Geology

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Geology 1989;17;1020-1024
doi:10.1130/0091-7613(1989)017<1020:IQURAT>2.3.CO;2

Notes

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ABSTRACT

Analysis of the altitudinal spacing of 14 flights of marine terraces indicates a spatial pattern of varying uplift rates that agrees with that determined from previously dated terraces for the past 3–81 ka, and temporal changes in uplift rates from <1 m/ka to 3–5 m/ka that may reflect response to changes in tectonic regime during passage of the Mendocino triple junction (MTJ). A possible mechanism for regional uplift is growth of a slab window south of the MTJ. The region of most rapid uplift is 25–43 km south of the MTJ, immediately south of the northern boundary of the slab window. The coastline is tilted upward to the south in the region directly above the southern edge of the subducted Gorda plate. At Point Delgada, 55 km south of the present MTJ, where the northern edge of the slab window passed ~300 ka, uplift rates have been 1.2 m/ka for at least 330 ka. More than 1.4 m.y. after passage of the southern edge of the subducted slab, at the Mendocino coast, uplift rates have been less than 0.4 m/ka for at least 330 ka.

INTRODUCTION

Some of the highest rates of late Quaternary uplift in the United States occur at the northern termination of the San Andreas transform boundary, the Mendocino triple junction (MTJ; Fig. 1). Previously determined rates of uplift based upon dating the lowest and youngest raised marine terraces span an order of magnitude from 0.3 m/ka near Fort Bragg to 4 m/ka just south of the triple junction (Kennedy et al., 1982; Lajoie et al., 1982). Studies of numerous marine-terrace remnants that span altitudes from near sea level to >400 m along many parts of the coastline provide a means of estimating longer term uplift rates. Our principal method of estimating ages of marine terraces centers on the correlation of their distinctive spacing of inner-edge altitudes with the global sea-level curve determined from flights of marine terraces that have been dated in New Guinea and elsewhere.

The record preserved in a flight of emergent terraces consists of a tectonic component from the rising land mass and a glacioeustatic component from an oscillatory ocean surface (Lajoie, 1986). Shore platforms and coral reefs appear to have formed at synchronous times in different parts of the world during sea-level highstands (Mesolella et al., 1969; Bloom et al., 1974; Ku et al., 1974; Chappell and Shackleton, 1986). Times and altitudes of sea-level highstands during the past 340 ka have been derived in New Guinea from radiometrically dated coralline marine terraces with the assumptions that uplift rates at each terrace traverse were uniform and that the last interglacial sea-level highstand (~125 ka) was 6 m in altitude (Veeh and Chappell, 1970; Bloom et al., 1974; Chappell, 1983; Chappell and Shackleton, 1986). Exceptional preservation and age control of the terraces establish New Guinea as a type area for correlation with flights of marine terraces elsewhere in the world.

A dearth of datable materials has precluded development of an independent record of sea-level fluctuation for coastal California, so past workers have used the New Guinea marine-terrace record to estimate uplift rates from individual dated terraces (e.g., McLaughlin et al., 1983a, 1983b). An alternative method in lieu of datable material is to examine entire flights of undated terraces (Bull, 1985; Bull and Cooper, 1986). Each uniform rate of uplift will produce a unique altitudinal spacing and number of terraces that can be used to infer the ages of each terrace within the flight and the overall uplift rate. A two-stage approach was used in this study to estimate terrace ages and to infer uplift rates. We first attempted to correlate terraces by surveying numerous adjacent flights of terraces and following individual terraces in the field, and by comparing soil profile development on shoreline deposits mantling terrace platforms. Constrained by these correlations, we then used the altitudinal spacing of terrace inner edges within each flight of terraces to correlate individual terraces with global marine terraces and to determine inferred uplift rates. The assigned terrace ages are viewed as predictions of the most probable ages, to be tested as further data are obtained.

ALTITUDINAL SPACING ANALYSIS AND INFERRED UPLIFT RATES

Fourteen flights of terraces and numerous individual terraces between Mendocino Headlands and Bear River (Fig. 1) were surveyed. Surveys were generally accurate within ±1 m, but the precision of defining inner-edge altitudes in the field commonly was ±2 m. Terrace preservation ranges from small (<10 m wide), flat bedrock benches with prominent inner edges and occasional shoreline deposits, to broad (10–400 m) bedrock benches mantled with 2–6 m of stratified marine shoreline deposits. Shells are common on Holocene terraces and pholad borings were found on many platforms up to 300 m in altitude. Terraces from Bear River to Smith Gulch and from Bruhel Point to Mendocino Headlands can be tentatively correlated on the basis of their altitudes (Fig. 1). Between 32 and 100 km is a region known as California's "Lost Coast" because of its extremely rugged terrain and inaccessibility. The broad complex of terraces followed southward from Bear River to Smith Gulch disappears, but ridgelines are marked by occasional notched spurs and minor to prominent bedrock benches. We chose the best sites in this region—Randall Creek and Kaluna Cliff—to survey prominent spurs. Because of the sparsity of data, we cannot even tentatively correlate terraces between Randall Creek and Kaluna Cliff on the basis of altitudinal position alone.

A soils chronosequence was developed for relative age correlation of coastal terraces with shoreline deposits (Fig. 1; D. Merritts et al., in

GEOLOGY, v. 17, p. 1020–1024, November 1989

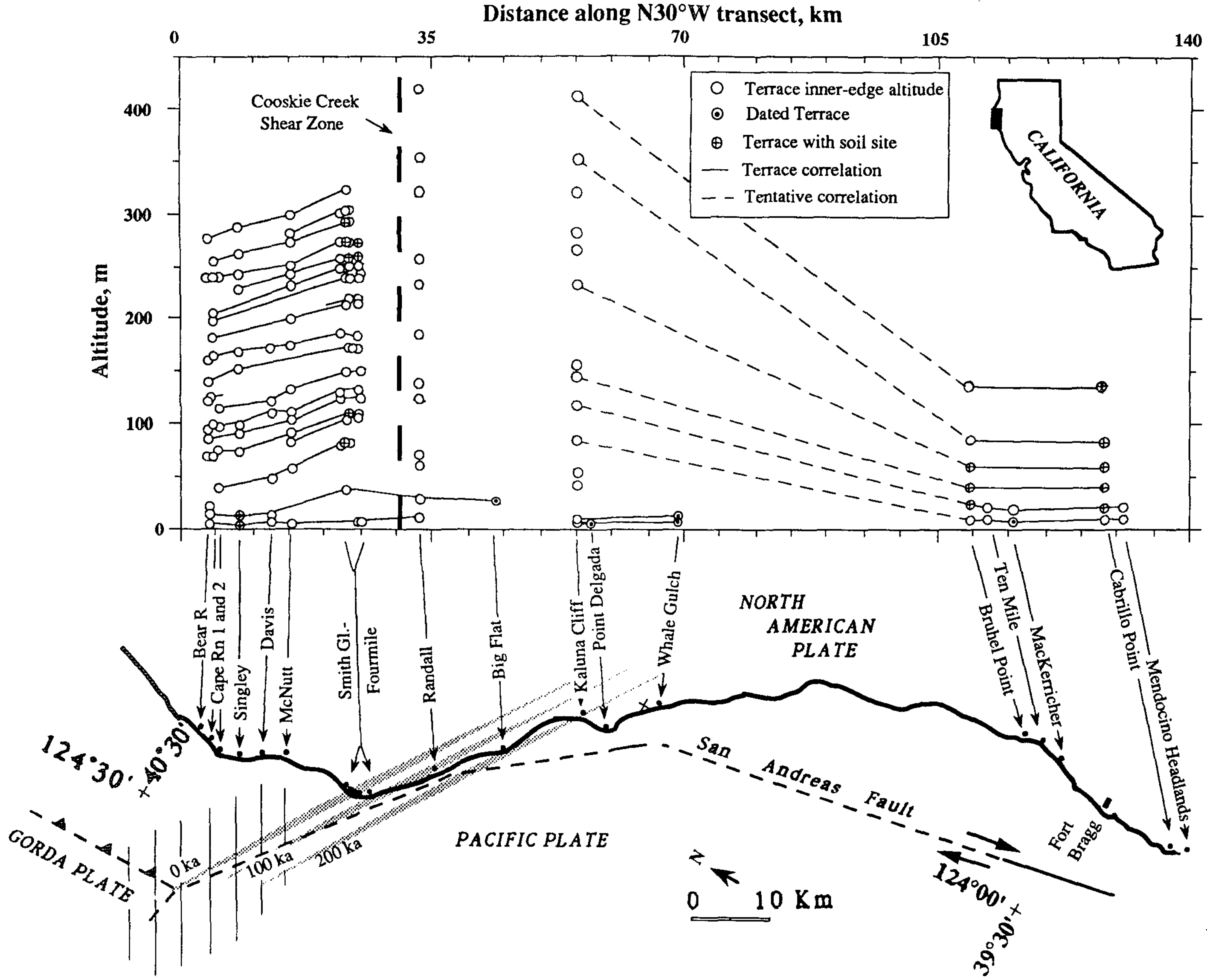
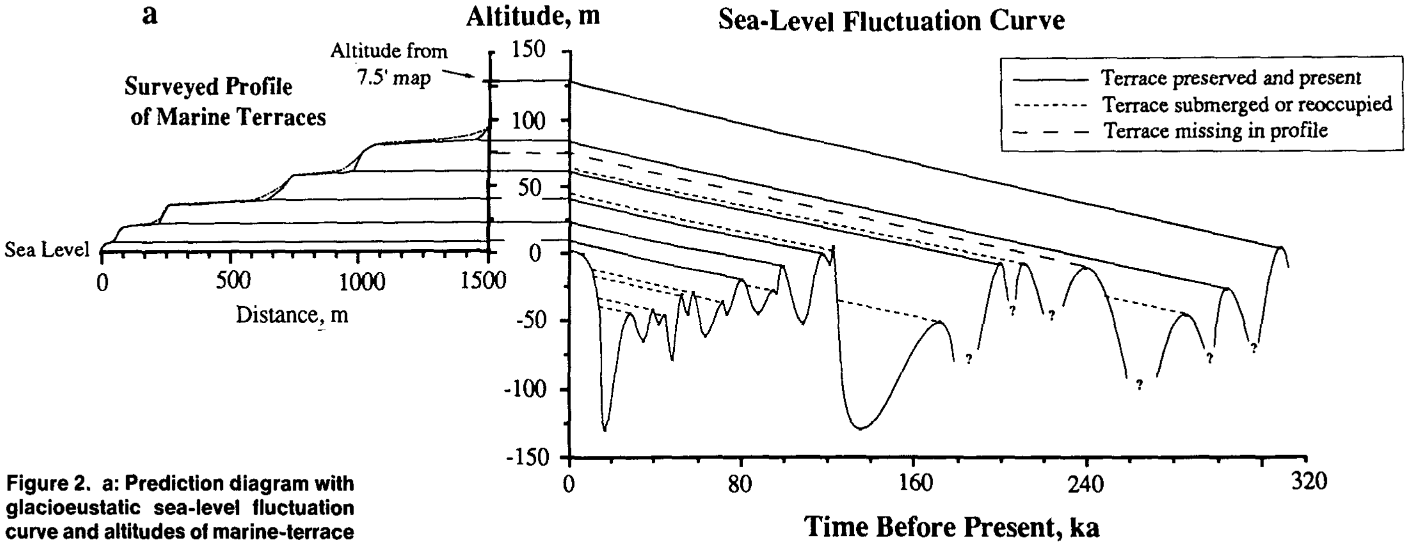


Figure 1. Location map, tectonic setting, and surveyed inner-edge altitudes of marine-terrace platforms. Present location of Mendocino triple junction (hachures) and locations of southern edge of subducted Gorda plate (shaded line) at 0, 100, and 200 ka are from Wilson (1986). Suggested terrace correlations are discussed in text.

prep.). Singley Flat (1.7 ka) is the only radiometrically dated terrace. Amino-acid racemization of marine molluscan fauna from the 10 m terrace at MacKerricher suggests correlation with the 81 or 100 ka New Guinea terraces (Kennedy et al., 1982). Soil development (total weight of accumulated clay, iron and aluminum oxides, and clay mineralogy) on all the terraces south of Bruhel Point is pronounced. Soil profiles on two of the lowest terraces at Bruhel Point (23 m and 40 m) are similar in degree of development to those on three of the highest Smith Gulch terraces (261 m, 273 m, and 294 m). Soil development on the two lowest Smith Gulch soil sites (83 m and 111 m terraces) is substantially less than at any of the other sites, with the exception of the Holocene soils at Singley Flat.

For each terrace flight, individual terraces were assigned ages and thus altitudes of formation by correlation with the New Guinea sea-level curve (ages and altitudes of formation tabulated by Bull from Chappell and Shackleton, 1986; Chappell, 1983; and J. M. Chappell, 1986, personal commun. to Bull). For each correlation, graphs were plotted of inferred uplift (altitudes of local terraces minus their New Guinea altitudes of formation) vs. inferred ages. The correlations were then evaluated for the most probable age assignments on the basis of (1) the configuration of points on the inferred uplift-rate diagrams (URD); (2) previously known terrace ages and soil-profile development; and (3) correlation of coastal terraces between adjacent flights based on altitudinal position. Three sites with different uplift rates illustrate the altitudinal spacing analysis: Bruhel Point—uniform, low rates of uplift; Kaluna Cliff—uniform, moderate rates of uplift; and Smith Gulch—several periods of uniform uplift rates that have increased during the past 300 ka.

South of transect distance 100 km, broad terraces with excellent platform exposures are known as the "Mendocino staircase" and have nearly identical inner-edge altitudes on five terrace platforms surveyed at sites that span 25 km (Fig. 1). Evidence of long-term low uplift rates includes the amino-acid racemization age estimate of 81 or 100 ka on the 10 m terrace, the pronounced degree of soil development on all terraces, the lack of Holocene marine terraces, ubiquitous estuarine river mouths, and the lateral extent and preservation of the terraces. The prediction diagram and altitudinal spacing anal-



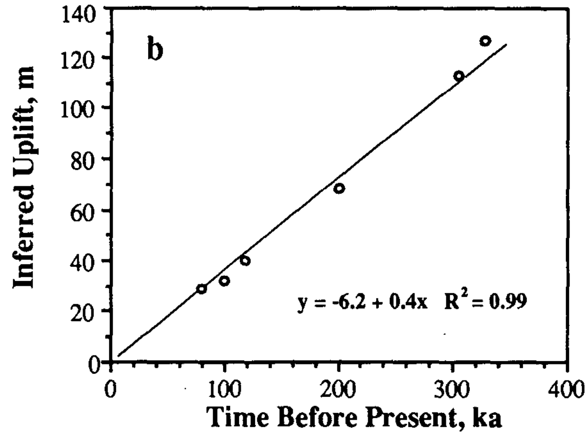


Figure 2. a: Prediction diagram with glacioeustatic sea-level fluctuation curve and altitudes of marine-terrace remnants for Bruhel Point transect. b: Inferred uplift rate diagram that corresponds to prediction attempt in a. Equation beside curve is determined from linear regression analysis, and indicates average uplift rate of 0.4 m/ka.

TABLE 1. MARINE TERRACE DATA

New Guinea		Bruhel Point, California	
Age (ka)	Altitude (m)	(A)*	(U)*
6	0	--	--
29	-44	--	--
40	-41	--	--
45	-45	--	--
53	-30	--	--
59	-28	--	--
72	-36	--	--
81	-19	10†	29
96	-26	--	--
100	-9	23	32
118	0	40	40
124	6	--	--
172	-50	--	--
200	-7	61	68
212	-7	--	--
240	-10	--	--
286	-46	--	--
305	-27	86	113
330	4	130§	126

Note:
New Guinea terrace ages and altitudes of formation tabulated by Bull from Chappell and Shackleton (1986), Chappell (1983), and Chappell (1986, personal communication to Bull).
*A is altitude of inner edge, determined from electronic distance meter survey (survey error ±0.2 m); U is inferred amount of uplift of terrace inner edge; dashes indicate that no terrace of that age is preserved.
†Terrace age determined independently from amino-acid racemization dating.
§Altitude determined from 7.5' topographic map (error ±4 m).

ysis represented in Figure 2 and Table 1 are based on an age assignment of 81 ka for the 10 m terrace, and correlation of each of the remaining terraces with major sea-level highstands that are most likely to be preserved (i.e., not reoccupied or destroyed by subsequent sea-level highstands). The URD indicates uniform uplift of 0.4 m/ka, and the best-fit line plots close to the origin. However, such a correlation is nonunique, because only six terraces are represented and many global marine terraces are assumed to have been destroyed. We consider our attempt to be the most reasonable, however, because so much other evidence indicates that uplift rates are low and because 0.3 m/ka is the most common uplift rate associated with the present San Andreas transform boundary tectonic regime.

Two low platforms (7 m and 12–15 m) at Point Delgada and Whale Gulch that have been radiometrically dated at 44 800 ±1300 ka and 42–>57 ka, respectively (McLaughlin et al., 1983a; Hagemann, 1982), can be followed 2 km northward to Kaluna Cliff (Fig. 1). Inner-edge altitudes of 14 terraces surveyed at Kaluna Cliff are plotted with the New Guinea sea-level curve in the prediction diagram of Figure 3. We assigned ages of 40 and 45 ka to the 7 and 12 m Kaluna Cliff terraces, and then assigned each successively higher terrace to older sea-level highstands, but attempted to maintain uniform rates of uplift (i.e., lines of constant slope in Fig. 3). In the resultant URD, nearly all points fall on a line that intersects the y-axis close to the origin and represents uniform uplift of 1.2 m/ka for the past 330 ka ($y = 3.8 + 1.2x$; $R^2 = 0.99$). No other correlations yielded a URD with uniform uplift rates and a line that plots close to the origin.

From Big Flat to Bear River, much evidence suggests that uplift rates are very high. A high-relief mountain range is flanked by a complex of mid-Holocene terraces that decreases in maximum altitude from 30 m near Big Flat to 6–12 m north of Smith Gulch. Well-defined, closely spaced notches on the complex of Holocene terraces may represent individual coseismic events and suggest that in this region each global sea-level highstand may be represented by more than one local marine-terrace inner edge. Valleys have steep-walled inner gorges, and convergent bedrock straths at the mouths of steep channels indicate uplift rates that exceed the rate of sea-level rise. Maximum relief and gradients of first- to third-order channels increase progressively from Bruhel Point northward to Randall Creek, and then decrease progressively from Randall Creek to Bear River (Merritts and Vincent, 1989).

Evidence of a *change* in uplift rates also exists in the landscape north of Fourmile Creek. A prominent complex of terraces above 239 m can be traced northward from Fourmile Creek to Bear River; in contrast, from Randall Creek southward to Big Flat Creek, the higher altitudes are knife-edge ridge crests. From Fourmile Creek northward, the topography above 239 m resembles the Bruhel Point coastline; below 239 m, a steep escarpment interrupted by small benches and notches drops abruptly seaward (Fig. 4a). We hypothesize that a significant increase in uplift rates has occurred since the time of formation of the lowest broad terrace at about 239 m. Inspection of inner-edge altitudes of 18 marine terrace remnants surveyed at five transects at Smith Gulch (Fig. 4a) reveals that no uniform uplift rate will produce such an altitudinal spacing; there seem to be too many terraces or too few highstands. We hypothesize that some of the clustered terraces may represent one sea-level highstand. The preferred marine-terrace–sea-level-highstand correlation and resultant URD consists of three segments, each having a uniform uplift rate within that segment's time period (Fig. 4b). The uplift rate for the broad terraces above 239 m is 0.4 m/ka, the same as the present rate south of Bruhel Point. The lowest segment indicates a uniform uplift of 3.4 m/ka from 59 ka to the present, consistent with Holocene rates estimated from the dated terraces at Singley Flat (2.8 m/ka) to the north and Big Flat (4 m/ka; Lajoie et al., 1982) to the south.

The URD for each of the three remaining transects north of Smith Gulch are very similar, and they have two periods of uniform uplift rates: 0.4 m/ka from 305 to 72 ka, and 2.9 to 3.5 m/ka from 72 ka to the present. Furthermore, uplift rates since 72 ka increase southward from 2.9 m/ka at Bear River, to 3.2 m/ka at Singley Flat, to 3.5 m/ka at McNutt Gulch. South of Smith Gulch, the URD for Randall Creek yields a uniform uplift rate of 0.7 m/ka between 330 and 124 ka, and a uniform uplift rate of 4.0 m/ka from ~124 ka to the present. If this correlation attempt is correct, it suggests a structural discontinuity between Randall Creek and nearby Smith Gulch that has resulted in different rates of uplift and offset of individual terrace lines (Fig. 1). A suture boundary between two terranes—the Cooskie Creek shear

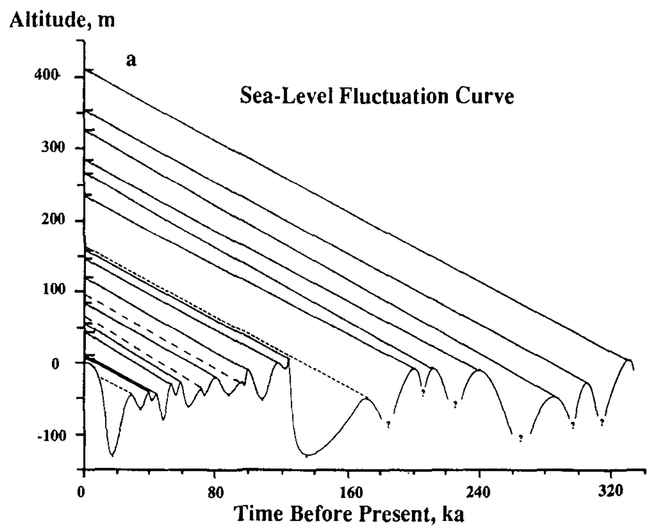


Figure 3. Prediction diagram with glacioeustatic sea-level fluctuation curve and altitudes of marine-terrace remnants for Kaluna Cliff transect. Line symbols same as in Figure 2a.

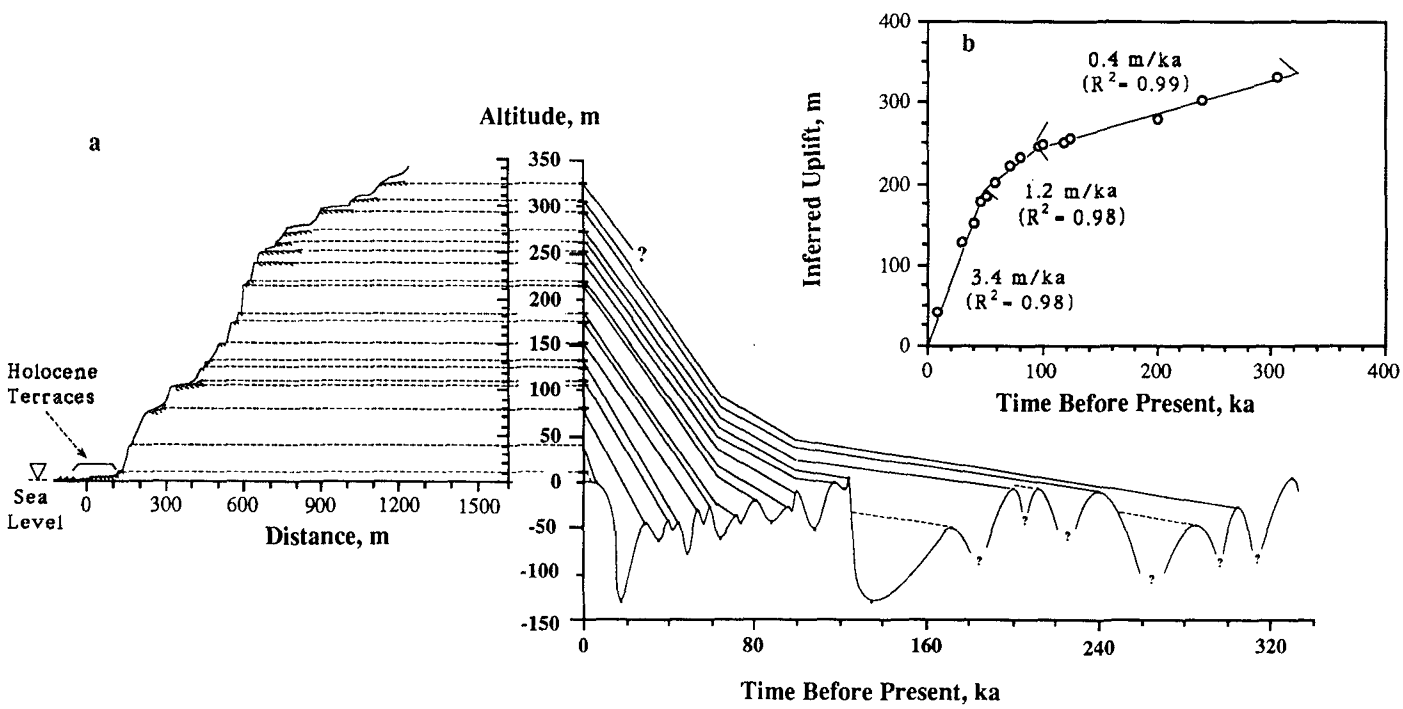


Figure 4. a: Prediction diagram with glacioeustatic sea-level fluctuation curve and altitudes of marine-terrace remnants for Smith Gulch transect. Line symbols same as in Figure 2a. b: Inferred uplift rate diagram that corresponds to prediction attempt in a. Numbers beside curves are average uplift rates determined from linear regression analysis of each line segment.

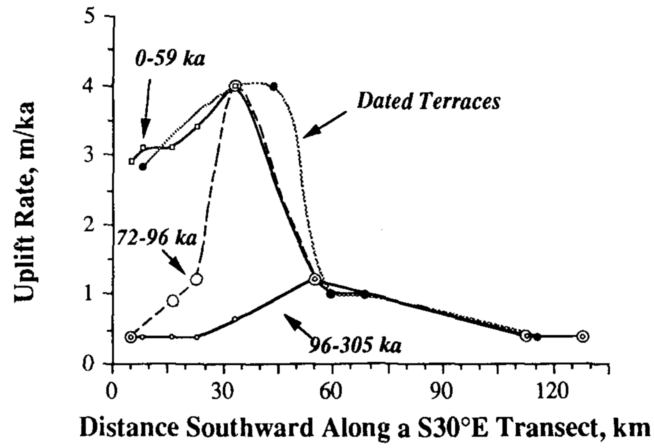


Figure 5. Inferred uplift rates at 0–59 ka, 72–96 ka, and 96–305 ka based on this study. Uplift rates from previously dated terraces projected along S30°E transect from Bear River to Mendocino Headlands.

between Randall Creek and Smith Gulch (Fig. 1); hence, terrace correlations are not made between Kaluna Cliff and Smith Gulch.

DISCUSSION OF INFERRED UPLIFT RATES AND MECHANISMS OF UPLIFT

Because coastal northern California is part of an active orogenic belt and because tectonic regimes are changing with time in response to MTJ migration, spatial and temporal variations in uplift rates are to be expected. Uplift rates obtained from individual dated terraces vary spatially, and major differences in landscape morphology indicate that variable uplift is the more likely case. Plots of inferred uplift rates for 0–59 ka, 59–96 ka, and 96–305 ka and uplift rates determined from absolute age control (Fig. 5) indicate a time-transgressive increase in uplift rates that moves northward in the wake of the MTJ. The current northern boundary of the slab window lies directly beneath Smith Gulch, where uplift rates began to increase about 72–96 ka (Figs. 1 and 4b). At ~100 ka, when the northern boundary of the slab window underlay Randall Creek (Fig. 1), uplift rates at Randall Creek increased from 0.7 to 4.0 m/ka. At Point Delgada, where the northern edge of the slab window passed 300–400 ka, uplift rates have been 1.2 m/ka for at least 330 ka. At the Mendocino staircase, 1.4 m.y. after passage of the slab window, uplift rates have been <0.4 m/ka for at least 330 ka.

A possible mechanism for regional uplift is growth of a "slab window" south of the MTJ and associated juxtaposition of hot asthenosphere against cold lithosphere of the North American plate (Furlong, 1984). The North American lithosphere responds to this thermal change and effective lithospheric thinning by thermal expansion of the crust and isostatic flexural uplift. Furlong (1984) has modeled the style of deformation as regional time-transgressive flexure of a thin, unbroken elastic plate that would create higher uplift rates in the wake of the MTJ. Furlong's calculation of total uplift response 1 m.y. after triple junction passage is 1000–1300 m. At Point Delgada, the approximate location of the MTJ 1 m.y. ago, the present highest nearby altitude is 1000 m. The uplift rate determined from uplift of about 1000 m over a 1 m.y. period (without correction for erosion) is 1.0 m/ka, which is very close to that determined radiometrically by McLaughlin et al. (1983a) for the past 45 ka (>1.0 m/ka), and to that inferred from our altitudinal spacing analysis for the past 330 ka (1.2 m/ka).

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ACKNOWLEDGMENTS

Financial assistance and logistical support were provided by the National Science Foundation (Doctoral Dissertation Improvement Grant EAR-8405360), the U.S. Geological Survey (Graduate Intern Program), the Geological Society of America (Robert K. Fahnestock award), Sigma Xi (field-support grant), the University of Arizona Graduate College, and the Bureau of Land Management. Many colleagues have generously helped us to develop ideas and complete field and lab work. We thank John C. Tinsley, David Hendricks, Ellen Wohl, Oliver Chadwick, Spence Smith, Janet Slate, Mary Ann McKittrick, Kirk Vincent, Raymond Burke, Gary Carver, Harvey Kelsey, and Ed Beutner for assistance.

Manuscript received February 27, 1989
Revised manuscript received June 22, 1989
Manuscript accepted July 19, 1989

Reviewer's comment

This paper stands an excellent chance of stimulating additional geological and geophysical research concerning the crustal processes that drive the pattern of deformation as revealed by the authors' geomorphic analysis.

John Tinsley