

Great Cascadia earthquakes and tsunamis of the past 6700 years, Coquille River estuary, southern coastal Oregon

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ABSTRACT

Cascadia subduction zone earthquakes dropped tidal marshes and low-lying forests to tidal flat elevations 12 times in the last 6700 cal yr B.P. at the Coquille River estuary in southwestern Oregon. The youngest buried soil, preserved in tidal marsh deposits near the estuary mouth, records the A.D. 1700 earthquake that ruptured the entire Cascadia margin. Eleven other buried marsh and upland soils found in tributary valleys of the estuary provide repeated evidence for rapid, lasting relative sea-level rise interpreted as coseismic subsidence. Additional stratigraphic criteria supporting a coseismic origin for soil burial include: lateral soil correlation over hundreds of meters, fossil diatom assemblages that indicate a maximum of 1.2–3.0 m of submergence, and sand deposits overlying buried soils consistent with earthquake-induced tsunamis that traveled 10 km up the estuary.

Twelve earthquakes occurred in the last 6500–6720 cal yr B.P., recurring on average every 570–590 yr. Intervals between earthquakes varied from a few hundred years to over 1000. Comparisons of the Coquille record to earthquake histories from adjacent sites in Oregon, southwestern Washington, and northwestern California suggest that at least two earthquakes in the last 4000 yr did not rupture the entire length of the subduction zone. An earthquake 760–1140 cal yr B.P. in southwestern Washington may have ruptured as far south as Coos Bay but probably stopped before it reached the Co-

quille estuary because no buried soil records the event, and tidal marsh conditions were set to record an earthquake. An earthquake limited to a southern segment of the Cascadia margin 1940–2130 cal yr B.P. probably did not rupture north of the Coquille estuary.

An analysis of relative sea-level histories from either side of the Coquille fault failed to find conclusive evidence for late Holocene vertical deformation. However, we cannot preclude recent upper-plate faulting. If the fault is active, as geomorphic features suggest, then constraints on the highest possible elevation of mean tide level allow a maximum vertical slip rate of 0.2–0.4 mm/yr in the past 6200–6310 cal yr B.P.

Keywords: Cascadia subduction zone, paleoseismology, plate boundaries, sea-level changes, subsidence, tsunamis.

INTRODUCTION

Despite combined geological and historical evidence for a M_w 9 Cascadia earthquake on 26 January A.D. 1700 (Satake et al., 1996), uncertainty remains regarding alternative rupture modes of the Cascadia subduction zone and the paleoseismicity of upper-plate structures above the locked plate interface. For instance, do earthquakes that rupture the Cascadia plate boundary always involve the entire length of the margin as in A.D. 1700 or are some earthquakes limited to segments of the subduction zone? In addition to uncertainties about the size and recurrence interval of plate-interface events, questions regarding the role of upper-plate structures in the Cascadia fore arc need further examination to improve prob-

abilistic seismic hazard models for the Pacific northwest. For example, do stratigraphic records of buried soils in coastal wetlands reflect deformation across shallow crustal faults in the North America plate (e.g., Kelsey et al., 2002; McNeil et al., 1998)? Do these faults rupture in concert with plate-interface earthquakes? Accurate earthquake chronologies for events prior to the A.D. 1700 earthquake are crucial to resolving these uncertainties.

The longest (>4000 yr) Cascadia earthquake records come from stratigraphic studies of coastal estuaries in southwestern Washington (Atwater and Hemphill-Haley, 1997) and southwestern Oregon (Kelsey et al., 2002; Witter, 1999) and from records of turbidites in submarine canyons offshore Oregon and Washington (Adams, 1990; Goldfinger et al., 2001) probably triggered by strong shaking during subduction zone events. Marsh stratigraphic records and radiocarbon analyses of plants rooted in the buried soil from A.D. 1700 at multiple estuaries demonstrate that the time of coseismic subsidence cannot be resolved more precisely than several decades (Nelson et al., 1995) except where they can be resolved to the nine months between two successive growing seasons by ring-width pattern matching along 90 km of the southern Washington coast (Yamaguchi et al., 1997). The ages of older prehistoric earthquakes are less precisely known. However, if separate plate-boundary earthquakes have occurred on individual segments of the margin more than several decades to 100 years apart, then radiocarbon age estimates for some coseismically buried soils along different segments of the margin should not overlap. Alternatively, buried marsh soils with unique ages may

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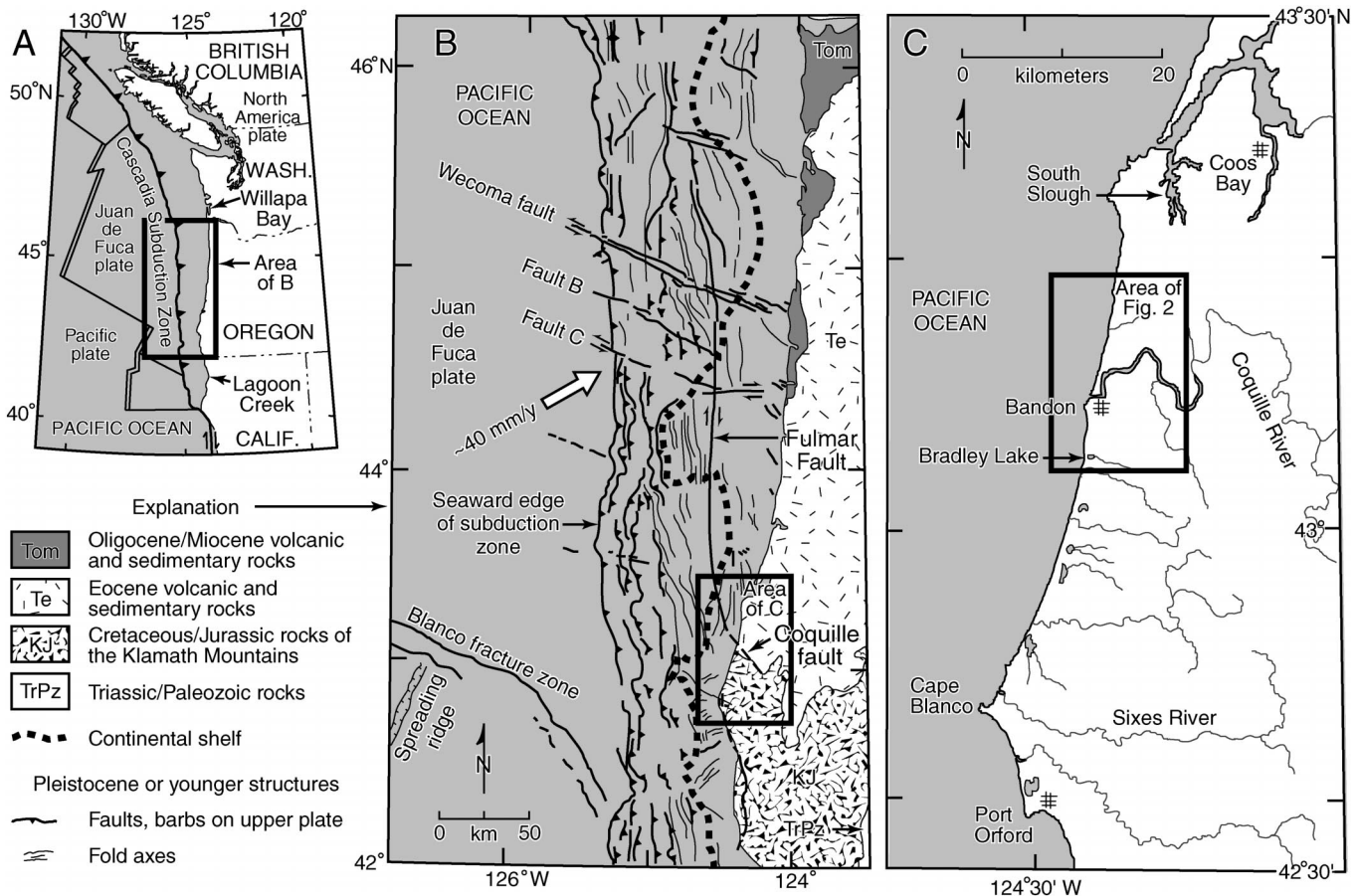


Figure 1. (A) Tectonic setting of Cascadia subduction zone. (B) Tectonic map of ocean floor and generalized geologic map of western Oregon. Offshore data from Snively (1992) and Goldfinger et al. (1992); onshore data from Walker and MacLeod (1991). Juan de Fuca plate is obliquely subducting beneath North America plate at ~ 40 mm/yr. (C) Location map of Coquille River estuary in southwestern Oregon ~ 25 km south of South Slough estuary at Coos Bay.

record subsidence due to upper-plate earthquakes.

The Coquille River estuary in southern Oregon (Fig. 1) provides a 6700 yr record of Cascadia subduction zone earthquakes and tsunamis. We present stratigraphic evidence for repeated coseismic subsidence of intertidal marshes and attribute multiple fining upward sandy deposits that abruptly bury fossil marshes to tsunamis generated by Cascadia earthquakes. We also compare the Coquille earthquake chronology to other >4000 -yr-long earthquake histories on the Cascadia margin. Finally, using relative sea-level data, we evaluate evidence for late Holocene deformation across the Coquille fault.

TECTONIC SETTING

The Coquille River estuary overlies the locked plate interface 70 km east of the seaward edge of the Cascadia subduction zone (Fig. 1). In adjacent coastal hills surrounding

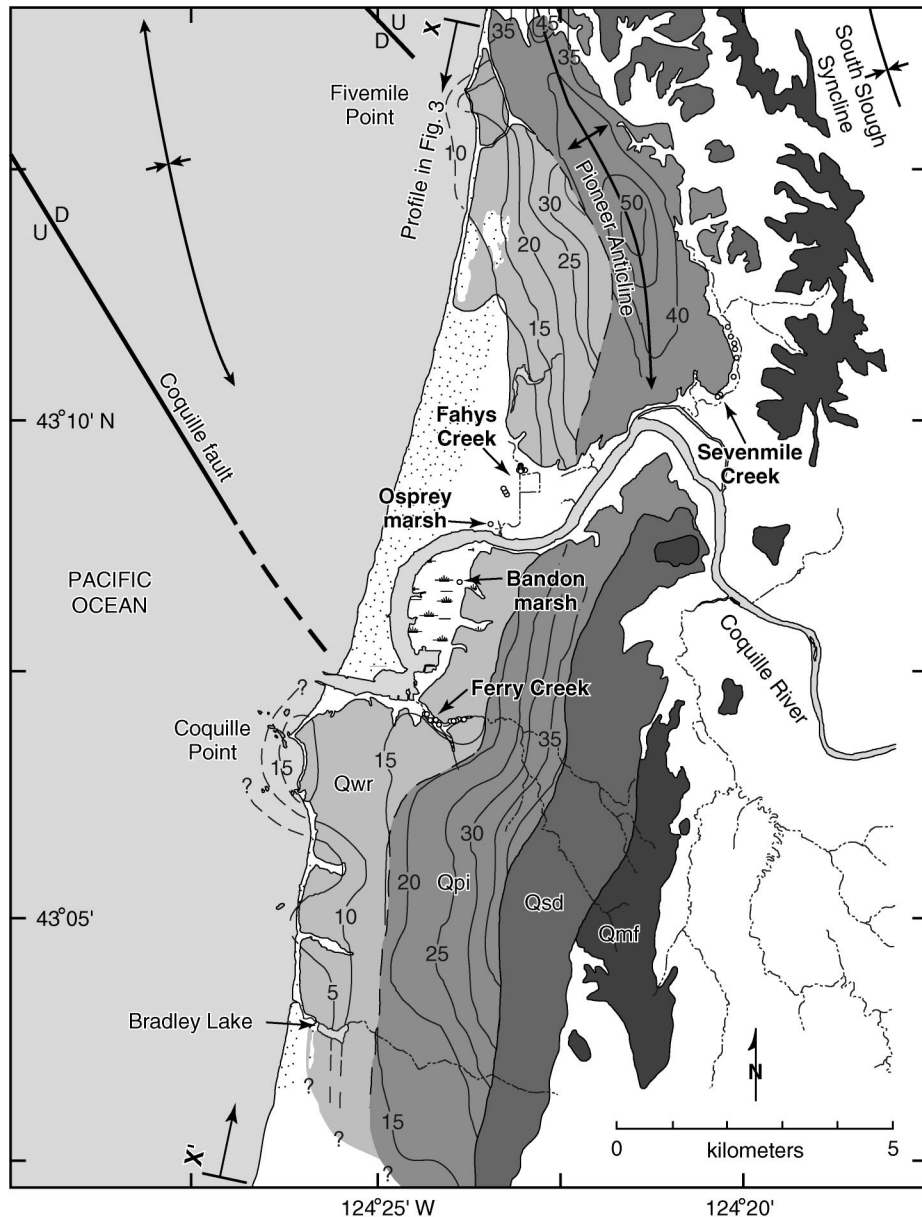
the estuary, a flight of four late Pleistocene marine terraces (Fig. 2) are locally faulted and deformed by north-northwest-trending open folds (McInelly and Kelsey, 1990). These upper-plate structures are part of the fold-and-thrust belt of the accretionary prism that encroaches onshore at the latitude of Coos Bay, 25 km north of the Coquille estuary (Goldfinger et al., 1992).

The Fulmar fault deforms late Neogene and Quaternary deposits within the accretionary wedge offshore Oregon (Clarke et al., 1985; Goldfinger et al., 1992; Snively, 1987; Tréhu et al., 1995) (Fig. 1B) and projects onshore near the Coquille estuary (Snively, 1987). The onshore projection of the fault coincides with the tectonostratigraphic boundary that juxtaposes Mesozoic rocks to the south against accreted Tertiary marine sediments and volcanic rocks to the north (Beaulieu and Hughes, 1975) (Fig. 1B). Dextral displacement of at least 200 km (Snively, 1987) indicates that the Fulmar fault may act to decouple upper-

plate deformation onshore from deformation of the offshore accretionary prism. Disruption of young seafloor sediment suggests that the Fulmar fault may be active (Tréhu et al., 1995).

McInelly and Kelsey (1990) infer that the Coquille fault is the southeastward expression of the Fulmar fault (Figs. 1B and 2) and that the fault offsets an 80,000-yr-old marine terrace at Coquille Point by ~ 50 m (Fig. 3). Maximum long-term (late Pleistocene) uplift rates at the latitude of the Coquille estuary range from 0.3–0.6 m/k.y. and may reach up to 0.8 m/k.y. on the upthrown (southern) block of the Coquille fault (McInelly and Kelsey, 1990).

Contemporary uplift rates at the latitude of the Coquille estuary, derived from leveling surveys and tide-gage records, exceed 4 mm/yr and reflect interseismic strain accumulation above the locked portion of the Cascadia subduction zone (Mitchell et al., 1994). The rapid interseismic uplift rate (>4 mm/yr) near the



Late Pleistocene marine terraces

- Qwr** Whiskey Run marine terrace
~80,000 years old
- Qpi** Pioneer marine terrace
~105,000 years old
- Qsd** Seven Devils marine terrace
~125,000 years old
- Qmf** Metcalf marine terrace
≥200,000 years old

Contour lines (5-m interval) map the deformed Whiskey Run and Pioneer wave-cut platforms (after McInelly and Kelsey, 1990)

- Stratigraphic core sites shown in Figs. 5, 7, and 8
- Fold axes
- Fault, dashed where approximate

Figure 2. Coquille River estuary shown in context with deformed late Pleistocene marine terraces and associated wave-cut platforms (McInelly and Kelsey, 1990). Stratigraphic investigations were carried out in tributary valleys and at Bandon and Osprey marshes. Near Fivemile Point, Whiskey Run platform tilts southwest on down-thrown side of Coquille fault. Platform is below sea level where Coquille fault projects onshore. To south, on up-thrown side of fault, platform reaches a maximum elevation of 18 m at Coquille Point and then descends southward, dropping below sea level near latitude of Bradley Lake. Coast-parallel profile depicts deformation of wave-cut platform in Figure 3. Three folds to east of Coquille fault are expressions of fold-and-thrust belt of Cascadia forearc that comes onshore at latitude of Coos Bay. X and X indicate coast-parallel profile shown on Figure 3. D—down-thrown fault block; U—up-thrown fault block.

Coquille fault exceeds the long-term permanent uplift rate of marine terrace platforms (0.3–0.8 m/k.y.) by five- to 13-fold. Along the coast of Oregon, local maxima in present-day uplift rates correspond to regions with higher long-term uplift rates and occur near late Pleistocene upper-plate structures such as the Coquille fault (Kelsey et al., 1994).

APPROACH AND METHODS

Tributary valleys of the lower Coquille River, formerly distal arms of a once broader estuary, preserve the longest record of buried marsh soils. To evaluate whether the buried soils and associated sand deposits record late Holocene Cascadia earthquakes and tsunamis, we employed three methods: detailed lithostratigraphic description of tidal marsh deposits, radiocarbon age analyses of detrital macrofossils, and fossil diatom analyses to evaluate paleoenvironmental changes (Hemphill-Haley, 1995a). Our approach examines five criteria proposed by Nelson et al. (1996b) to test for regional coseismic subsidence of tidal marsh deposits. Evaluating the activity of the Coquille fault utilized biostratigraphic and radiocarbon data to construct relative sea-level histories and sediment aggradation rates for two sites that bracket the fault.

We compiled lithostratigraphic descriptions of 67, 2.5-cm-diameter gouge cores from localities along three tributary creeks—18 cores at Sevenmile Creek, 21 cores at Fahys Creek, and 28 cores at Ferry Creek (Fig. 2). An additional 17, 7.5-cm-diameter vibracores (seven at Sevenmile Creek, four at Fahys Creek, and six at Ferry Creek) provided samples for diatom and radiocarbon analyses. Minimal compaction in the vibracores (typically less than 10%) was determined by comparison to depths of stratigraphic contacts in adjacent uncompacted gouge cores.

The cores consisted of stratigraphic sequences of interbedded tidal-marsh peat, forested upland soils, and intertidal mud. The term “soil” refers to laterally continuous, dark organic-rich horizons and oxidized, mineral-rich horizons with incipient granular structure. The organic content of marsh deposits ranges from peat or mucky peat with >40% loss on ignition (LOI) to peaty mud with <40% LOI. “Mud” refers to inorganic, massive silty clay to silty clay loam. A typical burial sequence consists of reduced olive gray mud (Munsell color 5Y 3/1) that grades upward (gradational contact >10 mm) into a dark-reddish, brown-to-black peaty soil (Munsell colors 2.5 Y–10YR 3/2). The soil terminates upward at a sharp (<3 mm) overlying contact with mul-

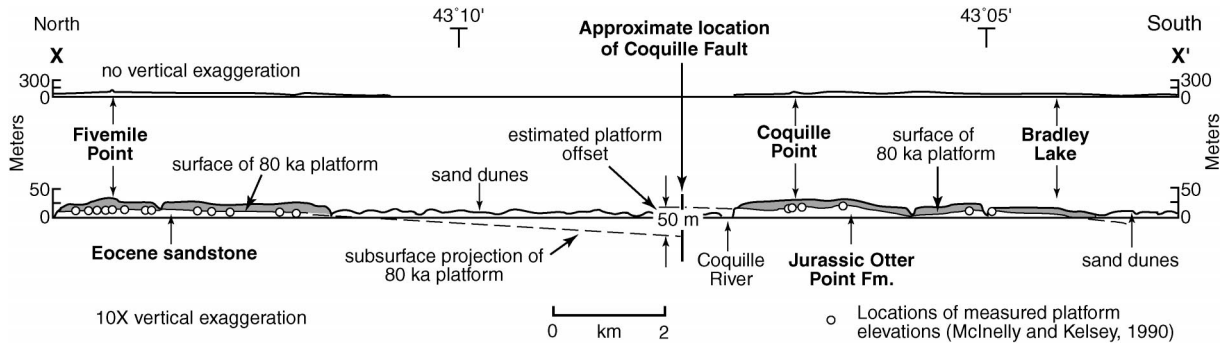


Figure 3. Coast-parallel profile (located on Fig. 2) showing variation in elevation of 80,000-yr-old Whisky Run wave-cut platform (McInelly and Kelsey, 1990). Southward-tilting platform near Fivemile Point is projected to inferred location of Coquille fault. Similarly, tilt of emergent platform at Coquille Point is projected northward to fault, where inferred platform offset is ~50 m. Offset may be less but is at least 18 m, highest elevation of platform at Coquille Point on up-thrown side of fault.

tiple muddy-sand to sandy-mud beds that gradually fine upward to mud similar to the deposits at the base of the sequence.

Accelerator mass spectrometry (AMS) analyses of delicate detrital material, typically conifer needles and cones, moss, deciduous leaves, and seeds of marsh plants, provide maximum limiting radiocarbon ages for the time of soil burial (Table 1). To reduce the reported uncertainty of conventional radiocarbon age estimates, we combined the ages of samples that originated from the same stratigraphic position that were statistically indistinguishable at the 95% confidence interval based on a chi-squared distribution (Ward and Wilson, 1978). Such ages were combined into one weighted-mean age (Table 1). Lab-reported ages and weighted-mean ages reflect radiocarbon years before present (^{14}C cal yr B.P.) where present is equivalent to A.D. 1950. Weighted-mean ages were calibrated with CALIB 4.3 software developed by Stuiver and Reimer (1993) using the INTCAL98 calibration data set of Stuiver et al. (1998). An interlaboratory error multiplier equal to one was used in the calibration procedure. Calibrated ages reported in Table 1 and in the text refer to calibrated (solar) years before A.D. 1950 (cal yr B.P.).

We assigned Arabic numbers to each age-distinguishable buried soil; soil 1 designates the youngest and soil 12 the oldest. Within one locality, we used lithostratigraphic characteristics, lateral continuity, and depth to correlate buried soils among cores. To correlate buried soils between the three localities, we relied on stratigraphic relationships among buried soil sequences and on statistically equivalent radiocarbon ages.

Diatom analyses were used to estimate the amount of submergence associated with soil

burial and to reconstruct relative sea-level histories. Studies of diatoms, foraminifers, and vegetation in Pacific Coast estuaries of the western United States recognize a three-tiered intertidal zonation including tidal flat, low marsh, and high marsh (Frenkel et al., 1981; Hemphill-Haley, 1995a; Jennings and Nelson, 1992; Nelson and Kashima, 1993). The marsh-upland transition zone is characterized by an absence of tidal marsh diatom species in upland soils (Hemphill-Haley, 1995b). The elevation ranges of the zones are controlled by the 2.14 m diurnal range of tide at the Coquille estuary (National Ocean Service, 1992) and estimated from modern ecological transects across southern Oregon tidal marshes, including the Bandon marsh, conducted by Nelson and Kashima (1993) (Fig. 4). Diatom assemblages were analyzed above and below the upper contact of each buried soil. The paleoecology of each sample was determined from qualitative analyses that recognized diatom assemblages from one of the three intertidal zones or the marsh-upland transition subzone following the methodology of Hemphill-Haley (1995a, b). The results of the diatom analyses are included in the Data Repository.¹

To estimate the amount of soil submergence, we subtract the elevation range of the intertidal or marsh-upland transition zone of the soil from the intertidal zone of mud that buries the soil, as determined by diatom analyses. In southern Oregon tidal marshes, the elevation of each zone boundary is diffuse over 20–30 cm, reflecting the variation in di-

¹GSA Data Repository item 2003140, diatom analyses for Sevenmile Creek core I and Ferry Creek cores H and S, is available on the Web at <http://www.geosociety.org/pubs/ft2003.htm>. Requests may also be sent to editing@geosociety.org.

urnal tides and other environmental factors within the marsh (Nelson and Kashima, 1993). We conservatively adopt an uncertainty range of 20–30 cm in the elevation of boundaries within the intertidal zone and 20 cm in the elevation of the boundary between the marsh-upland transition and the high marsh (Fig. 4). The estimated ranges of soil submergence determined by this method incorporate the uncertainty in elevation ranges due to overlapping intertidal zone boundaries.

EVIDENCE FOR THE A.D. 1700 EARTHQUAKE

A large tsunami recorded in Japanese archives was generated by a M_w 9 Cascadia earthquake on 26 January A.D. 1700 (Satake et al., 1996). Tree-ring dating of western red cedar snags, killed by coseismic subsidence in northwestern Oregon and southwestern Washington, confirms that the time of the most recent Cascadia earthquake was between the growing seasons of A.D. 1699 and 1700 (Yamaguchi et al., 1997). Sitka spruce trees that survived the earthquake showed signs of trauma in annular growth rings from the first years of the 1700s (Jacoby et al., 1997). Evidence for the A.D. 1700 earthquake and a tsunami occurs at several estuaries in southwestern Oregon including the Coquille River (Nelson 1992a, b), the Sixes River (Kelsey et al., 1998), and Euchre Creek (Witter et al., 2001).

We observed stratigraphic evidence for coseismic subsidence and tsunami inundation resulting from the most recent Cascadia earthquake in shallow (<1.5 m) cores at the Bandon and Osprey marshes (Fig. 2). Based on observations at the Bandon and Osprey marshes discussed below and observations of Nelson et al. (1995), we infer that the youngest buried tidal-marsh soil that is extensively

TABLE 1. RADIOCARBON DATA FOR DETRITAL PLANT MACROFOSSILS FROM THE COQUILLE ESTUARY, OREGON

Buried soil no. [†]	Core number [‡]	Sample interval (cm) [§]	Material dated	Lab number [#]	$\delta^{13}\text{C}$ (‰)	Lab reported age (¹⁴ C yr B.P., 1 σ) ^{††}	Weighted mean age (¹⁴ C yr B.P., 1 σ) ^{†††}	Calibrated age (cal yr B.P.) ^{§§}
1	OSP-96-A	(-) 0-2	Conifer needles	GX22597	-28	170 ± 50		
1	OC87-04	0	Leaf bases of <i>Carex lynbyei</i>	8 GX ages	-26.3	###	192 ± 17 ^{###}	0-290
1	OC87-04	0	Spruce root	BETA23193	###	290 ± 70 ^{##}		
1	OC87-04	0	Leaf bases of <i>Carex lynbyei</i>	AA4423	###	292 ± 61 ^{##}		
2	FC-98-O	(-) 0-4	Spruce needles	GX24244	-28.8	1340 ± 50		1170-1340
3 (?)	SM-97-M	0-3	Seeds	GX23843	-30	1540 ± 50 ^{†††}	1705 ± 37	1530-1700
3	FC-97-G	(-) 0-3	Seeds	GX23844	-29.2	1700 ± 50 ^{†††}		
3	FC-98-O	(-) 0-4	Spruce needles	GX24245	-27.9	1710 ± 50 ^{†††}		
4 (?)	BA 97 S	0-5	Hemlock needles	GX24171	-28.1	1940 ± 40		
4	FC-97-G	0-3	Seeds	GX23845	-27.5	2290 ± 50		2150-2360
5	FC-97-K	(-) 3- (+) 3	Seeds, conifer needle	GX23846	-26.4	2840 ± 50 ^{†††}	2922 ± 25	2960-3200
5	SM-97-A	0-3	Pine needles, seeds	GX23792	-28.4	2890 ± 40 ^{†††}		
5	BA 97 S	3-6	Spruce needles	GX24172	-28.8	2970 ± 50 ^{†††}		
5	BA-97-H	(-) 0-3	Spruce needles	GX24238	-28.5	3010 ± 50 ^{†††}		
6	BA-96-G	0-2	Moss	GX22596	-30.1	3200 ± 50 ^{†††}	3252 ± 22	3400-3550
6	SM-97-M	0-2	Seeds, pine and cedar leaves	GX23793	-28.1	3230 ± 40 ^{†††}		
6	SM-97-I	0-4	Conifer needles, seeds	GX23600	-28.6	3240 ± 50 ^{†††}		
6	FC-97-G	0-12	Seeds, conifer needle	GX23847	-27.9	3250 ± 50 ^{†††}		
6	BA 97 S	(-) 0-2	Spruce needles	GX24173	-27.9	3350 ± 50 ^{†††}		
6 (?)	BA-96-H	0-3	Cone fragment	GX22594	-25.4	3460 ± 50		
7	SM-97-M	0-2	Pine needles	GX23794	-29.6	3650 ± 50 ^{†††}	3660 ± 36	3870-4090
7	SM-97-I	0-2	Fir needles, cone fragments	GX23601	-25.8	3670 ± 50 ^{†††}		
8	SM-97-M	0-3	Moss	GX23795	-26.5	2360 ± 50 ^{†††}	4038 ± 31	4420-4610
8	FC-97-G	0-6	Alder and willow leaves	GX23848	-28.8	4000 ± 50 ^{†††}		
8	SM-97-I	0-2	Conifer needles	GX23532	-28.3	4060 ± 50 ^{†††}		
8	BA-97-H	(-) 1- (+) 8	Seeds	GX24239	-28.9	4060 ± 60 ^{†††}		
10	SM-97-M	0-3	Pine and fir needles, moss	GX23796	-28.7	4460 ± 40 ^{†††}	4491 ± 24	5040-5290
10	FC-97-H	7-11	Seeds	GX23849	-28	4480 ± 50 ^{†††}		
10	SM-97-I	0-5	Needles, moss, cone fragments	GX23602	-28.1	4520 ± 50 ^{†††}		
10	BA-97-H	(-) 0-4	Seeds	GX24240	-28.9	4520 ± 50 ^{†††}		
10	BA 97 S	(-) 0-9	Seeds	GX24174	-30.6	5050 ± 40		
11	BA-97-S	0-3	Hemlock and spruce needles	GX24241	-28.4	5390 ± 50 ^{†††}	5468 ± 32	6200-6310
11	SM-97-I	0-2	Conifer needles, cone fragments	GX23533	-29.2	5500 ± 50 ^{†††}		
11	BA-96-H	(-) 0-2	Conifer needles	GX22595	-28.3	5530 ± 60 ^{†††}		
12	SM-97-I	2-4	Conifer needles, seed	GX23534	-29.4	5770 ± 50 ^{†††}	5800 ± 37	6500-6720
12	SM-97-M	0-5	Pine, fir, cedar leaves, moss	GX23797	-28.5	5830 ± 50 ^{†††}		

[†]Radiocarbon age data grouped by buried soil number designated by stratigraphic relations observed in marsh cores.

[‡]Core number designates locality, year sampled, and specific core identified by letter. The localities are abbreviated as follows: SM—Sevenmile Creek; FC—Fahys Creek; OSP—Osprey marsh; BA—Ferry Creek; OC—south bank Coquille River opposite Rocky Point.

[§]Depth range relative to top of buried soil. Negative values (-) indicate sample interval below top of soil. Positive values (+) indicate sample interval above top of soil.

[#]Lab abbreviations: AA—University of Arizona, NSF Accelerator Facility; GX—Geochron Laboratories, Cambridge, Massachusetts; BETA—Beta Analytic.

^{††}Conventional ages reported by radiocarbon laboratory based upon Libby half-life (5570) for ¹⁴C.

^{†††}Weighted mean ages calculated for radiocarbon ages that are statistically equivalent at 95% significance level based on a chi-square test (Ward and Wilson, 1978); weighted mean ages computed with CALIB 4.3 (Stuiver and Reimer, 1993).

^{§§}Calibrated age ranges before AD 1950 reported to nearest decade, computed with CALIB 4.3 (Stuiver and Reimer, 1993; Stuiver et al., 1998) using a lab error multiplier of 1.0 and reported to 2 σ .

^{##}Radiocarbon data reported by Nelson (1992a) and Nelson et al. (1995); some sample categories listed in this table were not reported. The weighted mean age is combined age of eight ages on *Carex* leaf bases from south bank of Coquille River (A. Nelson, personal commun., 2002).

^{###}Statistically indistinguishable ages used to calculate weighted mean ages in column to right.

^{###}Anomalously young age compared to stratigraphically equivalent and stratigraphically older samples; sample contamination suspected.

preserved along the Coquille River and beneath tidal marshes proximal to the river channel subsided during the A.D. 1700 Cascadia earthquake.

SEVENMILE CREEK LOCALITY

Sediments in the lower Sevenmile Creek valley consist of interbedded tidal-marsh peat

and estuarine mud. Vegetation in the bottomland of Sevenmile Creek in the mid-1800s included primarily sedges and rushes with few trees (Benner, 1991). Today, mean higher high water lies above the southernmost core (core I) and 2.2 m below the elevation of the northernmost core site (core P). Diking and a tide gate prevent tidal water from inundating the lower valley.

Buried Upland and Tidal-Marsh Soils

Stratigraphic sequences beneath the lower Sevenmile Creek valley contain 11 buried soils (soils 2-12; Fig. 5). The buried soils dip down valley away from Eocene sedimentary rocks onto which they lap. Older soils generally dip to a greater degree than younger soils and probably reflect compaction of intertidal

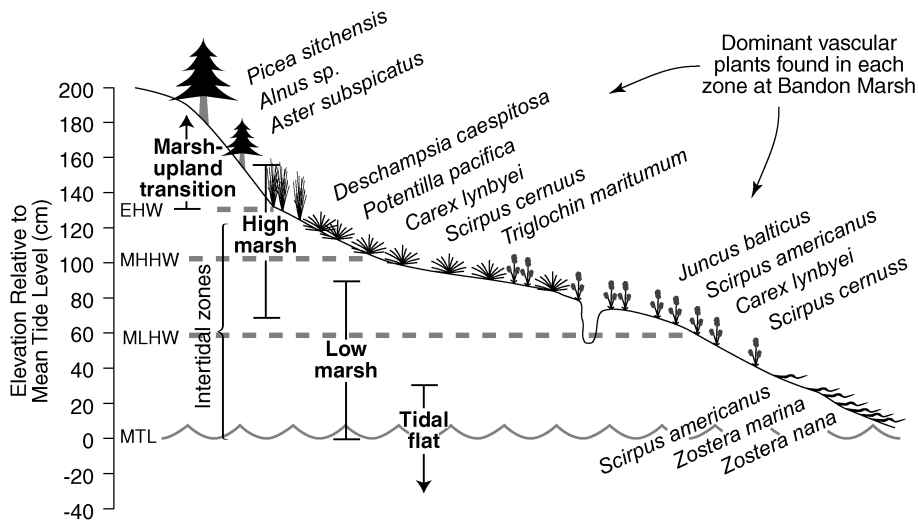


Figure 4. Elevation ranges for intertidal zones at Coquille River estuary based on distribution of vascular plants in Oregon tidal marshes (after Nelson and Kashima, 1993). Tidal data from National Ocean Service (1992): EHW, extreme high water; MHHW, mean higher high water; MLHW, mean lower high water; MLLW, mean lower low water; MTL, mean tide level. Intertidal zones overlap by 20–30 cm, reflecting vertical variation in zone boundaries (Nelson and Kashima, 1990) and include uncertainty in elevation of intertidal zones used to estimate paleo-mean tide level from fossil diatom assemblages (Table 3).

and subtidal mud that filled the lower Sevenmile Creek valley (e.g., Atwater and Hemphill-Haley, 1997; Cahoon et al., 1995).

Seventy-two percent of the observed buried soils (71 out of 98) exhibit sharp (<3 mm) upper contacts with overlying mud or sand (Table 2). Fourteen percent of the upper soil contacts observed were clear (3–10 mm), and the remaining 13% were gradual (>10 mm) (Table 2). Where the soil-mud contact was less distinct, bioturbation, pedogenesis, or weathering obscured the contact.

Nine of the 11 buried soils are preserved for at least 1300 m along the axis of the valley (Table 2). Exceptions included soil 2, which was observed in three cores that spanned 500 m, and soil 9, which was observed in the four northernmost, higher-elevation cores over a distance of 425 m.

Pumice clasts, depth-to-contact, and sand bed characteristics aided correlation of soils from core to core. Rounded pumice lapilli occurred in soils 10 and 8; the pumice was eroded from tephra deposits upstream and deposited in the Sevenmile marsh. Elemental abundances of glass in pumice from soil 10 have affinity with glass from Crater Lake set-O (Sarna-Wojcicki et al., 1983). The occurrence of pumice lapilli facilitated correlation of soils 8 and 10 from core to core (Fig. 5). Other aids to correlations included relative depth of peat-mud contacts, thickness of sand deposits overlying buried soils, and, in the

case of soils 11, 7, and 6, individual sandy beds that do not directly overlie a buried soil.

Sandy Deposits Overlying Buried Soils

Sandy deposits, ranging in thickness from 1–66 cm, occurred above 10 of 11 soils (Table 2). Sandy deposits buried soils 5–12 in 67% of the instances where soils occurred in cores. The texture of the sandy beds ranged from clean, fine-to-medium sand to sandy mud with less than 10% very fine to fine sand. Occasionally the deposits included mud clasts ripped up from underlying layers and forest litter, including spruce needles and cones. The beds typically were normally graded and in many cases consisted of multiple fining-upward deposits. The thickest sand, a 66-cm-thick deposit in core M above soil 8, consisted of eight fining-upward, fine-to-medium sand beds, each 4- to 15-cm thick. The sparsest sandy deposits encountered in the cores were predominantly slightly sandy mud with less than 10% very fine to fine sand. Thinner layers often correlated to thicker, coarser deposits in neighboring cores, indicating an uneven distribution of sand. Sandy deposits did not appear to become systematically thinner or finer up valley. Because the sandy layers contain diatom fragments with tidal sand flat affinities (see Data Repository), and because the texture of the sand is well sorted, the likely sand sources are the beach and tide flats near

the river mouth. If so, then the maximum transport distance for the sand is ~10 km.

Radiocarbon Ages of Buried Soils

Six radiocarbon ages from core I, six ages from core M, and a single age from core A provide a 6700-yr chronology of 11 instances of soil submergence and burial at Sevenmile Creek (Table 1). Based on statistically indistinguishable radiocarbon ages, soils 6, 7, 10, and 12 each were submerged simultaneously at core sites I and M, which are 850 m apart (Fig. 5). Thirteen radiocarbon ages estimate the time of burial of nine soils (Table 1). Exceptions include soils 4 and 2, which were not dated due to insufficient organic material.

Diatom Biostratigraphy: Evidence for Relative Sea-Level Change

Diatom assemblages from different intertidal zones preserved above and below the sharp upper contacts of buried soils in core I at Sevenmile Creek indicate that rapid relative sea-level rise attended the burial of each soil (Table 3; Data Repository). For each buried soil, diatom assemblages in the overlying muddy deposit indicated a lower intertidal environment than assemblages in the underlying soil.

We estimated the vertical rise of sea level that submerged the soils by evaluating the change in elevation of mean tide level relative to the sharp upper soil contact as indicated by fossil diatoms present in the buried soil and overlying mud (Table 3). Of the 11 buried soils, seven contained diatom assemblages from high marsh or upland environments and three contained diatoms from low marsh environments. We did not analyze diatoms from soil 9. The maximum estimated soil submergence was 3 m, based on a shift in the elevation of mean tide level that changed an upland to a sand flat (soil 3; Table 3). Uncertainty in the submergence estimates, due to the diffuse nature of intertidal zone boundaries, is encompassed by the submergence ranges; maximum submergence estimates range from 1.2–3.0 m; minimum estimates range from 0–1 m (Table 3). We adopt zero as the minimum estimate where negative submergence was indicated (Table 3) because in all cases both diatom analyses and lithological evidence attest to positive relative sea-level rise. Zero probably underestimates the actual amount of submergence because a change from tidal marsh to tidal flat requires measurable sea-level rise.

Relative sea level at Sevenmile Creek has risen 7–8 m from 6500–6720 cal yr B.P. to

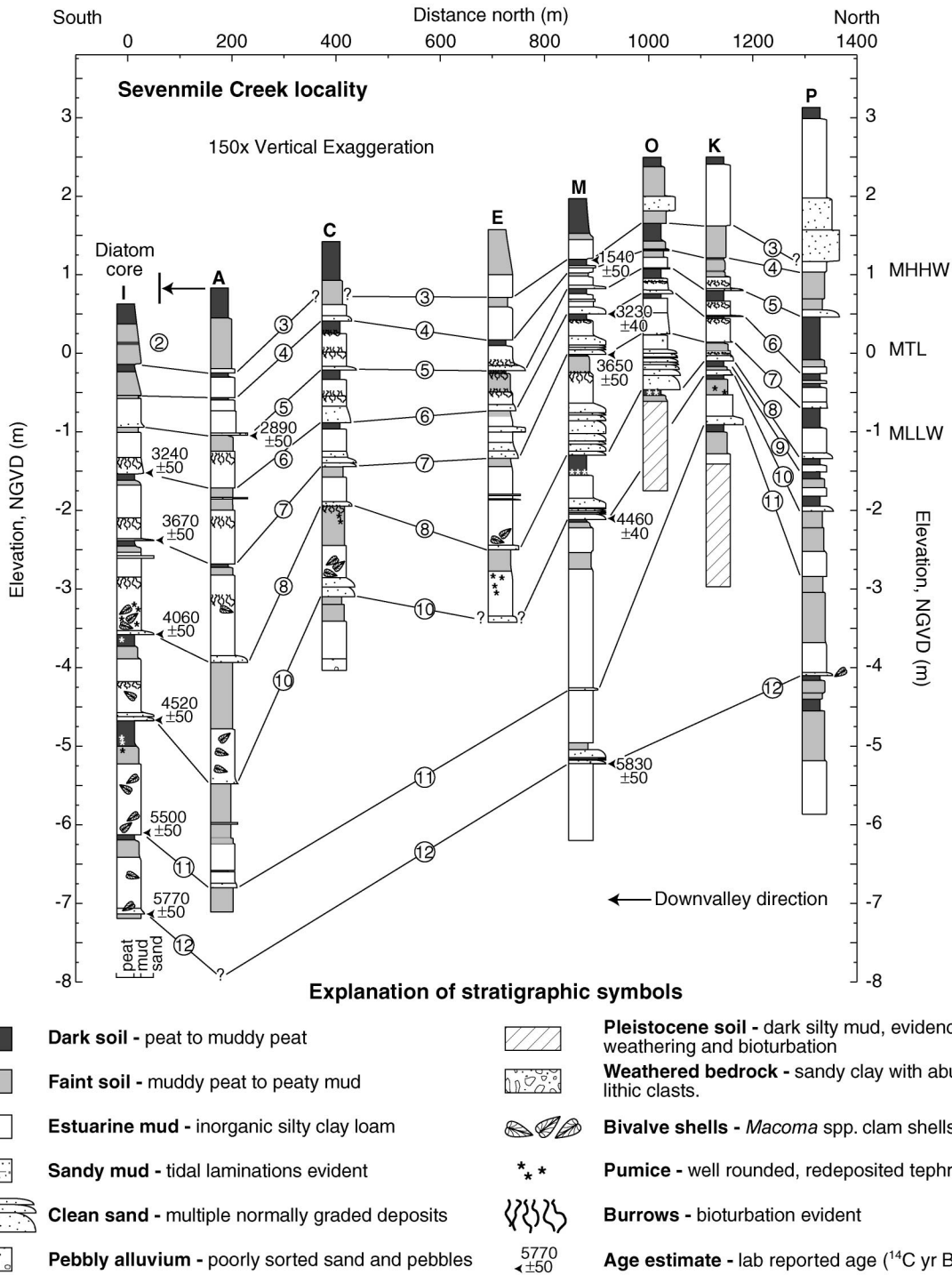


Figure 5. Stratigraphy of Sevenmile Creek. Numbers indicate soils buried by sand and mud. Core locations shown in Figure 2. Rounded pumice lapilli, reworked from tephra deposits in Coquille headwaters, aided in correlation of buried soils. Elevations based on theodolite survey (± 0.05 m closure error) tied to U.S. Coast and Geodetic Survey tidal benchmarks. MHHW—mean higher high water; MTL—mean tide level; MLLW—mean lower low water (National Ocean Service, 1992); NGVD—National Geodetic Vertical Datum.

present, but the long-term trend of relative sea level appears to have stabilized since the penultimate soil burial event 1170–1340 cal yr B.P. (Table 1; Fig. 6). The sediment aggradation curve shows that marsh accretion kept

pace with sea-level rise (Fig. 6) through the Middle to late Holocene.

The sawtoothed pattern of the relative sea-level curve depicts episodes of instantaneous sea-level rise that submerged the soils sepa-

rated by longer periods of gradual sea-level change coinciding with marsh aggradation (Fig. 6). Prior to 3600–4000 yr ago, rapid upward jerks in sea level were separated by periods of more gradual relative sea-level rise or

TABLE 2. ATTRIBUTES OF BURIED SOILS AND OVERLYING SAND DEPOSITS, SEVENMILE CREEK, COQUILLE ESTUARY

Buried soil no.	No. of cores that sample buried soil ^a	Depth range to upper soil contact (cm)	Nature of upper soil contact ^b	No. of cores that sample sandy deposit overlying buried soil	Thickness range of sandy deposit (cm)	No. of beds evident in sandy deposit ^c	Mean thickness of mud deposit overlying buried soil (cm)
2	2	49–62	1s, 1g	0	0	0	14.0
3	13	56–108.5	7s, 2c, 4g	1	7–11	1	19.4
4	12	88.5–229	4s, 4c, 4g	2	2.5–3.5	1	21.4
5	14	122–266	10s, 2c, 2g	12	3–9.5	1	28.7
6	12	173.5–338	11s, 1c	8	1–7.5	1	24.3
7	11	200–387	9s, 1c, 1g	9	2–23.5	4	37.0
8	11	242.5–505	11s	12 ^d	3–66	8	53.5
9	4	269.5–463	1s, 2c, 1g	3	4–10.5	1	10.0
10	9	306–630	8s, 1c	7	4.5–25	5	38.3
11	5	359–681.5	4s, 1c	4	2–5.5	1	33.8
12	5	372–775	5s	4	3.5–6	1	51.3

^aTotal of 18 gouge and vibracores analyzed.

^bUpper soil contact represented by peat/mud or peat/sandy-mud transitions. Nature of contacts includes sharp, <3 mm; (c) clear, >3–10 mm; and (g) gradual, >10 mm.

^cEach sandy bed fined upward from sand or muddy sand to silty mud.

^dSome sandy deposits were observed without an associated buried soil. We correlated such sandy beds with sandy deposits overlying buried soils in adjacent cores on the basis of stratigraphic depth.

TABLE 3. PALEO-MEAN TIDE LEVEL (MTL) ESTIMATES BEFORE AND AFTER SOIL SUBMERGENCE, CORE I, SEVENMILE CREEK

Buried soil no.	Calibrated age (cal yr before 1950) ^a	Elev. of upper soil contact (m, NGVD) ^b	Diatom sample elevation (m, NGVD)	Intertidal zone based on diatom assemblage ^c	Vertical position of diatom sample relative to paleo-MTL (m) ^d	Elevation of paleo-MTL (m, NGVD) ^e	Range of submergence (m) ^f
2	1170–1340	0.13	0.22 to 0.21 0.14 to 0.13 0.12 to 0.11	Low-to-high marsh Sand flat High-marsh	0 to 1.6 –0.7 to 0.3 0.7 to 1.6	0.8 to –0.2 –0.6 to –1.5	0.4 to 2.3
3	1530–1700	–0.14	0.02 to 0.01 –0.08 to –0.09 –0.13 to –0.14 –0.17 to –0.18	Sand flat Sand flat Sand flat Upland	–0.7 to 0.3 –0.7 to 0.3 –0.7 to 0.3 1.3 to 2.3	–1.4 to –2.4 0.2 to –1.4	1.0 to 3.0
4	2150–2360	–0.54	–0.28 to –0.29 –0.54 to –0.55 –0.6 to –0.61	Mud flat/low marsh High marsh Low marsh	–0.7 to 0.9 0.7 to 1.6 0 to 0.9	–1.2 to –2.1	0 to 2.3
5	2960–3200	–0.94	–0.78 to –0.79 –0.95 to –0.96	Mud flat High marsh/upland	–0.7 to 0.3 0.7 to 2.3	–0.2 to –1.2 –1.6 to –2.7	0.4 to 2.5
6	3400–3550	–1.54	–1.48 to –1.49 –1.54 to –1.55	Sand flat High marsh	–0.7 to 0.3 0.7 to 1.6	–0.8 to –1.8 –2.2 to –3.1	0.4 to 2.3
7	3870–4090	–2.38	–2.28 to –2.29 –2.39 to –2.4	Mud flat High marsh	–0.7 to 0.3 0.7 to 1.6	–1.7 to –2.7 –3.1 to –4.0	0.4 to 2.3
8	4420–4610	–3.56	–2.78 to –2.79 –3.38 to –3.39 –3.56 to –3.57	Mud flat Sand flat High-to-low marsh	–0.7 to 0.3 –0.7 to 0.3 0 to 1.6	–2.9 to –3.9 –3.6 to –5.2	0 to 2.3
10	5040–5290	–4.68	–3.98 to –3.99 –4.38 to –4.39 –4.65 to –4.66	Mud flat/low marsh Mud flat Sand flat	–0.7 to 0.9 –0.7 to 0.3 –0.7 to 0.3	–4.0 to –5.0 –5.4 to –6.3	0.4 to 2.3
11	6200–6310	–6.12	–4.69 to –4.7 –6.11 to –6.12	High marsh Mud flat	0.7 to 1.6 –0.7 to 0.3	–5.4 to –6.4	0 to 1.6
12	6500–6720	–7.13	–6.12 to –6.13 –7.12 to –7.13 –7.13 to –7.14	Low marsh Mud flat Lower low marsh	0 to 0.9 –0.7 to 0.3 0 to 0.5	–6.1 to –7.0 –6.4 to –7.4 –7.1 to –7.6	0 to 1.2

Note: No biostratigraphic data are reported for soil 9 because it was not observed in core I. NGVD—National Geodetic Vertical Datum.

^aCalibrated radiocarbon ages provide maximum-limiting estimates for time of soil submergence (Table 1).

^bUpper contact of buried soil observed in Core I, Sevenmile Creek (Fig. 5).

^cPaleoenvironment based on diatom assemblage recognized for each sample (see footnote 1 for Data Repository).

^dElevation ranges, depicted in Figure 4, for intertidal zones relative to mean tide level (MTL). Because tidal flat zone and marsh-upland transition zone lack lower and upper limits, respectively, we assign a range of 1.0 m to these zones to avoid unrealistic estimates of maximum submergence.

^eElevations of paleo-MTL (rounded to the nearest 0.1 m) relative to upper soil contact immediately before and after soil submergence are used to construct relative sea-level curve (Fig. 6).

^fEstimated range of submergence is derived by subtracting elevation of paleo-MTL for the buried marsh soil from elevation for overlying mud using elevation ranges in column at left. Only positive submergence estimates are shown if a negative value results from the calculation because a negative value indicates relative sea-level fall, which is precluded by stratigraphic transition from marsh to overlying tidal flat facies.

stasis. After 3600–4000 yr ago, episodes of rapid sea-level rise were separated by periods of gradual relative sea-level fall. This change probably reflects a decrease in the rate of eustatic sea-level rise ~3600 yr ago.

FAHYS CREEK LOCALITY

The Fahys Creek locality consists of a swamp in the north and a tidal marsh (Osprey marsh) to the south (Fig. 2). Original Land

Survey Notes from the mid 1800s (Benner, 1991) depict spruce and alder in the swamp and a salt marsh at the Osprey marsh. The elevation of Fahys swamp is 0.5–1 m higher than mean higher high water.

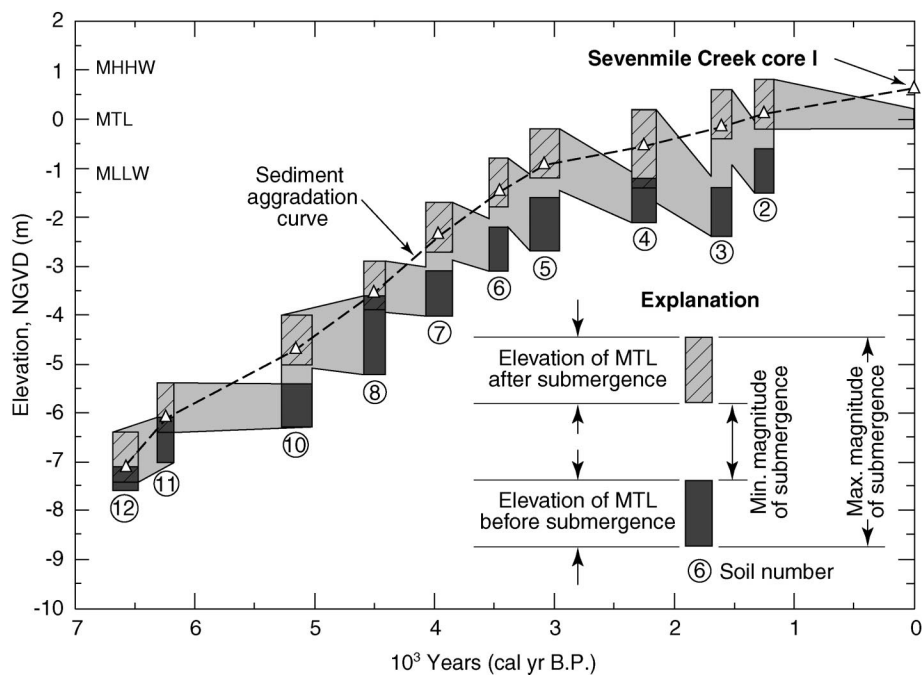


Figure 6. Relative sea-level curve tracking mean tide level (MTL) for Core I, Sevenmile Creek. Width of rectangle delineates time of soil burial based on radiocarbon age estimates (Table 1). Height of rectangle estimates MTL based on fossil diatom assemblages from soil (diagonal fill) and overlying mud (shaded fill) (Table 3). Envelope that encompasses rectangles approximates change in elevation of MTL through time and incorporates uncertainties related to radiocarbon age estimates and MTL elevation. Relative sea-level curve depicts episodes of instantaneous relative sea-level rise followed by periods of more gradual sea-level change. Triangles mark elevations of top of individual buried soils in core I. Dashed line reflects sediment aggradation rate. MHHW—mean higher high water; MLLW—mean lower low water; NGVD—National Geodetic Vertical Datum.

Older buried soils (soils 10, 8, 6, 5, 4, 3, and 2) are preserved at Fahys swamp (Fig. 7), whereas soil 1 is restricted to Osprey and Bandon marshes (Fig. 2) adjacent to the Coquille River. Between Fahys swamp and Osprey marsh, buried soils 2 and 3 are preserved (Fig. 7). Greater than 90% of the observed upper contacts of buried soils are sharp. Exceptions include soils 10, 3, and 2 (Table 4), where 38–62% of observed contacts are sharp. Radiocarbon ages, indistinguishable at 95% confidence according to the chi-square test of Ward and Wilson (1978), support stratigraphic correlations between buried soils at Fahys locality and those at Sevenmile Creek.

Stratigraphy at Fahys Swamp consists of bold, well-developed peaty soils near the base to thin (<1-cm-thick), incipient buried soils in the middle to peat-dominated facies near the top (Fig. 7). Peaty soils 10, 8, and 6 extend over an area of 1.7 ha and exhibit sharp upper contacts with overlying clean, fine, well-sorted sand deposits (Table 4). The Fahys site does not preserve soils 9 or 7. Incipient buried soils (5 and 4) occurred in six of 12 cores and con-

sisted of thin (<1-cm-thick), peaty mud layers in clear-to-sharp contact with overlying sand sheets (Fig. 7). The stratigraphy at and north of Osprey marsh has the best preservation of peat-rich buried soils 3, 2, and 1 (Fig. 7). Sand deposits occur above soils 10, 8, 6, 5, and 4 wherever these soils were observed (Table 4; Fig. 7). The sands are well sorted, range from 1.5–28 cm thick, and sand layers overlying soils 8 and 6 contain multiple fining-upward beds. A 2-cm-thick sand bed overlies soil 3 in core O (Fig. 7).

Based on statistically equivalent ages for soils 10, 8, 6, and 5 at both Sevenmile Creek and Fahys Swamp (Table 1), and based on similar stratigraphic relations between these buried soils at both sites, we infer that soil submergence and subsequent burial occurred simultaneously at both localities. Based on stratigraphic correlation among cores at the two sites, we use Fahys Creek ages for soils 4, 3, and 2 (Table 1) as best-estimate ages for soil burial at Sevenmile Creek. There was no stratigraphic evidence for simultaneous soil burial at Fahys Swamp for Sevenmile soils 9

and 7, and soils 12 and 11 predate the time sea level first reached the Fahys Swamp site.

FERRY CREEK LOCALITY

Ferry Creek occupies a 13.4 km² watershed and dissects uplifted late Pleistocene marine terraces deposited on platforms beveled into Jurassic sandstone (Fig. 2). Although the broad valley floor probably reflects infilling due to base-level rise during the late Holocene sea-level transgression, the lower valley is geomorphically distinct from Sevenmile Creek. In the mid-1800s, “upland forest” occupied the Ferry Creek valley, whereas the “marsh prairie” along Sevenmile Creek was occasionally inundated by high tides (Benner, 1991). This forested alluvial plain is not graded to tidal flats like other Coquille tributaries. Within several hundred meters of its confluence with the Coquille River, the high banks of Ferry Creek lie well above the reach of the highest tides. For example, elevations of core sites in lower Ferry Creek vary from 2.2–6.5 m above mean tide level, ranging 2.5–3 m higher than core sites surveyed at Sevenmile Creek. Ferry Creek has incised a ~2 m deep channel in the valley floor, has a higher gradient than Sevenmile Creek, and lacks a tide gate at the confluence with the Coquille River.

Cores from Ferry Creek contain seven buried alluvial soils (Fig. 8). The oldest buried soils at Ferry Creek, 11, 10, 9, 8, and 6, consist of faint, dark gray-brown (10YR 3/1) organic mud overlain by gravelly sand or sandy mud (Table 5). Unlike the sharp upper buried soil contacts observed at the Sevenmile and Fahys localities, the upward transitions of soils to mud often are gradual and obscured by bioturbation (Table 5). Burrows filled with overlying material typically penetrate several centimeters downward into buried soils. Soil 9 is faint and evident in only a few cores (Fig. 8).

Ferry Creek soils 5 and 4 range in texture from peaty loam to organic-rich peat, display sharp to gradual upper contacts with sand or gravel, and can be traced along the length of the valley (Table 5; Fig. 8). Both soils contain abundant forest litter, including spruce needles, cones, and moss. Soil 5 contains remnant roots and stumps of trees in growth position. Where the upper peat contact has been bioturbated, soil 5 appeared fainter in color and contained less organic material than the soil below. Soil 4 is oxidized within the modern soil profile and does not display a sharp upper contact. Soils younger than soil 4 were not observed at Ferry Creek.

Deposits of sand-to-muddy sand or gravel

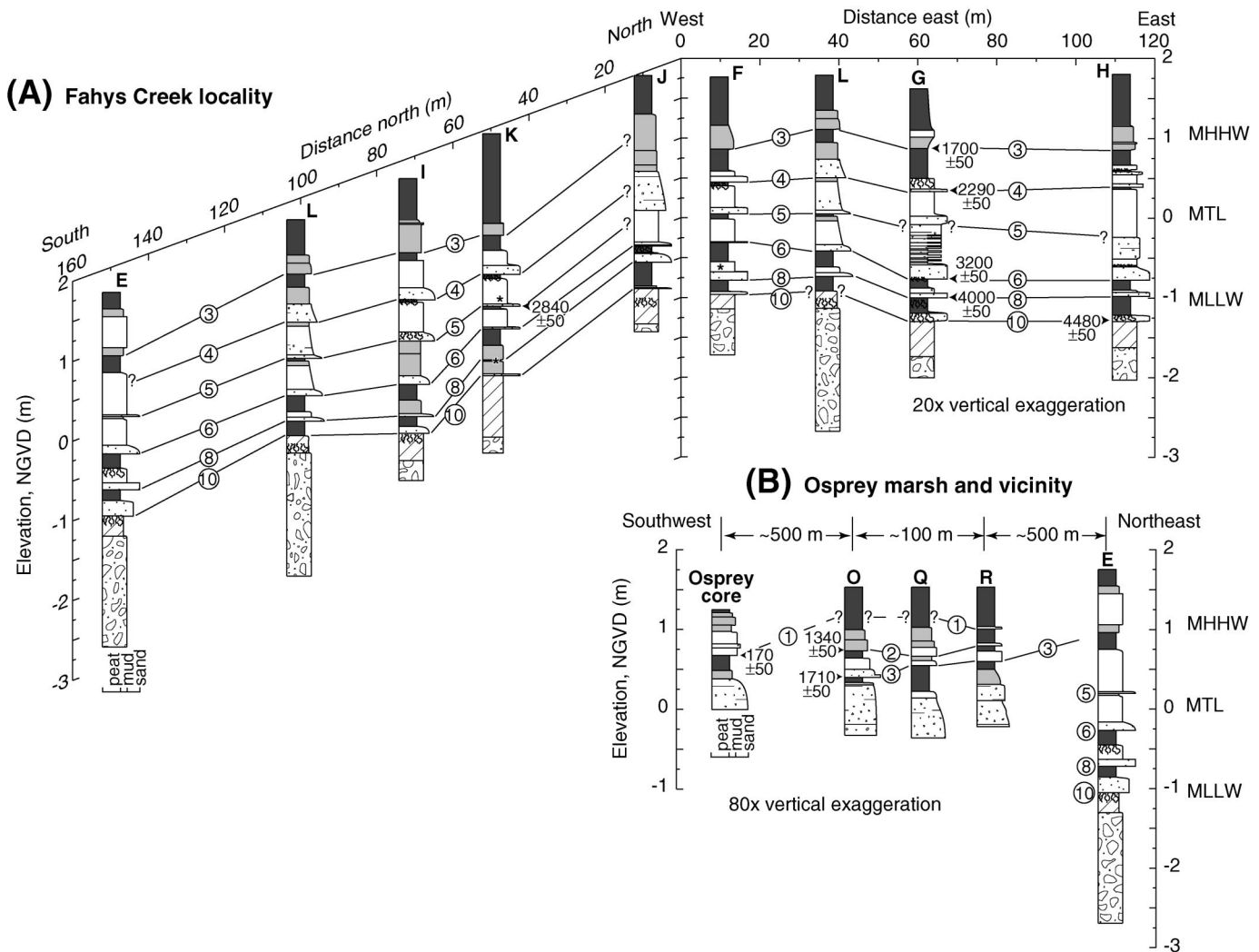


Figure 7. (A) Stratigraphy of Fahys Creek locality. Numbers indicate soils buried by sand and mud. Core locations shown in Figure 2. Burial of soils 12, 11, 9, and 7 were not recorded at Fahys Creek. (B) Stratigraphy of Osprey marsh and vicinity. See Figure 5 for stratigraphic explanation. Auto-level survey of core locations (closure <0.05 m) tied to U.S. Coast and Geodetic Survey tidal benchmarks. MHHW—mean higher high water; MTL—mean tide level; MLLW—mean lower low water (National Ocean Service, 1992).

TABLE 4. ATTRIBUTES OF BURIED SOILS FROM CORES AT FAHYS CREEK AND OSPREY MARSH LOCALITIES, COQUILLE ESTUARY

Buried soil no.	No. of cores that sample buried soil [†]	Depth range to upper soil contact (cm)	Nature of upper soil contact [‡]	No. of cores that sample sandy deposit overlying buried soil	Thickness range of sandy deposit (cm)	No. of beds evident in sandy deposit [§]	Mean thickness of mud deposit overlying buried soil (cm)
1	4 [#]	36–57.5	4s	2 [#]	2–2.5	1	16.3
2	8	54.5–87	3s, 1c, 4g	0	0	0	9.6
3	13	69–113.5	8s, 1c, 4g	1	2	1	17.6
4	7	125–152.5	7s	9 ^{††}	3–28	1	15.2
5	5	155–203	5s	7 ^{††}	1.5–13	1	38.7
6	12	178–257.5	12s	12	4.5–17.5	2	32.2
8	11	192–297.5	10s, 1c	11	3–12.5	3	7.1
10	8	253–319	4s, 2c, 2g	8	1.5–19.5	1	2.0

[†]Total of 21 gouge and vibracores analyzed.

[‡]Upper soil contact represented by peat/mud or peat/sandy-mud transitions. Nature of contacts includes sharp, <3 mm; (c) clear, >3–10 mm; and (g) gradual, >10 mm.

[§]Each sandy bed fined upward from sand or muddy sand to silty mud.

[#]Youngest buried soil crops out along banks of Coquille River as well as in reconnaissance cores from Osprey and Bandon marshes. Sand layers overlying this soil were observed at Bandon marsh and in a cutbank exposure on Randolph Island (Nelson, 1992a; Nelson, 1992b).

^{††}Some beds of sand were observed without an associated buried soil. We correlated such sandy beds with sandy deposits overlying buried soils in adjacent cores.

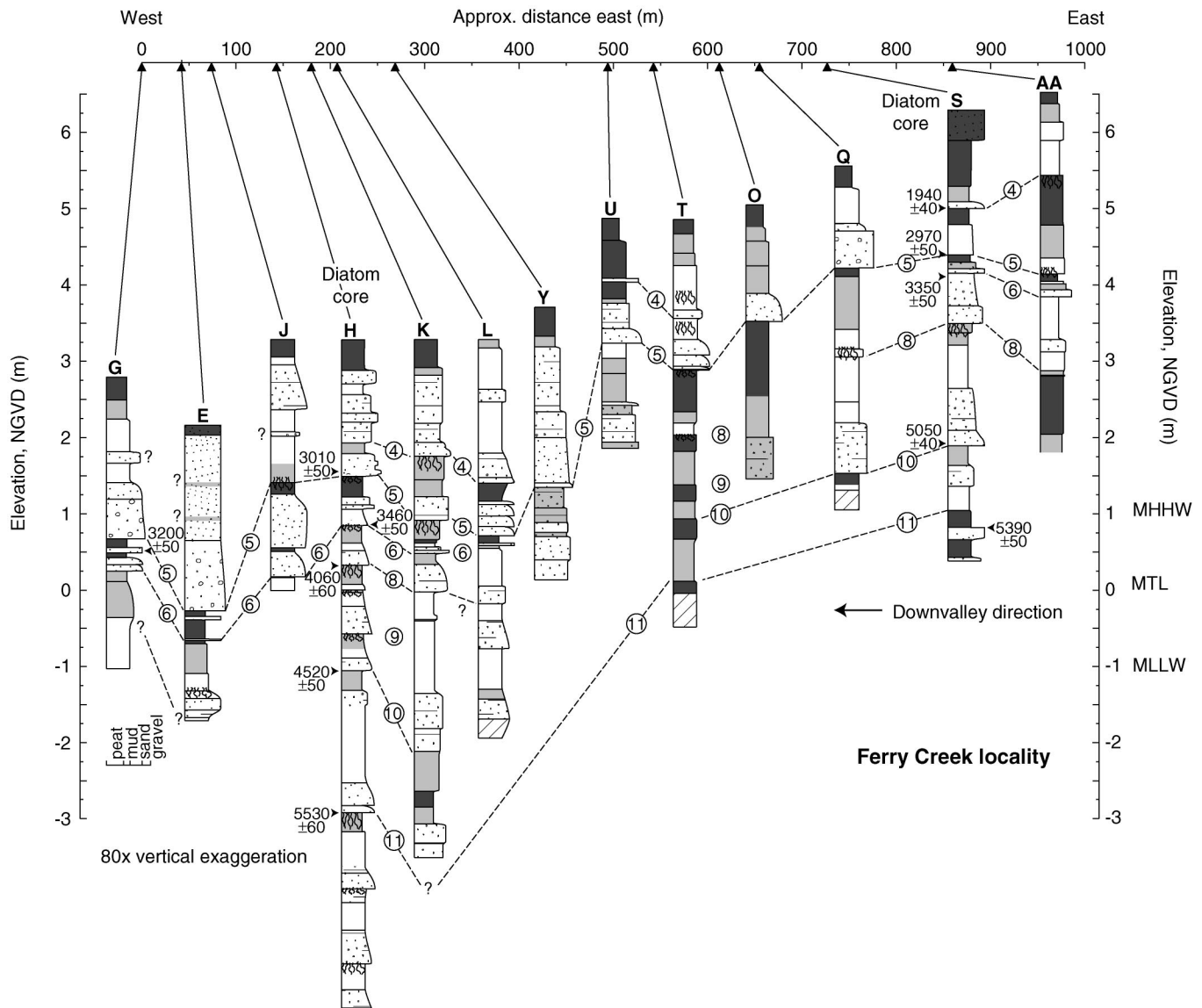


Figure 8. Stratigraphy of Ferry Creek. Numbers indicate soils buried by fluvial deposits. Core locations shown in Figure 2. Soils 11, 10, 8, 6, 5, and 3 correlate, based on statistically equivalent radiocarbon ages, to buried soils at Sevenmile Creek and Fahys Creek. See Figure 5 for stratigraphic explanation. Distances between cores based on field estimates and 1:200-scale topographic map of Bandon. Elevations based on auto-level survey (± 0.05 m closure error) tied to U.S. Coast and Geodetic Survey tidal benchmarks. MHHW—mean higher high water; MTL—mean tide level; MLLW—mean lower low water (National Ocean Service, 1992).

occur above each buried soil (Table 5; Fig. 8). Above soils 11, 10, 9, 8, and 5, sandy mud to well-sorted sand fines upward into silty mud; the deposit overlying soils 11, 6, and 4 displayed two distinct fining-upward intervals.

Coarse-grained deposits of sand and pebbles, consisting of up to four fining-upward intervals, erode into the top of soil 5. The grain size and sorting of these deposits were similar to the pebbly alluvium in the active channel of the creek. The coarse pebbly sand above soil 5 could be correlated among cores as much as 900 m apart. Based on the sedi-

mentological characteristics of the sand and gravel deposits and the nature of their lower contacts with buried soils, we infer that these coarse-grained deposits were deposited in freshwater fluvial environments similar to the modern setting of lower Ferry Creek valley.

Five of the soils at Ferry Creek were buried at the same time as widespread soil submergence elsewhere in the estuary (Table 1). The lower Ferry Creek soil chronology is based on six radiocarbon ages from core H and five ages from core S. Radiocarbon ages for the burial of soils 11, 10, 8, 6, and 5 are indistin-

guishable from correlative buried soils at Sevenmile Creek and Fahys Creek based on a chi-squared test at the 95% confidence level (Ward and Wilson, 1978) (Table 1). Age similarity does not preclude that a Ferry Creek soil was buried years to decades before or after submergence of a soil at Sevenmile Creek. However, because the age estimates for soil burial are statistically indistinguishable among sites throughout the estuary, we infer that the soils at Ferry Creek were buried by fluvial aggradation in response to instances of rapid relative sea-level rise.

TABLE 5. ATTRIBUTES OF BURIED SOILS FROM CORES AT FERRY CREEK, COQUILLE ESTUARY

Buried soil no.	No. of cores that sample buried soil [†]	Depth range to upper soil contact (cm)	Nature of upper soil contact [‡]	No. of cores that sample sandy deposit overlying buried soil	Thickness range of sandy deposit (cm)	No. of beds evident in sandy deposit [§]	Mean thickness of mud deposit overlying buried soil (cm)
3	6	83.5–149	1s, 2c, 3g	2	4.5–18	1	10.0
5	14	133.5–243	4s, 4c, 5g, 1b	11	2.5–65	4	n.d.
6	11	222.5–311.5	7s, 4g	8	6–45	2	24.5
8	5	279–415	1s, 4g, 1b	2	1–22	1	12.8
9	3	348–523.5	1s, 1g, 1b	1	34.5	1	44.0
10	5	392–540	2s, 3g	4	10–19.5	1	26.5
11	3	451–674	1s, 2g	1	54–74	2	107.8

Note: n.d.—not determined.

[†]Total of 28 gouge and vibracores analyzed.

[‡]Upper soil contact represented by peat/mud or peat/sandy mud transitions. Nature of contacts includes sharp, <3 mm; (c) clear, >3–10 mm; (g) gradual, >10 mm; and (b) obscured by bioturbation.

[§]Each bed fined upward from gravelly sand or muddy sand to silty mud.

Based on fossil diatoms, tidal water never reached upstream to Ferry Creek study sites at times when valley soils were buried. All diatom samples above and below peat-mud contacts at Ferry Creek core H and S either were barren or contained poorly preserved freshwater diatoms in low abundance (Table 6; Data Repository). We infer the samples were deposited in a forested floodplain environment where standing water supported freshwater diatoms. The Sevenmile Creek relative sea-level curve best approximates the late Holocene elevation of mean tide level at Ferry Creek; however, diatom data from core H allow a maximum elevation 1.2–1.28 m higher than the Sevenmile Creek curve at 6200–3610 cal yr B.P. (Fig. 9).

DISCUSSION

Evidence For Coseismic Subsidence and Tsunamis Induced by Great Earthquakes

The attributes of 12 tidal marsh soils at the Coquille estuary (Table 7) satisfy multiple criteria proposed by Nelson et al. (1996b) and Hemphill-Haley (1995a) for a coseismic origin of soil submergence and burial. These criteria include rapid relative sea-level rise evident from a sudden shift in paleoenvironment and a sharp upper soil contact, long-lasting submergence of tidal marshes, widespread submergence, relative sea-level rise greater than 0.5 m based on diatom analyses, concurrent tsunami deposition at the time of soil burial, and radiocarbon age estimates that correlate with ages of buried soils at other Pacific Northwest estuaries.

Evidence for Rapid Subsidence

The sharp (<3 mm) upper contacts of the buried soils (Tables 2, 4, and 5) indicate a rapid shift in the depositional environment of the estuary. This shift was accompanied by rapid

relative sea-level rise inferred from changes in fossil diatom assemblages. Environments shifted from upland, high-marsh, or low marsh to sand flat or mud flat (Table 3). If the environmental change was not rapid, then relative sea-level rise over a few weeks or months would have provided habitats for diatom growth as the site passed through progressively higher tidal zones (Hemphill-Haley, 1995a) and likely would have left a gradual (>10 mm) upper soil contact. Although we did not use a millimeter-scale sampling strategy necessary to test this assumption, in the samples analyzed we found no sign of diatom species that characterize intermediate assemblages between the upper soil contact and the overlying intertidal sand and mud. We attribute this evidence for repeated instances of rapid relative sea-level rise to coseismic subsidence caused by Cascadia earthquakes.

Evidence for Lasting Submergence

Fossil diatoms and bivalves in the thick (10–53.5 cm) deposits of mud and sand that bury the soils indicate a lasting shift from upland or marsh to mud flat or sand flat. Clams (*Macoma* spp.), common to intertidal flats (Kozloff, 1983), are present in the mud and sand overlying the soils, suggesting that invertebrate communities colonized the tidal flats over a period of several months to years. Tidal flat diatom assemblages also persist in mud deposited several decimeters above the soils. Deposition of 10–50 cm of mud (Table 2), assuming an average sediment aggradation rate for the Coquille estuary of ~1 mm/yr (based on radiocarbon ages from core I), would take no more than 100–500 yr. Deposition of mud by tidal processes may have taken as few as 50–150 yr based on the amount of time estimated for landscape recovery to occur at Willapa Bay and Grays Harbor, Washington, since the A.D. 1700 earthquake (Atwater et al., 2001; Atwater and Hemphill-

Haley, 1997). A few decades, the time required for tidal deposits to accumulate in Portage, Alaska, following the 1964 Prince William Sound earthquake (Atwater et al., 2001), probably underestimates the duration of submergence at the Coquille estuary because the Coquille has a much narrower tidal range (~2 m) compared to the 9–11-m tidal range of Turnagain Arm, Alaska. Such long-lasting submergence, over decades to hundreds of years, precludes temporary relative sea-level fluctuations caused by storms or El Niño, as explanations for soil submergence.

Amount of Coseismic Subsidence

The amount of coseismic subsidence inferred for 10 soils at the Coquille estuary was estimated by comparing diatom assemblages preserved above and below the upper contact of each soil (Table 3). Maximum estimates of subsidence were 2.3 m for soils 10, 8, 7, 6, 4, and 2, 2.5 m for soil 5, and 3 m for soil 3, where an upland environment dropped to tidal flat elevations (Table 3). By comparison, Hemphill-Haley (1995a) estimated 0.8 to >3.0 m of subsidence along the Niawiakum River in southwestern Washington during the A.D. 1700 earthquake. The 1964 Alaska earthquake dropped tidal marshes at Portage by 2.3 m (Plafker, 1969, 1972). Minimum estimates of coseismic subsidence at the Coquille estuary are greater than 0.4 m for most soils except for 12, 11, 8, and 4, where minimum subsidence was >0 m (Table 3). We infer that subsidence was greater than zero in all cases because stratigraphic and diatom evidence indicate that rapid relative sea-level rise caused by coseismic subsidence was significant enough to induce long-lived ecological change as tidal marshes were lowered to the elevation of intertidal flats. The uncertainty in the subsidence estimates, represented by submergence ranges (Table 3), incorporates errors due to the overlapping elevation ranges of intertidal

TABLE 6. UPPER-LIMITING CONSTRAINTS ON ELEVATION OF PALEO-MEAN TIDE LEVEL (MTL), CORE H, FERRY CREEK

Buried soil no.	Calibrated age (cal yr before 1950) [†]	Elevation of upper soil contact (m, NGVD) [‡]	Diatom sample elevation (m, NGVD)	Intertidal zone based on diatom assemblage [§]	Vertical position of diatom sample relative to paleo-MTL (m) [#]	Elevation of paleo-MTL (m, NGVD) ^{**}
3	1530–1700	1.88	n.d.	n.d.	>1.2 ^{**}	<0.7 ^{**}
5	2960–3200	1.44	1.44 to 1.45	upland (barren)	>1.2	<0.2
6	3400–3550	0.79	n.d.	n.d.	>1.2 ^{**}	<–0.4 ^{**}
8	4420–4610	0.28	n.d.	n.d.	>1.2 ^{**}	<–0.9 ^{**}
10	5040–5290	–1.1	–0.97 to –0.98 –1.07 to –1.07 –1.67 to –1.67	upland (barren) FW wetland FW wetland	>1.2	<–2.3
11	6200–6310	–2.99	–2.37 to –2.38 –2.67 to –2.68 –2.96 to –2.97 –3.17 to –3.18	upland (unid. frags) upland (barren) FW wetland upland (barren)	>1.2	<–4.2

Notes: n.d.—no data, NGVD—National Geodetic Vertical Datum.

[†]Calibrated radiocarbon ages provide maximum-limiting estimates for time of soil burial (Table 1).

[‡]Upper contact of buried soil observed in Core H, Ferry Creek (Fig. 8).

[§]Paleoenvironment based on diatom assemblage recognized for each sample (Data Repository).

[#]Elevation ranges, depicted in Figure 4, for intertidal zones relative to mean tide level (MTL). Because marsh-upland transition zone lacks an upper limit, we report maximum position of diatom sample relative to paleo-MTL.

^{**}Maximum possible elevations of paleo-mean tide level relative to elevation of buried soil.

^{**}On the basis of stratigraphic relations and alluvial deposits that bury these soils, we interpret that the paleoenvironment of these samples both before and after soil burial was upland or freshwater stream/wetland.

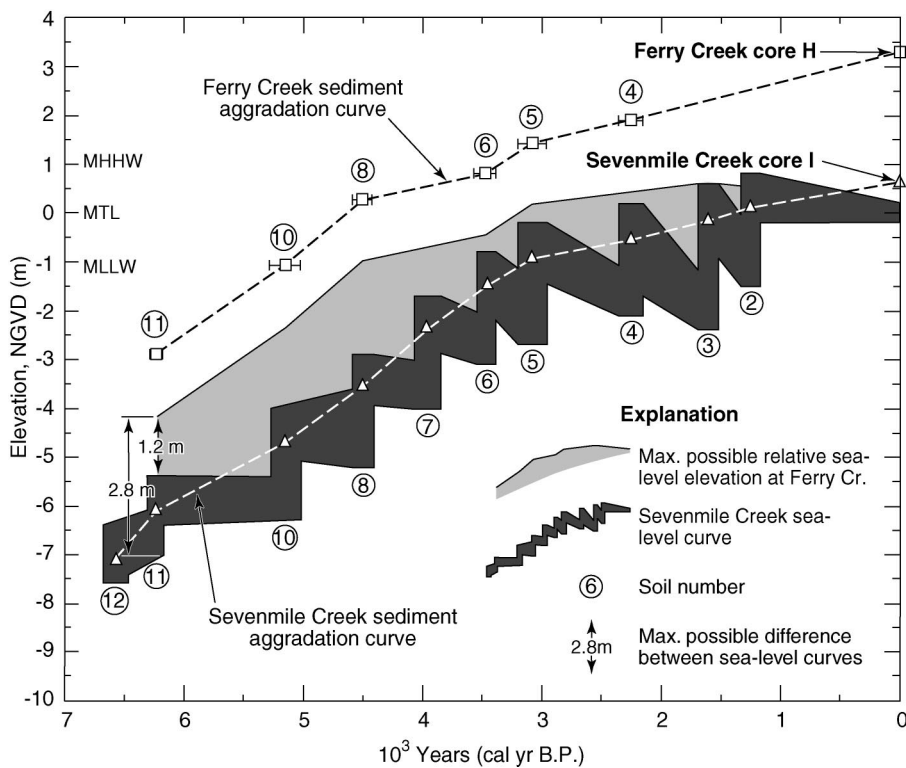


Figure 9. Comparisons of relative sea-level curves and sediment aggradation rates at Ferry Creek and Sevenmile Creek. Sevenmile Creek curve (dark envelope) is a plausible relative sea-level history for Ferry Creek locality. However, based on stratigraphic and paleoecological constraints that limit maximum elevation of relative sea level at Ferry Creek core H (light envelope), maximum possible difference in relative sea-level elevation between both sites is 1.2–2.8 m since 6200–6310 cal yr B.P. Aggradation rates differ between 4500 and 3500 yr ago. NGVD—National Geodetic Vertical Datum.

al zones used to reconstruct mean tide level (Fig. 4).

Evidence for Tsunami Inundation

Tsunamis, generated by dislocation of the ocean floor during subduction zone earthquakes, invaded the coast of Chile in 1960 and the coast of Alaska in 1964 (Plafker, 1972). Previous investigations document evidence for tsunamis generated by Cascadia earthquakes in the form of anomalous sand sheets deposited in coastal lowlands of Vancouver Island (Benson et al., 1997; Clague and Bobrowsky, 1994; Hutchinson et al., 1997), southwestern Washington (Atwater, 1992; Atwater and Hemphill-Haley, 1997; Hemphill-Haley, 1996), northwestern Oregon (Darienzo et al., 1994; Darienzo and Peterson, 1995), southwestern Oregon (Kelsey et al., 1998; Witter et al., 2001), and northwestern California (Abramson, 1998; Garrison-Laney, 1998). Characteristics of deposits likely emplaced by tsunamis include landward thinning sand sheets that drape or erode into preexisting topography, deposits that rise in elevation landward as the sediment texture fines, deposits that contain fossil marine organisms, deposits that consist of multiple laminae of alternating coarse- and fine-grained (or organic-debris-rich) sediment, and deposits that sharply overlie buried soils interpreted to record coseismic subsidence (Benson et al., 1997; Clague and Bobrowsky, 1994).

All but one of the twelve soils at the Coquille estuary are buried by normally graded, at times multiple-bedded, sandy deposits. The deposits contain fossil diatoms from both lower intertidal and sand flat environments (Data

TABLE 7. SUMMARY OF EVIDENCE FOR COSEISMIC ORIGIN OF BURIED SOILS, COQUILLE RIVER ESTUARY

Buried soil number recording coseismic subsidence	Calibrated age (cal yr before 1950) [†]	Years since prior earthquake	Evidence for Coseismic Subsidence [‡]						Relative confidence level (number of criteria met)
			Rapid relative sea-level rise	Long-lasting relative sea-level rise	Widespread soil submergence (spans estuary)	Estimated relative sea-level rise >0.5 m	Tsunami deposit overlies buried soil	Similar age to regional earth-quake evidence	
1	250	920–1090	•	•	•	•	•	•	6
2	1170–1340	190–530	•	•	•	•	•	•	5
3	1530–1700	450–830	•	•	•	•	•	•	6
4	2150–2360	600–1050	•	•	•	•	•	?	5
5	2960–3200	200–590	•	•	•	•	•	•	6
6	3400–3550	320–690	•	•	•	•	•	?	5
7	3870–4090	330–740	•	•	•	•	•	•	5
8	4420–4610	n.d.	•	•	•	•	•	?	5
9	n.d. [§]	n.d.	•	•	•	n.d.	•	?	2
10	5040–5290	910–1270	•	•	•	•	•	?	5
11	6200–6310	190–520	•	•	•	•	•	n.d.	5
12	6500–6720	n.d.	•	•	•	•	•	n.d.	4

Note: n.d.—no data.

[†]Maximum limiting calibrated ages reported in Table 1.

[‡]Evidence for coseismic subsidence includes criteria proposed by Nelson et al. (1996b) and Hemphill-Haley (1995a).

[§]No radiocarbon data available for buried soil 9.

Repository). The sparse abundance of sand flat diatoms suggests transport from an open estuary source. The presence of fossil tidal flat diatoms precludes deposition of sand by river flooding. Storm surge is not a viable depositional mechanism for sand because diatoms in the overlying mud demonstrate lasting ecological change. Multiple fining-upward, sandy beds overlying a single buried soil are consistent with deposition from multiple tsunami waves inundating the estuary after a single earthquake (Wilson and Torum, 1968). The fining-upward sandy beds were deposited out of suspension after the tsunami flooded the valley bottom. Based on the position of sand deposits in sharp contact above coseismically buried soils and biostratigraphic evidence for sand deposited by landward surges of marine water, we conclude that tsunamis induced by plate-boundary earthquakes inundated distal reaches of tributary valleys of the Coquille estuary reaching as far inland as 10 km from the river mouth.

Earthquake Recurrence Intervals

The average earthquake recurrence interval calculated for the Coquille estuary assumes a complete stratigraphic record of coseismic subsidence events. We infer that the combined Sevenmile Creek and Fahys Creek record is complete because the record of deposition is uninterrupted by periods of erosion. However, if an earthquake occurred <50–150 yr following a prior event, tidal marshes at the Coquille estuary may not have been set to record coseismic subsidence.

The average recurrence interval for great Cascadia earthquakes at the Coquille estuary ranges from 570–590 yr. The interval range is calculated by dividing the maximum and minimum time spans between the oldest earthquake (6500–6720 cal yr B.P., Table 1) and the A.D. 1700 earthquake (250 cal yr B.P.) by the 11 earthquakes inferred to have occurred since the oldest recorded event. The longest interval separating two earthquakes is greater than 1000 yr (Table 7). The shortest interval between earthquakes is 190 yr, considering the minimum time between burial of soils 2 and 3 and soils 11 and 12 (Table 7). By comparison, Kelsey et al. (2002) calculated a shorter average recurrence interval of 480–535 yr for 11 earthquakes in the past 5600 yr at the Sixes River estuary 35 km to the south of the Coquille estuary. At Willapa Bay in southwestern Washington (Fig. 1), Atwater and Hemphill-Haley (1997) reported an average recurrence interval of 500–540 yr for seven earthquakes over a period of 3500 yr.

Comparison of Cascadia Earthquake Chronologies

Earthquake chronologies documented at other estuaries in Oregon and Washington and a freshwater pond in California provide comparisons to the 6700-yr earthquake record at the Coquille estuary (Fig. 10). The other chronologies include a 4000 yr record from four estuaries in southwestern Washington (Atwater and Hemphill-Haley, 1997; B. Atwater, 2003, personal commun.); a 4800 yr record at Coos Bay, Oregon (Nelson et al., 1996a, 1998;

A. Nelson, 2003, personal commun.); a 5600 yr record at the Sixes River, southern Oregon (Kelsey et al., 2002); and a 3400 yr record of tsunamis generated by Cascadia earthquakes at Lagoon Creek, northern California (Abramson, 1998; Garrison-Laney, 1998).

Overlapping radiocarbon ages (at two standard deviations) among widely separated sites suggest that Coquille earthquakes 1, 2, and 3 ruptured at least 610 km (Fig. 10) and possibly the entire length of the subduction zone as hypothesized for the A.D. 1700 earthquake (Nelson et al., 1995; Satake et al., 1996). However, the lack of an age for Sixes soil II makes uncertain whether 2 and/or 3 at the Coquille estuary ruptured the entire margin. Correlation of Coquille soil 4 is problematic because the age comes from a single sample and potentially correlative soils either have no age or have an age range that only partially overlaps. Soil 7 may record an earthquake that broke 440–475 km of the plate boundary (Fig. 10).

Radiocarbon age estimates suggest that at least two earthquakes within the past 2000 yr (Sixes “III” and Willapa “W”) and possibly two earlier earthquakes (Coquille 5 and 6) did not rupture the entire length of the Cascadia subduction zone (Fig. 10). Kelsey et al. (2002) argued that the earthquake that buried soil III at the Sixes River lacks a correlative event at each of the three sites to the north (Fig. 10). Similarly, the penultimate earthquake recorded at Willapa Bay (Willapa “W”) and at Coos Bay (Coos Bay “2”) ~1000 yr ago lacks a correlative event to the south at the Coquille or Sixes estuaries. Also, there is a notable absence of a tsunami deposit at Lagoon Creek in northern California.

Is it likely that the Coquille record is missing stratigraphic evidence for an earthquake ~1000 yr ago? Furthermore, was there sufficient time to reestablish marsh conditions that would have recorded coseismic subsidence 760–1140 cal yr B.P.—the time when earthquake “W” at Willapa Bay would have struck the Coquille estuary? Three reasons suggest that the marsh recorder at the Coquille estuary was set and no earthquake occurred in southernmost Oregon. First, Atwater and Hemphill-Haley (1997) suggest that Cascadia estuaries probably require less than 150 yr to reset as earthquake recorders. For instance, spruce forests became reestablished within 50 yr after the A.D. 1700 event drowned coastal lowlands surrounding Willapa Bay and Grays Harbor (Benson et al., 2001). Because the tidal range at the Coquille estuary (~2 m) is similar to tidal ranges in southern Washington (<3 m), 50–150 yr is a reasonable estimate for the

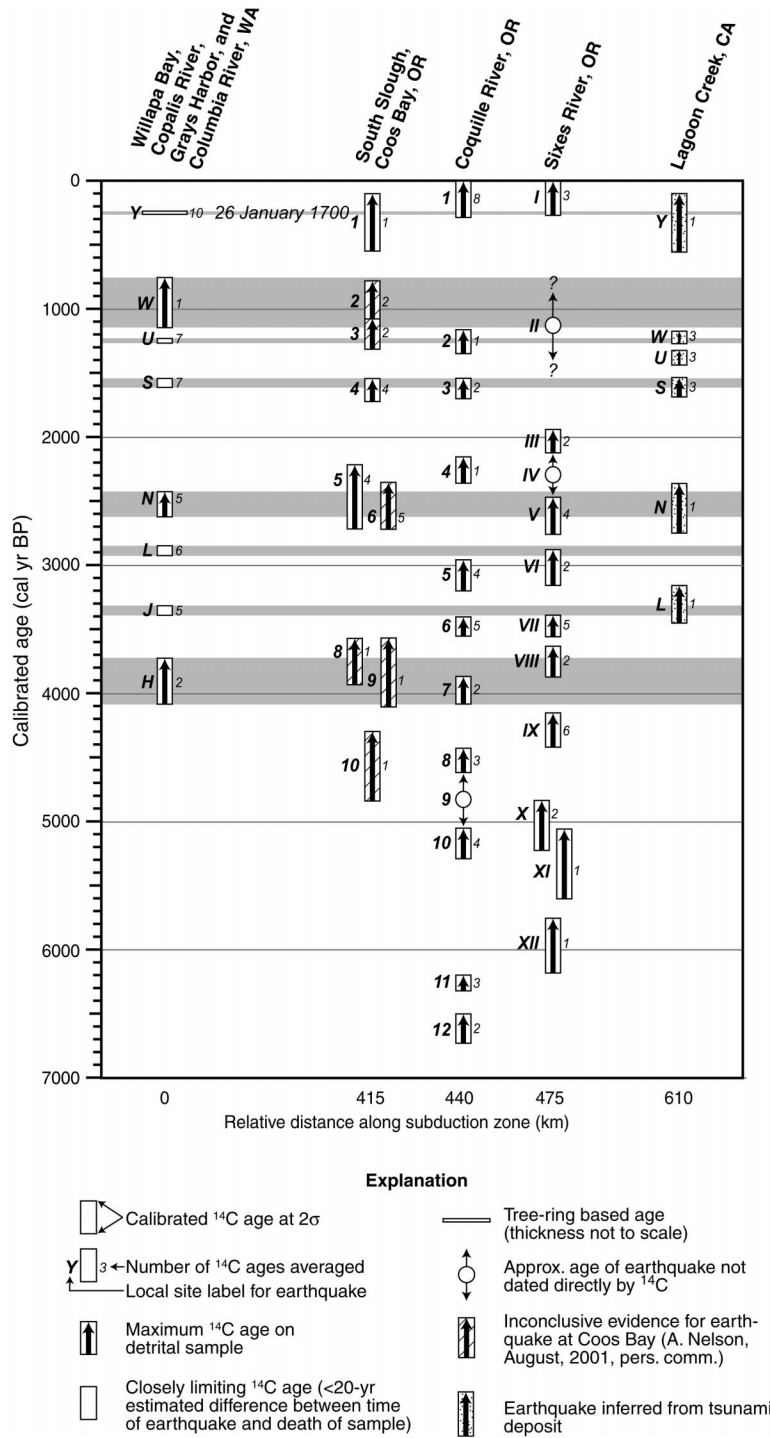


Figure 10. Comparison of calibrated radiocarbon age estimates for Cascadia subduction zone earthquakes recorded at Coquille estuary with earthquake age estimates from southwestern Washington (Atwater and Hemphill-Haley, 1997; Atwater, unpub. data), South Slough at Coos Bay (Nelson et al., 1996a, 1998; Nelson, unpub. data), Sixes River (Kelsey et al., 2002), and Lagoon Creek in northwestern California (Abramson, 1998; Garrison-Laney, 1998). Age comparisons suggest that at least two and possibly four earthquakes in last 4000 yr did not rupture entire subduction zone between southwestern Washington and southwestern Oregon.

amount of time required to reset Coquille marshes that can record coseismic subsidence.

Second, 9.6- to 14-cm-thick mud deposits that bury soil 2 (Tables 2 and 4) require a maximum of 95–140 yr to accumulate, assuming an average sedimentation rate of ~1 mm/yr. The actual time required may have been less than this estimate, because rates of deposition by tidal processes in the decades following the earthquake were probably higher (e.g., Atwater et al., 2001). Considering the time interval range between the two earthquakes (30–580 yr separate ages for Coquille “2” and Willapa “W”), we infer that sufficient time was available for the observed intertidal and subtidal deposits to accumulate and for estuarine conditions to become reset to record the next earthquake. Marshes at the Coquille estuary probably were not ready to record the event if it occurred within 50 yr of the prior earthquake.

Finally, no additional buried soils were observed between soil 2, buried 1170–1340 cal yr B.P. and the youngest soil buried in A.D. 1700. Because the Coquille estuary was ready to record an earthquake around the time of event “W” at Willapa Bay, and because there is no stratigraphic indication of such an event, we infer that earthquake “W” did not rupture the plate interface offshore southern Oregon at the latitude of the Coquille estuary.

The age estimates for two earlier earthquakes recorded by Coquille soils 5 and 6 do not overlap (at two standard deviations) with age estimates from sites to the north. However, both soil ages compare well with ages of soils VI and VII at the Sixes River (Fig. 10). This comparison suggests that two earthquakes, one 2960–3200 cal yr B.P. and another 3400–3550 cal yr B.P., ruptured the plate boundary offshore southern Oregon but not along the 415 km of coast between Coos Bay and southwestern Washington. Although the age estimates partially overlap, evidence for a tsunami deposit at Lagoon Creek possibly correlative with soil 6 provides less support for this hypothesis. Neither earthquake was recorded at the South Slough (Fig. 10). Because age estimates in Oregon provide maximum limits for soil submergence, correlation with soils L and J in southwestern Washington cannot be precluded.

If, unlike the A.D. 1700 earthquake, some Cascadia earthquakes did not rupture the entire plate boundary, then at least for some events, rupture terminated at a segment boundary in central or southern Oregon. Possible segment boundaries that may be responsible for arresting rupture lie offshore Yachats in central Oregon and Cape Blanco to the

south. Gravity anomalies that delineate a series of five forearc basins offshore Washington, Oregon, and northern California corroborate this possibility. Wells et al. (2002) recognized empirical correlations between forearc basins and regions of high coseismic slip for the largest historical circum-Pacific subduction earthquakes that suggest the Cascadia margin is segmented and may be characterized by a variety of rupture modes. Transverse gravity highs that separate basins in the Cascadia forearc occur adjacent to Yachats and Cape Blanco and may pose barriers to rupture during some great earthquakes (Wells et al., 2002). We propose that the Yachats or Cape Blanco gravity highs may have limited rupture propagation to the south during a Cascadia earthquake 760–1140 cal yr B.P. recorded in southwestern Washington and possibly arrested northward rupture propagation during Cascadia earthquakes in southern Oregon at 1940–2130 cal yr B.P. (Sixes “III”) and 3400–3550 cal yr B.P. (Coquille “6” and Sixes “VII”) (Fig. 10). The possibility that some earthquakes ruptured discrete segments several hundred kilometers shorter than the full (>900 km) length of the plate boundary constrains the size of some earthquakes to less than M_w 8.5.

Ruff (1996) summarized several historical examples of earthquake sequences at subduction zones that switch rupture modes. These examples provide realistic analogue scenarios for past Cascadia earthquake sequences shown in Figure 10. For example, the Columbia–Ecuador subduction zone ruptured in one great earthquake in 1906 (M_w 8.8), and subsequently re-ruptured in 1942 (M_w 7.9), 1958 (M_w 7.8), and 1979 (M_w 8.2) as three large earthquakes on separate segments of the plate boundary (Kanamori and McNally, 1982). The Nankai Trough also exhibits variable rupture lengths for great earthquakes (Ando, 1975). Better understanding of plate-boundary segment interaction in Cascadia will provide insight into subduction zone earthquake sequences, the range of earthquake magnitudes, and the variability in earthquake recurrence times.

Evaluating Possible Late Holocene Slip on the Coquille Fault

The Coquille fault vertically offsets the 80,000-yr-old Whiskey Run platform by as much as 50 m at the entrance to the Coquille estuary, but has the fault moved in the late Holocene? To address this question, we constructed relative sea-level curves from data on opposite sides of the fault to evaluate possible

evidence for vertical upper-plate deformation in the past 6200–6310 cal yr B.P. If vertical movement on the fault has occurred, then the trends of relative sea-level rise between Sevenmile Creek and Ferry Creek should diverge (Fig. 9). Because no estuarine diatoms were present in sediment from Ferry Creek, we cannot conclusively demonstrate that relative sea-level histories differ on either side of the fault. Therefore, we found no conclusive evidence for late Holocene slip on the Coquille fault.

However, several geomorphic observations are consistent with tectonic emergence of the lower Ferry Creek valley due to inferred vertical deformation on the upthrown (southern) side of the Coquille fault. First, the floodplain of the creek lies 2.5–3 m higher than the valley floor of Sevenmile Creek based on measured elevations along kilometer-long coring transects within several hundred meters of the main Coquille River channel in both valleys (Fig. 9). Second, the incised channel of Ferry Creek cuts down 2 m into floodplain deposits well above the reach of the highest tides, unlike the lower valley of Sevenmile Creek, which would be flooded daily by tides if not for a tide gate at the mouth of the creek. Third, the absence of buried soils younger than soil 4 suggests that after 2150–2360 cal yr B.P., the elevation of the valley floor was too high to record aggradation in response to coseismic subsidence of the estuary unlike lower environments that recorded events 3, 2, and the A.D. 1700 earthquake. Finally, the Ferry Creek floodplain does not grade to tidal flats like Sevenmile Creek, but instead projects 2–3 m above mean tide level where the creek meets the estuary.

Although we prefer a tectonic explanation for the relatively high geomorphic position of the Ferry Creek valley, without further study, some alternative explanations should be considered. For example, impoundment of Ferry Creek sediments behind dunes or levee deposits along the southern bank of the Coquille estuary could explain these observations. Alternatively, higher rates of sediment aggradation in the valley due to high weathering or erosion rates of local bedrock cannot explain the anomalous elevation of the valley floor, because aggradation rates at Sevenmile Creek equal or exceed those at Ferry Creek (Fig. 9).

If vertical displacement on the Coquille fault has occurred in the late Holocene, then constraints on the maximum elevation of mean tide level at Ferry Creek (Table 6) can be used to estimate a maximum slip-rate for the fault (Fig. 9). The maximum divergence in the trend of relative sea-level rise at Ferry Creek versus Sevenmile Creek is 1.2–2.8 m

over the past 6200–6310 cal yr B.P. (Fig. 9). If this difference is real, then it can be accounted for by a maximum vertical slip rate on the fault of 0.2–0.4 mm/yr. This slip rate estimate falls within the range of long-term vertical slip-rate estimates (0.1–0.6 mm/yr) for the Yaquina Bay fault and other upper-plate structures (Kelsey et al., 1996) that lie above the locked plate interface in Oregon.

CONCLUSIONS

Twelve Cascadia subduction zone earthquakes lowered tidal marshes and low-lying forests into the lower intertidal zone during the last 6500–6700 yr at the Coquille River estuary in southwestern Oregon. The A.D. 1700 earthquake tectonically subsided the youngest buried soil, which was preserved in the Bandon and Osprey marshes. Eleven other buried marsh and upland soils preserved in three tributary valleys of the estuary provide evidence for repeated episodes of coseismic subsidence triggered by rupture of the Cascadia plate boundary. Stratigraphic evidence for coseismic subsidence includes rapid, lasting relative sea-level rise; laterally continuous buried soils over hundreds of meters; fossil diatom assemblages that indicate maximum coseismic subsidence reached 1.2–3 m; and tsunami deposits that abruptly overlie the buried soils. Tsunamis inundated the Coquille estuary and deposited sand as much as 10 km up tributary valleys. The earthquakes occurred on average every 570–590 yr. Intervals between earthquakes lasted as little as a few hundred years to over 1000 yr.

Comparisons of the Cascadia earthquake history at the Coquille estuary with earthquake histories at several estuaries (Willapa Bay, Copalis River, Grays Harbor, and Columbia River) in southwestern Washington, South Slough, and the Sixes River in south-central Oregon and Lagoon Creek in northern California suggest that at least two and possibly four earthquakes in the last 4000 yr did not rupture the entire length of the subduction zone. Unlike the A.D. 1700 event, an earthquake 760–1140 cal yr B.P. was confined to a segment north of the Coquille estuary and an earthquake 1940–2130 cal yr B.P. was limited to a segment south of the Coquille estuary. Comparisons among ages also show that earthquakes recorded in southern Oregon 2960–3200 and 3400–3550 cal yr B.P. may not have propagated north of the Coquille estuary. Based on different earthquake histories region-wide, we infer that segment boundaries, perhaps near Yachats and Cape Blanco, may act as barriers to rupture propagation and

limit the size of some earthquakes to $M_w < 8.5$. Therefore, the recurrence and spatial distribution of earthquakes on the Cascadia subduction zone may best be explained by a variable rupture mode model, whereby giant earthquakes that rupture the entire margin may be followed by earthquakes of lesser extent that rupture segments of the subduction zone.

A comparison of the Sevenmile Creek relative sea-level curve to maximum constraints on the elevation of mean tide level at Ferry Creek failed to show conclusive evidence for late Holocene slip on the Coquille fault. However, geomorphic characteristics of the lower Ferry Creek valley that are consistent with localized tectonic uplift relative to tributary valleys studies elsewhere in the estuary show that late Holocene deformation cannot be precluded. If the fault is active, then the maximum vertical slip rate does not exceed 0.2–0.4 mm/yr.

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