A Study of Marine Terrace Formation Along the California Central Coast

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By

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ABSTRACT

Marine terrace formation is in many instances attributed to wave action, and shore platforms are often called "wave-cut". However, alternative models for marine terrace formation suggest that other types of physical and chemical weathering have a more central role in the formation of marine terraces than is widely acknowledged. Roering and Retallack (2012) concluded that the roles of subaerial physical and chemical weathering are significant, and played a major role in the formation of the terraces. In this study, weathering of beach cliffs and shore platforms associated with marine terraces at eight sites in two different locations along the central California Coast is assessed, and results are compared to those of Roering and Retallack.

Findings for rock hardness along the profile of modern shore platform and cliff face are similar to the results from the Roering and Retallack study: the Schmidt rock hardness of cliff faces within the bottom 1.5 meters above the modern shoreline angle are significantly lower than the rock hardness of the shore platform. Oxidation color of shore platforms, assessed using a Munsell color and described in Munsell color notation, is consistently within the Gley 1 range in both study areas. Beach cliff oxidation color varied from Gley to colors indicating oxidation. Oxidation on beach cliffs was more prevalent within the upper half meter of the part of the beach cliff that was sampled, and oxidation within fractures and cracks was also apparent in some cliff faces.

INTRODUCTION

Marine terraces are significant to geologic study in part because of the implications of their formation. Paleo-shoreline angles and relict wave cut notches of marine terraces are generally accepted within the geologic world as indicators of past sea level in tectonically active areas. Cogency of these indicators comes from the acceptance of traditional wave-cut model for marine terrace formation, in which the denudation of cliff faces and modern shore platforms is attributed primarily to wave action. In the wave-cut model, the formation and propagation of a new modern shore platform is a response to rises in sea level and tectonic uplift. During post-glacial periods of high sea level, such as in modern times, waves carve out the base of a beach cliff, resulting in mass wasting events. Debris from mass wasting events, and from the weathering of shore platform bedrock, is removed by waves and currents. Shore platforms are abandoned and new modern shore platforms develop when tectonic uplift is faster than the rate of beach cliff retreat. Contributions of different marine related denudational processes to formation of marine terraces has been noted in studies and descriptions of the wave-cut model, such as by Beirman and Montgomery (2012, Pg.265):

> "Wave cut platforms are maintained by a number of processes, including erosion from wave action, the abrasive effect of suspended and bed sediment on the bedrock, and waves sweeping away the weathering products that result from the mechanical and chemical disintegration of coastal bedrock that has been exposed to repeated wetting and drying in the surf zone."

Whereas the biochemical role of subaerial wet-dry cycling in breaking up the shore platform has been noted, it has traditionally been believed that the physical break up of rock driven by wave action is the most significant means of denudation. This assertion has been tested and supported in studies attempting to assess the role of subaerial weathering versus wave action. For example, one study done on Old Hat Island shore platform formation in New Zealand found that there is no substantial difference between the degree of weathering of beach cliffs and shore platforms, and no clear relation between subaerial weathering and shore platform formation. Old Hat Island shore platform formation is a function of a platforms exposure to wave energy, the rate of weathering, nearshore water depth, and rock resistance (Kennedy, 2010).

In addition, application of wave energy models (Trenhaile, 2008, 2010), storm surge models (Bartrum, 1935), differences in shore platform saturation (Trenhaile and Mercan, 1984; Trenhaile and Porter, 2007), and erratic Schmidt hammer rock hardness values in a shore platform study were determined to support wave action is the primary means of shore platform formation (CITE). Despite support for the wave-cut model of marine terrace formation, contention over the validity of the wave-cut model of marine terrace formation, centering around the extent of the role that differential, largely terrestrial subaerial biochemical weathering has in the formation of marine terraces, is long standing within the geologic community (Retallack and Roering, 2012). Evidence supporting weathering processes as the most dominant process shaping shore platforms, and alternative models explaining marine terrace formation have been put forth.

In a study of marine terraces along the Oregon Coast, a significant difference in the hardness of cliff faces and shore platforms was documented (Retallack and Roering, 2012), a result that differs from results culled from areas like the old hat islands, where the hardness of cliff rock and shore platform bedrock were very similar. It is asserted that a significant difference in the hardness of cliff faces compared to shore platforms is evidence that subaerial weathering plays the central role in marine terrace formation (Retallack and Roering, 2012). A model for marine terrace formation is proposed in which differential subaerial weathering plays a more prominent role than wave action in sculpting shore platforms (Retallack and Roering, 2012). Previous studies also propose similar models of marine terrace and shore platform development based on evidence similar to Retallack and Roering (2012), including the following: (1) the dominance of weathering in the formation of coastal shore platforms in the weathering in flanking cliffs (Bartrum, 1916; Berryman, 1993); (2) diminished energy of waves on platforms, patterns of differential rock strength by Schmidt hammer (Stephenson and Kirk, 2000; Kennedy and Beban, 2005); and (3) rock platforms in estuaries and bays protected from ocean waves (Hills, 1949; Kennedy and Paulik, 2006). In the model, modern shore platforms are weakened by differential chemical weathering. When a platform is eroded down to the modern groundwater table, erosion slows because the bedrock of the shore platform is no longer being subjected to weathering from wet dry cycling. Eventually, the water-table shore platform is abandoned, and a new terrace begins to form because uplift is occurring faster than weathering and erosion (Retallack and Roering, 2012). Retallack and Roering (2012) found that there was a decrease in rock hardness above the zone of frequent wet and dry cycling, and conjecture that rock above this zone of fluctuation is weakened by subaerial weathering.

The purpose of this study is to test the validity of the Roering and Retallack (2012) model of marine terrace formation along the California Central Coast, and to determine whether the formation of marine terraces is primarily due to subaerial weathering or wave action. This was achieved through study of marine terraces at Rancho Marino Reserve in Cambria and in Harmony Headlands State Park, San Luis Obispo County. Two types of data also analyzed in Roering and Retallack (2012): Schmidt hammer rock hardness, and Munsell color of the rocks that compose the shore platforms and beach cliffs.

Location and Relevant Geology of Study Sites

Marine terrace formation along the San Luis Obispo County coast, in Cambria and Cayucous, is driven by tectonic convergence occurring along the San Andreas fault, and resulting uplift of coastal areas (Lettis and Hanson, 1992). Marine terraces in Harmony Headlands and the Kenneth S. Rancho Marino Natural Reserve are primarily formed in greywacke sandstone, in association with Jurassic-Crestaceous age Franciscan complex mudstone that is locally emplaced into the sandstone as diapirs (Hall et al, 1979; Becker and Cloos, 1985). In both areas, beds of greywacke sandstone are mostly pitched along a steep dip. Sedimentary landslide deposits can be found around stream inlets. These areas of sediment deposit, and outcroppings of the Franciscan Complex mudstone of mudstone, were not tested for Schmidt hammer rock hardness in this study (Figure 1). Uplift rates along the studied coastline are between 0.01-0.09mm/yr since c.125 ka. (Stokes and Garcia, 2009)

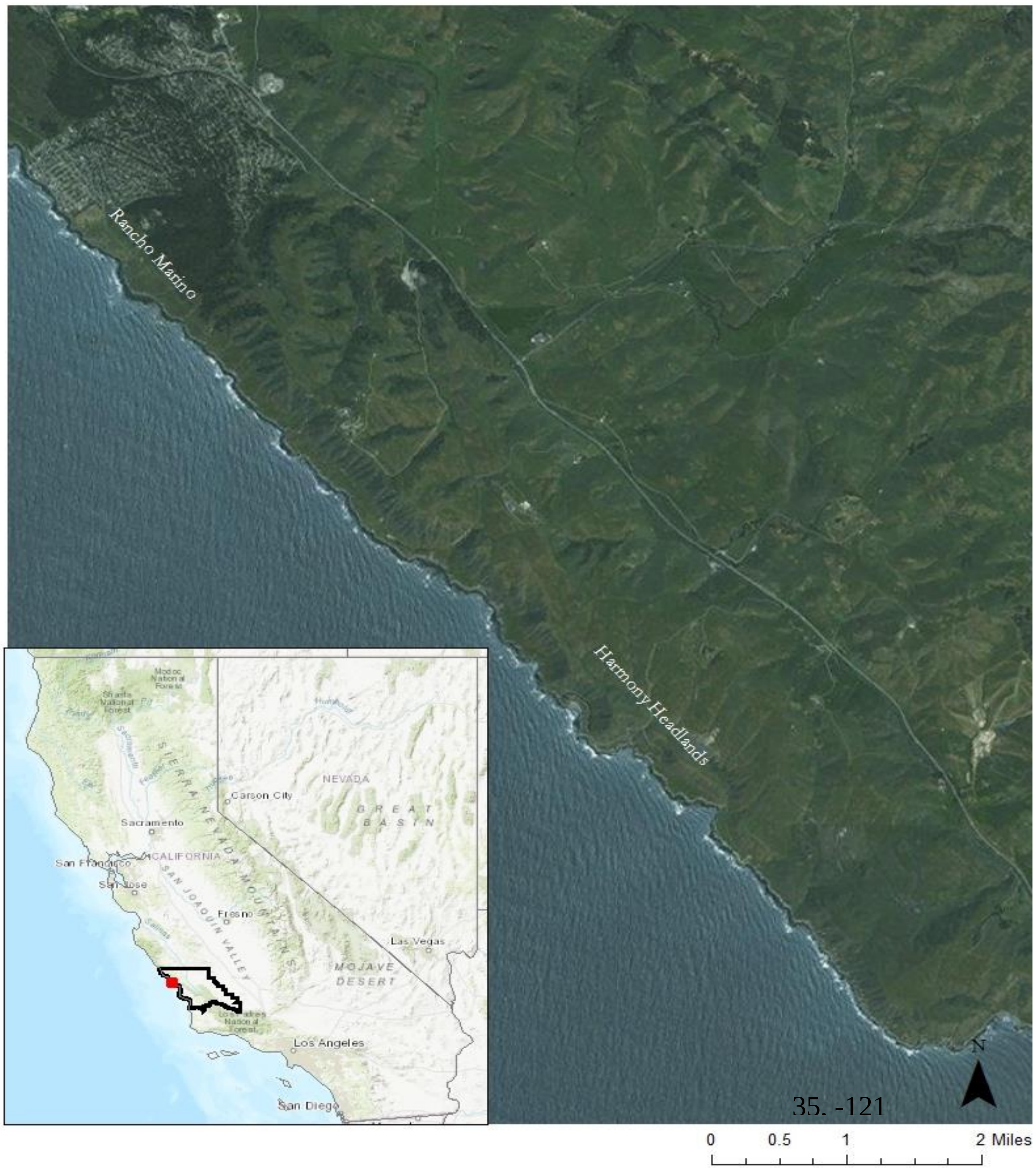

Figure 1. Area map showing location of San Luis Obispo County on the California coast (outlined in black on the map). The red square on the map indicates the area depicted in the aerial view of the 2 study areas.

METHODS AND MATERIALS

Comparing the Degree of Weathering of Shore Platforms and Beach Cliffs

In the differential weathering model of marine terrace formation proposed by Roering and Retallack, it is asserted that observed differences in the strength of the shore platforms and beach cliffs are evidence that differential weathering plays a significant role in marine terrace formation. It is stated that If rock platforms are cut by waves alone, no difference in weathering or strength of the platform and cliff would be apparent. (Retallack and Roering, 2012)

In their study, Roering and Retallack tested differences in weathering between beach cliffs and shore platforms in Sunset bay, Oregon, using two indicators of weathering: rock strength and oxidation colors. In this study, the Schmidt rock hardness test is used to assess differences in strength between the shore platform and beach cliffs of marine terraces, and a standard Munsell Color book was used to assess color of shore platforms and beach cliff (Munsell Color, 1975). Oxidation color of the cliff face and bedrock provides qualitative evidence of weathering differences between the cliff face and shore platform.

Schmidt Hammer Rock Hardness

Originally developed to test the strength of concrete, the Schmidt hammer rock hardness test has become a widely accepted method of quantifying the hardness of rocks (Selby, 1982). Schmidt hardness (*R*) was collected through the application of an N-Type Schmidt hammer. Schmidt hammers measure the distance of rebound from the impact of a spring-loaded piston hitting a hard surface. (Selby, 1982, p.63) In this study, Schmidt rock hardness of the hammer is reported as "N-Type Schmidt Hammer Rock Hardness" rather than converting to newtons (N), which is a widely accepted practice (e.g., Selby, 1982; Retallack and Roering, 2012). The hardness of each cliff face site was tested within the lower 1.5 meters of the modern shoreline angle, where the base of the cliff meets the modern shore platform. Rock hardness of the shore platform sites was tested within 6 meters of the modern shoreline angle.

Oxidation Color

Like the Schmidt hammer rock hardness test, the Munsell color book was not developed for geological application. It was originally used, and still most commonly used, to characterize soil, but has been adopted as a widely accepted tool in Geology. Assessments of rock color in this study are described in the standard Munsell color format.

RESULTS

Mean Schmidt Hammer R-Values

All beach cliff measurements were made between 1 to 1.5 M above the high tide line as denoted by the coastward extent of rounded gravel on the shore platform. All beds on which measurements were made dip steeply, and are composed solely of sandstone. Each cliff face ("CF *n*") corresponds with a shore platform site in the nearby area. For example, CF 1 measurements were taken in the same general location as SP 1. Twenty five measurements were made at each CF *n* and SP *n* site, except at CF 2 Harmony Headlands, 23 measurements were made, and SP 4 at Rancho Marino, where 20 measurements were made.

Harmony Headlands: Beach Cliff Face

Site	N Type Schmidt Hammer Rock Hardness
CF 1	34.40
CF 2	41. 61
CF 3	31.24
CF 4	42.24
CF 5	29.84
CF 6	42.00
CF 7	35.16
CF 8	30. 36
Overall Mean:	**35.81**

25 measurements were made at each site, except CF 2 where 23 measurements were made

Harmony Headlands: Shore Platform

Site	N Type Schmidt Hammer Rock Hardness
SP 1	43.24
SP 2	38.88
SP 3	44.36
SP 4	43.56
SP 5	49.88
SP 6	52.28
SP 7	46.04
SP 8	49.33
Overall Mean:	**45.95**

25 measurements were made at each site

Rancho Marino: Beach Cliff Face

Site	Mean N Type Schmidt Hammer Rock Hardness
CF 1	22.08
CF 2	22.52
CF 3	23.65
CF 4	29.16
CF 5	26.16
CF 6	35.68
CF 7	33.84
CF 8	38.18
Overall Mean:	**28.91**

25 measurements were made at each site

Rancho Marino: Shore Platform

Site	Mean N Type Schmidt Hammer Rock Hardness
SP 1	59.80
SP 2	55.24
SP 3	38.18
SP 4	48.60
SP 5	44.12
SP 6	50.52
SP 7	54.33
SP 8	46.44
Overall Mean:	**49.65**

25 measurements were made at each site, except CF 2 where 23 measurements were made

Munsell Color

Colors Each Cliff Face site corresponds with a shore platform site in the nearby area. For example, CF 1 Munsell color was taken in the same general location as SP 1.

Harmony Headlands: Beach Cliff Face

Site	Munsell Color
CF 1	Gley1 5/10Y
CF 2	Gley1 5/10Y
CF 3	Gley 1 6/10Y, upper 1/4 m 2.5Y 1/4
CF 4	Gley 1 6/10Y
CF 5	Gley 1 6/10Y, fractures, exhumed surfaces and upper 1/4 m 2.5Y 5/4
CF 6	2.5Y 5/4
CF 7	Gley 1 6/10Y
CF 8	Gley 1 6/10Y

Harmony Headlands: Shore Platform

Site	Munsell Color
SP 1	Gley1 5/10Y
SP 2	Gley1 5/10Y
SP 3	Gley 1 5/10Y
SP 4	Gley 1 4/10Y
SP 5	Gley 1 4/10Y
SP 6	Gley 1 4/10Y
SP 7	Gley 1 4/N
SP 8	Gley 1 5/N

Rancho Marino: Beach Cliff Face

Site	Munsell Color
CF 1	2.5y 5/4
CF 2	2.5y 5/4
CF 3	Gley 1 5/10YR, 2.5 Y 5/3 *
CF 4	Gley1 3/10Y
CF 5	2.5Y 5/3 upper 1 -1.5 m of outcrop, Gley 1/4 N lower 1m of outcrop
CF 6	Gley1 4/N
CF 7	Gley1 4/N
CF 8	Gley 1 5/10YR
	* = Fractures and Exhumed features

Rancho Marino: Shore Platform

Site	Munsell Color
SP 1	Gley1 3/10 Y
SP 2	Gley1 3/10 Y
SP 3	Gley 1 4/N
SP 4	Gley 1 4/N
SP 5	Gley 1 4/N
SP 6	Gley 1 4/N
SP 7	Gley 1 4/N
SP 8	Gley 1 4/N

DISCUSSION AND CONCLUSIONS

Mean Schmidt hammer rock hardness from test sites in Harmony Headlands and Rancho Marino suggest a distinct discontinuity between the cliff face and the shore platform: shore platforms are generally harder than beach cliff bedrock above the shoreline angle. There is variability in the hardness of shore platforms and cliff faces, but mean cliff hardness is lower than mean shore platform hardness in every site studied. This result is in congruence with the findings of Retallack and Roering (2012), in which Schmidt hammer rock hardness declines abruptly at the break between the beach cliff and shore platform, and platform hardness is high and variable while cliff hardness remains uniformly low. In Sunset Bay, Oregon, Schmidt hammer rock hardness declines abruptly above the shoreline angle of the shore platform and cliff. Platform hardness in sunset bay was high, but variable, while cliff hardness was uniformly low (Retallack and Roering, 2012)

Oxidation within the upper fractures of cliff rock, and uniform gley color of the shore platform at Rancho Marino and Harmony Headlands sites are similar to those reported for Sunset Bay, Oregon (Retallack and Roering, 2012). However, the variance in the oxidation color of beach cliffs is greater in Rancho Marino and Harmony Headlands than it is at Sunset Bay, Oregon (Retallack and Roering, 2012). Despite the relative congruence of this study's findings to those of

Roering and Retallack, whether or not paleo-shoreline angles can be assuredly correlated with paleo-water table height is unclear in this area. In the Roering and Retallack model it is proposed that erosion slows when a shore platform grades to mean water table level because the bedrock of the shore platform is not subjected to wet dry cycling. In Rancho Marino and Harmony Headlands, it is not clear whether abandonment of shore platforms can be attributed to this model, or to increased rates of uplift that exceed the rate of a shore platforms inland propagation, causing abandonment.

Whether marine terrace formation in Rancho Marino and Harmony Headlands can be attributed primarily to subaerial weathering remains dubious. In the model of Retallack and Roering (2012) it is suggested that a marine terrace cliff erodes faster than the shore platform because it is more weathered than the shore platform, and that debris from mass wasting of marine cliffs, and debris from differential wet/dry weathering on the shore platform is moved by the waves. However, is a difference in rock hardness truly indicative that this model is widely applicable? A difference in rock hardness between the cliff face and shore platform where the cliff face exhibits a greater degree of weathering could potentially be a result of wave action stripping weathered rock away from the shore platform faster than weathered rock is stripped from the beach cliff. In this case, differential weathering is due simply to the shore platform being exposed to more consistent and energetic wave action than the beach cliff. Differential weathering of the shore platform and beach cliff is not the mechanism that determines the positions of the shore platform and the beach cliff at the coastline, it is the result of the positions of the shore platform and the beach cliff at the coastline. As such, it may be incorrect to assume that measured differences in strength and color between the shore platform and beach cliff are sufficient enough evidence to determine a dominance of subaerial weathering over wave action in marine terrace formation along the California Coast. Further study of the sites, including a test of beach cliff rock hardness following a mass wasting event on the site, might provide some greater insight into the mechanism shaping terraces along the Central Coast.

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