Late Holocene Coseismic Subsidence and Coincident Tsunamis, Southern Cascadia Subduction Zone, Hookton Slough, Wigi (Humboldt Bay), California

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ABSTRACT

In the past 3,650 years (cal. yr. B.P.) evidence of coseismic subsidence was recorded five times in stratigraphy of bay margin deposits in southern Humboldt Bay, California. There are five buried marsh soils along a 1-kilometer long transect adjacent to Hookton Slough, a tidal channel tributary in Humboldt Bay. Using the lateral extent of burial, the abrupt upper contacts to the soils, and the diatom biostratigraphy, soils subsided coseismically and those soil burials were accompanied by abrupt rises in relative sea level. Tsunami-transported sand, observed in the stratigraphy from Hookton Slough, was deposited directly on two soils at the time of subsidence. Buried soils at Hookton Slough are best explained by coseismic subsidence during Cascadia subduction zone earthquakes. Radiocarbon age estimates constrain timing of subsidence and allow me to estimate a recurrence interval of Cascadia subduction zone earthquakes in the Humboldt Bay region. A recurrence interval for these large earthquakes ranges from 650 to 720 years for the last 2,400 years. Three of the buried soils correlate to similar buried soils found at other sites around Humboldt Bay, and timing of subduction zone earthquakes at Hookton Slough overlaps with timing of earthquakes on the Little Salmon fault.

The largest subsidence estimates based on the paleoelevation method are determined to be a minimum of 0.9 meters. This minimum estimate is increased by utilizing the relief of the upper contact for one buried soil. The relief of the upper contact was over two meters. Since the paleoecology of the soil was freshwater pre-submergence, and the entire soil was coseismically buried by tsunami sands and then by tidal silts to clay-silts, the subsidence estimate is increased from less than one, to greater than two meters.

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INTRODUCTION

The principal objective of this study is to identify buried tidal marsh soils in sediments near Hookton Slough and assess whether each soil was buried due to abrupt tectonic subsidence and whether land level changes are concurrent with tsunami. Timing of the abrupt change is constrained with radiocarbon age determinations. Finally, correlations are made between the Hookton Slough earthquake chronology and the regional earthquake history.

Hookton Slough core sites are in a low-lying brackish marsh that mostly exists below mean higher high water, MHHW (Figure 1). Levees constructed up to the late 1920s (Shapiro and others, 1980) now prevent tidal inundation to core sites. However, portions of the study area are perennially submerged because levees restrict drainage of ground and surface water. At times the study site becomes flooded with as much as two meters of standing water, and flooding contributes to the preservation of subsurface stratigraphy.

METHODS

Paleoseismic investigations provide data on earthquake history. Atwater (1987) first suggested evidence of coseismic deformation of late Holocene estuarine deposits along the coast of Washington. Atwater (1987); Clarke and Carver (1992); Clague and Bobrowsky (1994); Nelson and others (1996a, 1996b, 1998); Hemphill-Haley (1995); Atwater and Hemphill-Haley, (1997); Kelsey, and others (2002); and Witter and others (2003) interpret mid- to late-Holocene buried tidal marsh soils to be caused by vertical land-level changes related to Cascadia subduction zone (CSZ) earthquakes. Since buried soils are not often exposed in cut banks in southern Humboldt Bay, research on buried soils requires coring in tidal marshes.

Fifty-three, 3-centimeter diameter gouge cores were hand driven to sample subsurface stratigraphy along the one kilometer transect: West, Center, and East Sections (Figure 1). In addition to gouge cores, nine vibra cores (7.5-centimeter diameter aluminum tubes) were taken at sites where gouge cores had the most complete stratigraphic section. The cores were driven down to 6 meters depth or until resistance by coarse sediment (pebbles up to 3-centimeter diameter) prevented further penetration. The core transect is sub-parallel to the break in slope, along the historic high tide line. Three main sub-transects, West, Center, and East sections, are separated by historic channels (blue lines; Figure 1).

If buried soils are to be considered evidence for coseismic subsidence, there are five criteria that could be satisfied (Nelson, 1996b). They include (1) suddenness of submergence, (2) submergence greater than or equal to 0.5 meters, (3) lateral extent of submergence over hundreds of meters, (4) coincidence of submergence with tsunami sands, and (5) synchronous submergence of correlative buried soils. In addition, Hemphill-Haley (1995) suggests three additional criteria: a significant change in diatom assemblage across a stratigraphic contact inferring a sudden change in land elevation, submergence indicated by the persistence of environmental change, and the presence of sand flat diatom species in the sand capping the mud. In this study not all five criteria were satisfied in order to demonstrate coseismic subsidence.

Fossil diatoms sampled from specific strata in vibra cores are used to infer changes in paleoenvironment relative to mean tidal level. Paleoenvironmental interpretation is based on the observation that Humboldt Bay organisms live in tidal range-restricted habitats based on salinity (Li, 1992; Manhart, 1992; Carver and others, 1998). Hemphill-Haley (1995) developed techniques to estimate paleoenvironment based on diatom assemblages in Willapa Bay, Washington using the Brackish Intertidal Diatom Index (BIDI). The BIDI is a ratio of the counts of groups of diatoms based on their modern tidal range and provides a qualitative estimate of paleoenvironment. BIDI values range from zero, inferring a sub-tidal environment, to one, inferring a more freshwater, high-marsh environment.

Age control for deposits is constrained using accelerator mass spectrometry 14C age estimates (Jacoby and others, 1995; Nelson and others, 1996b; Atwater and Hemphill-Haley, 1997). Only identifiable plant material was used for age control. Samples that likely persist through time (large chunks of wood, charcoal) were not chosen because they are more likely to be reworked, thus overestimating the age of the deposit.

RESULTS

The Hookton Slough cores show evidence of soils recurrently buried suddenly by mud to muddy peat. Sandy deposits abruptly overlie three buried soils. Abrupt and persistent paleoenvironmental change, as inferred from diatom analysis, accompanies the abrupt and persistent lithostratigraphic change. Accelerator mass spectrometry 14C age estimates constrain the timing of these changes.

Lithostratigraphy

Five buried muddy-peat to peat horizons are found (buried soils 1-5). Soil 1 is the most recent buried soil and soil 5 is the oldest buried soil. The soils are abruptly buried by either muds (soils 5 and 2) or by sands (soils 1, 3, and 4). The soils contain up to 100% fibrous peat.

The mud found between the buried soils has an abrupt (< 2 cm) lower contact (Figure 2) and a gradual (5 to 15 cm) upper contact. The abrupt lower contact indicates a rapid stratigraphic change and the gradual upper contact indicates a slower stratigraphic change. The mud consists of silty clay to silt loam.

The sand overlying soils 3 and 4 commonly consists of multiple normally graded beds of sand to sandy loam. The sand’s lower contact is abrupt, often with a wavy 1- to 4-centimeter relief. Commonly incorporated within the sand are 0.5- to 3-centimeter diameter rip-up clasts consisting of pieces of mud and pieces of fibrous peat (possibly from the underlying soil; Figure 2).

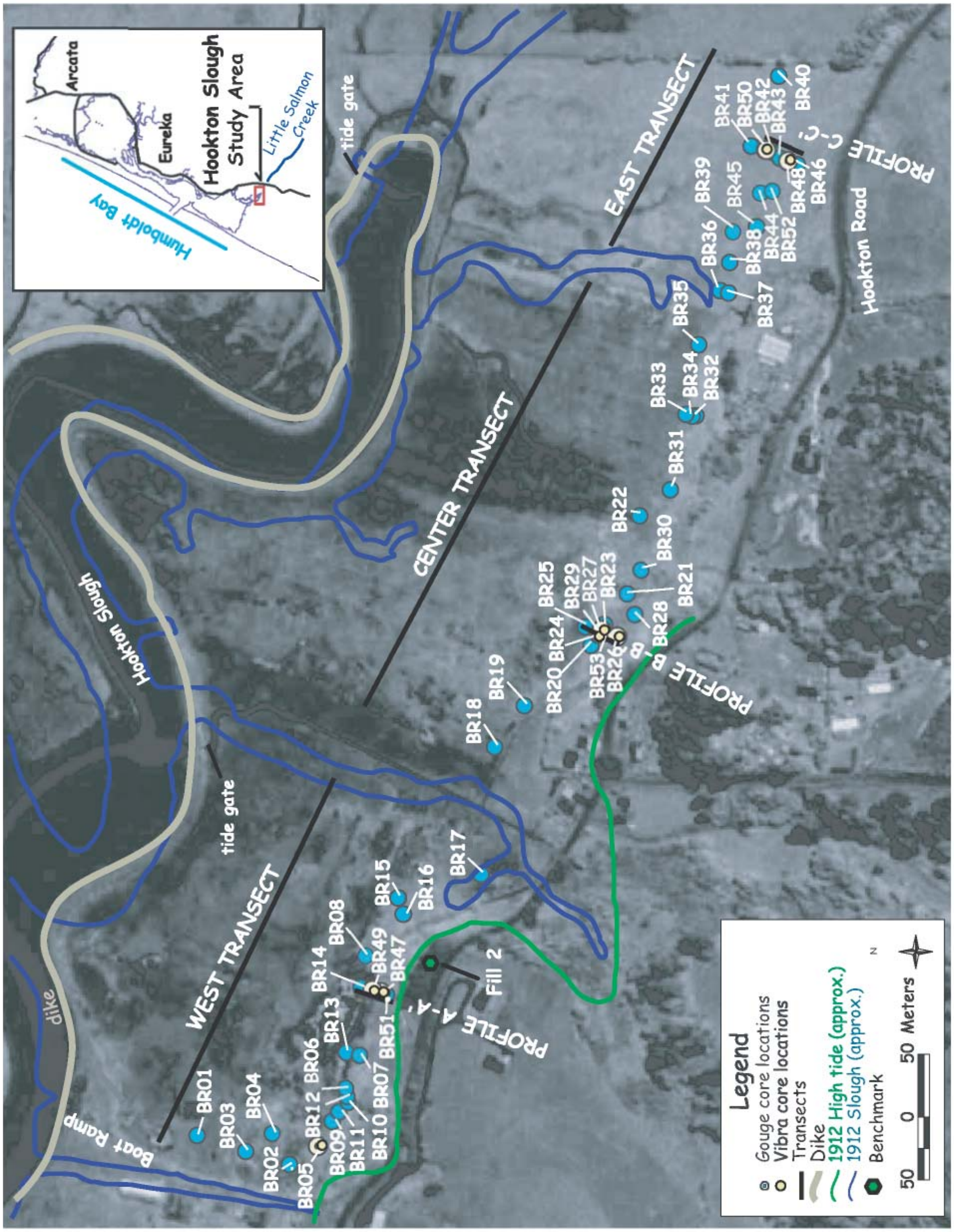


Figure 1. Hookton Slough core location map. Blue circles mark locations of gouge cores. Yellow circles mark locations of vibra cores. West, Center, and East transects are separated by historic tidal channels in green. 1912 high tide line in blue shows that all core locations were tidally inundated before the levees were constructed (Coast and Geodetic Survey, chart 18622, 1912). Tide gates permit partial tidal influence to study area. Imagery is a USGS panchromatic Digital Orthophoto Quarter Quadrangle, Fields Landing, 1989, with one meter pixels. Figure 4 photo point is shown along boat ramp. Hexagon indicates the location of the USGS benchmark (PID LV0658) “Fill 2.”

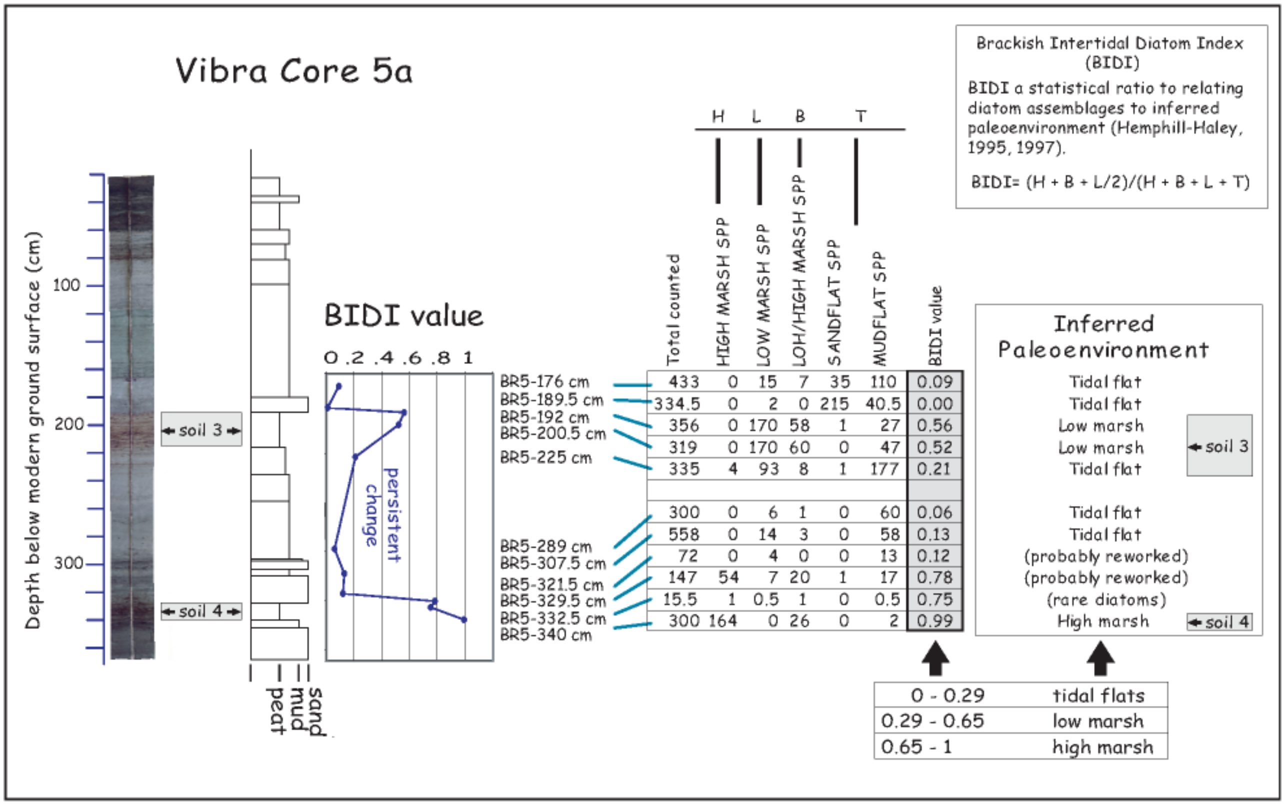
Coarse gravelly sand to sandy loam defines the depth of core refusal, which ranges from 1.5 to 6.1 meters depth (Figure 2). These deposits are interpreted to be colluvium from the Pleistocene Hookton Formation, found in outcrop directly upslope to the south of the coring transect.

Biostratigraphy

Based on plants (Triglochin) and diatom assemblages, soils found at Hookton Slough were likely developed in high marsh to upland environments and the overlying muds were deposited in low marsh environments (Figure 3). Environmental change inferred from fossil diatoms in cores 5A and 49 (analysis by Eileen Hemphill-Haley) reflects a high marsh to upland paleoenvironment abruptly changing to a tidal flat paleoenvironment for burial of soil four and a low marsh paleoenvironment to tidal flat paleoenvironment for burial of soil three (Figure 3). The abrupt change in inferred environment correlates with an abrupt lithostratigraphic change. A freshwater paleoenvironment of the coarse gravelly sand to sandy loam below the oldest buried soils is based on diatoms and the presence of phytoliths.

Radiocarbon Age Determinations

Hookton Slough buried soils 1, 3, 4, and 5 contained materials suitable for radiocarbon age determinations. Age control is poor to non-existent for soils 1 and 2.Radiocarbon age determinations for soils 3, 4, and 5 are summarized in figure 4.



Brackish Intertidal Diatom Index (BIDI)

BIDI a statistical ratio to relating diatom assemblages to inferred paleoenvironment (Hemphill-Haley, 1995, 1997).

BIDI= (H + B + L/2)/(H + B + L + T)

	Total counted	HIGH MARSH SPP	LOW MARSH SPP	LOH/HIGH MARSH SPP	SANDFLAT SPP	MUDFLAT SPP	BIDI value	Inferred Paleoenvironment
BR5-176 cm	433	0	15	7	35	110	0.09	Tidal flat
BR5-189.5 cm	334.5	0	2	0	215	40.5	0.00	Tidal flat
BR5-192 cm	356	0	170	58	1	27	0.56	Low marsh
BR5-200.5 cm	319	0	170	60	0	47	0.52	Low marsh
BR5-225 cm	335	4	93	8	1	177	0.21	Tidal flat
BR5-289 cm	300	0	6	1	0	60	0.06	Tidal flat
BR5-307.5 cm	558	0	14	3	0	58	0.13	Tidal flat
BR5-321.5 cm	72	0	4	0	0	13	0.12	(probably reworked)
BR5-329.5 cm	147	54	7	20	1	17	0.78	(probably reworked)
BR5-332.5 cm	15.5	1	0.5	1	0	0.5	0.75	(rare diatoms)
BR5-340 cm	300	164	0	26	0	2	0.99	High marsh

0 - 0.29	tidal flats
0.29 - 0.65	low marsh
0.65 - 1	high marsh

Figure 3. Diatom biostratigraphy in core 5a using the Brackish Intertidal Diatom Index (BIDI), developed by Hemphill-Haley (1995). In conjunction with disconformities above peats three and four, an abrupt change in inferred paleoenvironment occurs. Note that environmental change is persistent.

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DISCUSSION

Subsidence Mechanism

Criteria used to infer coseismic subsidence of the five soils identified from cores in Hookton Slough include: 1) suddenness of change in depositional environment, 2) amount of subsidence, 3) lateral extent, 4) presence of sand capping peat, and 5) synchroneity of buried soils (Nelson, 1996b; Hemphill-Haley, 1995). These criteria are satisfied robustly for three of the five soils (Table 1).

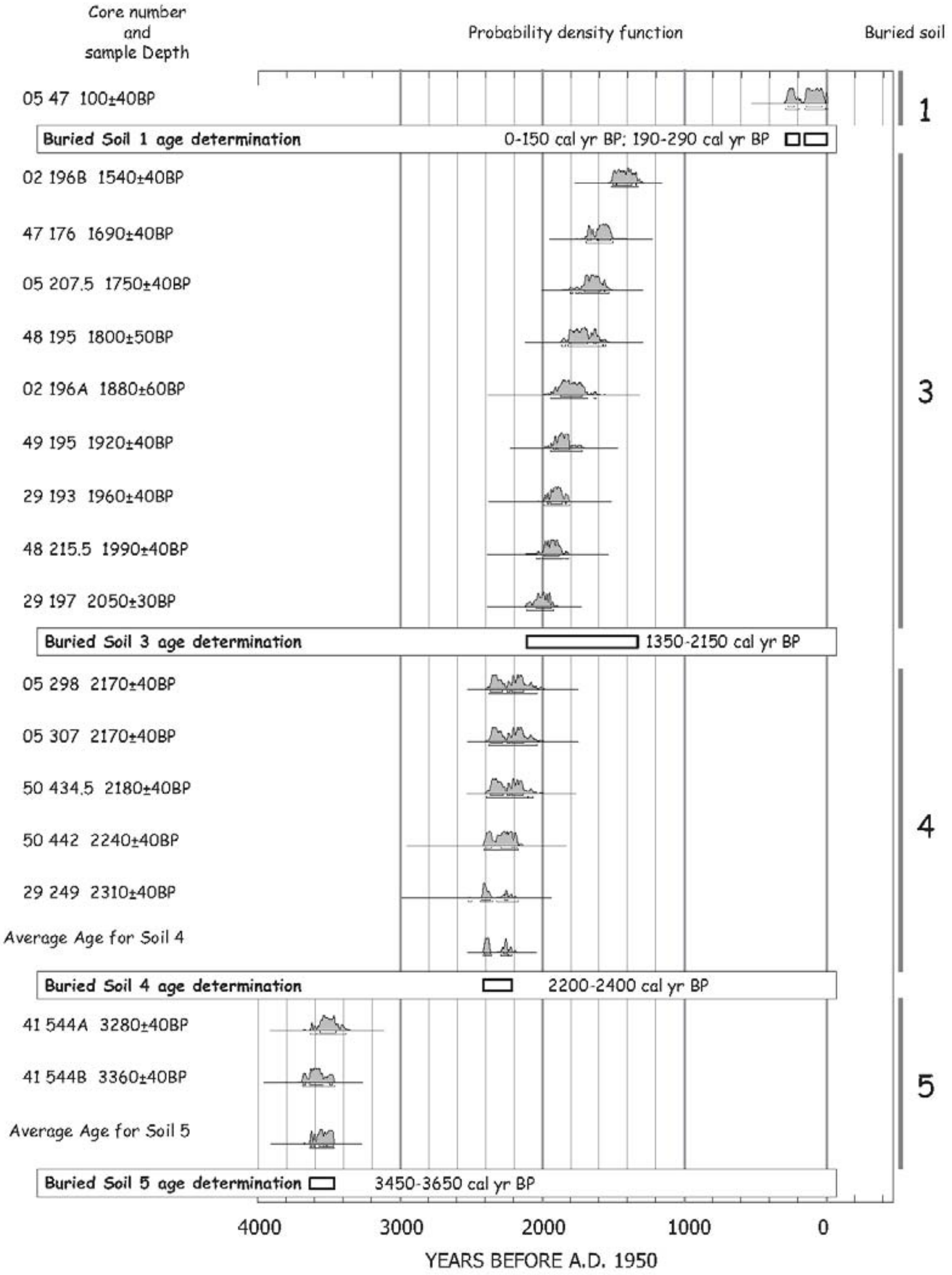

Figure 4. Radiocarbon Probability Density Function plots of sequence analysis procedure using Bronk-Ramsey (1995, 2001). Lab reported age estimates are combined before calibration resulting in averaged calibration ages. Interpreted age ranges for each buried soil are delineated by rectangles. Due to potential problems with soil 3 sample material, soil 3 age is determined with the span of individual calibrated ages. Soils 4 and 5 ages are interpreted from calibrated average ages. Sample nomenclature and axis values are the same as for figure 9. Atmospheric data from Stuiver and others (1998a, 1998b); Calibration software: OxCal v3.5 (Bronk Ramsey 1995, 2001); and Calib (Stuiver and Reimer, 1986, 1993)

Possible alternative explanations for all soil burials include cut-and-fill by tidal streams, sediment deposition by storms or floods, fluctuations in sea level, or intermittent closure of the mouth to Humboldt Bay. None of these alternative explanations is supported by field data.

In summary, abrupt and persistent lithostratigraphic and biostratigraphic changes coincide in sufficient frequency and over a sufficiently broad area (at least 48,000 m2) to verify the inference that several tidal marsh soils at Hookton Slough were buried by coseismic subsidence accompanying CSZ earthquakes. Coseismic subsidence occurred five times in the Hookton Slough region in the last 3,700 years.

Table 1. Lateral extent and stratigraphic characteristics for the buried soils at Hookton Slough, Humboldt Bay.

Buried Soil	Number of cores that sampled buried soil *	Minimum lateral extent of buried soil *	Depth range of buried soil (MLLW, cm) †	Number of cores with overlying sandy deposit *	Maximum thickness (cm) of sandy deposit	Maximum number of beds in sandy deposit
1	44	940 m	111 to 41	1	10	1
2	17	900 m	75 to 22	0		
3	29	1,000 m	-28 to -153	4	24	5
4	20	920 m	-121 to -353	9	45	9
5	1	1 m	-380	0		

* see Figure 10

† Mean Lower Low Water (MLLW)

Subsidence Magnitude

Estimates of subsidence magnitude may be made using the paleoelevation estimate and augmented by the pre-burial ground surface relief estimate. Paleoenvironment based on fossil diatoms is used to estimate paleoelevation range (Kelsey and others, 2002; Witter and others, 2003; Figure 5). Paleoenvironment is based on elevation relations between modern vascular plants and modern diatom zonation in southern Oregon (Nelson and Kashima, 1993). Changes of paleoelevation are determined by subtracting paleoelevation ranges of the buried soil from the overlying mud (Figure 5-A). Minimum and maximum paleoelevation estimates of submergence for soil 4 are 0.9 and 3.1 meters, respectively. Minimum and maximum paleoelevation estimates of submergence for soil 3 are 0.0 and 1.6 meters, respectively. Because the upland and mudflat elevation ranges are limited to 1 meter by truncating the unbounded upper and lower ends respectively (Figure 5), this method does not measure maximum submergence greater than 0.9 meters. Therefore, the maximum submergence estimate can be larger and is thus a lower limiting maximum.

For estimates using the pre-burial ground surface relief measurements, minimum submergence is larger than the paleoelevation method. Assuming the relief of buried soil 4's upper contact represents pre-existing topography, all of soil 4 was in an upland setting, and mud overlying buried soil 4 was deposited in a tidal flat setting (Figures 3 and 5), pre-subsidence elevation of soil 4 is constrained by paleoelevation estimate for sediment sampled from core 5A (Figure 5-B, a). Post subsidence elevation control is based on the highest position for soil 4 being at the highest elevation in the mudflat ecological range. Minimum submergence estimates are made by subtracting the lowest possible elevation of the topographically highest position of soil 4 in core 5A (pre-subsidence elevation minimum = 3.2-meters MLLW) from the highest possible elevation of the same highest topographic position of soil 4 in core 5A (post-subsidence elevation maximum = 0.3-meters MLLW). Modern tidal range is almost as large as the relief of soil 4. Only soil 4 upper contacts are sufficiently large with respect to tidal range to reliably use the relief method for a submergence estimate.

The paleoelevation minimum subsidence estimate cannot measure submergence larger than 0.9 meters. Given the uncertainty in paleoelevation estimates for the range of elevations of soil 4, topographically above soil 4 in core 5A, the relief derived minimum submergence estimate for soil 4 is 2.9 meters.

Maximum submergence cannot be completely measured with either method, because upper bounds of upland environments and lower bounds of mudflat environments cannot be constrained. Maximum submergence estimate methods need to be improved to better estimate subsidence maxima. Because the paleoelevation method cannot measure minimum submergence greater than 0.9 meters, the soil relief method is necessary in future studies to make better estimates of submergence in cases where subsidence may be greater than 0.9 meters, in this case, 2.9 m.

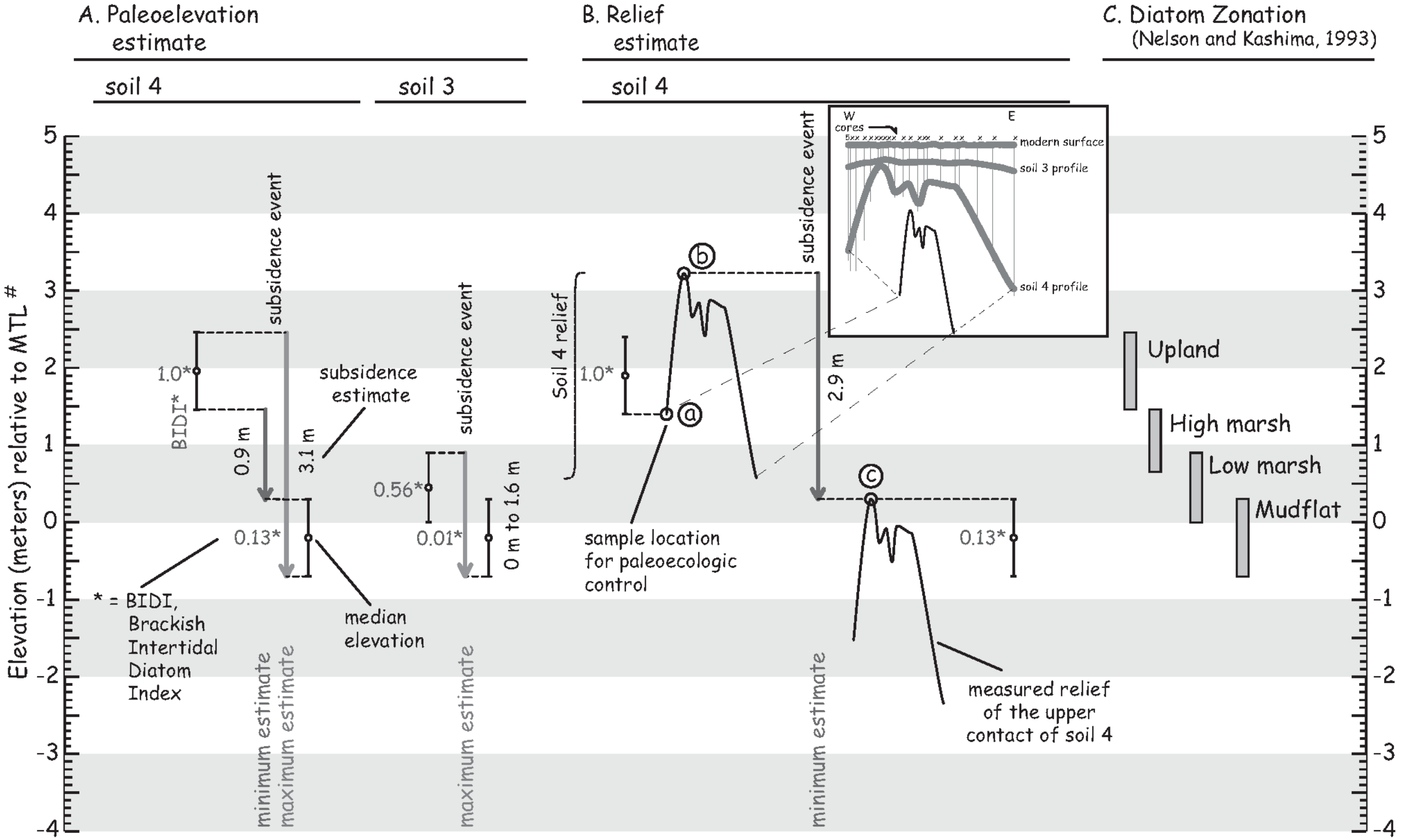

Figure 5. Subsidence magnitude estimates are made using paleoelevation and topographic relief methods. A. Changes of paleoelevation are determined by subtracting paleoelevation ranges of the buried soil from the overlying mud. B. Minimum submergence estimates are made by subtracting the lowest possible elevation of the topographically highest position of soil 4 in core 5A (post-subsidence elevation minimum = 3.2-meters MLLW; Fig. 12-B, b) from the highest possible elevation of the same highest topographic position of soil 4 in core 5A (post-subsidence elevation maximum = 0.3-meters MLLW; Fig. 12-B, c). Pre-subsidence elevation of soil 4 is constrained by paleoelevation estimate for sediment sampled from core 5A (Fig. 12-B, a). Post subsidence elevation control is based on the position of the highest position for soil 4 being at the highest elevation in the mudflat ecological range (Fig. 12-B, c). C. Diatom zonation is based on modern diatom ecology from coastal marshes in Oregon. The upper limit of the upland elevation range is truncated so that the range is 1 meter (Kelsey and others, 2002, Witter and others, 2003). Likewise, the mudflat elevation range is truncated on the lower end so that the range is 1 meter.

Coarse Sediment Deposition

There are several stratigraphic and paleontologic attributes of the Hookton Slough sandy sediment (“sand”) that permit an interpretation that it is of tsunamigenic origin. A sand-laden tsunami inundated Hookton Slough following at least two coseismic subsidence events. Rip-up clasts and sand intrusions into the underlying soil imply the tsunami had high flow velocities sufficient to erode the buried soil substrate. Multiple fining-upward sandy beds imply that the tsunami for each earthquake consisted of multiple waves. The coincidence of the tsunami deposits and the magnitude of soil burial, taken together, support the conclusion that CSZ earthquakes caused the subsidence at Hookton Slough.

In addition to tsunami deposits associated with buried soils 3 and 4 at Hookton Slough, Carver and others (1998) identified tsunami deposits in southwestern Humboldt Bay, six kilometers west of the Hookton Slough site.

Ages of Coseismic Subsidence Events

Hookton Slough stratigraphy records at least five coseismic events within the last 3,700 years. Radiocarbon age estimates are made on four of the inferred events (Figure 4).

In summary, five subduction zone earthquakes occurred in the last ca. 3,500 years in southern Humboldt Bay. The most recent was the A.D. 1700 earthquake and the other three age constrained buried soils (3, 4, and 5) record earthquakes in the age windows of 1,350 to 2,150 yrs BP, 2,200 to 2,400 yrs BP, and 3,450 to 3,650 yrs BP respectively.

Recurrence Interval for Subduction Zone Earthquakes

A recurrence interval estimate for subduction zone earthquakes causing coseismic subsidence near Hookton Slough is 650 to 720 years. This estimate assumes buried soils 1, 2, 3, and 4 each record a subduction zone earthquake. Three interseismic intervals that span these four soils have a cumulative age span of 1,950 to 2,150 years assuming soil 1 subsided in 250 years BP and soil 4 subsided 2,200 to 2,400 years BP. Three intervals in a 2,200 to 2,400 year period yield a 650 to 720 year recurrence interval.

Correlation of Hookton Slough Earthquake Record to other Humboldt Bay Paleoseismic Sites and Tectonic Role of Little Salmon Fault

Using radiocarbon ages and stratigraphic relations, earthquake records at Hookton Slough are correlated to other Humboldt Bay paleoseismic sites at Salmon Creek valley (Carver and Burke, 1988; Clarke and Carver, 1992), Swiss Hall (Witter and others, 2002), and Mad River Slough (Vick, 1988; Jacoby and others, 1995)(Figure 6).

Inferred earthquakes near Swiss Hall (located two to three kilometers east of Hookton Slough) are correlated with inferred coseismic subsidence events at Hookton Slough (Figure 6). At the Swiss Hall site there is evidence for three, and possibly four earthquakes in sediment cores and trenches that crossed the western trace of the LSF at the bay margin (events 1, 2, 3, and 4, Figure 6). Based on stratigraphic relations and fossil diatom evidence, Witter and others (2002) conclude that the study site coseismically subsided three times, over an estimated area of at least 5,500 m2 (events 2, 3, and 4, Figure 6). Witter and others (2002) also conclude that the study site also folded the buried soils during at least one event on the LSF (event 1, Figure 6). Within radiocarbon error, three buried soils (Hookton Slough events 2, 3, and 4, Figure 6) at Hookton Slough appear to correlate with three buried soils at Swiss Hall (Swiss Hall events 2, 3, and 4, Figure 6). Within radiocarbon error Hookton Slough buried soil 1 correlates to the Swiss Hall folding event 1(Figure 6). At Hookton Slough three of the correlative buried soils (soils 1, 3, and 4) are capped by sand sheets that include multiple graded beds and mud or peat or peaty mud rip-up clasts.

Salmon Creek valley fault trench studies conclude at least three earthquakes occurred in the last 2,000 years (Figure 6). Within large radiocarbon age determination error, three earthquakes at Hookton Slough (Hookton Slough events 1, 2, and 3, Figure 6) correlate with three earthquakes at Salmon Creek Valley (Salmon Creek valley events 1, 2, and 3, Figure 6). Salmon Creek valley fault relations record LSF history. Hookton Slough strata record CSZ earthquake induced subsidence. If these three earthquakes are correlative, then LSF and CSZ earthquakes coincide.

If Hookton Slough is sensitive to both CSZ and LSF earthquakes, and LSF earthquakes are independent and chronologically distinct, then we would expect more earthquakes in the stratigraphic record at Hookton Slough (which we don't). Therefore, either 1) CSZ and LSF earthquakes are coincident and Hookton Slough is sensitive to both earthquakes' deformation, 2) CSZ and LSF earthquakes are not coincident and Hookton Slough is not sensitive to LSF earthquake deformation, but sensitive only to CSZ deformation, or 3) CSZ and LSF earthquakes are coincident and Hookton Slough is not sensitive to LSF earthquake deformation, but sensitive to CSZ deformation. Swiss Hall is probably sensitive to both CSZ earthquakes and LSF earthquakes. Witter and others (2002) conclude that subsidence at Swiss Hall may be due to either the CSZ or the LSF. However, for the earthquake that buried soils ca. 540 – 1,230 years BP, subsidence occurred in both the footwall and the hanging wall (Witter and others, 2002). Therefore, the CSZ is probably responsible for the subsidence during this earthquake.

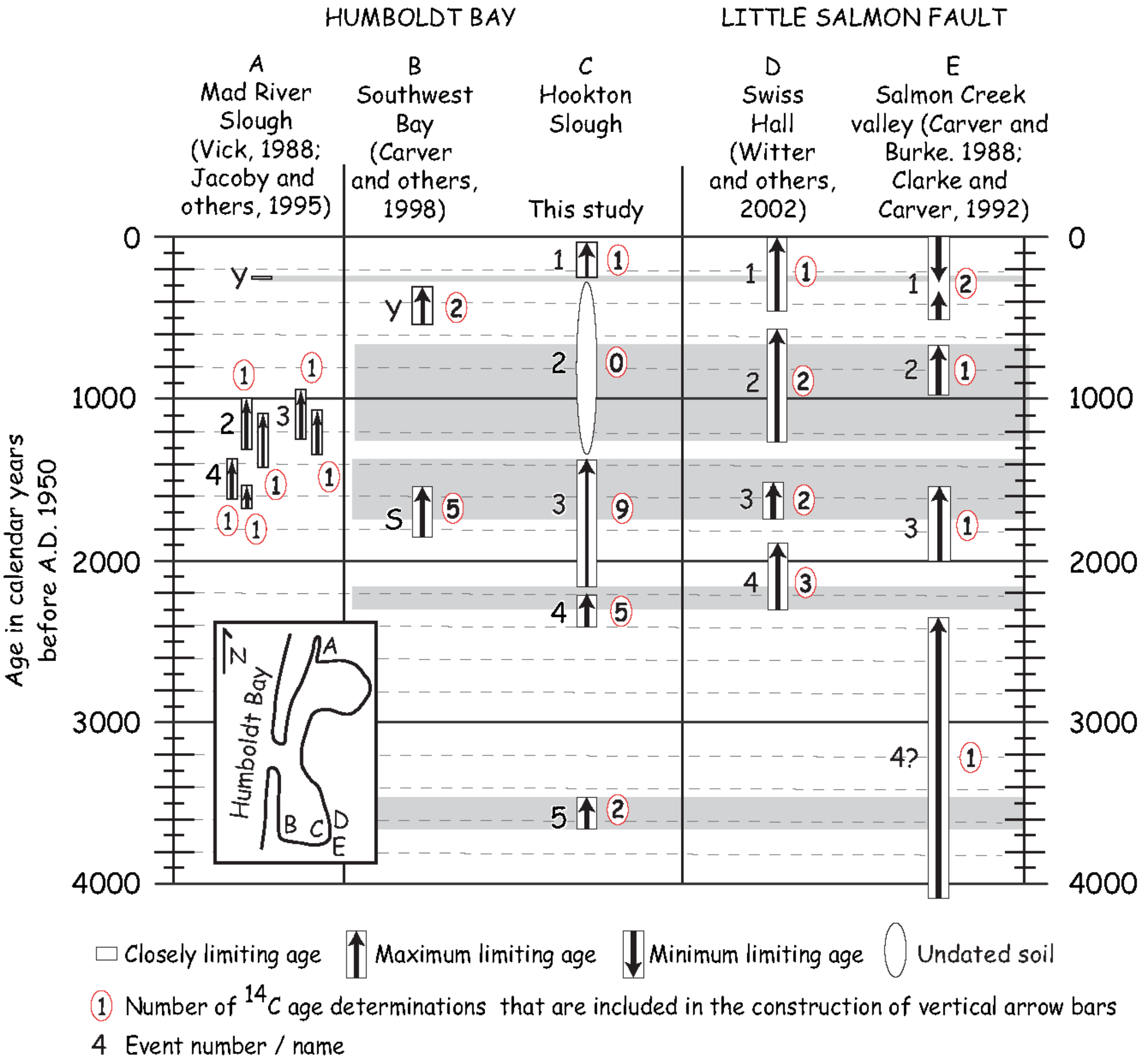

Figure 6. Correlation of earthquakes among Humboldt Bay study sites based on radiocarbon ages and stratigraphy.

Together the Hookton Slough and Swiss Hall studies demonstrate that, at least for some earthquakes, coseismic subsidence caused by earthquakes on the CSZ extends thousands of meters in the southern Humboldt Bay region and was coincident with generation of large tsunami and may be coincident with earthquakes on the LSF.

CONCLUSION

Southern Humboldt Bay has experienced at least four and possibly five CSZ earthquakes that caused subsidence and burial of tidal marsh soils in the past 3,700 years. Tsunami incursion in southern Humboldt Bay coincided with at least two earthquakes in the last 2,450 years. Preservation of tsunami deposits is highly localized.

Earthquakes at Hookton Slough occurred between 3,650 and 3,450, between 2,400 and 2,200, between 2,150 and 1,350, probably between 1,350 and 250, and finally around 250 years before A.D. 1950.

Four of these soils are correlated with earthquakes at the Swiss Hall site and they may correlate to the last three earthquakes at the Salmon Creek Valley trench site. A recurrence interval estimate for subduction zone earthquakes causing coseismic subsidence near Hookton Slough is 650 to 720 years.

Coincidence of tsunami deposits with abrupt subsidence provides evidence that CSZ earthquakes caused the subsidence observed at Hookton Slough and Swiss Hall. Within radiocarbon age determination error, upper-plate LSF earthquakes are coincident with CSZ earthquakes and thus the LSF may not be a source of coseismic subsidence independent of the subduction zone.

REFERENCES CITED

Atwater, B. F., 1987. Evidence for Great Holocene Earthquakes Along the Outer Coast of Washington State, *Science*, vol. 236: 942-944.

Atwater, B. F., Nelson, A. R., Clague, J. L., Carver, G. A., Yamaguchi, D. K., Bobrowsky, P. T., Bourgeois, J., Darienzo, M. E., Grant, W. C., Hemphill-Haley, E., Kelsey, H. M., Jacoby, G, Nishenko, S., Palmer, S., Peterson, C. D., and Reinhart, M-A., 1995, Summary of Coastal Geologic Evidence for Past Great Earthquakes at the Cascadia Subduction Zone, *Earthquake Spectra*, vol. 11: 1-18.

Atwater, B., and Hemphill-Haley, E., 1997. Recurrence Intervals for Great Earthquakes of the Past 3,500 Years at Northeastern Willapa Bay, Washington, States Geological Survey Professional Paper 1576. United States Government Printing Office, Washington, 108 p.

Bronk Ramsey C., 1995, Radiocarbon Calibration and Analysis of Stratigraphy: The OxCal Program, *Radiocarbon*, vol. 37: 425-430.

Bronk Ramsey C., 2001, Development of the Radiocarbon Program OxCal, *Radiocarbon*, vol. 43: 355-363.

Carver, G.A ., Burke, R. M., 1988, Final Report Trenching Investigations of Northwestern California Faults Humboldt Bay Region, United States Geological Survey Grant 14-08-0001-G1082, 53 p.

Carver, G.A., Abramson, H.A., Garrison-Laney, C.E., and Leroy, T., 1998, Paleotsunami evidence of subduction earthquakes for northern California: Final Report for Pacific Gas and Electric Co., 164 p., plus appendices.

Clague, J. J., Bobrowsky, P. T., 1994, Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia, in *Geological Society of America Bulletin*, vol. 106: 1293-1303.

Clarke, S. H., and Carver, G. C., 1992. Late Holocene Tectonics and Paleoseismicity, Southern Cascadia Subduction Zone, *Science*, vol. 255: 188-192.

Hemphill-Haley, E., 1995. Diatom evidence for earthquake-induced subsidence and tsunami 300 yr ago in southern coastal Washington, *Geological Society of America Bulletin*, vol. 107: 367-378.

Jacoby, G., Carver, G., Wagner, W., 1995. Trees and herbs killed by an earthquake ~300 yr ago at Humboldt Bay, California, *Geology,* vol. 23: 77-80.

Jacoby, G., Bunker, D. E., and Benson, B. E., 1997. Tree-ring evidence for an A. D. 1700 Cascadia earthquake in Washington and northern Oregon, *Geology,* vol. 25: 999-1002.

Kelsey, H. M., Witter, R. C., and Hemphill-Haley, E., 2002. Plate-boundary earthquakes and tsunamis of the past 5,500 yr, Sixes River estuary, southern Oregon, *Geological Society of America Bulletin,* vol. 114: 298-314.

Li, Wen-Hao, 1992, Evidence for the late Holocene coseismic subsidence in the lower Eel River Valley, Humboldt County, northern California: an application of foraminiferal zonation to indicate tectonic submergence: M.S. thesis, Arcata, California, Humboldt State University, Department of Geology, 87 p.

Manhart, C. S., 1992, High-Resolution Foraminiferid Stratigraphy as Evidence for Rapid, Coseismic Subsidence: Preliminary results, in Carver, G. A., Burke. R. M. [eds.] *Friends of the Pleistocene Field Guidebook,* Humboldt State University, Department of Geology, Arcata, CA, 265 p.

Nelson, A. R., Kashima, K., 1993. Diatom Zonation in southern Oregon Tidal Marshes Relative to Vascular Plants, Foraminifera, and Sea Level, *Journal of Coastal Research,* vol. 9: 673-697.

Nelson, A. L., Jennings, A. E., and Kashima, K., 1996a. An earthquake history derived from stratigraphic and microfossil evidence of relative sea-level change at Coos Bay, southern coastal Oregon, *Geological Society of America Bulletin,* vol. 108: 141-154.

Nelson, A. R., Shennan, I., and Long, A. J., 1996b. Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascadia subduction zone of western North America, *Journal of Geophysical Research,* vol. 101: 6115-6135.

Nelson, A. R., Ota, Y., Umitsu, M., Kashima, K., and Matsushima, Y., 1998. Seismic of hydrodynamic control of rapid late-Holocene sea-level rises in southern coastal Oregon, USA?, *The Holocene,* vol. 8: 287-299.

National Oceanographic and Atmospheric Administration, NOAA, 2000. Gill, S. K. and Schultz, J. R., [eds.] Tidal Datums and Their Applications, NOAA Special Publication NOS CO-OPS 1, U. S. Department of Commerce, National Ocean Service, Center for Operational Oceanographic Products and Services, Silver Spring, Maryland, 115 p.

Shapiro and Associates, (1980). Humboldt Bay Wetlands Review and Baylands Analysis, Report to Army Corps of Engineers, Vol. 1, 2, and 3.

Stuiver, M., and Reimer, P. J., 1986, A computer program for radiocarbon age calibration, *Radiocarbon,* vol. 28:1022-1030.

Stuiver, M., and Reimer, P. J., 1993, Extended 14C database and revised CALIB radiocarbon calibration program, *Radiocarbon,* vol. 35:215-230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v. d. Plicht, J., and Spurk, M., 1998a. INTCAL98 Radiocarbon age calibration 24,000 - 0 cal BP, *Radiocarbon,* vol. 40:1041-1083.

Stuiver, M., Reimer, P.J., and Braziunas, T. F. 1998b. High-precision radiocarbon age calibration for terrestrial and marine samples, *Radiocarbon,* vol. 40:1127-1151.

Vick, G., 1988, Late Holocene Paleoseismicity and relative vertical crustal movements, Mad River Slough, Humboldt Bay, California: M.S. thesis, Arcata, California, Humboldt State University, 88 p.

Witter, R. C., Patton, J. R., Carver, G. C., Kelsey, H. M., Garrison-Laney, C., Koehler, R. D., and Hemphill-Haley, E., 2002. Final Technical Report: Upper Plate Earthquakes on the Western Little Salmon Fault and Contemporaneous Subsidence of Southern Humboldt Bay over the past 3,600 Years, Northwestern California. United States Geological Survey, National Earthquake Hazards Reduction Program, Award No. 01HQGR0215, 37 p.