

LATE QUATERNARY DEFORMATION OF MARINE
TERRACES ON THE CASCADIA SUBDUCTION ZONE
NEAR CAPE BLANCO, OREGON

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Abstract. The Cape Blanco region of south coastal Oregon sits on the upper plate of the Cascadia subduction zone about 60-70 km east of the base of the continental slope. Though the region has no historic coseismic deformation, late Quaternary deposits and landforms show abundant evidence of uplift, folding, and faulting. A set of five late Quaternary marine terraces and one uplifted Holocene beach berm are preserved in the Cape Blanco region. Stratigraphic and altitudinal surveys of these physiographic features, combined with several numerical and correlation age determinations, permit a reconstruction of tectonic deformation near Cape Blanco in approximately the last 200,000 years. The most cogent aspects of the neotectonics in this part of the Cascadia subduction zone are that an east-west trending anticline deforms the lower three terraces (80-125 ka) as well as accounting for uplift of the Holocene storm berm. Latest movement on the anticline was no more than 2,000 years ago, but the anticline also deforms sediments as old as Middle Miocene. The

anticline is consistent with a north-south principal contraction axis at Cape Blanco in about the last 100,000 years. An older terrace at Cape Blanco (approximately 200 ka) is offset by two reactivated faults whose movements prior to the Eocene served to suture several terranes to the North American continent. Tectonic tilting in the older terrace is not consistent with a north-south principle axis of contraction, but the axis of tilt is parallel to north-northwest striking structures developed in the Quaternary fold belt offshore on the continental shelf. The observed deformation indicates that regional stress in the vicinity of Cape Blanco in the late Quaternary has been accommodated by a variable pattern of strain.

INTRODUCTION

Rates and styles of tectonic deformation along convergent margins vary both in space and time. Such variation has generally been documented at two quite different time scales--the historic time scale, where resolution of deformation is comparatively excellent; and the time scale recorded by plate motions, where resolution is limited by the magnetic reversal record on the sea floor to millions of years. However, by studying

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deformed marine terraces along uplifted coastlines, both rates and styles of deformation along segments of convergent margins can be documented at an intermediary time scale less precise than measurements provided by the short historic record but more precise than estimates of deformation inferred from recorded plate motions.

The purpose of this paper is to describe late Quaternary deformation in the vicinity of Cape Blanco, Oregon (Figure 1). Cape Blanco is the closest (60 km) point of land to the base of the continental slope that defines the leading edge of the North American plate (Figure 1). At times of high sea level in the

late Quaternary [Bloom et al., 1974; Chappell and Shackleton, 1986], wave erosion beveled a set of marine platforms at Cape Blanco and inland to the east. These platforms have been partially preserved due to tectonic uplift. Terrace sediments, 6.5-55 m thick, cover these platforms. The younger (western) terraces are well preserved, and the older (eastern) terraces are only preserved as flat-topped benches or accordant ridge summits. Wave-cut platforms in south coastal Oregon show clear evidence of uplift, tilting and/or faulting. Because the shoreline angles of wave-cut platforms were roughly horizontal (in a shore-parallel sense) at times of formation, the platforms are excellent marker horizons for assessing deformation.

I describe the distribution and age of the late Quaternary marine terraces and marine deposits at Cape Blanco and the pattern of uplift and the degree of variability in uplift of these terraces and deposits. To do so, I present stratigraphic, pedologic, elevation and age data on the wave-cut platforms or the overlying sediments. On the basis of the observations, I discuss the late Pleistocene and Holocene tectonic history of the Cascadia forearc in the vicinity of Cape Blanco.

GEOLOGY OF THE CAPE BLANCO AREA

The Cape Blanco area (Figure 1) is the northernmost portion of the Oregon coast where accreted Mesozoic rocks make up the coastal ranges [Wells and Peck, 1961; Dott, 1962, 1971; Koch, 1966; Brownfield et al., 1982; Blake et al., 1985; Bourgeois and Dott, 1985]. North of Bandon (Figure 1), Eocene and younger rocks underlie the coastal ranges [Wells and Peck, 1961; Baldwin, 1974].

Therefore, marine terrace deformation at Cape Blanco records the type of deformation near the north end of the exposed Mesozoic accreted terrain in coastal Oregon.

Along the Oregon coast south of Port Orford (Figure 1), Neogene deposits of significant extent are not present [Dott,

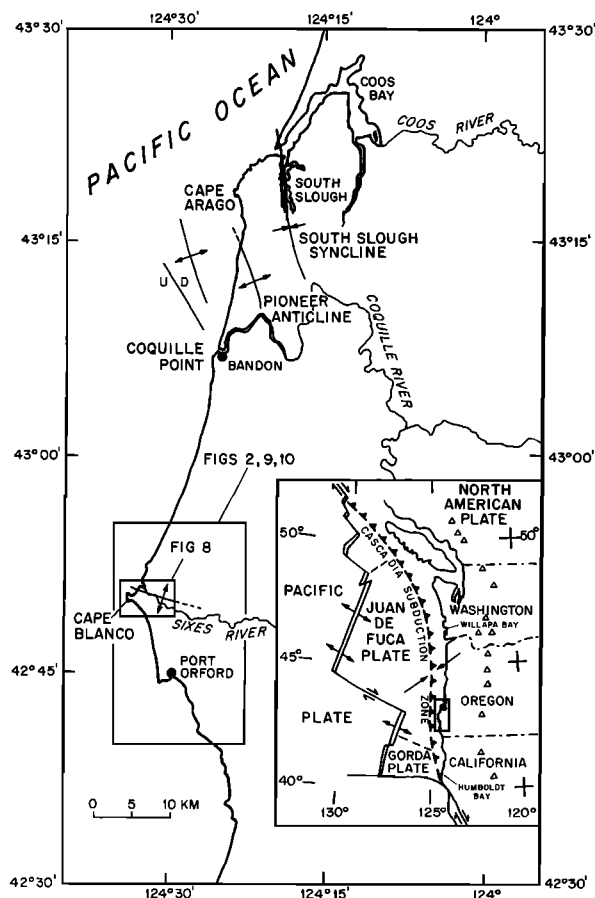


Fig. 1. Location map of the study area in south coastal Oregon in the context of the Cascadia subduction zone and the Pacific, Juan de Fuca, and North American plates. The triangles denote volcanoes of the Cascade Range.

1971]. However, between Port Orford and just north of Cape Blanco, sea cliffs expose the most complete section of late Cenozoic rocks found anywhere on the Oregon coast [Baldwin, 1945; Armentrout, 1980; Addicott, 1964, 1983; Leithold and Bourgeois, 1984]. Within this extended exposure, several units, separated by at least three unconformities, dip to the southeast with progressively shallower dips on the younger units. These deposits are in turn overlain unconformably by Late Pleistocene marine terrace sediments, which dip approximately 0.4° to the southeast. The terrace sediments dip from a high point at Cape Blanco 9.75 km to the southeast where they merge with the modern beach at Garrison Lake (Figures 2 and 3). Thus, the Neogene and Quaternary sequence records progressive tilt with time. North of Cape Blanco, Miocene sandstones [Leithold and Bourgeois, 1984] tilt north and the overlying late Pleistocene wave-cut platform (cut unconformably on the Miocene rocks) tilts north and merges to the north with the modern beach at Floras Lake, 9 km north of Cape Blanco. The Neogene and early Quaternary units, as well as the Late Pleistocene terrace surfaces, are therefore deformed in an approximately east-west trending anticline whose axis passes through Cape Blanco (Figure 1) [R.J. Janda, unpublished manuscript, Field guide to Pleistocene sediments and landforms and soil development in the Cape Arago-Cape Blanco area of Coos and Curry Counties, southern coastal Oregon, Friends of the Pleistocene, October 9-11, 1970; hereinafter referred to as (Janda, 1970)]. The late Quaternary expression of the anticline is evident from a shore-parallel profile of the late Quaternary marine terraces (Figure 3).

Griggs [1945] mapped five marine terraces in the Cape Arago-Bandon area, 35-55 km north of Cape Blanco (Figure 1), as part of a study of chromite-bearing black sand deposits that occur along the terrace backedges. Griggs [1945] named the lower three terraces in ascending order, the Whiskey Run, Pioneer, and Seven Devils terraces. Janda [1969], (1970)

defined four marine terrace platforms in the Cape Blanco vicinity differentiated on the basis of elevation, cover stratigraphy, and soil development. Janda [1969] correlated the lower extensive marine surface at Cape Blanco with the Pioneer surface further north near Cape Arago. Janda (1970) introduced new names for the three upper marine terraces east of Cape Blanco area: the Silver Butte, Indian Creek, and Poverty Ridge terraces.

The lowest terrace at Cape Blanco has been estimated to be 45-75 ka in age [Wehmiller et al., 1977] based on amino acid data from mollusks at both Cape Blanco and Coquille Point near Bandon. The age estimate was a correlated age using a $^{230}\text{Th}/^{234}\text{U}$ age determination on the coral *Balanophyllia elegans* from the cover sediments of the Whiskey Run terrace at Coquille Point of 72.2 ± 5.3 ka (unpublished date of T.-L. Ku cited in Kennedy et al. [1982]). However, the $^{231}\text{Pa}/^{253}\text{U}$ ratio for this coral was greater than 1.00, which is discordant with the $^{230}\text{Th}/^{234}\text{U}$ age [Muhs et al., 1990]. More recent age information is discussed below.

The terrace platform at Cape Blanco reportedly has the highest uplift rate of any marine platform on the Oregon coast [West and McCrumb, 1988]. This uplift rate was calculated employing the age estimates of Wehmiller et al. [1977]. I present evidence below for multiple reoccupation of the Cape Blanco flat surface by several high stands of sea level; recognition of reoccupation necessitates a reassessment of the number of wave-cut platforms and of the pattern of uplift depicted by these platforms.

LATE QUATERNARY MARINE TERRACES IN THE VICINITY OF CAPE BLANCO

I identified and differentiated marine terraces on the basis of elevation of the terrace surface and recognition of terrace backedges, elevation of the underlying wave-cut platform (where exposed), stratigraphy of the marine sediments on the wave-cut platform, degree of soil development and correlated-age

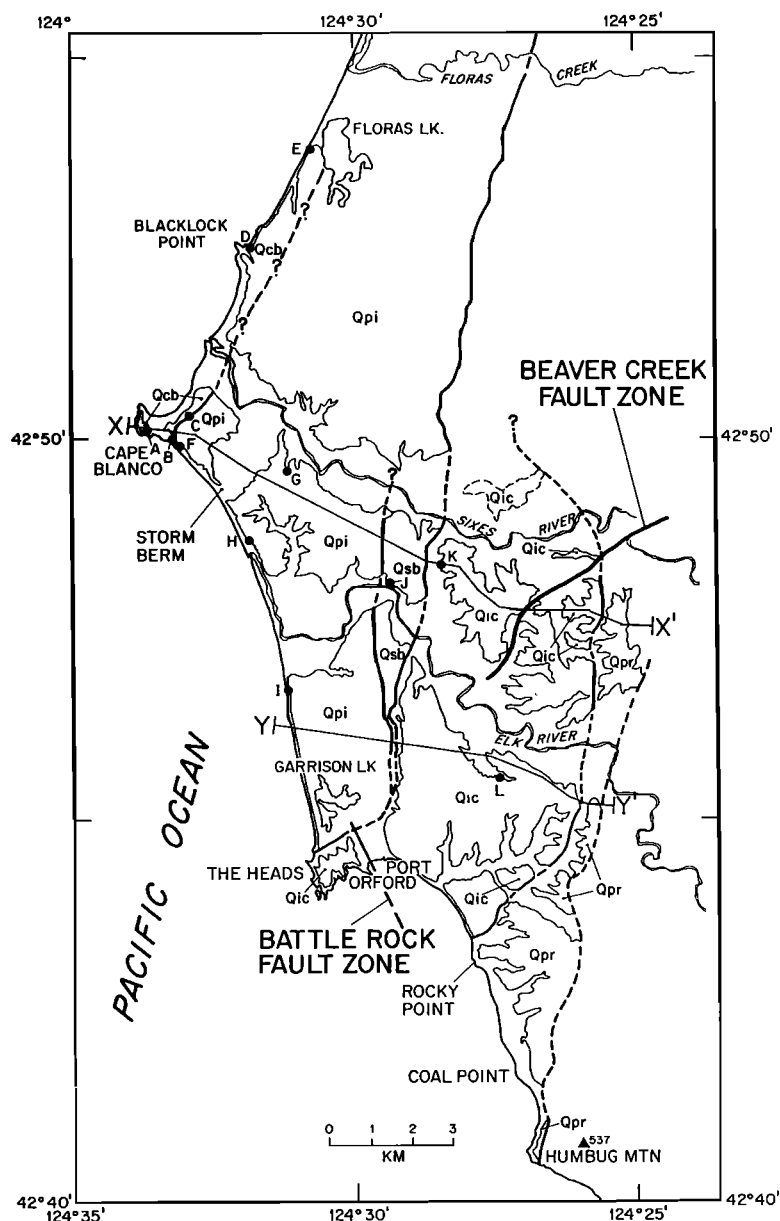


Fig. 2. Geologic map of late Quaternary marine terrace sediments in the vicinity of Cape Blanco, Oregon. The bold lines show the two major fault zones that offset geologic units of Quaternary age. Marine terrace sediments from youngest to oldest: Qcb, Cape Blanco terrace sediments; Qpi, Pioneer terrace sediments; Qsb, Silver Butte terrace sediments; Qic, Indian Creek terrace sediments; Qpr, Poverty Ridge terrace sediments. The heavier solid or dashed line at the eastern margin of each terrace is the estimated position of the backedge (shoreline angle) of the terrace. Note that the backedge contacts of Qcb-Qpi and Qpi-Qsb cannot be traced north of the Sixes River. These backedge contacts are subtle to non-existent because a single expansive wave-cut platform underlies units Qcb, Qpi and Qsb (see Figure 9). Solid circles are locations of measured stratigraphic sections in the terrace sediments (keyed by letter to the columns shown on Figures 6 and 7). Cross-sections X-X' and Y-Y' are shown in Figures 4 and 5 respectively.

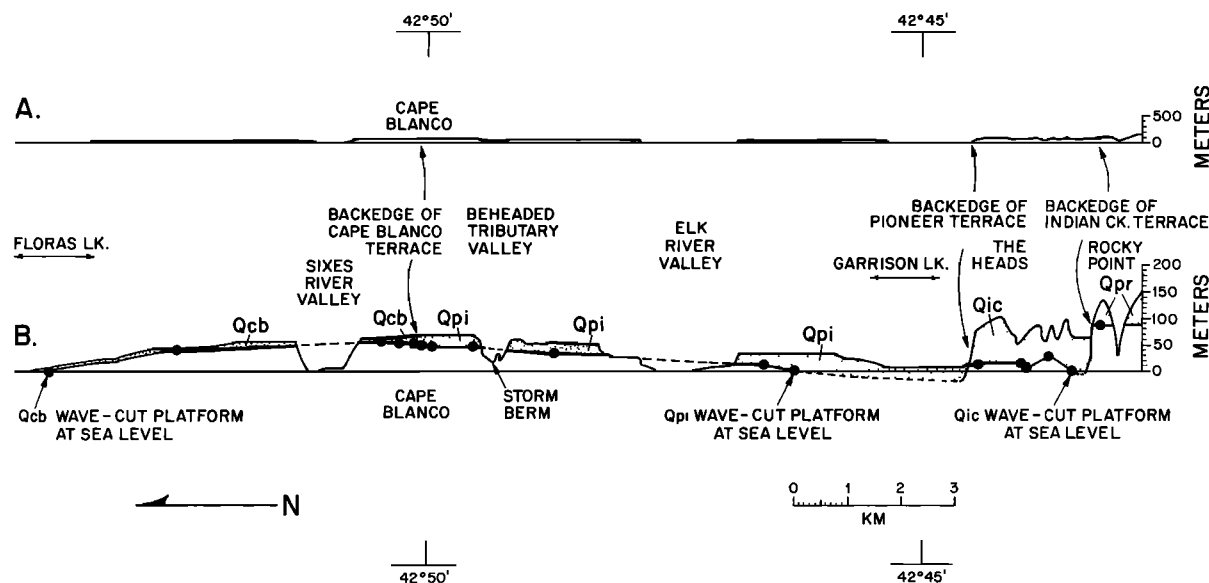


Fig. 3. Shore-parallel topographic profile from Rocky Point northward to Floras Lake. (a) no vertical exaggeration; (b) 10 x vertical exaggeration. All data points are projected westward onto a north-south trending vertical plane that runs through the outermost (western) tip of Cape Blanco. The topographic profile connects elevation points from the top of seacliffs or the top of steep hillslopes rising from the beach. Solid dots denote a measured elevation on a marine wave-cut platform. Qcb, Qpi, Qic, Qpr, marine terrace sediments on the Cape Blanco, Pioneer, Indian Creek and Poverty Ridge terraces, respectively. Note that the lowest marine terrace at various points along the coast is represented by four progressively older terraces from Cape Blanco south to Rocky Point.

determinations. Wave-cut platform elevations were determined from 1:24,000-scale topographic maps, where elevation accuracy is ± 3 m for flat terrace surfaces and ± 6 m for terrain with slopes $> 2^\circ$. I used water well driller's logs to ascertain additional depths to wave-cut platforms. Well log accuracy is ± 6 m.

Morphology and Stratigraphy

The sequence of marine terraces near Cape Blanco is best preserved along two transects: a WNW-to-ESE transect of five marine terraces from Cape Blanco inland to the uplands that separate the Elk and Sixes Rivers (Cape Blanco transect, Figures 2 and 4), and an E-W transect of the upper four marine terraces from north of Garrison Lake to the benchlands just south of the Elk River Valley (Garrison

Lake transect, Figures 2 and 5). Janda [1969], (1970) recognized the four highest terraces (Table 1), but did not recognize the lowest one. The complete set of marine terraces is preserved along the Cape Blanco transect (Figure 4) because resistant rocks of the upper Jurassic Otter Point Formation [Dott, 1962; 1971] at the tip of Cape Blanco makes the cape an effective erosional buttress that maximizes preservation of wave-cut platforms. Geologic data for the five terraces (tabulated in part from measurements along the Cape Blanco transect) are compared in Table 1.

The youngest terrace, hereinafter called the Cape Blanco terrace, is only preserved in the immediate vicinity of Cape Blanco (Figures 2, 3 and 4). Along the transect of Figure 4, the Cape Blanco terrace backedge height is 8 m. Terrace

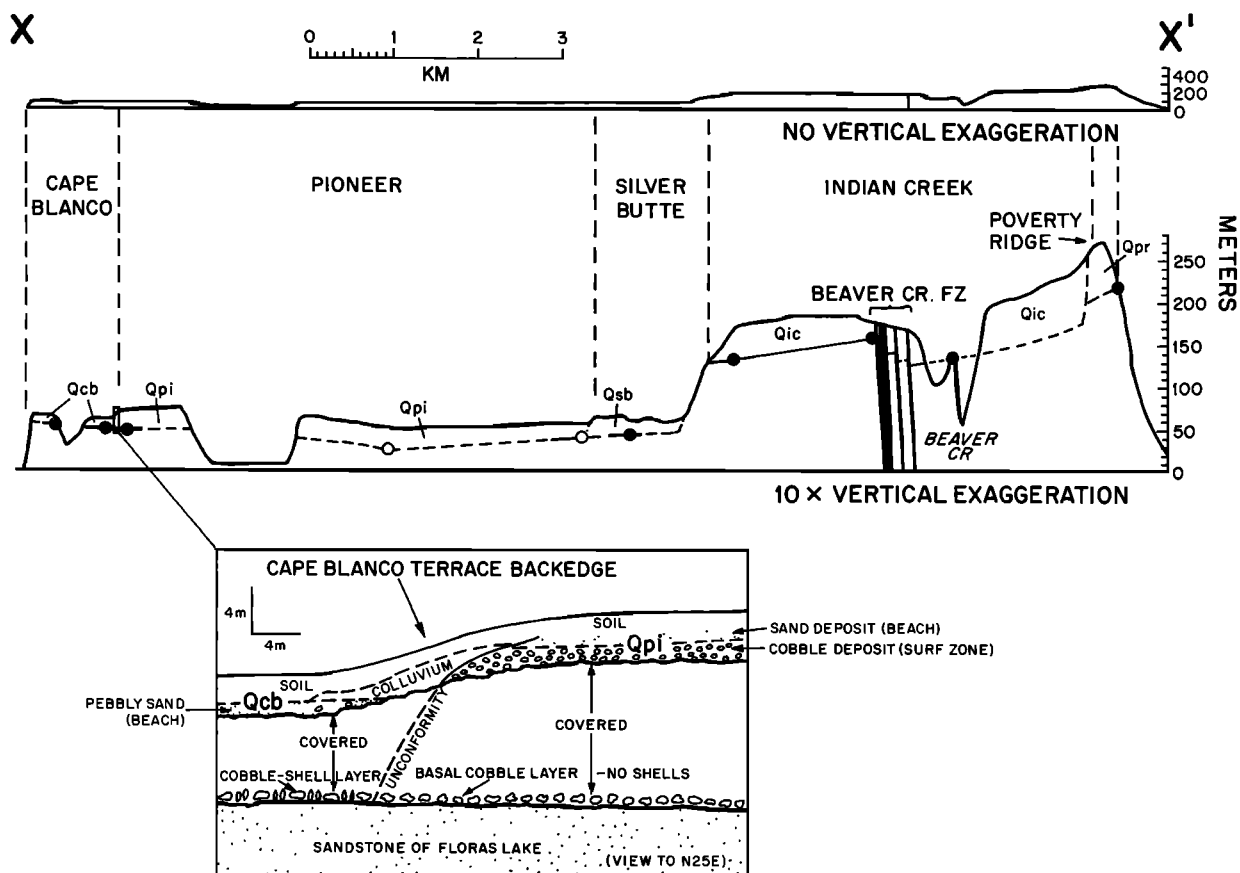


Fig. 4. Cross-section of the marine terrace sequence from Cape Blanco east-southeast to the uplands between the Sixes and Elk Rivers. Location of this profile (X-X') shown on Figure 2. Qcb, Qpi, Qsb, Qic, Qpr, marine terrace sediments on the Cape Blanco, Pioneer, Silver Butte, Indian Creek and Poverty Ridge terraces, respectively. Solid dots, altitude control from field mapping; open dots, altitude control from well logs. Diameter of the dot is equal to the approximate vertical uncertainty in altitude. Framed box shows stratigraphic relations exposed in the sea cliff of the contact between Qcb and Qpi. The sea-cliff exposure is about 400 m south of the location where the cross-section line crosses the Qcb-Qpi contact.

cover sediments range in thickness from 6.4-9.0 m and generally grade upwards from surf zone to beach deposits (columns A, C, D and E, Figure 6). Janda [1969], (1970) and West and McCrumb [1988] did not recognize this terrace but rather included it with the Pioneer terrace, which is the next highest and most extensive of the terraces (Figure 2).

The contact between the Cape Blanco and Pioneer terrace sediments is well exposed in a sea cliff cross section that is

schematically shown in Figure 4. Below the Cape Blanco terrace backedge, Cape Blanco terrace sediments rest on an erosional unconformity that truncates both the soil and the uppermost gravels of the Pioneer sediments (Figure 4). The two terrace sediments are of different thicknesses and the unconformity juxtaposes marine sediments of different depositional environments (Figure 4). Though the wave-cut platforms that underlies the adjacent Cape Blanco and

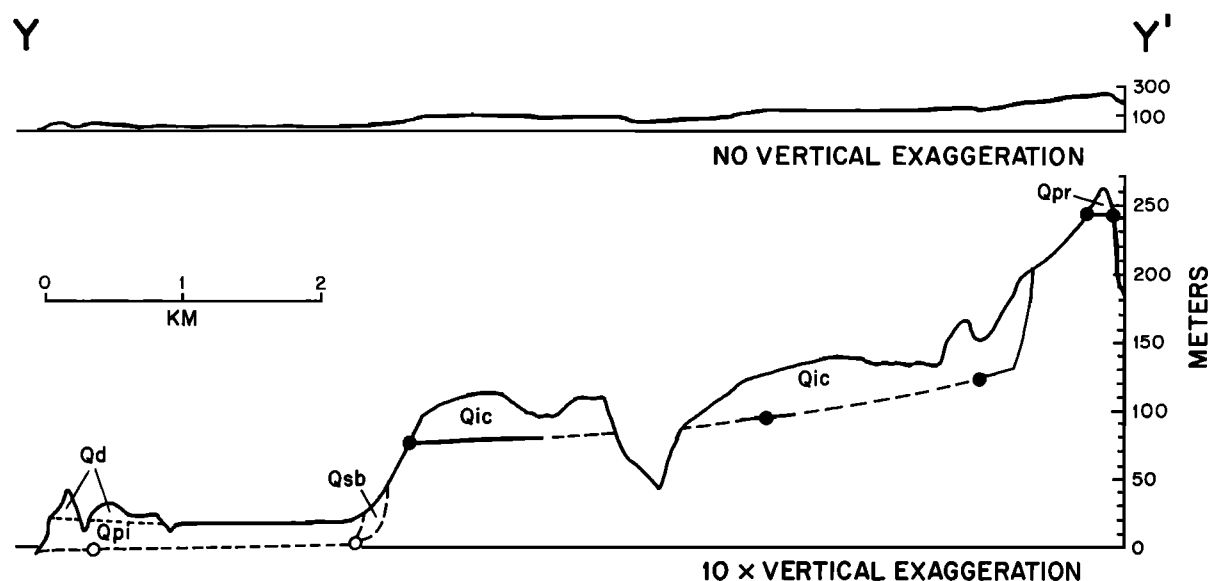


Fig. 5. Cross-section of the marine terrace sequence from Garrison Lake eastward to the Elk River ridge. Location of this profile (Y-Y') shown on Figure 2. See Figure 4 caption for explanation of open versus solid dots and of abbreviations of marine terrace sediments. Qd, Quaternary dunes.

Pioneer sediments is not of the same age, the platforms are about the same elevation. The molluscan fossil locality of the base of the wave-cut platform at Cape Blanco [Addicott, 1964; Kennedy, 1978] is confined to the Cape Blanco terrace deposits. The eastern termination of this basal shell-rich layer occurs where the Cape Blanco terrace backedge intersects the sea cliff, and the base of the neighboring Pioneer wave-cut platform contains no such shell-rich layer (Figure 4).

The Pioneer terrace (Figures 2, 3 and 4) (Table 1) can be consistently distinguished from the Cape Blanco terrace by a thicker cover bed sequence (Figure 6). Pioneer terrace deposits represent a wide range of depositional environments and, using the criteria of Clifton et al. [1971], include nearshore sediments deposited below the surf zone that grade upwards to shallower-water surf zone deposits and beach deposits (columns F, G, H and I of Figure 6). Where they are adjacent, the difference in surface elevation of the Cape Blanco and Pioneer marine terraces is almost solely due to a difference in cover bed thickness (Figures 3 and 4).

The unconformity that separates the Pioneer from the Cape Blanco terrace sediments represents complete erosional stripping of the 17 to 23 m thick Pioneer terrace sediments and subsequent deposition of the thinner 6 to 9 m thick Cape Blanco sediments. This unconformity is a regional feature because the distinctly different cover stratigraphy on the two terraces occurs over at least a 50 km² area (Figure 6 in conjunction with the localities on Figure 2).

Where the Silver Butte terrace (see below) is not present, the Pioneer terrace has a prominent backedge. The backedge can be traced to the north for 61 km from the town of Port Orford north to Floras Creek (Figure 2), and further north across the Coquille River to where the backedge is well defined at the type locality of the Pioneer terrace [Griggs, 1945] at the Pioneer mine between Bandon and Cape Arago, Oregon.

The next highest terrace, the Silver Butte terrace, is preserved only as a small 2.6 km² remnant between the broad Pioneer and Indian Creek terraces in the vicinity of the Elk and Sixes Rivers (Figure 2). Though only a small portion

TABLE 1. Characteristics of Marine Terraces near Cape Blanco^a

Terrace name This paper	Janda (1970)	Preservation and Occurrence	Elevation (m)		Terrace Cover Sediment Thickness (m)	Depositional environment ^b	Faults Cutting Terraces
			Along Transect	Backhedge Height			
Cape Blanco	unrecognized	well preserved; limited extent	57-62	8	6.4-9.0	surf zone, beach	none
Pioneer	Pioneer	well preserved; regionally extensive	48-73	4-9	16.5-23	near shore, surf zone, beach	minor--near Goldwasher's Gully
Silver Butte	Silver Butte	extremely limited	56-65	135	20-35	surf zone, beach dune	none
Indian Creek	Indian Creek	regionally extensive; highly dissected	165-230	35	30-40	outer portion: off-shore to deeper nearshore; inner portion: nearshore to beach to dune	Beaver Creek fault zone; Battle Rock fault zone
Poverty Ridge	Poverty Ridge	regionally extensive; extremely dissected	265-280	not exposed	55	lowest 2.5-5 m: nearshore & beach; upper 50m: alluvial	none

^a Numerical data taken along WNW-trending transect from Cape Blanco (Figure 4).^b Inferred from criteria of Clifton et al. [1971].

of the Silver Butte terrace is preserved, the 100 m of relief characteristic of most of the Pioneer terrace backedge (Figure 5) must have developed during the Silver Butte sea-level high stand because the Silver Butte and Pioneer wave-cut platforms are essentially at the same elevation (Figures 4 and 5). Silver Butte sediments are only exposed in one road cut. Here, the marine sediments are mixed with late Pleistocene alluvial sediments of the Sixes River (Column J, Figure 7). The stratigraphy at this site suggests alluvial progradation followed by submergence and then another cycle of progradation followed by submergence, and finally capped by surf zone and beach deposits.

The Indian Creek terrace, once a broad platform about as extensive as the Pioneer, is now highly dissected. Despite extensive erosion, flat terrace remnants are moderately well preserved and are flanked on the east by an erosionally subdued backedge that along the two transects is 30-40 m high (Figures 4 and 5). Cuts along a county road that runs east-west across this terrace provide excellent exposures of the cover bed stratigraphy and the soils. The Indian Creek wave-cut platform has a thick 30-36 m marine sediment cover (columns K and L, Figure 7). Near the outer edge, the terrace cover consists of offshore to relatively deep nearshore deposits (Figure 7b). Four km further east adjacent to the backedge, terrace cover grades upward from nearshore to beach to eolian dune deposits (Janda, 1970).

The highest terrace in the area, the Poverty Ridge terrace (Figures 2, 3 and 4) (Table 1), has no distinct terrace morphology, and is recognized by the sediment cover and the approximate elevational accordence of ridge summits underlain by the deposits. The terrace is about 30 m above the younger Indian Creek terrace. The Poverty Ridge terrace has the thickest sediment cover--approximately 55 m. In some places, the eastern extent of the terrace is defined by a subdued backedge. In the eastern (inland) portion of the terrace, approximately 2.5-5 m of interstratified

marine sand and pea gravel occur at the base (Janda, 1970), and the remainder of the terrace deposit consists of pebble-cobble alluvium with all clasts derived locally from the early Cretaceous Rocky Point Formation of Koch [1966]. The alluvium grades westward into marine sand and gravel. The Poverty Ridge terrace is distinctive in that alluvium, rather than shallow marine sediments, constitute a substantial part of the cover bed stratigraphy. However, the platform is a wave-cut strath because the basal sediments are in all observed cases marine (Janda, 1970).

Soils

I conducted a reconnaissance investigation of soils on the lowest 4 of the 5 marine terraces, in order to evaluate the relative age of the soils. The investigation consisted of one or two soil descriptions for each terrace. Presently, a more comprehensive study of the soils on all five of the Cape Blanco terraces is in progress and therefore soils data will be only briefly discussed in this paper. The following description is a product of my reconnaissance investigation and preliminary findings of the more comprehensive investigation (J.G. Bockheim, written communication, September, 1989).

Soils on the Cape Blanco, Pioneer, Silver Butte, and Indian Creek surfaces can be distinguished on the basis of solum thickness (combined thickness of the A and B horizons), presence or absence of an E horizon, type of B horizon, thickness of B horizon, depth to oxidized parent material, and presence or absence of saprolite in the subsoil. The Cape Blanco and Pioneer soils are most similar in degree of development. However, the Pioneer soil shows development of an E horizon and the Cape Blanco soil does not, and the Pioneer soil has more iron cementation in the B horizon than the Cape Blanco soil. The Silver Butte soil is a significantly better developed soil than either the Pioneer or the Cape Blanco soil, and the Indian Creek soil is significantly better developed than the

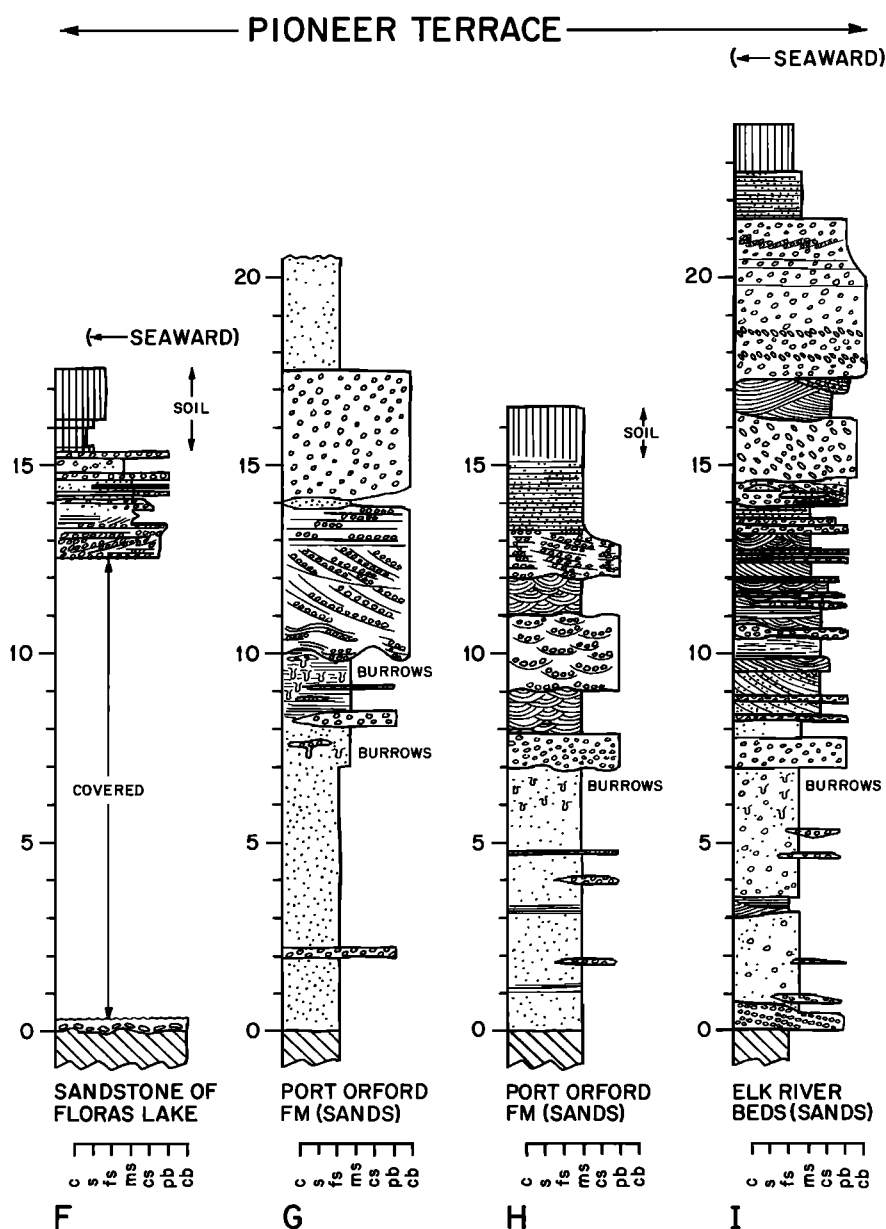


Fig. 6. (continued)

sea [Muhs et al., 1990]. The rationale for these age determinations is briefly discussed below. A thorough explanation of these age determinations is presented in a companion paper by Muhs et al. [1990]. The Cape Blanco terrace age determination is a correlation-age estimate because the extent of epimerization of amino acids of *Saxidomus* shells on the Cape Blanco terrace is the

same as the extent of epimerization of amino acids in shells of the same genus on the numerically-dated Whisky Run terrace at Coquille Point [Muhs et al., 1990]. The terminology of correlation-age versus numerical-age is after Colman et al. [1987]. The Pioneer terrace near Cape Blanco has a correlated-age estimate of 105 ka because the extent of epimerization of amino acids in *Saxidomus* from this

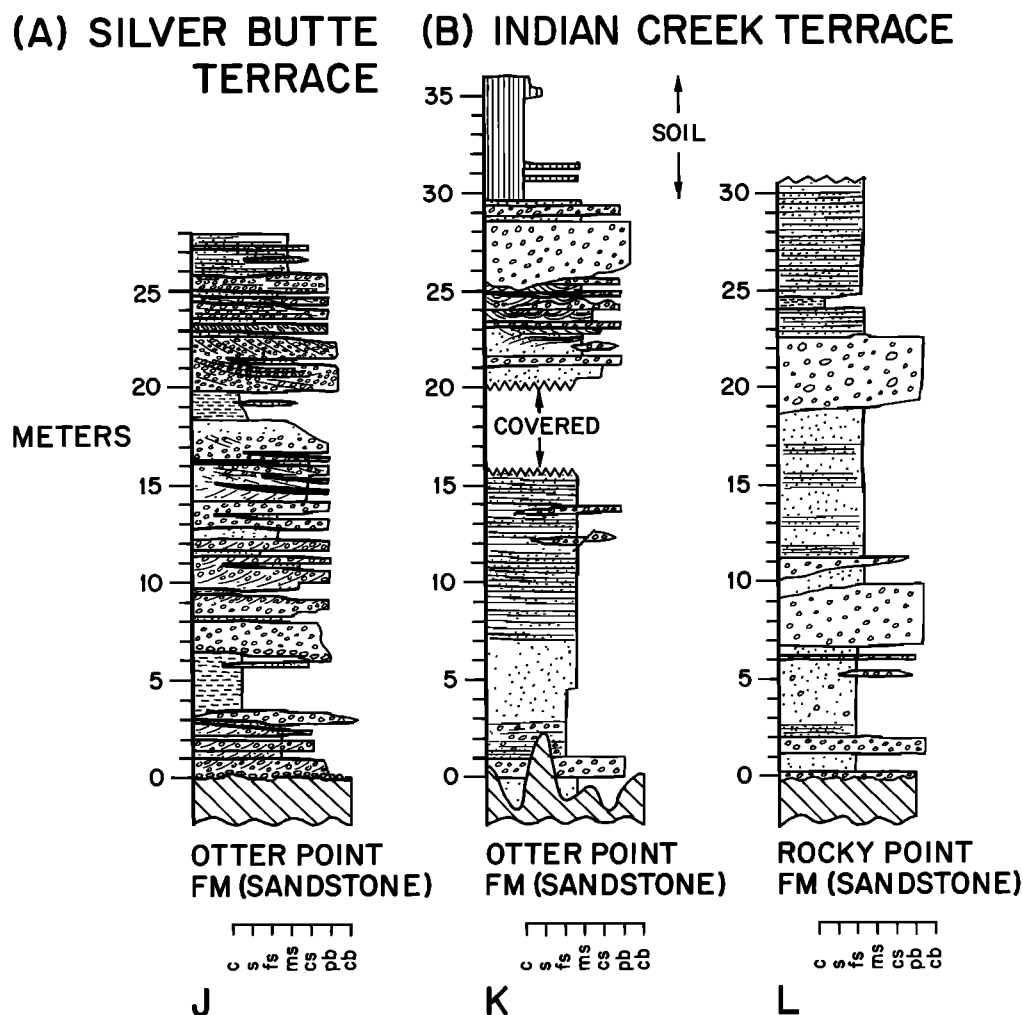


Fig. 7. (a) Stratigraphic column J showing stratigraphy exposed on the Silver Butte wave-cut platform just north of the Elk River. Location of column on Figure 2. (b) Typical stratigraphy on the mid to outer portion of the Indian Creek terrace wave-cut platform, east of Cape Blanco, exemplified by columns K and L. Sediments grade upward from nearshore fine sand to gravels deposited in the nearshore above storm wave base. The thick soil on top of column K is developed in surf zone deposits. The beach deposits have possibly been stripped away during backwearing of the outer edge of this terrace.

terrace is indistinguishable from the extent of epimerization of shells on the 80 ka terrace, which implies that the Pioneer terrace is not greatly older than the Cape Blanco terrace [Muhs et al., 1990]. As discussed above, the unconformity between the Pioneer and the Cape Blanco terrace sediments represents a major and widespread erosional event. I

feel that such an event most probably represents at least one regional transgression that separated two interstadial sea-level high stands. Therefore, the Pioneer terrace probably correlates with the next oldest interstadial high stand of sea, namely that at 105 ka [Muhs et al., 1990]. If, however, the Pioneer terrace were to

represent the 125 ka interglacial high stand of sea, then epimerization of amino acids from shells on the Pioneer terrace should be distinguishable from epimerization of shells on the Cape Blanco terrace [Muhs et al., 1990].

No fossils were found in the Silver Butte terrace deposits. However, I reason that the Silver Butte wave-cut platform was formed during the last interglacial at about 125 ka. These deposits are noticeably more weathered than the Pioneer and Cape Blanco terrace sediments, on the basis of soil observations. The Silver Butte terrace could conceivably be older than 125 ka; if this is the case, then the last interglacial is not represented in the marine terrace sequence at Cape Blanco.

The Indian Creek and Poverty Ridge terraces are not directly dated because no fossils were found. However, soils data indicate that they both clearly predate the last interglacial. The Indian Creek terrace is not likely younger than about 200 ka, because 200 ka is the next time prior to 125 ka when a sea-level high stand attained a height approaching that of sea level at 125 ka [Mesolella et al., 1969; Harmon et al., 1983]. Also, I infer from the degree of soil development that the Indian Creek terrace is significantly older than the Silver Butte terrace.

The age of the Poverty Ridge terrace is unknown. Janda (1970) notes the presence of a lower Pleistocene *Clinocardium* fossil in the Poverty Ridge deposits and assigns the Poverty Ridge terrace to an Early to Late Pleistocene age. The deep saprolite that underlies the Poverty Ridge soil makes an Early Pleistocene age feasible.

EMERGENT HOLOCENE MARINE DEPOSITS: BEACH BERM SOUTH OF CAPE BLANCO

At numerous coastal sites on the convergent plate margin throughout the Pacific basin, emergent Holocene wave-cut platforms or emergent Holocene beach berms attest to late Holocene tectonic uplift. In New Zealand, Alaska, Chile, Japan, and Mexico, historic coseismic coastal uplift has elevated such features [Wellman, 1967; Plafker, 1969, 1972; Matsuda et al., 1978;

Bodin and Klinger, 1986; Berryman et al., 1989]; and by association, many prehistoric Holocene emergent marine platforms or beach ridges probably owe their origin to co-seismic uplifts.

On the Oregon coast 2.2 km southeast of Cape Blanco, an elevated mound of sand capped by cobbles occurs in a gap in an otherwise solid facade of sea cliffs (see "storm berm", Figure 2). The gap is a former tributary valley to the Sixes River (Figure 8), beheaded by coastal retreat during the last marine transgression, filled with late Holocene sediment, and then blocked by sand dunes. In the latest Holocene, the former tributary valley has been occupied by an ox-bow meander (now cut off) of the Sixes River (Figure 8). The cobble berm in the gap is an elongate mound, 78 m (length) x 14 m (width) x 5 m (maximum relief), that parallels the coast. The deposit rests on beach or dune sand and consists of sand with a 0.3-0.5 m thick veneer of well-rounded cobbles (Figure 8). The cobble deposit is composed of clasts of both resistant rock types (blueschist, diorite, metavolcanic) and weakly indurated sandstone. The resistant clasts are derived from the conglomeratic lower Pleistocene Port Orford Formation of Baldwin [1945], which is exposed only 0.5 km northwest along the beach. The weakly indurated sandstone clasts also are locally derived from Miocene units (described by Addicott [1983]) in the adjoining sea cliff and all such clasts have borings of pholadids, which are rock-boring clams. In a few places where the deposit can be seen in place, the deposit is clast-supported with a well developed landward-dipping imbrication. The deposit is most likely marine and I interpret it to be a beach storm berm, as was first suggested by Janda (1970).

The sea cliff gap is a reasonable site for preservation of a beach berm deposited by one or more great storms. In the gap, the berm would be less vulnerable to wave attack during lesser storms and could be therefore preserved at its original depositional height for a prolonged period of time.

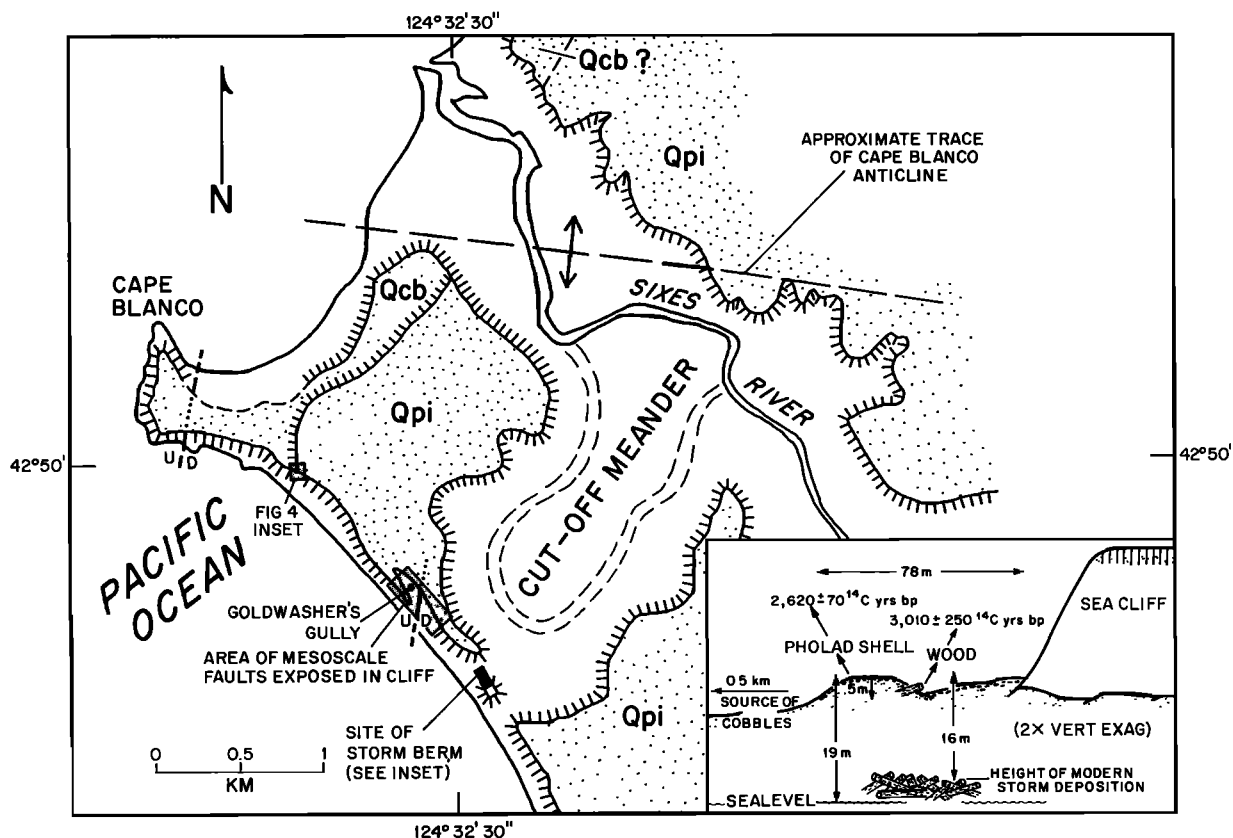


Fig. 8. Coastline at Cape Blanco showing position of storm berm in gap in sea cliff. The gap marks the position of a former tributary stream valley of the Sixes River, which was subsequently occupied by a meander of the Sixes River, now cut off. Hachures, position of sea cliff or river-cut cliff. Dots, extent of marine terrace cover of the Cape Blanco (Qcb) and Pioneer (Qpi) terraces. Inset: cross-sectional depiction of storm berm that shows the berm elevation relative to both the elevation of modern storm-deposited driftwood and sea level. Inset also shows age determinations from wood and shell within the berm. The age determinations are uncorrected ages (see text for corrected, calendar ages).

Wood protruding from this deposit, collected in approximately 1968, yielded an age of $3,010 \pm 250$ ^{14}C yr B. P. (Janda, 1970), or a calibrated age of $3,212 \pm 300$ yr B. P. [Pearson et al., 1986]. Hoping to test Janda's (1970) late Holocene age for this feature, I collected shell material from this berm. I found no wood. Numerous samples of the pholadid *Penitella penita* (Conrad) were recovered from borings in a sandstone cobble that was part of the berm. These shells yield a ^{14}C age (adjusted for heavy isotope fractionation in shell material) of $2,620 \pm 70$ ^{14}C yr B. P. (Beta Analytic sample

no. 23275). The ^{14}C age for shells grown in the ocean, such as the pholadid shells within storm-berm cobbles, is too old because atmospheric changes in ^{14}C are attenuated in a reservoir such as the ocean [Stuiver et al., 1986]. To account for the reservoir effect, I made a reservoir age correction, using Figure 11D of Stuiver et al [1986], after accounting for the difference, ΔR , in reservoir age for the west coast of North America at the latitude of Cape Blanco ($\Delta R = 390 \pm 25$ ^{14}C years [Stuiver et al., 1986]). With the reservoir age correction, the time of death of the pholadid shells is 122 years

A.D. $\pm$ 170 years, or 1,820 $\pm$ 170 years B. P. The revised shell age indicates that the age of the berm based on the estimated time of death of the pholadids is about 900 - 1,850 year younger than the minimum age of the berm based on the calibrated wood age.

The two age determinations suggest that the berm formed between about 1,800 and 3,200 years B.P. The younger age is more likely to be correct because the pholadids probably were killed by berm deposition, whereas the wood is probably driftwood and killed an indeterminate time before deposition in the berm.

The storm berm deposit indicates tectonic uplift because it is of marine origin yet is 19 m above mean sea level. The deposit is 16 m above the maximum height at which storms of the last few decades have deposited driftwood and 12.5 m higher than the height that the severest conceivable storm could have deposited material, had all of the beach been eroded away. Assuming the berm was uplifted above sea level when the pholadids died 1,820 $\pm$ 170 years B. P., assuming negligible rise in eustatic sea level in the last 3,000 years, and given the uncertainty as to the initial height of storm deposition, the storm berm has been tectonically uplifted at an average rate of 6-10 mm/yr in the late Holocene.

Another candidate explanation for the present elevation of the berm is deposition at the present height by a tsunami. The highest run-up of a tsunami, as recorded by its gravel deposits, is 17 m above sea level on the island of Hawaii [Moore and Moore, 1984]. Substantially higher waves, with run-ups greater than 300 m, have been documented [Moore and Moore, 1984], but the waves were probably induced by landslides originating on submarine topographic escarpments that have no counterpart off the Oregon coast. A tsunami origin for the berm dictates 12.5-19 m of tsunami run-up, but a gap in a sea cliff is an unlikely site for maximum tsunami run-up. The gap provides no topographic backstop to cause deposition of cobbles during tsunami wave advance or backflow. Thus, because of the large run-up required and a coastal

morphology that makes such a run-up improbable, I feel deposition of the berm by tsunami, without subsequent tectonic uplift, is not a plausible explanation of origin.

I investigated the coastline shown in Figure 8 for any other evidence of emergent Holocene marine platforms or deposits. I found no such evidence. The modern wave-cut platform at the Cape Blanco headland has an average relief of 1.5-2.0 m and is 100-220 m wide. If a coseismic uplift event of several meters had occurred at Cape Blanco in the last few hundred years, it is likely the remnants of such an elevated platform would be apparent. However, wave energy is concentrated on the Cape Blanco headland and any emergent Holocene platform would be short-lived due to rapid coastal retreat. Due to a position in the sea-cliff gap, however, the storm berm would have a much higher preservation potential than a wave-cut platform uplifted by the same event.

MULTIPLE REOCCUPATION BY THE SEA OF THE BROAD FLAT SURFACE AT CAPE BLANCO

Formerly horizontal wave-cut platforms in the vicinity of Cape Blanco are now tilted, warped and uplifted. At their time of formation, wave-cut platforms have about a 0.3°-2.0° range of initial, non-tectonic seaward tilt, with the larger tilts evident only in the narrow (300-600 m) inshore segment [Bradley and Griggs, 1976]. The direction of tilt is perpendicular to the paleo-shoreline. A structure contour map on the surface of a wave-cut platform shows the extent of deformation since the platform was cut. Platform elevation data were sufficient for construction of three structure contour maps, one for a wave-cut platform that appears to be common to the lowest three marine terraces, one for the Indian Creek platform and one for the Poverty Ridge platform (Figure 9).

A single continuous, though warped, wave-cut surface extends from Cape Blanco to the northeast, east and southeast (Figure 4, and "reoccupied platform" of

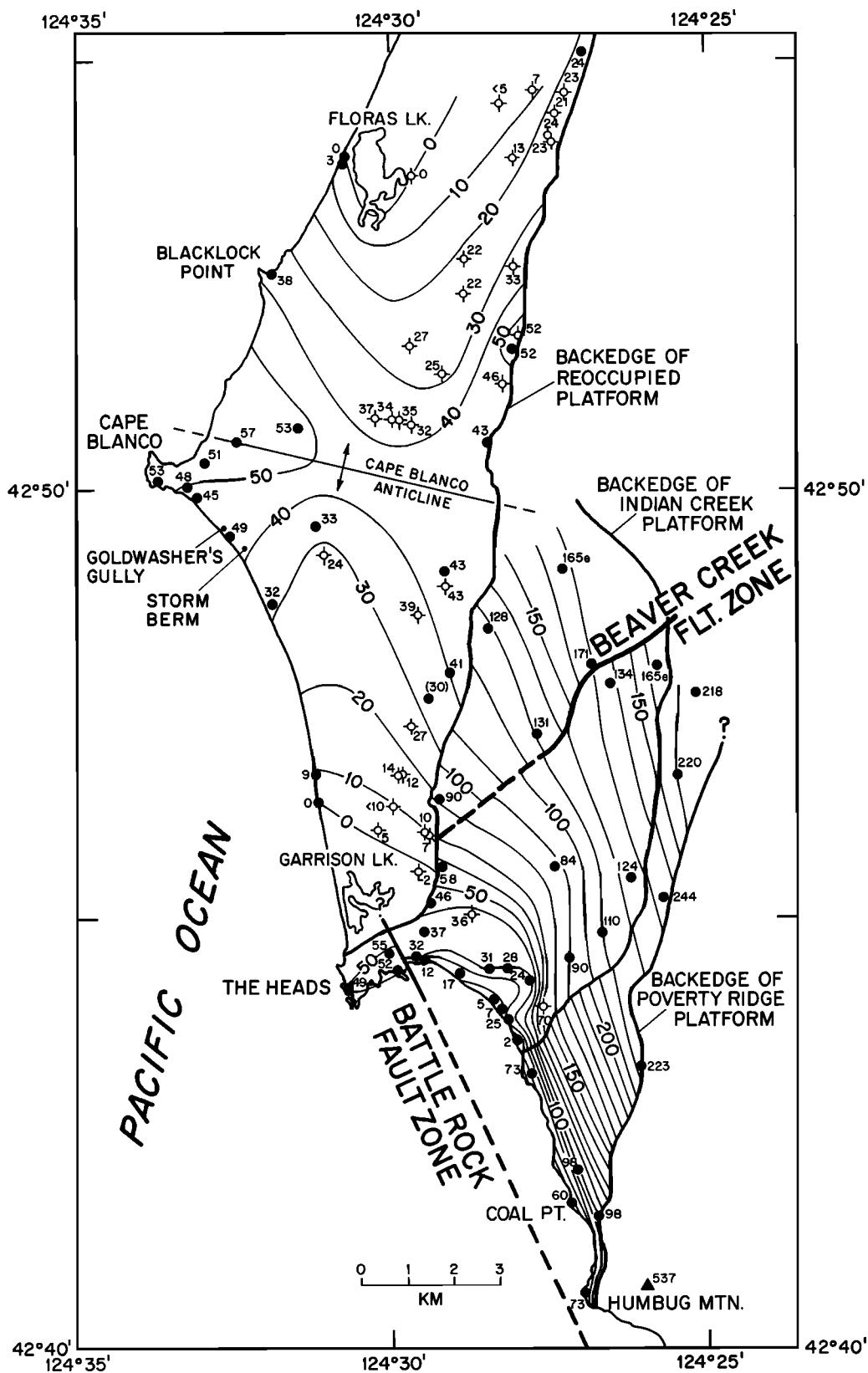


Figure 9). The wave-cut surface contains three different ages of marine terrace deposits--from west to east: Cape Blanco, Pioneer and Silver Butte deposits (Figure 4). On the basis of the extent of these three marine terrace deposits of different ages (Figure 2) and the underlying wave-cut platform elevations (Figures 3 and 9), I infer that the warped wave-cut platform extending from Cape Blanco to the prominent backedge east of Silver Butte ("backedge of reoccupied platform" in Figure 9) was cut in Silver Butte time (that is, the time immediately prior to deposition of the Silver Butte deposits) and was partially reoccupied by high stands of eustatic sea level in Pioneer and Cape Blanco time.

Evidence for reoccupation is that three marine terrace deposits of different ages, morphologically separated by backedges and each characterized by distinctive marine sediments, all rest on one continuous wave-cut platform (compare Figures 2, 6, 7, and 9). The bedrock platform is warped but shows no abrupt elevational discontinuity beneath the backedges, which are cut in the overlying Quaternary deposits. The stratigraphic relation at the Cape Blanco terrace backedge (near site B, Figure 2) demonstrates that the Cape Blanco and Pioneer terraces rest on the same wave-cut platform (Figure 4). An erosional unconformity separates the Pioneer and Cape Blanco deposits and there is no scarp in the wave-cut platform directly below this unconformity (Figure 4).

The contact between Pioneer and Silver Butte marine terrace deposits, described by Janda (1970), runs along the 4- to 9-m-high Pioneer backedge cut entirely in Silver Butte deposits. The soil developed

on the Pioneer deposits to the west of this backedge is notably less developed than the soil developed on Silver Butte sediments to the east of the backedge, but water well stratigraphic logs show no abrupt elevation change in the wave-cut platform below the terrace backedge (Figures 4, 5 and 9).

The recognition of reoccupation by the sea of previously cut platforms is necessary for deciphering late Quaternary history at Cape Blanco. Misinterpretations have resulted from assuming the broad flat surface extending east from Cape Blanco represents one sea level high stand. For instance, West and McCrumb [1988] made the above assumption and then assumed sequential surfaces separated by topographically prominent backedges represented sequential sea level high stands. By assigning a numerical age to the Cape Blanco molluscan fossil locality (based on data in Kennedy et al. [1982]), West and McCrumb [1988] correlated the Cape Blanco terrace with the 60 ka high stand of sea and correlated the outer edge of the next highest surface (called the "120 m Cape Blanco terrace" [West and McCrumb, 1988]) with the 80 ka high stand of sea. The "120 m surface" of West and McCrumb [1988] is actually the outer edge of the Indian Creek terrace surface, which is not likely to be younger than about 200 ka (see discussion earlier).

DEFORMATION OF WAVE-CUT PLATFORMS

Late Quaternary Folding, Tilting and Uplift

The wave-cut platform common to the lowest three marine terraces is deformed

Fig. 9. Structure contour maps that define the configuration of tectonically deformed wave-cut platforms and late Quaternary faults near Cape Blanco. Contour interval is 10 meters. The three adjoining structure contour maps represent wave-cut platforms of different ages. The three platforms, separated by marine terrace backedges, are progressively younger towards the northwest. The northwesternmost platform (the reoccupied platform) was cut by more than one sea level high stand. See further discussion in text. Solid dot, altitude of wave-cut platform determined from field outcrop. Open dot with cross, altitude of wave-cut platform beneath a well site for which stratigraphic well log data was available.

by an east-west trending, doubly-plunging anticline (Figure 9), forming an antiformal depression that roughly coincides with the lowermost reaches of the Sixes River. The axial trace intersects the coast about 1-2 km north of Cape Blanco. The deformed surface, defined by a structure contour map of the combined Cape Blanco-Pioneer-Silver Butte wave-cut platform, has a flattened, saddle shape (Figure 9). The Holocene storm berm is located on the landward-tilted western flank of the saddle (Figure 9). The Cape Blanco anticline is also apparent on the along-coast topographic profile of marine terrace heights (Figure 3). The next two terraces above the reoccupied platform, the Indian Creek and Poverty Ridge terraces (Figure 2), are both tilted to the southwest (Figure 9).

The original non-tectonic tilt of the wave-cut platforms at Cape Blanco would have been about $0.3\text{--}1.0^\circ$ seaward for the offshore segment that starts about 300-600 m seaward of the sea cliff [Bradley and Griggs, 1976]. The tilt is in a direction normal to the trend of the backedge. Given this original tilt magnitude and direction, the magnitude and direction of tectonic tilt since platform cutting can be approximated from a map of present-day tilts calculated for selected locations on the platforms (Figure 10). These tilts are derived from the structure contours in Figure 9. The length of the tilt arrows (Figure 10) denotes the map-distance length over which tilt was calculated. Most of the Poverty Ridge terrace is tilted seaward to the southwest by several degrees in excess of the original, non-tectonic seaward tilt. However, the northeastern portion of this terrace tilts northeast, suggesting that the terrace is deformed into an anticline (Figure 10). The Indian Creek terrace is tilted seaward to the southwest and the magnitude of seaward tilt is also greater than the original tilt, though not as great as for the Poverty Ridge terrace (Figure 10). Seaward tilts on both the Poverty Ridge and Indian Creek terraces increase in proximity to the Battle Rock fault zone (Figures 9 and 10). From these observations, I infer that the Indian

Creek and Poverty Ridge platforms record progressive southwest-directed tilting with time and that the mechanism of seaward tilt may possibly be in part block rotation during movement on the Battle Rock fault zone. It is possible that this southwest tilt represents the west flank of an anticline, the axis of which is for the most part east of the late Quaternary terraces (Figure 10).

On the reoccupied platform, the Cape Blanco anticline axis is tilted landward 0.3° in a direction roughly perpendicular to the backedge of the reoccupied platform (Figure 10). Assuming an original $0.3\text{--}1.0^\circ$ seaward tilt along this axial trend and a 105 ka age for the Pioneer platform on which the axial trace occurs, the landward tilt rate for the anticline axis is $1.0\text{--}22 \times 10^{-8} \text{ rad yr}^{-1}$. This tilt rate compares favorably with present-day east-west tilt rates in southern and central coastal Oregon, as calculated from geodetic leveling [Reilinger and Adams, 1982; Adams, 1984], though the geodetic tilt rate may be an inter-seismic tilt rate and as such not related to the long-term tilt rate deduced from marine terrace deformation.

The anticlinal deformation of the reoccupied platform (Figure 9) results in a variety of tilt magnitudes and directions (Figure 10). However, the tilt magnitudes and directions preclude the possibility that the platform has been tectonically tilted seaward. Rather, the western portion of the reoccupied platform is tectonically tilted landward, and closer to the backedge the eastern portion has a tilt roughly equal to the original non-tectonic seaward tilt (Figure 10).

Comparison of Late Neogene and Early to Middle Quaternary Folding to Late Quaternary Folding

The style of folding of late Neogene and early to middle Quaternary sediments in the Cape Blanco vicinity is similar to that of the late Quaternary wave-cut platforms. The lower to middle Miocene sandstone of Floras Lake [Addicott, 1983; Leithold and Bourgeois, 1984] unconformably overlies both the Jurassic

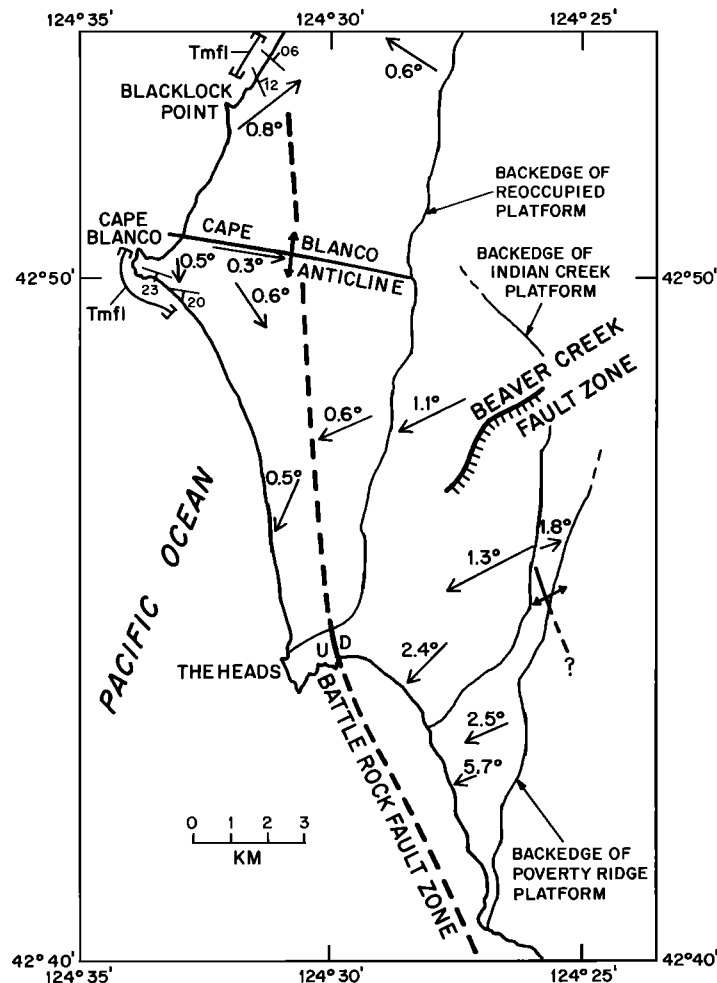


Fig. 10. Map showing selected Neogene and Quaternary structural data for the Cape Blanco area. Strike and dip data is for the Lower to Middle Miocene sandstone of Floras Lake, the coastal extent of which is delineated by bracketed lines labeled Tmfl. The arrows denote tilt directions on the late Quaternary wave-cut platforms. The length of the arrow indicates the length over which an average tilt magnitude (measured as a deviation from the horizontal to the nearest 0.1°) was calculated. Platform tilts and the anticline axis are defined on the basis of structure contours on Late Pleistocene wave-cut platforms, shown in Figure 9. The Battle Rock fault zone has Quaternary offset only near The Heads; otherwise the trace of the Battle Rock fault zone is inferred from offset of pre-Neogene units.

Otter Point Formation and late Cretaceous strata [Dott, 1962] and is exposed along the coast both to the southeast of Cape Blanco and 5.5 km to the north-northeast of Cape Blanco (Figure 10). On the basis of strike and dip data for the sandstone of Floras Lake (shown on Figure 10), this

unit is deformed into a west-northwest trending anticline that plunges to the east. The sandstone therefore records the anticlinal folding that is apparent in the late Quaternary wave-cut platforms; the sandstone is also offset by several tens of meters on a vertical fault at the Cape

Blanco headland (Figure 8) [Dott, 1962], but the fault does not offset the overlying wave-cut platform.

Stratigraphically separating the sandstone of Floras Lake from the late Pleistocene marine terrace sediments, and exposed along the beach between Cape Blanco and the mouth of the Elk River (Figure 2), are three other unconformity-bounded late Neogene or Quaternary units [Roth, 1979; Armentrout, 1980; Addicott, 1983]. These units are, in decreasing age, the upper Miocene Empire Formation [Addicott, 1983], a Lower Pleistocene pebbly sandstone unit described by Baldwin [1945] as the lowermost Port Orford Formation and described as a separate formation by Roth [1979], and a Pleistocene sequence containing the Port Orford Formation and the overlying Elk River Beds [Baldwin, 1945; Addicott, 1964].

Cliff face exposures indicate that each successively older unconformity-bounded unit has a greater dip to the south or southeast. The precise strike and dip of these shallowly-dipping Pleistocene units is difficult to measure, but the dip direction of the units south of the cape must generally be to the south, because both the underlying Miocene units and the overlying late Quaternary wave-cut platforms have southerly tilts. I infer that each older unit records progressive tilting to the south or southeast on the south limb of the anticline defined by the sandstone of Floras Lake. On the basis of the structural data, therefore, it is likely that anticlinal deformation at Cape Blanco has been occurring at least since the Middle Miocene.

Late Quaternary Fault Zones

The Battle Rock fault zone offsets the Indian Creek wave-cut platform in the vicinity of Port Orford (Figure 9). The fault zone offsets the headland at Port Orford from the rest of the platform by approximately 20 m of west-side-up displacement. Indian Creek marine terrace sediments on top of the Battle Rock sea stack and adjacent sea cliffs within the Port Orford city limits are pervasively

cut by mesoscale faults with less than a few meters of offset. The Battle Rock fault zone is the late Quaternary trace of the tectonostratigraphic terrane-bounding Whalehead fault zone of Blake et al. [1985]. The Whalehead fault zone has probably accommodated major dextral strike-slip displacement in pre-Eocene time [Blake et al., 1985; Bourgeois and Dott, 1985] and may have accommodated further dextral offset since then [Dott, 1979]. The Battle Rock fault zone is therefore a Quaternary fault that occurs along a major crustal discontinuity separating different Mesozoic accreted terranes. On the basis of the strike-slip offset history of the Whalehead fault zone, I infer that the late Pleistocene movement on the Battle Rock fault zone occurs on a steeply-dipping fault.

Assuming that the Battle Rock fault zone follows the trace of the Whalehead fault zone to the north of Port Orford [Blake et al., 1985] where it is buried by sediments of the Pioneer and Cape Blanco terraces, the Battle Rock fault zone intersects the coast north of Blacklock Point, about 6 km north-northwest of Cape Blanco (Figure 10). Latest significant movement on the Battle Rock fault zone is probably before cutting of the Pioneer wave-cut platform because the Pioneer backedge is not laterally offset and the Pioneer platform is not vertically offset by the fault zone, within the ± 6 m altitudinal resolution of the well log data.

The Beaver Creek fault zone (Janda, 1970) (Figures 2, 3, and 10) is the other major fault zone in the vicinity of Cape Blanco that has accommodated significant late Quaternary offset. The northeast-trending fault zone, which consists of at least six closely-spaced normal faults that dip 60° - 75° to the southeast, offsets the Indian Creek terrace surface. At least two of the faults cumulatively offset the B horizon of the marine terrace soil by 4.5 m. A step in the wave-cut platform at the fault zone (Figures 4 and 9) indicates a maximum of approximately 40 m of northwest-side-up normal displacement on the Indian Creek surface since the Indian Creek platform was cut.

Displacement along the fault zone decreases to the southwest (Figure 9). Latest movement on the Beaver Creek fault zone is probably younger than latest movement on the Battle Rock fault zone because the Indian Creek soil is offset only in the case of the Beaver Creek fault zone.

The Beaver Creek fault zone has accommodated a large but undetermined amount of total displacement because it separates the Jurassic-Cretaceous Sixes River terrane from the Cretaceous Rocky Point Formation [Koch, 1966] of the Elk subterrane [Blake et al., 1985]. Original movement on the fault predates the Eocene overlap assemblage of south coastal Oregon [Blake et al., 1985] and the trend of the fault reflects a discontinuity in Mesozoic accreted crust. The Beaver Creek fault is notable as a forearc fault that has caused net extension, not contraction, of the crust underlying the Indian Creek marine terrace in late Pleistocene time.

Several mesoscale faults offset Pleistocene strata in the vicinity of the storm berm and Goldwasher's Gully (shaded area near Goldwasher's Gully on Figure 8). All the faults trend N20°W to N14°E and have vertical displacements up to 5 m. One of these faults, a reverse fault at Goldwasher's Gully (Figure 8), offsets the lower Pleistocene pebbly sandstone of Roth [1979] by 5 m but does not offset overlying strata. The other mesoscale faults, which occur in the sea cliff 150 m southeast of Goldwasher's Gully, trend parallel and subparallel to the trend of Goldwasher's Gully and offset the Pioneer terrace sediments by several meters down-to-the-southwest on low angle (18½-29½) normal faults. At least one of the faults offsets the soil on the Pioneer marine terrace.

UPLIFT RATES AND CONSTRAINTS ON REOCCUPATION

Late Quaternary Uplift Rates

Calculation of uplift rates for wave-cut platforms requires age estimates for the platforms. As previously discussed, the age estimates for the three terraces

of the reoccupied platform are 80, 105, and 125 ka (Table 2). The ages of the sea level high stands are averages based on the marine terrace chronologies developed for Barbados, New Guinea and California [Mesolella et al., 1969; Bloom et al., 1974; Chappell and Shackleton, 1986; Muhs et al., 1988].

Uncertainties for the paleo-sea level curve for coastal Oregon combined with the anticlinal deformation on the reoccupied platform pose several difficulties in calculating uplift rates. For seaward-dipping platforms, the point of maximum elevation coincides with a point on the shoreline angle, which is the angle formed by the junction of the wave-cut platform and the sea cliff. For landward-dipping platforms, the point of maximum elevation is seaward of the shoreline angle; and when the shoreline angle was cut, the point was below the interstadial or interglacial sea-level high stand elevation. The original depth of this point depends on the initial seaward tilt of the platform. Hence, estimates of subsequent uplift of a point seaward of the shoreline angle must account for the paleo-water depth at this point, as well as for the paleo sea-level elevation. To correct for the range of possible paleo depths, I have used measured gradients of modern wave-cut platforms in Bradley and Griggs [1976]. The approximate gradient of the modern platform offshore of Cape Blanco, from the coast out to about 3 km, is 9-14 m/km, as measured from bathymetric contours on U. S. Geological Survey topographic maps. This gradient range is within the gradient range measured by Bradley and Griggs [1976] for the planar offshore segment (starting 300-600 m offshore), which is 5-17 m/km.

Another essential factor in calculating platform uplift rates is the paleo sea-level high stand elevations. I have employed two alternative late Pleistocene paleo sea-level models, the New Guinea model (using the revised data of Chappell and Shackleton [1986]) and the California-Japan model, which utilizes sea level data from Machida [1975] and Muhs et al. [1988] (Table 2).

TABLE 2. Marine Terraces in the Vicinity of Cape Blanco: Estimated Ages and Uplift Rates

Marine Terrace	Estimated Age (ka) ^a	Maximum Shoreline Angle Elevation ^b (m)	Maximum Elevation ^c (m)	Shore-Normal Distance From Shore-Line Angle (km) ^d	Original Gradient of Platform ^e (m/km)	Original Depth of Platform ^f (m)	Paleo-Sea Level ^g (m)	Sea Level Model ^h	Tectonic Uplift at Shoreline ⁱ Angle (m)	Uplift Rate at Shoreline ⁱ Angle (m/kyr)	Tectonic Uplift at Maximum Elevation ⁱ (m)	Maximum Uplift Rate ⁱ (m/kyr)
Cape Blanco	80	50	53	0.7	15	11	-19 ± 5	NG	69 ± 5	.86 ± .07	83 ± 5	1.04 ± .06
	80	50	53	0.7	40	28	-19 ± 5	NG	69 ± 5	.86 ± .07	100 ± 5	1.25 ± .06
	80	50	53	0.7	15	11	-5 ± 2	C-J	55 ± 2	.69 ± .03	69 ± 2	0.86 ± .03
	80	50	53	0.7	40	28	-5 ± 2	C-J	55 ± 2	.69 ± .03	86 ± 2	1.08 ± .03
Pioneer	105	39	57	5.2	5	26	-9 ± 3	NG	48 ± 3	.46 ± .03	92 ± 3	0.88 ± .03
	105	39	57	5.2	17	88	-9 ± 3	NG	48 ± 3	.46 ± .03	154 ± 3	1.47 ± .03
	105	39	57	5.2	5	28	-2	C-J	41	.39	85	0.81
	105	39	57	5.2	17	88	-2	C-J	41	.39	147	1.40
Silver Butte	125	43	43	1.0	10	10	+6	both	49	.39	59	0.47
	125	43	43	1.0	29	29	16	both	49	.39	78	0.62

^a Ages of sea level high stands are averages based on sea level high stand chronology developed in Barbados, New Guinea and California [Mesolella et al., 1969; Bloom et al., 1974; Muhs et al., 1986].

^b Maximum shoreline angle elevation measured along inferred trace of the Cape Blanco anticline.

^c Elevation (relative to present sea level) is the highest field measured elevation on the wave-cut platform. These elevations are on or near the inferred trace of the Cape Blanco anticline.

^d Horizontal distance from highest point of elevation on the platform to the shoreline angle.

^e Gradients from Bradley and Griggs [1976]. If shore-normal distance (previous column of table) is ≤ 0.8 km, then the gradient range is 15-40 m/km. Starting at a shore-normal distance of 0.8 km, the gradient is 5-17 m/km. The inferred gradient ranges for the platforms (this column) reflect the shore-normal distances (previous column).

^f Depth below sea level at time of terrace formation.

^g Relative to present sea level.

^h NG, New Guinea model from Chappell and Shackleton [1986]; C-J, California-Japan model from Machida [1975] and Muhs et al. [1989].

ⁱ Uncertainties are paleo-sea level uncertainties.

Table 2 provides uplift and uplift rate data for two points on each terrace, the point of maximum elevation and the point of maximum elevation on the shoreline angle. All of these points fall on the Cape Blanco anticline axis. The point of maximum uplift on each platform is located at varying shore-normal distances from the shoreline angle of the respective platform (Table 2). Because the anticline axis on the reoccupied platform plunges to the east over most of its extent (Figure 9), the highest point on the wave-cut platform of each of the Cape Blanco and Pioneer terraces is at the western edge. For the Silver Butte terrace, the maximum platform elevation is near the center of the small remnant of this platform. Because the anticline deforms all three platforms and uplift rate is more dependent on position within the anticline than on the age of formation of the platform, comparison of uplift rates among platforms using calculated maximum uplift rates cannot be used to detect any regional changes in uplift rate with successively younger platforms.

The ranges of possible maximum uplift rates for the three platforms are 0.8-1.3 m/ky for the Cape Blanco platform, 0.8-1.5 m/ky for the Pioneer platform, and 0.5-0.6 m/ky for the Silver Butte platform (Table 2). The large ranges reflect both paleo-water depth and paleo sea-level uncertainties for the platforms. The lower uplift rates and the lower ranges for the Silver Butte platform reflect the landward position of this terrace in the lowest portion of the anticline axis as well as an assumed +6 m [Ku et al., 1974; Harmon et al., 1983] elevation for the 125 ka interglacial sea-level high stand. The ranges of maximum uplift rates for the Cape Blanco and Pioneer terraces, which are similar, reflect both the position of the points of maximum elevation for both of these platforms on the anticline axis near Cape Blanco and a similar degree of uncertainty about paleo-water depths and sea-level elevations.

The uplift rates for the shoreline angle positions (Table 2), which are not dependent on estimates of platform gradient, show similar uplift rates for

the Silver Butte and Pioneer platforms and a significantly greater uplift rate for the Cape Blanco platform. The uplift rate variation is again a function of shoreline angle position relative to position along the anticline axis. The Cape Blanco shoreline angle is at Cape Blanco where the anticline axis is highest and the Pioneer and Silver Butte shoreline angles are in the eastern portion of the reoccupied platform where the anticline axis is relatively low.

The calculation of tectonic uplift at the shoreline angle (Column 10, Table 2) assumes the shoreline angle altitude is initially the same at all points on the shoreline and that this initial altitude is given by the sea level model (Column 9, Table 2). However, the original altitude of the shoreline angle can vary locally by up to 4 m, depending on the geological factors and on the degree of embayment of the coastline [Wright, 1970; Trenhaile, 1980]. Accounting for this variation, tectonic uplift at the shoreline angle has an additional uncertainty of ± 2 m that is not incorporated into Table 2.

Reoccupation and Constraints on Interstadial Uplift Rate

To what extent does the fact that the lowest three wave-cut platforms at Cape Blanco merge into one surface (the reoccupied platform) impose constraints on uplift or subsidence rates in the interstadial periods between sea-level high stands at 125 and 105 ka and at 105 and 80 ka? To answer this question, I assumed that for reoccupation to occur, the point that is presently at the maximum elevation on a wave-cut platform (Column 4, Table 2) had to be, at the time of reoccupation, no higher than the shoreline angle elevation of the successive sea-level high stand. If this point was significantly higher, then the successive sea-level high stand would carve a sea cliff below that point and there would be clear spatial separation of the platforms. If this point was significantly lower, then the successive sea level high stand would carve a platform higher than the

prior platform, burying or eroding the prior platform. Using this assumption, I calculated the uplift (or subsidence), U , necessary for the point of maximum elevation in order for this point to be in a position to be reoccupied by the subsequent sea level high stand,

$$U = H_2 - (H_1 + D) = H_2 - H_1 - D$$

where H_2 , H_1 and D are defined in Table 3. I then calculated the interstadial uplift rate (or subsidence rate), dU/dt , permissible for reoccupation to occur for two cases: Silver Butte platform (125 ka) reoccupied by Pioneer sea-level high stand (105 ka, $dt=20$ ky), and Pioneer platform (105 ka) reoccupied by Cape Blanco sea-level high stand (80 ka, $dt=25$ ky) (Table 3). Figure 11 graphically depicts how uplift is the numerical difference between H_2 and the sum (H_1+D). Figure 11 also shows how the range of starting heights and the range of ending heights that allow for reoccupation together yield maximum and minimum possible uplift (or subsidence) magnitudes.

The magnitude of subsidence or uplift required for the first case, Silver Butte reoccupied by Pioneer, is -5 to 21 m (Table 3). The required magnitude of uplift required for the second case, Pioneer reoccupied by Cape Blanco, is 16 to 85 m (Table 3). The interstadial uplift, or subsidence, rates required for reoccupation are -0.25 m/ky to 1.05 m/ky for Silver Butte reoccupied by Pioneer (105-125 ky) and 0.7 m/ky to 3.4 m/ky for Pioneer reoccupied by Cape Blanco (80-105 ky) (Table 3). The large range of these values reflect, again, both paleo-depth uncertainties for the point of maximum uplift and paleo-sea level uncertainties (Table 2).

Therefore, the two successive instances of platform reoccupation could have occurred under conditions of subsidence followed by uplift, no change in elevation followed by uplift, or persistent uplift. It is notable that even though the Cape Blanco sea-level high stand elevation was somewhere between 3-24 m lower than the Pioneer sea-level high stand elevation (Tables 2 and 3), uplift is necessary

between 105 and 80 ka for the Pioneer platform to have been reoccupied by the Cape Blanco sea-level high stand because of the original depth of the Pioneer platform (Column 7, Table 2). Because the reoccupation at 105 ka and 80 ka occurred at two different positions on the anticline axis, local deformation due to continued growth of the anticline probably exerts a greater control on the calculated interstadial uplift rates, and hence on the possibility of reoccupation, than any regional change in uplift rate.

The above analysis shows that reoccupation of previously-cut marine platforms can occur under a range of conditions of platform gradient, paleo-sea level high stand elevation and deformation history. Instances of reoccupation, such as at Cape Blanco, should not be unusual and should be evident on other coastlines with negligible to moderate uplift and/or subsidence rates.

DISCUSSION

Local Structures and Temporal and Spatial Variations in Uplift

Maximum Late Pleistocene and Holocene uplift occurs at the latitude of Cape Blanco. Subsidence is occurring along the coast only 10 km to the north and south of Cape Blanco (Figure 3). The storm berm, whose uplift rate is unusually high for the coast along the Cascadia subduction zone, occurs near the axis of the Cape Blanco anticline. This fold has been growing throughout the latest Pleistocene and Holocene. The uplift rate for the berm is characteristic only of the hinge region of this local structure. The Late Pleistocene folding has therefore generated significant spatial variation in uplift rate in the Cape Blanco area (Figures 3 and 9). Such spatial variation in uplift rate due to folding is also the case for wave-cut platforms in the Cape Arago region, 55 km to the north (Figure 1) [McInelly and Kelsey, 1990]. Figure 12 graphically shows spatial variation in uplift rate along the Cape Blanco anticline axis. Within the limits of

TABLE 3. Uplift (U) and Uplift Rates (dU/dt) that are Permissible for Reoccupation of a Wave-cut Platform by Subsequent Interstadial Sea-level High Stands

Case I: Silver Butte (125ka) reoccupied by Pioneer (105 ka)					Case II: Pioneer (105 ka) reoccupied by Cape Blanco (80 ka)				
$H_2 = H_{105ka}^a$ (m)	$H_1 = H_{125ka}^b$ (m)	D^c (m)	U^d (m)	dU/dt^e (m/ky)	$H_2 = H_{80ka}^a$ (m)	$H_1 = H_{105ka}^b$ (m)	D^c (m)	U^d (m)	dU/dt^f (m/ky)
-9 ± 3	6	-10	- 5 ± 3	-0.25 ± .15	-19 ± 5	-9 ± 3	-26	16 ± 8	0.7 ± 0.4
-9 ± 3	6	-29	14 ± 3	0.7 ± .15	-19 ± 5	-9 ± 3	-88	78 ± 8	3.1 ± 0.3
-2	6	-10	2	0.10	- 5 ± 2	-2	-26	23 ± 2	0.9 ± 0.1
-2	6	-29	21	.05	- 5 ± 2	-2	-88	85 ± 2	3.4 ± 0.1
All elevations relative to present sea level.									

^a H_2 is elevation of the point of maximum elevation at 105 or 80 ka in order to be occupied by the shoreline angle position of the 105 or 80 ka high stand of sea-level (elevation of the 105 or 80 ka interstadial sea level high stand, using two alternative sea-level models, see Table 2).

^b H_1 is elevation of the 125 or 105 interstadial sea level high stand (using two alternative sea-level models, see Table 2).

^c D is original depth (expressed as elevation relative to modern sea level) at time of terrace formation on the 125 or 105 ka platform for the present day point of maximum elevation (see Table 2).

^d $U = H_2 - (H_1 + D) = H_2 - H_1 - D$. U is uplift at point of maximum elevation on the 125 or 105 ka platform necessary for reoccupation of the 125 or 105 ka platform at that point by the shoreline angle position of the successive sea-level high stand.

^e Interstadial (80-105ka) uplift or subsidence rate permissible for reoccupation by subsequent sea-level high stand, given height and depth parameters H_2 , D , and H_1 .

^f Interstadial (105-125ka) uplift rate permissible for reoccupation by subsequent sea-level high stand, given height and depth parameters H_2 , D , and H_1 .

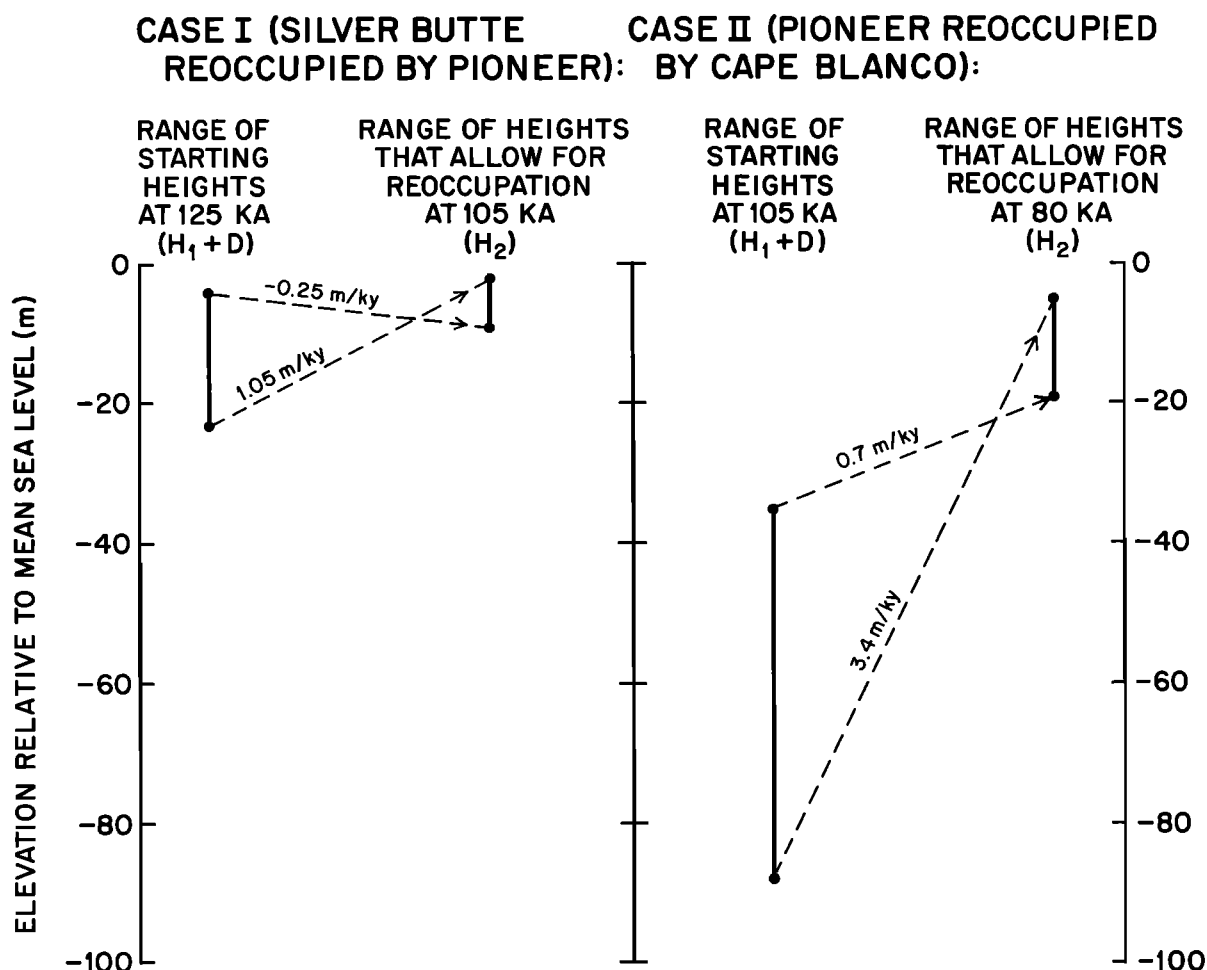


Fig. 11. Graphical depiction showing how maximum and minimum uplift rates (dU/dt in Table 3) were derived from variables H_1 , H_2 and D for the periods 125 to 105 ka (Case I) and 105 to 80 ka (Case II), using constraints imposed by terrace reoccupation. These constraints are enumerated in Table 2. $U = \text{Uplift} = H_2 - H_1 - D$. Uplift calculations are for the present-day point of maximum elevation (H_1) of the Silver Butte (Case I) and Pioneer (Case II) terraces. D is the depth of this point at time of platform formation.

error, there is a decreasing uplift rate to the east along the axis.

At two locations along the anticline axis, it is possible to evaluate whether there has been a change in uplift rate over time--on the axis 1-2 km east of Cape Blanco and on the axis about 6-6.5 km east of Cape Blanco (Figure 12). Six km east of the cape, average uplift rate is the same within resolution of the data for the time periods 0-125, 0-105, and 105-125 ka (Figure 12). In contrast, for the region 1-2 km east of the cape, average uplift

rate is the same within resolution of the data for the periods 0-80, 0-105, and 80-105 ka, but average uplift rate is significantly greater for the period 0-2 ka. In this area, the average uplift rate in the last 80 ky is 0.7-1.5 m/ky, whereas the average uplift rate in the last 2 ky is 6-10 m/ky.

Mechanism of Late Holocene Uplift at Cape Blanco

I hypothesize that the elevation of the storm berm near Cape Blanco is the product

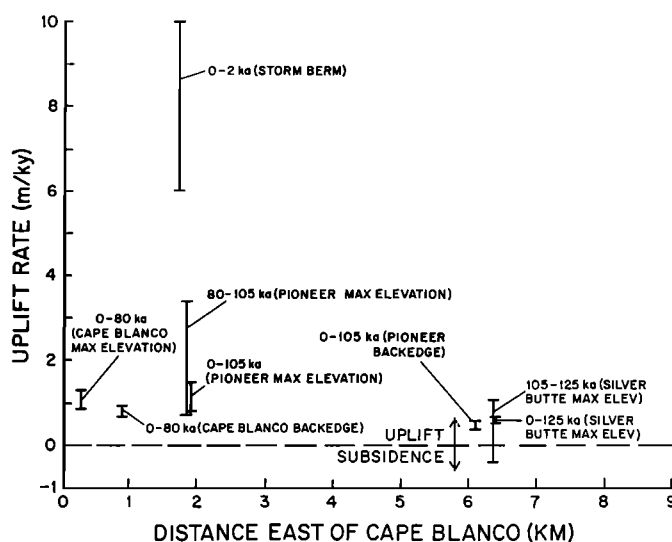


Fig. 12. Temporal and spatial variations in uplift rate for the three youngest wave-cut platforms near Cape Blanco, the Cape Blanco (80 ka), Pioneer (105 ka) and Silver Butte (125 ka) platforms. Uplift rate data are for points along the Cape Blanco anticline axis, except for the storm berm data, which are projected onto the axis from a point 1.3 km to the south. Uplift rates are from Tables 2 and 3, with the exception of the rate for 0-2 ka (see text).

of several coseismic uplift events at the apex of a fold growing in the accretionary margin in the late Holocene. The storm berm provides no data from which to infer the uplift mechanism. However, coseismic deformation of such a local structure as the Cape Blanco anticline is conceivable because only 55 km to the north in the Cape Arago-South Slough region, coseismic uplift and subsidence both have probably occurred during Holocene tightening of another fold, the South Slough syncline (Figure 1) [Nelson, 1987; Nelson et al., 1988; McInelly and Kelsey, 1990]. Nelson [1987] and Peterson and Darienzo [1989] describe stratigraphic evidence for as many as 7 or 8 abruptly buried salt marsh surfaces along the axial trace of the syncline. These abrupt subsidence events have all occurred during the late Holocene time span of the storm berm, and coseismic deformation of the synclinal fold is the most reasonable explanation for the buried surfaces.

Work elsewhere along the coast of Cascadia, including to the north of Cape Blanco at Netarts Bay in northwest Oregon [Darienzo and Peterson, 1990] and at

Willapa Bay in southwest Washington (Figure 1) [Atwater, 1987, 1988] and to the south of Cape Blanco at Humboldt Bay (Figure 1) [Carver and Burke, 1989] suggests at least four earthquakes on the Cascadia subduction zone during the time interval since the storm berm was deposited. The earthquake events that may have uplifted the berm would not necessarily be coincident in time with the earthquake events to the north and the south, but major earthquakes along the Cascadia zone are sufficiently frequent to accommodate several coseismic uplift events of the Cape Blanco anticline in the last two thousand years.

Cape Blanco Deformation in the Context of Observed Regional Strain and Inferred Regional Stress

The deformation observed in the marine terraces at Cape Blanco probably is an on-land expression of the north-northwest-trending fold belt on the continental shelf of the Cascadia margin (Figure 13) [Kulm and Fowler, 1974; Clarke et al., 1985; Peterson et al., 1986]. Structural

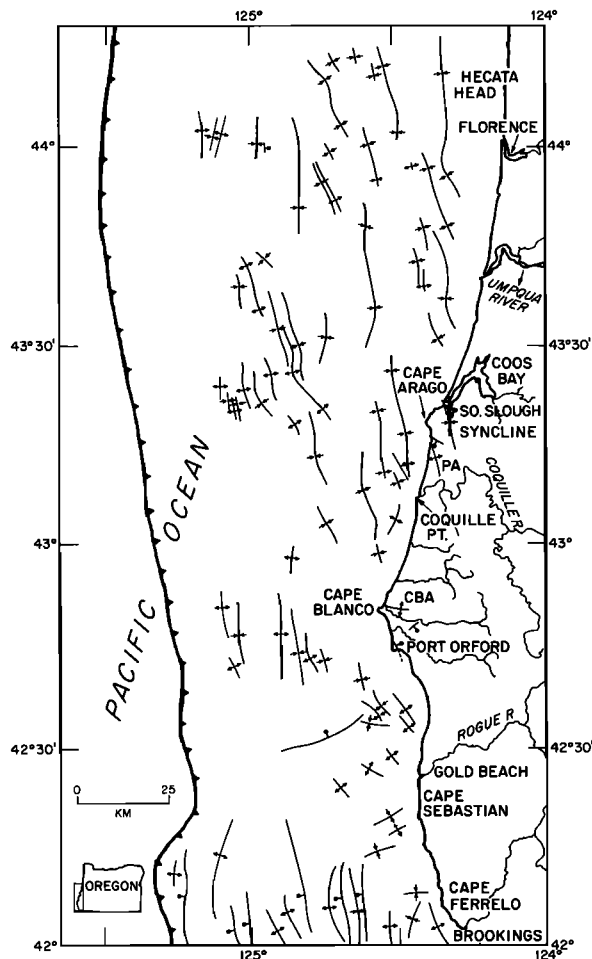


Fig. 13. Tectonic map of the southern Oregon continental margin. Offshore data north of 43° from Clarke et al. [1985]; only those folds that produce sea floor relief and only those faults that show sea floor offset are shown. Ball and bar on downthrown side of faults. Offshore data south of 43° from Peterson et al. [1986]. The offshore structures south of 43° are all those known to deform sediments of the continental margin and, in contrast to the data from Clarke et al. [1985], are not restricted to the most recent structures. Folds and faults onshore in the vicinity of Cape Arago and Cape Blanco are major structures that deform late Quaternary wave-cut platforms. PA, Pioneer anticline; CBA, Cape Blanco anticline. Line with teeth near western margin of map is the approximate location of the bathymetric boundary between the continental slope and the abyssal plain, taken from Peterson et al. [1986].

elements of the offshore fold belt occur onshore both to the north at Cape Arago [McInelly and Kelsey, 1990; Peterson and Darienzo, 1989] and to the south in the Humboldt Bay region of northern California [Carver and Burke, 1989]. At Cape Arago, the South Slough syncline and the Pioneer anticline (Figure 1) reflect onshore deformation related to this fold belt. The southwest tilting of the oldest two marine platforms in the Cape Blanco area (Figures 9 and 10) is also consistent with the north-northwest structural trend observed in folds that are along strike and offshore to the north-northwest. However, some components of the structure at Cape Blanco are not consistent with the dominant north-northwest structural grain of the fold belt.

The Cape Blanco anticline records a north to north-northeast direction of maximum contraction (Figure 9). The two oldest wave-cut platforms at Cape Blanco, however, have different down-tilt directions than the Cape Blanco anticline that deforms the younger, reoccupied platform. The different strains are recorded on platforms of different age and either the variable strain reflects a change in strain regime over time or different strains are occurring in adjacent areas concurrently. The Cape Blanco anticline probably has been growing since at least Middle Miocene time, suggesting that the style of strain has been fairly consistent over time for this particular structure and that different strain patterns have developed concurrently in adjacent areas.

The north to north-northeast contraction evident from folding of the reoccupied platform is consistent with the last 25 years of sparse seismicity data that shows regional north-south compression of the overriding North American plate in coastal Oregon [Spence, 1989]. Contraction of the reoccupied platform is also consistent with a north-south maximum horizontal compression direction determined for northwest Oregon on the basis of borehole breakout data for 18 wells in the Coast Range and Willamette Valley [Werner et al., 1988]. An

unresolved question is whether this apparent north-south compression is indeed regional, as suggested by the sparse seismicity and borehole breakout data, or whether the compression is spatially variable. If the regional stress in coastal Oregon has a consistently north-south principle compression axis, then in the vicinity of Cape Blanco this stress is manifest by a variable strain that includes east-west-trending folding of the youngest platforms and north-northwest trending folding of the older platforms and the offshore fold belt.

CONCLUSIONS

Five elevated marine terraces occur in the vicinity of Cape Blanco in south coastal Oregon. The youngest three terraces were formed during the 125, 105, and 80 ka high stands of sea and the deposits of these terraces rest on a single, deformed wave-cut platform. The 80 and 105 ka ages are correlated ages and have a greater degree of certainty than the 125 ka age, which is an inference based on the fact that a prominent sea-level high stand occurred at this time and the terrace soil is conceivably 125 ky old. The combined 80-105-125 ka wave-cut platform is deformed into an east-west trending anticline with the axial trace passing just north of Cape Blanco. The fact that this platform was reoccupied twice by high stands of the sea after it was initially cut at 125 ka places broad constraints on the history of vertical deformation in the vicinity of the anticline axis. Either subsidence or uplift could have occurred between 125 and 105 ka but uplift must have occurred between 105 and 80 ka in order for platform reoccupation to have taken place. With the exception of the last 2 ky when maximum uplift rate is 6-10 m/ky, average maximum uplift rates since 125 ka are modest and on the order of 0.5-1.4 m/ky along the anticline axis. In addition to the possibility of nonuniform uplift rate in the late Quaternary, uplift rates are spatially variable as well. Cape Blanco has been uplifted to an elevation of 53 m

since 80 ka at the same time that subsidence has been occurring along the coast less than 10 km to both the north and south. A late Holocene storm berm rests near the axis of the anticline and the berm has been tectonically uplifted 12-16 m in the last 2,000 years. The elevation of the berm attests to late Holocene growth of the anticline. Coseismic deformation has occurred repeatedly along the Cascadia margin and it is possible that uplift of the berm occurs coseismically during earthquake events that further tighten the fold.

The late Pleistocene and Holocene deformation at Cape Blanco is an on-land expression of a fold belt that trends north-northwest on the continental shelf of Oregon. Folding of marine terraces at Cape Arago, 55 km to the north, and tilting of the oldest two marine terraces at Cape Blanco are both consistent with the deformation trend in this fold belt. However, strain recorded by the Cape Blanco anticline in the latest Pleistocene marine terraces is most consistent with a north to north-northeast-oriented principal axis of contraction. Strain recorded by the anticline is compatible with present-day north-south compression as deduced from seismicity and borehole breakout data in the western Oregon portion of the North American plate in the last few decades [Werner et al., 1988; Spence, 1989]. If the regional stress in coastal Oregon has a north-south principle compression axis, then this stress is manifest by a variable pattern of strain in the general region of Cape Blanco.

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