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Coastal landscape evolution as a function of eustasy and surface uplift rate, Cascadia margin, southern Oregon

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ABSTRACT

We explore the relative importance of eustatic versus tectonic factors in sculpting, preserving, and modifying coastal landforms. The study area is a 30-km coastal reach in southern Oregon. Using degree of soil development as a means of correlating wave-cut platforms along the coast, we document that surface uplift rate is variable in a shore-parallel sense, variability being a function of differential vertical displacement of crustal blocks along faults and flexures in the upper plate of the Cascadia subduction zone. A consequence of this variability is that in areas of moderate uplift rate (0.7–0.9 m/k.y.), flights of up to seven emergent wave-cut platforms are preserved along the interfluves of coastal drainages, whereas in areas of low uplift rate (0.05–0.2 m/k.y.), only one wave-cut platform commonly exists, within a few meters of present sea level. Preservation of shore platforms in both areas is the result of the interaction of tectonic uplift and eustatic sea-level changes operating on a high-energy coast subject to platform planation. Platform reoccupation can be a consequence of late Pleistocene eustatic sea-level changes operating on low-uplift-rate coasts. Particularly in the cases of the ~200 ka and ~125 ka high sea stands, reoccupation by the later highstand is probable when coastal uplift rates are about 0.2 m/k.y. The same eustatic history, operating on a higher-uplift-rate section of the coast, results in multiple emergent platforms and no instances of reoccupation. Coastal drainage basins in the size range of 5–10 km^2 have different hypsometries, reflecting whether platforms in coastal basins are preserved over a range of altitudes or only near sea level. The hypsometric differences are thus a product of differences in uplift rate. The dominant mechanism of base-level fall varies between the two areas: coastal retreat during sea-level highstands drives base-level fall in lower-uplift-rate basins, whereas tectonic uplift mainly drives base-level fall in moderate-uplift-rate basins, even though the magnitude of coastal retreat may be about the same in the two areas. Where coastal retreat largely provides the mechanism for base-level fall, steep coastal drainages discharge their debris onto coastal piedmonts ("benches"), and the resultant alluvial fans prograde over marine deposits. In southern Oregon, the alluvial fan-building episode was relatively short, about 2–20 k.y. in duration. Fan aggradation ceased as a consequence of fan entrenchment, most likely brought on by buildup and steepening of the fan over time.

INTRODUCTION

The Cascadia subduction zone extends along the western margin of North America for 1,100 km and accommodates convergence of the Gorda/Juan de Fuca Plate with the much larger North American plate. The need to evaluate seismic hazard along this convergent margin (for example, Heaton and Kanamori, 1984) has engendered much scientific study of the seismicity and structure of the margin. Study of the subaerially exposed portion of the accretionary prism of Cascadia in northern California and Oregon has shown that there is as much as an order of magnitude of variation in long-term uplift rates along this margin over the last 100,000 yr (Carver and others, 1985; Kelsey, 1990; McInelly and Kelsey, 1990). This variability in uplift rate can be attributed to local structures, both faults and folds, that develop in the overriding plate (Adams, 1984; Kelsey and Carver, 1988; Kelsey, 1990; McInelly and Kelsey, 1990; Muhs and others, 1990; Clark and Carver, 1992). These local structures owe their origin to the fact that stresses induced by convergence must act upon crust of varying age with inherited zones of weakness. In turn, the localized growth of structures in the overriding plate results in a variable erosional response of the coastal area.

In this report, we describe cases where local structures result in shore-parallel variations in surface uplift rate in Cascadia and then discuss the consequences in terms of evolution of coastal basins, preservation of marine terraces, and soil development. The central theme is that variations in coastal landscape evolution, though ultimately driven by variable surface uplift rates, are most directly a function of the relative importance of tectonic versus glacioeustatic factors. These factors control cutting of wave-cut platforms, base-level fluctuations for coastal drainages, marine terrace preservation, and deposition of alluvial fans on coastal piedmonts. We focus on a 30-km-long coastal area in southernmost Oregon, in the vicinity of the coastal community of Brookings (Fig. 1), where local structural control has resulted in a shore-parallel transition over a short distance from a tectonically stable coastline to one of relatively rapid surface uplift.

MARINE TERRACES

Introduction

Uplifted wave-cut platforms are a valuable means to study neotectonic deformation patterns and rates because the sea cliff/wave-cut platform junction, also called the shoreline angle, forms a shore-parallel contact that is horizontal (plus or minus a few meters) at its time of formation (Wright, 1970; Trenhaile, 1980), and subsequent deformation of this horizontal datum is a reflection of crustal deformation. Both the genesis and subsequent preservation of wave-cut platforms and the nature of the cover sediments characteristic of these platforms have been described else-

Data Repository item 9426 contains additional material related to this article.

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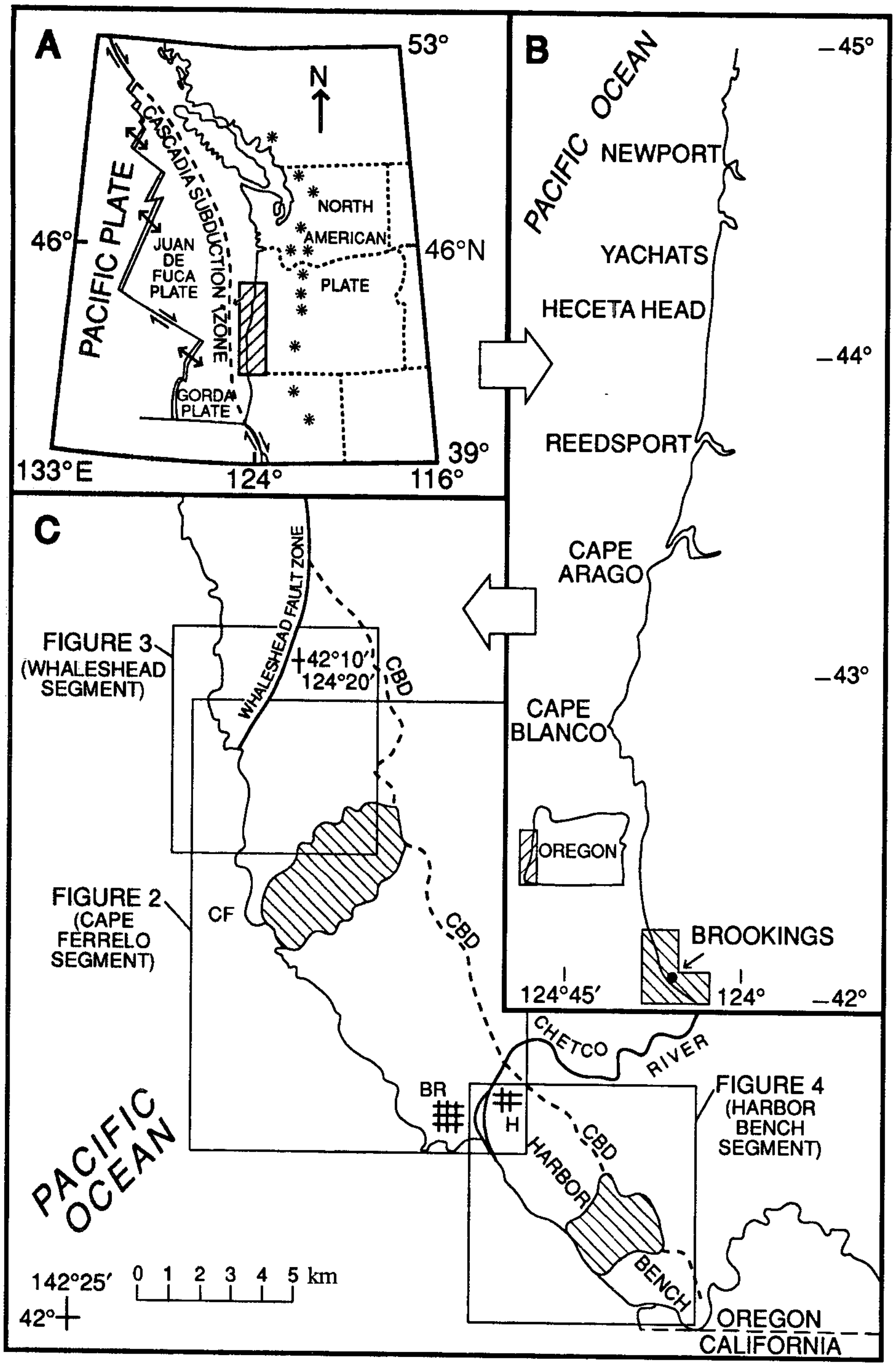

Figure 1. A. Location of southern and central coastal Oregon within the context of a plate tectonic map for the Pacific northwest; stars denote the Cascade volcanoes. B. Map of southern and central Oregon coast showing localities mentioned in the text; study area is shaded portion at bottom of the map. C. Study area in southern coastal Oregon. CBD, coastal basins divide; CF, Cape Ferrelo; BR, Brookings; H, Harbor. Diagonally shaded areas are the drainage basin study units mentioned in text. Rectangles show borders for figures that show the late Quaternary geology for the Cape Ferrelo, Whaleshead, and Harbor Bench segments.

where (Clifton and others, 1971; Bradley and Griggs, 1976; Hunter, 1980; Lajoie, 1986; Kelsey, 1990). We use the pattern of preservation of marine terraces in the Brookings area and the progression in soil development on flights of marine terraces to document growth of local structures. Only those platforms cut at interglacial or interstadial sea-level highstands have the potential to be preserved. Therefore, the possible ages for uplifted wave-cut platforms are a finite set of ages corresponding to late Pleistocene sea-level highstands (Mesolella and others, 1969; Bloom and others, 1974; Chappell and Shackleton, 1986). We hypothesize that in the Brookings area, the variable pattern of preservation of marine terraces and their variable elevations are a function of the shore-parallel variation in tectonic uplift and coastal erosion.

The southwesternmost 30 km of the Oregon coast (Fig. 1) is one of diverse geomorphology, where the number of uplifted marine terraces ranges from seven (the most seen anywhere along the Cascadia margin) to only one, known locally as the Harbor Bench. The bedrock geology is composed of Mesozoic sedimentary rocks (Dott, 1971). The Whaleshead fault zone (Fig. 1), a tectonostratigraphic terrane-bounding crustal fault, offsets the terraces and juxtaposes Otter Point Formation rocks of the Gold Beach Terrane to the northwest against Dothan Formation rocks of the Yolla Bolly terrane to the southeast (Dott, 1971; Blake and others, 1985).

The coastal zone can be divided physiographically into three segments from south to north: the Harbor Bench segment, the Cape Ferrelo segment, and the Whaleshead segment, respectively (Fig. 1). North of the Chetco River, a well-developed marine terrace sequence, consisting of seven uplifted wave-cut platforms, is preserved in the Cape Ferrelo coastal segment (Fig. 2). In the Whaleshead segment, north of the Whaleshead fault zone (Fig. 3), there are four wave-cut platforms that are less well preserved than farther to the south because of the inherently more unstable rocks of the Otter Point Formation. In the Harbor Bench segment, south of the Chetco River (Fig. 4), there is only one broad marine platform (locally called the Harbor Bench) that occurs 6–35 m above sea level.

The seven uplifted marine terraces range in elevation from a few meters above sea level to 320 m (Table 1). Abelli (1988) was the first to describe these terraces. We identified and mapped terrace remnants on aerial photo-

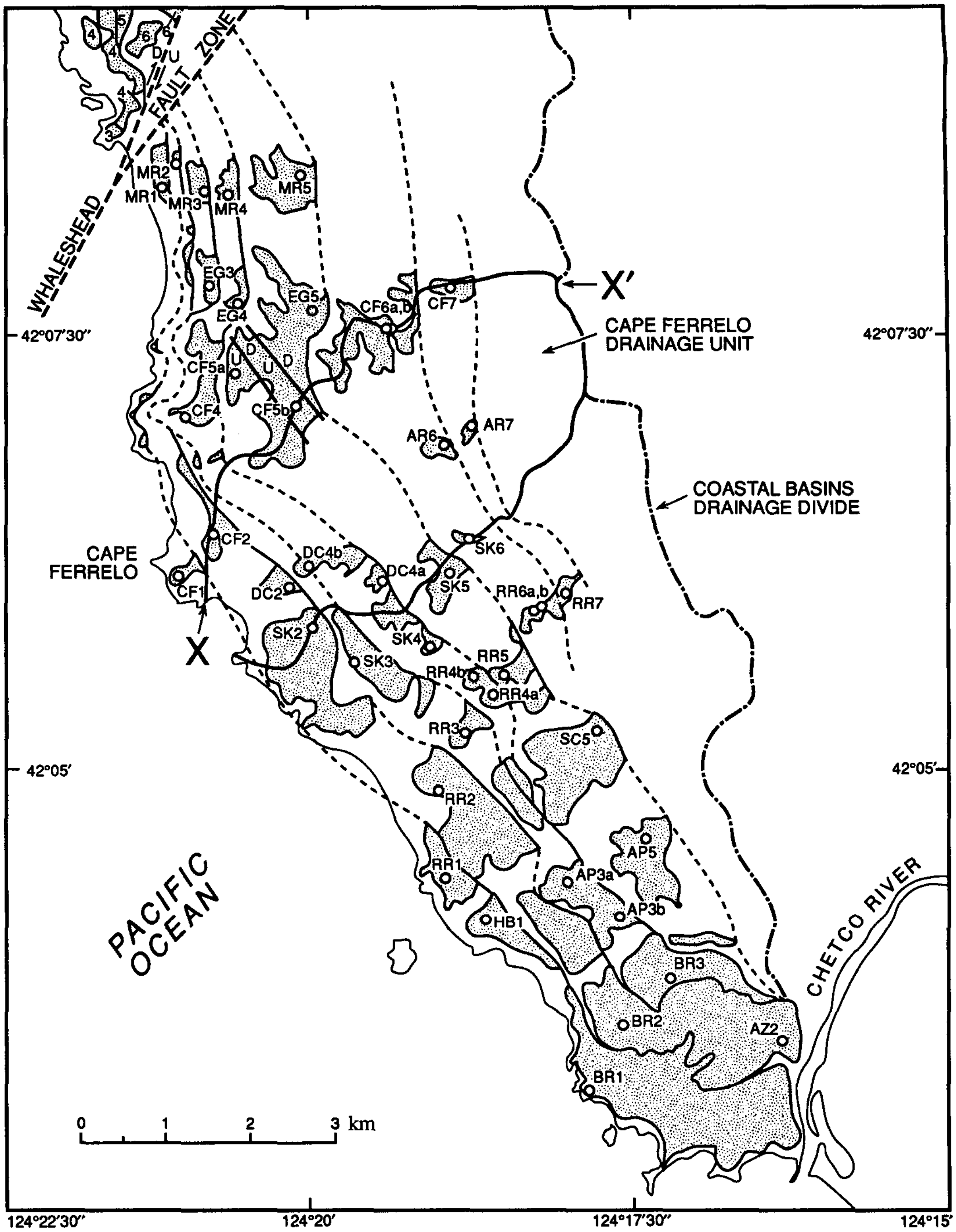

Figure 2. Remnants of late Pleistocene marine terraces (dot pattern) for the Cape Ferrelo coastal segment. Terraces are numbered 1 through 7 (see Table 1). Back edges (paleo–sea cliffs) to these terraces are solid lines where mapped, dashed where approximately located. Open circles are soil description localities for the Cape Ferrelo segment. Solid line delineates the 9.70 km^2 Cape Ferrelo drainage unit. X–X′ delineates location of interfluve topographic profile shown in Figure 9. For map data south of Chetco River, see Figure 4.

graphs and then located exposures of the wave-cut platform in the field. The altitude of the bedrock platform was determined by locating the site on 1:24,000 topographic maps. The error in assigned altitude reflects the accuracy limits of the topography and is equal to ±6 m, where 6 m is one-half the contour interval. This error is acceptable because the altitudinal spacing of marine terraces of different ages is >6 m and altitudinal variation for any one terrace due to shore-parallel terrace tilt is significantly greater than 6 m.

Soils on Marine Terraces

Soil development on the flights of marine terraces provides relative ages for the wave-cut platforms, and soil development provides a means of correlating terraces across faults or major river valleys that interrupt surface continuity. We first mapped the terraces based on morphology and altitudinal position (Figs. 2, 3, and 4) and then tested the terrace correlations across river valleys and across the Whaleshead fault zone by describing soils in all the coastal segments using shore-normal terrace transects that ascended the ridges (interfluves) between the coastal drainages. There were seven of these transects; each transect included three to seven individual soil descriptions depending on the number of terraces preserved on the specific interfluve. Two of the transects (RR and CF in Fig. 2) contained remnants of all seven terraces. In all, we described soils at 67 localities (Figs. 2, 3, and 4). For the RR and CF transects, 15 soil pits were excavated to 2 m and then

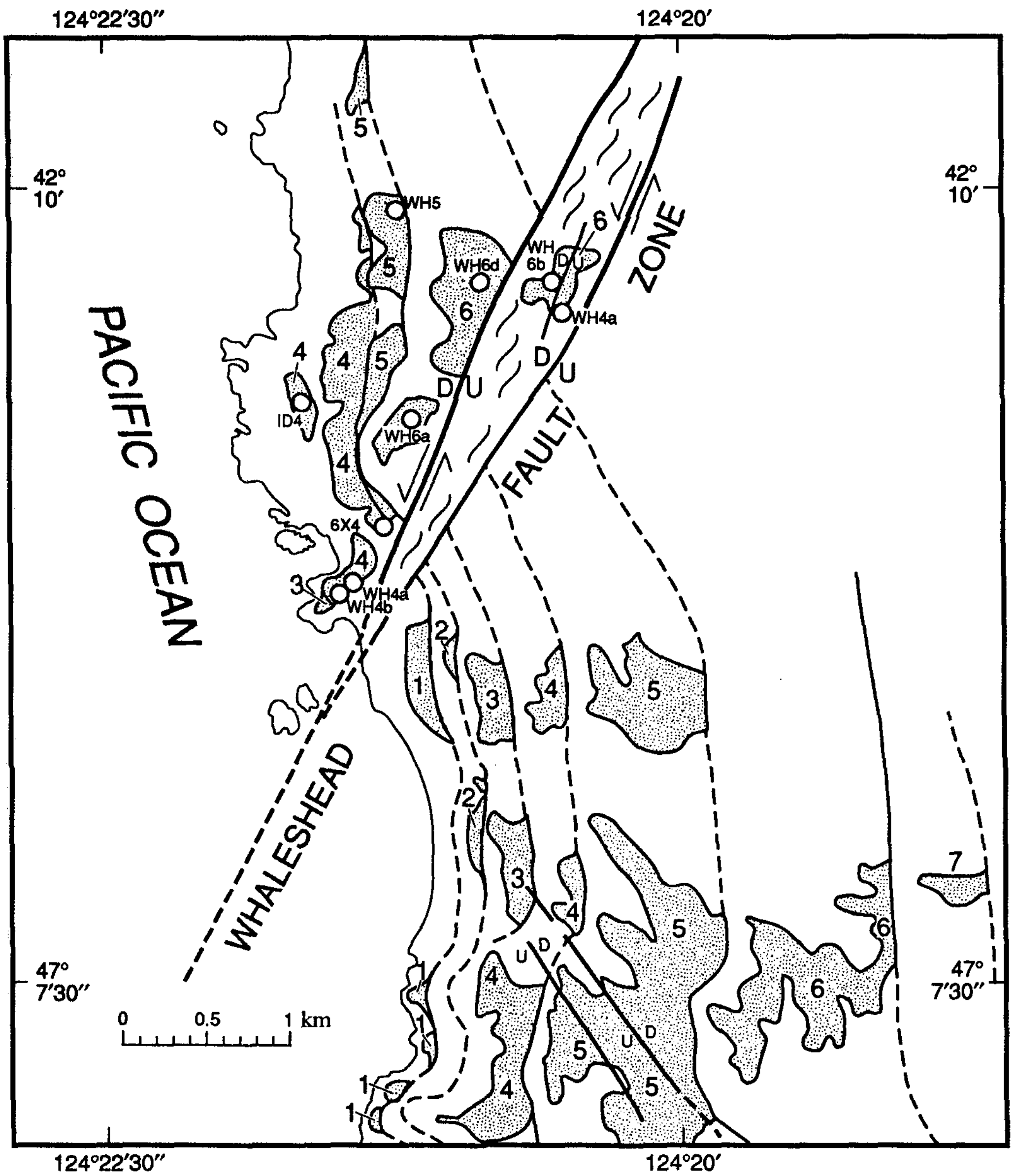

Figure 3. Remnants of late Pleistocene marine terraces (dot pattern) for the Whaleshead coastal segment. Only terraces numbered 3 through 6 (see Table 1) are preserved north of the Whaleshead Fault zone. Back edges (paleo–sea cliffs) to these terraces are solid lines where mapped, dashed where approximately located. Open circles are soil description localities north of the Whaleshead Fault zone. Note that the back edges of terraces 4, 5, and 6 are sinistrally offset by late Quaternary movement on the Whaleshead Fault zone.

probed with a 7.6-cm-diameter auger to total depths as great as 6 m, where necessary, in an attempt to reach the C horizon. For the remaining 52 soil localities on seven interfluve transects, we collected field descriptions using a 10-cm-diameter bucket auger.

Each of the 67 soils was assigned to one of seven development stages. These stages are based primarily on depth to the C horizon, thickness of the clay-enriched (Bt) horizon, estimated clay content, and degree of development of clay films (Table 2). The development stage assignments bear out the fact that soils on the older terraces in the sequence are progressively more developed.

We used the soils described in the central Cape Ferrelo segment (Fig. 2) to identify soil properties useful in distinguishing among the terraces. We concentrated on soil properties that seem to be time-dependent based on soil chronosequence studies carried out elsewhere (Bockheim, 1980; Birkeland, 1984; Bockheim and others, 1992). These properties include Bt horizon thickness, B hue, depth to Cox horizon, maximum texture, maximum estimated clay content in the B horizon, maximum clay skins, and weathering stage (Table 3). On this basis, soils were useful in distinguishing among the following terraces: 1, 2, 3, 4–6, and 7. In our plots of soil properties in relation to terrace number (Fig. 5), we combined data for terraces 4, 5, and 6 because soil properties did not allow us to distinguish among these terraces; taken together, however, these terraces were distinguishable from the others. The thickness of the solum (A, B, and BC horizons) increases from about 1 m on terrace 1 to >3 m on terrace 7 (Fig. 5A). In addition to an increase in Bt horizon thickness (Fig. 5B), the maximum estimated clay content in the B horizon increases from 24% to 37% (Fig. 5C), and the maximum hue (expressed as increasing redness) steadily increases (Fig. 5D). The increase in clay content is accompanied by an increase in the abundance and thickness of clay films (Table 3). The relation between weathering and terrace number is nearly linear, ranging from 1.4 on terrace 1 to 6.0 on terrace 7 (Fig. 5E).

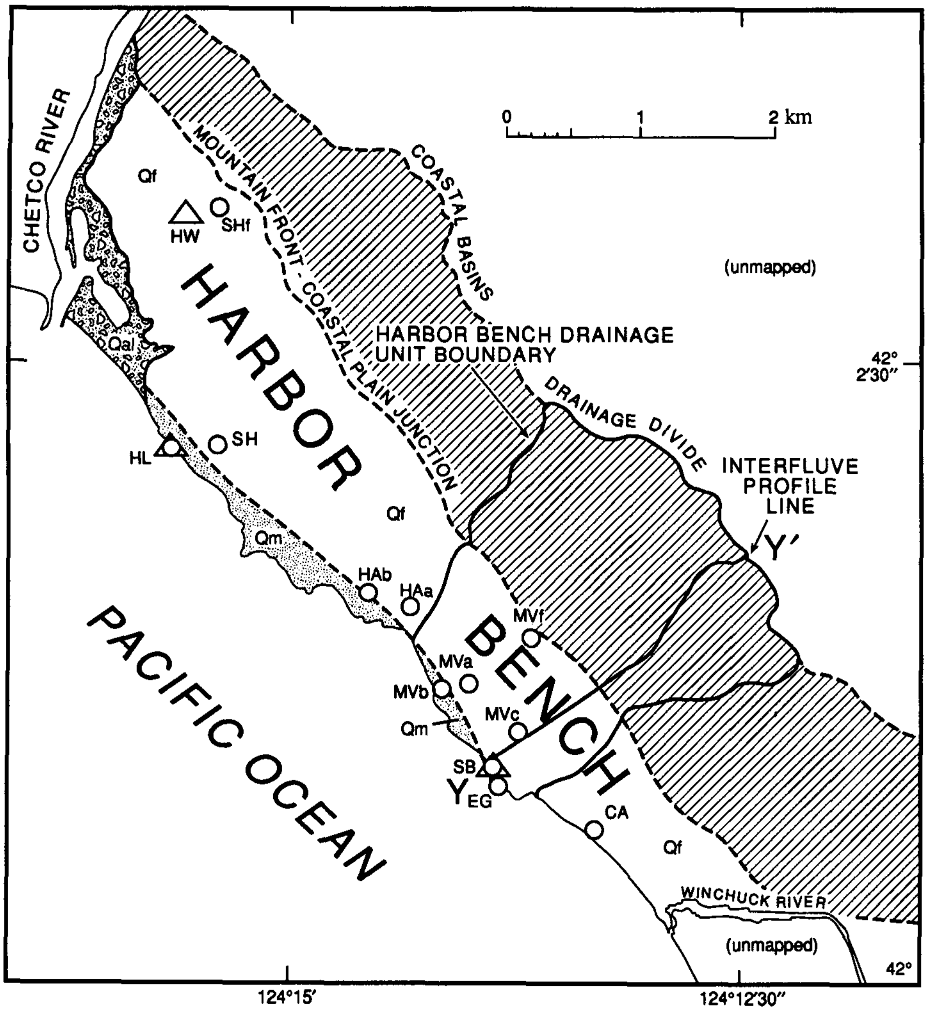

Figure 4. Late Quaternary geologic map of the Harbor Bench segment. Geologic units on Harbor Bench: Qal, Late Quaternary alluvium (pebble pattern); Qm, Late Quaternary marine surf-zone gravels and beach sands (dot pattern); Qf, Quaternary alluvial-fan deposits (no pattern). Diagonal line pattern designates area of coastal basins that drain onto the Harbor Bench. Open circles are soil description localities on the Harbor Bench; open triangles, sites of stratigraphic column descriptions shown in Figure 10. Solid line delineates the boundary of the 4.58 km^2 Harbor Bench drainage unit. Y–Y′ delineates location of interfluve topographic profile shown in Figure 10. Dashed lines show contact between marine sands and alluvial fan, contact between alluvial fan and mountain front, and location of coastal drainage divide.

Detailed field descriptions of soils in the RR transect, which includes all seven terraces, and particle size analyses for the RR transect that were carried out on selected horizons in six of the seven soils are available in the GSA Data Repository.[1] In general, the relative abundance of silt in the solum increases with age, and both the maximum clay content and the total amount of clay in the profile increase with age as well. These data, in conjunction with the presence of many moderately thick to thick clay films on ped faces, indicate that clay translocation is occurring in these soils.

Correlation of Terraces Across Drainages and Faults Using Soils

We correlated terraces across drainages and faults during initial mapping, and we checked these correlations using soils. In a few cases, we revised terrace correlations based on soils. To the north, soils were instrumental in correlating terraces across the Whaleshead fault zone. The three well-preserved terraces north of the fault zone have soil properties that are not distinguishable among each other. However, these soils as a group are correlative with the combined terraces 4 through 6 south of the fault zone (Tables 3 and 4). The terraces north of the fault zone are not correlative with the younger two terraces, or with terrace number 7, which has the most strongly developed soil. We therefore conclude that the well-preserved terraces north of the Whaleshead fault zone are correlated with terraces 4, 5, and 6 south of the fault zone (Fig. 6).

From geomorphic relations and altitude measurements of the platforms in the south-

[1]GSA Data Repository item 9426, one table and one figure, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

TABLE 1. CHARACTERISTICS OF MARINE TERRACES IN THE CAPE FERRELO–BROOKINGS AREA

Terrace number	Terrace name	Assigned age (equivalent oxygen isotope stage)	Erosional preservation where not removed by coastal retreat	Range in wave-cut platform elevations (m)			Range in terrace cover bed sediment thickness for Cape Ferrelo segment (m)*
				Whaleshead segment	Cape Ferrelo segment	Harbor Bench segment	
1	Harris Butte	80 ka (5a)	well preserved	np†	30–62	np	7.5, n = 1
2	Brookings	105 ka (5c)	slightly dissected	np	57–90	np	2–12, n = 2
3	Gowman	125 ka (5e)	moderately dissected	46–58	72–134	2–29	4–12, n = 3
4	Aqua Vista	200 ka (7)	moderately dissected	98–118	127–168	np	6–13, n = 5
5	Cornett	?	moderately dissected	134–147	137–214	np	11–19, n = 4
6	Homestead	?	highly dissected	206	207–271	np	10–13, n = 2
7	Alder Ridge	?	extremely sparse	np	227–321	np	no data

*n = number of thickness measurements.
†np = platform not preserved.

TABLE 2. DEVELOPMENT STAGES OF SOILS ON ELEVATED MARINE TERRACES ALONG THE CENTRAL AND SOUTHERN OREGON COAST

Development stage	Depth to Cox (m)	B horizon hue	Bt thickness (cm)	Maximum B horizon texture* (% clay)[§]	Maximum clay films[†]
1	0.8–1.4	7.5–10YR	0	sil, l, sl (<30)	1–3npfpo
2	1.0–1.4	7.5YR	<50	sicl, cl, scl (30–40)	2–3n-mkpfpo
3	1.0–1.7	7.5YR	<50	sicl, cl, scl (30–40)	2–3mkpfpo
4	1.4–1.8	5–7.5YR	50–100	sicl, sic, cl, c (35–42)	3–4mkpfpo
5	1.9–2.8	5–7.5YR	100–200	sic, c (40–58)	3–4mk-kpfpo
6	2.6–4.5	5YR	>200	sic, c (40–65)	3–4mk-kpfpo
7	3.2–>4.5	2.5YR	>200	sic, c (45–65)	3–4mk-kpfpo

*l, loam; sl, sandy loam; sil, silt loam; sicl, silty clay loam; sic, silty clay; cl, clay loam; scl, sandy clay loam; c, clay. Abbreviations follow Soil Survey Staff (1951).

[†]Notations for clay films; number denotes extent of ped faces covered by film: vl, <5%; 1, 5%–25%; 2, 25%–50%; 3, 50%–90%; 4, >90%; n, thin; mk, moderately thick; k, thick; pf, film on ped face; po, film lines the pores. Abbreviations follow Soil Survey Staff (1951).

[§]We estimated percent clay for each horizon at each soil locality during field work. We have confidence in our ability to estimate clay content in the field because we obtained a significant correlation (r^2 = 0.66; $p \leq 0.01$) between percent clay estimated in the field and percent clay measured in the laboratory (28 samples).

ern half of the area, we concluded that the wave-cut platform that underlies the Harbor Bench is correlative with terrace 3 to the north across the Chetco River. Soils developed on beach deposits on the Harbor Bench are comparable to soils developed on similar materials on terrace 3 north of the Chetco River (Tables 3 and 5), corroborating our correlation (Fig. 6). The correlation of the Harbor Bench surface to terrace 3 is unambiguous in that several of the time-dependent soil properties for the Harbor Bench closely match those of terrace 3 and do not closely match soil properties of either terrace 2 or 4. These properties include Bt horizon thickness, depth to Cox horizon, and maximum thickness and extent of clay skins (Tables 3 and 5).

TABLE 3. SUMMARY OF SOIL PROPERTIES USED AS RELATIVE AGE INDICATORS FOR THE SEVEN TERRACES IN THE CAPE FERRELO SEGMENT

Terrace locality	Bt horizon thickness (cm)	B horizon hue	Depth to Cox (cm)	Max. B texture*	Maximum estimated % clay*	Maximum clay skins*	Development stage
MR1	0	—	116	l	25	2npf	1
CF1	0	10YR	93	scl	22	1npf	1
BR1	0	10YR	143	sl	16	2npf	1
RR1	0	7.5YR	118	l	20	2npf	1
HB1	39	7.5YR	90	sicl	37	3mkpf	3
Avg. for 1	8	7.5–10YR	112	··	24	2npf	1.4
BR2	0	··	143	sil	··	··	1
MR2	66	7.5YR	113	sicl	35	1npf	3
CF2	69	10YR	110	sicl	31	3mkpf	3
AZ2	63	5YR	144	sicl	27	2npf	3
DC2	53	7.5YR	108	sicl	32	4mkpf	3
SK2	0	10YR–2.5Y	104	sil	22	3npf	1
RR2	60	5–7.5YR	133	cl	34	3mkpf	3
Avg. for 2	44	7.5YR	122	sicl	30	3n-mkpf	2.4
AP3a	0	10YR	88	cl	28	1npf	1
AP3b	0	10YR	90	sil	18	··	1
EG3	232	7.5YR	380	sicl	40	4kpf	6
MR3	88	7.5YR	162	sicl	35	3mkpf	4
SK3	117	5YR	248	sicl	37	3n-mkpf	4
BR3	56	5YR	145	cl	34	3mkpf	3
RR3	65	7.5YR	156	sicl	32	3mkpf	3
Avg. for 3	80	7.5YR	181	sicl	32	3mkpf	3.1
EG4	258	5YR	318	sicl	40	4kpf	7
MR4	146	5YR	208	sicl	40	3kpf	5
CF4	124	10YR	230	sicl	38	3kpf	5
DC4a	75	10YR	160	cl	31	4mkpf	3
DC4b	219	5YR	278	sic	40	4mkpf	7
SK4	92	10YR	198	sic	38	4kpf	4
RR4a	147	7.5YR	294	sicl	39	3kpf	5
RR4b	123	··	187	··	··	··	5
Avg. for 4	148	7.5YR	234	sicl	38	3–4kpf	5.1
EG5	85	5YR	151	cl	34	4mkpf	4
MR5	173	7.5YR	231	sicl	40	3kpf	5
CF5b	82	5YR	246	sicl	34	3kpf	4
SK5	39	10YR	133	cl	30	2mkpf	2
RR5	75	7.5YR	124	sic	40	4kpf	4
CF5a	96	10YR	170	sicl	37	3kpf	4
SC5	138	5–7.5YR	232	cl	34	4mk-kpf	5
AP5	60	2.5YR	207	cl	32	3npf	4
Avg. for 5	94	5–7.5YR	187	sicl	35	3–4mk-kpf	4.0
CF6a	41	2.5YR	170	cl	34	2npo	3
CF6b	41	7.5YR	75	cl	30	3mkpf	3
AR6	255	5YR	>450	sic	42	4kpf	7
SK6	97	5YR	176	sicl	39	3mkpf	4
RR6a	168	2.5YR	293	sic	42	4kpf	5
RR6b	46	2.5YR	81	sicl	35	3n-mkpf	4
Avg. for 6	108	5YR	208	sicl	37	3mkpf	4.3
CF7	219	5–7.5YR	324	sic	42	4kpf	6
AR7	232	2.5YR	332	sic	42	4kpf	7
RR7	157	2.5YR	279	sic	45	3mk-kpf	5
Avg. for 7	203	2.5–5YR	312	sic	43	4kpf	6.0

*See Table 2 for explanations.

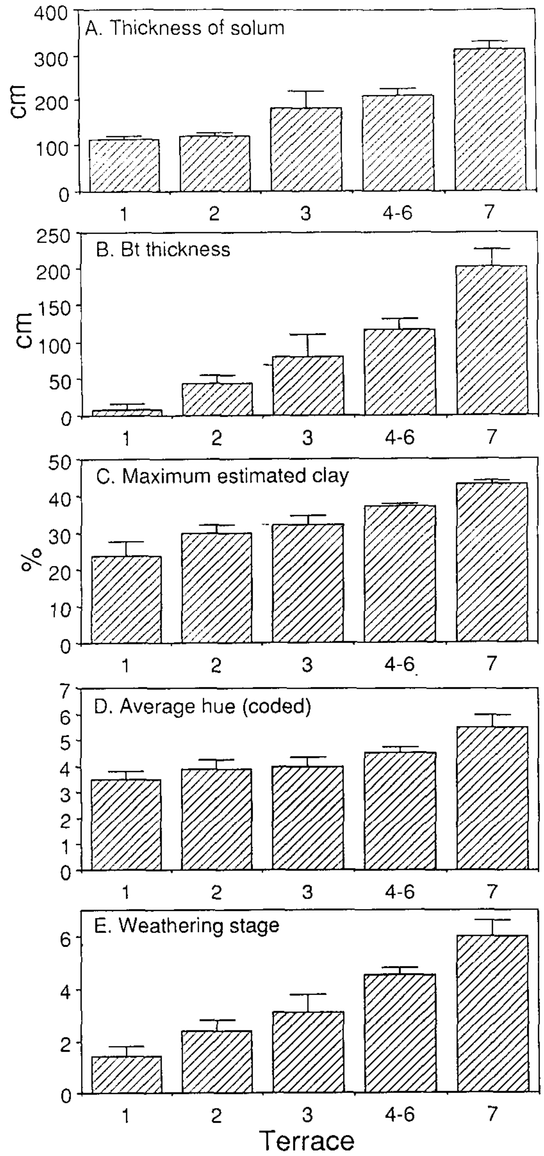

Figure 5. Graphic depiction of soil properties for marine terraces in the central (Cape Ferrelo) segment, from Brookings to Whaleshead Fault. Error bars denote one standard error.

Terrace Ages and Range of Terrace Uplift Rates

We assign numerical ages for the morphologically better-preserved platforms, based on relative age criteria for the marine terrace soils, through correlation to wave-cut platforms farther north in Oregon that have numerical or assigned ages (Kelsey, 1990; Muhs and others, 1990; Bockheim and others, 1992).

By "terrace age," we specifically mean the age of the marine sediments that overlie the wave-cut platform and underlie the terrace surface. Because these sediments are laid down during a sea-level highstand or immediately after the highstand during initiation of eustatic sea-level fall, we imply that the "terrace age" is close to the age of platform cutting that accompanied the highstand. There are no numerical ages on fossils from marine terrace deposits in the Brookings area because these deposits lack fossils. However, the lowest two terraces in the Cape Blanco and Cape Arago areas, 90 km and 143 km to the north, respectively (Fig. 1B), have numerical or assigned ages based on one uranium-series age on coral in addition to several amino acid and oxygen isotope correlation ages on fossil mollusks. The age investigations have been documented by Muhs and others (1990). The lower two terraces at Cape Arago and Cape Blanco have probable ages of 80 and 105 ka, corresponding to oxygen isotope stages 5a and 5c, respectively (Kelsey, 1990; McInelly and Kelsey, 1990; Muhs and others, 1990). The correlation of terraces 1 and 2 at Brookings to the lowermost two terraces at Capes Arago and Blanco is based on the similar and distinctive degree of soil

TABLE 4. SUMMARY OF SOIL PROPERTIES USED AS RELATIVE AGE INDICATORS IN THE WHALESHEAD AREA

Terrace locality	Bt horizon thickness (cm)	B horizon hue	Depth to Cox (cm)	Maximum B horizon texture*	Maximum estimated % clay*	Maximum clay films*	Development stage
WH4a	>313	7.5–10YR	>400	sic	40	4kpf	6
WH4b	203	7.5YR	276	sic	45	4kpf	5
SX4	420	5YR	600	sicl	42	4kpf	7
ID4	38	5YR	217	sicl	30	3npf	3
Avg.	244	5–7.5YR	373	sicl	39	4mkpf	5.2
WH5	>194	7.5YR	>275	sicl	38	3mkpf	6
WH6a	>175	7.5YR	>280	sic	42	4kpf	6
WH6b	105	10YR	172	sicl	38	3npf	4
WH6c	71	7.5YR	153	sic	42	4mkpf	4
WH6d	>225	10YR	>300	sic	42	4mkpf	6
Avg.	>144	7.5–10YR	>226	sic	41	4mkpf	5.0
Avg. all†	194	7.5YR	297	sicl	40	3–4mkpf	5.2
Avg. 4–6 (CF)§	120	5–7.5YR	217	sicl	37	3–4mk-kpf	4.5

*See Table 2 for explanations.
†Average for all soil localities on terraces 4, 5, and 6 in the Whaleshead coastal segment.
§Average for all soil localities on terraces 4, 5, and 6 in the central (Cape Ferrelo) segment.

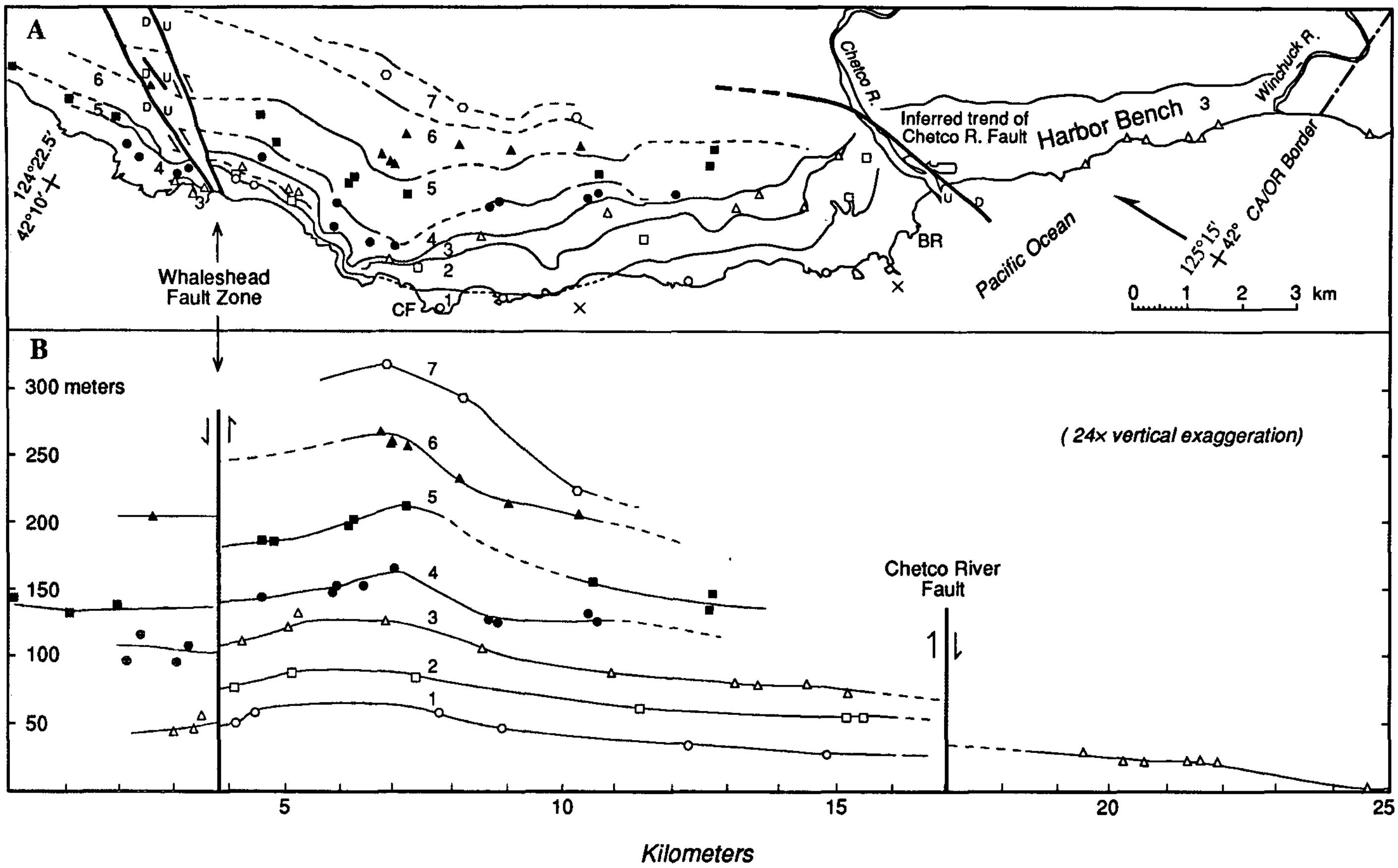

Figure 6. A. Map depicting location of marine terrace back edges and showing sites where wave-cut platform altitudes were measured. B. View looking northeast showing altitudinal variation in wave-cut platforms, as projected onto a vertical plane trending N33°W. Wave-cut platforms are correlated based on transect sequence on individual interfluves, altitude, and soil characteristics of the terraces. Elevations in B are corrected to the equivalent shoreline-angle elevation using the average platform gradient at the time of formation, following Bradley and Griggs (1976), and using the measured distance from the site (shown in A) to the shoreline angle.

development common to terraces 1 and 2 in all three areas (Bockheim and others, 1992) (Table 6), as well as on similarities in terrace morphology and degree of preservation. On the basis of the times when sea level was as high or higher than the present in the late Quaternary (Chen and others, 1991; Harmon and others, 1983), the minimum possible age for terrace 3 in all three areas is 125 ka (oxygen isotope stage 5e) (Kelsey, 1990; McInelly and Kelsey, 1990; Bockheim and others, 1992), and we assign terrace 3 an ~125 ka age. Using the same reasoning as above but applied to studies of older-than–stage 5 marine terraces (Mesolella and others, 1969; Chappell and Veeh, 1978; Chappell and Shackleton, 1986), we suggest that terrace 4 could not have been cut later than ~200 ka. Hence, we assign terrace 4 a lower-limiting age of ~200 ka. The ~125 ka and ~200 ka age assignments are reasonable assuming that terraces representing all the major late Pleistocene sea-level highstands are present. Considering that the Brookings area has seven preserved terraces, the most observed anywhere in coastal Oregon, the assumption is a reasonable one.

Maximum and minimum uplift rates for the Brookings coastal area are calculated based on the altitudinal position of shoreline angles for the ~125 ka platform (terrace 3) on the Harbor Bench and for the ~80, 105, and 125 ka platforms (terraces 1, 2, and 3) in the Cape Ferrelo area. These maximum and minimum uplift rates are 0.7–0.9 m/k.y. (Cape Ferrelo) and 0.05–0.2 m/k.y. (Harbor Bench) (Table 7).

LOCAL STRUCTURES AND VARIATIONS IN UPLIFT RATE

The terrace correlations shown in Figure 6 depict the differential uplift of the terraces and illustrate the role that local structures play in the differential uplift. Terrace correlations, in conjunction with assigned terrace ages, indicate that the Whaleshead fault zone has been active in the late Quaternary and has an average vertical displacement rate of about 0.5 m/k.y. The fault has a component of sinistral slip as indicated by left-lateral offset of correlative paleo–sea cliffs (Fig. 3). On the basis of the approximate offset of paleo–sea cliffs of the no. 4 terrace, the sinistral rate of slip on the Whaleshead fault zone since ~200 ka is about 2.5 m/k.y. A set of subvertical faults that are conjugate to the Whaleshead Fault Zone cuts the late Pleistocene terraces (Fig. 3), although separations are only a few meters. The inferred steep dip of the Whaleshead fault zone (Fig. 6) is consistent with the existence of this set of steeply dipping conjugate faults, although it is not possible to measure the dip of the Whaleshead fault zone from available exposures.

On the basis of terrace correlations, we imply the presence of a crustal flexure or fault in the vicinity of the Chetco River (Fig. 6). A fault at this locality seems likely because plat-

TABLE 5. SUMMARY OF SOIL PROPERTIES USED AS RELATIVE AGE INDICATORS ON THE HARBOR BENCH

Locality	Parent material	Bt horizon thickness (cm)	B horizon hue	Depth to Cox (cm)	Maximum B horizon texture*	Maximum estimated % clay*	Maximum clay skins*	Development stage
Surface soils								
HAa	alluvial fan	>70	10YR	>187	sicl	38	4kpf	4
HAb	alluvial fan	>80	7.5YR	>142	sic	41	4kpf	5
MVc	alluvial fan	>144	10YR	>250	sicl	40	4kpf	5
MVa	alluvial fan	73	10YR	>175	sicl	40	3mkpf	4
SH	alluvial fan	105	10YR	>195	sicl	34	3n-mkpf	4
SHf	alluvial fan	52	7.5–10YR	>127	sicl	32	3mkpf	3
MVf	alluvial fan	76	10YR	275	sic	42	3mkpf	4
Avg.	alluvial fan	>86	10YR	>193	sicl	38	3mkpf	4.1
MVb	sand	58	10YR	162	cl	33	4mkpf	3
CA	sand	62	10YR	>150	sicl	34	4mkpf	4
HL	sand	77	7.5YR	197	sil	25	4mkpf	4
Avg.	sand	66	10YR	>180	sicl	31	4mkpf	3.7
Avg. CF3†	sand	80	7.5YR	181	sicl	32	3mkpf	3.1
Buried soil								
SB	sand	53	10YR	na§	l	25	2npfpo	1
EG	sand	69	10YR	na§	scl	20	vlk	2

*See Table 2 for explanations.
†This row summarizes average soil properties for terrace 3 from the Cape Ferrelo segment.
§Total depth to Cox horizon is a meaningless measurement for a soil buried by younger sediments.

forms just north of the Chetco River in the town of Brookings show no flexure. As is clear from Figure 6, the hypothesized Chetco River fault, the Whaleshead fault zone, and the related fold are the cause of the major difference in surface uplift rate between the Harbor Bench and Cape Ferrelo areas.

Local structural control on uplift rates, as shown in Figure 6, is typical of the Cascadia margin in coastal Oregon. Latitudinal variations in uplift rate have been documented along much of the southern Oregon coast (Kelsey, 1990; McInelly and Kelsey, 1990; Bockheim and others, 1992), and along the central Oregon coast (Ticknor, 1992), using the same technique of platform mapping and correlation described here for the Brookings area. These latitudinal variations in uplift rate are compiled in Figure 7; all major shore-parallel changes in uplift rate are related to late Quaternary activity of local structures, either faults or folds.

COASTAL LANDSCAPE EVOLUTION

Variable Basin Hypsometry as a Function of Uplift Rate

Local structures largely explain the latitudinal variation in coastal uplift rate and therefore may exert a significant influence on landscape evolution at the coast. Given similar geologic substrates and climate, contrasting modes of coastal landscape evolution could be largely a function of local variations in surface uplift rate. To explore the dependence of coastal basin evolution on tectonics, we selected two coastal drainage units that are identical in geology and climate, approximately similar in drainage area and relief, but notably different in average late Pleistocene uplift rate (Table 8). We selected a portion of the Harbor Bench area (Fig. 4) as the low-uplift-rate (0.05–0.2 m/k.y.) drainage unit and several drainages near Cape Ferrelo (Fig. 2) to represent the moderate-uplift-rate (0.7–0.9 m/k.y.) drainage unit. We call the latter uplift rate "moderate" only because we reserve the term *high-uplift rate* for coastal areas where average surface uplift exceeds 1 m/k.y. However, rankings of uplift are relative; for instance, Merritts and Vincent (1989) considered 1–3 m/k.y. as "intermediate" and >3 m/k.y. as "high" for the Cape Mendocino, California, area.

We summarize the contrasting geomorphology of these two drainage units by means of a hypsometric (area-altitude) analysis (Strahler, 1952) (Fig. 8). For the Harbor Bench drainage unit, which typifies the coastal basins that drain onto the Harbor Bench, 35% of the drainage area occurs in the lowest 15% of total relief (Fig. 8). As a consequence, about a third of this drainage unit occurs near sea level and is a low-gradient coastal plain (the Harbor Bench). In contrast, in the Cape Ferrelo drainage unit, the basin

TABLE 6. CORRELATION OF TERRACE SEQUENCES BASED ON DEVELOPMENT STAGES (DS)

Terrace number	Brookings*		Cape Blanco*		Cape Arago*		Newport-Yachats*	
	Terrace name	DS†	Terrace name	DS	Terrace name	DS	Terrace name	DS
1	Harris Beach	1.4	Cape Blanco	1.4	Whiskey Run	1.0	Newport	1.8
2	Brookings	2.4	Pioneer	1.6	Pioneer	1.0	Wakonda	2.7
3	Gowman	3.1	Silver Butte	3.4	Seven Devils	3.8	Yachats	4.0
4	Aqua Vista	5.1	Indian Creek	3.6	Metcalf	4.2	Crestview	4.9
5	Cornett	4.0					Fern Ridge	6.0
6	Homestead	4.3					Alder Grove	5.7
7	Alder Ridge	6.0	Poverty Ridge	4.3				

*See Figure 1B for locations.
†Development stage.

TABLE 7. UPLIFT RATES FOR THE HARBOR BENCH AND CAPE FERRELO COASTAL SEGMENTS

Latitude in degrees (south to north)	Coastal locality	Present elevation (m)	Distance from back edge (m)	Elevation range adjusted to back edge (m)*	Age of platform (ka)	Paleo-highstand elevation when platform was cut (m)†	Amount of surface uplift (min/max) (m)	Range of uplift rates (min/max) (m/k.y.)
Harbor Bench coastal segment								
42.02	N. of Winchuck R.	5§	730	14.5	125	6	8.5	0.07
				25		6	19	0.15
42.025	McVay State Park	4§	850	13.7	125	6	7.7	0.06
				24.8		6	18.8	0.15
42.03	S. of Red Point	7§	1,180	17.2	125	6	11.2	0.09
				30.1		6	24.1	0.19
Cape Ferrelo coastal segment								
42.06	Brookings	53**	0	53	80	−3	56	0.70
						−7	60	0.75
42.09	Rainbow Rock Road	89**	250	94	125	6	88	0.70
				99		6	93	0.74
42.11	Cape Ferrelo	86**	90	88	105	−2	90	0.86
				90		−2	92	0.88
42.14	Martin Ranch	53**	0	53	80	−3	56	0.70
						−7	60	0.75

*Elevation adjustment (a correction to a higher elevation) is 0.02–.04 times distance to back edge for distances ≤450 m, and .007–.0017 times distance to back edge for distances >450 m; the adjustment accounts for the range of platform gradients cited in Bradley and Griggs (1976).
†Employing California sea-level model (Muhs and others, 1992): 105 ka sea level = −2 m; 80 ka sea level = −5 ± 2 m.
§Elevation surveyed to beach cliff and has precision of ±3 m.
**Present elevation taken from topographic map and has precision of ±6 m.

surface area is concentrated in the middle third of the basin where 33% of the relief encompasses 43% of the area; this is in contrast to Harbor Bench drainages where the middle 33% of the relief encompasses only 21% of the area. These area-altitude differences are primarily the consequence of where uplifted wave-cut platforms are preserved in the basin. In the moderate-uplift-rate basins of the Cape Ferrelo drainage unit, multiple wave-cut platforms are preserved on broad interfluves at the middle altitudes, over an elevation range of 75–330 m (Fig. 9). In contrast, in the low-uplift-rate basins of the Harbor Bench drainage unit, a single broad, emergent platform is preserved near sea level (Fig. 10).

Although the interfluve profiles and hypsometries of the two drainage units differ, the streams of both drainage units are similar in that they barely flow in the summer months and have sustained flows during the rainy winter season, approximately from November through April. These streams transport significant quantities of sediment only during storm-runoff periods. Streams such as these can respond to base-level changes by incising or aggrading. However, because of the limited stream power of these streams, the rate of incision or aggradation can be slow (Merritts and Vincent, 1989), especially in relation to the rate of certain processes that promote base-level change, such as sea-cliff retreat or eustatic sea-level fluctuation.

Mechanisms of Base-Level Lowering: Surface Uplift Versus Coastal Retreat

Emergent platforms in both drainage units testify to the lowering of base level during basin evolution. Because eustatic sea-level fluctuations are superimposed on relatively constant tectonic uplift, base-level lowering in coastal drainages can occur by different mechanisms: surface uplift, eustatic sea-level fall, and/or coastline retreat. Short-term base-level lowering can be induced by a single eustatic sea-level fall that occurs over a period of several thousands of years. Over time spans greater than 100,000 yr, which will span at least one major and several minor eustatic sea-level cycles, the net lowering of

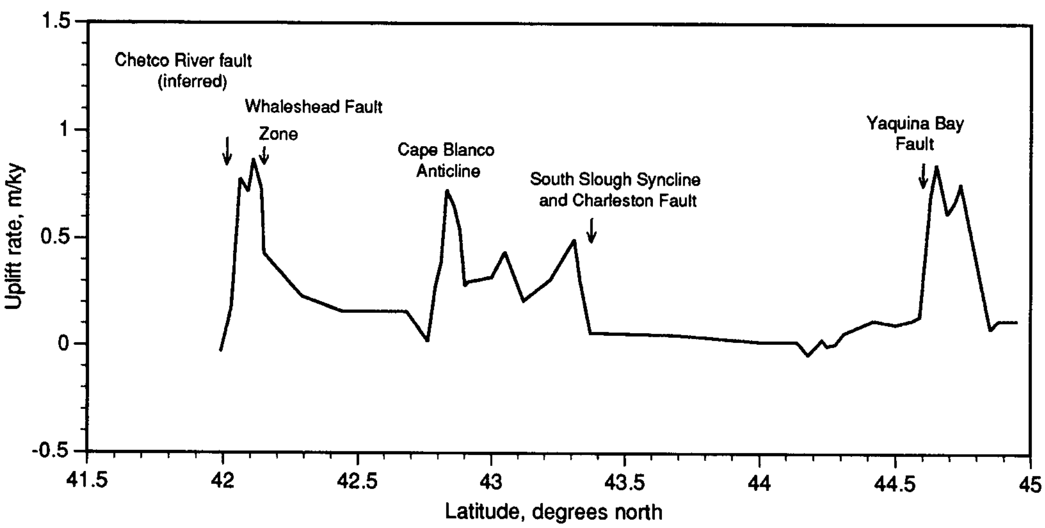

Figure 7. Latitudinal variation in uplift rate within the context of the location of geologic structures, southern and central Oregon coast. Error range for uplift rates: ±0.05 mm/yr. Data sources for uplift rates and geologic structures (in terms of latitudinal range): 42°–42.5°, this paper; 42.5°–43°, Kelsey (1990); 43°–43.4°, McInelly and Kelsey (1990); 43.4°–44°, Kelsey, unpub. data; 44°–45°, Ticknor (1992).

TABLE 8. CHARACTERISTICS OF THE HARBOR BENCH AND CAPE FERRELO DRAINAGE UNITS

Drainage unit	Geology*	Drainage area (km^2)	Relief (m)	Range of uplift rates (m/k.y.)
Harbor Bench	Jd	4.58	420	0–0.2
Cape Ferrelo	Jd	9.70	520	0.7–0.9

*Jd = Jurassic Dothan Formation.

base level is not a consequence of eustatic sea-level fall, but rather of surface uplift (Merritts and Vincent, 1989) and/or landward retreat of the coastline, both of which induce downcutting.

In cases where coastal basins are downcutting, tectonic uplift is usually the dominant mechanism of base-level fall. The only exception is the case where tectonic uplift rates are low (<~0.2 m/k.y.) and two or more successive sea-level highstands attain levels such that coastline retreat resumes at the same shoreline angle elevation. In this case, former wave-cut platforms are reoccupied, and downcutting may be primarily a response to retreat of the coastline.

Platform Reoccupation and the Eustatic Versus the Tectonic Factor

Platform reoccupation is the process by which a eustatic sea-level highstand reoccupies a wave-cut platform occupied by a former sea-level highstand. The conditions under which reoccupation can occur depend on the interplay of eustasy and tectonic uplift. Reoccupation can occur under a range of surface uplift/subsidence rates depending on the elevation differences of two successive sea-level highstands and on whether reoccupation encompasses the whole platform up to the shoreline angle or only part of the platform (Kelsey, 1990).

Consider the case of a seaward-dipping wave-cut platform (Fig. 11). Two successive sea-level highstands occur at times T_A and T_B and attain highstand elevations H_A and H_B, respectively (relative to present sea level). The vertical displacement, relative to a fixed datum, of point P on the platform between T_A and T_B is U_P. Positive U_P is surface uplift and negative U_P is surface subsidence. For a platform undergoing vertical tectonic displacement (uplift or subsidence), total reoccupation of a platform cut at T_A by a successive sea-level highstand at T_B can occur only if

$$U_P = H_B - H_A$$

where U_P is the tectonic factor and $H_B - H_A$ is the eustatic factor (Fig. 11A). Partial reoccupation of a platform will occur if the successive sea-level highstand inundates part of the platform but not all of it. Partial reoccupation of a platform is possible under conditions of net uplift even if the successive sea-level highstand is lower than the one that precedes it (Fig. 11B), because the difference in sea-level highstand elevations can be considerably less than the range in elevation of a single platform.

In low-uplift-rate coastal basins, the difference in height between successive eustatic sea-level highstands can approximate the net vertical displacement of former shoreline angles in the inter-highstand period ($U_P \sim H_B - H_A$), if the vertical displacements U_P and $H_B - H_A$ are both in the same direction. In this case, complete reoccupation of a wave-cut platform can occur. Low-uplift-rate basins, compared to moderate or rapid-uplift-rate basins, are therefore subject to long-term base-level lowering due more to coastal retreat, which occurs periodically during eustatic sea-level highstands, than to surface uplift. However, if the rate of sea-cliff retreat is negligible, then surface uplift will be the dominant control on base-level fall.

In moderate-uplift-rate basins, such as those east of Cape Ferrelo, the vertical displacement of former shoreline angles between major eustatic sea-level highstands is much greater than the elevation difference between successive eustatic sea-level highstands ($U_P >> H_B - H_A$). Thus, multiple former shoreline positions, denoting multiple sites of coastal retreat during former highstands, are morphologically preserved as platforms on interfluves. Long-term base-level lowering is of a greater magnitude than in low-uplift-rate coastal basins and is mostly due to surface uplift.

Platform reoccupation is a common occurrence in the coastal stratigraphic record. For instance, the Silver Butte platform at Cape Blanco, Oregon, has been partially reoccupied twice since ~125 ka (once at ~105 ka and again at ~80 ka [Kelsey, 1990]). In both instances, the succeeding sea-level highstand

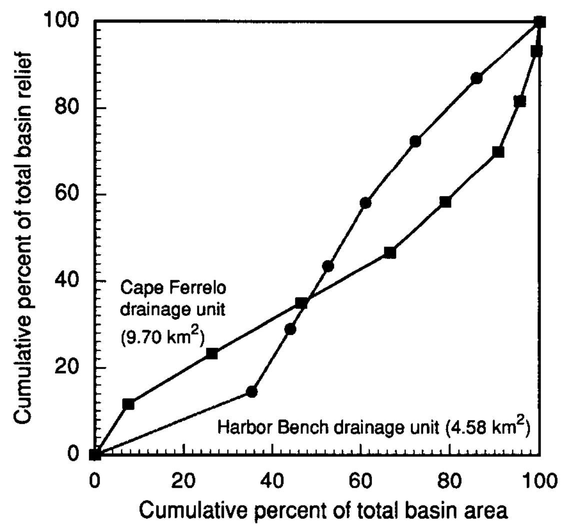

Figure 8. Cumulative percentage of total basin area versus cumulative percentage of total basin relief for the Cape Ferrelo and Harbor Bench drainage units. This is a slightly modified rendition of the area-altitude method described by Strahler (1952). Analysis was performed by counting squares on ten-squares-to-the-centimeter graph paper overlying 1:24,000 topographic map sheets.

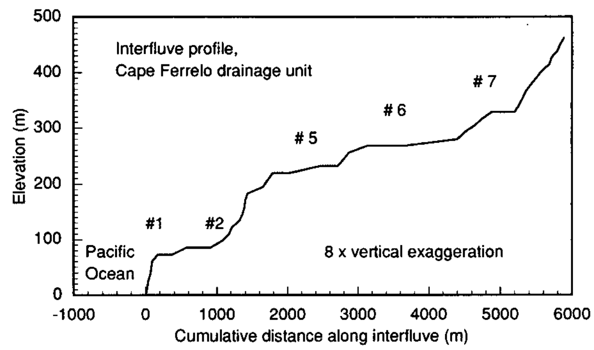

Figure 9. Interfluve profile for the moderate-uplift (0.72–0.87 m/k.y.) drainage unit at Cape Ferrelo (see X–X′ in Fig. 2). The numbers refer to the marine terrace sequence described in Table 1. Terraces 3 and 4 were removed by coastal erosion prior to cutting of the youngest terraces.

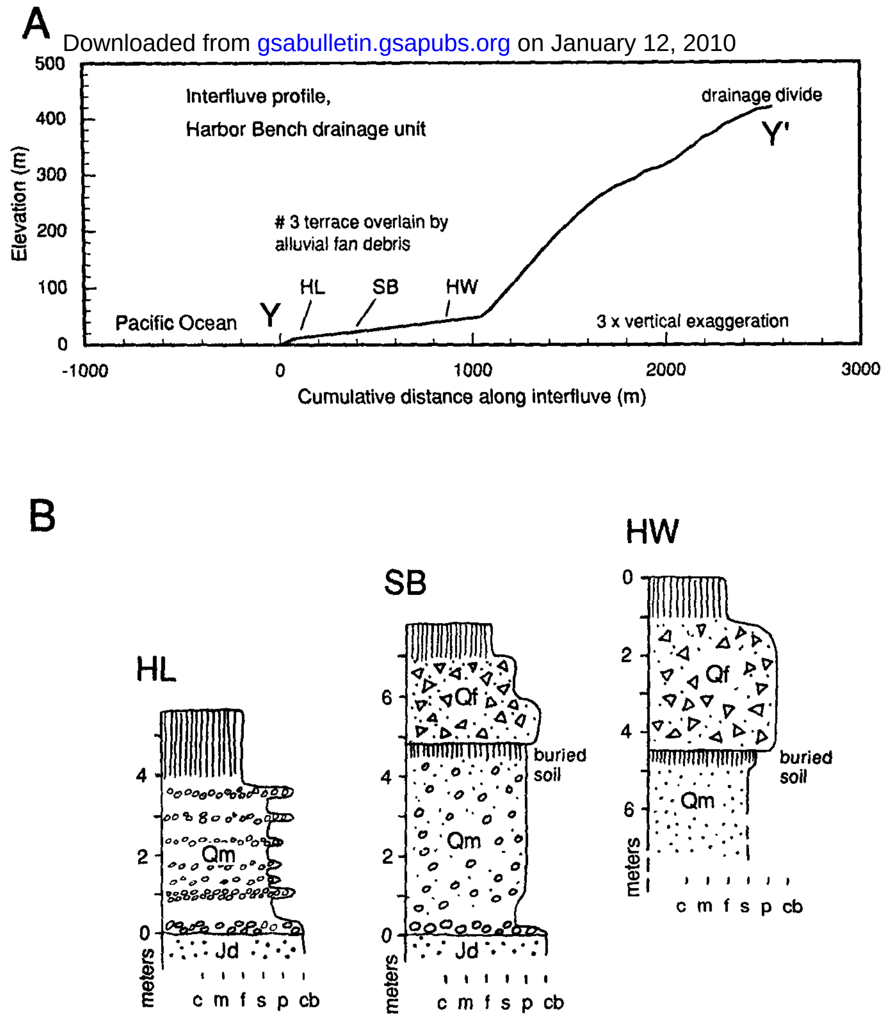

Figure 10. A. Interfluve profile for low-uplift (0–0.2 m/k.y.) drainage unit at Harbor Bench (see Y–Y′ in Fig. 4). B. Three stratigraphic columns showing representative stratigraphy at different distances from fan head on alluvial fan: HL, Holly Lane; SB, Sunday Beach; HW, Hall Way (see locations in Fig. 4). Column thicknesses for localities HL and SB are measured upward from the wave-cut platform; column thickness for locality HW, measured downward from ground surface because the excavation was not deep enough to expose the wave-cut platform. Symbols for columns: Jd, Jurassic Dothan Formation sandstone; Qm, well-rounded to subrounded surf zone gravels and beach sands that overlie wave-cut platform; Qf, subrounded to subangular cobble-pebble alluvial-fan deposits that overlie buried soil developed on marine sands; vertical-line pattern, zone of soil development. Lowercase letters on horizontal axis depict grain sizes: c, clay; m, silt; f, fine sand; s, sand; p, pebble; cb, cobble.

was lower, but the 125 ka platform was wide enough so that it was partially reoccupied under conditions of uplift. Another example in central Oregon is the Yachats-to-Heceta-Head area (Fig. 1), where the ~125 ka platform is presently being partially reoccupied by the modern sea-level highstand (Ticknor, 1992).

Platform reoccupation is also documented along the southern Peruvian and the northern Chilean coasts of South America. At these coastal sites, the uplift rate is 0.1–0.2 m/k.y., and fossil aminostratigraphic data from marine sediments overlying the lowest platform provide evidence that this platform has been occupied by the stage 5 (~80–125 ka) and stage 7 (~200 ka) sea-level highstands and perhaps even by the stage 9 (~320 ka) highstand (Hsu and others, 1989). Leonard and Wehmiller (1992) cited similar evidence that platform reoccupation has occurred in northern Chile on at least one older, higher marine terrace as well. In contrast, along the south-central Peruvian coast where the Nazca Plate is being subducted beneath the continental margin and uplift rates exceed 0.5 m/k.y., there is no evidence of platform reoccupation, and there is clear spatial separation of the uplifted stage 5 (~80–125 ka) and older wave-cut platforms (Hsu and others, 1989).

Paleo-Sea Levels and a Test of the Platform Reoccupation Model

Platform width is a function of the length of the highstand during which the platform is cut, the extent to which the platform is removed by wave attack during the subsequent highstand, the nature of the platform bedrock, and orientation of the coastline relative to direction of wave attack (Emery and Kuhn, 1980; Trenhaile, 1980). If the latter two variables remain constant along a specified region of coastline from one highstand to the next, then platform width is determined by the duration of platform cutting during one highstand and extent of destruction of this platform during the next highstand. As discussed above, the subsequent highstand may reoccupy the platform of the preceding highstand, in which case the earlier platform is erosionally modified and widened, but not eroded and physically isolated by a new sea cliff. For the platforms on either side of the Chetco River, the variables of rock type and coastal orientation (Fig. 1) remain unchanged from one highstand to the next and thus are not significant influences on relative platform width. The Harbor Bench platform (no. 3 platform), which comprises the low-elevation coastal plain of the Harbor Bench drainage unit just south of the Chetco River, is much wider (1–1.7 km) than the equivalent no. 3 platform to the north of the Chetco River (0.3- to 0.6-km width). Furthermore, the combined width of terraces 3 and 4 to the north of the Chetco River is about similar to the width of terrace 3 on the Harbor Bench south of the Chetco River. We therefore hypothesize that the Harbor Bench is relatively wide primarily because it is a reoccupied platform; specifically, it was eroded during occupation of the platform by at least two sea-level highstands, the highstand at ~125 ka and a highstand prior to 125 ka.

The youngest highstand prior to 125 ka occurred during oxygen isotope stage 7 and has been variously dated at ca. 200 ka (Harmon and others, 1983) or as a series of three highstands at ca. 180, 200, and 220 ka (Mesolella and others, 1969; Bender and others, 1979; Chappell, 1983). We use an age of ~200 ka for this highstand.

We can independently test the hypothesis that the Harbor Bench is a reoccupied plat-

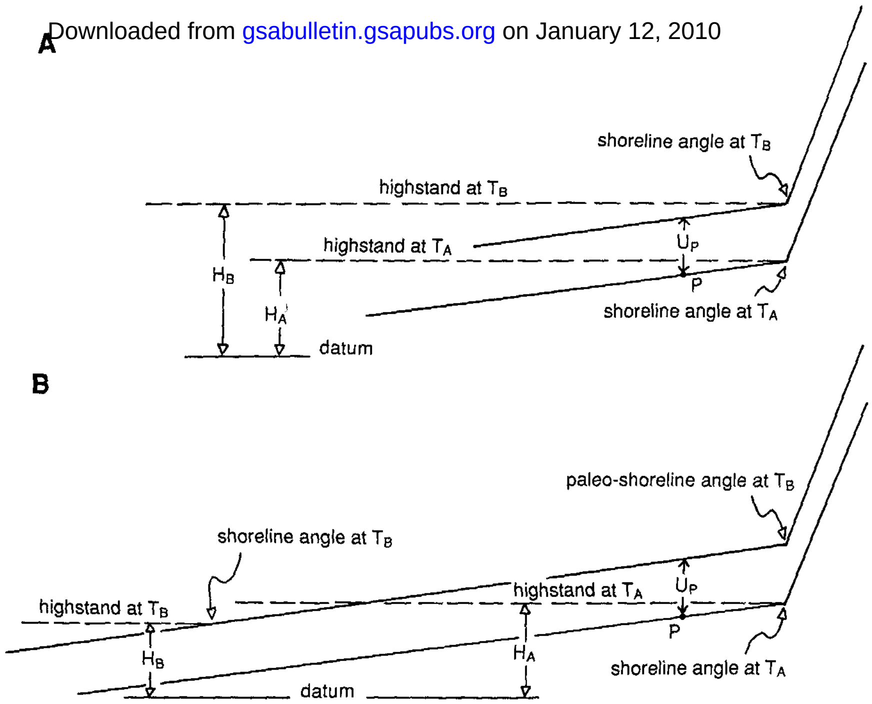

Figure 11. Schematic depiction of the sea cliff–platform junction, showing the variables that define the eustatic versus tectonic factors instrumental in driving coastal retreat and coastal basin incision. H_A and H_B are heights of the two successive highstands (relative to an arbitrary datum); T_A and T_B are times of the two successive highstands; U_P is the vertical displacement of the platform at P between T_A and T_B (U_P is positive for surface uplift and negative for surface subsidence). A. This figure shows the same wave-cut platform, displaced vertically by the amount U_P. Because $U_P = H_B - H_A$, the later sea-level highstand will totally reoccupy the platform cut during the earlier sea-level highstand. B. Under conditions of $U_P > H_B - H_A$, the sea-level highstand at T_B partially reoccupies the platform cut at T_A. Platform reoccupation occurs under conditions of uplift even though the successive sea-level highstand is lower because the platform elevation range (platform gradient is 20–40 m/km [Bradley and Griggs, 1976]) is considerably greater than the range in elevation between successive sea-level highstands.

form, cut during the eustatic sea-level highstand at ~200 ka and reoccupied during the terrace 3 highstand at 125 ka. The eustatic sea-level highstand at 125 ka, denoted H_{125}, is 6 m (Chen and others, 1991; Harmon and others, 1983) and T_3 = 125 ka. The range of surface uplift rate of the Harbor Bench in the last 125 ka is 0.05–0.2 m/k.y. (Table 7). Applying this uplift rate to the ~200- to 125-k.y. time interval, U_P = 3.8–15.0 m. For total reoccupation to occur, $H_{125} - H_{200} = U_P$. This can only be the case if H_{200} (eustatic highstand elevation at ~200 ka) is in the range +2 to −9 m. Estimates of sea-level highstand elevation at ca. 200 ka, derived from U-series age determinations on high-sea-stand coral reefs on tectonically stable coasts, range from no lower than −5 m in the Bahamas (Foos and Muhs, 1991) to +2 m for Belmont Formation corals on Bermuda (Harmon and others, 1983). Although our estimate of paleo–sea level at ~200 ka has an 11-m range, it spans the above range of estimates for this paleo–sea level. Therefore, the hypothesis that the Harbor Bench platform was cut during the ~200 ka eustatic highstand and was reoccupied and widened during the ~125 ka highstand is consistent with best estimates for the ~200 ka paleo–sea level highstand.

Alluvial Fans in the Piedmont Zone of Low-Uplift-Rate Coastal Basins

A consequence of platform reoccupation in the lowermost portions of coastal basins is that platforms cut during an earlier sea-level highstand can be further widened during the subsequent highstand. The resultant wide coastal benches, situated near sea level, are potential sites for deposition of terrestrial sediments by either eolian or fluvial processes. Fluvial deposition on the benches is especially likely if the bench lies within the deposition zone, or piedmont zone (Schumm, 1977), of coastal drainages.

In the Harbor Bench area, coastal alluvial fans blanket the one low-elevation marine terrace (Fig. 4). Although the fans coalesce at their distal ends, each fan has a distinctive lobate morphology and the fan head is clearly associated with the mouth of a coastal drainage basin. In the past, these drainages were the source of the fan deposits, but at present the streams discharging from these drainages are entrenched below the fan surface. The stratigraphy underlying the fan surface is distinctive in that continentally derived fan sediments have prograded over beach deposits that overlie an uplifted wave-cut platform (Fig. 10B). The fans thus bury a marine terrace, and the fan deposits bury a soil that was developed on the terrace prior to burial (Fig. 10B).

We collected data on the ground soil developed on the fan deposits and the ground soil developed on the adjacent beach deposits to the west of the fans (Fig. 4; Table 5). The fan soil is generally similar to, though slightly better developed than, the soil developed on the unburied beach sands (Table 5). We suspect that this is the case because the fan parent material consists in part of transported, preweathered sandstone colluvium from the uplands. The fan and beach ground soils are both well-developed Ultisols. Based on a soil chronosequence for Oregon marine terraces (Bockheim and others, 1992), the soils on the marine terrace have been developing for about the last 100 k.y.

The marine terrace soil that is buried by the fan debris (sites SB and HW, Fig. 10B) is considerably less developed than the surface soil developed on the marine terrace sands (Table 5). Relative soil development on the Harbor Bench thus leads us to hypothesize that fan deposition, which buried much of the Harbor Bench marine terrace, occurred shortly after marine terrace emergence.

DISCUSSION

Alluvial-Fan Deposition on Marine Terraces: Alternative Hypotheses for the Entrenchment and Preservation of the Fans

The purpose of this section is to speculate on the conditions of origin of the Harbor Bench alluvial fans. Within the Harbor Bench drainage unit, between 3 and 4.5 million m^3 of fan debris is preserved from a source area of 3 km^3 (Table 9). The volume of the fans is therefore substantial; they represent the equivalent of up to a half-meter thickness of soil uniformly eroded from the basin source area. Because additional fine-grained sediment bypassed the fan and was deposited in the ocean, the actual thickness of soil eroded during the period of fan building was even greater.

TABLE 9. CALCULATION OF DURATION OF FAN AGGRADATION FOR HARBOR BENCH DRAINAGE UNIT

Attribute	Unit	Quantity	Source
1. Surface area of fan	km^2	1.51	field data
2. Average fan depth	m	2–3	field data
3. Volume of alluvial fan	m^3	3.02×10^6–4.53×10^6	field data
4. Drainage area above fan head	km^2	3.07	field data
5. Density of fan debris	$g(cm)^{-3}$	0.8–1.3	field data
6. Annual sediment yield from Harbor Bench drainage unit during period of fan aggradation	$m^3(km^2yr)^{-1}$	150–1,000	Kelsey, 1977; Reneau and Dietrich, 1991*
7. Fraction of annual total yield that is deposited on fan	dimensionless	0.5–0.8	see footnote†
8. Sediment volume contributed by fans each year	$m^3(yr)^{-1}$	230–2,500	product of (4) (6) (7)
9. Time to build Harbor Bench drainage unit fans	yr	1,200–20,000	product of (3) (8^{-1})

*Compiled sediment basin yields in these references are used to estimate range of annual yields for mixed grassland-forest watersheds underlain by incompetent sandstone of the Jurassic Dothan Formation.

†Assumes the remainder of the suspended sediment fraction is deposited farther down on the fan or delivered directly to ocean.

The Harbor Bench was last occupied by a sea-level highstand during the last interglacial (~125 ka). Because the Harbor Bench fans overlie sublittoral deposits and beach sand, they were deposited after sea level had already started to fall from its highstand position. Coastal basins did not respond to the fall in eustatic sea level by downcutting. Rather, fans aggraded because the piedmont streams had insufficient stream power to carry sediment discharged to the fan head across the emerging coastal plain to the ocean. Fan aggradation ceased at the time of entrenchment, and this occurred during a eustatic sea level lower than that of the last interglacial. Fan aggradation has not resumed; and the distal (western) edge of the fan presently is retreating by coastal erosion. Eustatic highstands at ~105 and ~80 ka probably also eroded the western margin of the fans.

How long did fan building persist? We can calculate the approximate duration of the fan aggradation on the Harbor Bench, which commenced ~115–120 ka (the age of the end of the last interglacial [Chen and others, 1991]). The calculation assumes a range of values for average fan depth, density of fan material, annual sediment yield from the upland drainage basin, and the fraction of this annual yield that was deposited on the fan (Table 9). The duration of fan deposition at the end of the last interglacial could have been as short as a few thousand years but probably not longer than about 20,000 yr (Table 9). We thus infer that sediments on the Harbor Bench record a relatively short fan-building episode that started about 120 ka and was completed before ~100 ka. This inference is consistent with the facts that the soil buried by the fan is poorly developed and the soil on the fan surface is a well-developed Ultisol. The fan soil is similar in degree of development to the adjacent soil developed on beach deposits.

Entrenchment of the fans in the late Pleistocene is responsible for their preservation. We propose two alternative hypotheses for the initiation of fan entrenchment: entrenchment caused by headward propagation of a knickpoint in response to an increase in the gradient of the fan or entrenchment caused by a decrease in sediment supply to the fan without necessitating changes in fan gradient over time. The processes at work in either hypothesis result in a decrease in the amount of stream power required to transport sediment, in one case because less sediment is available and in the other case because less power is needed to transport the same amount of sediment on a steeper gradient.

For the first hypothesis, an increased gradient could be the result of fan aggradation, which steepens the fan over time. Gradient increases could also be in response to sea-cliff retreat of the fan edge, the retreat being triggered by a eustatic sea-level rise. Steepening leads to entrenchment, which then propagates upstream through the headward migration of a knickpoint.

In the second hypothesis, a decrease in coastal basin sediment yield triggers entrenchment. If the sediment supply drops off, incision would occur in response to available stream power, grading coastal streams to the lowered base level. This hypothesis allows for subsequent upstream propagation of a knickpoint, triggered by cliff retreat during a sea-level rise. However, knickpoint migration would not be the cause of entrenchment, but rather would be accommodated within a preexisting entrenched stream.

The first hypothesis does not require a change in sediment yield, but it does require that as fan aggradation proceeds, the fan gradient becomes significantly steeper than the original platform gradient. The first hypothesis is more attractive in that the Harbor Bench fans did steepen with time, regardless of whether or not there had been changes in sediment yield over time. Presently, fan gradients on the Harbor Bench are steeper than underlying platform gradients, because the fans pinch out going from their proximal ends at the fan head to their distal ends on the oceanward side of the platform (Fig. 10).

Based on the Harbor Bench fan data, however, the possibility of sediment-yield changes between 125 and 100 ka cannot be rejected. If there were relatively high sediment yields at the end of the last interglacial, then changes in sediment yield would coincide with the early stages of global cooling at this time. Therefore, it would be useful to further test both hypotheses. One such test would be to document late Pleistocene chronostratigraphic histories for other Pacific coastal sites that are similar to that for the Harbor Bench. For instance, on San Clemente Island in southern California, where uplift rates are 0.2 m/k.y., alluvial fans up to 10 m thick, originating from drainage basins that are <0.2 km^2, cover parts of the ~125 ka marine terrace (Muhs, 1983). At another site in the coastal Santa Monica Mountains in southern California where uplift rates are 0.1–0.4 m/k.y., Birkeland (1972) reported that alluvial fans with thicknesses as great as 30 m cover ~105 and 125 ka marine terraces. Better chronostratigraphic and lithostratigraphic data are needed from these and similar sites. Another type of exposure worth examining is aggradation deposits on uplifted fluvial strath surfaces along Pacific coast river valleys. If the change-in-sediment-yield hypothesis is valid, these sediments should provide a cluster of ages of ca. 120–100 ka. Fluvial terraces, which feasibly could be in this age range, occur on uplifted strath surfaces along most west-draining Oregon Coast Range Rivers (Personius, 1993). A test of the alternative hypotheses, in this case, requires more reliable methods of age determination for fluvial sediments in this age range.

SUMMARY

This paper employs wave-cut platforms and techniques of landform correlation using soils to identify variable tectonic uplift rates along the coast. Once establishing the tectonic environment, we evaluate landform evolution of coastal basins where both tectonic uplift and coastal erosion in response to eustasy play fundamental roles in driving base-level fall. We examine two small coastal drainage units that have distinctly different late Pleistocene uplift rates. For each site, the drainage divide is within 2.5–5 km of the coast. Through our choice of study sites, we evaluate the influence of coastline dynamics on coastal basin evolution. We recognize, however, that our study design does not allow evaluation of the significant influence that large rivers can have on coasts immediately adjacent to river mouths. Our conclusions are pertinent to convergent and transcurrent plate margins at midlatitudes in the Pacific Ocean basin.

In moderate-uplift-rate coastal basins, multiple wave-cut platforms are preserved on basin interfluves. The individual paleo–sea cliffs attest to the influence of coastline retreat on basin evolution. However, basin topography has been mainly generated by surface uplift because the multiple platforms, all cut within about 20 m of present sea level, now span an altitude of 75–330 m.

In contrast, in low-uplift-rate basins, coastal retreat is a more important mechanism of base-level fall in the late Quaternary because tectonic uplift between sea-level highstands is small and approximately equal to the vertical difference between successive sea-level highstands. Repeated instances of coastline retreat at the same basin position will occur under conditions of total reoccupation of a wave-cut platform. Such periodic coastline retreat events on the same platform create broad platforms near sea level, as exemplified by the Harbor Bench. For the Harbor Bench drainage unit, the break in slope in both the hypsometric curve and the interfluve profile represents the locus of coastal retreat that created the Harbor Bench platform. Even under conditions of partial reoccupation, broad platforms can be preserved by virtue of the fact that they are not subject to erosion by the successive highstand, although a partial reoccupation will not result in further erosion of the back edge of the platform.

Broad platforms such as the Harbor Bench remain within the piedmont zone of coastal basins for hundreds or thousands of years. In this setting, these platforms can accumulate fluvial deposits from upland coastal basins during time periods following eustatic sea-level fall. Such deposits are rare because sea level during most of the Quaternary has been lower than today, and most deposits that record coastal events during times of lower eustatic sea level are now submerged.

The Harbor Bench alluvial fans accumulated during an ~2- to 20-k.y. period following the sea-level highstand at ca. 125 ka. The fans aggraded out onto the low-gradient, 125-k.y. marine terrace that became emergent during sea-level fall. We propose two alternative hypotheses for the subsequent entrenchment and preservation of these fans. We favor the hypothesis in which entrenchment occurs in response to an increase in the gradient of the fan, the gradient increase being a result of buildup of the fan over time. Alternatively, entrenchment may have been caused by a decrease in sediment supply to the fan at the end of the last interglacial period. These hypotheses need to be further evaluated through chronostratigraphic study of other late Pleistocene aggradation deposits in coastal Pacific settings.

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