Response of a small Oregon estuary to coseismic subsidence and postseismic uplift in the past 300 years

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ABSTRACT

The Sixes River estuary, south coastal Oregon, sits above the locked portion of the Cascadia subduction zone, which intermittently releases in subduction-zone earthquakes. One such Cascadia earthquake ~300 years ago caused subsidence and a tsunami at the Sixes estuary. The subsidence raised the river's base level, resulting in an ~3 km upstream shift of the head of tide of the estuary. At the upper end of the expanded estuary, more than 4 m of overbank sediment was deposited in the first decades or century after subsidence. Subsequent incision through the overbank deposits accompanied the gradual emergence of the estuary, and attendant downstream shift of the head of tide, as relative sea level fell in response to interseismic uplift.

INTRODUCTION

Three hundred years ago, probably on January 26, 1700, the coast of Washington, Oregon, and northern California underwent a great ($M_w \geq 8$) earthquake associated with rupture of the Cascadia subduction zone (Nelson et al., 1995; Satake et al., 1996; Jacoby et al., 1997; Yamaguchi et al., 1997). The earthquake was accompanied by coastal subsidence, liquefaction, and tsunami inundation (Atwater et al., 1995). On the basis of analogy to other subduction zones (Plafker, 1969, 1972; Brown et al., 1977; Thatcher, 1984) and geodetic survey results from Cascadia (Savage and Lisowski, 1991; Savage et al., 1991), the coastline of the Cascadia subduction zone responds to plate convergence through an earthquake deformation cycle whereby coseismic subsidence is followed by postseismic rebound and interseismic uplift as stress again builds up on the subduction-zone interface. If this earthquake cycle operates in the southern portion of the Cascadia margin, sedimentary sequences in river estuaries should record a predictable succession of relative sea-level changes occurring over the past three centuries. In this paper we report the effects of a subduction zone earthquake, probably the one that struck Cascadia in January 1700 on the Sixes River estuary (Boggs and Jones, 1976) in south coastal Oregon (Fig. 1).

Following the definition of Dalrymple et al. (1992), we consider the upvalley extent of the Sixes estuary to be the upvalley extent of the freshwater tidal zone, or head of tide. The head of tide is the upvalley limit of tidally induced daily rise and fall of river stage. In the winter months, the Sixes River remains freshwater below the head of tide because high winter discharges flush directly to the ocean. In the summer months, the estuary is freshwater (<5‰ salinity) except for a 1–3-m-thick saline (~25‰) wedge that extends ~1500 m up from the mouth.

The head of tide should shift upstream immediately after coseismic subsidence and then should shift gradually downstream during interseismic emergence. Because the Sixes estuary is not saline for most of the 3.2 km distance between the river mouth and head of tide (Fig. 1), a subsidence-induced upvalley shift of the head of tide may not be accompanied by a notable increase in salinity, although water-table levels would rise. However, the base level of the Sixes River would shift upstream, influencing the loci of fluvial deposition in the upper reaches of the estuary. Stratigraphy at three sites along the lower Sixes River (Fig. 1) records changes consistent with this model.

SEDIMENTARY SEQUENCES AND DIATOM BIOSTRATIGRAPHY AT THE SIXES RIVER MOUTH

The mouth of the Sixes River is flanked by a low terrace underlain by nested sedimentary sequences (Fig. 2). The cut and fill cycles recorded in this terrace are the result of abrupt submergence of subaerially exposed former estuarine sediments, followed by gradual re-emergence over the past several centuries.

Strata underlying the low terrace consist of six sedimentary sequences, bounded by unconformities (Fig. 2). The terrace has 2 m of relief; the relief is a consequence of erosion and deposition as sequences were added to the area. Deposition of fluvial gravels that constitute the oldest sequence

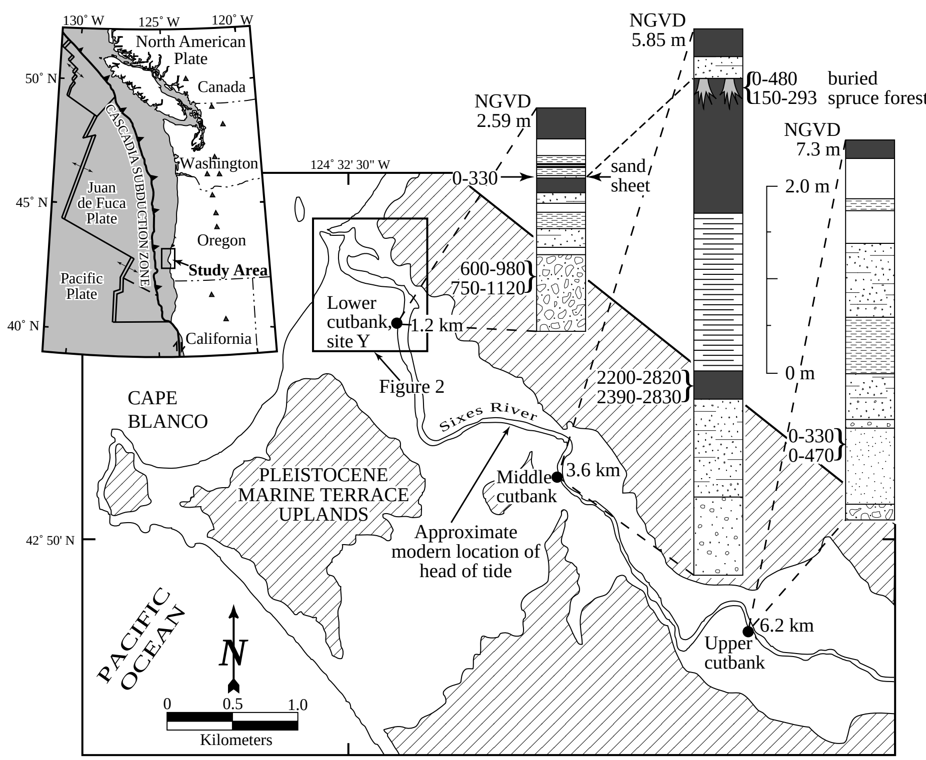

Figure 1. Lower 8 km of Sixes River valley, showing stratigraphic data at cutbank sites 1.2, 3.6, and 6.2 km above river mouth. Fluvial terrace elevations in meters are surveyed to National Geodetic Vertical Datum (NGVD); mean higher high water is 1.0 m. Low-water river stage is about 0.5 m, 1.3 m, and 3.2 m at three cutbank sites. Age ranges are years before A.D. 2000 (Table 1). Lithologic patterns are explained in Figure 3. Diagonally lined area is late Pleistocene marine terrace deposits (Kelsey, 1990).

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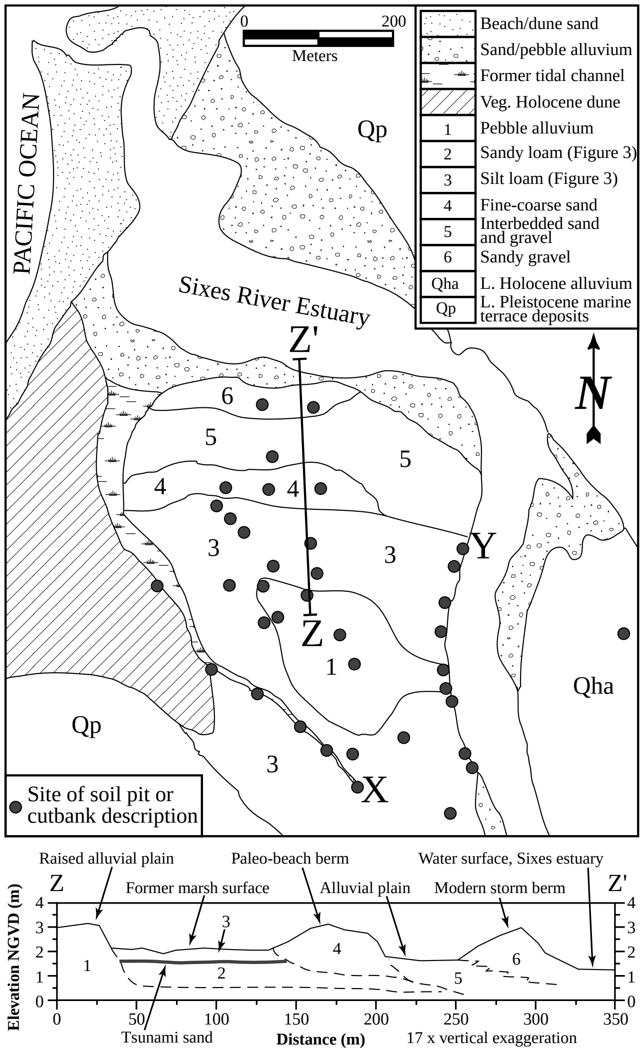

Figure 2. Top: Geologic map of low terrace in lower Sixes River valley showing six stratigraphic sequences that underlie terrace, deposited during progressive relative sea-level changes. Bottom: Cross section through six stratigraphic sequences; solid line is surveyed surface topography and dashed lines are approximately located subsurface contacts.

(1) occurred during and prior to 600–1120 yr ago, on the basis of ^{14}C dates near the top of sequence 1 (Fig. 3, Table 1). The next-to-oldest sequence (2) is a coarsening-upward sequence from silt loam to loamy sand; a soil is developed on top (site Y, Figs. 1 and 3); the soil is bioturbated by roots and burrows, showing that the top of sequence 2 was a subaerially exposed surface long enough to develop an A horizon characteristic of an upland soil (soil profile description, Table 1A[1]).

The basal unit of sequence 3 is a well-sorted fine sand that is overlain by silt loam and loam (Fig. 3). A surface soil, similar in character to the buried soil of sequence 2 (Table 1A; see footnote 1), is developed on top of sequence 3 (Fig. 3). The sand was deposited as a 20–50-mm-thick sheet over the entire flood-plain area containing sequence 3 deposits (Fig. 2), and is in abrupt (<1 mm) contact over the buried soil. In a former tidal channel near site X (Figs. 2 and 3), sand thickness reaches a maximum of 35 cm. From fining-upward sand beds at this site, we infer the sand was deposited in at least two, and perhaps three, separate pulses (Fig. 3). Wood detritus deposited with the last pulse has a maximum age of 330 yr ago (A.D. 1670) (Fig. 3, Table 1).

Diatom analyses (Fig. 3; more comprehensive data are in Tables A2 and A3; see footnote 1) help establish the depositional environments of sequences 2 and 3. These sequences are presently above mean higher high water (MHHW) (Fig. 2), based on elevation surveys tied to the tidal datum at the Port Orford tide gage (National Ocean Survey, 1997) 12 km south of the Sixes River. The environment of deposition of sequence 2 sediment is estuarine, on the basis of the presence of brackish-marine diatoms. The buried soil at the top of sequence 2 has a mix of in situ fresh-brackish diatoms and remnant, dissolution-resistant brackish-marine diatoms, consistent with development of a freshwater meadow on emerged tidal-flat deposits. The sand at the base of sequence 3 contains brackish-marine diatom species consistent with deposition from a marine source (Hemphill-Haley, 1996). The sedimentary units that buried the soil show a relative reduction in remnant brackish-marine species and increase in species typical of fresh-brackish wetlands (Fig. 3). The same fresh-brackish species (species that can tolerate salinites up to 5‰–10‰) are found before as after this event (e.g., *Cosmioneis pusilla*, *Hantzschia amphioxys*, *Pinnularia lagerstedtii*; Tables A2, A3); therefore, no abrupt rise in salinity is evident. However, relatively higher numbers of better-preserved specimens show that the depositional regime shifted from a drier to wetter environment more conducive to diatom productivity.

In the past ~400 yr, the sediment that makes up the buried soil at site Y (Fig. 3) has undergone at least two reversals in direction of vertical movement relative to sea level. First, the sediment emerged (relative sea-level fall) and weathered to a soil, and then was submerged by an abrupt relative sea-level rise, which raised ground-water level, converting the dry meadow to a freshwater to fresh-brackish marsh. After submergence, site Y was more prone to overbank deposition by the Sixes River, and 0.7 m of silt loam and loam accumulated above the buried soil. Gradually, the site again emerged above the water table coincident with relative sea-level fall, bringing the soil to its present position above MHHW (Fig. 3).

SEDIMENTARY RESPONSE TO THE SEISMIC CYCLE

The sequence of sedimentation in the lowermost Sixes River valley is consistent with progressive vertical displacements occurring in the course of a subduction-zone earthquake cycle (Fig. 4). The emergence of sequences 1 and 2 sometime after 600–1120 yr ago (Y, Fig. 3) coincided with a period of strain accumulation on the subduction zone. Next, an abrupt rise in relative sea level accompanied coseismic subsidence brought on by a subduction-zone earthquake. The sand immediately above the sequence 2 soil was deposited by a multiple-wave tsunami generated by the earthquake, which occurred sometime after A.D. 1670 (Fig. 3, Table 1), but before European settlement in A.D. 1870 (Masterson, 1994). Subsidence shifted the head of tide upvalley and coverted the dry meadow at Y to a fresh-brackish wetland. Fresh and fresh-brackish sediment of sequence 3 accreted in the wetland, and wind-driven waves in the expanded lower estuary built a west-trending sand beach berm (sequence 4, Fig. 2) adjacent to sequence 3 deposits at the southern estuary margin. Detrital marine fossils in the berm support the contention that it consists of sand brought into the estuary from the beach zone.

The subsequent gradual emergence of, and soil development on, sequence 3 deposits mark the inception of uplift of the upper plate in response to strain accumulation on the subduction-zone interface; this uplift has been on the order of 4 mm/yr from A.D. 1950 to 1990 (Mitchell et al., 1994). As relative sea level fell, the sequence 4 beach berm was abandoned and alluvial sediment (sequence 5, Fig. 2) prograded over this and

[1]GSA Data Repository item 9826, soil and diatom analyses, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

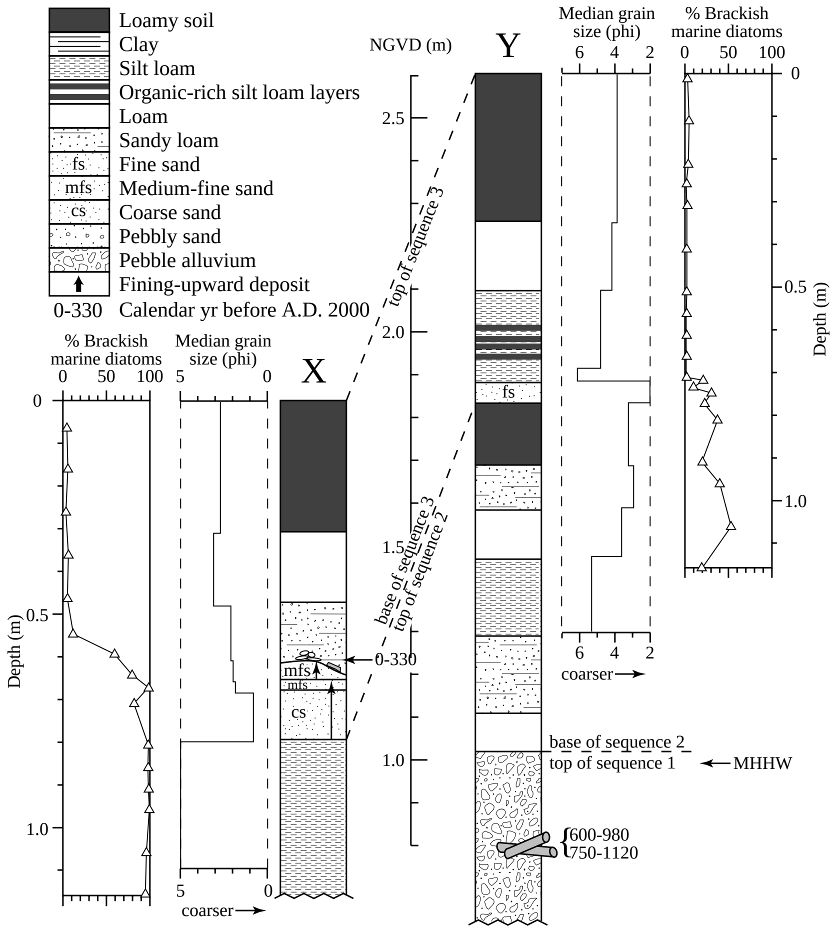

Figure 3. Stratigraphy, grain size, and diatom biostratigraphy for sites X and Y on low terrace at mouth of Sixes River (locations in Figure 2). Relative elevation of two sites is depicted by vertical scale. Column X shows deposits at former tidal slough; column Y is cutbank exposure. Thin sand layer above buried soil at Y is correlative to thicker sand deposited at X, which is composed of two fining-upward units (black arrows), with discontinuous layer of pebbles at base of next overlying unit. Each fining-upward unit represents a pulse of deposition; pebble layer may be basal deposit of third pulse. Ages are years before A.D. 2000 (Table 1). MHHW, mean higher high water.

TABLE 1. RADIOCARBON AGES, LOWER SIXES RIVER VALLEY

Lab number*	$\delta^{13}C$	Age and reported error (^{14}C yr B.P.)	Calibrated age, yr before A.D. 2000 † (yr ago)	Sample material
Lower cutbank at river km 1.2				
AA 19422	-25.1	120 ± 50	0-330	piece of tree bark
B 45877	n.m.*	800 ± 70	600-980	6 mm diameter twig
B 45878	n.m.	990 ± 60	750-1120	4 mm diameter twig
Middle cutbank at river km 3.6				
B 40002	n.m.	190 ± 50	0-480	spruce root
QL-4910	-24.2	183 ± 13	150-222, 274-293	spruce root
B 47082	n.m.	2450 ± 80	2200-2820	6 mm diameter roots
GX 19892	-26.8	2499 ± 66	2390-2830	herbaceous roots
Upper cutbank at river km 6.2				
B 45875	n.m.	100 ± 60	0-330	one 20 g stick
GX 22342	-26.3	160 ± 60	0-470	leaf parts and small branches with bark

*B, Beta Analytic, proportional gas counting method, n.m. = $\delta^{13}C$ not measured, adjusted ages are normalized to -25=$\delta^{13}C_{(Peedee\ belemnite)}$; GX, Geochron, accelerator mass spectrometry; AA, University of Arizona, accelerator mass spectrometry; QL, Quaternary Isotope Lab, University of Washington, high precision ^{14}C age determination on ring numbers 38-42 in from bark.

†Calibration data of Stuiver and Reimer (1993), using 95% confidence interval and an error multiplier of 1.5. For sample QL-4910, 40 years was added to calibrated age to account for sampling site relative to bark.

older sequences. Sequence 5 alluvium is thus nested into the beach berm as well as into finer-grained sequence 3 deposits (Fig. 2). A storm berm (sequence 6, Fig. 2), parallel to but north of the berm that marked the short-lived expanded estuary, has built up at the southern margin of the modern small estuary at the mouth.

EXPANSION AND CONTRACTION OF THE ESTUARY AND OVERBANK DEPOSITION

The abrupt relative sea-level rise documented at the Sixes River mouth initiated an episode of overbank deposition within the lower 6.2 km of the river valley. At the lower site (river km 1.2), as much as 0.7 m of overbank deposition occurred shortly after the burial of the soil between A.D. 1670 and 1870 (Fig. 1). The middle cutbank site is similar to the lower cutbank in that a buried soil (upper buried soil, middle column, Fig. 1) is overlain by 0.5 m of overbank deposits. The buried soil, exposed along 250 m of cutbank, was an upland soil supporting a spruce forest. On the basis of a high precision ^{14}C age for a spruce root (Table 1), the forest died before A.D. 1850 but after A.D. 1707. Our favored interpretation, consistent with the ^{14}C age data, is that the buried soils at the middle and lower cutbanks are correlative (Fig. 1), and that the overbank sediment above the buried soils was deposited within the same time period following subsidence. If the earthquake occurred in A.D. 1700, then the middle cutbank trees survived for several years after the earthquake.

At the upper cutbank site ~6.2 km upstream of the mouth, and exending along the cutbank for ~1 km, more than 4 m of overbank sediment was deposited after A.D. 1530–1670 (Fig. 1, Table 1). Because the sediment does not contain soil horizons, it appears to have been deposited over a short interval without periods of land surface stability.

On the basis of the ^{14}C data, overbank deposition at the upper site could have occurred concurrently with the lower two sites or as much as a century earlier. The first alternative implies that deposition at the upper site occurred shortly after subsidence and soil burial at the lower site, at a time when relative sea level was at its highest. In this favored alternative, upper cutbank overbank deposition took place after an upstream shift of the head of tide effectively raised the base level of the Sixes River.

The base level created by an upstream shift of the head of tide is analogous to the base level created at the upper end of a dam impoundment. River response to raised base level above dams is aggradation over a period of years to a few decades in the reach immediately upstream (25–300 m) of the new base level (Leopold and Bull, 1979). In the Sixes River estuary, the hypothesized 3–4 km upstream shift of the head of tide caused suspended sediment to accumulate rapidly (decades to less than a century) at the upper cutbank site. Deposition occurred as the sediment-laden winter flood flows of the Sixes River decelerated on reaching the tide-induced backwater.

Although rapid relative sea-level rise initiated overbank deposition at all three sites, the thickness of deposits was greatest at the upper cutbank. The abrupt decrease in hydraulic gradient induced by the head of tide at the upper cutbank promoted suspended sediment deposition at the upstream most site. Compared to the upper cutbank, less overbank sediment could be deposited at the middle cutbank because it supported a forest and was higher relative to the channel. The upper cutbank site, being relatively lower, could accommodate a greater thickness of sediment before the surface aggraded to an elevation less prone to overbank deposition.

In the decades following subsidence and relative sea-level rise, the head of tide has moved downstream as relative sea level gradually fell. As a result, the Sixes River incised; incision probably is ongoing because the area has a geodetically derived uplift rate of about 4 mm/yr (Mitchell et al., 1994). All three cutbank sites are currently too high to be regularly inundated by the river.

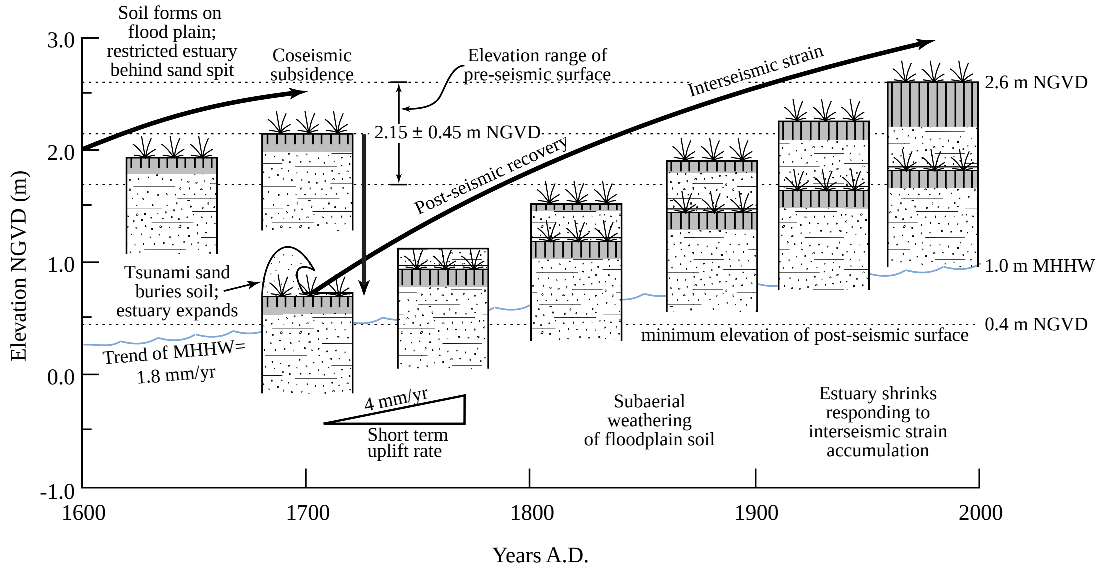

Figure 4. Schematic depiction of vertical displacement of buried soil at site Y in response to seismic cycle. Vertical displacements brought about successively by gradual strain accumulation (A.D. 1600–1700), coseismic subsidence (A.D. 1700), and postseismic rebound and renewed gradual strain accumulation (A.D. 1700 to 2000). Trend of mean higher high water (MHHW) based on Port Orford tide data (http://www.olld.nos.noaa.gov), and rate of sea-level rise in preceding four centuries (taken to be 1.8 ± 1 mm/yr, the global mean sea-level rise over past 80 years [Douglas, 1991]). Surface elevation of pre-earthquake soil constrained to be not higher than present soil (2.6 m; based both on soil data and diatom biostratigraphy for modern versus buried soil [Tables A1 and A2, see text footnote 1]) and not lower than 1.70 m (based on ~50 yr of historic uplift at 4 mm/yr [Mitchell et al., 1994] plus observed postsubsidence sediment accretion of 0.7 m). Minimum coseismic subsidence is 0.7 m (if 0.7 m of accretion above buried soil was brought on by minimum relative sea-level rise of 0.7 m). Because sediment overlying soil does not have brackish-marine diatoms, soil could not have subsided below MHHW of 300 yr ago (0.4 m), therefore maximum coseismic subsidence is 2.2 m (2.6 m–0.4 m).

CONCLUSION

In a small Oregon estuary where river stage is affected by tidal rise and fall but the estuary is largely fresh to fresh-brackish (<5‰ salinity), a flood-plain meadow coseismically subsided to become a fresh-brackish marsh. Subsidence occurred without an accompanying rise in salinity great enough to introduce different diatom assemblages. Diatom paleoecologic changes accompanying subsidence involved increased numbers and better preservation of fresh-brackish species as the deposition setting shifted from a drier meadow to wetter marsh.

Through mapping and surveying of stratigraphic sequences combined with diatom paleoecology, and applying a model that links relative sea-level change coincident with strain accumulation and release on a subduction zone to base-level-induced fluvial sedimentation, we chronicle the expansion and contraction of an estuary on the Oregon coast and the resulting pattern of fluvial and estuarine sedimentation during the course of uplift, abrupt coseismic subsidence and resumed uplift. Abrupt subsidence, probably the result of a subduction-zone earthquake in January 1700 induced a ~3 km upstream shift of the head of tide of the estuary, raising the base level of the Sixes River and inducing an episode of overbank deposition. Subsequent gradual uplift caused re-emergence of the estuary and renewed incision. These changes are consistent with the hypothesis that the Sixes River estuary is above that portion of the Cascadia subduction zone that is intermittently locked and released during ongoing plate convergence.

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