JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. B7, PAGES 14,031–14,050, JULY 10, 1994

Long river profiles, tectonism, and eustasy: A guide to interpreting fluvial terraces

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Abstract. Along three rivers at the Mendocino triple junction, northern California, strath, cut, and fill terraces have formed in response to tectonic and eustatic processes. Detailed surveying and radiometric dating at multiple sites indicate that lower reaches of the rivers are dominated by the effects of oscillating sea level, primarily aggradation and formation of fill terraces during sea level high stands, alternating with deep incision during low stands. A eustasy-driven depositional wedge extends tens of kilometers upstream on all rivers (tapering to zero thickness). This distance is greater than expected from studies of the effects of check dams on much smaller streams elsewhere, due in part to the large size of these rivers. However, the change in gradient is nearly identical to other base level rise studies: the depositional gradient is about half that of the original channel. Middle to upper reaches of each river are dominated by the effects of long-term uplift, primarily lateral and vertical erosion and formation of steep, unpaired strath terraces exposed only upstream of the depositional wedge. Vertical incision at a rate similar to that of uplift has occurred even during the present sea level high stand along rivers with highest uplift rates. Strath terraces have steeper gradients than the modern channel bed and do not merge with marine terraces at the river mouth; consequently, they cannot be used to determine altitudes of sea level high stands. Strath formation is a continuous process of response to long-term uplift, and its occurrence varies spatially along a river depending on stream power, and hence position, upstream. Strath terraces are found only along certain parts of a coastal stream: upstream of the aggradational effects of oscillating sea level, and far enough downstream that stream power is in excess of that needed to transport the prevailing sediment load. For a given size river, the greater the uplift rate, the greater the rate of vertical incision and, consequently, the less the likelihood of strath terrace formation and preservation.

Introduction

Historical Prelude

The general objective of this work is to achieve greater understanding of the interplay of long-term base level change with fluvial processes of incision and sediment deposition. Base level is the altitudinal lower limit of the erosive capacity of a river [*Powell*, 1961; *Davis*, 1902]; the ultimate base level for all rivers is a planar surface extending from sea level beneath the land [*Mallott*, 1928]. Regional base level change is the result of two processes: tectonic upheaval or subsidence of the land surface, and eustatic rise or fall of sea level. Contemplation of the effects of the former, crustal instability, led to cyclic schemes of erosional history of landscapes which predominated early twentieth century geomorphic research [e.g., *Davis*, 1954; *Johnson*, 1931]. Contemplation of the effects of the latter, sea level change, began with *Suess*'s [1888] postulate that synchronous oscillations of sea level were the cause of widespread, correlatable erosional surfaces, and culminated in the "great unifying generalization" that dominated European studies of denudation chronology [*Chorley*, 1963]. Since then, the plate tectonic revolution and recognition of the eustatic effects of repeated Quaternary glaciation have resulted in greater understanding of the dynamic nature of both land and sea levels and provide the impetus for the following examination of fluvial response to simultaneous tectonic and eustatic processes.

Paper number 94JB00857.
0148-0227/94/94JB-00857$05.00

Base Level Change and Fluvial Terraces

River terraces are landforms that were at one time constructed and maintained as the active floor of a river but are now abandoned. As such, they can be used to deduce the timing and external cause of abandonment: base level change, climate change, or tectonic activity. A river's bed and its floodplain can be used to represent the longitudinal profile (vertical section) of the currently active stream. The long profile of a river generally decreases in gradient downstream as a function of increasing discharge of the river [*Bagnold*, 1977] and tangentially approaches sea level in a coastal river [*Bloom*, 1991]. In an alluvial river, channel boundaries are composed of sediment that can be transported by the river. In a bedrock channel, the boundaries are cut into rock. Both types, with exception of mountainous areas of very steep relief, form floodplains in response to continuously variable discharge.

Alluvial channels are very sensitive to active tectonics [e.g., *Burnett and Schumm*, 1983; *Ouchi*, 1985], and adjust to vertical deformation or base level change by channel modification, specifically by incising, aggrading, or altering sinuosity. Extensive valley aggradation buries evidence of a stream's prior history, but cessation of aggradation and subsequent incision will result in formation of one fill terrace and possibly lower cut terraces carved into the fill if incision is episodic (Figure 1a). The long profile of a bedrock channel, in contrast, responds more slowly to changes in gradient or base level, as its boundaries are more rigid [*Shepherd and Schumm*, 1974]. Few studies have been made of the long profiles of bedrock rivers, and even fewer studies have been made of their response to base level change [cf. *Summerfield*, 1991]. Field study of a small tributary to the South Fork of the Eel River, northern California, has documented that

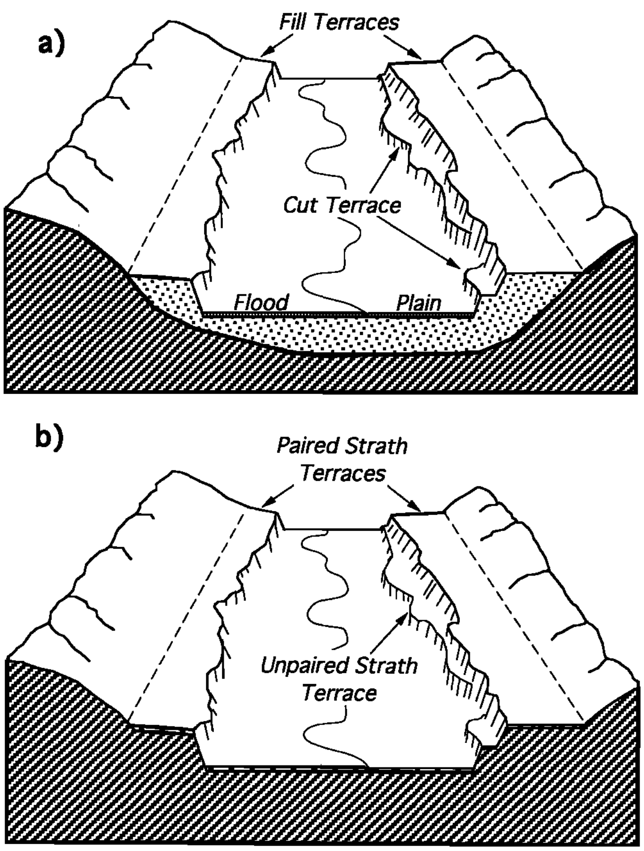

Figure 1. Relations among the floodplain, valley floor, and terrace formation. (a) Valley filling and subsequent episodic incision results in formation of one set of paired fill terraces and one small, unpaired, cut terrace carved from the alluvium above the floodplain. (b) Lateral valley floor beveling followed by sudden vertical incision that is episodic results in formation of one set of paired strath terraces, one small, unpaired strath terrace, and one active strath, all carved from the valley-wall bedrock.

incision of the bedrock floor of the channel in response to local base level change is concurrent with upstream propagation of a knickpoint that retreats in parallel fashion, leaving in its wake an abandoned channel floor mantled by a thin veneer of sediments [*Seidl and Dietrich*, 1992]. As in the case of the alluvial channel, this surface is also a terrace but is referred to specifically as a strath terrace (Figure 1b) [*Bucher*, 1932; *Leopold et al.*, 1964]. For both alluvial and bedrock channels, if episodic vertical incision occurs, paired terraces are formed; if lateral erosion as well as continuous vertical incision occurs, unpaired terraces result (Figures 1a and 1b).

The utility of fluvial terraces to tectonic studies is obvious. Their occurrence is ubiquitous worldwide [*Fairbridge*, 1968], and if they are tilted, faulted, or folded, they can be used to deduce history and rates of tectonic deformation [e.g., *Keller and Rockwell*, 1984; *Rockwell et al.*, 1984]. Their ages can be determined by radiometric dating of organic material from within the veneer of deposits on strath surfaces or from within the alluvium of cut and fill terraces [e.g., *Weldon*, 1986]. Finally, the existence of a terrace might indicate that base level change occurred, due either to vertical deformation [e.g., *Bull and Knuepfer*, 1987] or changing sea level [e.g., *Pazzaglia and Gardner*, this issue]. The difficulty of fully utilizing terraces in tectonic studies, however, is that our knowledge of fluvial response to base level processes (especially for bedrock rivers) is insufficient at present to enable us to infer with confidence the history of tectonic and eustatic processes from the terrace record (compare discussion by *Seidl and Dietrich* [1992]).

Project Design, Location, and Objectives

The approach used here to provide greater understanding of the tectonic and eustatic controls on terrace formation is to examine the geomorphic response of several coastal rivers to long-term base level change, as recorded by their fill, cut, and strath terraces. Marine terraces at the mouth of each river provide estimates of rates of late Quaternary base level change. We surveyed and radiometrically dated fluvial landforms along three rivers (Bear, Mattole, and Ten Mile) in a tectonically active area in northern California, near the Mendocino triple junction (MTJ; Figure 2). The rivers were chosen specifically because of their close similarities in bedrock type (Franciscan argillaceous sandstones and mudstones) and climate (discussed below) and large dissimilarities in uplift rates [*Merritts et al.*, 1989]. Late Pleistocene uplift rates increase an order of magnitude northward along the coast of California, from about 0.4 m/kyr at the Ten Mile River, to 2.5-3 m/kyr (locally as high as 4 m/kyr) along the Mattole River [*Merritts and Bull*, 1989]. The late Pleistocene uplift rate at the mouth of the Bear River is intermediate, at about 2-2.5 m/kyr [*Merritts and Bull*, 1989]. In this paper, we focus on analysis of the largest of these rivers, the Mattole (drainage basin area 655 km^2; trunk stream length 97 km), and make comparisons with the other two in the discussion of results (Bear's drainage basin area is 189 km^2 and trunk stream length is 44 km; Ten Mile's drainage basin area is 267 km^2 and trunk stream length 36 km).

By working with rivers for which approximate rates of base level change through time are known, our goal is to address the following questions regarding the formation and significance of terraces:

When does a river carve the bedrock surface of a strath terrace? During sea level high stands or low stands? Or while sea level is rising or falling?

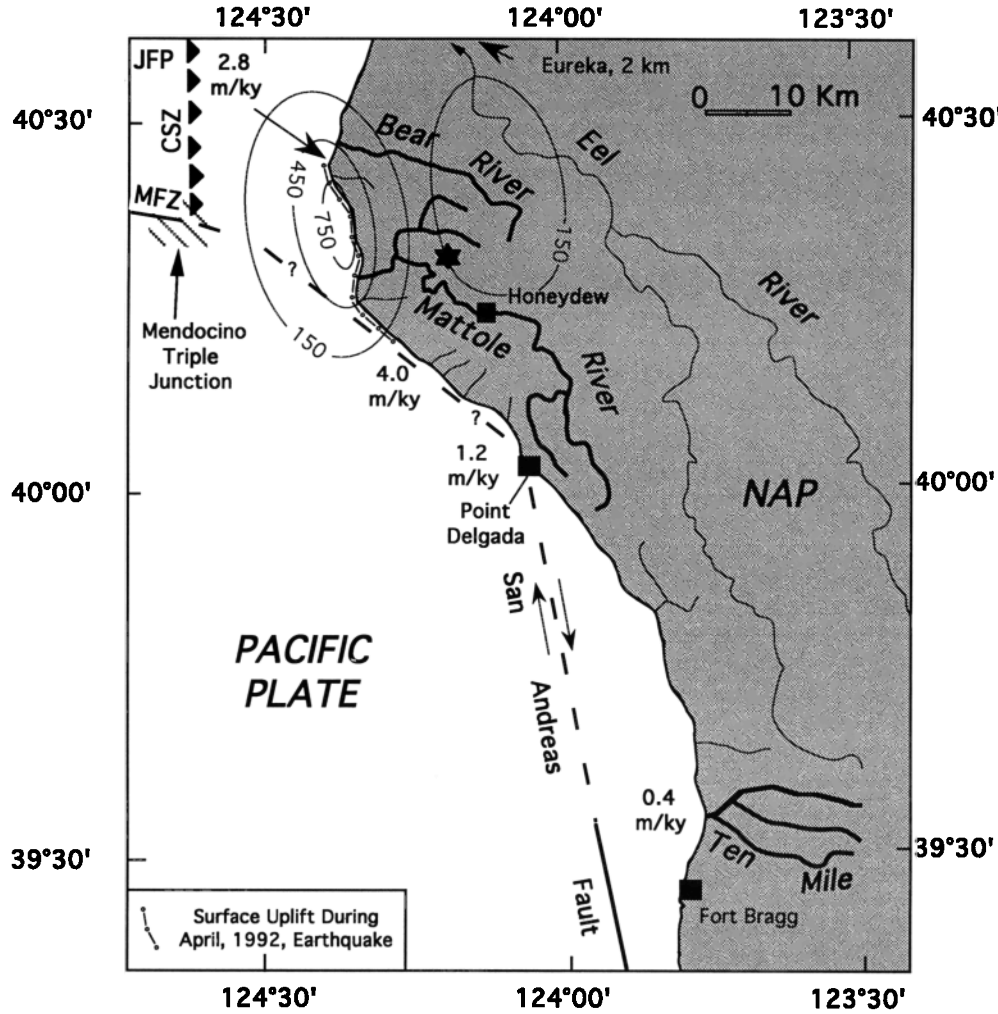

Figure 2. Plate tectonic and location map of coastal northern California. Star marks epicenter of April 25, 1992, M_s 7.1 thrust earthquake. Late Pleistocene rates of uplift are from *Merritts and Bull* [1989]. Location of zone of coseismic surface uplift from surveys of die-off of marine organisms and modeled surface displacement contours (150 mm contour interval) are from *Oppenheimer et al.* [1993]. The triple junction boundary between the North American (NAP), Pacific (PP), and Juan de Fuca plates (JFP) formed about 29 m. y. ago, when part of the ancestral spreading center of the Farallon (present-day JFP) plate was subducted beneath the NAP [*Atwater*, 1970; *Dickinson and Snyder*, 1979a, b]. Subduction of the JFP has continued north of the triple junction along the Cascadia subduction zone (CSZ), while south of it right-lateral shear between the PP and NAP has developed into the San Andreas transform boundary. Right-lateral shear also occurs between the JFP and PP along the Mendocino fracture zone (MFZ).

Can terraces along a large, meandering, bedrock river be correlated in order to reconstruct past longitudinal profiles?

Do strath and fill terraces indicate that base level change has occurred?

How far upstream are effects of base level change transmitted?

Do adjacent rivers have similar numbers and spacing of fluvial terraces that are synchronous?

Following discussion of a conceptual model of base level change, a brief survey of previous terrace studies, and presentation of the results of analysis of the Mattole River, these questions are addressed. To conclude, we summarize the relation between terrace formation and base level change in coastal northern California. Our goal is to provide the earth scientist considering the use of terraces as tectonic indicators with guidelines to their analysis and interpretation.

The Graded River, Base Level Change, and Fluvial Terraces

Conceptual Models of the Graded River

Mackin [1948, p. 464] described a graded stream as one with a

> . . . slope that will provide the velocity required for transportation of all the load supplied to it from above. . . [it] is a slope of transportation; . . . influenced directly neither by the corrasive power of the stream nor bedrock resistance to corrasion.

Mackin viewed the long profile of a graded river as an indication of a system in steady state equilibrium, a system adjusted to the prevailing sediment load. Le Chatelier, a chemist, had earlier described the reaction of a closed system in equilibrium to a change [cf. *Prigogine and Defay*, 1954], and *Mackin* [1948, p. 464] applied this principle to the case of streams as open systems: "If any stress is brought to bear on a system in equilibrium, a reaction occurs, displacing the equilibrium in a direction which absorbs the effect of the stress." This reasoning could be interpreted by geologists to mean that if the level of water at the mouth of a stream is lowered (base level fall) and the stream's gradient is increased as a consequence, the channel will incise in order to reduce its gradient to its previous level [e.g., *Leopold and Bull*, 1979; *Summerfield*, 1985]. Conversely, if base level is raised and the stream's gradient is decreased, the channel will aggrade in order to increase its gradient [e.g., *Fisk*, 1944; *Zeuner*, 1945]. From this basic model, geologists developed a number of questions regarding how base level change is transmitted along a stream, and how far upstream the effect of such a change is transmitted. A fundamental question was simply how one determines whether or not a stream is graded. *Leopold and Bull* [1979] responded by stating that a graded stream is one that is neither aggrading or degrading, according to the original ideas of *Gilbert* [1877].

In an active orogenic belt, one might suppose that no streams should be in equilibrium, as all are actively degrading. *Merritts and Vincent* [1989], however, working in coastal northern California, showed that a stream incising bedrock in response to an effective base level fall can maintain a steady longitudinal shape by uniform incision along its length, with one condition. According to this model, the size and power of a stream are of great importance in determining the ability of the stream to incise vertically. For a given rate of uplift, smaller streams will be steeper than larger streams in order to maintain the power necessary to incise vertically at a rate equal to that of the uplift rate. Thus, the stream is able to incise uniformly only if it is able to transmit all of the base level fall from its mouth upstream along its length. If a reach is encountered in which stream flow has insufficient power to incise vertically at an amount equal to the base level fall, the bed altitude and consequently the gradient of that reach will increase relative to the next downstream reach. At any given point, the altitude of the bed will change at a rate equal to the rate of uplift minus the rate of incision.

This conceptual model can be used to consider the occurrence of fluvial terraces in the same region. Only the largest streams and rivers in coastal northern California have strath terraces along substantial parts of their lengths, and these are unpaired. The hypotheses drawn from these observations are that (1) for a given uplift rate, a stream must have sufficient drainage area, and hence power, to erode laterally as well as incise vertically, in order to leave a record of unpaired terraces; and (2) the vertical component of incision will be directly proportional to the uplift rate. These ideas are explored further in this paper.

The Graded River and Terrace Formation: Previous Terrace Studies

Some workers have considered *Mackin's* [1948] definition of a graded river and Le Chatelier's model of system response to change as an indication that river terrace formation (by abandonment) represents discrete events which acted to displace the system from equilibrium. A fill terrace might represent aggradational response to fluctuations in sediment loads due to climatic change [e.g., *Leopold et al.*, 1964; *Weldon*, 1986; *Bull and Knuepfer*, 1987], and abandonment of a strath surface might represent sudden movement along a fault or an increased rate of uplift [e.g., *Bull*, 1990]. The historic development of thought regarding sea level oscillations and the "eustatic approach" of using terraces correlated along the length of a river to estimate the heights of interglacial sea level high stands is relevant to this study [*Lamothe*, 1918; *Ramsay*, 1931; *Zeuner*, 1945; *Sibinga*, 1953]. A special case of near-horizontal fill terraces, called thalassostatic, refers to terraces formed along the lower, estuarine reaches of a coastal river in response to sea level high stands and drowning of the river mouth [*Ramsay*, 1931; *Zeuner*, 1945]. In practice, few such terraces have been identified with certainty, and interpretations of the relation between aggradation at the mouth and fluvial processes upstream during high stands have spanned the spectrum from extension of aggradation well upstream, to concurrent incision upstream [cf. *Clayton*, 1968].

Many of the earliest ideas regarding eustatic terraces originated with the classic work of *Lamothe* [1918] on the Somme River, western Europe, a river nearly identical in size to the Mattole. The Somme studies are relevant to the results of this work, as the approach was very similar, but the results are far different. The Somme is outside the region of European glaciation and is fringed with strath surfaces mantled with a vertical sequence of deposits interpreted as both glacial (older and lower deposits) and interglacial (younger and higher deposits) [*Breuil*, 1939] in age, and capped with loess interpreted as synchronous with glacial maxima. As discussed by *Fairbridge* [1968, pp. 1129-1130],

> . . . it was . . . General Leon de Lamothe, who noticed the remarkable parallelism of terraces, both fluvial (in . . . eastern France) and marine (in Algeria); the marine terraces he interpreted, with *Suess* [1888], as eustatic, which would necessarily be high in interglacials, but he discovered . . . that they merge with the high fluvial terraces, which . . . were identified by Penck [*Penck and Bruckner*, 1909] as glacial [in age]. De Lamothe extended his surveys over about half a century. . . [and over] other major rivers in western Europe. He claimed a general correlation with the Algerian sea level data, with absolute altimetric identity. . . No allowance was made for . . . tectonics.

Figure 3 illustrates Lamothe's estimation of interglacial sea level high stand altitudes from the Somme strath terraces. Figure 3 will be compared later with the results for the Mattole River, also in a nonglacial setting.

Tectonic and Climatic Setting, Coastal Northern California

The sinuous Mattole River originates less than 5 km from the coast near Point Delgada, flows inland and northwestward 80 km along the region of greatest uplift rates in the MTJ, and exits north of the rugged King Range, the westernmost of California's Coast Ranges (Figure 2). Pronounced relief (up to 1246 m), rapid uplift rates (≥2.5-3 m/kyr) [*Merritts and Bull*, 1989; *Merritts et al.*, 1992a, b], and high seismicity are the result of complex interactions among the three plates joined along the migrating Mendocino triple junction (MTJ; Figure 2). Several isostatic, thermal, and mechanical models have been proposed to explain the mechanism(s) of crustal deformation at the MTJ and especially the rapid rates of surface uplift between Point Delgada and Cape Mendocino [c. f. *Jachens and Griscom*, 1983; *Furlong*, 1984; *Merritts and Bull*, 1989; *Dumitru*, 1991; *Merritts and Bonita*, 1991; *Merritts et al.*, 1992a, b]. The cause of rapid uplift is not treated here. For the purposes of this paper, the rates and

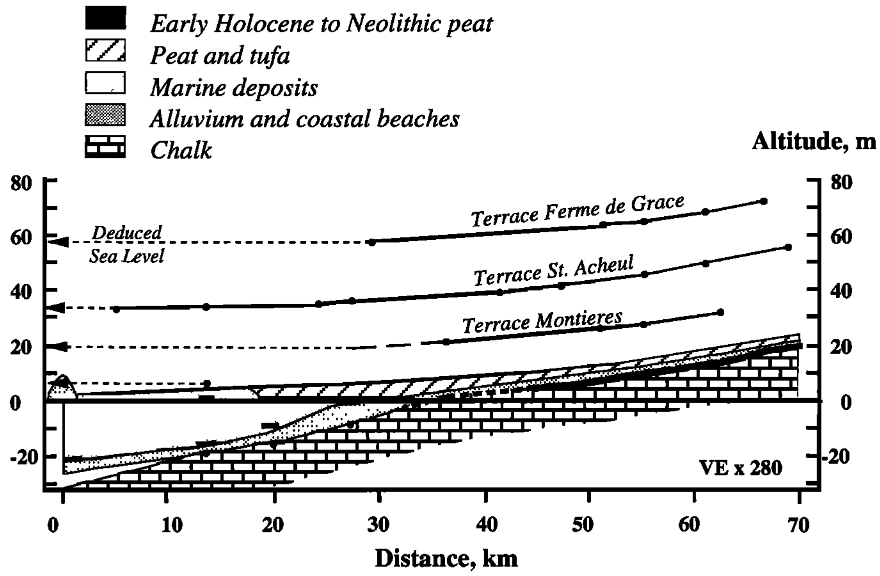

Figure 3. Longitudinal profiles of the Somme River channel bed and strath terraces, with subsurface data (black dots mark positions of drill holes) and terrace projections to presumed sea level high stands. Active channel bed shown as bold line. (Modified from *Lamothe* [1918] and *Clayton* [1968]).

spatial patterns of uplift are important and are discussed below for the case of the Mattole.

Ongoing uplift of the coast at the mouth of the Mattole River is documented by emergent Pleistocene and Holocene marine terraces, as well as by the recent coseismic emergence of up to 1.4 m during the April 25, 1992, Cape Mendocino M_s 7.1 earthquake (Figure 2) [*Merritts and Bull*, 1989; *Merritts et al.*, 1992a, b; *Oppenheimer et al.*, 1993]. The existence of Holocene and late Pleistocene marine platforms as far south as just north of Point Delgada, however, indicates that the coast along the entire length of the Mattole River has been subject to rapid surface uplift at rates of 2.5-3 m/kyr (and locally up to 4 m/kyr) over time periods of tens of thousands of years (Figure 2) [*Merritts and Bull*, 1989; *Merritts and Bonita*, 1991]. As the entire King Range terrane block, which extends inland to the Mattole trunk stream, has been uplifted during the Quaternary [*McLaughlin et al.*, 1982; *Dumitru*, 1991] and is at very high altitudes within 4-5 km of the coast, at least the western part of the Mattole Valley (which drains the King Range) and the trunk stream are presumed to have been subject to rapid rates of uplift during most of this time. Apatite fission track studies in the King Range and adjacent Coastal terranes indicate that Quaternary uplift and unroofing decreases in magnitude northeastward, from a local high in the King Range [*Dumitru*, 1991].

Modern and glacial climates of northern California are described here to support the assumption that modern climate is similar for the Ten Mile, Mattole, and Bear Rivers, and because past climates have some bearing on the possibility that environmental change might have invoked terrace formation. The northern California coastal region has a cool, temperate, highly seasonal Mediterranean climate, characterized by mild, wet winters and a prolonged summer dry season. During the winter, cold, dry air from the Asiatic continental anticyclone moves into the trough of the Aleutian low-pressure system, growing warmer and moister as it moves until, as the polar Pacific air mass, it encounters the orographic influence of the California Coast Ranges and inland high pressure systems, creating precipitation [*Heusser*, 1960, 1985; *Mitchell*, 1976]. Regional climate is unusually constant, and daily climatic data are almost identical for the Fort Bragg and Eureka coastal stations, near the Ten Mile and Bear Rivers, respectively (Figure 2). Mean monthly temperatures vary less than 6°C throughout the year; mean annual temperatures are 12-14°C; and more than 90% of the mean annual precipitation of 1.0 m occurs as rain resulting from regional maritime air masses during mild winters [*National Oceanic and Atmospheric Administration* (*NOAA*), 1985].

Within the center of the study area, however, local precipitation and fog cover are modified by the orographic effects of the King Range. Measured mean annual precipitation at the coast at Point Delgada is 1.65 m, and over the King Range crest at Honeydew it is 1.70-2.50 m. These differences probably affect water discharge and sediment yield within the King Range and consequently in western tributaries to the Mattole River. Despite evidence of local climatic variations; however, the dominant control on fluvial processes (as indicated by substantial seasonal variations in discharge (U.S. Geological Survey gauging station records for the Mattole and Ten Mile Rivers)) is regional, heavy winter rainfall, which probably affects all coastal drainages in a similar manner.

The late Pleistocene climate of northern coastal California was characterized by a series of cool-moist (glacial) and warm-dry (interglacial) alternations [*Heusser*, 1960], but alternations were of a much lesser magnitude than those that produced the major climatic changes of glaciated and continental interior regions [*Johnson*, 1977]. Climatic variations between glacial and interglacial periods were stabilized by maritime influences on intensities of temperature and precipitation gradients, and paleontological evidence indicates that the northern California coastal zone acted as an "ice age refugium" for cold-sensitive species displaced elsewhere [*Johnson*, 1977]. During the most recent full-glacial climatic conditions at 18 ka, estimated sea surface summer (August) temperatures (13°C) were similar to modern sea surface summer temperatures (~13°C; <1°C difference); however, winter temperature gradients were intensified, and estimated full-glacial winter (February) sea surface temperatures (7°C) were 4°C cooler than the modern winter temperature of

11°C [*CLIMAP Project Members*, 1981]. Although the region was not glaciated and is known to have acted as an ice-age refugium, the decreased winter temperatures might have resulted in sufficient environmental change to have an impact on onshore sediment yields and consequently terrace formation.

Methods of Surveying, Mapping, and Sampling

Prominent terrace surfaces are ubiquitous and nearly continuous along the lower 40 km of the Mattole River downstream from Honeydew (Figure 2). In the summer of 1991, we surveyed 1300 points and mapped in detail the active channel width and bottom, gravel bars, floodplain, and terraces (alluvial and strath surfaces; Plate 1) along the lowermost 40 km of the Mattole River with a Lietz total geodetic station (angular accuracy ±3 arc minutes at one standard deviation; linear accuracy ±(5mm + 3ppm) at one standard deviation). Surveying began at the mouth of the river, where marine terraces previously had been surveyed [*Merritts and Bull*, 1989; *Merritts and Bonita*, 1991; *Merritts et al.*, 1992a, b]. The survey transect ended at about 40 km, near the town of Honeydew, just upstream of which several large tributaries converge and the remaining 57 km of the trunk stream flows in a narrow bedrock gorge with few to no terraces. Because the survey traversed a 40-km-long strip of rugged topography, it was not possible within the several month survey period to return to the original starting position to close the entire survey. To minimize random survey errors, at least three temporary bench marks were surveyed and resurveyed prior to and after each time the total station was moved in order to check accuracy and close each survey loop. After surveying, tidal charts and bench marks were used to correlate surveyed altitudes to absolute altitudes. Similar surveys were done for the Bear and Ten Mile Rivers in 1990 and 1989, respectively [*Merritts et al.*, 1989, 1991].

The coordinates of survey points were plotted with a computer as a large-scale (~1:7000) plan view map and combined with field maps and notes to create a geomorphic and topographic base map (schematic example in Figure 4). This map (3 m in length for the Mattole River) was then used to construct a midvalley axial line drawn along the midpoint between the bedrock valley walls (dashed line in Figure 4). This line is less sinuous than the modern river channel. All points for long profiles were projected perpendicularly to this midvalley line, as is illustrated in the top of Figure 4. The distance to each point from the Pacific Ocean at the river mouth was measured with an Alteck digitizer, with a resolution of ±0.2 m at the scale of our map. Although the instrument has great precision, as a result of repeated stopping and starting to get cumulative distances to each point, the total error for distance along the river is about ±100 m out of 40,000 m. Distances and altitudes of each point were then plotted to construct long profiles for each terrace surface, the active channel bed, gravel bars, and the water surface (Figure 5b).

Samples of charcoal and wood were collected from strata within fill terraces or above strath surfaces for radiocarbon age dating at eight sites on the Mattole, 12 sites on the Bear, and two sites on the Ten Mile Rivers. Age estimates and their uncertainties were corrected for carbon reservoir effects and calibrated to a dendrochronologically-tuned record of varying carbon 14 in the

Plate 1. Two strath terraces on the right bank at km 34 on the Mattole River. Note solid line added to highlight strath surfaces and riser between them. Thickness of alluvial deposits above lower strath surface is about 2.5 m, and above upper surface about 3 m. Deposits fine upward, from channel bed gravel immediately above strath to fine-grained (clay, silt, and fine sand) overbank deposits. Upper surface is the same as that dated at ≥9.9 ka on left bank, 0.5 km upstream.

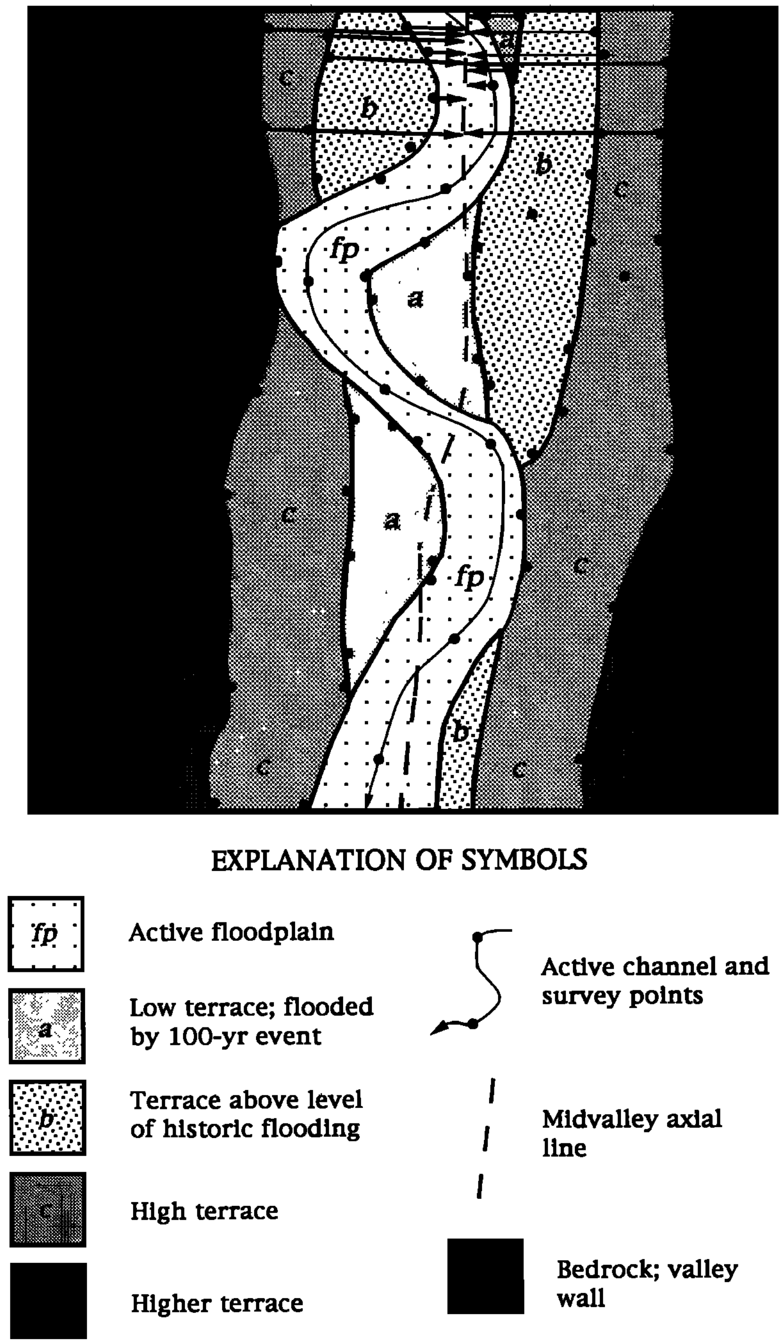

Figure 4. Schematic map illustrating method of constructing a geomorphic map of a river system, including its active channel (thalweg and banks), floodplain, terraces, and valley floor walls. Dashed axial line is constructed from midpoints along valley. Arrows in top part of diagram show how survey points are projected perpendicularly to midvalley axial line. Distance to each point along the midvalley line is then determined with a digitizer to construct longitudinal profiles.

atmosphere, according to established methods (Table 1). In some cases, calibration of carbon-14 ages with the dendrochronological record results in more than one likely possibility for the age range, and ages are presented as multiple ranges. In the text, ages are presented as the calibrated age range for ±one standard deviation, in years B.P., according to protocol (e.g., 2000-2575 cal years B.P.); for brevity, they are referred to by the centroid of this range on some figures. Radiometric age estimates mentioned in the text below include the sample number for identification in Table 1.

Results of Terrace Investigations

General Observations

The longitudinal profile of the Mattole River obtained from 7.5 arc minute topographic maps (Figure 5a) is segmented. The reach within longitudinal distances of zero and 60 km is composed of two linear segments that join at about 30 km. Upstream of 30 km, the river has a gradient of 0.0032 (meters per meter), but downstream of 30 km the gradient is 0.0014, a decrease in gradient of ~55%. Only ~8 km of the steeper segment is depicted

Table 1. Summary of Radiocarbon Dates From Sediments in Strath and Fill Terrace Deposits in Upstream Order.

Sample	Lab	Lab Number	Carbon 13 Adjusted Age ± One S.D., Years B.P.	Calibrated Age Range ± One S.D., Calibrated Years B.P.	Calibrated Age Range Centroid, Calibrated Years B.P.	Stratigraphic Description	Calibration Reference
NC-1-87	Krueger Enterprises, Inc.	GX-16205	6295 ± 335	6163-6863	6472	mussel shell cemented to marine platform	*Stuiver and Pearson* [1993]
M2-1-91	Beta Analytic Inc.	47147	2310 ± 140	2143-2469	2338	charcoal from blue clay 2 m below top of interbedded sand, silt, and gravel of fill terrace	*Stuiver and Pearson* [1993]
M4-5-91	Beta Analytic Inc.	46475	4260 ± 180	4536-4993; 5011-5035	4835	charcoal from burned tree roots (in situ) in floodplain silts 2 m above strath surface, immediately above channel bed gravels	*Stuiver and Pearson* [1993]
M5-5-91	Beta Analytic Inc.	46478	1305 ± 55	1171-1285	1263	charcoal from floodplain silts 0.5 m above strath surface, immediately above channel bed gravels	*Stuiver and Pearson* [1993]
M5-3-91	Beta Analytic Inc.	47149	4280 ± 110	4650-4673; 4704-4758; 4815-4878; 4934-4972	4839	charcoal from sand interbedded with cross-bedded fine gravel, 2.3 m above strath surface, at base of flooplain silts	*Stuiver and Pearson* [1993]
MT-A-1	USGS	2224	5145 ± 40	5896-5929	5912	charcoal from thin beds of interbedded very fine sand and silt 2 m above strath, immediately above channel bed gravels	*Stuiver and Pearson* [1993]
MT-A-3	USGS	2226	5435 ± 45	6191-6289	6214; 6227; 6274	charcoal from thin beds of interbedded very fine sand and silt 2 m above strath, immediately above channel bed gravels	*Stuiver and Pearson* [1993]
MT-A-2	USGS	2225	9230 ± 290	9951-10545; 10766-10784	10157; 10180; 10195; 10261; 10278	log in channel bed gravels, <1 m above strath surface	*Kromer and Becker* [1993]
M6-1-91	Beta Analytic Inc.	46479	7740 ± 70	8410-8550	8436; 8471; 8484	charcoal from base of clayey sand to fine sandy silt, ~10 m above strath overlain by coarse, bouldery channel bed gravel from tributary on left bank	*Linick et al.* [1986], *Pearson et al.* [1993]

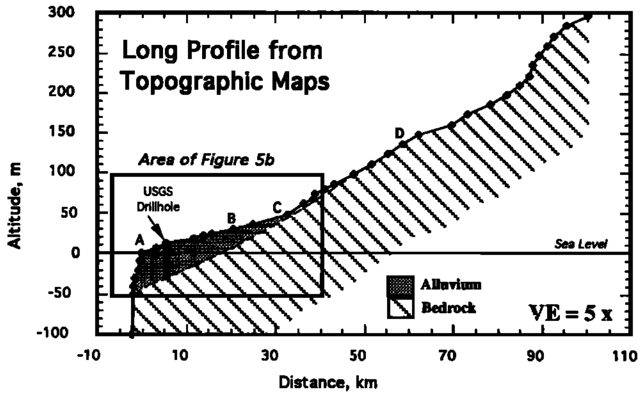

Figure 5a. Longitudinal profiles of the Mattole River. Channel-bed profile from 1:24,000 topographic maps and 1:250,000 offshore bathymetry (diamonds indicate data points). Note that gradient of reach A-C is 0.0014, while gradient of reach C-D is 0.0032. Reach A-B is zone of fill terrace occurrence, and reach B-D is zone of strath terrace occurrence.

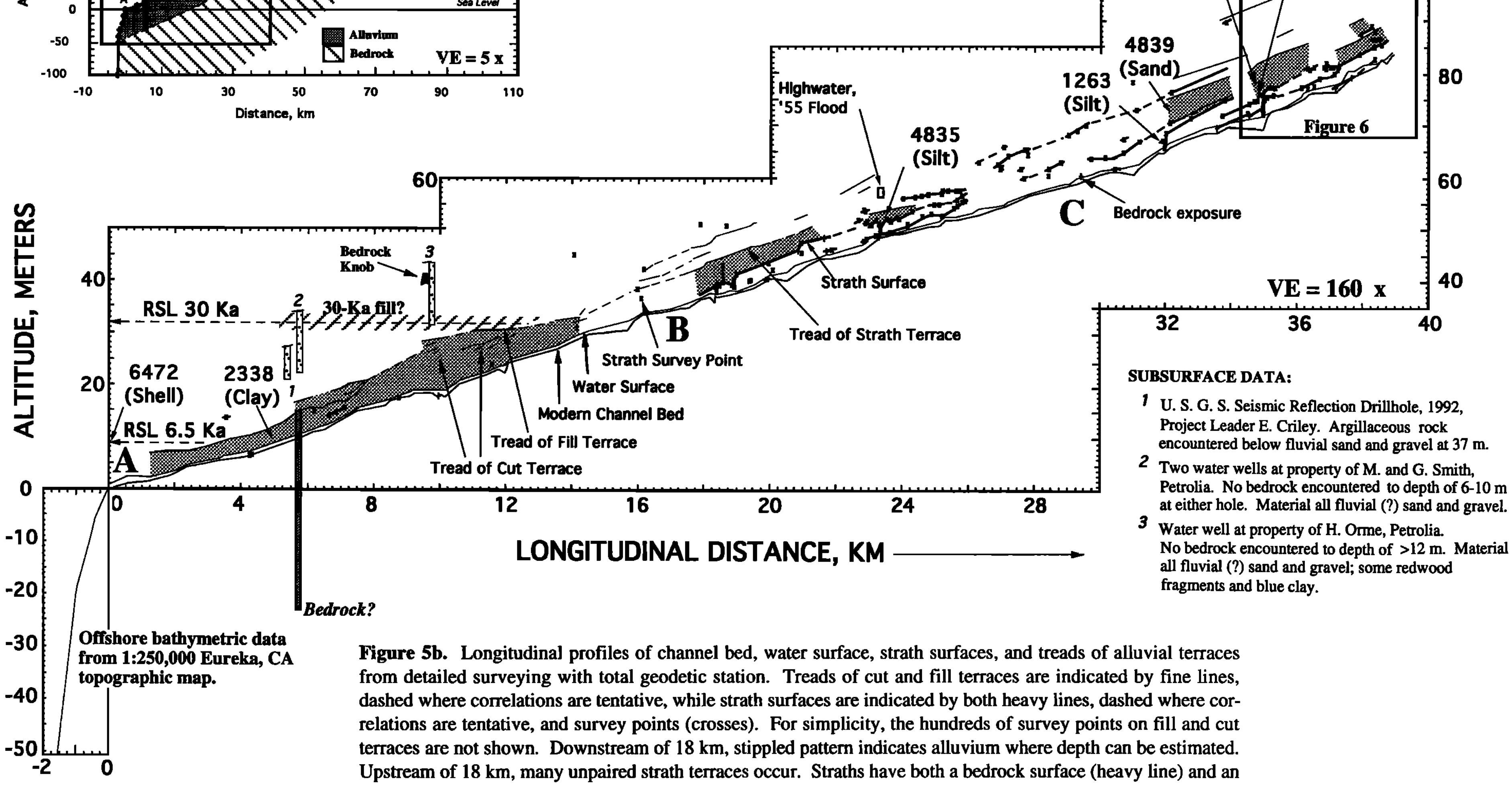

Figure 5b. Longitudinal profiles of channel bed, water surface, strath surfaces, and treads of alluvial terraces from detailed surveying with total geodetic station. Treads of cut and fill terraces are indicated by fine lines, dashed where correlations are tentative, while strath surfaces are indicated by both heavy lines, dashed where correlations are tentative, and survey points (crosses). For simplicity, the hundreds of survey points on fill and cut terraces are not shown. Downstream of 18 km, stippled pattern indicates alluvium where depth can be estimated. Upstream of 18 km, many unpaired strath terraces occur. Straths have both a bedrock surface (heavy line) and an overlying alluvial tread (fine line), so stippled patterns for gravels and fine sediments overlying straths would overlap. Only deposits at several sites are shown as stippled pattern to indicate corresponding straths and treads. Radiocarbon dates are centroids of calibrated age ranges in years before present (see Table 1 for complete data). RSL, relative sea level determined from both sea level change and landmass uplift (see text); ka, kiloannum, or thousand years before present.

on the detailed survey profile of Figure 5b, but, for the segment below 30 km, the profiles of the channel bed (thalweg), water surface, and gravel bars are parallel and remarkably straight. For example, linear regression results (in meters) for the channel bed and water surface (from survey points) yield $y = -1.30 + 0.0014\,x$ ($R^2 = 0.99$) and $y = -0.81 + 0.0014\,x$ ($R^2 = 1.00$), respectively. The variable vertical difference between the channel bed and water surface profiles illustrates alternating pool and riffle sequences [*Wohl et al.*, 1993].

A second important observation is that two different types of terraces exist along the Mattole River, and the type has a general association with valley floor width and distance upstream. From 0 to 18 km, the wide (1-2 km) valley floor is dominated by alluvial terraces. From 18 to 40 km, the valley floor is narrower than that downstream (0.3-0.5 km), and is fringed with a stepped series of unpaired strath terraces with cover sediments. Upstream of 40 km, the valley becomes a narrow gorge, with no or occasional strath terraces and a bedrock floor.

Terraces and the active channel floor along the lower ~18 km of the river are compossed of alluvium (cut and fill terraces; shown as fine lines in Figure 5b). Occasional bedrock knobs are surrounded by alluvium, as at km 10 (altitude = 40 m). An estimate of the minimum thickness of the alluvium comprising the elevated fill terrace at km 10 is available from multiple water-well logs which indicate that sand, gravel, and clay occur to a depth of at least 12 m. In an upstream direction from km 18, the occurrence of strath terraces along the valley walls and of bedrock in the channel floor increases in frequency (e.g., Plate 1; straths shown as heavy lines in Figure 5b). These surfaces are distinct, can be followed for up to several kilometers, and in some places merge together upstream, as at km 26, 32, and 37. At all locations, straths are overlain by up to 1-2 m of coarse gravels, which in turn are overlain by up to 1-3 m of fine-grained sands and silts (Plate 1). Alluvial fans at tributary mouths cause these deposits to be locally much thicker (up to 12 m). The tops of these sediments overlying the strath surfaces are shown also as fine lines in Figure 5. These terrace treads, unlike those downstream, do not represent the surfaces of fill or cut terraces but rather the capping of sediments on a strath surface.

A third observation is that the active channel floor of the lower part of the Mattole (0 to 30 km) is the top of a gravel wedge that tapers to zero upstream. The surface of this wedge (Figure 5a, reach A-C) has a gentler gradient (0.0014) than the bedrock reach upstream (Figure 5a, reach C-D, gradient 0.0032). An estimate of the total thickness of the gravel veneer near the mouth, at km five, is obtained from recent U.S. Geological Survey (USGS) drilling along the right bank of the channel (Figures 5a and 5b). Bedrock was not encountered until a depth of least 37 m, when a large mass of blue, argillaceous rock, identical to the local bedrock, was hit (T. Dunklin, drill logger, personal communication, 1992, USGS Cape Mendocino Seismic Reflection Experiment; E. Criley project director). At km 35, deep bedrock pools alternate with gravel riffles on the active channel floor, and the gravel veneer is less than several meters thick. The long profile of the Mattole obtained from topographic maps (1:24,000) reveals additional information to the survey and subsurface data (Figure 5a). The river's long profile in bedrock reach C-D is nearly straight at this scale and, if projected downstream beneath the gravel wedge (Figure 5a), would occur just beneath the 37-m depth to estimated bedrock. This upper reach and its gradient might indicate a zone of adjustment to long-term uplift.

The final general observation is that straths project into the modern channel bed between 18 and 38 km, forming a series of benches that emerge from the channel, one after the other, as one follows the river upstream. Although strath surfaces are subparallel to one another, they are steeper than the modern channel bed downstream of 32 km (0.0032 gradient versus 0.0014), have the same gradient as reach C-D (Figure 5a) of the Mattole, and do not merge with marine terraces at the river mouth (Figure 5b). The upstream breaks in slope of prominent, near-horizontal fill terraces along the river at 3 and 12 km, coincide with the inner edge altitudes of the two youngest marine terraces, 6.5 and 30 ka in age, respectively. The position of the 30 ka interstadial sea level high stand marine terrace (inferred from altitudinal spacing analysis [see *Merritts and Bull*, 1989]) is obtained from surveys along the coast 1 km south of the mouth of the Mattole. The position of the inner edge of the mid-Holocene marine platform (the preemergence terrace), dated via a mussel shell (NC-1-87) attached to the platform (6163-6863 cal years B.P.), is from a survey 1 km north of the mouth [*Merritts et al.*, 1992a, b].

Interpretation of Deposits Overlying Strath Surfaces

The coarse, bouldery, subrounded to rounded gravels overlying strath surfaces (Plate 1) are similar in size, sorting, and shape to those in the active channel bed, and we assume that they were left as deposits upon the straths after abandonment by the channel. Ages of these channel bed gravel deposits probably are roughly synchronous with the time of formation of the strath surface. In contrast, cumulic, stratified, very fine-grained sands, silts, and clays which cap the gravels postdate the time of strath formation and are the result of flood events that were large enough to overtop the terrace gravels. These are referred to here as overbank deposits.

Radiometric dating of overbank deposits at multiple sites on both the Bear and Mattole Rivers indicates that they can be at least as much as 3000 years younger than the underlying gravels at a given locality. For example, at km 34.8 on the Mattole (Figures 5 and 6), a log in channel bed gravels <1 m above a strath yielded an age of 9951-10545 or 10766-10784 cal years B.P. (MT-A-2). Two samples of charcoal from thin beds of very fine-grained sand and interbedded silt directly above the gravel, 2 m above the strath, yielded ages of 5896-5929 cal years B.P. (MT-A-1) and 6191-6289 cal years B.P. (MT-A-3). The older date from the gravels is a minimum age for the strath (strath ≥9.9 ka), but is much closer to the strath age than a date from the overlying sand and silt (strath >>5.8-6.3 ka). Terrace gravels provide an upper limit on the altitudinal position of the channel floor associated with the strath and a minimum limit on the time of strath formation (Figure 6). The overbank deposits are also useful, in that they provide an approximate age and an upper limit for the altitudinal position of the channel bed that flooded to that level to deposit the fine-grained material (Figure 6).

Interpretation of Deposits Within Cut and Fill Terraces

Near the Mattole River mouth, several of the alluvial terrace surfaces are nearly horizontal, while others have steeper gradients and converge upstream with them, as at 10-12 km (Figure 5b). We conclude that these represent both fill and cut terraces, respectively, with the latter cut from the alluvium of the former. Few exposures of the strata that comprise the fill and cut terraces occur, except in occasional gullies. Even these provide little stratigraphic information because of slumping and the ubiquitous cover of poison oak, vines, and nettles. Where exposures do exist, however, no bedrock is found, with exception of occasional isolated knobs. Data from numerous water wells indicate that all terraces downstream of about 14-18 km are composed of thick sequences of cobbles, sand, silt, and blue clay (discussions with

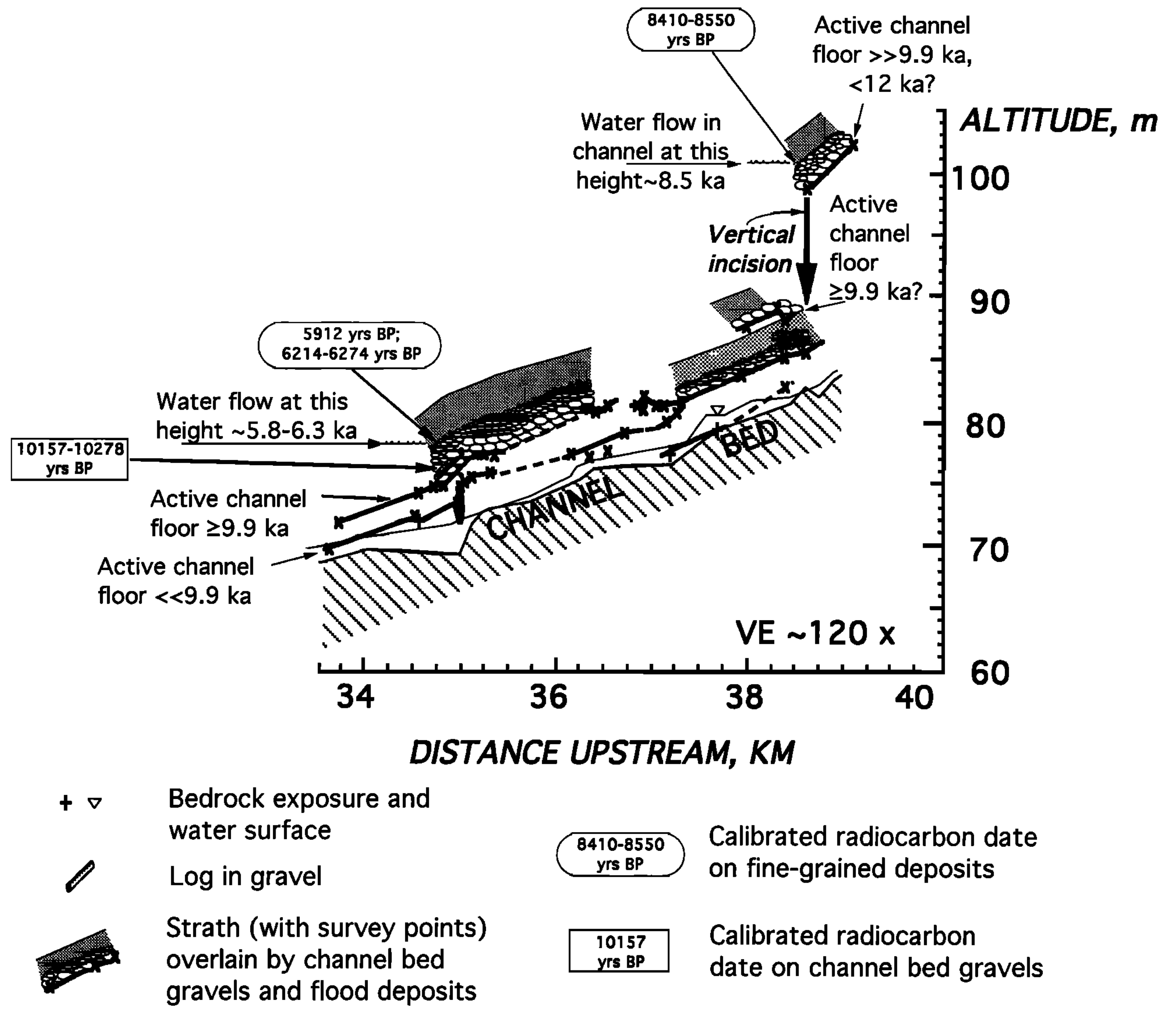

Figure 6. Detailed stratigraphy and terrace correlation from 34 to 39 km, indicating means of estimating rates of vertical incision.

local drillers and landowners in Petrolia). As local groundwater levels are high, drillers rarely go below depths of 12 m, and actual well log data were only obtained for wells at km 6 and 10 (Figure 5b). These well logs indicate that the upper 12 m of alluvium are probably dominantly fluvial and estuarine rather than marine (no shells noted) and composed of sediments similar to that found at the present mouth. The blue clay is described by locals as very common and likely to be found anywhere one drills along this part of the river. Blue clay is a common weathering product from argillaceous rocks of the California Coastal and King Range terranes. However, blue clay also commonly indicates reducing conditions and might be similar to the estuarine clays noted by *Ota et al.* [1991] in the strata examined in the mouths of rivers in New Zealand.

Results

Terrace Surfaces and Reconstruction of Paleo-Long Profiles

Just as it is possible to construct a long profile of the active channel and floodplain for the modern Mattole River, it is also possible from the data presented in Figure 5b to reconstruct approximate paleo-long profiles. Because the channel is sinuous and the positions of meanders migrate with time, we do not know the exact location of all points along the river's channel for a given time. For this reason, and because age control is not available for all terraces or for all reaches of the river, the recon-

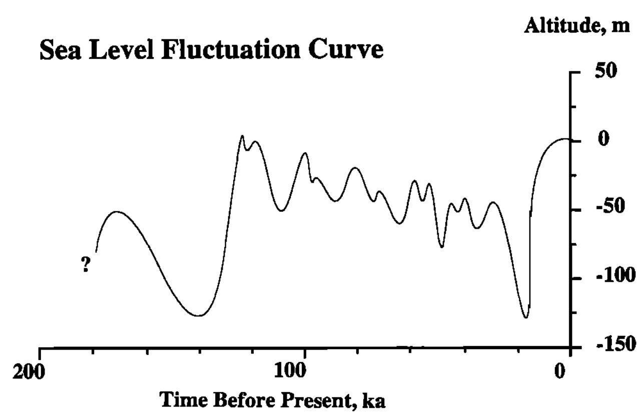

Figure 7a. Late Pleistocene sea level curve from *Chappell and Shackleton* [1986]. Note that sea level has been low for most of the past 125 kyr, and reached its lowest stand about 18 ka.

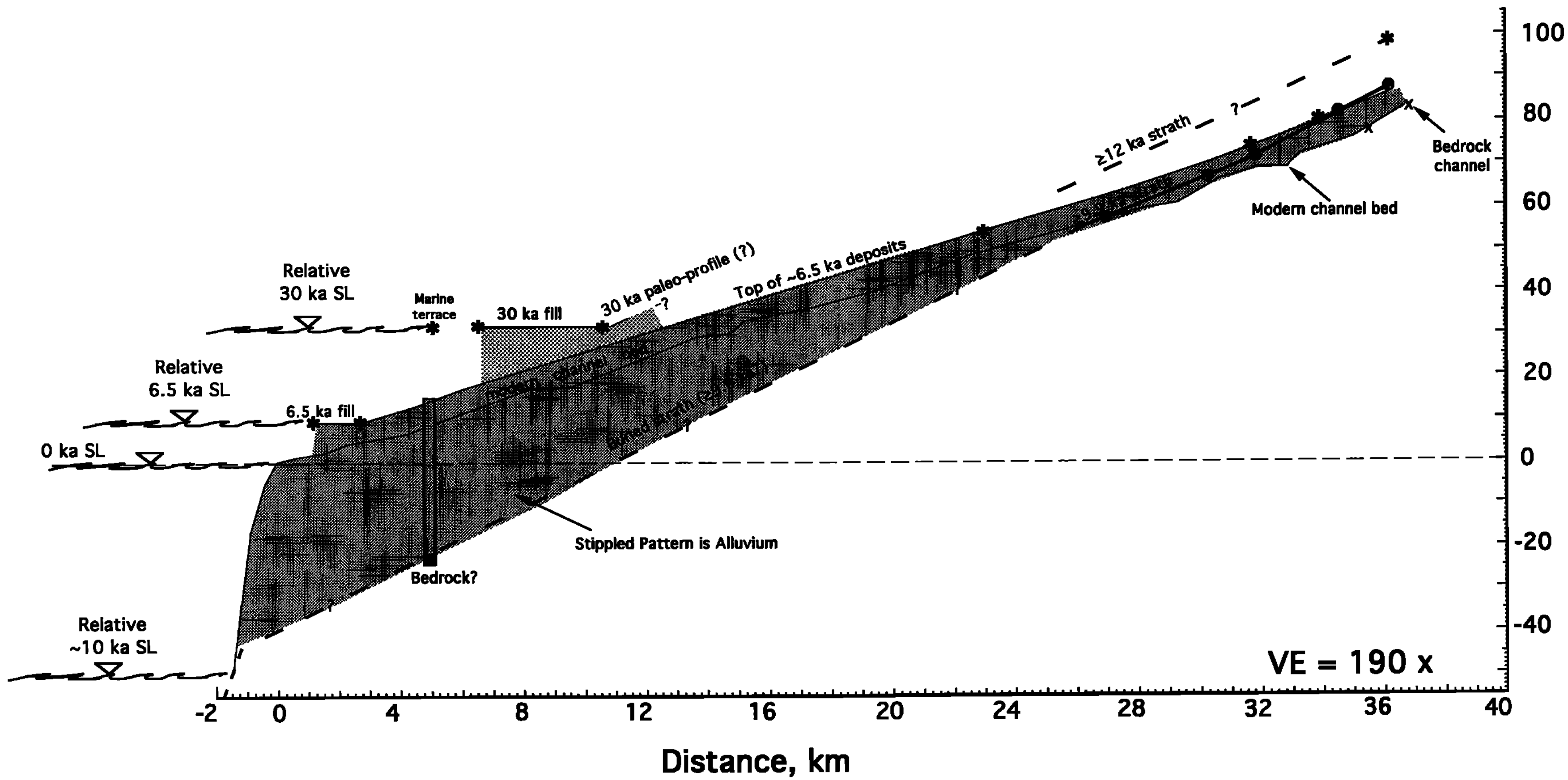

Figure 7b. Interpretation of paleoprofiles of Mattole River from 30 ka to the present. Heavy lines are strath surfaces from Figure 5b. Bold asterisks indicate "anchor" points for constraining positions of paleoprofiles. Anchor points for strath surfaces are indicated as circled asterisks. The ≥9.9 ka strath is tentatively projected beneath the modern gravel stream bed and downstream toward the altitude of the estimated sea level low stand at that time and beneath the base of the USGS drill hole which encountered gravel to a minimum depth of 37 m, and possibly bedrock at that depth.

structed paleoprofiles are referred to as approximate. They are anchored by the survey and age data available, as illustrated in the following example for reconstructing a 6.5 ka paleo-long profile.

A maximum height for the altitudinal position of the Mattole River channel bed during the ~6.5 ka sea level high stand is reconstructed from four "anchor" points along the river's length (stars on Figure 7b). At the downstream end, we anchor the profile at the terrace break in slope which is coincident with the horizontal projection of the inner edge altitude of the marine platform dated at 6163-6863 cal years B.P. (NC-1-87), where it coincides with the break in slope in the alluvial fill terrace. The ~6.5 ka marine terrace occurs 7-10 m above sea level today (due to 17 m of uplift since its formation at an altitude of about -10 m [*Fairbanks*, 1989]). At the upstream end, at km 35, we anchor the profile just below the fine-grained deposits that date at 5896-5929 cal years B.P. (MT-A-1) and 6191-6289 cal years B.P. (MT-A-3). To deposit sand and silt in the channel or over the bank, the channel bed itself had to be at or below the level of the dated deposits, but within the range of maximum possible overbank flooding (Figure 6). At present, this range is about 7 m, based on the maximum stage of the largest flood in historic time, the 1955 event (Figure 5, km 24). Between the downstream and upstream endpoints, we project the 6.5 ka profile below fine-grained deposits at two sites (32 and 24 km) that yield dates from near the tops of the deposits of ~4650-4972 cal years B.P. (M5-3-91), and ~4536-5035 cal years B.P. (M4-5-91). We assume that deposits that are 6.5 ka in age exist below the younger overbank deposits. The final approximate paleoprofile constructed for 6.5 ka is shown in Figure 7b.

We use similar reasoning to reconstruct long profiles for the 9.9 and 12 ka profiles of the Mattole River (Figure 7b). Several details of these correlations are as follows. The paleoprofile on the age-constrained ≥9.9 ka surface (from the date on a basal log) is obtained merely by following the well-exposed surface. Note that this surface has a nearly constant gradient (0.003) that is similar to that of all other straths and to that of bedrock reach C-D (Figure 5a) of the Mattole River. Paleoprofiles for older straths are not as well-constrained. A higher strath at km 39 has a minimum radiometric age of 8410-8550 cal years B.P. (M6-1-91), based on charcoal from the base of the fine-grained deposits overlying the strath. This date indicates that the strath formed more than ~8.5 kyr ago, and perhaps more than 11 or 12 kyr ago, if deposition of silts and sands postdates strath formation by as much as 3.5 kyr (the maximum age difference from dated sites on the Mattole and Bear Rivers). It also indicates that a channel existed below that altitude at ~8.5 ka, with floodwaters rising to that level at that time (Figure 6). We assume an approximate age of ≥12 ka for the time of formation of this strath surface, by adding 3.5 kyr to ~8.5 ka. The profile for this paleobedrock surface is then determined by noting that all continuous bedrock straths have about the same gradient (Figure 5b), and using this observation as an assumption to determine the gradient of the ~12 ka surface. For the 30 ka profile, we only have anchor points at the mouth, where a prominent, near-horizontal fill terrace is at the same altitude as the inferred 30 ka marine terrace [*Merritts and Bull*, 1989]. However, we assume that the channel bed upstream was higher than all younger straths, as the channel later incised to those levels. These straths provide a minimum height for the profile. Furthermore, if we assume an average long-term incision rate for the river (see discussion below) of 0.8-1.5 m/kyr, the 30 ka paleoprofile would be at least 24-45 m above the present channel upstream of km 32 (Figure 5b). This paleoprofile is the least well-constrained, but still provides useful information for later analysis.

Why Straths Are Steeper Than the Modern Stream Bed

One of our major observations (Figure 5b) is that the Mattole River strath terraces are roughly parallel to each other but are steeper than the active stream bed by 0.0018 m/m. In a downstream direction, the straths converge with and disappear into the channel bed. One explanation for this difference in gradient is that the terraces have been tilted by tectonic processes. This hypothesis can be evaluated by examining the hypothesized sequence of events required to cause such tilt. First, older straths are nearly parallel to the ≥9.9 ka strath surface downstream of 36 km. Therefore, no tectonic tilt occurred during the period of about 20-30 ka to 9.9 ka, but since 9.9 ka, significant tilt has occurred. As a consequence, ten thousand years is the maximum tilt duration. If we assume that the stream gradient at the time of strath formation was the same as that of the active channel bed (0.0014), the tilt magnitude is 0.0018 m/m. This converts to a minimum tilt rate of 0.18 m km^{-1} kyr^{-1} (equivalent to 0.18 μrad yr^{-1}; this is a very rapid rate of tilt relative to other known rates in the world).

Uplift of the King Range is not uniform. For example, along the coast between Cape Mendocino and Big Flat, differential uplift has resulted in tectonic tilt of 0.04 μrad yr^{-1} over the past 70 kyr or so [*Merritts and Vincent*, 1989]. This stretch of coast is parallel to but outboard of the middle reach of the Mattole. Although the differential uplift along this middle reach (where straths occur) is unknown, the required tilt rate (0.18 μrad yr^{-1}) is almost five times greater than that observed along the coast. Furthermore, evidence suggests that the uplift rates (and therefore tilt) probably decrease inland from the coast rather than increase. Recent analysis of Holocene surface uplift rates obtained from marine platforms at the coast determined that rates are high from Cape Mendocino to just north of Point Delgada, parallel to the length of the Mattole River [*Merritts et al.*, 1992a, b]. However, during the 1992 Cape Mendocino earthquake, the magnitude of surface uplift decreased to zero inland from the coast (Figure 2) [*Oppenheimer et al.*, 1993]. Furthermore, apatite fission track [*Dumitru*, 1991] and vitrinite reflectance [*Underwood et al.*, 1988; *Laughland et al.*, 1990] studies indicate that rapid Quaternary rock uplift and unroofing decrease northeastward from the King Range, perpendicular to the length of the Mattole (see above discussion in section on tectonic and climatic setting). In conclusion, tectonic tilt as the cause for strath terraces being so much steeper than the modern channel bed seems unlikely.

A more reasonable explanation for why straths are steeper is that repeated, rapid sea level rise during the Quaternary Period has caused a wedge of sediment backfilling (Figure 5a) that has migrated upstream, with decreased gradient, and buried the extension of the straths shown on Figure 5b. Study of the effect of base level rise on streams has centered largely on the effect of small check dams built across very small streams [e.g., *Leopold and Bull*, 1979; *Leopold*, 1992]. The conclusion of these studies is that base level rise will cause a wedge of sediment deposition to migrate upstream a relatively short distance in a short time, after which it will remain stable. When deposition is complete, the gradient of deposition is about half the gradient of the original channel (*Leopold*, 1992). The depositional wedge on the Mattole (Figure 5a) extends upstream about 30 km (31% of the total stream length) and to an altitude of about 60 m above sea level (in effect the lip of the check dam). These values of distance and height are large compared to those of smaller streams and might be the result of the much greater size of the Mattole River. The one parameter directly comparable to previous work on small streams is the change in gradient to about one half during aggradation. As mentioned, the gradient of the lower or depositional reach of the Mattole is 45% of the gradient of the channel upstream of the wedge.

History of Terrace Formation

From constraints regarding the position of the mouth of the Mattole River during sea level high stands [*Merritts and Bull*, 1989] and its channel bed altitudinal position at different times between 30 ka and the present, we can examine its response to sea level fall from 30 ka to 18 ka, and to rapid sea level rise from then until about 6.5 ka (Figure 7a). Since 6.5 ka, sea level has risen very slowly relative to the preceding 12 kyr. As no local sea level curve is available, data from New Guinea [*Bloom et al.*, 1974; *Chappell and Shackleton*, 1986] and Barbados [*Fairbanks*, 1989] are used (Figure 7a). Their use is considered valid for this analysis, as it depends only on general and relative trends with time. Note that we assume the simplest case of base level fall due to uplift, i.e., that an average uplift rate of 2.6 m/kyr is uniform along the length of the Mattole, and tilting or folding along its length are insignificant.

Terraces and Sea Level Fall From 30 to 18 ka

The most recent sea level high stand before the present was 30 kyr ago, at -44 m. This high stand caused inundation and backfilling of what is now the lowermost 6-12 km of the mouth of the Mattole (Figures 6b and 7b), although the upstream extent of the depositional wedge is unknown. The level of the northern California coastal land mass has been uplifted about 76 m since that time, and the relative position of the 30 ka high stand is now ~32 m above modern sea level (2.6 m/kyr * 30 kyr + (-44 m) = 32 m). Between 30 and 6.5 ka, global eustatic sea level reached its lowest stand in perhaps the past 125 kyr, about -125 m at ~17-18 ka. During this period of exceptionally low global sea level, including the 12 kyr of sea level fall just prior to it, we propose that alluvium and bedrock in the river mouth were removed by deep incision, and strath surfaces were formed that dip more steeply than the modern, backfilled channel bed.

The USGS drilling data provides corroborative evidence that the bedrock floor of the valley is below many 10s of meters of gravel 5 km upstream of the channel mouth (Figure 5 and 7b). We have no other data regarding the nature of the bedrock valley floor at the mouth, except from offshore bathymetry, which indicates a narrow (<3 km wide) and very steep continental shelf and a deep submarine canyon (Mattole Canyon) just north of the present river mouth. The offshore profile of the Mattole River shown in Figures 5b and 7b follows the Mattole Canyon. The buried bedrock valley floor might be a prominent knickpoint which acts much like a bedrock waterfall when exposed, or a series of knickpoints between the mouth and the first clear evidence of exposed bedrock valley floor (at 34-38 km on Figure 5a). Regardless, the steepness of the shelf and offshore canyon are such that the slope of the bedrock valley floor must steepen rapidly somewhere near the present mouth.

Terraces and Sea Level Rise From 18 to 6.5 ka

Between 18 ka and 6.5 ka, sea level rose rapidly in response to global melting of ice sheets and valley glaciers. Although the rate of eustatic rise (up to 24 m/kyr at 12 ka in Barbados [*Fairbanks*, 1989]) exceeded that of tectonic uplift in northern California, sea level was still low relative to its earlier interstadial high stand at 30 ka, and it was not until between 9 and 6 ka that straths at the mouth of the river were submerged and buried during backfilling, at an altitude of ~-10 to -20 m relative to modern sea level. We tentatively project, in a downstream direction, straths exposed upstream of 18 km beneath the channel bed, below the minimum depth to bedrock of -37 m near the mouth, and to the coast (Figure 7b), where we indicate the estimated relative position of sea level about 10 ka (using the sea level history data of [*Fairbanks*, 1989] from Barbados, and an uplift rate of 2.6 m/kyr).

Sea level has been so low since the last major interglacial high stand at 125 ka, that even during times of sea level rise prior to each interstadial high stand, it was low relative to the bedrock lip presumed to be buried beneath the gravel at the mouth of the Mattole gorge (Figure 7a). Because of this local base level control, it is possible that the channel was flowing on bedrock downstream of 40 km during times of rising as well as falling sea level. Supporting evidence for this interpretation is the radiocarbon date of ~9.9-10.8 ka for the log sampled from channel bed gravels on the strath at 35 km (Table 1; Figures 5 and 6). This date indicates that gravel was being transported across the strath, and hence it was probably active, at that time, while sea level was rising at the mouth. As this strath is now 5-7 m above the active channel bed (Figure 6), net vertical incision has occurred since then, during a time of decelerating sea level rise, but net tectonic uplift of 7-10 m.

Terraces and Relative Base Level Fall From 6.5 ka to the Present

During and since the time of stabilizing sea level at ~6.5 ka, wave-cut bedrock marine platforms have formed along the coast immediately north and south of the mouth of the Mattole River, but inundation of the incised valley mouth gorge, from which much bedrock and alluvium probably had been removed already during earlier times of relatively low sea level, was associated with aggradation and formation of a fill terrace. Near the mouth, this deposit is a mixture of interbedded gravel, sand, silt, and blue clay. Charcoal from a 1.5-m bed of blue clay 2 m below the top of the fill terrace at 5 km yields a radiometric age of 2143-2469 cal years B.P. (M2-1-91). The resulting deposit decreases rapidly in thickness upstream but perhaps was associated with burial of older strath surfaces as far upstream as km 24-35, where mid-Holocene age overbank deposits overlie strath surfaces and early Holocene gravels. The river has incised about 5-7 m at km 35 since ~6.5-10 ka, and consequently it has exposed older strath terraces that were partially buried during the early- to mid-Holocene sea level rise.

Conclusions Regarding Terraces, Eustasy, and Tectonism

Tectonic and Eustatic Significance of Strath and Fill Terraces

The response of the Mattole River to high-frequency fluctuations of sea level and long-term tectonic uplift supports the conclusions of *Leopold and Bull* [1979] and *Leopold* [1992] regarding the impact of base level rise on a river's long profile. Furthermore, the results discussed here add important scale relations for a river much larger than those which they studied. Sea level high stands have resulted in episodic backfilling at the river mouth when the water surface rises relative to the land mass. Fill terraces with gentle gradients also occur at the mouths of the Bear and Ten Mile Rivers. Aggradation has been restricted to the lower reaches of the rivers, however, and even as sea level continued to rise at the coast, vertical bedrock incision occurred upstream at km 35 on the Mattole since ~6 kyr ago. Although aggradation probably also occurs in response to climate change [e.g., *Weldon*, 1986; *Bull*, 1990], the evidence that full-glacial climates were not substantially different than at present in this region, the location of fill terraces along only the lower reaches of the rivers, and the overwhelming evidence of tectonic and eustatic controls on terrace formation, suggest that climate plays a relatively minor role.

The nature of the straths shown in Figure 5b (subparallel, closely spaced, upstream-merging surfaces with about the same gradient as bedrock reach C-D of the Mattole, Figure 5a) indicates that despite repeated sea level high stands, the dominant long-term trend of the Mattole upstream of ~18 km has been one of nearly continuous vertical incision, as well as lateral erosion, due to long-term tectonic uplift. The terraces formed by incision are unpaired and do not indicate periods of base level stability and lateral valley floor beveling punctuated by episodic incision. As noted by *Davis* [1902, 1954], a meandering channel swinging sideways while also incising downwards will remove parts of older terraces during its sweeps back and forth across the valley width, and leave unpaired remnants that are parts of what can be imagined as a continuously downward-moving, switch-backing surface (dashed line in Figure 8), of which only marginal remnants now exist. The time of formation of a strath surface is synchronous with the river's sweeping along a bedrock surface inclined toward the valley bottom, but the time of formation of the riser (and hence the terrace itself) is synchronous with the sideways sweep of the river that removed the rest of the inclined surface.

It is curious that a river that is nearly continuously incising would form a series of terraces instead of a V-shaped gorge. Many such valleys with few or no terraces do exist in the region, including the uppermost 50-60 km of the Mattole and numerous adjacent rivers in the Coast Ranges (compare discussion of nearby inner gorges by *Kelsey* [1988]). The critical factor for terrace formation is upstream drainage area, as it relates to discharge and hence stream power. The size and valley-ward slope of the terrace remnants are controlled by the ratio of the rate of lateral migration to the rate of vertical incision. The former is a function of discharge and stream power (and therefore mainly drainage area), while the latter is a function of the long-term rate of uplift. If the ratio is very large, the valley-ward slope will be gentle, and broad strath surfaces will be carved (Figures 8e and 8g); if it is small, steep, narrow surfaces will be carved (Figure 8f and 8h). If it is very small, a V-shaped gorge with no terraces will form. A functional power/incision rate ratio can be defined for each reach of a river, for which the greater the value of this ratio, the greater the likelihood of formation of broad strath surfaces.

The fact that few to no terraces occur in the bedrock gorge farther upstream in the Mattole valley, and none in the smaller rivers immediately to its south, indicates that erosion there is dominantly vertical, and the lateral component, or meander migration, is insufficient to form and preserve strath terraces (i.e., the power/incision rate ratio is small). Rivers with large drainage areas are more likely than small ones to have the power to erode laterally at rates greater than vertical incision (compare Figures 8a and 8c with 8b and 8d). For a given size river, the greater the uplift rate, the greater the rate of vertical incision, and consequently the less the likelihood of formation and preservation of broad strath terraces (compare Figures 8a and 8b with 8c and 8d).

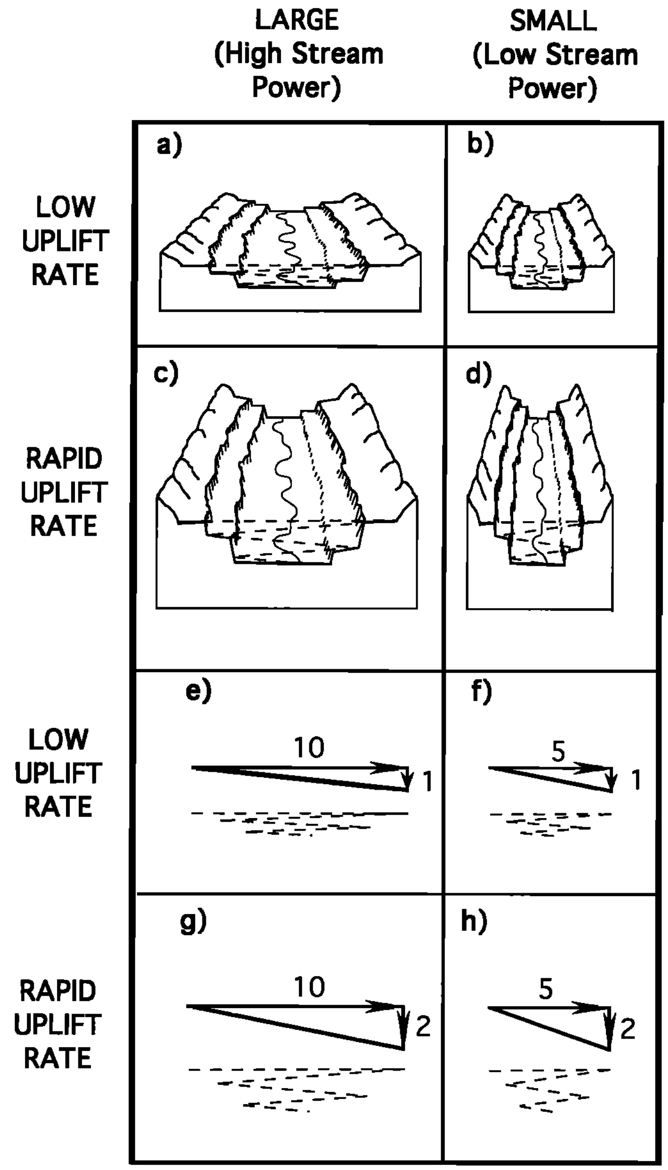

Figure 8 Model of strath surface development along a meandering bedrock river for two uplift rates (relative units of 1 and 2) and two sizes of river. Sketches in Figures 8a, 8b, 8e, and 8f are for low uplift rate, while sketches in Figures 8c, 8d, 8g, and 8h are for a rate two times greater. Sketches in Figures 8a, 8c, 8e, and 8g are for a large river with high stream power, while sketches in Figures 8b, 8d, 8f, and 8h are for a river with a valley width half that size and small stream power. These proportions indicate relative lateral erosion (units of 10 and 5) versus vertical incision (units of 1 and 2). Units are arbitrary. Dashed line indicates switch-backing path of incision along which terrace remnants occur.

These interpretations lead us to conclude that strath terraces will form only along certain parts of a coastal stream during times of fluctuating sea level. This location is upstream of the aggradational effects of a bobbing sea level surface, and far enough downstream from the headwaters that stream power is in excess of that needed to overcome resistance, to transport the prevailing sediment load, and to execute vertical incision. Uplift rate is the maximum rate of incision possible, and maximum incision occurs where a stream transmits all base level fall upstream. Along the length of the stream, if incision is less than the rate of uplift, the channel gradient steepens [*Merritts and Vincent*, 1989]. Downstream of this point, however, straths will form if the stream has excess power for meander migration and lateral erosion.

For the Mattole, we can compare rates of uplift at the coast (2.5-3 m/kyr) with average rates of net vertical incision into bedrock. Two vertical bedrock incision rates can be estimated at km 34-36 on the Mattole (Figure 6). The ≥9.9 ka strath is 7 m above the channel bed, which is thinly mantled with gravel. Assuming that about 7 m of net vertical incision have occurred since at least 9.9 ka results in a maximum, average incision rate of 0.7 m/kyr. The next higher strath, which is older than 8.5 ka and perhaps at least as old as 12 ka (and must be older than the lower 9.9 ka gravel), is 18 m above the present channel bed. Assuming an age of at least 12 ka yields a net vertical incision rate of 1.5 m/kyr for the past ~12 kyr. This rate is uncertain because of the poor constraints on the strath age; however, a maximum incision rate of 1.8 m/kyr is certain, because a minimum age for this strath is 9.9 ka. Therefore, possible incision rates range from 0.7 to 1.8 m/kyr and are 23-72% of the long-term average uplift rate of 2.5-3 m/kyr at the river mouth (Figure 6) [*Merritts and Bull*, 1989]. This similarity suggests that the long-term uplift rate controls the long-term rate of vertical incision into bedrock, as recently noted also by *Bull* [1990].

The Ten Mile River (uplift rate ~0.4 m/kyr) has formed in a manner similar to the Mattole and Bear Rivers. However, the reduced amount of base level fall over a given time period due to uplift rates an order of magnitude lower results in a "vertically compressed" series of strath surfaces pinched close together. Furthermore, the estuary is much larger than that of the Mattole, and the tidal influence occurs several kilometers upstream. For these reasons, backfilling during sea level high stands has buried most bedrock surfaces for many kilometers upstream, and the intermediate zone of strath exposure before the upstream canyon is only several kilometers in length.

Problems in Correlating Terraces in Order to Reconstruct Past Longitudinal Profiles

A number of problems make it very difficult to correlate unpaired terraces along a meandering coastal river that is nearly continuously incising. The four most obvious are related to stratigraphy, burial history, the nature of unpaired terraces, and methods of surveying and correlation:

1. Much caution must be used to correlate terraces based on radiometric ages. Datable material in the sediments above strath surfaces provides minimum ages for the time of strath formation but can span a long time period if the strath remains within the zone of overbank deposition by extreme floods. Base level rise after strath formation can result in overbank deposition up to thousands of years after the original strath formed.

2. The treads of strath terraces may be buried by subsequent fill terraces, especially in lower reaches near the coast, as at km 18-26 along the Mattole River.

3. Strath surfaces are incised vertically as well as laterally during their abandonment, resulting in upstream convergence that produces a very complex record of time-transgressive surfaces [cf. *Seidl and Dietrich*, 1992].

4. Correlation of terraces among reaches based on isolated surveys within each reach, and matching by relative heights above the channel bed (the most commonly used method [cf. *Thornbury*, 1969]), is not likely to yield enough information to reveal the potential complexities of terrace sequences. Continuous, detailed surveying from reach to reach, and correlation based on following surfaces rather than matching relative positions, is critical to avoid subjectivity and error.

This last problem, terrace correlation, is perhaps the greatest. Until recently, regional terrace studies have been limited by the practical necessity of obtaining most altitudinal control from small-scale topographic maps and of correlating terraces based primarily on local studies of altitudinal position within each reach. With recently developed equipment such as total geodetic stations, however, one can survey a large river and its terraces in several months and produce highly detailed, large-scale maps from which to generate long profiles.

In the case of the Mattole, both approaches were used: the former in the late 1980s (preliminary mapping and local hand level surveying; terrace profiles published by *Merritts and Vincent* [1989]), and the latter in this work. The results are different, and the two main reasons for this have important ramifications for terrace studies worldwide. First, in the earlier work we did not clearly recognize the fact that the gradients of strath terraces might be significantly steeper than that of the modern channel bed (more than 2 times). Second, we correlated terraces among reaches based on altitudinal position (i.e., height above the river).

A comparison of the two approaches is shown in Figure 9, in a schematic but accurate portrayal of the Mattole studies. Consider Figure 9a, in which data points representing the heights of terraces above the channel bed were obtained from local hand level surveys at several reaches, and the long profile of the active channel was obtained from a topographic map. With no other data, one might correlate the terraces as in Figure 9b, the obvious and most simple solution (as done by *Merritts and Vincent* [1989]). The subsequent sequence of landscape evolution is dominated by long-term incision, with the river maintaining a nearly constant form through time. Strath terraces merge with marine platforms at the mouth, as in the case of the Somme River, western Europe (Figure 3). This solution is appealing because the correlations match an already present pattern, the shape of the modern channel bed during the present sea level high stand. It is inevitable for many geomorphologists to assume that rivers tend to maintain a fairly constant profile shape over time (the graded river) and furthermore to assume that the modern profile is a good representation of this preferred state.

Now consider Figure 9c with the same database as in Figure 9a, but with the modern channel profile removed to prevent pattern recognition and bias, and with additional altitudinal control provided from continuous geodetic surveying. From these data, terraces are correlated as in Figure 9d and are steeper than the modern channel bed. Correlation of fluvial terraces based on topographic maps for altitudinal control, relative terrace position, and an array of radiometric dates (see problem 1 above) would probably not have led to such an interpretation. However, based on our recent detailed survey results from the Mattole, Bear, and Ten Mile Rivers, this solution is correct, with exception of the correlations in reach a-b. In this reach, it might be reasonable to conclude that the fluvial terraces merge with the marine terraces (as in Figure 9b) and hence further to deduce that lateral valley floor planation occurs during times of sea level high stands [cf. *Bull*, 1990]. However, in Figure 9e, the total station survey data

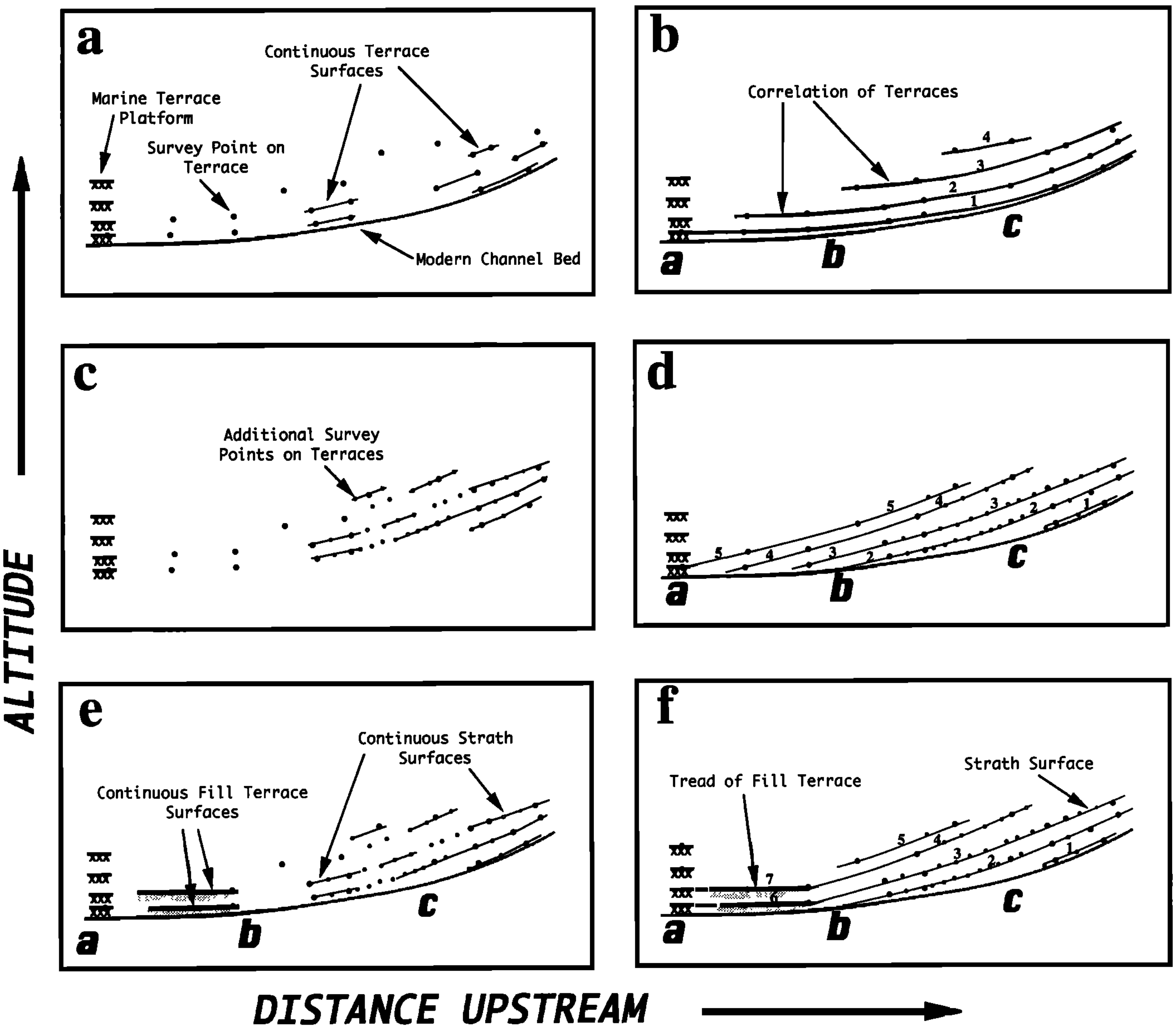

Figure 9. Idealized terrace survey data (Figures 9a, 9c, and 9e) with three alternative correlations and interpretations of the original continuity of the fluvial surfaces (Figures 9b, 9d, and 9f). In Figures 9a and 9b, data are from local surveys of height of terrace above channel. In Figures 9c-9f, data are from continuous geodetic surveying. The interpretations presented in Figures 9e and 9f are discussed in the conclusions and are similar to the results of the analysis of the Mattole, Bear, and Ten Mile Rivers. Note that only four terraces occur in Figure 9b whereas five occur in Figure 9d, and seven occur in Figure 9f. In Figure 9f, the terraces 6 and 7 are unrelated in origin to terraces 1-5.

indicate that terrace treads in reach a-b are not steep, and farther upstream in reach b-c they partially bury straths with gradients much steeper than the modern channel slope. The final interpretation (Figure 9f) makes it clear that two types of terraces with different slopes occur: fill terraces near the mouth that formed during times of sea level high stands, and strath terraces farther upstream that form most of the time as a result of ongoing net vertical incision.

Comparison of the Mattole, Somme, and Susquehanna Rivers

Earlier, the classic example of the nonglaciated Somme River, along the western European passive continental margin, was given to illustrate the historical development of thought regarding sea level change and formation of fluvial terraces (Figure 3). *Lamothe* [1918] and others [e.g., *Breuil*, 1939] proposed that fill (thalassostatic) terraces at the mouths of coastal rivers formed during times of sea level high stands. Lamothe also correlated strath terraces along the Somme with fill terraces at its mouth and concluded that he could use the profiles of terraces along the length of a river to deduce the altitudes of late Pleistocene sea level high stands. In the case of the Mattole River, also in a nonglaciated setting but on an active rather than a passive plate margin, we conclude that strath surfaces have much steeper slopes than both the modern channel bed and the fill terraces at its mouth. Consequently, they cannot be projected downstream to where they merge with high stand fills, nor can they be used to deduce the altitudes of sea level high stands. Their formation is not limited to, or necessarily associated with, times of sea level high stands.

A U.S. river that is perhaps more similar to the Somme, the Susquehanna along the western Atlantic passive margin, also has a series of late Cenozoic, strath terraces along its length and fill terraces at its mouth. Like the Somme, both are interpreted to have formed during times of rising sea level prior to and during major interglacials [*Pazzaglia and Gardner*, this issue]. However, Lamothe did not consider the effects of tectonics on the Somme River. Pazzaglia and Gardner, in contrast, modeled fluvial response to both sea level change and flexure of the North American crust (due to denudation and offshore loading), and concluded that straths form in areas of long-term, slow crustal uplift and tilt resulting from isostasy and flexure and are at peak formation during times of rising sea level. According to their interpretation, peak strath formation is the result of maximum lateral incision at times of high base level. In contrast, in this study of rivers in a region of rapid uplift, we conclude that strath formation along a meandering river is not isolated to times of high sea level or stable base level but rather occurs continuously in reaches that have both excess stream power and are upstream of the reach affected by sea level rise.

The results of the study described here are similar to those from investigations of smaller rivers and base level change. As observed by *Leopold and Bull* [1979, p. 195], a stream reacts to processes of aggradation or degradation in "closely adjoining reaches, and not to a base level far removed in space". Base level rise will result in a depositional wedge that migrates upstream, but it will only migrate upstream until a gradient of deposition is established [*Leopold*, 1992]. Upstream of that point, the base level rise has no influence. Rather, the stream responds to upstream controls (climate-influenced supply of sediment and water). If, however, this upstream reach is in an area of long-term base level fall induced by uplift, as is the case for the Mattole and Bear Rivers in northern California, it may continue to downcut even during a sea level highstand, because of the presence of nearby knickpoints migrating upstream that have their origin in base level fall from long ago.

In sum, interpretation of the terraces along any coastal river, be it on an active or a passive continental margin, requires examination of both eustatic and tectonic processes of base level change. The ratio of lateral erosion to vertical incision varies due to uplift rate, sea level position, and upstream drainage area, resulting in complex flights of terraces that differ in number, spacing, and age distribution even along a single coastline. Adjacent rivers with the same uplift rate do not have similar numbers and ages of strath terraces because these landforms are not the result of instantaneous, external events but rather are part of a time-continuum that represents constant adjustment to changing base level. The degree of adjustment, or fine tuning, depends upon the size and power of the river relative to the rate of tectonic uplift.

Acknowledgments. For permission to work along the Mattole, Bear, and Ten Mile Rivers, we are grateful to J. Zanone, J. Cooke, B. McBride, M. Etter, J. Wilson, J. Short, S. Lowry, M. and G. Smith; the Roscoe families; and many more. We are indebted to many at the Bureau of Land Management, the U.S. Geological Survey, the Georgia-Pacific Lumber Company, and the Mattole Restoration Council, for technical and logistical support. We are especially grateful to J. Tinsley, T. Dunklin, R. McLaughlin, D. Simpson, J. McAbery, and Jere Melo. We also thank S. Schumm, F. Ethridge, and N. Humphrey for helpful suggestions. We thank the following for financial support: National Science Foundation (Doctoral Dissertation Improvement grant EAR-8405360 to Merritts; Research at Undergraduate Institutions grants EAR-89-04785 and 89-17116; supplemental grant EAR-91-49176), and the U.S. Geological Survey (NEHRP grant 14-08-0001-G N2334). Support for reproduction of the color plate has been provided by NASA grant NAGW-3338 to Michael A. Ellis. Finally, we give a special thank you to the geology students inaugurated to long field seasons in this area: S. Polaski, R. Ticknor, L. Hammack, G. Dudkiewiscz, R. Bruant, J. Buchman, I. Rose, and many others. Thorough reviews by W. Dietrich, R. Anderson, M. Ellis, and an anonymous reviewer greatly improved the manuscript.

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(Received April 12, 1993; revised February 16, 1994; accepted March 31, 1994.)