments on this beach were predominantly a coarse mix of lithic clasts, shell, and coral fragments.

Playa Pelada (Fig. 1B), eleven kilometers south of Playa San Juanillo, lies between two rocky headlands and has a gentle arcuate shape. The beach receives partially obstructed wave energy directly from the west due to the presence of rocky headlands and intertidal platforms. A small estuary flows out at the head of the sand dominated portion of the beach.

Playa Garza (Fig. 1C) lies six kilometers south of Playa Pelada in a sheltered cove behind a large rocky headland. The portion surveyed faces east and waves arrive at the beach after refracting around the headland and dissipating across the rocky tidal platform. The sediment on this beach is coarse grained and poorly sorted, being close to the rocky headland from which it is sourced. At the time of field study, the highest berm on this beach is reworked into a pattern of beach cusps with alternating troughs and horns. There is a small estuary feeding the beach, but at the time of study the channel was choked with coarse rock rubble, woody debris, and human trash.

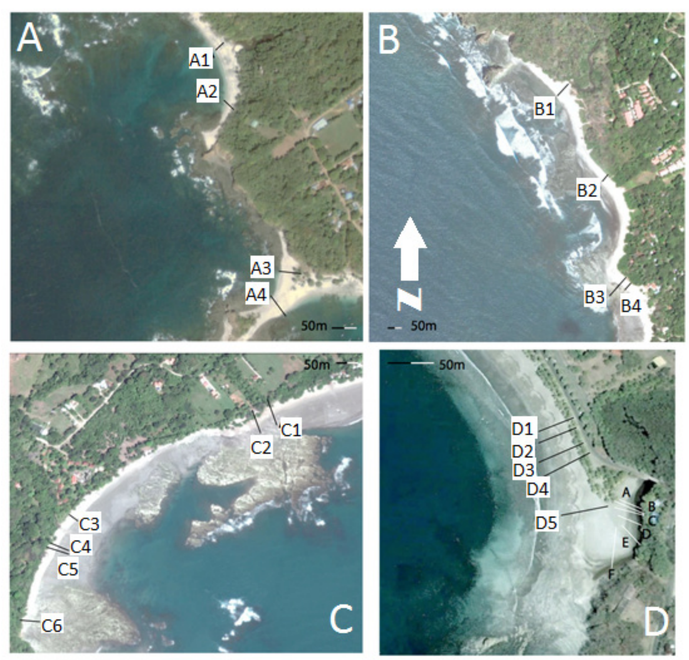

Figure 1. Aerial photographs of four beaches (A-D) examined in this study, listed from north to south along Nicoya coast. The locations of topographic transects are shown as numbered lines. Note that the map scale is not consistent form beach to beach. See text for description of beach morphology. A) Playa San Juanillo, B) Playa Pelada, C) Playa Garza, D) Playa Carrillo.

Playa Carrillo (Fig. 1D), eighteen kilometers southeast along the coast from Playa Garza, is the most gently sloping of the beaches surveyed, with an arcuate, predominantly sandy beach fed by multiple estuary drainages. The beach faces south and waves are directed through two rocky headlands before they arrive at the shore. At the time of study, a pattern of smaller beach cusps spanned the entire beach.

METHODS

Data Collection

In an effort to characterize the morphology of these beaches, we conducted hand level and stadia rod surveys perpendicular to the shore at several locations at each beach, with detailed notes regarding the locations of geomorphic markers resulting from previous and present high tide. The series of beach-perpendicular transects at each site captures the presence of beach parallel, wave generated features such as berms and debris lines, as well as overall beach slope and topography. Locations of transect lines were based on their intersection with significant geomorphic markers. Transect lines began at the current water level and continued until evidence of wave action was absent, such as dense vegetation, or another significant obstacle, such as a road was encountered. Elevations were later corrected against the daily tidal curve to establish a common mean sea level baseline. To account for the variable nature of the geomorphic signatures used to measure the uplift, an uncertainty of ±0.2 m was assigned to resulting elevation values to reflect the inherent error of the hand level and stadia rod surveying method (e.g Marshall and Anderson, 1995).

Data Analysis

Beach topographic profiles were plotted using Excel software and elevation differences between relict and present markers were compiled. From these plots, along with site notes, elevation difference values were determined. Berm height difference was the preferred uplift marker, but in the absence of obvious berms, debris lines were utilized.

RESULTS

Profiles

In general, the beach topographic profiles showed a gentle slope (2° to 8°) near mean sea level that gradually increased (4° to 12°) to meet the present high tide berm. Most profiles showed a second berm, or debris line at an elevation higher than the present berm.

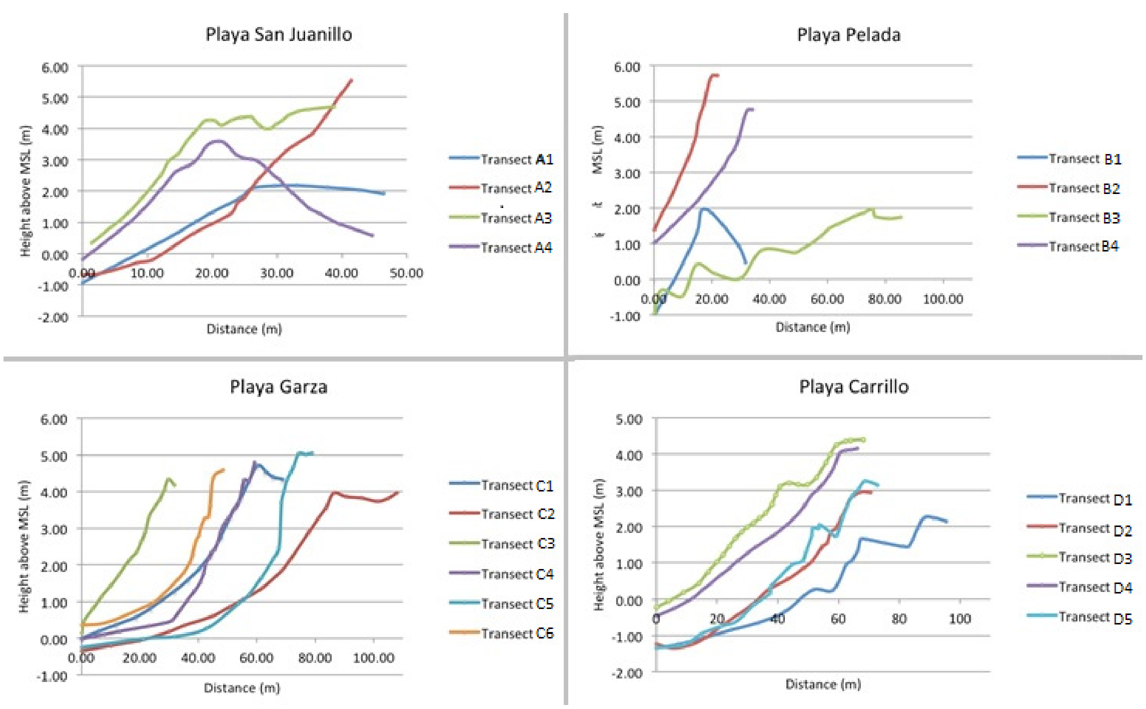

Figure 2. Beach topographic profiles from study beaches A-D. The location of each transect is marked on Figure 1. Slope and morphology is not dependent on beach aspect, but rather proximity to a bedrock platform or active estuary outlet. Coarse grained and sediment starved Playa Garza shows an upward concavity and steeper slope not mirrored in the finer grained beaches. The two-berm signature of coseismic uplift is most evident from profiles at Playa Carrillo.

Playa San Juanillo (Figs. 1A and 2A) profiles showed significant morphologic difference based on wave access to the cove, with the topographic profiles with greater wave access (A1 and A2) showing a more concave shape than those with more restricted wave access (A3 and A4). The profile across the tombolo showed a significant change in berm height (0.5 m), and the estuary proximal profile lacked any marker of previous high tide influence.

Playa Pelada (Figs. 1B and 2B) slopes steeply at roughly 10°, and although the aspect of each profile was similar, the resultant profile morphology dramatically differed. The profile measured alongside the estuary (B1) showed a sharp single berm while that taken across the rocky platform (B3) showed one berm as well as the irregularities of the platform itself. The two remaining profiles (B2 and B4) lacked a two berm signature but showed new vegetation growth down the beach face.

Beach profiles from Playa Garza (Figs. 1C and 2C) all have a distinct berm, with clear concavity from the base to profile top. Beach slopes range from ~4° to ~10° with the most shallow slope on a profile (C2) obstructed by a bedrock platform and the most steep (C3) on a portion of unobstructed beach.

Playa Carrillo (Figs. 1D and 2D) profiles showed a consistent slope of ~2°. Two distinct berms were evident, only slightly obstructed by the trough and horn cusp pattern. No debris was present on this high traffic beach as people regularly cleared and burned it. The upward concavity seen at Garza was not mirrored here.

The most distinct features of the profiles were their slopes as well as the presence and magnitude of stepped berms. Profiles from Playa Garza and Playa Carillo were internally consistent while those from Playa San Juanillo and Playa Pelada showed significant variation in profile length, slope, and shape.

Uplift markers and coseismic uplift

The relict pre-earthquake beach berm and debris line elevations measured on Playa Garza showed a strong correlation (Figure 3), thus providing a clear indication of coseismic uplift when compared to their post-earthquake analogs. As these features mark the highest water extent, are formed in moderate rather than storm conditions (Scheffers, 2012), and are assumed to have experienced little erosion in the period between the earthquake and the study, they are interpreted as an indication of coseismic uplift. These uplift values ranged from 0.46 m at San Juanillo in the north to 1.15 m at Carrillo. While geomorphic uplift values showed slight variations at each site, the most notable trend was the overall increase in measured uplift from the northern to the southern study sites. Figure 4 shows the southward increase in distance between relict and modern berms, as well as vertical uplift reported from GPS data (Protti et al., 2014) The two data sets report different uplift values with the highest GPS value being roughly half of the highest geomorphic value. The GPS values were collected at more evenly spaced latitudes while the geomorphic values are a more clustered data set.

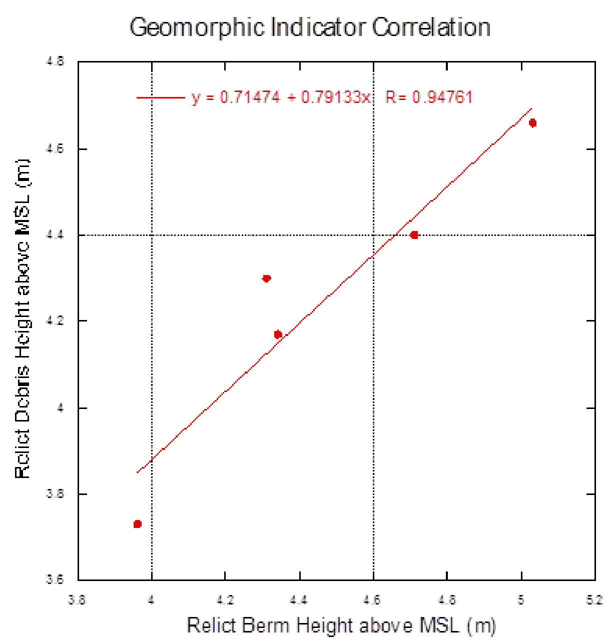

Figure 3. In the absence of a distinct two-berm signature, the elevation of debris lines was taken as the high tide proxy. This comparison, from Playa Garza where both berms and debris lines were abundant, shows the correlation between the debris and berm signature.

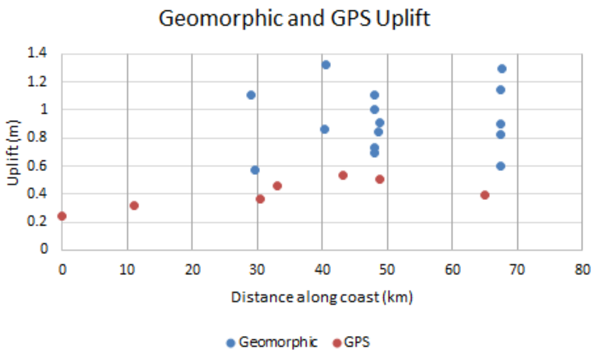

Figure 4. Geomorphic uplift values from this study plotted alongside GPS values reported in Protti et al., 2014 as a function of latitude to show the rough increasing southward trend in uplift.

DISCUSSION

The Pacific coast of the Nicoya Peninsula experienced abrupt coseismic uplift along ~60 km of shoreline during the 2012 M7.6 earthquake (Marshall et al., 2013; Protti et al., 2014). As a result, uplifted beaches show a measurable geomorphic signature of vertical shifts in the level of high tides. The data collected in this study at four beaches within the uplift zone show offsets in the position of both beach berms and high tide debris lines. Measurements of these offsets show an increasing trend toward the south, consistent with other post-earthquake geomorphic measurements and GPS geodetic data. This similarity indicates that beach berm and debris line offsets indeed reflect coseismic uplift. On less steeply sloping beaches, such as those at Playa Carillo, the two berm signature was very evident, while steeper beaches such as Playa Pelada and Playa Garza, recorded the uplift more notably in debris lines and new vegetation growth.

Playa Garza and Playa San Juanillo showed that profile aspect (orientation relative to approaching wave energy) had a limited effect on the profile shape. Importantly, no differences were seen in the offset of berms or debris lines with changing beach aspect at the same location. However, it was apparent that the presence of bedrock tidal platforms obstructing the beaches prevented the formation of a clear uplift signature. At Playa Garza the limited sediment supply resulted in a more distinctly concave beach shape. The profiles measured next to estuaries at Playa Pelada and Playa San Juanillo lacked any uplift signature, and suggested that the estuary sites are too dynamic to record any long-term geomorphic signature.

This study revealed several important controls on beach morphology at these sites, including sediment grain size influencing beach slope, and overall sediment supply influencing beach concavity. Comparing coarser grained Playa Garza to distinctly finer grained Playa Carrillo it was evident that the slopes at Playa Garza were greater than those at Playa Carrillo. Also comparing the two beaches, Playa Carrillo being in a less sheltered cove than Playa Garza, the difference in beach concavity was apparent, and it seemed that coarser grained, more obstructed Playa Garza showed more upward concavity in its beach profiles.

Because beach berms form at the furthest extent of wave action on the beach face, they are particularly sensitive to relative changes in sea level, such as that caused by coseismic uplift. This study showed that a distinct two-berm signature formed on many beaches in response to coseismic uplift, and suggests that this geomorphic indicator is an easily obtainable proxy for tectonic uplift. Because beach morphology is a net result of a highly dynamic system operating under a suite of controls (e.g., tidal changes, wave energy, sediment grain size, etc.), beach geomorphic measurements include significant uncertainties. Although the uncertainty in geomorphic measurements of berm offsets and debris lines is greater than that obtained in high-resolution GPS measurements, the overall magnitude and spatial trends in uplift can be recorded with moderate accuracy using these methods. To best constrain coastal uplift using beach geomorphology, measurements in a particular study area should include a variety of beach environments with differing slope, aspect, grain size, and sediment supply in order to isolate the impact of multiple controls on beach morphology.

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