

UPLIFT AND DEFORMATION OF MARINE TERRACES ALONG THE SAN ANDREAS FAULT: FORT ROSS TO DUNCAN'S LANDING, CALIFORNIA

BREANYN MACINNES

Carleton College

Sponsor: Cameron Davidson

INTRODUCTION

Marine terraces line the coast of northern California, imprinting a history of sea-level change on the uplifting coastline by their staircase-like appearance (Merritts and Bull, 1989; Anderson, 1990; Lajoie et al., 1991; Grove, 1998). The mechanisms for creating terraces have been in place since at least the beginning of the Quaternary (Rosenbloom and Anderson, 1994; Anderson et al., 1999) providing a calibrated continuum through which to study fault characteristics. This study examines a section of the emerging California coastline in order to determine the rate of uplift and deformation along the San Andreas Fault.

The field area is located between Fort Ross and Duncan's Landing, California, just north of Bodega Bay (figure 1 in Merritts and Garner, this volume). The San Andreas Fault is located onshore in the northernmost region. It comes offshore just south of Fort Ross, but lies only a few kilometers from the coastline. Within the region of study, there is a minimum of six identifiable marine terraces.

Methods

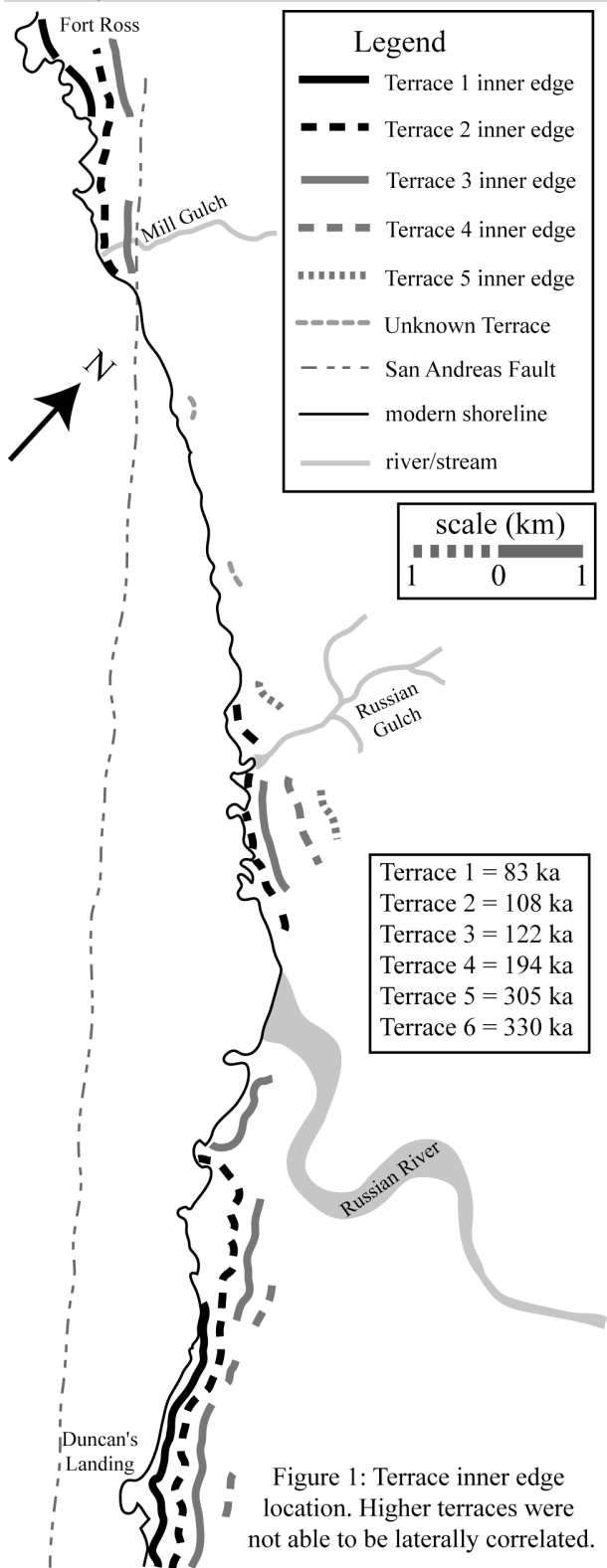
Initial preparation consisted of mapping elevation changes using aerial photographs, digital orthophotograph quadrangles, and topographic maps. Fieldwork incorporated field mapping and the use of Trimble GPS Pathfinder Pro XR receivers to record the exact coordinate locations of specific terrace components. Of particular importance was determining the elevation of the inner edge.

This elevation defines the highest paleoshoreline of a sea-level high-stand (see Merritts and Gardner, this volume). With GPS units, we walked perpendicularly to terraces in areas with multiple terraces exposed, or at places where an inner edge was predicted from aerial photographs. Each surveyed point included the Northing, Easting, elevation, location on the terrace, and the depth to bedrock if it was known.

Between the Russian River and Russian Gulch, the property east of Highway One was inaccessible for fieldwork. To prevent a large data gap, virtual transects were created using topographic maps and Adobe Illustrator to find inner edge elevations. The distance between forty-foot contour lines was graphed against elevation. Inner edges were identifiable, although the resolution was low.

In order to accurately represent the true uplift of terraces, bedrock elevation was calculated. Exposure in the field is rare and most elevation readings incorporated local sediment cover. If a bedrock reading existed somewhere on the tread or outer edge of a terrace, the inner edge was estimated by projecting a line with a 2-4° slope, the average gradient of a wave-cut platform (Bradley, 1976), to where it intersects the position of the sediment-inner edge. The result is a range for the bedrock-inner edge elevation. In some situations, a range of bedrock elevations was determined from the average sediment cover of nearby terraces.

Analysis



Terrace Identification and Correlation-

Analysis of transect data identified a minimum of six terraces near Duncan's Landing but only one terrace just south of Fort Ross. Transects between these two sites generally have a decreasing number of terraces to the north (figure 1). Aerial photograph mapping

enables the connection of the lower terraces, but correlation of higher terraces was severely hindered by terrace degradation and stream incision. The oldest terraces are often indistinguishable from other topographic variations (Anderson, 1999).

The northward decrease in terrace preservation is due to the high erodibility of the bedrock. Motion along the fault has reduced bedrock strength resulting in a high rate of sea cliff retreat and reducing the number of inner edges preserved. Also, some higher inner edges may have formed on the Pacific Plate but are now translated out of the field area along the San Andreas.

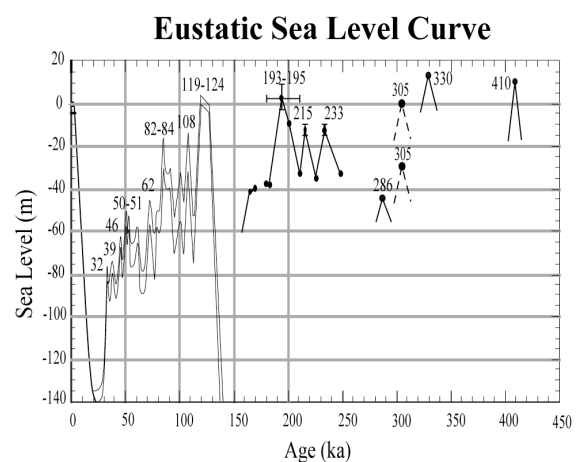


Figure 2: Sea level curve modified from Darter, 2000, Lambeck and Chappell, 2001, and Muhs, 2003. Peaks are sea level high-stands while troughs are low-stands. The 305 ka high-stand has been recorded at both -28 m (Darter, 2000) and 0 m (Muhs, 2003).

Age Assignment and Uplift Rate- Terrace age delegations are based on correlation with radiometrically dated sea-level high-stands (Darter, 2000; Lambeck et al., 2001; Muhs, 2003) (figure 2) and two assumptions. The first is that at least one terrace can be accurately assigned with an age and, using the principle that older terraces are higher and further inland than younger terraces, the other terrace ages are sequential (Grove, 1998). Other methods of dating were either not possible in this field area or were unavailable at the time of study. The second assumption is that for any given transect, uplift remains constant over time. The argument for this is that the tectonic regime driving uplift has not substantially changed on the time scale of terrace formation (Lajoie et al., 1991).

In keeping with these assumptions, trial and error determined an age of 83 ka for the lowest terrace. The rate of uplift for transects containing Terrace 1, calculated using the equation

$$\text{Uplift} = \frac{(\text{Present Elevation} - \text{Elevation at Formation})}{\text{Age of Terrace}}$$

is approximately 0.5 mm/yr. Terraces preserved by 0.5 mm/yr uplift rate are from the 83, 108, 122, 194, 305, 330 and 410 ka high-stands. These ages, beginning with Terrace 1, were assigned to sequential terraces.

The grouping of terrace inner edge points into specific terraces shows a north-south variation in uplift rates (figure 3). In the southernmost area, the uplift is calculated at 0.5 mm/yr. Following the terraces northward towards the Russian River, the inner edge elevations decrease and the corresponding uplift rate drops, just before the river, to 0.4 mm/yr. The elevations are well-constrained, incorporating bedrock inner edge readings. Just across the Russian River, the uplift rate jumps to 0.6 mm/yr, although other than Terrace 2, the points here are derived from topographic maps and so are less accurate. The uplift rate near Russian Gulch is 0.45 mm/yr. North of the gulch, the San Andreas is closer to shore and

the bedrock erodes rapidly, so few inner edges remain. Projecting the slight decrease in uplift rate between the Russian River and Russian Gulch through that area enables the dating of those points but the terrace assignment is much less certain. The closest terrace to the fault was designated Terrace 4, giving an uplift rate of 0.4 mm/yr. Across the fault at Fort Ross, the uplift is again well constrained at 0.5 mm/yr.

Discussion

The decrease in terrace elevation south of the Russian River at first appears to be related to the river. However, it cannot be the reflection of a paleo-flood plain because the channel is deeply incised and has been for at least 200 ka. A different method of offsetting terrace elevation is motion along a fault (Grove, 1998; Sojourner, 1997). The San Andreas Fault system is a complicated and broad deformation zone with many splays (Wallace, 1990) as opposed to one linear strike/slip fault. Considering the nature of the San Andreas where it is mapped in detail elsewhere in northern California, it is likely that more than one strand exists in our field area as well.

Evidence of minor faulting could be seen in sag-ponds and sheared rock at Russian Gulch and a newly identified sag pond at Eagle

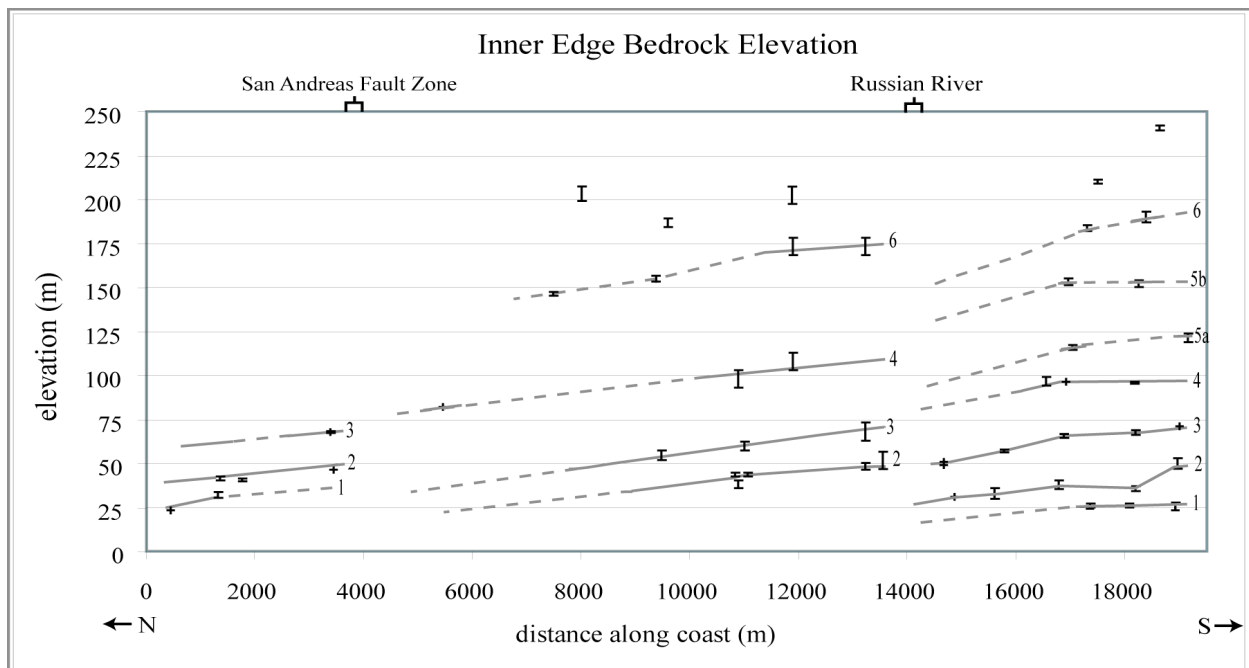


Figure 3: Inner edge elevation mapped against a cross-section of the coast. Solid lines show lateral continuation of terraces evident in aerial photograph or field mapping. Dashed lines are possible correlations across areas where the inner edge no longer exists. Terraces that are assigned ages are numbered 1-6. Inner edges above Terrace 6 were not studied. Terrace 5a and 5b are the 305 ka high-stands at either -28 m or 0 m (see figure 2).

Rock. Faulting is theorized to account for the anomalously high inner edge reading of Terrace 2 on the Eagle Rock transect because it corresponds to an unusually marshy area. The fault geometry proposed in this paper is that the San Andreas Fault at this point on the coast forms a flower structure and that one of the splays is contiguous with the Russian River (figure 4). Because rivers commonly form along sheared rocks with low resistance to erosion, the fault is predicted to lie along the river channel. As such, there are three distinct uplifting units moving horizontally and vertically at different rates.

Conclusion

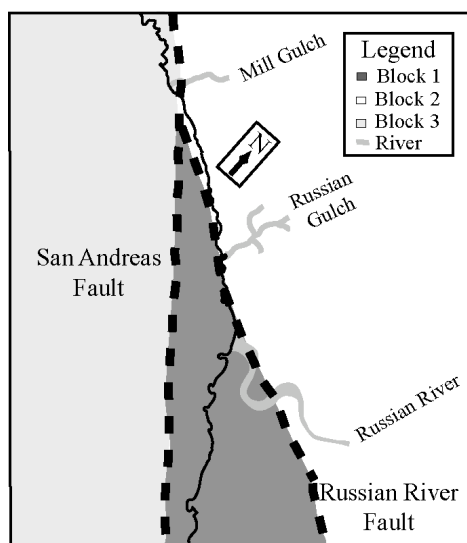


Figure 4: The geometry of the San Andreas Fault and the proposed Russian River Fault.

Analysis of data gathered on the coast of northern California identified at least six marine terraces. Correlation between transects was difficult due to degradation and erasure of some terraces. Younger terraces were easily traced in aerial photographs and in the field, but older terraces are no longer spatially continuous.

Assuming an age of 83 ka for the lowest terrace, uplift rates vary between 0.4 and 0.6 mm/yr along the coast. Originally horizontal terraces gradually tilt down to the north to either the Russian River or to the San Andreas Fault. Variation in uplift rates suggests that there are three separate fault blocks isolated by the San Andreas Fault and a proposed fault at the Russian River. Further study could advance this work by confirming the age

assignments and/or finding more evidence of the proposed fault.

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