Using marine terraces to determine tectonic uplift rates and patterns on the Gualala block, California: Gualala to Point Arena

Stacy F. Tellinghuisen
Department of Geology, 1 N. College St., Carleton College, Northfield, MN 55057
Faculty Sponsor: David Bice, Carleton College

INTRODUCTION

Geologic Setting. The San Andreas Fault (SAF) system displays predominantly strike-slip motion, but also has smaller components of compressional and extensional motion. As the SAF system grew, it captured pieces of the North American continental crust; the Gualala block is one of these captured slivers of continental crust. Uplift has created a series of emergent marine terraces on the Gualala block; each of these terraces formed at a sea level highstand. We mapped and then correlated the terraces to sea level highstands to determine the rates and patterns of uplift on the Gualala block.

The paleo-marine terraces on the Gualala block are broad platforms that extend laterally along the coast, are bounded by steep risers or cliffs on the seaward and inland sides, and are covered by a thin veneer of marine deposits including marine sands and small, rounded quartzose pebbles. The presence of these deposits supports the identification of terraces as marine, rather than fluvial. The soil cover and weathering of the youngest terraces is minimal (generally, bedrock is not deeper than two meters below the surface); older terraces have more extensive weathering and a thicker soil cover. As terraces age, weathering, erosion, landslides, and streams blur the distinction between terraces and the location and elevation of inner edges become more difficult to identify.

METHODS

In the field, the main goal was to locate and map series of terraces using Trimble Global Positioning System (GPS) equipment. My field partners and I sought transects that had as many terraces as possible, in hopes of getting a complete sequence of preserved terraces. Nine transects that spanned the 25 km northern section of the Gualala block were selected and mapped (figure 1). As we surveyed, we noted the most important, characteristic terrace features, including inner edges, mid-risers, outer edges, and mid-treads. Of these points, the inner edge elevation was the most crucial, because inner edges form at the best approximation of mean sea level. Therefore, this point is the most accurate point to correlate to a sea level highstand. In addition, we tried to find bedrock exposures or to estimate the depth from the surface to the bedrock platform. From these data, I extracted the elevation of the inner edge of each terrace in two ways: where possible, I used the actual data point that we collected in the field. In other cases, especially with older terraces, I projected the terrace slope back to an approximate bedrock inner edge, to account for deposition of material above the surface. By correlating terrace inner edges to sea level high stands, an uplift rate was determined for each transect. The uplift rates for the transects were then compared to determine an overall pattern of uplift of the northern Gualala block.

RESULTS

The transect data were analyzed, and elevations of terrace inner edges were correlated with sea-level highstands, building off of the known age of 80 ka for the lowest terrace. The sea level high-stands used include 80, 105, 124, 194, and 305 ka. For each transect, the elevation of each of the terraces is plotted against its assumed age in an uplift plot; the slope of this line provides the uplift rate for the series of terraces. Uplift rates vary between .47 and .65 m/ka along the coast.

Correlating Gualala Block Terraces with Sea Level Highstands. To correlate the terraces with a recently compiled sea level curve, I initially made several assumptions. First, I assumed that the lowest terrace on all transects (with the exception of the Curley Lane transect) was created from the same sea level highstand. This terrace can be followed laterally through most of this section of the Gualala block using aerial photos and topographic maps. Using U-series dating, two corals found at Point Arena have been dated to 76,000±4000 and 88,000±2000 yr (Muhs et al, 1994); therefore, the lowest terrace is correlated with the 80 ka sea level highstand.

I also assumed that the uplift rates have not changed over time. Without this assumption, older terraces could be correlated to any of the sea level highstands, because none of the older terraces have been dated. Having made this assumption, the second terrace correlates to the 105 ka highstand. The third terrace then correlates to the 124 ka highstand, a highstand that, due to its elevation above present sea level, left a prominent mark around the world by forming an especially broad terrace (Bordoni et al, 1998). These three youngest terraces have distinct

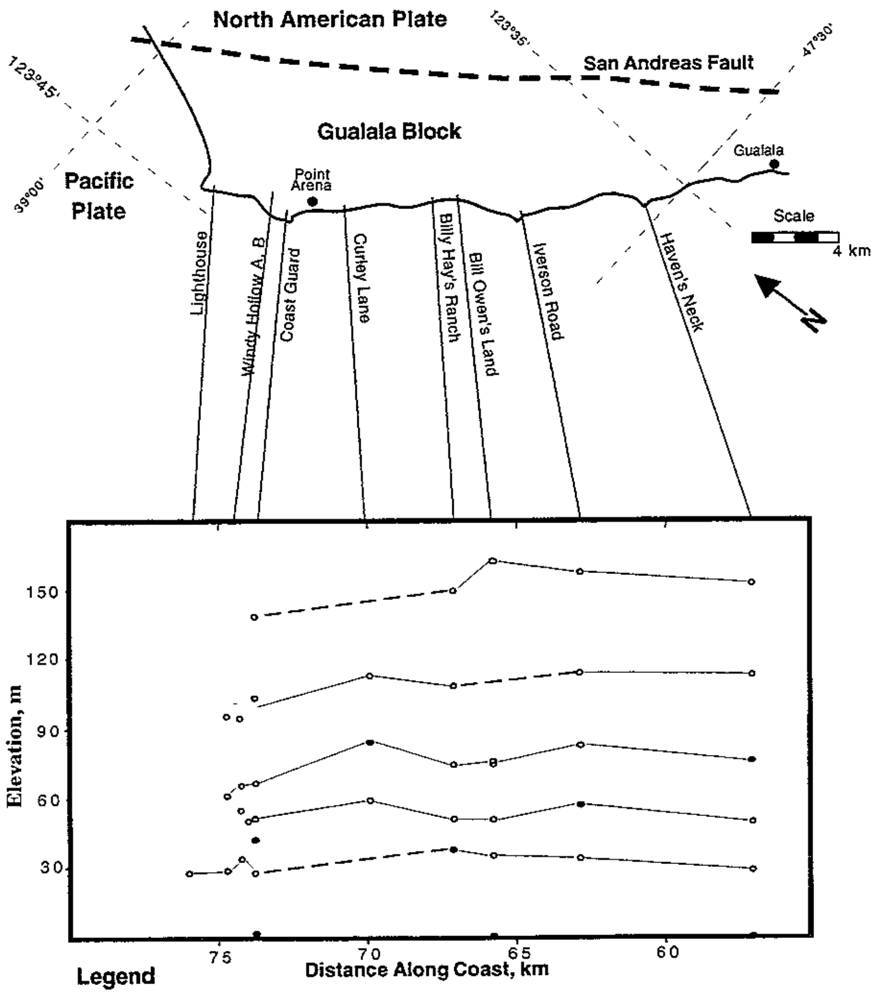

Figure 1: Locations of transects along coast of Gualala Block. On the graph, each vertical line of points is a transect; each point represents the inner edge of a terrace. Terrace inner edges are correlated laterally with thin lines. Figure adapted from Merritts et al (1989).

geomorphic characteristics, similar elevations and altitudinal spacing in all profiles, and when correlated to the sea level curve, fit a constant rate of uplift.

The older terraces become more difficult to identify, connect laterally to terraces in adjacent profiles, and correlate to a sea level curve. As before, I assumed a constant rate of uplift and that the fourth terrace in all profiles was formed during the same sea level highstand, based on its similar elevation. This terrace is difficult to follow laterally using aerial photos or topographic maps as a result of stream dissection and weathering, and does not have distinguishable geomorphic characteristics. Several sea level highstands exist to which the fourth terrace could be correlated. Based on the rate of uplift found using the three lowest terraces, the fourth terrace could have formed during either the 194 or 215 ka highstand, and still fit a nearly constant rate of uplift. The terrace could have formed during the 215 ka highstand and been reoccupied during the 194 ka highstand, a scenario that would have contributed to its more widely varied elevation and geomorphic characteristics.

The highest terrace surveyed, or the fifth terrace, becomes even more difficult to connect laterally and correlate to a sea level curve. In older terraces, the elevations of points are taken on thicker soil cover, and the depth to bedrock is undeterminable. Despite these uncertainties, I have correlated this terrace with the 305 ka highstand, 27 m below present sea level. From these correlations, an overall trend of uplift rates emerges: the rates gradually increase from the south to the north, dropping off sharply at the very northern end of the Gualala block (figure 2). Based on the information in Figures 1 and 2, this trend is disrupted locally; several areas appear to have been dissected by localized faulting.

Localized Tectonic Activity. Thrust faulting and folding is evident in cliff exposures of Miocene rocks

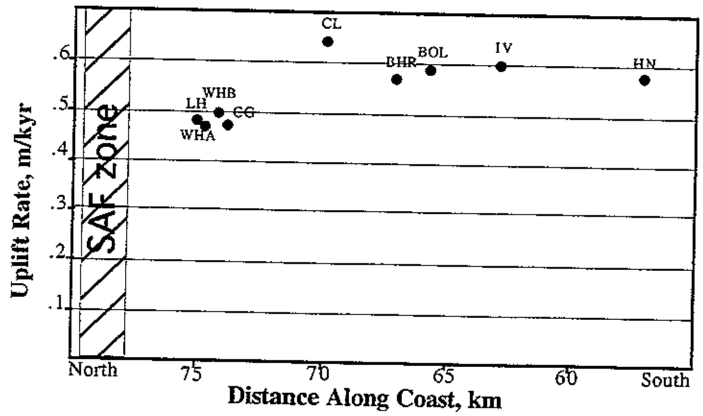

Figure 2: Uplift rates in the northern section of the Gualala block; notice how the rates decrease sharply near the SAF.

along the coast; this tectonic activity has been active in the Pleistocene, cutting marine terrace deposits at Point Arena. The elevation of the terraces at Billy Hay's and Bill Owen's ranches is consistently lower than the elevation of corresponding terraces to the north or south. The lowest, youngest terrace is the only exception; its elevation is equivalent to the elevations of the youngest terrace in nearby transects. Each of the older terraces is offset by approximately 10 m, starting with the second (105 ka) terrace. This suggests that tectonic activity has lowered the terraces locally, and occurred before the youngest terrace formed, 80 ka, but after the formation of the 105 ka terrace. Tectonic activity has also affected the terraces in the transect directly north of Billy Hay's Ranch, Curley Lane; the terraces in this area slope inland. At the northernmost end of the Gualala block, the elevations of the terraces drop, resulting in a decrease in uplift rates from .64 (uplift rate for an adjacent, unaffected transect to the south) to .47 m/kyr. Models for this tectonic activity will be proposed in the following section.

DISCUSSION

Overall Trends. Uplift along the Gualala block indicates that the San Andreas exhibits a small degree of compressional motion, rather than pure strike-slip motion. A small bend in the fault (northern end to the west) could potentially create compressional forces; alternatively, if the motion between the Pacific and North American plates is not purely transform, but has a component of compression, then the vertical orientation of the SAF could also affect uplift. At the Mendocino triple junction, the SAF makes a sharp bend to the left, potentially causing compression along the northern San Andreas.

In general, uplift rates in the northern section of the Gualala block increase from south to north. Along the Gualala block, the SAF and San Gregorio fault are combined. In northern California the San Gregorio fault has an orientation of 70 °, dipping to the east, and has a significant component of transpressional motion along it (Anderson et al, 1994). Although this dip suggests that compression would cause uplift of the land on the North American plate rather than uplift on the Gualala block, thrust faults splaying off of the main SAF could also cause uplift on the Gualala block. I find this a better explanation of the cause of uplift on the Gualala block than the bend in the fault at Punta Gorda.

Terrace Displacement at Transects Billy Hay's Ranch (BHR) and Bill Owen's Land (BOL). Along the transects at BHR and BOL, the terraces older than 80 ka have lower elevations than equivalent terraces in adjacent transects; I propose that conjugate thrust faults on the northern and southern ends of the BHR and BOL transects have caused that section to have a relatively lower elevation. Because the youngest, 80 ka terrace in this section is continuous with the 80 ka terrace in adjacent transects, the faulting must have occurred before the 80 ka terrace formed. The majority of motion probably occurred after formation of the 105 ka, based on the relative displacement of terraces (i.e., the elevation of the 124 and 194 terraces are not offset *more* than the 105 ka terrace, relative to terrace elevations in adjacent transects). In the third dimension, if the thrust fault to the north of BHR/BOL is a shallow, listric thrust fault with a ramp, it may have also resulted in the tilting of terraces at Curley Lane (CL). All of the terraces in this transect are backtilted, suggesting that the tilting occurred after the 105 ka terrace formed. The 80 ka terrace is not present in this section, so a younger time constraint for the faulting cannot be determined. Evidence of faulting and folding in cliff faces in the area just north of BHR and BOL supports this model. Because the dominant force within the Gualala block appears to be compression, normal faulting was not considered for the displacement of the terraces in this region.

Terrace Displacement at Point Arena. The terrace elevations and uplift rates drop from .64 to .48 m/kyr at Point Arena, as they near the San Andreas fault. The existence of another thrust or reverse fault is the simplest explanation for this drop in elevations and uplift rates. This fault, most likely in the vicinity of the Coast Guard Station and dipping southward, would cause the northern tip of the Gualala block to have a relatively lower elevation. The lowest, 80 ka terrace has a lower elevation than expected, based on uplift patterns along the block, suggesting that faulting has probably been active since it formed. In sea cliff and sink hole exposures near the Coast Guard Station, several thrust faults cut marine terrace deposits (Prentice et al, 1991), supporting this model.

Another possible explanation for this change in uplift rate involves thrust faulting on a much larger scale; a shallow, listric thrust fault, underlying much of the Gualala block, reaches the surface at the northern end of the Gualala block, also most likely near the Coast Guard Station. The Gualala block (including complete terrace sequences) would effectively ride on this shallow thrust fault until the fault reaches the surface; in this zone, terrace elevations on adjacent transects would differ considerably. The terrace elevations and uplift rates at the northern end of the block gradually (but quickly) decrease. This suggests that as the shallow thrust fault nears the surface, it breaks into several splays. Each of the splays would absorb some of the total motion of the thrust fault, causing the gradual decrease in terrace elevations.

In an alternative model, the sharp decrease in uplift rates creates an image of the tip of the Gualala block being dragged along the San Andreas fault; I find this model the most convincing. While evidence of active thrust faulting is abundant, the low uplift rates Toomey (this volume) found (.1 - .2 m/ka) strongly support the notion of fault interference in normal convergence and uplift patterns. In the region directly adjacent to the SAF where transform motion between the two plates dominates, the fault probably exerts a "drag" on the Pacific and NAM plates. Thrust faulting does occur at Point Arena, but probably does not account for the amount of terrace displacement and rapid changes in uplift rates observed.

CONCLUSION

The Gualala block of Northern California, a piece of continental crust captured by the San Andreas fault, now part of the Pacific plate, has been uplifted as a result of a small degree of convergence between the North American and Pacific plates. This uplift has resulted in a series of emergent marine terraces. I mapped nine transects, almost all of which traversed five marine terraces, in hopes of determining uplift rates and patterns. I then correlated each terrace with a sea level highstand and determined uplift rates.

In the northern section of the Gualala block, uplift rates increase gradually from south to north; this overall pattern of uplift is disected by localized thrust faulting. Vertically offset terraces on the transects at Billy Hay's Ranch and Bill Owen's Land and backtilted terraces at Curley Lane can be explained with a model of conjugate thrust faulting. In this region, the terraces are relatively lower than equivalent terraces in adjacent profiles; normal faulting was not considered, because the dominant force within the Gualala block is compression, rather than extension. At the northernmost end of the Gualala block, near the SAF, uplift rates decrease sharply, suggesting that the SAF is interfering with normal patterns of uplift. In the actual fault zone, the plates may "drag" along each other and the dominant transform motion may mask compression. Despite these local complexities, the trend in uplift rates is clear: the uplift rates increase from the southernmost transect, .56 m/ka, northward to the Curley Lane transect, .64 m/ka, then decrease sharply at Point Arena to .47 m/ka as the terrace transects near the fault. Further mapping of local faulting will help identify the cause of this drop in uplift rates at Point Arena and the terrace displacement at BHR and BOL.

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