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COASTAL UPLIFT AND MORTALITY OF INTERTIDAL ORGANISMS FROM A 7.6 MW EARTHQUAKE, NICOYA PENINSULA, COSTA RICA

CLAIRE MARTINI, Whitman College
Research Advisors: Kevin Pogue and Bob Carson

INTRODUCTION

Coastal uplift produced by the Mw 7.6 Costa Rica earthquake of 5 September 2012 caused widespread mortality of intertidal organisms along the central coast of the Nicoya Peninsula. Preliminary measurements of this die-off were made as part of post-earthquake geomorphic fieldwork that documented the distribution and magnitude of coastal uplift (Marshall et al., 2013). These geomorphic measurements, coupled with geodetic data from the Nicoya GPS network (Protti et al., 2014), show that coseismic deformation extended along ~80 km of coastline, with pronounced uplift of ≥ 0.4 m along the central 30 km. The goal of this study is to further examine the intertidal mortality along this zone in order to provide additional detailed constraints on coseismic coastal uplift.

At the seismically active subduction interface of the Nicoya Peninsula, the Cocos Plate subducts beneath the Caribbean Plate at about 8.5 cm/yr. Prior to 2012, the last major rupture of the Nicoya seismogenic zone was an Mw 7.8 earthquake in 1950 (Protti et al., 2001). That earthquake generated significant coseismic coastal uplift, followed by several decades of interseismic subsidence (Marshall and Anderson, 1995). Leading up to the 2012 event, global positioning system (GPS) geodesy was used to identify a locked patch, approximately 60 km in length along strike (Feng et al., 2012). The 5 September 2012 earthquake occurred directly under the Nicoya Peninsula, rupturing the lateral and down-dip extent of the previously locked plate interface (Yue et al., 2013; Protti et al., 2014).

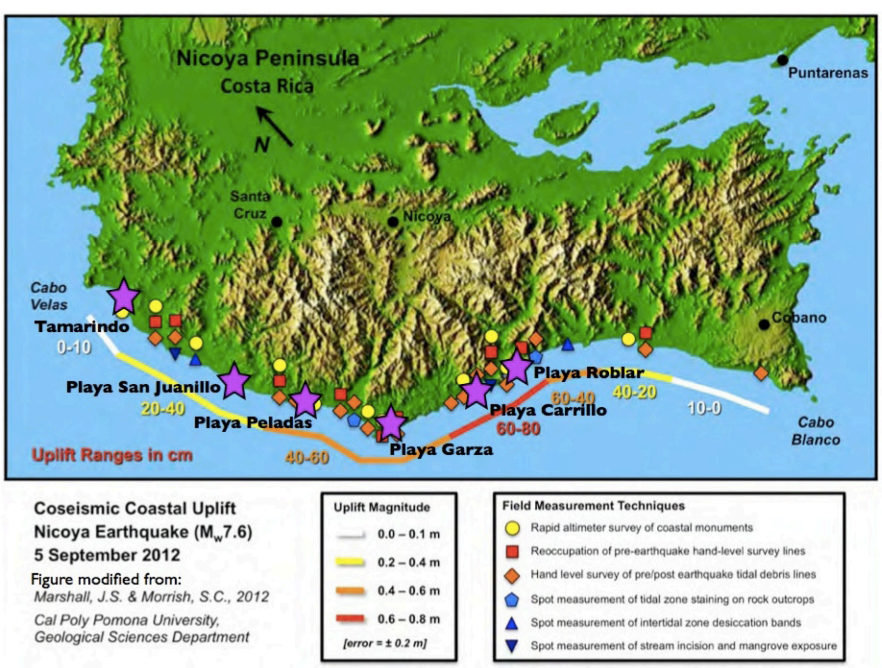

Figure 1. Uplift along the Nicoya Peninsula. Stars represent study sites along the coast of the Nicoya Peninsula. Playa Carrillo is onshore of the rupture patch in the 2012 earthquake; the epicenter was off Punta Guiones, just west of Playa Garza. Note that tide gauge used for MSL calibration is in Puntarenas, and although not located on the peninsula, tides are accurate for the Nicoya coast. (After Marshall and Morrish, 2012.)

Within the surveyed area, GPS indicated that uplift ranged from less than 10 cm to about 60 cm. No subsidence was observed on the Pacific coast of the Nicoya Peninsula. These observations are consistent with models of tectonic deformation that result from subduction at the Middle American Trench. The Nicoya Peninsula occupies a high-potential seismic gap, with seismic cycle deformation recurring approximately every 50 years; the net uplift and topographic relief observed on the Peninsula likely result from seismic cycle strain and crustal thickening due to tectonic erosion and underplating (Marshall et al., 2012).

BIOMARKERS

Intertidal organisms have been used to measure uplift in Chile (Saint-Amand, 1961; Plafker and Savage, 1970; Castilla, 1988), Alaska (Plafker, 1965 and 1969), Mexico (Bodin and Klinger, 1986), California (Carver et al., 1994). Bodin and Klinger (1986) defined the range of intertidal die-off from coseismic uplift as the "vertical extent of mortality" (VEM).

In this study, VEM measurements were recorded at seven coastal field sites to estimate the magnitude of coseismic uplift along rupture area of the Nicoya seismogenic zone. Field measurements, photographs, and eyewitness accounts of intertidal mortality recorded two weeks after the earthquake in September 2012 (Marshall et al., 2013) were compared with spot measurements, surveys, and population counts taken during this Keck Project in June-July 2013. The VEM was measured by surveying the vertical distribution and mortality of selected biomarkers on rocky platforms and headlands. To characterize earthquake-related mortality in the intertidal zone, the VEM of three sessile species was measured: a clam (Chama echinata), the ribbed barnacle (*Tetraclita stalactifera*) and green crustose algae (Sibaja, 2006).

Chamidae, commonly known as "jewel box" clams, are a family of saltwater clams endemic to tropical waters near Costa Rica (Sibaja, 2006). The jewel boxes are readily identifiable due to lurid coloration and distinctive flattened spines, irregularly arranged in radial rows. Clams attach to the rock by their left anterior valve, with the surface of the right valve covered with close-set, small spines. These clams are adapted to water with little suspended material, and are cemented to massive rocks in exposed areas from the low intertidal zone to a depth of several meters. *Tetraclita stalactifera* , the ribbed barnacle, has distinctive conical to tubular morphology, with calcareous plates. It lives in the upper to mid intertidal range (Sibaja, 2006). As observed on the Nicoya Peninsula, microhabitat distribution and wave geometry impact the settlement patterns of all populations of biomarker species. Recolonization rates of a microalga after uplift in central Chile were found to be in excess of 1 year (Castilla and Oliva, 1990).

Semi-diurnal tides in Costa Rica have a maximum range of 3.5 m. It was assumed that intertidal organisms prefer to occupy roughly the same elevation above Mean Sea Level (MSL measures mean sea level as an average of low and high tides), throughout their geographic distribution on the Peninsula. Because each species has a maximum duration of emergence (the amount of time it can exist out of the water at low tide), populations have a distinct upper boundary. When an organism is found far above its normal range, it is likely due to coseismic uplift.

STUDY SITES AND LITHOLOGY

Study sites spanned almost 40 km on the Pacific coast of the Nicoya Peninsula. From north to south, the sites surveyed were Tamarindo, Playa San Juanillo, Playa Peladas, Playa Garza, Playa Carrillo, and Playa Roblar. These sites (Fig. 1) span the full range of coseismic uplift as measured by post-earthquake fieldwork and GPS stations (Marshall et al., 2013; Protti et al., 2014). With the exception of Playa Peladas and Playa Garza (upper Cretaceous to Paleogene deep-sea sedimentary strata), the substrate at all sites consisted of Nicoya Complex basement rocks (Jurassic-upper Cretaceous basalts, gabbros, and plagiogranites) (Dengo, 1962). We noted little difference in the abundance of intertidal species between basaltic and sedimentary substrate.

METHODS

The upper and lower extents of the three biomarker species were surveyed using a laser rangefinder. Mortality counts were conducted by hand, within a 25x25 cm square grid placed randomly at different

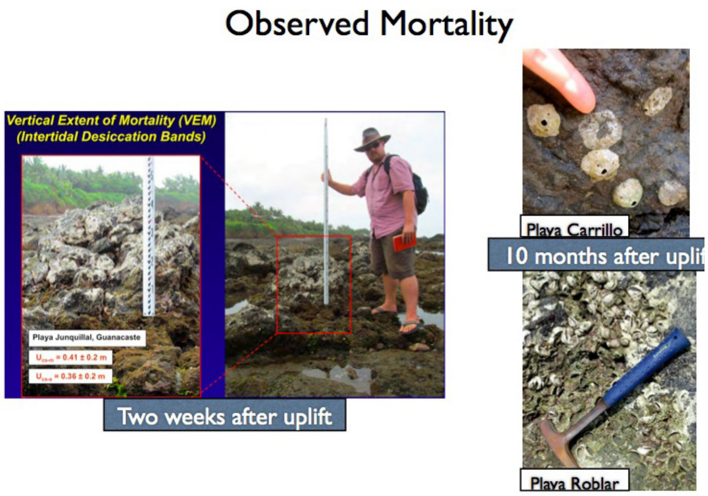

Figure 2. On the left, Marshall and Morrish measure a white desiccation band during rapid response surveys two weeks after the earthquake (after Marshall, 2012). 10 months after uplift, mortality of barnacles is evident as calcified rings ("scars"), from Tetraclita stalactifera, shown at Playa Carrillo with a finger for scale. Lower right photo depicts 100% mortality of bivalves at Carrillo. Also note the presence of live algae (green color) in the bottom of the photo, versus the bleached white shells and algae near the handle of the rock hammer.

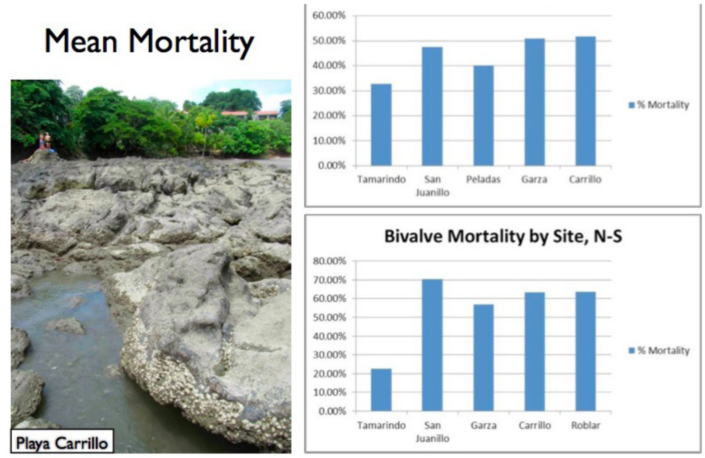

Figure 3. Barcharts illustrate the mean mortality of intertidal organisms. Both bivalves and barnacles show significant post-earthquake mortality on uplifted wavecut platforms (see photograph). The surveys of Tetraclita stalactifera have a smaller sample size (larger organism and less dense colonies mean fewer individuals fell within the sample square), and may be less statistically significant. Also, the mean mortality of barnacles at Peladas may be lower because of a higher proportion of samples taken at the bottom of the barnacle range.

sites to characterize intertidal "dead zones" (Fig. 2). Our reference point (null site) was surveyed at Tamarindo, on a rocky intertidal platform that was uplifted <10 cm in the 2012 earthquake (Marshall et al., 2013).

DATA ANALYSES

Surveys were calibrated to mean sea level (MSL, an average of high and low tides) by taking a data point at the current tide and using time of day and a sine function to recreate the tidal cycle. Mortality was calculated as the proportion of dead organisms relative to the total. For barnacles, "scars" were counted as dead organisms (Fig. 2); because the scars were more abundant at the top of the range of *Tetraclita stalactifera* (and absent at Tamarindo), we assumed that if an organism died shortly after being uplifted out of its range, the intense wave action could conceivably knock the empty shell off the rock between date of death and survey date (survey date was up to 10 months after the earthquake).

RESULTS

A profile of each study site was constructed using elevation data, tide calibrations, and mortality surveys. Figure 4 shows normal ranges, surveyed at Tamarindo. At the survey site unaffected by uplift, the mean mortality of the barnacles that populate the upper intertidal zone was 36%. The lower half of the intertidal zone, populated by jewel box clams, had mean mortality of 54%. Using this data as a reference for normal ranges and mortality, abnormal mortality likely due to uplift was defined as mortality above 36% for barnacles and greater than 54% for bivalves. At each survey site, mean mortality of the population was greater than that of the population at Tamarindo (Fig. 5).

In addition to bivalves and barnacles, a notable biomarker was an orange-tan band of dead algae (Fig. 6). The band occupies the former high-tide range, and is interpreted as a high-tide desiccation band. This desiccation band was used as a direct indicator marking the zone of coseismic uplift (Fig. 7). The width of the band corresponds directly to the vertical magnitude of uplift. Likely because of variation in beach morphology, the desiccation band was most apparent at Playa Peladas and Playa Garza (rocky intertidal platforms with significant and regular vertical relief). In other survey locations where the wavecut platform terminated in beach sand or a distal cliff face, beach morphology was thought to prevent the growth of significant algal mats that could be used to measure uplift.

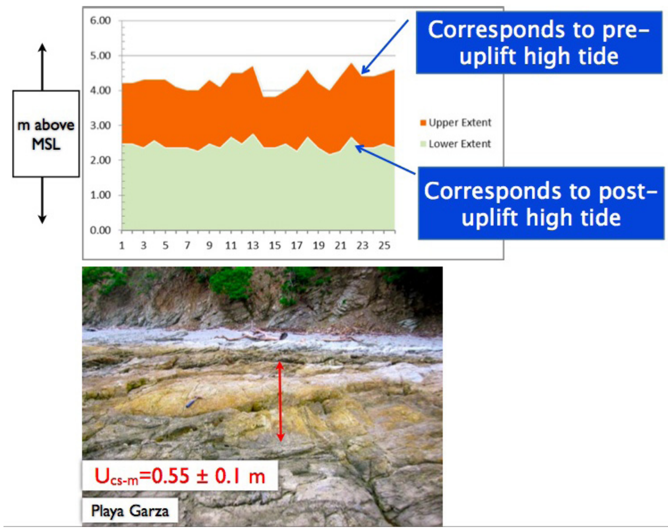

Figure 4. Photo of high tide desiccation band. Though it appeared a subtle orange at the time of the surveys, when observed two weeks after the earthquake this band consisted of a distinct white zone of dead algae. Graphic depicts upper and lower extent of high tide desiccation band at Playa Garza. The Y axis represents elevation above MSL in meters. Note that the lines connecting the points of the upper boundary and lower boundary vary together. Because wave geometry is largely the same as before coseismic uplift, the new high tide line mimics the old.

Because both geomorphic and GPS measurements of uplift (Marshall et al., 2013; Protti et al., 2014) exceed the measured extent of mortality at Playa Peladas, Playa Garza, Playa Carrillo, and Playa Roblar, we propose that the measured VEM estimates minimum uplift. In these places, the pre-earthquake range of these organisms was less than the vertical magnitude of uplift. Carver et al (1992) proposed that VEM could be called "minimum limiting" in these situations. Figure 8 summarizes VEM-measured uplift versus GPS-measured uplift by site.

DISCUSSION

In the field, several possible confounding variables were observed, including pollutants in the water (sewage effluent pipes near study sites), turbidity, and human gathering of shellfish (for example, oysters were not deemed to be a viable biomarker because of their popular use in local cuisine). We presume that after uplift has shifted organisms out of their range, re-colonization will occur; however, significant colonization of barnacles, bivalves, or algae is unlikely within the 10 month window between coseismic uplift and most of our surveys.

Results

Study Site and Biomarker Measure	GPS Uplift (m)	VEM Uplift (m)	Notes
Tamarindo	<0.1	0	Null site
San Juanillo Barnacles	0.2-0.4	0.41 +/- 0.1	VEM corresponds with GPS
Playa Peladas Desiccation Band	0.4-0.6	0.57 +/- 0.1	VEM corresponds with GPS
Playa Garza Desiccation Band	0.4-0.6	0.55+/0.1	VEM corresponds with GPS
Playa Carrillo Barnacles	0.6-0.8	0.4 +/- 0.1	Likely a minimum; uplift may exceed VEM
Playa Roblar Bivalves	0.4-0.6	0.4+/-0.1	Likely a minimum; uplift may exceed VEM

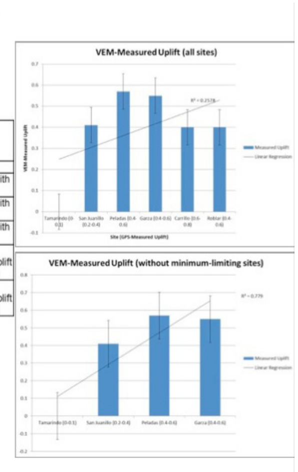

Figure 5. GPS-measured uplift compared to VEM-measured uplift shows that some sites were minimum-limiting. Top right shows measured uplift for all sites (including Playa Carrillo and Playa Roblar, sites found to be minimum-limiting). Bottom right shows measured uplift at sites where vertical magnitude of uplift is less than or equal to the extent of biomarkers.

Complex swash and splash patterns on rocky intertidal areas influence the distribution and elevation of biomarkers. We observed the jewel box clams living in cracks, fractures, and tide pools, moist places in which they can avoid desiccation during maximum exposure at lowest low tides.

To ascertain correlation between VEM and previously measured uplift using GPS and rapid-response geomorphic data (Fig. 9), we calculated an r^2 value of about 0.26, indicating weak correlation between VEM and GPS-measured uplift for all data sites measured. However, when minimum-limiting sites Playa Carrillo and Playa Roblar are excluded from the plot of measured uplift (Fig. 10), r^2=0.78, indicating strong correlation between observed VEM and GPS-measured uplift. When biomarker organisms occupy a wide vertical range, observed mortality correlates to vertical magnitude of uplift recorded by GPS.

CONCLUSIONS

This study uses biological markers to measure coseismic uplift from the 2012 Mw7.6 Nicoya Earthquake on the Pacific coast of Costa Rica. Measuring the mortality and vertical extent of the ribbed barnacle, jewel box clam, and a crustose algae, we find that observed mortality correlates strongly with prior measured vertical uplift (geomorphic and GPS). This technique may be used in the future where organisms occupy a significant vertical range in the intertidal zone to create more detailed models of local uplift, with particular utility in Costa Rica for the study of shallow near-shore subduction earthquakes.

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