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Late Quaternary stream incision and uplift in the forearc of the Cascadia subduction zone, western Oregon

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Abstract. Documentation of a latest Pleistocene/earliest Holocene episode of strath formation and fluvial aggradation in the Oregon Coast Range provides a datum from which long-term bedrock stream incision rates are determined. Variations in long-term incision rates probably reflect cumulative differential uplift in the forearc of the Cascadia subduction zone, although factors such as bedrock and climatic controls and isostatic adjustments to erosion obscure the precise relationship between surface uplift and stream incision. Patterns of differential incision are most striking near the latitude of Newport, where a steep gradient divides a region of higher rates (~0.6-0.9 mm/yr) in the northern Coast Range from a region of lower rates (~0.1-0.3 mm/yr) in the central Coast Range. The steep incision gradient is nearly coincident with abrupt changes in marine terrace (~80-125 kyr) uplift rates, the locations of Quaternary faults, and the southern flank of a saddle of low historic (~40-70 years) uplift. The exact causes of these variable patterns of incision/uplift are unknown. Analogies with uplift patterns in other subduction zones and comparisons with other neotectonic data in the region indicate that patterns of differential incision probably are caused by variations in permanent strain accumulation along the Cascadia subduction zone. Such variations may be related to differences in seismic moment release during individual earthquakes, to changes in plate geometry or rates of wedge accretion, to segmentation of earthquake ruptures, and/or to deformation on active structures in the North American plate and accretionary wedge.

Introduction

The purpose of this work is to characterize rates and styles of late Quaternary deformation in the Oregon Coast Range (hereafter referred to as the Coast Range), a high-relief, deeply dissected mountain range that is part of a belt of elevated coastal mountains reaching from northern California to British Columbia. These ranges form a high forearc that lies 100-200 km east of the deformation front of the Cascadia subduction zone (Figure 1). Marine magnetic anomaly studies indicate that the Juan de Fuca plate is being subducted beneath the North American plate in a northeasterly direction at a rate of ~4 cm/yr [*DeMets et al.*, 1990]. Deformation in forearc regions in similar tectonic settings commonly is characterized by active folding, faulting, and large-scale uplift, subsidence, and tilting of the land surface. Examples of these phenomena have been observed historically during large subduction zone earthquakes, such as those in Alaska, Chile, and Japan [*Plafker*, 1972; *Ando*, 1975] and have been inferred from the prehistoric record, primarily through study of uplifted marine terraces [e.g., *Berryman et al.*, 1989; *Ota*, 1991].

The dearth of interplate seismicity [e.g., *Ludwin et al.*, 1991] has forced earth scientists to rely on other geophysical and geologic studies to describe the modern tectonic setting of the Cascadia subduction zone. Recent geodetic studies [*Savage et al.*, 1991; *Mitchell et al.*, 1994] have identified both latitudinal and longitudinal variations in historic uplift across the forearc. In the prehistoric record, most studies of Quaternary deformation in the region are focused on coastal areas and are primarily concerned with late Holocene salt marsh sequences and late Quaternary marine terraces [cf. *Atwater et al.*, 1995, and references therein]. As a consequence, existing geologic studies leave large land areas (essentially the entire inland forearc) and time periods (>5 ka and <80 ka) largely unstudied. The goal of the present study is to use the widespread distribution of fluvial terraces in the Coast Range to bridge these temporal and spatial gaps and to help resolve the earthquake potential of the Cascadia subduction zone.

Fluvial terraces are used as datums for tectonic studies in many settings around the world, perhaps most commonly to demonstrate Quaternary faulting and folding [e.g., *Lensen*, 1964; *Rockwell et al.*, 1984, 1988]. Fluvial terraces also are used to calculate stream incision rates as proxies for regional uplift rates [e.g., *Pillans*, 1986; *Gardner et al.*, 1992; *Merritts et al.*, 1994]. Previous research on fluvial terraces in the Coast Range mostly consists of studies of stream capture and probable antecedence of ancient westward flowing streams in western Oregon [*Niem*, 1976; *Baldwin*, 1981] and reconnaissance mapping of Quaternary deposits [e.g., *Schlicker and Deacon*, 1974; *Snavely et al.*, 1976a, b]. Only a few studies have looked at fluvial terraces and stream patterns in the context of recent tectonics [*Adams*, 1984; *Rhea*, 1993].

The results presented here supplement recently published data on fluvial terraces in the region [*Personius*, 1993; *Personius et al.*, 1993] and are focused on broad patterns of vertical incision determined from heights and ages of bedrock straths that underlie most fluvial terraces in the Coast Range. The term "stream incision" as discussed hereafter refers to vertical incision of stream channels into bedrock and should not be confused with processes of lateral incision that accompany stream meandering. The rivers examined in this study

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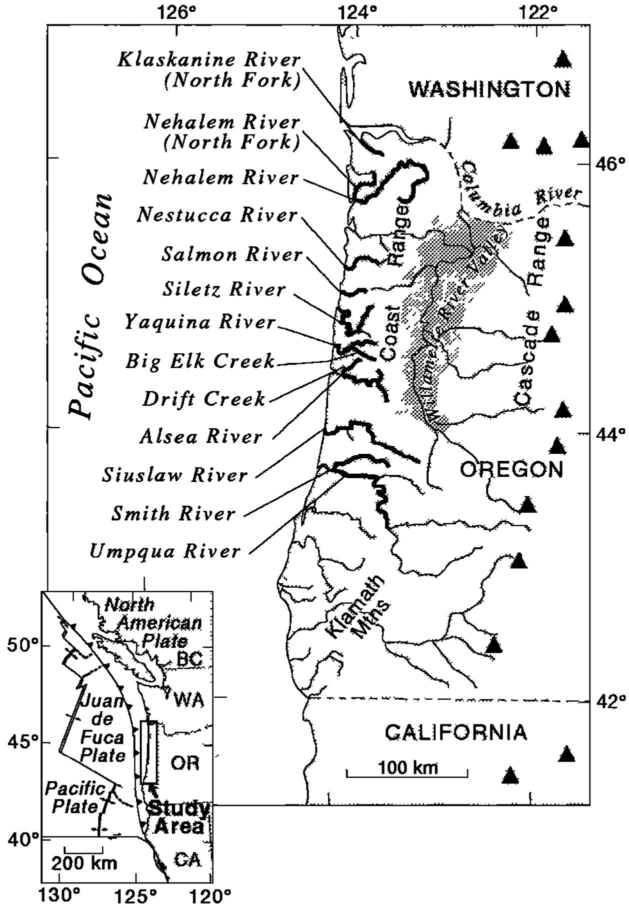

Figure 1. Map showing locations of major rivers in the Oregon Coast Range. Heavier lines mark reaches of rivers examined in this study, and triangles mark locations of major Quaternary volcanoes in the Cascade Range.

drain the central and northern Coast Range (Figure 1) and have drainage basins that range in size from 80 km^2 (North Fork Klaskanine River) to 11,800 km^2 (Umpqua River; Table 1). Streams were selected because of their relatively good terrace preservation, their distribution in a broad area of western Oregon, and the similar bedrock that underlies most drainage basins. The first part of this paper is focused on the methods and assumptions used to determine incision rates. The tectonic implications of differential incision in the region are discussed in the second part of the paper.

Geologic Setting of Coast Range Streams

Upstream from the head of tide, which defines the limit of tidal influence on streamflows, Coast Range streams primarily flow on bedrock in deeply entrenched, V-shaped valleys. Valley morphology and lack of characteristic glacial landforms indicate that the Coast Range was not glaciated in the late Pleistocene [e.g., *Porter et al.*, 1983]. In most cases these streams presently transport only a thin, discontinuous veneer of gravelly sediment. Bedrock channels are incised into a simple sequence of Eocene sedimentary and volcanic rocks (Figure 2; see also *Walker and MacLeod* [1991]). Much of the central Coast Range is underlain by the Eocene Tyee Formation, a thick sequence of arkosic and lithic turbidite sandstone and siltstone. The northern Coast Range is underlain by a more complex sequence of basaltic submarine (Siletz River Volcanics) and subaerial (Tillamook Volcanics) volcanic rocks and tuffaceous siltstones and sandstones. Stream channels in massive sandstones and dense volcanic rocks typically are incised into bedrock in narrow inner channels that vary from meandering to straight segments (Figure 3). In some reaches, channels are armored with a meter or two of gravelly sediment, but such reaches are short and discontinuous, and they make up only a small percentage (<10-20%) of the nontidal reaches of many streams in the central and northern Coast Range. Stream channels commonly are flanked by narrow platforms of beveled bedrock that lie within a few tens of centimeters of low-water (late summer) stream levels (Figure 3). Most channels are flanked by nearly continuous steep-walled, 6- to 15-m-high terrace risers that tightly confine the floodplain (Figure 4). The treads of the flanking terraces are reoccupied briefly during large flood events, such as during the winter floods of 1964, but mean annual floods commonly peak at 4-6 m above low water levels and ordinarily do not reach these surfaces in nontidal reaches. The annual flood levels locally are marked by discontinuous fill-cut terraces inset into the higher continuous terraces.

In their tidal reaches, Coast Range rivers have very low gradients and relatively poorly preserved terraces (Figure 5). The lower reaches of the studied rivers were deeply entrenched during sea level low stands but are now filled with thick sections of fine-grained fluvial and estuarine sediment. For example, in the Reedsport area on the lower Umpqua River, water wells have penetrated more than 40 m of fluvial and estuarine sediment without encountering bedrock [*Curtiss et al.*, 1984]. A single low fill terrace is present along most tidal reaches; these terrace treads are physically continuous with the lowest continuous terraces on upstream reaches, but they are nowhere underlain by exposed bedrock straths. The lack of exposed straths and presence of thick sediment fills in these lower valleys indicate that eustatic sea level fluctuations induced deep incision and subsequent aggradation along lower stream reaches. Because of eustatic base level changes and lack of observable straths in these lower reaches, the rest of this paper will focus on the upstream, nontidal reaches of Coast Range streams.

Fluvial terraces provide the datums from which I calculated incision rates in the Coast Range. Fortunately, terraces found along nontidal stream reaches in this study are remarkably similar, regardless of height above present river level. Nearly all terraces are strath terraces, cut into bedrock, and have cover sediments consisting of a 1- to 2-m-thick channel facies of sandy pebble and cobble gravel, which in turn is overlain by a 2- to 10-m-thick overbank facies of fine sand and silt (Figure 4). Such terraces are preserved as much as 200 m above modern Coast Range streams, but most higher terraces are restricted to small eroded remnants that are difficult to correlate (Figure 5). With the exception of a few thermoluminescence- (TL) and radiocarbon-dated sites [*Personius*, 1993], most higher terraces are undated and cannot be used in the incision analysis.

Despite the numerous terrace remnants preserved along Coast Range streams, only a single example of a nearly continuous terrace is preserved well enough to correlate in most drainage basins. Upstream from the tidal limit the tread of this terrace is 6-15 m above river level and is underlain by 2-11 m of fluvial sediment and a beveled bedrock strath. The

Table 1. Incision Rates in the Oregon Coast Range

Field Site	River km[a]	Latitude and Longitude	Reported Age, 1σ Lab Error, and Sample Number[b]	Calibrated or Estimated Age and Estimated Error, years[c]	Strath Height and Error, m[d]	Incision Rate and Error, mm/yr[e]	Symbol Used in Figure 7[f]	Bedrock Type[g]	Rock Strength Rating[h]	Remarks
				Umpqua River (11,800 km²)[i]						
Mile 81 terrace	131	43°28.98'N 123°30.88'W	6,440 ± 60 years B.P. USGS 2722 6,550 ± 80 years B.P. PITT-0126	7,330 ± 500	1.5 ± 0.5	0.2 ± 0.3	solid circle	ss, slt	65	average of two ^{14}C ages used in calibration
Elkton	78	43°38.00'N 123°34.11'W	8,630 ± 100 years B.P. AA-2752	9,530 ± 500	1.7 ± 0.5	0.2 ± 0.3	solid circle	ss, slt	65	strath height from better exposure 2 km upstream
McGee Creek 1	120	43°31.45'N 123°32.54'W	9,120 ± 150 years B.P. BETA-27962	9,970 ± 500	3.0 ± 0.25	0.3 ± 0.1	solid circle	ss, slt	65	
McGee Creek 2	120.5	43°31.44'N 123°32.21'W	9,800 ± 410 years B.P. BETA-22662	10,920 ± 1,500	3.5 ± 0.5	0.3 ± 0.2	solid circle	ss, slt	65	
Henderer Road	75	43°38.39'N 123°36.30W	116,000 ± 20 ka ITL118	125,000 ± 20,000	37 ± 5	0.3 ± 0.2	solid circle	ss, slt	66	TL age; may correlate with substage 5e marine terrace sediments at coast
Crestview	18.5	43°41.00'N 124°05.81'W	>200,000 ka ITL173	>200,000 ± 50,000	81 ± 5	<0.4 ± 0.3	solid circle	ss	77	TL age
				Smith River (900 km²)						
Gunter	109	43°46.75"N 123°32.97'W	...	10,500 ± 1,000 (es)	0	0	diamond	ss, slt	68	estimated incision site
Bear Creek	49	43°48.14'N 123°48.44'W	>43,600 years B.P. AA-2753	>43,600 ± 5,000	12 ± 5	<0.3 ± 0.3	solid circle	ss, slt	68	
Hudson Slough	8.5	43°45.58'N 123°04.00'W	>39,500 years B.P. BETA-26504	>39,500 ± 5,000	7 ± 1	<0.2 ± 0.2	solid circle	ss, slt	68	site on tributary of Smith River; from *Reneau* [1988]
				Siuslaw River (2,000 km²)						
Alma bridge	131.5	43°53.25'N 123°28.92'W	...	10,500 ± 1,000 (es)	0	0	diamond	ss	72	estimated incision site
Firo	38	44°03.72'N 123°52.98'W	7,010 ± 90 years B.P. BETA-27967	7,810 ± 500	1.5 ± 0.5	0.2 ± 0.3	solid circle	ss	72	average of 5 strath measurements
Sweet Creek	37	43°56.45'N 123°53.87'W	>42,000 years B.P. AA-2543	>42,000 ± 5,000	5.5 ± 1	<0.1 ± 0.2	solid circle	ss	72	site on tributary of Siuslaw River; from *Reneau* [1988]
				Alsea River (1,200 km²)						
Wayside bridge	34	44°23.19'N 123°49.82'W	...	11,000 ± 1,000 (es)	1.6 ± 0.25	0.2 ± 0.2	diamond	ss	65	estimated incision site
Mill Creek bridge	76.5	44°23.11'N 123°37.24'W	...	11,000 ± 1,000 (es)	2.0 ± 0.5	0.2 ± 0.3	diamond	ss, sh	56	estimated incision site
South Fork	90	44°20.29'N 123°31.33'W	...	11,000 ± 1,000 (es)	0	0	diamond	ss, sh	56	estimated incision site on South Fork Alsea River
				Drift Creek (190 km²)						
Lower Drift Creek	14	44°27.96'N 123°57.65'W	10,620 ± 140 years B.P. GX-18330-AMS	11,920 ± 500	3 ± 0.5	0.2 ± 0.2	solid circle	ss	65	
Drift Creek Meadows	37	44°30.66'N 123°49.99'W	10,710 ± 330 years B.P. BETA-34398	12,010 ± 1,500	1 ± 0.25	0.1 ± 0.3	solid circle	ss	65	age from *Grabau* [1990], trench 3

Table 1. (continued)

Field Site	River km[a]	Latitude and Longitude	Reported Age, 1σ Lab Error, and Sample Number[b]	Calibrated or Estimated Age and Estimated Error, years[c]	Strath Height and Error, m[d]	Incision Rate and Error, mm/yr[e]	Symbol Used in Figure 7[f]	Bedrock Type[g]	Rock Strength Rating[h]	Remarks
Big Elk Creek (220 km²)										
Harlan camp	33	44°32.62'N 123°43.27'W	...	11,000 ± 1,000 (es)	3 ± 1.0	0.3 ± 0.3	diamond	slt, sh	55	estimated incision site
Yaquina River (630 km²)										
Mile 39 bridge	63	44°39.19'N 123°45.20'W	...	11,000 ± 1,000 (es)	2 ± 0.5	0.2 ± 0.3	diamond	slt, sh	55	estimated incision site
Siletz River (800 km²)										
Butterfield	31	44°48.12'N 123°59.75'W	400 ± 60 years B.P. GX-18331-AMS	500 ± 100	2.6 ± 0.5	<5.2 ± 0.2	...	ss, sh	58	site in tide range; young ^{14}C age indicates strath reoccupation
Camp Twelve	64	44°42.89'N 123°55.92"W	12,110 ± 100 years B.P. BETA-28357	14,300 ± 1,000	18 ± 5	<1.3 ± 0.3	...	ss, sh	58	probably minimum age and maximum incision rate
Moonshine	84.5	44°46.70'N 123°50.07'W	2,230 ± 60 years B.P. USGS 2723	2,210 ± 250	1.5 ± .25	0.7 ± 0.2	solid circle	ss, sh	58	
Logsden pit	79	44°44.63'N 123°47.76'W	9,030 ± 110 years B.P. BETA-27966	9,920 ± 500	7 ± 1	0.7 ± 0.2	solid circle	ss, sh	58	average of 3 strath measurements
Siletz terrace	60	44°43.79'N 123°55.42'W	9,695 ± 440 years B.P. GX-15311	10,860 ± 1,000	7.5 ± 0.5	0.7 ± 0.1	solid circle	ss, sh	58	
Lower Gorge	88.5	44°47.17'N 123°47.75'W	41,600 ± 1,300 years B.P. USGS 2724	41,600 ± 5,000	30 ± 5	0.7 ± 0.2	solid circle	basalt	77	additional age of >36,000 years B.P. may indicate maximum incision rate
Salmon River (200 km²)										
Rose Lodge	12.5	45°00.30'N 123°53.87'W	2,260 ± 60 years B.P. GX-19403-AMS	2,320 ± 400 11,000 ± 1,000 (es)	3.1 ± 0.25	<1.3 ± 0.2 0.3 ± 0.1 (es)	open circle	slt	62	young age probably indicates inclusion of younger organic matter or strath reoccupation
Nestucca River (650 km²)										
Mile 22 terrace	35	45°17.02'N 123°44.16'W	2,500 ± 60 years B.P. GX-18329-AMS	2,560 ± 250 11,000 ± 1,000 (es)	5.5 ± 0.5	<2.1 ± 0.1 0.5 ± 0.1 (es)	open circle	slt, sh	60	young age probably indicates inclusion of younger organic matter or strath reoccupation
Camelback	34.5	45°17.19'N 123°44.53'W	6,370 ± 80 years B.P. GX-19402-AMS	7,230 ± 400 15,000 ± 1,000 (es)	7 ± 0.5	<1.0 ± 0.1 0.5 ± 0.1 (es)	open circle	slt, sh	60	young age probably indicates inclusion of younger organic matter or strath reoccupation
Tony Creek	31	45°16.71'N 123°46.73'W	12,570 ± 130 years B.P. GX-18328-AMS	15,400 ± 1,000	7.2 ± 0.5	0.5 ± 0.1	solid circle	slt, sh	60	
North Fork Nehalem River (300 km²)										
Soapstone Creek	17	45°48.82'N 123°46.15'W	7,860 ± 100 years B.P. GX-18327-AMS	8,570 ± 700	5.7 ± 0.5	0.7 ± 0.1	solid circle	slt, sh	60	
Cougar Creek	13	45°48.28'N 123°48.89'W	10,230 ± 110 years B.P. GX-19067-AMS	12,030 ± 1,000	11 ± 1	0.9 ± 0.1	solid circle	slt, sh	60	

Table 1. (continued)

Field Site	River km[a]	Latitude and Longitude	Reported Age, 1σ Lab Error, and Sample Number[b]	Calibrated or Estimated Age and Estimated Error, years[c]	Strath Height and Error, m[d]	Incision Rate and Error, mm/yr[e]	Symbol Used in Figure 7[f]	Bedrock Type[g]	Rock Strength Rating[h]	Remarks
				Nehalem River (2,240 km²)						
Batterson	21	45°42.03'N 123°45.53'W	4,300 ± 70 years B.P. GX-19401-AMS	4,860 ± 500 11,000 ± 1,000 (es)	6 ± 0.5	<1.2 ± 0.2 0.5 ± 0.2 (es)	open circle	basalt	78	average of 3 strath heights; young age probably indicates inclusion of younger organic matter or strath reoccupation
Vernonia bridge	172	45°45.63'N 123°17.81'W	9,240 ± 110 years B.P. GX-19066-AMS	10,320 ± 600	1.4 ± 0.25	0.1 ± 0.2	solid circle	sh	60	
Vesper	99	45°58.89'N 123°22.16'W	10,500 ± 90 years B.P. AA-9905	11,800 ± 500	1.3 ± 0.25	0.1 ± 0.2	solid circle	sh	60	
				North Fork Klaskanine River (80 km²)						
Wayside terrace	7	46°05.55'N 123°43.34'W	5,410 ± 70 years B.P. GX-19400-AMS	6,190 ± 300 11,000 ± 1,000 (es)	3.2 ± 0.5	<0.5 ± 0.2 0.3 ± 0.2 (es)	open circle	sh	52	

[a]Distance from river mouth; most distances converted from mileage marks on 1:24,000-scale topographic maps. Distances for tributary sites are total distance from trunk stream mouth.

[b]Radiocarbon ages are listed in "years B.P." (years before present, i.e. 1950); thermoluminescence (TL) ages are listed in "ka" (thousands of years ago). Radiocarbon laboratory abbreviations: AA, University of Arizona/NSF Accelerator Facility, Tucson; BETA, Beta Analytic, Inc., Coral Gables, Florida; GX, Geochron Laboratories, Cambridge, Massachusetts; PITT, University of Pittsburgh Radiocarbon Laboratory, Pittsburgh, Pennsylvania; USGS, U.S. Geological Survey Radiocarbon Laboratory, Menlo Park, California. TL ages were determined by Steven L. Forman while at Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, Boulder. Estimated incision sites, where no radiometric ages were obtained, are denoted by three dots.

[c]Radiocarbon ages younger than 20 ka are calibrated to account for variations in atmospheric ^{14}C with the computer program CALIB 3.0 [*Stuiver and Reimer*, 1993]; calibrations resulting in multiple intercepts are listed as single midpoint values with error limits that encompass the calibrated 2σ age range. Radiocarbon ages older than 20 ka have not been calibrated, but estimated errors have been increased to account for atmospheric ^{14}C variations. One TL age has been adjusted by apparent correlation with marine terrace deposits at the coast [*Personius*, 1993]. Estimated ages (es) are based on correlations to dated fluvial sediments; correlations are based on similar terrace heights and sediment weathering characteristics.

[d]Height measured from bedrock abrasion platforms flanking channel or base of bedrock channel to upper surface of bedrock strath.

[e]All incision rates are expressed in "mm/yr" so they can be directly compared with rates of geodetic uplift in the region (see text). However, the calculated rates are based on heights measured in meters, and all strath ages are at least several thousand years old, so they should more appropriately be listed in "m/kyr". Both units may be used interchangeably with the listed values. Estimated rates are denoted with "es".

[f]Symbols denote how incision rates are used in Figure 7: three dots, not used in Figure 7; solid circle, radiocarbon- or TL-dated site; open circle, site with anomalously young radiometric age that yields maximum incision rate; at these sites, estimated rates (es) are used on Figure 7; diamond, site with no radiometric age control; these strath ages are estimated from terrace correlations and weathering characteristics.

[g]Rock type abbreviations: ss, sandstone; slt, siltstone; and sh, shale.

[h]Rock mass strength classification of *Selby* [1980] and *Moon* [1984]; ratings: very strong, 91-100; strong, 71-90; moderate, 51-70; weak, 26-50; and very weak, <26.

[i]Approximate drainage basin area.

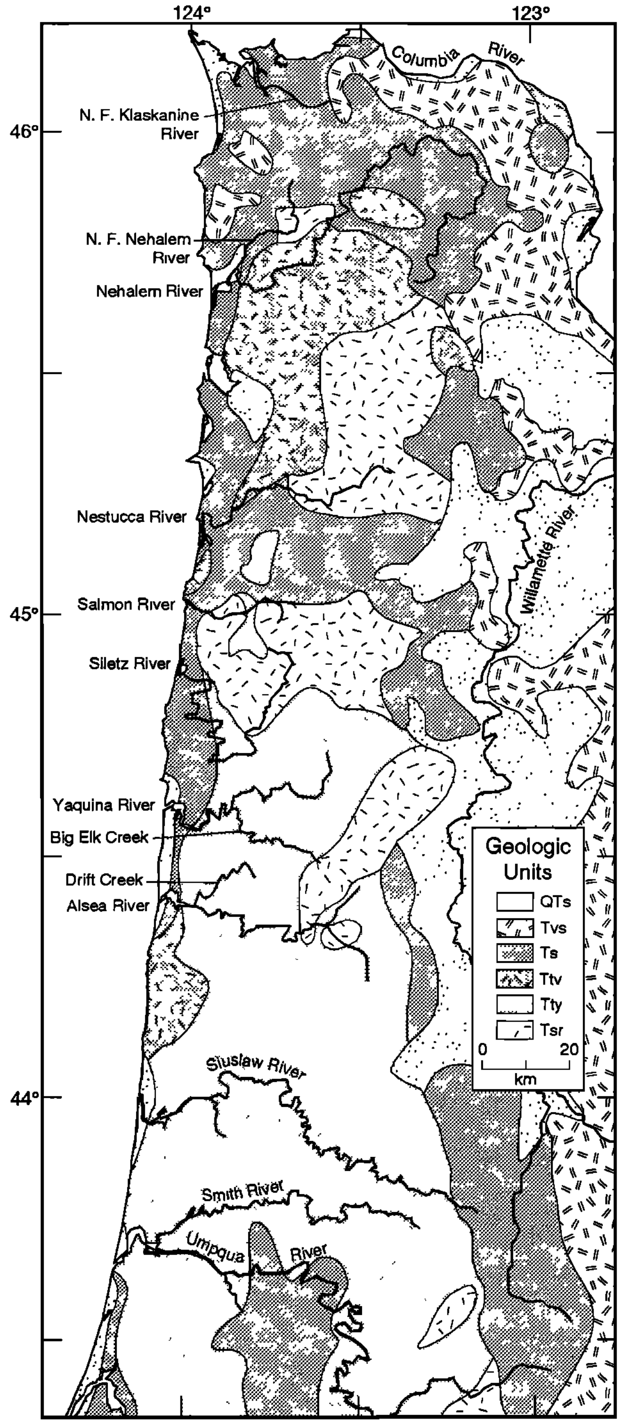

Figure 2. Geologic map of western Oregon, generalized from the digitized version of *Walker and MacLeod* [1991]. Units: QTs, Quaternary and minor late Pliocene sediments; Tvs, Pliocene to Oligocene volcanic and volcaniclastic rocks; unit includes part of the Miocene Columbia River Basalt Group and older volcanic rocks in the Cascade Range; Ts, middle Miocene to late Eocene marine siltstone and sandstone; unit locally includes minor basaltic volcanic rocks; Ttv, late and middle Eocene subarial and submarine basaltic volcanic and volcaniclastic rocks; mostly consists of Tillamook Volcanics; Tty, middle Eocene to Paleocene (?) marine sandstone and siltstone; mostly consists of the Eocene Tyee Formation; Tsr, middle Eocene to Paleocene marine basaltic volcanic and volcaniclastic rocks of the Siletz River Volcanics; unit locally includes mafic intrusive igneous rocks of Eocene and Oligocene age with similar weathering characteristics.

terrace is commonly several hundred meters wide, is physically continuous along most reaches, may be paired or unpaired, and is present in most drainage basins in the Coast Range. *Grabau* [1990], *Personius* [1993], and *Personius et al.* [1993] used numerous radiocarbon ages and the widespread occurrence of this terrace to infer a brief climate-driven episode of increased input of sediment into Coast Range streams during the Pleistocene-Holocene transition. The combination of the uniform age (9-12 ka) and near-ubiquitous presence of the lowest continuous strath terrace makes it an excellent datum for comparing stream incision across the region and thus is a major focus of this work.

Stream Incision in the Coast Range

Modern Incision Processes

The processes that control rates of bedrock stream incision are incompletely understood and difficult to quantify, because process rates are slow and commonly affected by hydrologic and geologic variables [e.g., *Shepherd and Schumm*, 1974; *Gardner*, 1983; *Miller*, 1991; *Wohl et al.*, 1994], However, a recent study of bedrock incision in coastal streams of northern California and south central Oregon [*Seidl and Dietrich*, 1992] used theoretical and field data to infer that incision on main stem streams occurs primarily by knickpoint propagation, by abrasion of the streambed by transported particles, and by dissolution. In this study I assumed that such processes are likely to be responsible for incision in the modern channels of most streams in the central and northern Coast Range.

Controls on Paleoincision

A detailed analysis of the processes responsible for creating the straths that underlie most terraces in the Coast Range is beyond the scope of this paper. However, a general description of the extensive strath underlying the lowest continuous terrace is helpful in supporting the assumptions used to calculate long-term vertical incision rates. Straths underlying the lowest continuous terrace are relatively smooth and slope gently toward the channel and downstream. Cross-valley variations in strath height are difficult to measure because complete exposures of terrace straths rarely are observed. However, examinations of exhumed straths, exposures in tributary stream cuts, and limited auger, trench, and geophysical surveys [*Feiereisen*, 1981; *Grabau*, 1990; *Personius*, 1993; *Personius et al.*, 1993] indicate that cross-valley variations in strath height are usually less than ±1 m. Longitudinal variations in strath surface roughness over distances of less than a few hundred meters are rarely more than about ±50 cm and more commonly are less than ±20 cm.

Most streams in the Coast Range flow across bedrock that has a variety of resistance to erosion, so rock mass strength measurements [*Selby*, 1980; *Moon*, 1984] were made at representative sites to assess the extent of bedrock control on stream incision (Table 1). Most values measured in Eocene sedimentary rocks are 51-70 and are classified as "moderate" strength rocks. In a few places, massive sandstone units reach values in the lower part of the "strong" category (71-90), but most rocks in this category are volcanic or intrusive igneous rocks. Strath heights in the Coast Range are not affected significantly by these variations in bedrock resistance. For instance, strath heights are nearly constant along reaches that flow across interbedded sedimentary and volcanic or intrusive igneous rocks, such as on the Siletz and Nestucca Rivers, or across interbedded massive sandstone and thinner bedded siltstone, such as along the Umpqua River.

In contrast, rock type does appear to have a noticeable influence on stream channel and valley morphology. Harder basalt or massive sandstone units commonly are the locations of entrenched inner channels or form ledges, riffles, and small rapids in the modern channel, and bedrock type appears to control terrace formation by restricting the ability of streams to migrate laterally. On reaches where streams are flowing on hard, dense bedrock, such as massive sandstone and Eocene basalt, streams are restricted to narrow gorges where gradients are higher and extensive terraces have not formed. This response cannot be simply a reflection of insufficient stream power [cf. *Merritts et al.*, 1994], because terraces are commonly present where bedrock changes occur upstream of narrow gorges [*Personius*, 1993]. Such limited bedrock control on gradient is the only consistent morphological response of Coast Range streams to lithology documented by *Rhea* [1993] in a recent study of stream morphology in the region. I conclude that lithologic controls are restricted to modifications to channel morphology and inhibition of lateral incision and extensive terrace formation, rather than to significant variations in the rates of vertical stream incision.

The morphology of the straths underlying the lowest continuous terraces described above clearly indicates that they were formed under hydraulic conditions different from those of the modern stream channels. *Grabau* [1990], *Personius* [1993], and *Personius et al.* [1993] used the age and morphology of these terraces to infer a brief episode of increased sediment input into streams that may have clogged the channels and induced lateral incision over a broad area of the valley bottom about 9-12 ka. A decrease in sediment supply in the Holocene allowed the streams to resume primarily vertical, rather than lateral, incision. Although stream channel morphology during the widespread strath-forming episode is unknown, I found no evidence of major changes in

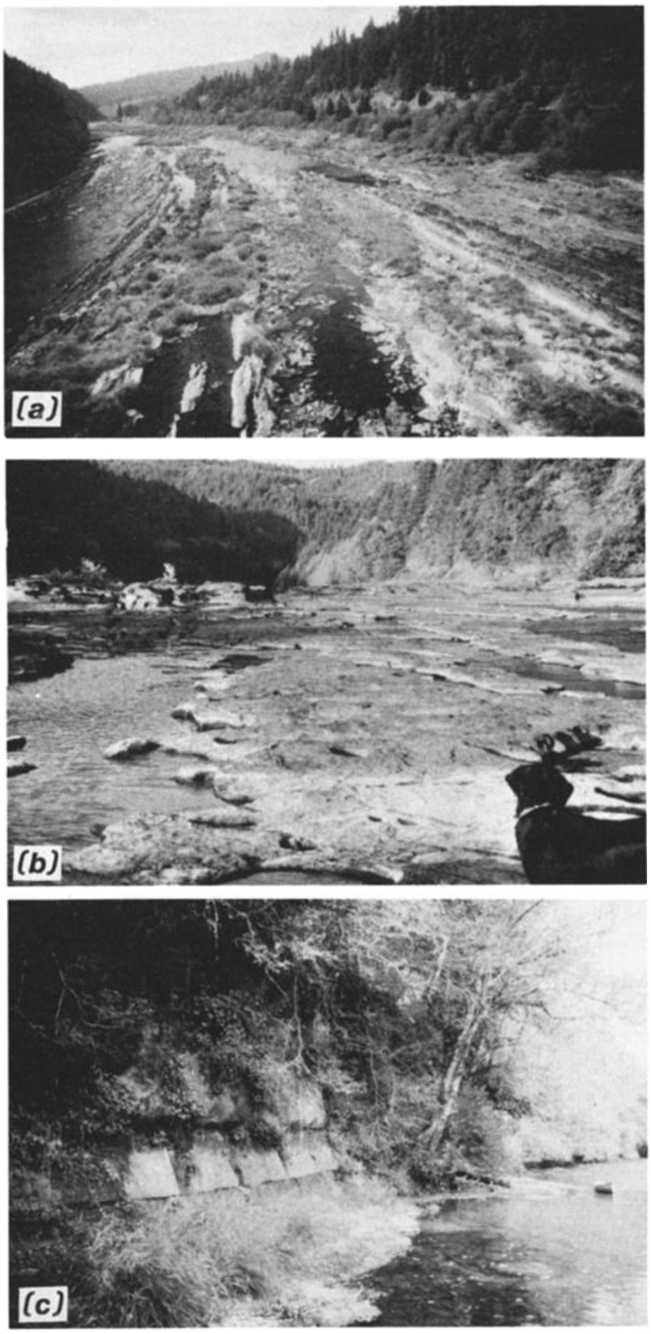

Figure 3. Examples of stream channels in the Oregon Coast Range, photographed in August 1992 during near-historic low water levels: (a) Umpqua River at km 128; note wide, irregular channel bed formed in interbedded sandstone and siltstone (unit Tty); (b) Umpqua River at km 61; note modern abrasion platform, incised channels, and remnants of a 2- to 3-m-high exhumed strath (upper left); bedrock is massive sandstone (unit Tty); (c) Siletz River at km 76; note narrow modern abrasion platform, flanked by strath riser formed in interbedded sandstone and siltstone (unit Tty) that confines the channel at this location. Strath tread (hidden by vegetation) is about 7 m above river level.

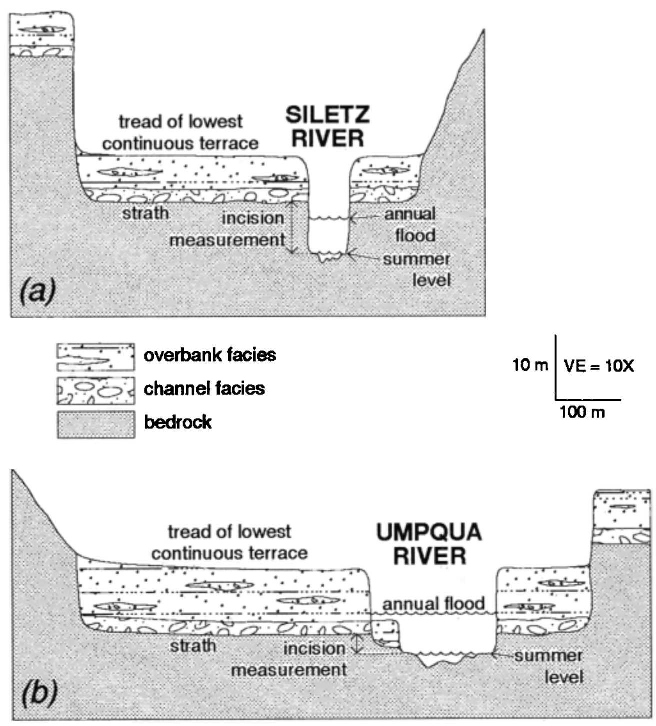

Figure 4. Diagrammatic cross sections of the (a) Siletz and (b) Umpqua Rivers; both sections are located about 80 km upstream from the coast. Note similar stratigraphic sequences, regardless of terrace height above the river, and significantly greater vertical bedrock incision of Siletz River. Radiocarbon dates from near the base of sediments underlying the lowest continuous terrace on both rivers yield calibrated ages of ~9-12 ka (Table 1).

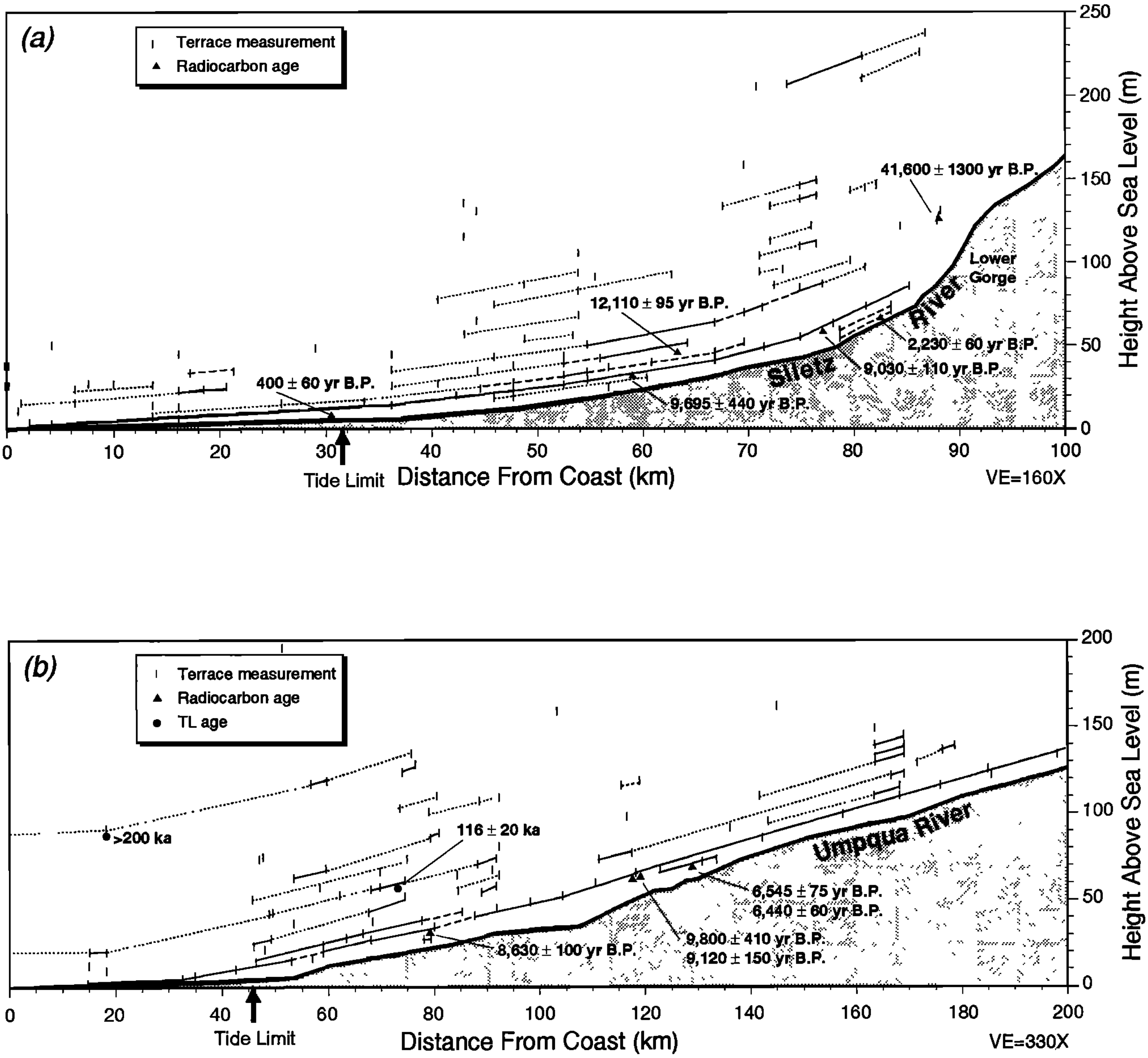

Figure 5. Profiles of fluvial terrace treads on the (a) Siletz and (b) Umpqua Rivers. Line conventions: heavy solid lines are elevations of the river bottom, lighter solid lines connect treads that are physically continuous, dashed lines connect treads that are probably correlative, and dotted lines are speculative correlations. Note the good preservation of a single low terrace on both rivers and increasingly poorer preservation of older fluvial terraces. See Table 1 for additional data on radiocarbon and TL ages.

paleosinuosity or paleogradient that could be responsible for a significant fraction of the poststrath incision. In addition, paleohydrology studies by *Grabau* [1990] indicate that the coarsest grains observed in the terrace sediments along Drift Creek could be transported under flow conditions that occur frequently under the present flow regime, so unusually high discharges were not required for transport of the terrace sediments. Despite the obvious apparent differences in incision behavior, I conclude that the long record of similar strath formation and near-ubiquitous confinement of Coast Range streams in narrow bedrock valleys indicates that extensive straths are caused by processes related to brief, climatically driven episodes of increased sediment supply. Such episodes represent a geomorphically significant but temporally small part of the incision history of most Coast Range streams.

Methods and Assumptions

Measuring Incision and Profile Construction

Measurements of vertical incision are restricted mostly to nontidal stream reaches that lie >20-50 km upstream from the coast. Strath heights were measured with tape, level, or digital altimeter, depending on the height of the strath, from the surface of the strath to the narrow abrasion platforms that flank many Coast Range streams (Figures 3 and 4). Where present, these platforms are within ±20 cm of low water levels and commonly have little alluvium on their surfaces. The heights of these flanking benches apparently are maintained by erosion during high streamflows in the winter months, but processes responsible for their formation are not well understood [e.g., *Wohl*, 1992]. These narrow platforms provide a more uniform datum from which to measure strath heights than do the channel floors, which can be as much as 5 m deep in inner channel reaches. Such wide variations in the depths of inner channels are a common attribute of bedrock streams [e.g., *Bretz*, 1924; *Shepherd and Schumm*, 1974].

Heights and distances of terrace straths and treads are plotted as along-channel profiles (Figures 5 and 6), with distances measured from 1:24,000 scale topographic maps. Correlations of the lower continuous terraces are based on radiocarbon dating and physical continuity [*Personius*, 1993]; correlations of most higher terrace treads are based on physical continuity where possible and are otherwise speculative (Figure 5). With a few exceptions (see section on discussion of results below), older terraces are too poorly preserved and dated to allow any conclusions about the rates or styles of pre-Holocene incision.

Small knickpoints are common in the channels of most Coast Range streams. A few knickpoints on the Umpqua River are 1-2 m high but typically are less than 50 cm high on most streams I studied. Such variations amount to a substantial fraction of the total strath height along some rivers in the Coast Range (i.e., the Umpqua River, Figure 6c) and may be responsible for much of the height variability of straths along streams undergoing low rates of incision. Variations of 1-2

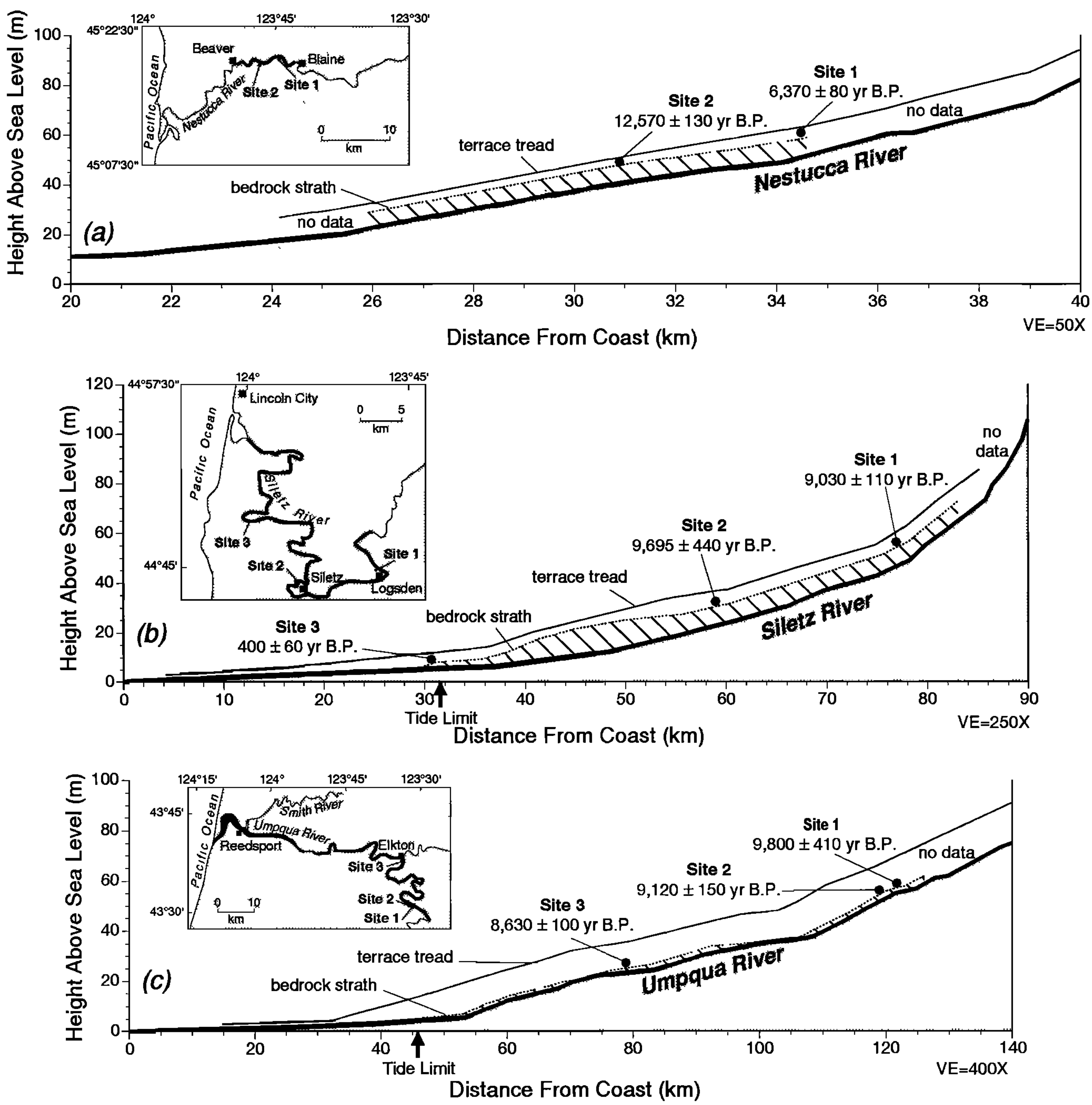

Figure 6. Profiles of lowest continuous terrace treads and underlying bedrock straths (hatched area) along the (a) Nestucca, (b) Siletz, and (c) Umpqua Rivers. Vertical scales are equal, but note differences in vertical exaggeration. Heavier lines on location maps mark reaches shown in the profiles.

m, however, are relatively insignificant to the measurement of higher straths (i.e., the Siletz and Nestucca Rivers, Figures 6a and 6b).

Determining Strath Ages

Bedrock straths cannot be dated directly, but I assume that reasonable minimum ages can be estimated by determining the ages of the overlying cover sediments [*Merritts et al.*, 1994]. The validity of this assumption is difficult to test, because the relationship between strath planation and the overlying sediment is uncertain. However, I interpret the basal channel facies (Figure 4) as lag deposits of coarse bedload sediment that probably were the "tools" used by Coast Range streams to bevel the strath [e.g., *Bull*, 1991]; the overlying overbank deposits stratigraphically represent a return to a period of channel degradation and periodic flooding that has continued to the present. Scattered radiocarbon ages obtained from the overbank deposits [*Personius*, 1993] show that the terrace treads have aggraded throughout the Holocene and thus cannot be used as incision datums. I do not know how long the straths were surfaces of active planation, but radiocarbon ages from the channel facies or the base of the overbank facies should yield reasonable estimates of the times of strath abandonment and thus can be used to calculate incision rates (Table 1).

One of the most serious obstacles to using the age of overlying sediment as a proxy for strath ages is the potential for subsequent strath stripping and reoccupation. Localized examples of strath reoccupation are present on some Coast Range streams, but most are recognizable as lower inset terraces or channel fills that yield younger radiocarbon ages [*Grabau*, 1990; *Personius*, 1993]. Wholesale stripping and reoccupation of the lowest continuous straths are unlikely, given their size (Figure 4) and apparent uniform age.

Most strath ages (Table 1) are estimated by radiocarbon analysis of small (most <5 mm in diameter) detrital charcoal fragments collected from the base of the silty overbank sediment, because charcoal rarely occurs in the underlying gravelly channel facies. No detailed comparison of radiocarbon ages between these two facies is possible, but the lack of a prominent unconformity and multiple ages from a few sites indicate no significant difference in age between the lower part of the overbank facies and the basal channel facies [*Personius*, 1993; *Personius et al.*, 1993]. The detrital nature and small size of the charcoal samples indicate some sample reworking prior to deposition [e.g., *Blong and Gillespie*, 1978], but *Personius* [1993] found that inclusion of small pieces of burned or partially decomposed roots and/or bioturbation of younger charcoal was a more significant problem than inherited age in Coast Range detrital charcoal samples. Thin fluvial sequences are especially susceptible to sample contamination by bioturbation and intrusion of anomalously young organic matter. For example, several sites in the northern Coast Range yielded anomalously young radiocarbon ages from sediments overlying straths that probably correlate with the widespread lowest continuous strath formed about 9-12 ka (Table 1). Such ages yield maximum incision rates. In cases where ages were more than 40% younger than correlations based on terrace heights and sediment weathering characteristics, I also calculated incision rates with ages estimated from nearby dated sites. These estimated rates are poorly constrained.

At sites where radiocarbon control is completely absent, age estimates are based solely on terrace position and weathering characteristics (Table 1). In most cases these sites are correlated with the 9- to 12-ka strath underlying the lowest continuous terrace and are located along tributaries of rivers where the ages of correlative straths are established with radiocarbon dating. Although the incision rates derived from these sites are not supported by radiometric data, the widespread and characteristic occurrence of the lowest continuous terraces in the Coast Range indicates that such correlations are reasonable.

The ages of two older straths along the Umpqua River are estimated by experimental thermoluminescence (TL) dating of fine-grained fluvial sediment [*Personius*, 1993]. Although these two ages yield incision rates that are consistent with rates from younger, radiocarbon-dated sites, other TL ages yielded conflicting results [*Personius*, 1993]. None of the TL ages obtained in this study are corroborated with other numerical dating methods, so these older ages should be viewed with caution. The potential problems with radiocarbon and TL dating discussed above are the most significant sources of potential error in the incision rate calculations (Table 1).

Assumptions

Interpretations of the long-term stream incision data obtained in this study are based on the following assumptions: (1) Coast Range streams have undergone a long history of incision, as evidenced by numerous strath terraces of similar appearance at great heights above the modern stream. (2) Extensive strath terraces represent short (<1-3 kyr) periods of climate-induced aggradation, which briefly interrupt long-term trends of nearly continuous vertical incision. (3) Radiocarbon ages from the channel facies or the base of the overbank facies yield reasonable estimates of the time of strath abandonment and thus can be used to calculate long-term incision rates. (4) Strath-to-strath incision measurements yield the most accurate incision rates, but only a single strath is preserved well enough to allow regional correlations. As a result, narrow benches that lie near low-water (late summer) stream levels are used as proxies for modern straths. (5) Over the long term (tens of thousands of years), powerful streams in the Coast Range incise their channels uniformly along any given reach at about the rate of regional uplift. Exceptions include reaches where major intrinsic hydraulic changes have occurred and times when brief periods of equilibrium or aggradation prevent continuous incision. These latter periods force streams to subsequently "catch up" by incising at faster rates over shorter (less than a few thousand years) time intervals [e.g., *Bull and Knuepfer*, 1987; *Hamblin*, 1994].

Discussion of Results

Spatial and Temporal Incision Patterns

Several patterns of differential incision are apparent in the contoured stream incision data obtained in this study (Figure 7). The most striking difference in regional incision is evident near the latitude of Newport, where a steep gradient divides western Oregon into a region of higher incision rates (~0.6-0.9 mm/yr) in the northern Coast Range and a region of lower rates (~0.1-0.3 mm/yr) in the central Coast Range. Slight north-south variations in incision in the northern Coast Range appear to define two subregions or blocks of higher incision, but incision sites are so sparse in this region

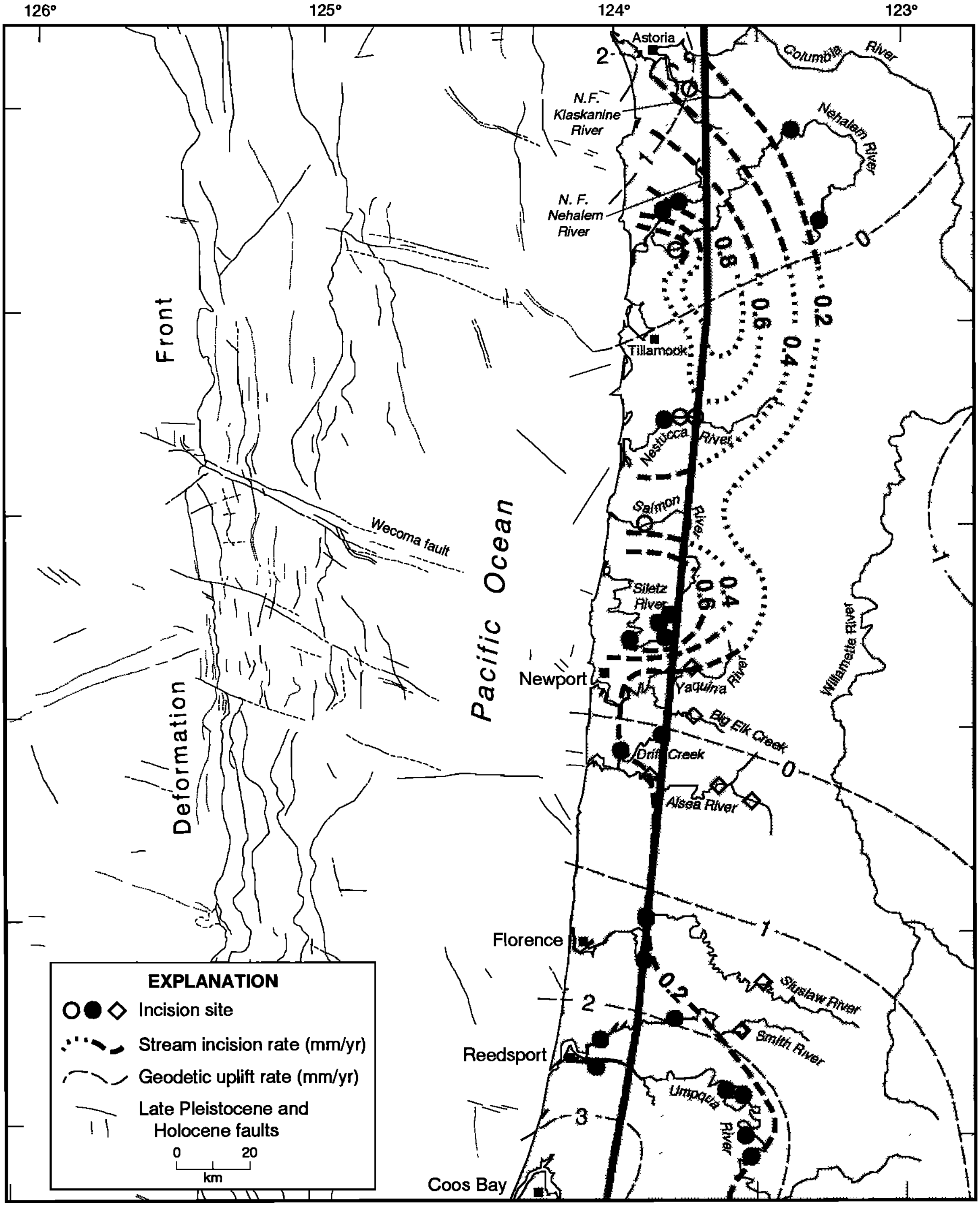

Figure 7. Contoured stream incision rates (heavier lines) and geodetic uplift rates (lighter lines) in the central and northern Oregon Coast Range. Symbols mark locations of incision sites: solid circles, radiocarbon or TL-dated sites; open circles, radiometrically dated sites that yield anomalously young ages and maximum incision rates; and diamonds, undated sites where strath ages are estimated from terrace correlations and sediment weathering characteristics. Dashed incision contours are fitted to rates listed in Table 1. Dotted incision contours are speculative and are based on variations in topography and brief reconnaissance of streams draining the eastern flank of the Coast Range. Geodetic contours are from *Mitchell et al.* [1994]. Offshore structural data are from a digital version of *Goldfinger et al.* [1992b]; most north-trending structures are thrust faults, and most northwest-trending structures are left-lateral strike-slip faults. North-south line through the Coast Range marks location of profiles in Figure 8.

that these small variations could be a reflection of the large errors inherent in the incision rate determinations (Table 1). Incision patterns in northwestern Oregon also may reflect a component of down-to-the-east tilting, consistent with geodetic [*Adams*, 1984; *Mitchell et al.*, 1994] and geomorphic [*Rhea*, 1993] studies in the region. Incision sites are too sparse and rates are too low to show any consistent pattern of tilt in the central Coast Range.

Only limited data are available to enable evaluation of the extent of incision rate variations through time. Incision rates calculated from radiometrically dated sites of various ages were obtained on only two rivers, the Umpqua and Siletz Rivers (Figure 5, Table 1). Along the Umpqua River, incision rates from a ~6.5-kyr terrace (0.2 mm/yr) are similar to rates of 0.2-0.3 mm/yr from the lowest continuous terrace (~9-12 kyr) and older (~125 kyr) terraces at nearby sites. With the exception of one site, incision rates along the Siletz River are consistently ~0.7 mm/yr at sites ranging in age from ~2.2 kyr to ~42 kyr. Such results support my assumptions that Coast Range streams have undergone a long history of incision and that straths underlying the lowest continuous terraces yield reasonable estimates of late Quaternary incision rates. In contrast, examples of varying incision rates such as those on the Nestucca River probably are related to strath reoccupation, rather than nonuniform incision. Although the incision data are sparse, I conclude that averaged over periods of tens of thousands of years, incision rates on any given reach appear to be relatively uniform in the central and northern Coast Range. Such consistency is unusual in comparison with areas such as New Zealand that have undergone more drastic climatic changes in the late Quaternary [cf. *Pillans*, 1986; *Bull and Knuepfer*, 1987].

Climatic Controls on Incision

I interpret the regional nature of the incision patterns apparent in Figure 7 as evidence that local perturbations such as changes in bedrock resistance or channel morphology are not major influences on long-term stream incision in the Coast Range. However, one factor that could control incision on a regional scale is climate, particularly precipitation. Precipitation in the form of rain falls mostly in the winter months, and annual amounts vary significantly in the Coast Range. Rainfall varies both latitudinally and with elevation, with annual amounts ranging from 120-150 cm in the south to more than 300 cm in the highest parts of the range in northern Oregon (Figure 8). Higher rates of stream incision are coincident with higher annual rainfall amounts in northern Oregon, but this apparent correlation does not hold in the central Coast Range, where a large increase in annual rainfall between 43.5°N and 44.5°N is not accompanied by an increase in incision rates. However, the coincidence of sharp increases in incision and rainfall rates near latitude 44.5° could be interpreted as evidence of a threshold phenomenon, where incision

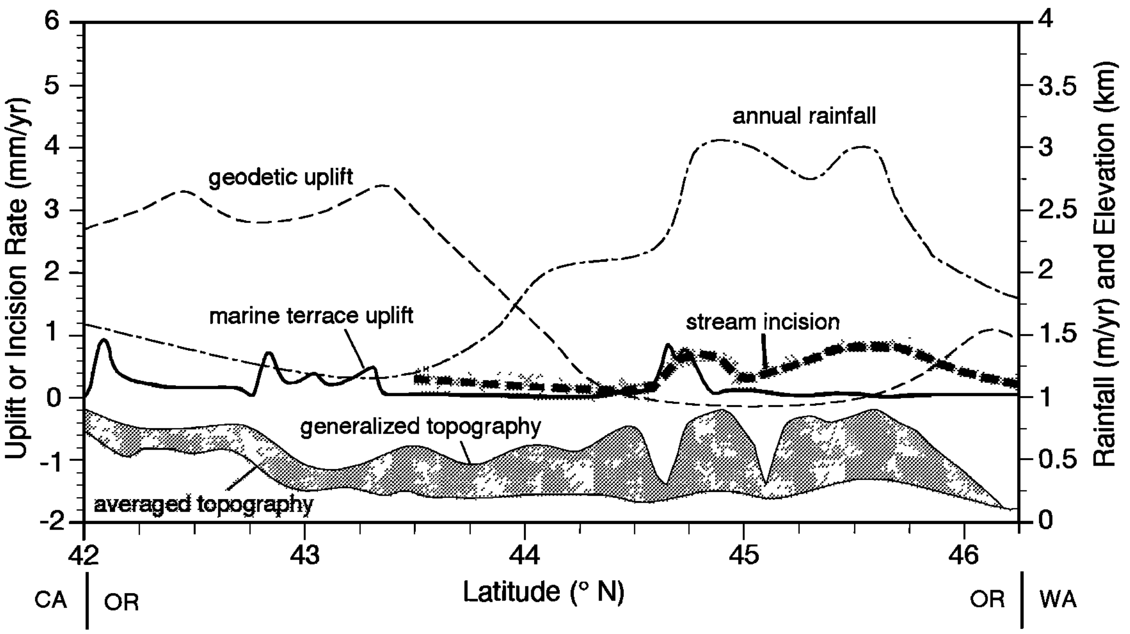

Figure 8. North-south profiles of stream incision, annual rainfall, geodetic and marine terrace uplift, and topography in the Oregon Coast Range. Uplift rates include long-term (~80-125 kyr) rates from marine terraces along the coast and short-term (~40-70 years) rates from releveling and tide-gauge studies. Incision rates profile is shown with ±0.2-mm/yr error limits. The marine terrace data from the California-Oregon border to 45° are generalized from *Kelsey et al.* [1994]; marine terrace rates north of 45° are modified from *West and McCrumb* [1988]. The geodetic data are from *Mitchell et al.* [1994], and the rainfall data are from the National Oceanic and Atmospheric Administration [*Gale Research Company*, 1985]. The incision, geodetic, and rainfall profiles were measured along the profile line shown in Figure 7. The generalized topographic profile was measured on 1:250,000 scale topographic maps along the profile line shown on Figure 7; the averaged topographic profile is from a digital elevation model measured in a 80- to 90-km-wide swath along the length of the Coast Range [*Kelsey et al.*, 1994, Figure 2]. Both topographic profiles yield similar patterns: a region of higher topography in the Klamath Mountains in southern Oregon (42° to 42.75° latitude), a region of lower topography in central Oregon (43° to 44.5° latitude), and a region of higher topography in northern Oregon (44.75° to 45.75° latitude).

increases only when some "threshold" amount of annual rainfall is reached, in this case about 200 cm. Such a relationship might explain the sharp increase in incision rates near latitude 44.5°, but evidence of threshold control is lacking at the northern end of the rainfall high near the Oregon-Washington border (Figure 8). Here the area of high incision rates extends well north of the sharp drop in rainfall, and incision rates decrease gradually toward the Columbia River. Although a threshold effect cannot be ruled out, the apparent correlation of rainfall and incision in some basins is more likely the result of orographic effects on precipitation.

A climatically related control on stream behavior is stream power, which can have a strong influence on rates and patterns of incision [*Merritts et al.*, 1994]. Although I made a few incision measurements along smaller streams (<200-km^2 drainage area), most of the Coast Range data are from trunk streams with drainage basins larger than 500 km^2 (Table 1). In regions of lower and higher incision rates (Figures 7 and 8), all these streams appear to have more than sufficient stream power to actively incise their beds at present and to have created sequences of multiple strath terraces in the past. Such relations indicate that variations in stream power cannot be the sole cause of regional differences in stream incision in the Coast Range. Sufficient stream power also may minimize the influence of variations in relief, such as the higher topography in the northern Coast Range, on rates of regional incision (Figure 8).

Relations Between Incision and Uplift

Given the tectonic setting of the Coast Range, differential tectonic uplift is a likely cause of regional variations in stream incision. Measurements of tectonic (surface) uplift must be corrected for the influence of exhumation or erosional denudation and subsequent isostatic compensation [*England and Molnar*, 1990]. However, *Kelsey et al.* [1994] conclude that erosion has a negligible effect on the heights of geodetic benchmarks and marine terraces in western Oregon, and studies of hillslope colluvial deposits show that rates of denudation may be significantly lower than stream incision and uplift rates in the region. Hillslope erosion studies in the central Coast Range [*Dietrich and Dunne*, 1978; *Reneau and Dietrich*, 1991] and in the Olympic Mountains of western Washington [*Reneau et al.*, 1989] yield similar latest Pleistocene and Holocene hillslope erosion rates of 0.03-0.07 mm/yr. In places these rates are as much as an order of magnitude less than rates of stream incision in the Oregon Coast Range (Table 1) and rates of uplift in the Olympic Mountains [*West and McCrumb*, 1988; *Savage et al.*, 1991; *Brandon and Vance*, 1992; *Thackray and Pazzaglia*, 1994]. These erosion rates imply that the post-latest Pleistocene isostatic adjustments to regional denudation in the Coast Range may be too small to have a significant impact on rates of incision along powerful trunk streams in the region.

An additional potential contribution to surface deformation in the Pacific Northwest is the far-field isostatic response to late Pleistocene deglaciation. Although few detailed studies of postglacial sea level history have been conducted in western Oregon [*Hutchinson*, 1992], recent geophysical modeling of isostatic adjustments to post-14 ka deglaciation of the Cordilleran ice sheet in Washington and southern British Columbia indicates that western Oregon should be currently undergoing ~0.5-1.0 mm/yr of subsidence (sea level rise) in response to collapse of the isostatic forebulge that formed adjacent to the front of the Cordilleran ice complex [*Peltier*, 1986; *Peltier and Tushingham*, 1989]. These rates have not been substantiated, but nearby studies in the Puget Lowland [e.g., *Mathews et al.*, 1970; *Thorson*, 1989] document that rapid isostatic deformation was completed in a few thousand year period following deglaciation. Holocene sea level curves constructed for the Pacific Northwest [*Hutchinson*, 1992] cannot distinguish isostatic effects from eustatic or tectonic controls on sea level, and regional assessments of marine terraces along the Oregon coast do not appear to show evidence of rebound-related deformation [*Mitchell et al.*, 1994]. Geodetic studies in the region differ on the importance of postglacial rebound in determining modern uplift rates [e.g., *Savage et al.*, 1991; *Mitchell et al.*, 1994], so until detailed chronologies of late Quaternary isostatic and tectonic deformation are available, the influence of isostatic adjustments on regional deformation and patterns of stream behavior in the region cannot be adequately accessed.

A comparison between Coast Range stream incision data and better documented uplift data would be very helpful, but unfortunately, there are no uplift data sets that are temporally or spatially comparable. However, three sets of uplift data at different time scales are available: (1) releveling and tide-gauge geodetic data, (2) marine terrace uplift data, and (3) regional topographic data. The most recent geodetic data document land level changes in the last ~40-70 years, both along the Oregon coast and in east-west transects across the Coast Range [*Mitchell et al.*, 1994]. These studies document uplift rates of 0-4 mm/yr in the central and northern Coast Range (Figures 7 and 8). Marine terrace data are restricted to narrow zones along the coast, so they cannot be contoured at the scale of Figure 7. However, several recent studies document uplift in the last ~80-125 kyr along the Oregon coast [*West and McCrumb*, 1988; *Kelsey*, 1990; *McInelly and Kelsey*, 1990; *Muhs et al.*, 1990; *Ticknor*, 1993; *Kelsey and Bockheim*, 1994; *Kelsey et al.*, 1994]. Generally, marine terrace uplift rates along the Oregon coast are low (<0.4 mm/yr), except where folding and faulting have deformed the terraces. Topographic data are shown as two north-south profiles on Figure 8. Broad regional differences in topography may be a reflection of variations in uplift over time periods of millions of years [*Kelsey et al.*, 1994].

Latitudinal variations are evident in the geodetic, marine terrace, topographic, and incision rate profiles shown in Figure 8. In a region of low topography in the central Coast Range (latitude ~43.5°-44.5°), rates of stream incision and marine terrace uplift are nearly indistinguishable despite their spatial and temporal differences. Both incision and marine terrace uplift rates increase near the south flank of a region of higher Coast Range topography near latitude 44.6° and then diverge near latitude 44.75°; recent marine terrace studies in this area [*Ticknor*, 1993; *Kelsey et al.*, 1994] indicate that active structures are in part controlling changes in uplift rates along this part of the Oregon coast. Similar patterns also are obvious in the marine terrace data in southern Oregon, where localized folds and faults are recorded in the marine terrace data between Coos Bay (43.4°) and the California border [*Kelsey*, 1990; *McInelly and Kelsey*, 1990; *Kelsey and Bockheim*, 1994]. The strongest variations in stream incision occur in a broad "saddle" of null geodetic uplift that is roughly coincident with the region of higher topography in the northern

Coast Range. Incision rates remain consistently higher than rates of marine terrace uplift in the saddle between 44.8° and 45.8° and then mimic the trend of decreasing topography northward toward the Columbia River (Figure 8).

Tectonic Implications

Analogies with uplift patterns from other subduction zones and analysis of other neotectonic data in the region indicate that differential incision patterns are related at least in part to cumulative along-strike variations in permanent strain accumulation along the Cascadia subduction zone. In other subduction zones, such along-strike variations are attributed to complex interactions between variations in patterns of earthquake rupture, wedge accretion, the geometry of the subducting plate, rupture segmentation, and deformation on structures in the upper plate and accretionary wedge. Possible influences of these factors on rates of stream incision and uplift in the Cascadia forearc are described below.

Subduction Zone Earthquake Deformation

Late Quaternary uplift records, such as those provided by marine terraces and stream incision in the Cascadia forearc, represent cumulative deformation of the earth surface over many seismic cycles [e.g., *Fitch and Scholz*, 1971]. Unfortunately, earthquake records in most subduction zones are too short to describe deformation over more than one seismic cycle, and models of elastic or viscoelastic behavior commonly cannot account for long-term rates of permanent (unrecovered) deformation [*Thatcher*, 1986]. However, *Thatcher* [1984] used the long earthquake record in Japan to describe several possible causes of cumulative deformation at subduction zones. Nearest the trench, permanent deformation results from "coseismic overshoot," where steepening of the plate boundary and splay faulting induce more coseismic slip than can be recovered in the interseismic period. These regions may correspond in part to localized concentrations of slip or moment such as those modeled by *Yabuki and Matsu'ura* [1992], which are common attributes of earthquake ruptures at many plate boundaries [*Thatcher*, 1990]. If slip or moment concentrations were repeated through many earthquake cycles, then such variations could have caused some patterns of differential uplift and incision in parts of the Cascadia forearc that lie close to the trench. The opposite situation is more likely in areas farther from the trench, where permanent deformation is related to interseismic deformation rates that exceed rates of coseismic recovery [*Thatcher*, 1984]. The sources of such interseismic deformation are unknown, but geologic studies of forearc evolution commonly attribute permanent uplift at convergent margins to deep-seated flow, underplating, or aseismic shortening within the accretionary wedge; such processes may be contributing to uplift of the Olympic Mountains in northern Washington [*Pavlis and Bruhn*, 1983; *Brandon and Calderwood*, 1990] and other parts of the Cascadia forearc.

A few areas undergoing high rates of uplift, such as near Cape Blanco in southern Oregon, may be attributable to "coseismic overshoot." In contrast, if the northern Oregon and Washington coasts are characterized by coseismic subsidence [*Atwater*, 1987, 1992; *Darienzo and Peterson*, 1990], then permanent uplift of much of the onshore Cascadia forearc should be attributable to unrecovered interseismic uplift [e.g., *Kelsey et al.*, 1994]. Consistently low rates of stream incision and marine terrace uplift in the central Coast Range may be indicative of interseismic uplift, but variations in historic uplift raise questions about the rate and direction of interseismic deformation in the northern Coast Range. For instance, delineation of a region of null historic uplift between Newport and Tillamook (Figures 7 and 8) led *Mitchell et al.* [1994] to conclude that areas where rates of long-term uplift exceed rates of historic deformation may be subject to coseismic uplift rather than subsidence during subduction zone events. This idea is intriguing, because it implies that parts of the northern Coast Range may have accumulated permanent strain by "coseismic overshoot," rather than by relatively high rates of interseismic recovery, and calls into question the assertion that coastal Oregon typically undergoes regional coseismic subsidence during subduction zone earthquakes. Although the geodetic record probably is too short to describe accurately the long-term interseismic behavior of Cascadia, the presence of high long-term incision rates in a region of low historic interseismic uplift may mean that parts of northern Oregon are characterized by coseismic uplift during subduction zone earthquakes. This possibility is counter to the prevailing view that the northern Oregon coast has undergone repeated coseismic subsidence [*Darienzo and Peterson*, 1990] and lends support to the suggestions of *Goldfinger et al.* [1992a], *Nelson* [1992], and *Ticknor* [1993] that some subsided marsh sequences along the Oregon coast are formed by movement on individual synclines, rather than in response to regional submergence during subduction zone earthquakes.

Plate Geometry

Along-strike differences in uplift patterns may be attributed to subduction of seamounts, aseismic ridges, or other topographic features on the downgoing plate [e.g., *Gardner et al.*, 1992]. In Cascadia, seamounts or other topographic disruptions are restricted to the southwestern part of the Juan de Fuca plate [*EEZ-SCAN 84 Scientific Staff*, 1988, Figure 1] and are substantially smaller than the regional patterns of stream incision identified in the present study. In addition, I found no evidence of topographic disruptions of the accretionary wedge that are characteristic of subducted seamounts in other subduction zones [e.g., *Yamazaki and Okamura*, 1989].

Variations in the geometry of the upper or lower plates may also control patterns of long-term uplift. For example, much of the anomalous uplift of the Olympic Mountains has been attributed to arching of the Juan de Fuca plate [*Brandon and Calderwood*, 1990]. However, determination of the detailed geometry of the Juan de Fuca plate in Oregon is difficult because of the scarcity of earthquake data on the plate interface [e.g., *Ludwin et al.*, 1991], and most studies using age/subsidence models [*Kelsey et al.*, 1994], or geophysical techniques [e.g., *Rasmussen and Humphreys*, 1988; *Keach et al.*, 1989; *Wannamaker et al.*, 1989] are poorly constrained or too widely spaced to determine slab geometry in detail. An exception may be a recent study by *Trehu et al.* [1994] in which seismic reflection profiling is used to describe variations in thickness of the Siletz terrane, an accreted oceanic terrane that forms the basement of the North American plate under much of the Cascadia forearc. In a north-south velocity profile that lies 30-50 km east of the Coast Range crest, the Siletz terrane thins significantly between 45.25° and 45.75° [*Trehu et al.*, 1994, Figure 2], in a region that roughly coincides with an area of higher incision rates in the northern

Coast Range (Figures 7 and 8). However, no other variations in stream incision appear to correlate with changes in the geometry of the Siletz terrane or plate interface, so until more geophysical data are obtained, speculations about the relationship between patterns of long-term incision/uplift and plate geometry in western Oregon cannot be substantiated.

Rupture Segmentation

Another possible cause of differential patterns of uplift in the Coast Range is segmentation of the Cascadia subduction zone. Numerous geological and geophysical studies have discussed segmentation scenarios in Cascadia. Studies of Cascade Range volcanoes [*Hughes et al.*, 1980; *Weaver and Michaelson*, 1985; *Guffanti and Weaver*, 1988] seismicity [*Weaver and Michaelson*, 1985; *Weaver and Baker*, 1988; *Spence*, 1989], plate geometry [*Weaver and Michaelson*, 1985; *Spence*, 1989], the distribution of prehistoric coseismic subsidence events [*Nelson and Personius*, 1991], variations in historic uplift rates [*Kelsey et al.*, 1994; *Mitchell et al.*, 1994], and the presence of onshore and offshore active faults [*Snavely*, 1987; *Goldfinger et al.*, 1991a, 1992a; *Appelgate et al.*, 1992; *Kelsey et al.*, 1994] have all identified possible segment boundaries in the upper or lower plates between 44° and 46° latitude in western Oregon. A detailed description of these segmentation models is beyond the scope of this paper, but one reasonable explanation for regional, along-strike variations in stream incision is differential cumulative deformation on decoupled segments. The geometry of possible segments and segment boundaries in northern Oregon is open to question, but the coincidence of sharp gradients in stream incision, topography, and marine terrace uplift indicates that the Newport area (Figure 8) is a likely location for a late Quaternary segment boundary in either the Juan de Fuca or North American plates.

Active Structures

Some details of the structural geology of the North American plate and accretionary wedge in western Oregon indicate that active folds and faults may also play a role in patterns of differential incision. For example, recent studies have identified several active faults in the vicinity of Newport. The best studied of these structures, the Wecoma fault, splays into several strands at its eastern end and may project into the Oregon coast 15-20 km north of Newport [*Goldfinger et al.*, 1991a, b, 1992a, b; *Appelgate et al.*, 1992; *Kelsey et al.*, 1994]. *Snavely et al.* [1976a, b] also map northwest trending faults in bedrock north of Newport that may correlate with offshore faults [*Snavely*, 1987, p. 319], and *Ticknor* [1993] and *Kelsey et al.* [1994] map the Yaquina Bay fault, which offsets marine terrace platforms just south of Newport. With the exception of an onshore splay of the Wecoma fault discussed by *Kelsey et al.* [1994], nearly all of these faults have down-to-the-south displacements and lie between the higher incision rates documented along the Siletz River and lower rates to the south (Figures 7 and 8). Although there is no evidence that these faults offset Quaternary deposits inland from the coast, their displacement directions are consistent with changes in late Quaternary incision rates in this part of the Coast Range. Other large-scale, northwest trending strike-slip faults mapped offshore [*Goldfinger et al.*, 1992a, b] apparently project onshore and offset Quaternary deposits along the coast near Tillamook [*Wells et al.*, 1992], but the stream incision data are constrained too poorly in this area to support speculations about possible correlation of incision patterns and active structures.

Well-documented evidence of rotation of early Tertiary volcanic rocks in the Coast Range [e.g., *Simpson and Cox*, 1977] also supports an upper plate structural origin for some incision patterns. Paleomagnetic data [e.g., *Wells and Heller*, 1988] are used in a recent model [*Wells and Weaver*, 1992] to describe the Coast Range as a series of clockwise rotating crustal blocks formed as a result of dextral shear and north-south shortening in response to oblique subduction. Some recently documented faults offshore of coastal Oregon may be secondary shears within the dextral shear couple driven by the oblique convergence of the Juan de Fuca and North American plates [*Goldfinger et al.*, 1992a]. These faults, which have a thrust component onshore [*Wells et al.*, 1992], and other related structures may form the active boundaries of the rotating blocks [*Goldfinger et al.*, 1992a; *Wells and Weaver*, 1992]. A similar model based on seismic reflection and other geophysical data in the Puget Lowland [e.g., *Johnson et al.*, 1994; *Pratt et al.*, 1994] envisages the Coast Ranges as a series of thrust sheets whose master structures sole into a decollement at the top of the subducting Juan de Fuca plate [*Unruh et al.*, 1994; T. L. Pratt, written communication, 1993]. Changes in incision rates near Newport and possibly Tillamook (Figure 7) are coincident with these proposed block boundary structures.

The relations described above may indicate that some incision patterns are caused by cumulative late Quaternary deformation on active folds and faults in the North American plate and accretionary wedge. Such deformation on active structures may be the most likely cause of uplift variations documented in marine terrace sequences in Cascadia and elsewhere in the Pacific rim [*Berryman et al.*, 1989; *Muhs et al.*, 1990; *Kelsey et al.*, 1994]. However, given the coincidence of active upper plate structures with known segment boundaries in other subduction zones, the occurrence of active structures near Newport also may support the presence of a segment boundary in this area [*Ticknor*, 1993; *Kelsey et al.*, 1994]. Thus the incision patterns presented here may be consistent with deformation on active structures and/or segmentation of either the North American or Juan de Fuca plates. However, the incision data presented herein are not precise enough to determine the relative importance of these possible sources of deformation.

Conclusion

Radiometric ages and the heights of fluvial strath terraces are used to calculate long-term bedrock stream incision rates in a wide area of the Oregon Coast Range. Several lines of evidence indicate that broad variations in stream incision are caused by cumulative differential uplift along the Cascadia subduction zone, but bedrock and climatic controls and isostatic adjustments prevent calculation of absolute rates of surface uplift. Significant differences in rates are useful in determining patterns of differential uplift on a regional basis and are helpful in describing the late Quaternary tectonic setting of the onshore part of the Cascadia forearc.

Near the latitude of Newport, changes in regional incision divide the Coast Range into a region of higher incision rates to the north and a region of lower incision rates to the south. Comparisons with similar uplift patterns elsewhere and with other neotectonic data in the region indicate that differential patterns of incision probably are caused by along-strike variations in permanent strain accumulation along the Cascadia subduction zone. The causes of these along-strike variations are unknown, but they may be related to variations in seismic moment release during individual subduction zone earthquakes, to variations in plate geometry or rates of wedge accretion, to segmentation of earthquake ruptures, and/or to deformation on active structures in the North American plate and accretionary wedge. The coincidence of steep incision gradients, abrupt changes in marine terrace uplift rates, and active faults that offset marine terraces indicates that the region near Newport may mark a persistent segment boundary in the Cascadia subduction zone.

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