

Late Quaternary Tectonic Deformation in the Cape Arago-Bandon Region of Coastal Oregon as Deduced From Wave-Cut Platforms

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The Cape Arago region of south central Oregon sits on the upper plate of the Cascadia subduction zone about 80 km east of the base of the continental slope. The style of late Pleistocene deformation along the Cascadia forearc near Cape Arago is well expressed by the altitudinal variation of a set of five uplifted wave-cut platforms. These platforms record open folding, with a half wavelength of about 6–7 km, as well as late Quaternary offset on flexural-slip reverse faults that parallel bedding in the underlying bedrock. The folds have produced both landward and seaward tilts to the uplifted wave-cut platforms. Because the folds cut obliquely across the coastline, the magnitude of coastal uplift is variable. In the case of the lowest, 80 ka wave-cut platform, this variable uplift has resulted in coastal deformation ranging from subsidence to a maximum uplift rate of 0.8 m/kyr. Quantitative analysis of the mechanism of flexural slip folding for the South Slough syncline near Cape Arago indicates that the late Quaternary strain rate has decreased in the last 200 kyr. Evidence of past great subduction-style earthquakes, such as regional uplift and regional landward tilting of wave-cut platforms, or regional submergence of coastlands, is lacking in the Cape Arago region. Instead, the deformational style is controlled by folding. Though localized folding is dominant, the occurrence of great subduction-style earthquakes is not precluded because localized folding could occur concurrently with regional coseismic deformation.

INTRODUCTION

Late Pleistocene marine terraces, formed by wave abrasion during interglacial and interstadial eustatic high stands of sea, are preserved in several localities along the Cascadia forearc [Griggs, 1945; Adams, 1984; West and McCrumb, 1988; R. J. Janda, 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Blanco area of Coos and Curry Counties, southern coastal Oregon, Friends of the Pleistocene, hereinafter referred to as unpublished guidebook, 1970]. Such platforms represent spatial and temporal reference surfaces from which the style, rates, and mechanisms of supracrustal tectonic deformation may be deduced [Lajoie, 1986].

One of the best areas within the Cascadia forearc for analysis of tectonic deformation of marine terraces is the Cape Arago region of southwestern Oregon (Figure 1). At Cape Arago a flight of five marine terraces, four of which are extensively preserved, have been uplifted and deformed [Griggs, 1945; Baldwin, 1945, 1966; Lund, 1973; Ehlen, 1967; Beaulieu and Hughes, 1975; Armentrout, 1980; Adams, 1984; R. J. Janda, unpublished guidebook, 1970]. Cape Arago is 52 km north of Cape Blanco in the southern portion of the Cascadia subduction zone and lies within 80 km east of the Cascadia trench (Figure 1, inset). The three youngest terraces at Cape Arago are the Whisky Run, Pioneer, and Seven Devils terraces, respectively [Griggs, 1945]. The fourth terrace is the Metcalf terrace [Adams, 1984]. The fifth and oldest terrace is herein informally designated as the Arago Peak terrace.

The marine terraces are cut into sediments that range in age from Eocene to Pliocene [Baldwin, 1966; Armentrout, 1980]. Most of the rocks are part of an Eocene and Oligocene

overlap assemblage in the Oregon coast ranges and consist of arkosic sandstones, siltstones, and mudstones. Sediments of the "Miocene beds" and the Pliocene Empire Formation [Armentrout, 1980] overlie the Eocene and Oligocene bedrock on the margins of Coos Bay near Charleston.

The northern portion of the study area (Figure 1) is underlain by the north plunging South Slough syncline. The syncline is an asymmetric fold, steeper on the west limb, with an axis that coincides with South Slough [Baldwin, 1966] (Figures 1 and 2). Initiation of folding began at least by pre-Miocene time based on the angular discordance between Oligocene and Miocene sediments [Armentrout, 1980; Baldwin, 1966].

On the basis of marine terrace tilting and geodetic leveling surveys, Adams [1984] reported shortening rates of as much as 25 mm/yr within the westernmost continental margin in the vicinity of Cape Arago. Adams [1984] suggested that the eastward (landward) tilt of the terraces at Cape Arago is, in large part, due to progressive tightening of the underlying South Slough syncline. On the basis of volumetric considerations of a growing fold, Adams predicted interruptions of the smooth eastward tilt of the Cape Arago terraces by successive bedding-plane flexural-slip faults. One such bedding-plane fault displaces the Whisky Run terrace platform at Yoakam Point [Baldwin, 1966; Adams, 1884] (Figure 2).

The purpose of our paper is to document late Pleistocene and Holocene deformation along the Cascadia subduction zone in the Cape Arago to Bandon portion of the Oregon coast (Figure 1). We analysed deformation by mapping the distribution, structure, and altitudinal variation of uplifted wave-cut platforms. In light of the uncertainty surrounding the response of the Cascadia forearc to subduction [Heaton and Kanamori, 1984; Atwater, 1987; Spence, 1989] the distinction between a deformation event restricted to a few folds near Cape Arago and a more regional deformation event that includes local folds is significant. Therefore a second purpose of our paper is to comment on the role of local folds in subduction tectonics, using the late Quaternary

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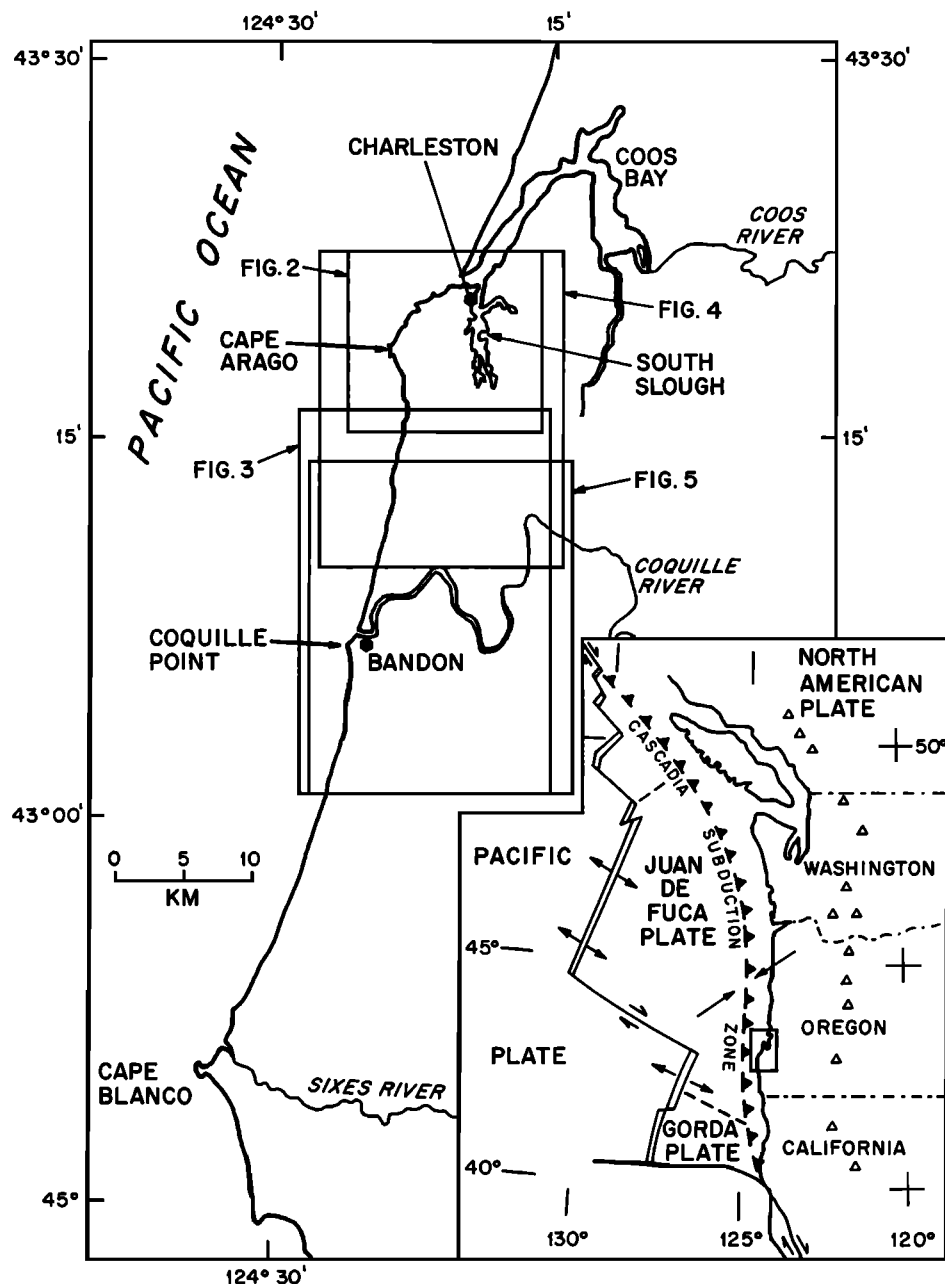


Fig. 1. Location map of the study area (boxes locate Figures 2–5) within the context of the regional tectonic setting of the Pacific Northwest and the Cascadia subduction zone (inset). Triangles are volcanoes of the Cascade Range.

folds in the Cape Arago-Bandon region as a basis of discussion.

DISTRIBUTION OF MARINE TERRACES

We differentiated marine terraces on the basis of elevation and degree of erosional dissection. Marine terrace distribution in all cases except for the area immediately east of South Slough closely follows terrace distribution as originally mapped by *Griggs* [1945]. For these terraces, platform elevations were obtained by altimeter survey (error of ± 2 m) or well log data (error of ± 6 m). All altimeter surveys were closed on either a U.S. Geological Survey bench mark or point of known altitude. We obtained platform altitudes along the coast exclusively by altimeter survey. Quantitative

analysis of uplift history and strain rate (see below) used only elevation data obtained by the more accurate altimeter method.

East of South Slough, marine terraces were previously undifferentiated. In this area we mapped terrace distribution exclusively by aerial photograph interpretation. With the exception of coastal exposures we obtained relatively limited and poorer quality platform altitude data in this area.

The four younger terraces (Whisky Run, Pioneer, Seven Devils, and Metcalf) are regionally extensive and extend from Coos Bay to about 12 km south of Bandon (Figures 2 and 3). Highly dissected remnants of the fifth and oldest terrace (Arago Peak terrace) are found only at higher elevations on the Cape Arago headlands (Figure 2). The terrace

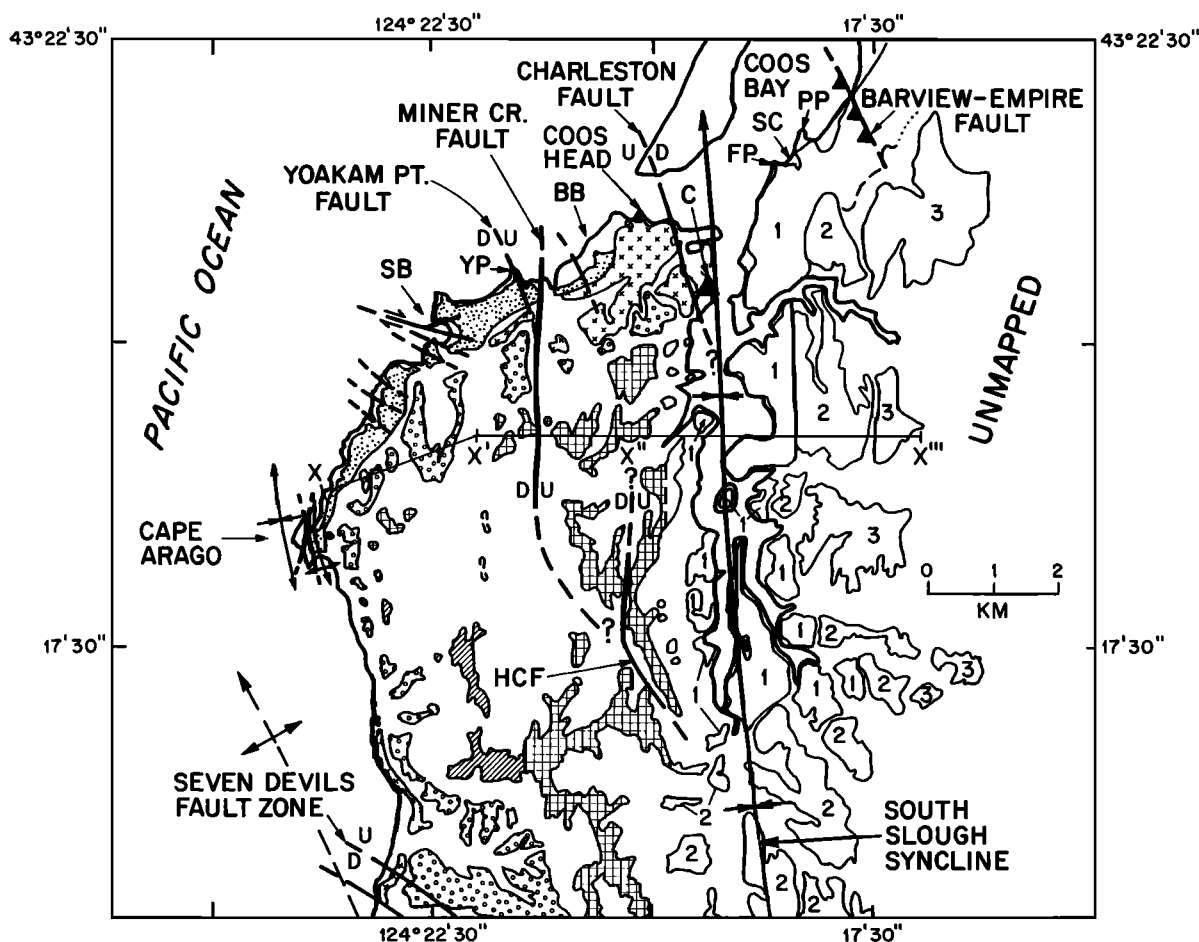


Fig. 2. Map showing distribution of late Pleistocene marine terrace sediments for the five uplifted surfaces in northern portion of study area. Map units for cover sediments on Quaternary wave-cut platforms: solid circles, Whisky Run; crosses, Pioneer; open circles, Seven Devils; checked pattern, Metcalf; diagonal shading, Arago Peak. Map units for cover sediments on Quaternary wave-cut platforms east of South Slough: 1, lowest surface; 2, middle surface; 3, upper surface. SB, Sunset Bay; YP, Yoakam Point; BB, Bastendorff Beach; CH, Coos Head; C, Charleston; FP, Fossil Point; SC, Stinky Cove; PP, Pigeon Point; HCF, Hayward Creek fault. Onshore structural data in part from Baldwin [1966], Ehlen [1967], R. J. Janda (unpublished guidebook, 1970), and Armentrout [1980]. Offshore data from Newton *et al.* [1980] and Clarke *et al.* [1985].

surfaces are moderately to well dissected in the northern portion of the study area (Figure 2). In contrast, in the southern portion of the study area the lower three terraces form a relatively undissected, broad coastal plain at lower elevations (Figure 3).

The Whisky Run and Pioneer terraces are younger and therefore, in general, better preserved than the Seven Devils and Metcalf terraces (Figures 2 and 3). Between Cape Arago and Charleston the Whisky Run terrace forms a prominent, nearly continuous surface.

We recognize three distinct surfaces to the east and northeast of South Slough (Figure 2). Individual surfaces are less apparent because relatively low uplift rates east of the South Slough syncline have minimized spacial separation of Pleistocene wave-cut platforms [Adams, 1984]. There is presently no basis, other than altitude, for correlation of these surfaces with surfaces across South Slough to the west.

We follow previous workers and tentatively correlate the lowest surface east of South Slough with Whisky Run terrace [Baldwin, 1966; R. J. Janda, unpublished guidebook,

1970]. However, the presence of the Charleston fault (Figure 2) raises the possibility that the platform underlying this lowest surface may be correlative with the Pioneer platform. Alternatively, the platform may have been cut in Pioneer or Seven Devils time and reoccupied by the Whisky Run eustatic sea level high stand. We retain the Whisky Run terrace designation for the lowest surface but acknowledge that the surface may be older than Whisky Run.

Marine cover sediments of the Metcalf, Seven Devils, Pioneer, and Whisky Run terraces vary in thickness from about 2.5 to 20 m (Table 1). Sediments on terraces in the Cape Arago area are generally no thicker than about 6 m, although the sediments of the Pioneer terrace are about 15 m thick near Coos Head (Figure 2). South of the Cape Arago headland, sediment thicknesses for the three lower terraces increase to about 20 m. The variation in sediment thickness on the modern wave-cut platforms in the Cape Arago area is consistent with the variation in sediment thickness on late Pleistocene wave-cut platforms, as described by Peterson *et al.* [1987]. The present coastline to the northeast of the Cape Arago headland is generally stripped of sand, while beaches

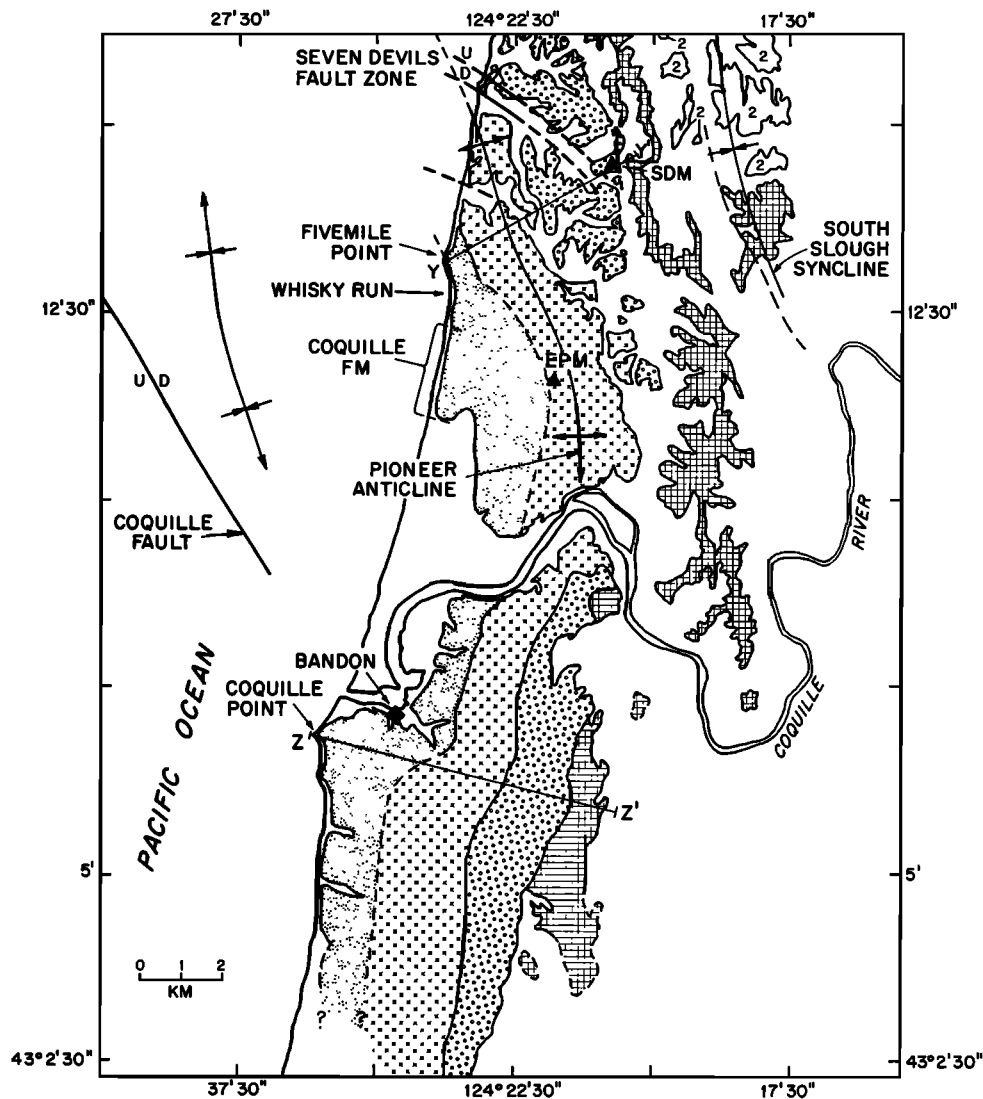


Fig. 3. Map showing distribution of late Pleistocene marine terrace sediments for the four extensively preserved surfaces in southern portion of study area. For explanation of map units, see caption for Figure 2. Triangles locate placer mines: SDM, Seven Devils Mine; EPM, Eagle-Pioneer Mine. Offshore data from Newton *et al.* [1980] and Clarke *et al.* [1985].

to the south of the headland have relatively thick accumulations of sand; cover sediments on the uplifted terraces show the same pattern.

DEFORMATION OF WAVE-CUT PLATFORMS

Overview

Differential uplift of wave-cut platforms along the coast reflects late Quaternary folding and faulting of the underlying bedrock. Platforms west of South Slough rise to the southwest from Coos Head to maximum elevations in the vicinity of Cape Arago, where the oldest platform is uplifted to 212 m (Figures 2 and 4). The platforms also descend gradually to the south from Cape Arago and reach elevation minimums 12–15 km south of Bandon (Figures 4 and 5). The Whisky Run platform descends from a high point at Cape Arago (35 m) to sea level just north of the Coquille River (Figures 4 and 5). South of the Coquille River, the Whisky Run platform is

again emergent and again descends to sea level near the southern boundary of the study area (Figure 5).

East of South Slough, terrace cover sediments have been uplifted to about 90 m [Griggs, 1945]. The terrace surfaces slope toward South Slough (Figure 6).

Deformation Associated With South Slough Syncline

Evidence for late Quaternary growth of the South Slough syncline comes from the more steeply dipping and better exposed west limb. On the west limb, wave-cut platforms are back tilted from initial seaward dips of about 1° (seaward dip estimate from Bradley and Griggs [1976]). The back tilted platforms dip toward the axis of the syncline [Griggs, 1945; Adams, 1984; R. J. Janda, unpublished guidebook, 1970]. On the basis of platform elevation data (Figure 4) the Metcalf platform dips about $N60^\circ E$ (downdip) with a slope of 1.0° between Cape Arago and Charleston. The relative north versus east component of tilt for the Seven Devils, Pioneer,

TABLE 1. Characteristics of Marine Terraces: Cape Arago Region

Terrace	Radiometric Age, ka	Preservation and Occurrence	Platform Elevation Range, m	Backedge Elevation Range, m	Terrace Sediment Thickness, m	Faults Cutting Terrace Platforms
Whisky Run	80 ^a	well preserved, regionally extensive	0–35	0–31	3–20	Miner Creek Yoakam Point Bastendorf Beach Barview-Empire Sunset Bay Coquille (?)
Pioneer	...	well preserved, regionally extensive	5–60	15–60	4–20	Miner Creek Charleston Yoakam Point (?) Sunset Bay (?)
Seven Devils	...	well preserved, regionally extensive, moderately dissected	43–104	50–91	3–18	Miner Creek Seven Devils
Metcalf	...	moderately well preserved, regionally extensive, highly dissected	87–167	169–?	3–16	Miner Creek Hayward Creek
Arago Peak	...	poorly preserved, extremely limited, highly dissected	212	?	17 (?)	?

^aMuhs *et al.* [this issue] and Kennedy *et al.* [1982].

and Whisky Run terraces cannot be resolved from the spatial distribution of altitude data. However, these data are consistent with a N60°E tilt direction (Figure 4). Altitude differences between Cape Arago and the Coos Head–Charleston area for the Metcalf, Seven Devils, Pioneer, and Whisky Run platforms are 82, 47, 36, and 16 m, respectively. The increasing altitudinal difference documents the progressive tilting of the west limb of the syncline in the late Pleistocene.

On the west limb of the syncline, bedding-plane, flexural-slip faults parallel to the bedding planes of the underlying folded strata offset the wave-cut platforms up to the east (Figures 6 and 7). The structural blocks defined by these faults are rotated down to the east and movement on these faults accommodates strain during tightening of the syncline [Adams, 1984; McNelly *et al.*, 1989]. Three bedding-plane faults cut the Whisky Run platform east of Sunset Bay (Figures 4 and 7). Vertical displacements of the Whisky Run platform on the Yoakam Point [Baldwin, 1966], Miner Creek, and Bastendorf Beach faults are 4, 5, and 4 m, respectively. Flexural-slip faults also cut the Metcalf and/or Seven Devils platforms (Figures 2, 4, and 6) (Table 1). Minimum vertical displacements of the Metcalf wave-cut platform are 25 and 6 m for the Miner Creek (Figure 6) and Hayward Creek faults, respectively. A possible third bedding-plane fault may offset the Seven Devils platform by as much as 12 m (Figure 6, segment X-X').

The Charleston fault (Figure 4) displaces the Pioneer platform by 19 m in a down-to-the-east sense of displacement. Compared to other faults west of South Slough, the Charleston fault has an opposite offset sense, cuts across bedding planes of the Tertiary bedrock and is steeply dipping to subvertical. The main fault plane is not exposed, but mesoscale faults directly adjacent to the main fault are steeply dipping, conjugate normal faults. On the basis of a mapped trend of N15°W, the Charleston fault may be the onshore extension of one of a group of north-northwest trending, up-to-the-west faults that deform seafloor sediments northwest of Coos Bay [Clarke *et al.*, 1985].

The Charleston fault appears to be a more regionally significant fault than the neighboring flexural-slip faults. The fault separates steeply dipping (40°–70°) beds on the west limb of the South Slough syncline from gently dipping (12°–30°) beds on the east limb. In addition, the fault has displaced the Whisky Run wave-cut platform such that if this platform is projected eastward across the Charleston fault to the axis of the South Slough syncline, the platform is approximately 20 m above sea level. In the absence of offset and tilt due to the Charleston fault the Whisky Run platform would probably project below the level of South Slough. The 19 m offset on the Charleston fault may be therefore younger than the Whisky Run platform.

Holocene Deformation on the Shores of Outer Coos Bay

The eastern shoreline of outer Coos Bay (Figure 2) provides evidence for Holocene growth of the South Slough syncline. Along this shore the Whisky Run platform undulates above and below sea level at least twice. At one locality, platform submergence is associated with offset on the low angle Barview-Empire fault (Figures 2 and 4).

The Barview-Empire fault is inferred to be a thrust fault on the basis of mesoscale thrust faults exposed in the overlying terrace cover sediments above the fault trace. Slip indicators for the mesoscale faults show dip-slip motion. The inferred thrust fault is coplanar with bedding (N25°W, 28°SW) of the underlying Miocene beds and we infer that the Barview-Empire fault is a flexural-slip fault similar to bedding-plane faults west of South Slough.

A group of five drowned Sitka spruce stumps occur within the intertidal zone on the downthrown side of the Barview-Empire fault. The stumps are 0.6–1.5 m below the rooting level of adjacent living Sitka spruce trees. The stumps occur only in proximity to the fault and therefore appear to be related to displacement on the fault. Samples from two of the drowned stumps yield ages of 220 ± 50 ¹⁴C years B.P. (Beta

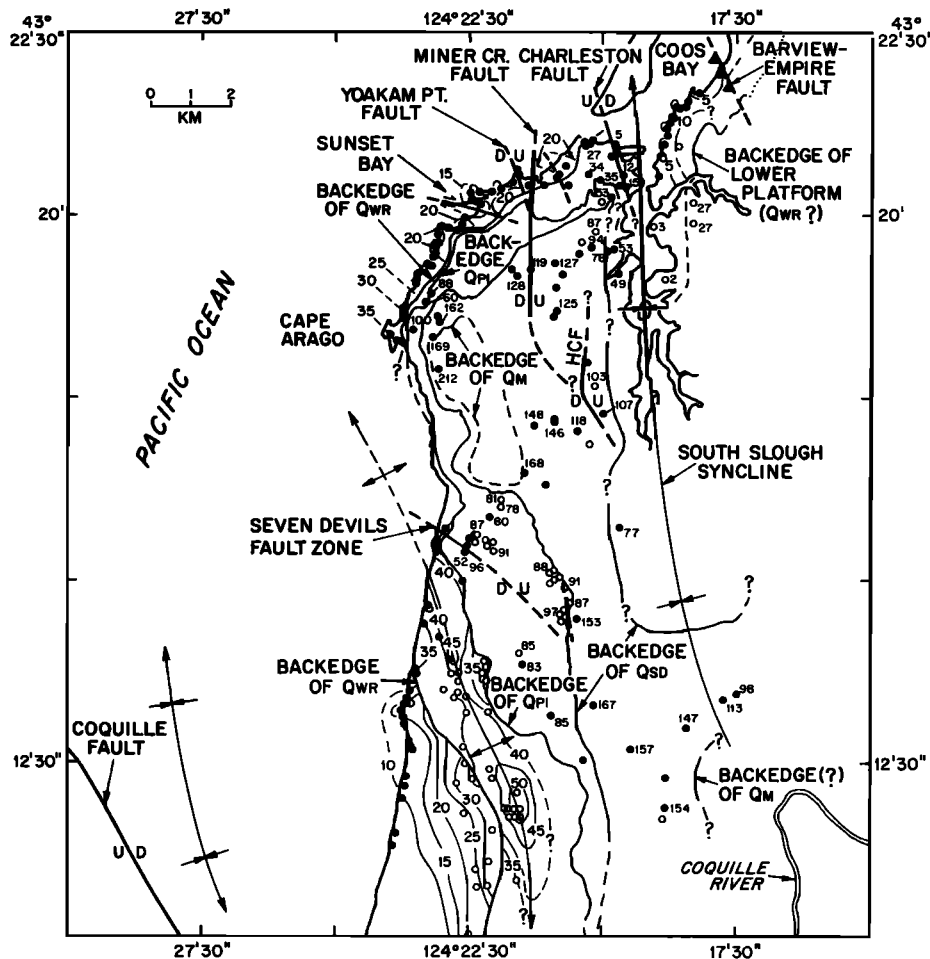


Fig. 4. Wave-cut platform elevation and contour map showing postemergence platform deformation, northern portion of study area. Contour interval is 5 m. Note the northeast dip of all wave-cut platforms on the west limb of the South Slough syncline between Cape Arago and outer Coos Bay. Late Pleistocene to Holocene(?) folding and faulting has warped the wave-cut platforms in the southern portion of the figure. Solid circles are altimeter survey locations, open circles represent platform altitudes calculated from water well logs or minerals exploration boreholes. Labeled backedges on the figure refer to the position of the shoreline angle for the following marine terraces: Qwr, Whisky Run; Qpi, Pioneer; Qsd, Seven Devils; Qm, Metcalf; HCF, Hayward Creek fault. Offshore data from Newton *et al.* [1980] and Clarke *et al.* [1985].

analytic sample Beta-23276) and modern (A. R. Nelson, personal communication; 1988; University of Pittsburgh sample Pitt-185). On the basis of the age of the stumps, we infer late Holocene activity on the Barview-Empire fault. The Whisky Run wave-cut platform is also submerged at Pigeon Point (PP, Figure 2), 1 km southwest of the Barview-Empire fault, and this abrupt change in elevation may be fault controlled as well.

Pioneer Anticline and Coquille Fault

To the southwest and south of the South Slough Syncline, platform warping is controlled mainly by the Pioneer anticline. The northwest trending Pioneer anticline is delineated by the structure contours of the Pioneer wave-cut surface (Figure 4). The half wavelength of the Pioneer anticline is about 6–7 km. The east limb of the Pioneer anticline is cut by high-angle reverse faults of the Seven Devils fault zone (Figure 8). The N50°W strike of the Seven Devils fault zone matches the strike of the underlying Eocene siltstone. Both the reverse sense of slip and the coplanarity of the fault zone

and bedding (Figure 8) lead us to suggest the Seven Devils fault is a bedding-plane flexural-slip fault as well. The Seven Devils fault zone extends to the Seven Devils Mine area (SDM, Figure 3) where Griggs [1945] documents a northwest striking fault which cuts Seven Devils terrace sediments. The fault last moved prior to cutting of the Pioneer terrace, which is not deformed by the fault zone.

Between Fivemile Point and the mouth of the Coquille River the southwest dip of the Whisky Run platform is related to folding of the Pioneer anticline. An abrupt gain in elevation at Coquille Point (Figure 5), however, is accompanied by a distinctive change in platform tilt from southwest to west. This abrupt elevation gain and change in tilt may correspond to an onshore extension of the informally designated Coquille fault (Figure 5). Offshore, the Coquille fault trends N30°W and displaces Pleistocene sediments in a down-to-the-northeast sense [Clarke *et al.*, 1985]. The extrapolated southeast extension of the fault intersects the coast at the mouth of the Coquille River (Figure 5). The wave-cut platforms south of the Coquille River generally dip

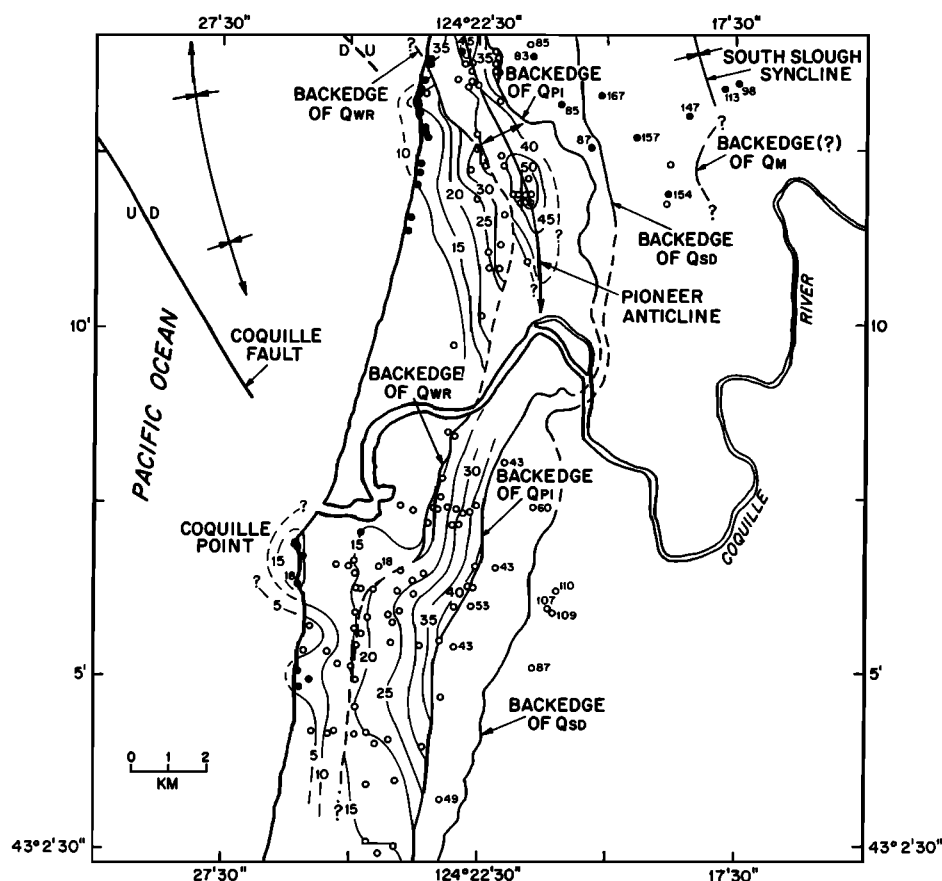


Fig. 5. Wave-cut platform elevation and contour map showing postemergence platform deformation, southern portion of study area. Also shown are offshore structures in this area. Contour interval is 5 m. Note that the Whisky Run platform descends below sea level north of the Coquille River and rises abruptly to 18 m south of the Coquille River. Platforms south of the Coquille River dip seaward in contrast to the back tilted platforms in the vicinity of Cape Arago. Terrace platform elevations gradually descend south of the Coquille River and dip below sea level south of the study area. Symbols and abbreviations are the same as for Figure 4. Offshore data from Newton *et al.* [1980] and Clark *et al.* [1985].

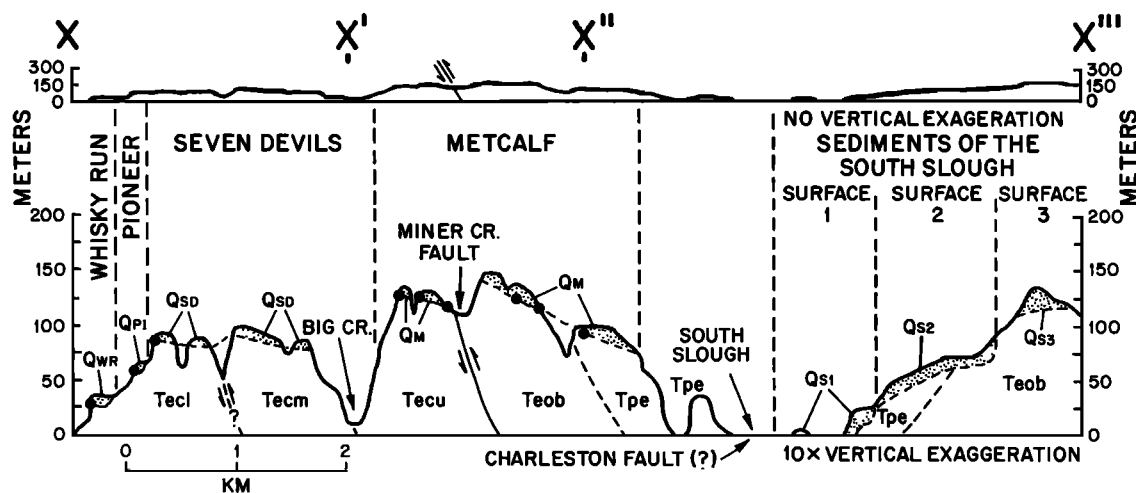


Fig. 6. Northeast to east trending cross section (view to north) showing tilting and faulting of wave-cut platforms near Cape Arago. Differential back tilt of the wave-cut platforms occurs due to offset on flexural-slip faults such as the Miner Creek fault. Surfaces 1, 2, and 3, east of South Slough, slope west toward the syncline axis. Bedrock stratigraphy: Tpe, Pliocene Empire Formation; Totp, Oligocene Tunnel Point Formation; Teob, Eocene-Oligocene Bastendorff Formation; Tecu, Eocene Coaledo Formation, upper member; Tecm, Eocene Coaledo Formation, middle member; Tecl, Eocene Coaledo Formation, lower member; Tees, Eocene Elkton Siltstone Formation. See Figure 2 for location of cross section X to X''.

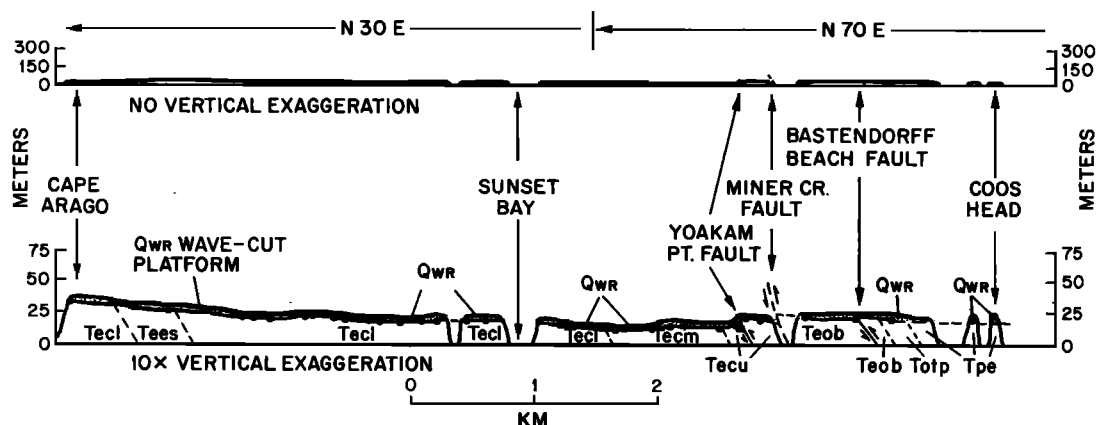


Fig. 7. Post-80 ka deformation of the Whisky Run wave-cut platform is illustrated in this coastwise transect from Cape Arago to Coos Head (view to northwest and north-northwest). Solid circles are altimeter survey locations. Data are projected onto a line that trends N30°E from Cape Arago to Sunset Bay, then N70°E to Coos Head. The gradual descent of the Whisky Run Wave-cut platform from Cape Arago to Coos Head is interrupted repeatedly by flexural-slip faults at Yoakam Point, Miner Creek, and Bastendorff Beach. Geologic units are same as previous figure.

west, except the Whisky Run platform at Coquille Point where it is slightly back tilted (Figures 5 and 9).

TERRACE AGES

We obtained a revised, numerical age estimate for the Whisky Run terrace and a correlation age estimate for the Pioneer terrace. Age assignments for the older terraces are speculative.

To obtain a numerical age estimate for the Whisky Run terrace, we collected fossils for U series, amino acid, and oxygen isotope analyses. Solitary corals (*Balanophyllia ele-*

gans) and bivalve mollusks (*Saxidomus giganteus* and *Mya truncata*) were collected at Coquille Point (U.S. Geological Survey (USGS) locality M2798; Los Angeles County Museum of Natural History (LACMNH) locality 2636), and bivalve mollusks were collected at Cape Blanco (USGS locality M1450 and M1452; LACMNH locality 2641). Analyses of the fossils from both localities are reported by Muhs *et al.* [this issue].

U series analyses of the fossil coral yields an age of 83 ± 5 ka for the Whisky Run terrace at Coquille Point [Muhs *et al.*, this issue]. Kennedy *et al.* [1982] reported a U

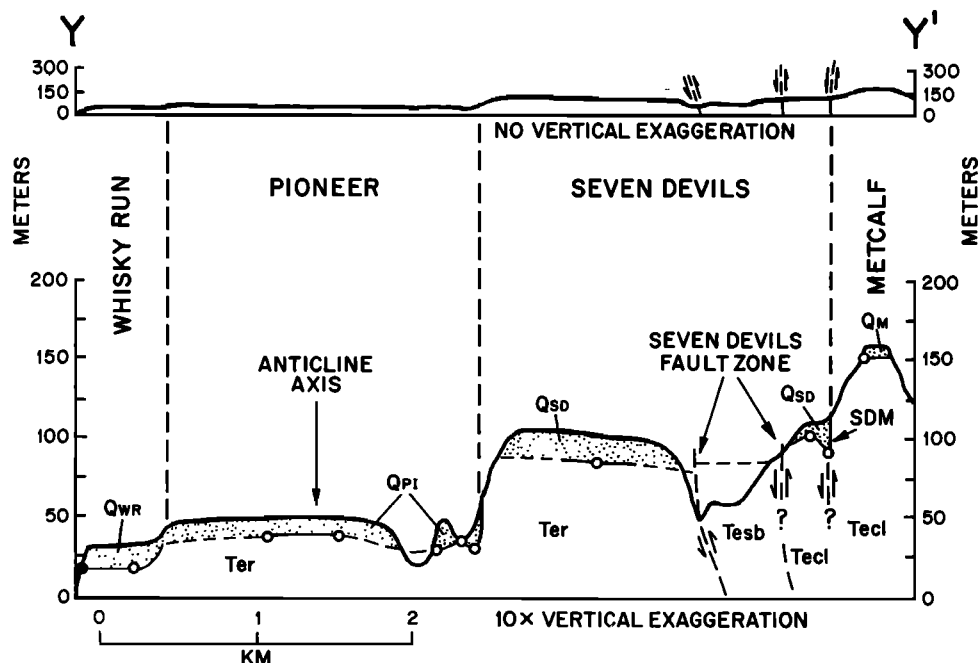


Fig. 8. Cross section Y-Y' (view to northwest) showing anticlinal warping of the Pioneer wave-cut platform. The section is located in the transition zone between wave-cut platforms with eastward tilts (northern portion of study area) and platforms with westward tilts (southern portion of study area). Bedrock stratigraphy: Ter, Eocene Roseburg Formation; Tesb, Eocene Sacchi Beach Beds; Tec1, Eocene Coaledo Formation, lower member. SDM is the Seven Devils placer mine. Displacement of the Seven Devils platform in the Seven Devils fault zone is accommodated either within the siltstone of the Sacchi Beach Beds or along the formation contacts. See Figure 3 for location of cross section.

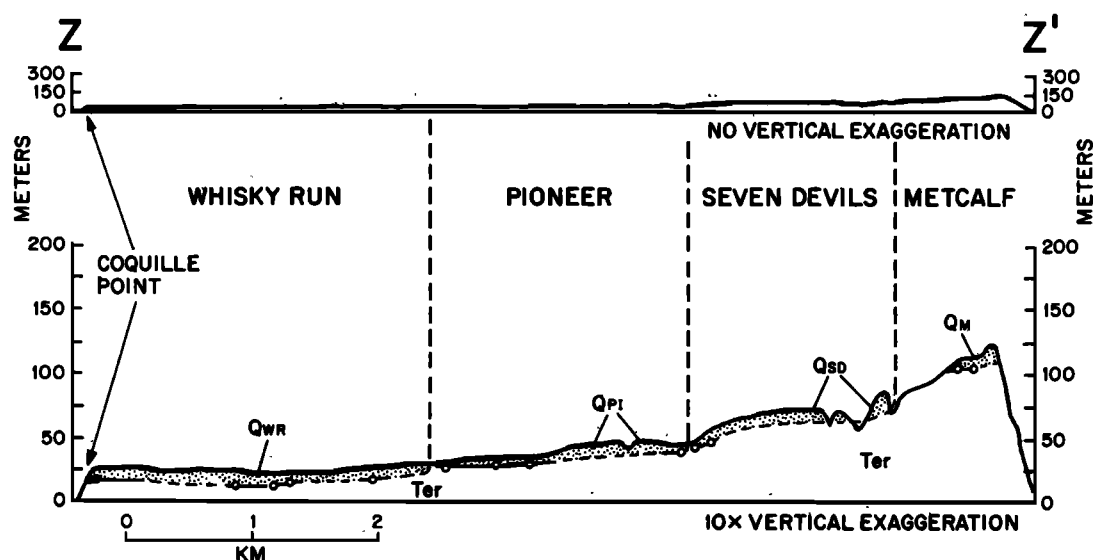


Fig. 9. Cross section Z-Z' (view to north) showing only slightly deformed wave-cut platforms in southern portion of study area. Solid circles are altimeter survey locations; open circles represent altitudes derived from water well logs. Terrace platforms dip seaward, and younger platforms show successively less relief at backedges. A slight downwarping of the Whisky Run platform can be seen east of Coquille Point. See Figure 3 for cross-section location.

series age of approximately 72 ka determined on fossil coral from the same locality but noted isotopic discordance in their fossil corals. *Muhs et al.* [this issue] correlate the Whisky Run wave-cut platform at Coquille Point with the circa 80 ka eustatic high stand of sea level (deep-sea isotope stage 5a) of *Mesolella et al.* [1969] and *Shackleton and Opdyke* [1973]. Amino acid and oxygen isotope data from bivalve shells collected at Cape Blanco suggest that the two lowest terraces at Cape Blanco, the newly designated Cape Blanco terrace [*Muhs et al.*, this issue; *Kelsey*, 1990] and the Pioneer terrace [*Janda*, 1969, also unpublished guidebook, 1970], are probably correlative with the 80 and 105 ka sea level high stands, respectively [*Muhs et al.*, this issue]. Platform elevation data, determined from water well logs, show physical continuity between the 105 ka Pioneer wave-cut platform at Cape Blanco and the Pioneer wave-cut platform at Coquille Point. Therefore the Pioneer platform at Coquille Point was probably formed during the circa 105 ka sea level high stand.

A minimum feasible age for the Seven Devils wave-cut platform is 125 ka, which is the age of the interglacial high stand of sea level that directly preceded the 105 ka high stand. It is possible that the 125 ka terrace was totally removed in the Cape Arago area due to coastal retreat, in which case the Seven Devils terrace is older than 125 ka. We feel our 125 ka age assignment is feasible because the 125 ka sea level was 6 m above present sea level [*Ku et al.*, 1974; *Harmon et al.*, 1983] and platforms attributed to this high stand are present worldwide on both tectonically stable and uplifted coastlines (see review by *Muhs et al.* [this issue]).

The Metcalf terrace must have been cut during a relatively high stand of the sea sometime in the late Pleistocene prior to 125 ka. A minimum age of platform cutting for the Metcalf is about 200 ka (oxygen isotope stage 7 of *Shackleton and Opdyke* [1973]). On the tectonically stable platform of Bermuda, sea level was at 2-m elevation at about 200 ka [*Harmon et al.*, 1983]; and data from Barbados [*Bender et al.*, 1979] and from the tectonically stable New Providence

Islands of the Bahamas [*Muhs and Bush*, 1987; D. R. Muhs, personal communication, 1989] also lead to the conclusion that sea level was a few meters above present at about 200 ka. We recognize, however, that the age of the Metcalf platform could be significantly older than 200 ka.

RATES OF DEFORMATION

Uplift Rates

Maximum rates of uplift for wave-cut platforms at Cape Arago range from 0.5 to 0.8 m/kyr (Table 2). Calculation of maximum uplift rate depends on the age of the platform, the elevation of paleo-sea level (with respect to present sea level) at the time of platform formation, and the present elevation of the platform. In order to calculate alternative uplift rates we employed two different Pleistocene paleo-sea level curves, one for New Guinea [*Bloom et al.*, 1974; *Chappell and Shackleton*, 1986] and one based on data for Japan [*Machida*, 1975] and California and Baja California [*Muhs et al.*, 1988] (Table 2). For platforms that are not landward tilted the shoreline angle (the base of the paleo-sea cliff) is the point of maximum uplift. The shoreline angle is assumed to have been cut during a eustatic sea level high stand and thus represents the paleo-sea level at the time of platform formation. At Cape Arago the wave-cut platforms are tilted landward and the point of maximum uplift for these platforms is seaward of the paleoshoreline angle. Therefore the point of maximum uplift had an initial elevation that was lower than the elevation of paleo-sea level during the time of platform formation. The degree to which the initial elevation is lower than the paleoshoreline angle is dependent on the initial, nontectonic, seaward slope of the wave-cut platform. Modern and ancient wave-cut platforms cut on sandstones similar to the bedrock at Cape Arago have seaward slopes of 20–40 m/km for a 300–600 m wide segment near the backedges and a 7–17 m/km slope farther offshore [*Bradley and Griggs*, 1976]. These seaward slopes are used as a

TABLE 2. Marine Wave-Cut Platforms at Cape Arago: Ages, Uplift Rates, Tilt Rates, and Horizontal Strain Rates

Wave-Cut Platform	Estimated Age, ka	Maximum Elevation, ^a m	Shore-Normal Distance From Shoreline Angle, km	Original Gradient of Platform, m/km	Original Depth of Platform, m	Paleo-Sea Level, Level, ^b m	Sea Level Model ^c	Maximum Uplift Rate, ^d m/kyr	Elevation of Shoreline Angle, m	Uplift Rate at Shoreline angle, m/kyr	Maximum Observed Tilt, ^e rad	Tilt Rate rad/yr	Horizontal Strain Rate, ^f yr ⁻¹
Whisky Run	80	35	0.2	20	4	-19 ± 5	NG	0.73 ± 0.07	31	0.63 ± 0.07	2.3 × 10 ⁻³	2.9 × 10 ⁻⁸	0.44 × 10 ⁻⁷
	80	35	0.2	40	8	-19 ± 5	NG	0.78 ± 0.07	31	0.63 ± 0.07			
	80	35	0.2	20	4	-5 ± 2	CA-JP	0.55 ± 0.03	31	0.45 ± 0.03			
	80	35	0.2	40	8	-5 ± 2	CA-JP	0.60 ± 0.03	31	0.45 ± 0.03			
Pioneer	105	68 ^g	0	NA	0	-9 ± 3	NG	0.73 ± 0.03	68	0.73 ± 0.03	5.7 × 10 ⁻³	5.4 × 10 ⁻⁸	0.83 × 10 ⁻⁷
	105	68 ^g	0	NA	0	-2	CA-JP	0.67	68	0.67			
Seven Devils ^h	125	100	0.2	20	4	+6	both	0.78?	98 ^g	0.74?	8.1 × 10 ⁻³ ?	6.5 × 10 ⁻⁸ ?	1.0 × 10 ⁻⁷ ?
	125	100	0.2	40	8	+6	both	0.82?	98 ^g	0.74?			
Metcalf ^h	200?	169	0	NA	0	B + 2	both	0.84?	169	0.84?	17 × 10 ⁻³ ?	8.5 × 10 ⁻⁸	1.3 × 10 ⁻⁷ ?

^aFor Whisky Run and Seven Devils platforms, the maximum elevation near Cape Arago is 200 m seaward (westward) of the paleoshoreline angle. For Pioneer and Metcalf platforms the maximum elevation near Cape Arago is at the paleoshoreline angle. All platforms are landward tilted at Cape Arago.

^bRelative to present sea level.

^cNG, New Guinea model [Chappell and Shackleton, 1986]; CA-JP, California-Japan model [Machida, 1975; Muhs *et al.*, 1988]; B, Bermuda data for 200 ka high stand [Harmon *et al.*, 1983].

^dUncertainties for Whisky Run and Seven Devils wave-cut platforms: (1) paleo-sea level, (2) paleo-water depth during the 80 and 105 ka sea level high stands for the present point of maximum elevation.

^eFor all terrace platforms, tilt is measured from the vicinity of Cape Arago N60°E to the vicinity of South Slough. Tilts measured parallel to the N60°E down-dip direction.

^fSee assumptions for derivation of strain rate in text.

^gElevation is extrapolated from known distance measured in down-tilt direction and using average platform tilt.

^hThe estimated ages of the Seven Devils and Metcalf platforms are minimum ages and not constrained by isotopic data. Therefore all calculated rates based on these ages are maximum rates and are queried because of the large uncertainties.

correction for determining maximum uplift rates on landward tilted platforms (Table 2). For the Whisky Run and Seven Devils wave-cut platforms at Cape Arago, uncertainties in maximum uplift rates are therefore a combination of paleo-sea level uncertainties and the uncertainty as to the paleobathymetry during the 80 and 125 ka sea level high stands at the present points of maximum elevation. Maximum platform elevations on these two terraces are about 200 m westward of the respective terrace shoreline angles, so the correction for landward tilting involves an additional 4–8 m of uplift (Table 2). The maximum elevation of the Pioneer and Metcalf platforms at Cape Arago is at the shoreline angle because these platforms are not extensively preserved at the cape. Therefore no landward tilt correction is necessary for these latter two platforms (Table 2). For the lowest four platforms at Cape Arago we also tabulated uplift rates at the shoreline angle (Table 2) so that we could compare uplift rates among wave-cut platforms. In general, uplift rates increase slightly, within error limits, with increasing age of the terrace (Table 2). However, if the Seven Devils and Metcalf platforms are older than the suggested minimum ages, then there is no consistent trend in uplift rate with increasing age.

Tilt Rates

At Cape Arago the degree of landward tilt increases with increasing age of the wave-cut platform (Table 2). The increasing tilts reflect progressive tilting of platforms on the west limb of the South Slough syncline and also presumably reflects tightening of the syncline throughout late Pleistocene time.

During steady growth of a sinusoidal fold, tilt rates of bedding on the fold limbs decrease as the amount of horizontal shortening increases [Adams, 1984]. If a horizontal surface such as a wave-cut platform is cut across bedding on the limb of such a fold, the wave-cut platform will be tilted at the same rate as the underlying beds. Therefore, as folding progresses, greater amounts of horizontal shortening are required to produce the same degree of tilting for successively younger wave-cut platforms. Constant or decreasing shortening rates will be manifest as a progressive decrease in tilt rates for younger wave-cut platforms. Because tilt rates systematically change with constant shortening rates, horizontal strain rates are more meaningful in terms of analyses of deformation of the fold.

Horizontal Strain Rates

The maximum principal strain direction (direction of maximum contraction) for the South Slough syncline is parallel to the assumed N60°E tilt direction for the tilted wave-cut platforms. The magnitude of the maximum principal strain is

$$\epsilon_z = (L - D)(L^{-1}) \quad (1)$$

where L is the original horizontal length and D is the horizontal length after shortening (Figure 10). The strain rate ϵ'_z is the strain divided by the amount of time over which the strain occurred:

$$\epsilon'_z = (L - D)(L^{-1})(T^{-1}) \quad (2)$$

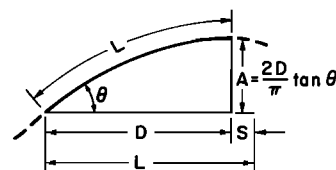


Fig. 10. Geometric relationships for a sinusoidal fold: original length along bedding (L), the horizontal extent across bedding after shortening (D), the amount of horizontal shortening (S), and the maximum flank dip (θ) at the point of inflection of the sinusoidal fold (modified from Rockwell *et al.* [1988]).

In order to calculate horizontal strain rate over time across the South Slough syncline the folded strata of the syncline are assumed to approximate sine curves [Currie *et al.*, 1962], and the syncline is modeled as a flexural-slip, sinusoidal fold using mathematical techniques outlined by Currie *et al.* [1962], Adams [1984], and Rockwell *et al.* [1988]. It is also assumed that original length along bedding is retained during folding, which necessitates that flexural slip must occur along bedding planes. The assumption of a flexural-slip fold mechanism is reasonable because of the occurrence of several flexural-slip faults in the Cape Arago region.

After folding the length L along a geologic stratum (originally a horizontal length) cannot be measured directly and must be calculated from the variable D [Rockwell *et al.*, 1988]:

$$L = (2D/\pi)(E(\theta)/\cos(\theta)) \quad (3)$$

where L is the length along a sine curve or geologic stratum (the original horizontal length) and D is the present horizontal length after shortening measured from the fold axis to the nearest point of inflection. D is therefore one-quarter of a complete sine curve and represents one-quarter of the wavelength of the fold. Theta (θ) is the maximum flank dip of the geologic stratum in the fold (slope of the sine curve), measured at the point of inflection on the fold limb (Figure 10), and $E(\theta)$ is the complete elliptic integral of the second kind (used to approximate the length along a sine curve and described by Weast [1979]). Theta (θ) was measured in the field, and D was measured from a published geologic map [Newton *et al.*, 1980].

To calculate the strain rate, the horizontal shortening rate must be calculated. The horizontal shortening rate is the rate at which the horizontal length D changes with time:

$$\frac{dD}{dt} = \frac{d}{dt} \left[\left(\frac{L\pi}{2} \right) \left(\frac{\cos(\theta)}{E(\theta)} \right) \right] \quad (4)$$

$$\frac{dD}{dt} = \frac{L\pi}{2} \left[\frac{E(\theta) \left(-\sin(\theta) \frac{d\theta}{dt} \right)}{[E(\theta)]^2} \right] - \left[\frac{\cos(\theta) E'(\theta)}{[E(\theta)]^2} \right] \quad (5)$$

$$\frac{dD}{dt} = \frac{L\pi \cos(\theta)}{2 E(\theta)} \left\{ \left[\frac{-E(\theta) \left(\tan(\theta) \frac{d\theta}{dt} \right)}{E(\theta)} \right] - \left[\frac{E'(\theta)}{E(\theta)} \right] \right\} \quad (6)$$

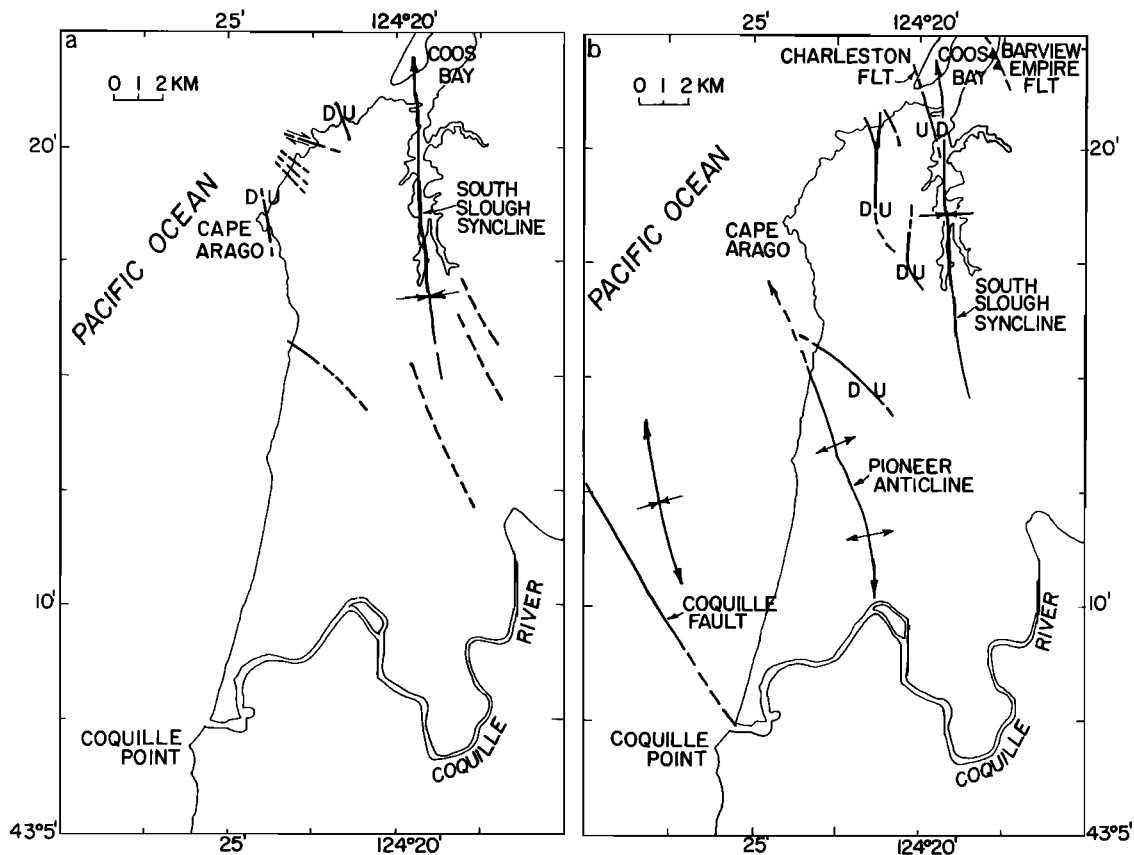


Fig. 11. (a) Tectonic map showing all folds and faults previously mapped in the Eocene to Pliocene bedrock [after Baldwin, 1966; Ehlen, 1967; Newton *et al.*, 1980]. (b) Tectonic map showing folds and faults expressed in late Quaternary wave-cut platforms in the Cape Arago area.

$$\frac{dD}{dt} = -\frac{L\pi \cos(\theta)}{2 E(\theta)} \left\{ \left[\frac{E'(\theta)}{E(\theta)} \right] + \left[\tan(\theta) \frac{d\theta}{dt} \right] \right\} \quad (7)$$

where $E'(\theta)$ is the rate of change of the complete elliptic integral of the second kind for a given change in θ .

Finally, the horizontal strain rate (ϵ'_z , units = yr^{-1}) is calculated by dividing the horizontal shortening rate by the original bedding length L :

$$\epsilon'_z = (dD/dt)(L^{-1}) \quad (8)$$

Application of the above technique to the South Slough syncline requires some relaxation of the assumptions for the model. It is uncertain if the point of inflection actually occurs where maximum flank dip was measured. Thus the measured horizontal distance D may not represent a full one-quarter of the fold wavelength. In addition, the South Slough syncline is not strictly sinusoidal because of the asymmetry of the fold. However, the west limb of the syncline roughly approximates one-quarter of a sine wave.

Recognizing the above uncertainties, evaluation of the deformation of the west limb of the South Slough syncline provides a first-order approximation of late Pleistocene crustal strain rates in the vicinity of Cape Arago. The late Pleistocene strain rates decrease with time (Table 2). In calculating the strain rates we use speculative ages for the Seven Devils and Metcalf platforms. The speculative ages are minimum possible ages, and all alternative ages would yield lower strain rates. Therefore for the two oldest plat-

forms in Table 2, strain rates may not decrease with time. A decrease in strain rate over time would reflect a slowing in the rate of east-west horizontal shortening on the west limb of the South Slough syncline during progressive tightening of the fold. As the total amount of horizontal shortening during folding grows large, horizontal shortening may begin to occur by other mechanisms [Currie *et al.*, 1962]. Therefore the apparent decreasing horizontal strain rates for the west limb of the South Slough syncline may indicate that a component of crustal shortening in the vicinity of Cape Arago is being accommodated elsewhere.

DISCUSSION

Folding: Dominant Style of Deformation

Late Pleistocene deformation of wave-cut platforms in the Cape Arago-Bandon region is dominated by open folds and related flexural-slip, bedding-plane faults. The open folds have half wavelengths of about 6–7 km and subaerially exposed axial lengths of 15–20 km. A comparison of folds and faults that have been previously mapped in the Tertiary bedrock [Ehlen, 1967; Newton *et al.*, 1980] with those that are expressed in the deformed wave-cut platforms (Figure 11) shows that most of the flexural-slip faults are only apparent from offset of late Pleistocene platforms. Furthermore, though the South Slough syncline deforms Eocene strata, the Pioneer anticline is a new fold that has developed in Quaternary sediments but is not apparent in older rocks

(Figure 11). Folding in this region along the Cascadia subduction zone therefore appears to be a persistent style of deformation at least since the late Oligocene, but growth on individual folds can be transitory. Flexural-slip faults are difficult to detect in the Tertiary sediments because they are parallel to bedding planes. The South Slough syncline and the Pioneer anticline are an on-land expression of the landward edge of a fold belt that deforms Cenozoic and Quaternary sediments on the continental shelf of the Cascadia margin [Kulm and Fowler, 1974; Clarke *et al.*, 1985; Peterson *et al.*, 1986].

The folds produce a wide variation in coastal uplift rates where the coastline cuts obliquely across structural trend (Figures 4, 5, and 11). This fold-induced variability in net uplift makes questionable assertions that coastal uplift rate is an indicator of the type of convergent margin [Uyeda and Kanamori, 1979] or the degree of plate interaction [Yonekura, 1983]. To the contrary, local structures can result in a wide range of late Pleistocene coastal uplift rates at any one subduction zone or subduction zone type [Muhs *et al.*, this issue].

While the association of flexural-slip, bedding-plane faults with the open folds is most evident, the folds may also be associated with other faults at depth. The flexural-slip, bedding-plane faults may be seismogenic, but they are not major seismic hazards [Yeats *et al.*, 1981], and such faults are probably not the primary source of seismicity in the Cape Arago-Bandon region. Rather, tightening of the South Slough syncline, subsidence of the axial region, and offset on associated flexural-slip faults may be triggered by reverse faulting on deeper structures.

Though results of our study do not elucidate how the folds grow, from several lines of circumstantial evidence we suggest that these folds may develop during earthquakes. First, in contractional setting similar to the Cape Arago area, earthquakes of magnitude 6.0–7.5 have occurred on blind thrust faults that lie beneath active folds [King and Vita-Finzi, 1981; Stein and King, 1984]. The folds apparently grow episodically during earthquakes generated by movements on these blind faults. Second, several instances of abrupt submergence in the late Holocene are documented in South Slough along the axis of the syncline. Both Nelson [1987, 1988] and Peterson and Darienzo [1989] observed seven to eight instances of abrupt submergence since 4–5 ka in the salt marsh stratigraphy of the slough. At other localities in southwestern Oregon including Coos Bay and the Coquille River estuary (Figure 1), Nelson [1987, 1988] and Peterson and Darienzo [1989] find no evidence of repeated instances of abrupt submergence. Nelson [1988] hypothesized that the local distribution of submerged peat layers in South Slough may record repeated localized Holocene coseismic contraction of the syncline.

We infer that flexural-slip faulting on the wave-cut platforms may occur simultaneously with the postulated coseismic subsidence along the South Slough syncline axis. The best evidence for coseismic flexural-slip faulting is the drowned Sitka spruce stumps in the intertidal zone on the downdropped block of the Barview-Empire fault (Figure 2). The submergence that killed these trees was either a rapid aseismic deformation or, more likely, a coseismic deformation that occurred contemporaneously with abrupt submergence along the syncline axis only 8 km to the southwest. The most recent episode of abrupt submergence of salt

marsh in South Slough, about 200–500 years ago [Nelson, 1988], could have been contemporaneous with the drowning of the Sitka spruce trees on the Barview-Empire fault.

Several observations with regards to the South Slough syncline are open to more than one interpretation. First, the decrease in strain rate on the west limb between 105 ka and the present (Table 2) may reflect a migration of contractional strain to neighboring structures or may reflect that the principal contraction direction is no longer east-west but rather north-south, which is the present direction of regional principal contraction as deduced from historical seismicity [Spence, 1989]. A change to a more northerly direction of principle contraction would result in progressively less contraction of structures with north trending fold axes, such as the South Slough syncline. Second, the role of the Charleston fault is problematic. The fault has the greatest amount of offset (20 m) of all the faults that disrupt the Whisky Run platform. Even though the fault strikes parallel to the syncline axis, the fault does not appear to be a flexural-slip fault because it is steeply dipping and cuts across bedding of the moderately inclined Tertiary strata. One plausible interpretation is that the inferred post-Whisky Run offset on the Charleston fault and the decrease in strain rate on the west limb of the syncline in the last 100 kyr may both be related to changing stress orientations in the Cape Arago region in the late Quaternary.

Regional Vertical Deformation Versus Localized Folding

The Cascadia subduction zone has not experienced historic great earthquakes [Heaton and Kanamori, 1984]. Yet the Cascadia subduction zone has several physical characteristics in common with subduction zones in Alaska, southwest Japan, Chile, and Columbia that have experienced great ($>M_w 8$) subduction-style earthquakes in historic time [Heaton and Kanamori, 1984; Heaton and Hartzell, 1987; Spence, 1989]. In the light of the prevalence of open folding in the forearc of the Cascadia subduction zone in the Cape Arago-Bandon region, as well as in the Cape Blanco region 55 km to the south [Kelsey, 1990], how common are folds along the other subduction zones that have produced great earthquakes?

The most obvious strain that is observed in historic, great subduction-style earthquakes is regional tilting, regional submergence, and regional uplift. For instance, during the 1960 earthquake in Chile and the 1964 earthquake in Alaska, large regions of the forearc (100,000–200,000 km²) underwent coseismic uplift and adjacent regions equally as large (80,000–190,000 km²) underwent coseismic subsidence [Plafker, 1969, 1972]. In southwest Japan, Ota [1986] describes a region of coastal uplift on Muroto Peninsula that developed in response to the 1946 earthquake in the Nankai Trough. The vertical deformation during the earthquake was accompanied by notable landward tilting of a 50-km-wide segment of the coast. Similar landward tilting accompanied coseismic uplift that was associated with the 1964 Alaska and 1960 Chile earthquakes [Plafker, 1972]. Although mapping of the deformation in Chile and Alaska was limited by accessible exposure, the coseismic vertical movements do not appear to have been dominated by development of local structures such as supracrustal folds or faults.

From historic data therefore it is evident that regional

vertical deformation of areas greater than 10^5 km^2 is associated with subduction-style great earthquakes. However, localized folding occurred during at least one of the above great earthquakes and may be more prevalent than recognized. Superimposed on the regional uplift during the 1964 Alaska earthquake was the growth of a localized anticlinal fold that pierces above sea level to form Middleton Island [Plafker, 1969], an island whose 30-km length is similar to the subaerially exposed axial length of folds at Cape Arago [Plafker, 1969]. The island consists of five uplifted wave-cut platforms of mid to late Holocene age. These five platforms record periodic abrupt emergence of this island, and a sixth uplifted platform was generated in 1964 when the island was again coseismically uplifted, this time by 3.3 m [Plafker, 1969]. The Middleton Island anticline therefore grew coseismically during the same 1964 event that elsewhere in the Alaskan forearc resulted in more regional vertical uplift or subsidence. It is likely that local growth of folds during the 1964 Alaska earthquake was more common than was documented because most folding probably occurred below sea level. From the Alaskan deformation data we reason that localized folds of the scale observed near Cape Arago can be generated by great earthquakes that deform a much larger region of the forearc.

SUMMARY

Late Quaternary strain in the Cape Arago region appears to be accommodated mostly by contraction on local folds with half wavelengths of 6–7 km and axial lengths of greater than 20 km. These folds produce both landward and seaward tilts to the wave-cut platforms rather than a uniform landward tilt to platforms such as is observed on the convergent margin in southwest Japan. The observed strain in south coastal Oregon therefore lacks in a simple sense the evidence for regional vertical uplift and subsidence associated with historic, large-magnitude subduction-related earthquakes elsewhere [Plafker, 1972].

Localized folding can occur during great earthquakes, as exemplified by the 1964 coseismic growth of the Middleton Island (Alaska) anticline, even though the historic record indicates that the most notable strain pattern during great earthquakes is regional vertical movement. Therefore, though the late Quaternary folds at Cape Arago need not develop during great subduction-related earthquakes, the folds do not preclude the possibility of great earthquakes whose deformation would include the Cape Arago portion of the Cascadia subduction zone.

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