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Preliminary Estimates of Recurrence Intervals for Great Earthquakes Of the Past 3500 Years at Northeastern Willapa Bay, Washington

by

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ABSTRACT

Plate-boundary earthquakes have occurred repeatedly during the past several thousand years at the Cascadia subduction zone, where they are widely recorded by buried marsh and forest soils beneath estuarine wetlands. This report adds to previous accounts of such soils along the Pacific coast of southern Washington State. Our new evidence comes from outcrop surveys, diatom analyses, and radiocarbon dating of soils exposed about 10 km apart in banks of the Niawiakum and Willapa Rivers, tidal arms of Willapa Bay. This new evidence helps to define and reduce uncertainty about recurrence intervals for plate-boundary earthquakes at this central part of the Cascadia subduction zone.

All the surveyed outcrops display buried soils that probably record tectonic subsidence during earthquakes. Although in many cases we cannot rule out every alternative to such coseismic subsidence, we found no evidence that stream migration, storm, flood, sea-level rise, barrier breaching, or settlement better explains any of the buried soils.

Each of the soils probably represents a marsh or forest that suddenly became a tidal flat and consequently was buried by tidal mud. In nearly every case we surveyed too much lateral continuity and too little relief for the surveyed soils to record cutting and filling by tidal streams. Plant fossils preserved within and above many of the soils show that storms or floods, if unaccompanied by lasting submergence, cannot account for burial of the soils. Where their remains are preserved, plants that had lived on the soils belong to species indicative of conditions in the uppermost 1/2 m of the intertidal zone— Sitka spruce in some cases, herbaceous species in others. By contrast, the main vascular-plant species preserved in mud above soils is *Triglochin maritima,* the main colonizer of saltwater tidal flats in southern coastal Washington. Assemblages of diatoms confirm these paleoecological interpretations and extend them to soils for which vascular-plant fossils are not preserved. In an outcrop along the Niawiakum River, for example, diatoms show that each of six successive soils represents a high marsh or an upland, and that mud above each of these soils represents an intertidal or subtidal mudflat.

Fossils further show that the change from high marsh or upland to mudflat probably happened too fast to have resulted from a gradual rise in sea level. For every soil studied for fossil diatoms, diatom assemblages imply that this change happened suddenly, without transition through low marsh. Gradual sea-level rise is further precluded for some soils by remains of vascular plants that had lived on buried soils. These remains include stems and leaves that were surrounded by mudflat deposits before they had time to decompose.

Other alternatives to coseismic subsidence can also be discounted. Brackish-water fossils in the soils tend to rule out submergence from breaching of any bay-mouth barrier that would have turned the bay into a freshwater lake. Such a barrier is unlikely to have formed, in any event, because Willapa Bay has a huge tidal prism that maintains the bay's connection with the sea. The presence of buried soils directly above well-consolidated Pleistocene deposits shows that the soils record tectonic subsidence of entire landscapes, not just localized settlement from earthquake-induced compaction of unconsolidated Holocene deposits. Moreover, where soils correlate among the surveyed outcrops (evidence summarized below), evidence for sudden tectonic subsidence at one outcrop can be extrapolated to correlative soils at other outcrops.

Plate-boundary earthquakes probably account for all the subsidence events. We explored an alternative explanation—earthquakes on faults in the North America plate—by checking for

signs of sudden land-level change on a late Cenozoic uplift 40 km long and 15 km wide, herein termed the South Bend antiform. This structural high, the largest in southern coastal Washington, has probably been active at least as recently as the Miocene. The South Bend antiform should subside during plate-boundary earthquakes that flex the North America plate throughout southern coastal Washington. By contrast, the antiform should fail to subside, and may grow upward, during an upper-plate earthquake that limits subsidence to late Cenozoic synclines. With these expectations in mind, we contrasted outcrops off the South Bend antiform (Niawiakum River) with outcrops on the antiform (Willapa River). We found no difference in sense or timing of earthquake-induced changes in land level. Like the surveyed outcrops along the Niawiakum River, the surveyed outcrops along the Willapa River contain buried soils indicative of earthquake-induced subsidence. The longest stratigraphic sequences exposed along both streams contain six or seven soils less than 3500 years old, and successive soils in these sequences appear widely correlative in abundance of peat, presence of spruce roots, and radiocarbon age. The buried-soil record of plate-boundary earthquakes at northeastern Willapa Bay has probably escaped contamination by upper-plate earthquakes during the past several thousand years or longer.

Though every buried soil in the surveyed outcrops probably records a plate-boundary earthquake, not every plate-boundary earthquake necessarily produced a lasting buried soil. Some earthquakes may correspond to buried soils that were obliterated through many centuries of oxidation high in the profiles of succeeding soils. Such oxidation destroyed most of the organic matter associated with several of the soils in each of the surveyed outcrops. Other earthquakes may have never been recorded by burial of a soil, owing to insufficient subsidence during the earthquakes or insufficient time between earthquakes. For an earthquake to be widely recorded by a buried soil at northeastern Willapa Bay, the amount of coseismic subsidence may need to exceed 1/2 m, and as much as 150 years may need to elapse before the next earthquake.

Willapa Bay's earthquake history in the past 3500 years probably includes seven events each comprising a single rupture or multiple contiguous ruptures on the Cascadia plate boundary along the southern coast of Washington. All these events probably included at least one earthquake of magnitude 8 or larger (great earthquake), as judged from likely rupture widths inferred from modern geophysical evidence, likely rupture lengths inferred from coastwise correlation of buried soils, and seismic-moment release deduced from plate motions and average recurrence intervals. The history begins with three events between 3300-3500 years ago and 2400-2800 years ago (ranges includes estimated 95-percent confidence interval). The next recorded events occurred 1400-1900 and 1200-1400 years ago. They were followed by a poorly dated event that may have been associated with rupture on inland faults in the North America plate 1000-1100 years ago. The most recent of the earthquakes happened close to 300 years ago.

The six intervals between earthquakes in this inferred history average 500-535 years. The narrowness of this range does not fully express uncertainties in counting the earthquakes, particularly the possibility that the buried-soil record of great earthquakes is incomplete. The average also fails to express variability among the recorded intervals, which range from a few centuries to about one millenium.

INTRODUCTION

At the Cascadia subduction zone (Figure 1) plate-boundary earthquakes are known primarily from geologic evidence for prehistoric land-level changes, tsunamis, and shaking. Average recurrence intervals estimated from this geologic evidence, as summarized in Figure 2, range from a few hundred to more than one thousand years (Adams, 1990; Clarke and Carver, 1992; Geomatrix Consultants, 1995; Darienzo and Peterson, 1995; Nelson and others, in press a; Atwater and others, 1995).

Much of this broad range in average recurrence intervals is due to uncertainties in the counting and dating of the inferred earthquakes (Figure 3). Such uncertainties affect even the clearest of the evidence for prehistoric plate-boundary earthquakes at the Cascadia subduction zone—buried marsh and swamp soils at estuaries along the Pacific coast between southern British Columbia and northern California. Many of these soils represent sudden tectonic subsidence of coastal land during plate-boundary earthquakes; the subsidence caused frequent tidal submergence and consequent estuarine burial of the soils (Atwater and others, 1995). However, burial of some of the soils may have resulted from non-seismic events, such as storms or rapid sea-level rise (Figure 3B) (Nelson and others, in press a, b), or from earthquakes on faults in the North America plate (Figure 3C) (Nelson, 1992a; Clarke and Carver, 1992; McCaffrey and Goldfinger, 1995). Still other soils may have disappeared through decomposition or erosion, or may have escaped burial through insufficient tidal submergence or sediment supply (Figure 3D). Moreover, the combined geologic and analytical errors in radiocarbon dating of the earthquakes can approach or exceed the lengths of time between them (Figure 3E) (Nelson, 1992b; Atwater, 1992).

We reduced such uncertainties in the counting and dating of earthquakes by studying sequences of buried soils in low-tide outcrops at northeastern Willapa Bay (Figure 4, Figure 5). The outcrops facilitate stratigraphic and paleontologic tests of alternatives to sudden tectonic subsidence, and they also allow identification of soils that have been widely destroyed. In addition, the structural setting of the outcrops provides a means for detecting earthquakes on faults in the North America plate. We found no strong evidence for contamination of buried-soil records, either by events other than coseismic subsidence or by earthquakes on faults in the North America plate. These findings, along with several new radiocarbon ages having unusually small geologic and analytical errors, show that about 500 years may have elapsed, on average, between plate-boundary earthquakes of magnitude 8 or larger in the past 3500 years at northeastern Willapa Bay. We also found, however, that the buried-soil record of such earthquakes is locally incomplete. Moreover, instead of recurring periodically as diagrammed in Figure 3F, the earthquakes probably occurred at intervals that varied in length (Figure 3G) by factors of two or more.

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PREVIOUS ESTIMATES OF RECURRENCE INTERVALS FOR PLATE-BOUNDARY EARTHQUAKES AT THE CASCADIA SUBDUCTION ZONE

Geologic attempts to estimate recurrence intervals for great (magnitude 8 or larger) Cascadia earthquakes began in the middle 1980s with work by Adams (1990), who used deposits of submarine channels as recorders of earthquakes. Earthquake-recurrence studies at coastal estuaries have yielded preliminary results since the late 1980s (Atwater and others, 1987) and were reported in refereed journals in the early 1990s.

Adams (1990) cited deep-sea turbidites as evidence that great earthquakes have recurred at an average interval of about 600 years off the Washington and Oregon coast. This estimate was based on counting, in cores from sites in deep-sea channels (Figure 1), 13 turbidites younger than a volcanic ash that erupted about 7500 calendric years ago. Adams inferred a one-for-one correspondence between turbidites and great plate-boundary earthquakes. He presented no strong evidence against two potential complications: (1) some great earthquakes were preceded by too little time for much sediment to accumulate in canyon heads where the turbidity currents originated; (2) some of the turbidites resulted from lesser earthquakes on faults in the North America plate. Adams used average rates of pelagic sedimentation to infer that the most recent of the earthquakes occurred about 240-360 years ago. If the turbidites and plate-boundary earthquakes correspond one for one, the average repeat time for the earthquakes is between about 550 and 630 years.

Clarke and Carver (1992) cited buried soils exposed at low tide along Mad River Slough—an arm of Humboldt Bay, California (Figure 1)—as evidence for earthquake recurrence intervals that average less than 500 years. They reported evidence for four or five earthquakes between about 1450-1750 years ago and about 300 years ago. They further inferred that three of these events were accompanied by surface rupture of a nearby thrust fault in the North America plate, but they proposed that this thrust faulting usually accompanied great earthquakes on the underlying plate boundary.

Darienzo and Peterson (1995) used buried soils to estimate average recurrence intervals less than 600 calendric years for great earthquakes between the Necanicum River and Alsea Bay, Oregon. They reported that the average interval could be as little as about 200 calendric years. The minimum average interval that we calculate from their data—about 400 years (Figure 2)—is longer for two reasons. (1) Our recalculation makes use of high-precision (quoted errors ± 10-15 ^{14}C yr) radiocarbon dating of trees and herbs killed by the most recent earthquake or earthquakes, which probably occurred between close to 300 years ago along most or all of the Cascadia subduction zone (Nelson and others, 1995) (see p. 26). By contrast, Darienzo and Peterson (1995) inferred that this seismicity could have have occurred as much as 680 years ago. This greater age reduces the minimum allowable time between the most recent earthquake and its predecessors, thus shortening the minimum average recurrence interval. It reflects quoted errors of about ± 50 ^{14}C yr and unreckoned errors from equating the time of coseismic subsidence with the age of peat that formed mainly before the subsidence. (2) We average the last five of the recurrence intervals inferred by Darienzo and Peterson (1995). The shortest recurrence intervals estimated by Darienzo and Peterson (1995) are based on only the last four intervals. These intervals exclude the interval between their events 5 and 6—the longest interval implied by their radiocarbon ages (Darienzo and Peterson, 1995, their Figure 4).

Nelson and others (in press a) obtained a broad range of earthquake-recurrence intervals from study of alternating peat and mud observed in cores at Winchester Creek, which is part of the South Slough arm of Coos Bay, along the southern Oregon coast. Relying largely on foraminifera and diatoms as indicators of land-level change, they inferred three probable earthquakes and as many as six doubtful earthquakes in the past 4290-4930 years. All their probable earthquakes date from the past 2350-3240 years, and two other peaty layers that might or might not represent earthquakes also fall in that time. Nelson and his coworkers (in press a) state that an unknown fraction of the earthquakes occurred on the plate boundary; others may have occurred independently on faults in the North America plate. If the five youngest peaty layers studied by Nelson and others (in press a) represent between three and five plate-boundary earthquakes, the average interval ranges from about 500 to 1500 years (Figure 2). A average interval of at least 500 years is indicated if their entire sequence of peat and mud records nine or fewer plate-boundary earthquakes between about 300 and 4290-4930 years ago.

STRUCTURAL SETTING AND TIDAL-WETLAND ENVIRONMENTS OF NORTHEASTERN WILLAPA BAY

Geologic structure

The northeastern part of Willapa Bay flanks and crosses a late Cenozoic uplift herein termed the South Bend antiform (Figure 4). This structural high, which extends about 40 km in a north-northwestward direction, is defined mainly by an exposed core of Crescent Formation—Eocene pillow basalt, basaltic breccia, and basaltic sedimentary rock (Wagner, 1967a, 1967b). Near the northern and southern ends of the antiform the Crescent is flanked to the east and west by younger sedimentary strata of Eocene and Oligocene age. North of Raymond, in the eastern part of the antiform, sedimentary rocks within the Crescent dip to the east and northeast, approximately parallel to dips in these younger strata, which probably rest conformably on the Crescent (Wagner, 1967a) (Figure 5). The antiform may be bounded on the west by an east-dipping thrust fault (Cowan and Potter, 1986; Palmer and Lingley, 1989, p. 11). Small but abundant outcrops of the Crescent near the Willapa River demonstrate that the antiform crosses the Willapa River, which forms the easternmost arm of Willapa Bay (Figure 5A).

The South Bend antiform has probably been active in post-Miocene time and has undergone net uplift, with or without continued folding, in the late Quaternary. Flanks of the antiform trend parallel to synclines that deform rocks as young as Miocene (Figure 4). *Net* Quaternary uplift is shown by estuarine and shallow marine deposits of probable Pleistocene age; Wagner (1967a, 1967b) mapped such deposits on the antiform to altitudes of 180 m. However, uplifted Pleistocene estuarine deposits extend beyond the antiform as well: they border much of Willapa Bay and Grays Harbor (Clifton, 1983; Walsh and others, 1987), and they even form a terrace in a Neogene syncline along the Naselle River (Wells, 1989) (Figure 4).

We say *net* Quaternary uplift because estuarine deposits at Willapa Bay contain buried soils indicative of sudden subsidence. These buried soils date not only from the Holocene (Atwater, 1987, 1992) but also from the Pleistocene (Table 1; Peterson and Darienzo, 1989), and they are located both on and beside the South Bend antiform (Figure 4). The net uplift implies that cumulative interseismic uplift has slightly exceeded cumulative coseismic subsidence (Atwater, 1987). However, rates of interseismic uplift at Willapa Bay are poorly known; geodetic estimates for the past 50 years range from near zero (Holdahl and others, 1989; Mitchell and others, 1994) to several millimeters per year (Ando and Balazs, 1979; Hyndman and Wang, 1995).

Tidal-wetland environments

Many of the buried soils described in this report represent vegetated wetlands dominated by herbaceous plants (*marshes*) or by trees (*swamps*). Modern analogs for these wetlands can be found high in the intertidal zone along streams tributary to Willapa Bay. Along the lower reaches of these streams the difference between mean lower low water and mean higher high water is about 3 m.

Most modern tidal marshes at Willapa Bay form nearly horizontal surfaces at or slightly above mean higher high water (*high marsh*). Additional tidal marsh of lower altitude (*low marsh*) descends to tidal flats and channels (Figure 6). The high marsh is mostly about 1 m higher than tidal mud flats being colonized by *Triglochin maritima*, a dominant low-marsh plant. This difference in level is labeled "D" in Figure 6.

Tidal swamps of modern Willapa Bay are restricted to mostly freshwater reaches of the bay's tidal streams. Though they resemble uplands in some of their vegetation, they are not much if any higher in the intertidal zone than are high marshes farther downstream. We found no such difference in level along the Niawiakum River near the Castle locality (Figure 6).

Dominant vascular-plant species of the modern wetlands are commonly zoned with respect to tide level and salinity (Weinmann and others, 1984; Kunze and Cornelius, 1982). On brackish-water high marsh the dominant species are tufted hair-grass (*Deschampsia caespitosa*), Baltic rush (*Juncus balticus*), and Pacific silverweed (*Potentilla pacifica*). Pickleweed (*Salicornia virginica*) is common in saline parts of high marsh and in the transition between high marsh and low marsh. A mainly upland tree, Sitka spruce (*Picea sitchensis*), is joined by western crabapple (*Pyrus fusca*) in tidal swamps served mainly by fresh water. Seaside arrowgrass (*Triglochin maritima*) is the chief vascular plant native to salt- and brackish-water low marsh; upstream it is supplanted by Lyngby's sedge (*Carex lyngbyei*), which is also common in brackish-water high marsh.

Diatoms also define vertical zones in Willapa Bay's modern wetlands. Studies of modern estuarine diatoms show that diatom assemblages differ among upland, tidal marsh, and tidal flat at the Cascadia subduction zone, both in central Oregon (Nelson and Kashima, 1994) and at Willapa Bay (Hemphill-Haley, 1995a). The studies at Willapa Bay show that marshes and tidal flats support distinctive assemblages of abundant diatoms, and that few if any diatoms are present in upland soils above the level of highest tides (extreme high water). These Willapa Bay studies further show that diatom assemblages differ between low marsh and high marsh.

To summarize vertical zonation of scores of diatom taxa, one of us (Hemphill-Haley) uses a ratio termed the brackish intertidal diatom index (BIDI). This ratio gives relative proportions of taxa that occur dominantly in modern high marshes (h), low marshes (l), both high and low marshes (b), or tidal flats and shallow subtidal channels (t) (Table 2):

$$\mathrm{BIDI} = (h + b + 0.5l)/(h + b + l + t).$$

For modern marsh samples the index differs consistently among high marsh (0.65-1.00), low marsh (0.29-0.65), and tidal flat and tidal channel (0.00-0.29). Such differences have been observed at 63 intertidal sites around Willapa Bay and at Puget Sound (Figure 7A), some of which are located along leveled transects at the Niawiakum River (Figure 7B,C).

METHODS

We made detailed studies of earthquake recurrence along two tidal streams: the Niawiakum River, at the western edge of the South Bend antiform; and the Willapa River where it crosses the antiform (Figure 5). Along each stream we delineated the stratigraphy—mainly, the buried wetland soils—of three low-tide outcrops several meters high and tens or hundreds of meters long (Plate 1). Most of the field work was done in July, 1994 except along the Niawiakum River at the Redtail locality (studied intermittently 1986-1992) and the Pool locality (surveyed 1995). From several of the outcrops we collected samples for study of fossil diatoms, and from most of the outcrops we also collected samples for radiocarbon dating.

Delineation of stratigraphic units

Buried soils of former marshes and swamps punctuate the stratigraphy of the surveyed outcrops (Plate 1; Figure 9-Figure 14). The horizon common to these soils is a dark surficial layer interpreted as a buried A or O horizon. In *bold soils* this horizon consists peaty mud or peat commonly 2-10 cm thick; in *faint soils* consists of mud 1-2 cm thick that is merely darker than mud above and below it. In many of the bold soils, the genetic term "soil" is amply justified by growth-position remains of herbs and trees rooted in them; these fossils clearly identify the peaty horizon as material on which plants grew. Other, less obvious features justify the use of "soil" in "faint soils": most of the faint soils resemble bold soils in lateral extent and relief (Plate 1); some grade laterally into bold soils in which vascular-plant fossils are preserved (p. 14, 20); and, in sections studied for fossil diatoms, faint soils contain diatom assemblages indicative of tidal-marsh conditions (Figure 10, Figure 12).

We assign each surveyed soil a name, such as "soil S", in which the capital letter denotes inferred position in a sequence of soils that we regard as correlative throughout the study area (p. 28). For the youngest soil we use a letter (Y) near the end of the alphabet; for progressively older soils we use letters nearer the front of the alphabet. Gaps in the sequence of letters leave room for soils that we may have overlooked. The sequence excludes letters easily confused with numerals.

We measured positions of the soils with respect to arbitrary datums particular to each of the outcrops (Plate 1). Horizontal measurements were made with a tape measure, vertical measurements with a tripod-mounted level. The vertical measurements include the heights of one or more low slack tides at each locality. These tidal heights, and the tide level predicted in tide tables of the National Oceanic and Atmospheric Administration, are plotted in Plate 1.

We observed continuity of soils between some surveyed points and inferred it between others—a distinction shown by line style in Plate 1. We define continuity as observed where differential erosion made a soil apparent in natural outcrop (for example, soils J, L, S, and Y in Figure 9B), or where the soil was exposed by cleaning of the outcrop with a shovel (soil U in Figure 9C). We inferred continuity between isolated exposures and between borings made with a gouge corer—a steel half-cylinder 2 cm in diameter and 1 m long. The borings were used only for soil H at the Redtail locality, soils H and J at the Pool locality and at the southern part of the Jensen locality, and Pleistocene deposits at both these localities.

Contrasting line symbols in Plate 1 depict each soil as bold, faint, or both. The symbols misrepresent lateral changes from bold to faint, which are depicted as abrupt but typically grade across a few to many meters.

Although we did not measure organic contents of the surficial horizons of the soils, such measurements have been made for a stratigraphic section containing three bold soils (probably correlative with soils L, S, and Y) and two faint soils (probably N and U) along the Johns River (Figure 4, Figure 8; locality 14 of Atwater, 1992). The measurements, made by James B. Phipps of Grays Harbor College (written communication, 1988), show organic contents of 30-40 percent (of dry weight) for the bold soils and less than 10 percent for the faint soils. Phipps found little or no difference in organic content between the faint soils and the mud that brackets them.

Mud above some of the soils—particularly soils S and Y—commonly contains more silt than does mud below their surficial horizons. This contrast is evident in well-washed outcrops in which layers of silt and sandy silt have been etched by water (Figure 14B). The contrast can also be seen on outcrops freshly faced with a shovel or machete; whereas the finer mud smears, the coarser mud peels roughly. Particle-size was measured for samples from the Redtail locality (Figure 10). The samples, collected at an average interval of 6.5 cm, came from slabs sampled also for fossil diatoms. Organic matter was removed in 30 percent H_2O_2. Counts were made with a Cimax hydrophotometer and rapid settling analyzer at a U.S. Geological Survey sedimentology laboratory in Palo Alto, California. Precision, estimated from calibration tests, is ±13 percent for the hydrophotometer and ±15 percent for the rapid settling analyzer. Particle-size distributions were determined with the technique of Torresan (1987).

Fossils

Identification and tabulation

Hemphill-Haley studied diatom assemblages from vertical slabs collected at the Oyster, Redtail, and Sewer localities. The diatoms were sampled, separated, and identified by procedures previously described (Hemphill-Haley, 1995a, 1995b). For the Oyster and Redtail localities, Hemphill-Haley counted an average of 388 valves per sample, of which an average of at least 100 proved useful in inference of depositional environment. Results of the diatom counts are listed in Table 3, Table 4, and Table 5. In each of these tables the diatoms are listed alphabetically in two categories, benthic and planktonic. Each table concludes with summary data that include the brackish intertidal diatom index (BIDI). This index, as defined above (p. 6) and plotted in Figure 10 and Figure 12, provides a convenient measure of relative vertical position of the depositional environment inferred from the diatom assemblages.

Atwater identified vascular-plant fossils in the field by comparing them with modern plants. Most of these identified fossils were found in growth position. They include woody roots, chiefly of Sitka spruce; stems and basal leaves of *Deschampsia caespitosa, Potentilla pacifica, Juncus balticus*, and *Salicornia virginica*; and rhizomes, chiefly of *Triglochin maritima.*

Comparisons between diatoms and vascular plants

Environments inferred from the fossil diatom assemblages resemble those inferred from vascular-plant fossils in most cases where the inferences can be compared (Figure 10, Figure 12). Such comparisons can be made for fossils inferred to record upland conditions at the Redtail locality, high marsh at the Oyster locality, and transitions from tidal flat to low marsh at both these localities.

Diatom assemblages suggestive of uplands are consistent with vascular-plant fossils in two of three cases at the Redtail locality (Figure 10). The upland assemblages, marked by valves that are scarce and fragmented, accord with the presence of many spruce roots in growth position in soils S and Y (Figure 9B; Plate 1). The diatom assemblage in soil Y further accords with archaeological evidence for a fishing camp on the soil (p. 13). However, an upland diatom assemblage in soil N contrasts with the lack of tree roots in this soil. This lack of tree roots cannot be explained by decomposition because, despite its typical faintness, soil N contains or is immediately overlain by well-preserved spruce cones, as shown by radiocarbon samples plotted in Plate 1. Moreover, soil N retains a peaty surficial horizon at the site of the cones dated 2475 ± 23 ^{14}C yr B.P.

Comparisons between diatoms and vascular-plant fossils show general agreement in the inference of high marsh for soils S, U, and Y at the Oyster locality (Figure 12). Although some of the diatom assemblages associated with high-marsh herbs yield BIDI values transitional between low marsh and high marsh, these values are due to probably allochthonous valves of heavily silicified and easily reworked tidal flat diatoms (p. 16). Diatoms in soil U accord with vascular-plant evidence that soil U represents a slightly lower-level high marsh than do soils S and Y (p. 16).

Transitions from tidal flat to low marsh can be inferred both from diatom assemblages and from vascular-plant fossils in mud above soils S, U, and Y at the Oyster locality (Figure 12). Each transition is marked in outcrop by first appearance of *Trigochin maritima* rhizomes in soft gray mud above the buried soil. The mud lacks other vascular-plant fossils in growth position but contains rhythmic layers ascribed to filamentous algae found today mainly at the transition between tidal flat and low marsh (p. 15). Diatom assemblages independently suggest that mud below the rhizomes represents a tidal flat or a shallow subtial conditions. However, the diatom assemblages, as summarized by BIDI values, place the transition to low marsh several tenths of a meter above the lowest *Triglochin maritima* rhizomes. This discrepancy may reflect patchy colonization of the tidal flat, which could have supported dominantly tidal-flat assemblages of diatoms until *Triglochin maritima* patches fully coalesced.

Inferences from rhizomes and diatoms differ somewhat for a tidal-flat-to-low-marsh transition between soils J and L at the Redtail locality (Figure 10). Diatoms found with the lowest *Triglochin maritima* rhizomes (at depth 310 cm) include such low-marsh species as *Caloneis westii* and *Diploneis interrupta.* However, the assemblage contains many more valves of the high-marsh diatom *Cosmioneis* *pusilla* var. 1. These valves, which could have been reworked from high marsh that may have fringed the upland beside the Redtail locality (Figure 5B), push the BIDI value into the high-marsh range (Figure 10).

Dating

Radiocarbon ages have been measured on samples of wood, peat, and rhizomes (below-ground stems of herbaceous plants) from the Oyster, Redtail, Pool, Jensen, and Sewer localities. In Table 6 and Plate 1 these ages are reported in conventional radiocarbon years before A.D. 1950 (^{14}C yr B.P.). Additional ages, from a site to the south along the Naselle River (Figure 4), are similarly reported in Table 7.

For Figure 2, Figure 8, Figure 15, and the text we converted radiocarbon ages to calendric-year ranges by means of the calibration data of Stuiver and Becker (1993) and version 3.0.3 of the radiocarbon calibration program of Stuiver and Reimer (1993). Our unit for most such ages is calendric years before A.D. 2000, which we state in the text as "years ago".

Figure 8 shows two calendric-age ranges for each ^{14}C age. The narrower range equals the 95-percent confidence interval if the error quoted by the lab equals one standard deviation of the age measurement. The wider range incorporates a published, generous error multiplier of 1.6 for ages measured at the University of Washington (lab code QL; Stuiver and Pearson, 1986) and an assumed and probably generous error multiplier of 2.0 for the other ages.

Most of the radiocarbon samples probably differ in age from the inferred earthquakes that we sought to date. For several samples of forest-floor litter this difference is probably negligible (Figure 8, "closely limiting" ages for soils J and N), and for some spruce-root samples the difference has been corrected by means of tree-ring counts (Atwater and others, 1991) (Figure 8, "closely limiting" ages for soil Y). For other samples, particularly of peat, the difference may amount to decades or centuries (Nelson, 1992b). Arrows in Figure 8 identify ages subject to such large discordance between age of material and time of inferred earthquake. These include ages on small woody roots that may have died long before an inferred earthquake (arrow pointing upward), ages on rhizomes that may have formed long after the earthquake (arrow pointing downward), and ages on peat and sticks that may either predate or postdate the earthquake (arrows pointing both directions).

Even the carefully selected and exhaustively cleaned stems of perennial herbaceous plants appear subject to differences between earthquake age and sample age. Ages measured on *Potentilla pacifica* and *Juncus balticus* rooted in soil Y at the Oyster locality (Table 6) average 40-50 radiocarbon years greater than the likely radiocarbon age of the earthquake (Nelson and others, 1995). Differences of this kind may also apply to the ages measured on the same species rooted in probable correlatives of soils U and S at the Naselle River (Table 7). Reasons for the differences are poorly understood. Possibilities include: (1) the dated material, coming from perennial plants, largely originated years or decades before the earthquake; (2) air used by the plants contained old CO_2 derived from decay of organic matter in the marsh soil, including litter at the ground surface; (3) a systematic difference exists between the New Zealand laboratory that dated the herbaceous plants and the University of Washington laboratory that provided ages used to narrow, to A.D. 1700-1720, the likely time of the earthquake (or series of earthquakes) marked by soil Y and its inferred correlatives. Nelson and others (1995) found that neither possibility (1) nor possibility (3) fully explain the relatively great ages obtained from the herbaceous fossils rooted in soil Y and its inferred correlatives. Possibility (2), suggested by Minze Stuiver (oral communication, 1995), has not been evaluated for tidal marshes at the Cascadia subduction zone.

Provisional radiocarbon ages of four important samples from outcrops along the Niawiakum River—three at the Oyster locality and one at the Pool locality—were being measured while this report was being completed. For future reference we describe the samples in Table 6 (laboratory numbers QL-4795 through -4798) and plot their locations in Plate 1.

SEQUENCES OF BURIED SOILS

Niawiakum River

The Niawiakum River is bordered by tidal marshes along the lowest 4 km of its valley. Upvalley from those marshes the river has a 5-km^2 drainage basin in Pleistocene estuarine deposits and the Crescent Formation. The marshes grade into a tidal swamp of Sitka spruce and western crabapple upvalley from the Pool locality (Figure 5B). Brackish water extends this far upstream because the river has little summertime discharge, which we guess to be on the order of 0.1 m^3/sec.

Buried soils along the tidal Niawiakum River have provided much previously reported evidence for repeated prehistoric earthquakes on the Cascadia plate boundary. Gouge cores penetrated as many as 8 successive buried soils along a cross section about 0.5 km northwest of the Pool locality (Atwater, 1987; location of cross section shown in our Figure 5B). Downstream from this cross section the uppermost of these soils (soil Y) is widely covered by tsunami deposits that are commonly several centimeters thick (Atwater, 1987, in press; Reinhart and Bourgeois, 1987, 1989; Hemphill-Haley, 1995b). Herbaceous stems and leaves rooted in soil Y and in another, lower soil (soil S) show that both these soils record subsidence that occurred suddenly (Atwater and Yamaguchi, 1991, their Figures 4, 5). Fossil diatoms at the Oyster and Redtail localities, and at two other sites farther upstream, independently confirm that soil Y underwent sudden subsidence (Hemphill-Haley, 1995b; her sites 1 and 2 are at the Oyster and Redtail localities, respectively). Radiocarbon evidence for extensive plate-boundary rupture at the Cascadia subduction zone includes high-precision ages of spruce stumps rooted in soil Y near the Pool locality (Atwater and others, 1991; locations of dated stumps shown in our Figure 5B) and multiple accelerator-mass-spectrometry ages on herbaceous stems and leaves rooted in soil Y at the Oyster locality (Nelson and others, 1995; ages listed in our Table 6, and approximate sample location plotted in our Plate 1).

We surveyed successive buried soils along the Niawiakum River at three places where they are especially well exposed—the Redtail, Oyster, and Pool localities (Figure 5; Plate 1). At very low tides the Redtail locality displays six buried soils from the past 3500 years, the Oyster locality four buried soils from the past 2000 years. Probable correlatives of five buried soils exposed at the Redtail locality can be seen in outcrop at the Pool locality.

Redtail locality

The Redtail locality comprises 65 m of stream bank—about 30 m along the Niawiakum River, the rest along an unnamed tributary (Figure 9A,B). The bank is capped by tidal marsh except at its west end, where it intersects a forested upland of Pleistocene estuarine deposits. The Pleistocene deposits, composed mainly of stiff mud, descend eastward beneath a Holocene section that contains seven buried soils.

Buried soils

Six buried soils are exposed at the Redtail locality at tides below mean lower low water. Four of these soils are commonly peaty and (or) woody enough to form prominent ledges (Figure 9A-C, soils J, L, S, and Y); the other two, which are characteristically faint, lack such topographic expression (soils N and U). A seventh soil (H), observed only in core, underlies soil J near the forested upland.

All the soils dip away from the Pleistocene deposits onto which they lap. Such dips are greatest for the oldest soils (Plate 1 and Figure 9B; soils H, J, and L). Soil J is 1.7 m lower near the unnamed tributary than it is on Pleistocene deposits—a difference far greater than the 0.5 m of relief on the modern bank-top marsh along the Niawiakum River, which furthermore lacks an overall slope toward the unnamed tributary (Plate 1). Most of the 1.7 m of relief on soil J, and most of the northeastward dip of other buried soils as well, was probably caused by settlement through compaction of soft Holocene mud. Such mud is probably many meters thick above the last-glacial thalweg of the unnamed tributary; during the last glaciation the lower Niawiakum River flowed tens of meters below modern sea level, as shown by highway borings near the Oyster locality (p. 14). Settlement caused by compaction of peat and mud is common in tidal wetlands, as recently shown for modern salt marshes of the southeastern United States (Cahoon and others, 1995).

Most of the soils are interrupted by muddy channel fills in the northeastern half of the outcrop (Plate 1). The channel fills are 2-10 m wide in the plane of the outcrop. We observed truncation of buried soils on one or both margins of each fill. The fills consist of soft gray mud; in one of them, near horizontal coordinate 35 m, the mud contains much detrital wood.

Abundance of peat in the surficial horizon varies greatly for many of the soils, as summarized simplistically by the symbols for bold and faint soils in Plate 1. In soil J the surficial horizon consists of woody peat 10 cm thick near the forested upland but grades, along 20 m of continuous outcrop beside the Niawiakum River, into slightly peaty mud 2 cm thick. The woody peat abounds in forest-floor litter—sticks, spruce cones, needles. Soil L consistently contains 20 cm of muddy peat along the Niawiakum River but lacks such peat in 9 m of outcrop along the unnamed tributary. There, the surficial horizon of soil L is made of slightly peaty mud having many undulations 5-10 cm high and 5-20 cm long—elk or deer hoofprints, perhaps. The surficial horizon of soil N, though typically limited to dark brownish gray mud 2 cm thick, is composed of woody peat 5 cm thick for several meters along the Niawiakum River. Like soil J, this peat contains many sticks and spruce cones. Soil S, which typically contains a surficial horizon of woody peat 5-10 cm thick (Figure 9C), becomes faint where it laps onto Pleistocene deposits.

These variations in abundance of peat are probably due to initial composition in some cases and later decomposition in others. An initial abundance of forest-floor litter in soils J and N probably accounts for their greater abundance of peat near the forested upland; these soils logically received most such litter near the forested upland. Later decomposition in the profile of soil S probably accounts for the widespread faintness of soil N, and decomposition in the profile of soil Y probably accounts for the general faintness of U and the localized faintness of soil S. We infer decomposition for several reasons.
(1) Fossil diatoms (p. 12) and vascular-plant fossils (p. 13) together show that each of these soils represents a marsh or forest. In either case, vascular plants should have rained much organic matter onto each soil and injected additional organic matter into it, whether or not the soil is currently bold.
(2) Soils N, S, and U are faint where the overlying and underlying mud is firm, probably from desiccation similar to that evident in the firm, brownish or brown-and-gray-mottled mud beneath the surficial horizon of most modern tidal-marsh and tidal-swamp soils in southern coastal Washington.
(3) Even characteristically bold soil Y is faint where such modern oxidation has extended into it at the Sewer locality (p. 20).
(4) For soil U at the Oyster locality, abundance of peat increases with preservation of vascular-plant fossils rooted within and just above the soil (p. 14).
(5) Also for soil U at the Oyster locality, diatom assemblages do not differ greatly between a section where this soil is faint (horizontal ccordinate 25 m) and a section where this soil is peaty (horizontal coordinate 165 m; Figure 12). This similarity in diatom assemblage implies that differences in later decomposition, not differences in environment of formation, account for the variation from faint to bold for soil U at the Oyster locality.

Tsunami deposit

A tsunami deposit discontinuously overlies soil Y at the Redtail locality. The deposit consists of micaceous sandy silt about 1 mm thick. Most of the sand is very fine. The sandy layer is separated from the underlying soil by as much as 3 mm of gray mud. Such mud layers are commonly part of the tsunami deposit on soil Y elsewhere along the Niawiakum River (Reinhart and Bourgeois, 1987; Atwater and Yamaguchi, 1991, their Fig. 5B), as illustrated at the Oyster locality (p. 15; Figure 11E).

Several points show that a tsunami probably deposited the sandy layer.
(1) The layer resulted from an unusual event. Other than cracked rock in cultural deposits (p. 13), the sandy layer is the coarsest inorganic material in the outcrop.
(2) The unusual event approximately coincided with subsidence recorded by intertidal submergence and burial of soil Y. This coincidence, shown by the position of the sandy layer just above the top of soil Y, would not be expected of a storm but would be expected of a tsunami generated by a plate-boundary earthquake at the southern Washington part of the Cascadia subduction zone (Atwater, 1987). The coincidence is further demonstrated by the preservation of herbaceous stems and leaves, in growth position, in the sandy deposit on soil Y at the Oyster locality (p. 15).
(3) The event entailed flow up the Niawiakum River valley, as shown by variation in thickness of correlative sand elsewhere along the Niawiakum River (Atwater, 1987, in press; Reinhart and Bourgeois, 1987), by oriented plant fossils at the Oyster locality (p. 15), and by diatoms—found immediately above soil Y at four sites between the Oyster and Pool localities—that were derived from sandy tidal flats (Hemphill-Haley, 1995b).
(4) The event comprised multiple pulses, as shown by the presence of five or six sandy layers within the sandy deposit on soil Y at the Oyster locality (p. 15; Figure 11E). A tsunami typically comprises a train of waves; each of the sandy layers can be ascribed to a separate wave in a tsunami wave train.
(5) Currents from a storm or seiche are unlikely to have been swift enough to account for the extent and grain-size trends of sandy deposits on soil Y along the Niawiakum River, according to an unpublished sediment-transport model by Reinhart and Bourgeois (1989). However, a storm surge at least 2.5 m high deposited sand, silt, and clay on tidal marshes along several kilometers of a Florida river in 1993 (Goodbred and Hine, 1995). For the time being, unusualness (point 1) and coincidence with subsidence (point 2) together provide the main available evidence that the sandy deposit on soil Y records a tsunami rather than a storm.

Fossil diatoms

Diatoms show that each of the six buried soils seen in outcrop at the Redtail locality formed higher in the intertidal zone than did mud above the soil (Figure 10). In addition, they provide further evidence for tsunami deposition on soil Y, and they hint at the presence of an otherwise invisible soil between soils U and Y.

Each of the six soils contains diatoms indicative of conditions at or above very high tides (Figure 10). Diatoms of soils J, L, and U are dominated by species—particularly *Navicula pusilla* and *Pinnularia lagerstedtii* (Table 3)—indicative of tidal marsh above mean higher high water. Even higher conditions are suggested by the small number and poor preservation of diatoms in the uppermost parts of soils S and Y, and by abundant spruce roots in these soils (p. 13). Such conditions are also implied by diatoms high in soil N but not by a lack of spruce roots in this soil (p. 8).

For all six buried soils the transition from soil to overlying mud coincides with an abrupt shift to assemblages of diverse diatom species indicative of intertidal flats or shallow subtidal areas (Table 3). For soils J, L, and U this shift bypassed low marsh, and for soils S and Y (and perhaps also soil N) it bypassed high marsh as well. The corresponding change in relative sea level, as inferred from modern wetlands and their diatom assemblages (Figure 6, Figure 7), is probably about 1 m or more in each case.

Diatoms provide supporting evidence that a tsunami deposited the very fine sandy silt a few millimeters above soil Y at the Redtail locality. A sample from this interval contains well-preserved estuarine tidal flat species and lacks freshwater diatoms (Table 3, sample from depth 0.74 m); this assemblage rules out the possibility that the sandy deposits records a freshwater flood down the Niawiakum

River. More than half the tidal flat species are diatoms typical of sandy tidal flats of Willapa Bay. These species show that the sand was not washed downstream by a flood of fresh water. Similarly high percentages of sandflat species are present in mud just above soils S and N, but neither of these soils is overlain by a bed as sandy or as close to the soil as the sandy bed above soil Y.

Diatoms collected about 1 m below the modern marsh surface in the cleaned outcrop face shown in Figure 9C may record the former presence of a soil between soils U and Y. Whereas high-marsh diatoms are dominant in a 2-cm thick interval near 1 m depth, tidal-flat species predominate in sediment above and below this interval. The interval may represent a soil correlative with soil W at the Oyster locality (see *Age and correlation* on p. 16). However, diatom preservation is too poor high in the profile of soil Y (see last page of Table 3) to provide convincing evidence for or against the presence of such a soil at the Redtail locality.

Growth-position fossils of vascular plants

Woody roots and herbaceous rhizomes, where preserved, are consistent with these paleoecological interpretations of fossil diatoms. Four of the buried soils contain spruce roots suggestive of conditions within or above the upper ½ m of the intertidal zone. The roots are most widespread in soils S and Y (Plate 1; Figure 9A-C). Spruce roots are also present in soil L, both at its juncture with Pleistocene deposits (Figure 9A) and along the tributary slough near the northeastern end of the surveyed outcrop (Plate 1). Soil J contains spruce roots only where it laps onto Pleistocene deposits (Figure 9A).

Mud above soils H and J contains rhizomes indicative of conditions lower in the intertidal zone. All these rhizomes are of *Triglochin maritima* except above soil H, where the mud also contains rhizomes of *Carex lyngbyei.*

Cultural deposits

Evidence of a human campsite at the Redtail locality confirms the high-level environment indicated by spruce roots and diatom assemblages in soil Y. This evidence, exposed along nearly 10 m of Niawiakum River outcrop (Plate 1), includes charcoal, cracked rock, heated bone, and reddish-brown lenses probably composed of ash from wood fires (Cole and others, 1996) (Figure 9D).

Age

High-precision ages can be assigned to the oldest and youngest buried soils recorded in outcrop at the Redtail locality (Figure 8). Radiocarbon ages on forest-floor litter at the Redtail locality (Table 6, lab numbers QL-4716, -4717, and -4718) show that the burial of soil J began 3300-3500 calendric years ago. Radiocarbon ages on spruce roots from nearby sites—a beach at Bay Center and river banks near the Pool locality (Figure 5)—show that the burial of soil Y began about 300 years ago (Atwater and others, 1991), probably between A.D. 1700 and 1720 (Nelson and others, 1995).

Additional radiocarbon ages from the Redtail locality suggest broad calendric ranges during which some of the other burial events probably occurred (Figure 8): 2500-3500 years ago for soil L, 2400-2800 years ago for soil N, and 1500-2000 years ago for soil S.

Two charcoal ages and a tree-ring count from soil Y show that the Redtail locality was used by people as early as A.D. 1000, and that it did not necessarily remain in human use when burial of soil Y probably began in the early 1700s. The older of the dated charcoal samples—630±90 ^{14}C yr B.P. , or A.D. 1000-1600 (Figure 8)—came from a cultural lens that is separated from the top of soil Y by 10 cm of archaeologically sterile peat. The younger charcoal sample gave an age of 250±60 ^{14}C yr B.P., which corresponds to a calendric range that includes A.D. 1700. Although this younger sample came from a fire pit that extends nearly to the top of soil Y, a spruce root having at least 60 annual rings grew into this fire pit (Plate 1). This spruce, like the others represented by roots in soil Y, probably died from submergence that initiated the burial of soil Y. In that case, the fire pit predates the submergence and initial burial of soil Y by at least 60 years.

Oyster locality

The Oyster locality, located 1 km west-northwest of the Redtail locality, comprises the northeast bank of the Niawiakum River about 100-300 m upriver from U.S. highway 101. The top of the bank is high marsh except for a mudflat 50 m wide at the confluence of two tidal creeks tributary to the river (Figure 11A, B; Plate 1). Since 1986 the upper half of the bank has been invaded by *Spartina alterniflora* (Figure 11C), an Atlantic-coast grass that began to spread rapidly at Willapa Bay in the early 1980s (Sayce, 1988; Mumford and others, 1990).

Buried soils

Four buried soils are widely exposed at the Oyster locality. The oldest and youngest of these are bold soils with ledge-forming peaty horizons (Figure 11B-D). The two intervening soils are characteristically faint and lack topographic expression except on well-washed, nearly vertical faces, from which they protrude a few centimeters more than does mud immediately above them. For reasons discussed under "*Age and correlation*" (p. 16), we equate the bold soils with soils S and Y of the Redtail locality, and the lower of the faint soils with Redtail soil U. We did not notice a correlative of soil W, the other faint soil at the Oyster locality, in studies of the Redtail locality, except perhaps as in diatom assemblages (p. 13).

All the soils at the Oyster locality dip gently southeastward (Figure 11B; Plate 1), diagonally away from the nearest upland. The oldest soils dip most steeply; soils S and U are nearly 1 m lower on the southeast than on the northwest. As at the Redtail locality (p. 10), most of this relief is probably due to compaction of soft Holocene mud, which may thicken southeastward beneath the Oyster locality, the direction toward the middle of the Niawiakum River valley (Figure 5B). Such thickening of soft mud has been observed in foundation borings along nearby U.S. 101 (Washington State Department of Transportation, Olympia, unpublished data, 1986). In these borings, the mud is thickest—about 30 m—about midway across the valley. Slumping along the Niawiakum River may have also contributed to relief on the buried soils at the Oyster locality. Such slumping is indicated by nearly vertical faults having less than 1/4 m offset and exposed on the modern bench between soils S and W in the southeastern half of the outcrop.

Soil U varies greatly in abundance of peat at the Oyster locality. At the northwest end of the outcrop the surficial horizon of soil U is barely recognizable as a band of mud about 1 cm thick that is slightly darker (by one unit of value in the Munsell color system) than the mud above and below it (Figure 11E). To the southeast, however, the surficial horizon of soil U grades laterally through peaty mud into muddy peat 5 cm thick. This southeastward gradation is accompanied by the appearance of vascular-plant fossils—rhizomes below and above the soil, stems and leaves of herbaceous plants rooted within the soil—that are absent to the northwest (Plate 1). The southeastward gradation is further accompanied by softening of the mud above and below soil U. It is not accompanied, however, by any major change in diatom assemblage (Figure 12). We infer that the lateral changes in vascular-plant remains reflect differential oxidation and desiccation during the time when soil Y was at the land surface. Such oxidation and desiccation are more likely to have attacked the northwest end of the outcrop, where soil U is 0.3 m below the top of soil Y, than the southeast end, where soil U is 1.0 m below the top of soil Y.

Soil W is everywhere fainter than the underlying part of soil U. At the northwest end of the outcrop soil W is not generally visible (Figure 11E)—probably because of oxidation in the profile of soil Y, the top of which is 0.2 m above soil W (Plate 1). Like soil U, soil W becomes more noticeable to the southeast, where it descends to as much as 0.4 m below the top of soil Y. Nowhere at the Oyster locality, however, is soil W peaty.

Tsunami deposit

A tsunami deposit overlies soil Y at the Oyster locality (Figure 11E). The deposit comprises five or six sandy laminae that alternate with mud (Atwater and Yamaguchi, 1991, their Figure 5). The lowest of these laminae, which is also the least distinct and least continuous, rests directly on the soil. The thickest and coarsest lamina is micaceous, silty, very fine sand 1 cm thick. The two uppermost laminae are a pair of silt partings. The total thickness of the deposit is mainly 5-7 cm.

The deposit accumulated around herbaceous plants rooted in soil Y. At the northwest end of the outcrop the surrounded tufts of *Deschampsia caespitosa* are flopped over to the east (Figure 11E)—upvalley (Figure 5)—as are the stems and basal leaves of *Potentilla pacifica.* The measured azimuths of 14 of these flopovers near the northwest end of the outcrop range from 065° to 120° and average 082° (M.A. Reinhart and S. McMullen, written communication, 1987). These orientations imply currents directed up the Niawiakum River valley.

There are no other sandy beds in the outcrop except in a probably correlative lens within the channel fill that underlies the mudflat at the confluence of tidal creeks (Figure 11C; Plate 1). This sandy lens, as much as 15 cm thick, consists of micaceous, silty, very fine to fine sand interbedded with mud. Several of the sand beds in the lens abound in flat-lying plant fragments—mainly bark-free twigs, pieces of bark as much as 1 cm thick, and a few leaf bases of *Triglochin maritima.* The twigs may have been recycled from an older deposit, as shown by their lack of bark and their radiocarbon age (p. 17).

Reasons for inferring that a tsunami deposited the sand on soil Y at the Oyster locality are listed above (p. 12).

Growth-position fossils of vascular plants

Vascular-plant fossils and algal layers imply that burial of soils S, U, and Y at the Oyster locality resulted from a relative sea level rise of at least 1 m. Rooted in each soil are stems and leaves of high-marsh plants. By contrast, mud above each soil contains growth-position rhizomes of the predominantly low-marsh species *Triglochin maritima.* These rhizomes imply a position near the lower growth limit of *Triglochin maritima* for two reasons: (1) Though well preserved, the lowest *Triglochin maritima* rhizomes above each of the three soils lack associated fossils of high-marsh plants. (2) These lowest rhizomes are underlain, above each of the three soils, by mud containing rhythmic organic laminae similar to those produced by filamentous algae on mudflats below the lowest *Triglochin martima* at the Oyster locality. Such laminae, which are among the geologic recorders of fully intertidal conditions at Willapa Bay (Clifton, 1983, p. 362), form today about 1.0-1.5 m below the level of high marsh at the Oyster locality (Figure 6, "algal mat").

Herbaceous plants rooted in Soils S and Y probably lived higher in the intertidal zone than did the plants rooted in soil U. All three soils bear tufts of the high-marsh grass *Deschampsia caespitosa,* as shown in photographs of soils S (Atwater and Yamaguchi, 1991, their Figure 4B) and Y (our Figure 11E). But only soil U bears stems of the pickleweed *Salicornia virginica,* which tolerates higher soil salinity than do other vascular plants of tidal marshes in the western United States (Mall, 1969; Barbour and Davis, 1970). Conversely, the less-saline high-marsh species *Juncus balticus* and *Potentilla pacifica* are commonly rooted in soils S and Y but appear absent from soil U. Soil U probably was inundated by salty tidewater about as frequently as the modern high marsh at the Oyster locality, on which *Salicornia* is common within 50 m of the Niawiakum River. The lack of *Salicornia* on soils S and Y implies less-frequent inundation by salty tidewater. This interpretation is supported by differences in diatom assemblages (p. 16).

Soil W probably represents a low marsh or an incipient high marsh above the lower growth limit of *Triglochin maritima.* We found no growth-position remains of vascular plants that might have been rooted on soil W or which might have colonized the overlying mud. However, rhizomes of *Triglochin maritima* are present 35 cm below the top of soil W near the southeastern end of the Oyster locality (Plate 1). These rhizomes probably formed near the lower limit of *Triglochin maritima*: as noted above, they are underlain by algal laminae commonly found near that limit (p. 15); moreover, mud among the rhizomes contains diatom assemblages indicative of the transition from tidal flat to low marsh (Figure 12, section at horizontal coordinate 165 m). After *Triglochin maritima* became established, the marsh probably aggraded to a position higher in the intertidal zone, as shown by an overall shoaling trend in diatom assemblages between soils U and W (Figure 12).

Fossil diatoms

Diatom analyses suggest that the four soils exposed at the Oyster locality represent tidal marshes, and that mud above each of these soils was deposited lower in the intertidal zone or perhaps in subtidal water (Figure 12). The diatoms further suggest that soils S and Y represent positions higher in the intertidal zone than do soils U and W, and that soil W represents the lowest position of any of the four soils.

Diatoms in soils S and Y are dominated by high-marsh species. However, they also contain large numbers of heavily silicified and easily reworked tidal flat diatoms (Table 4, Table 5). These probably allochthonous valves produce lower BIDI values than would be predicted for soils S and Y on the basis of vascular-plant fossils.

Diatoms in soil U imply a slightly lower-level high marsh than do diatoms for soils S and Y because, unlike soils S and Y, soil U contains a well-preserved assemblage of low-marsh species that require regular tidal inundation, particularly *Gyrosigma eximium.* Such an assemblage can be found today in stands of *Salicornia virginica* near mean higher high water on the riverward part of the modern marsh at the Oyster locality (Hemphill-Haley, 1995a). The fossil diatom assemblage thereby accords with the vascular-plant assemblage rooted in soil U; the vascular plants rooted in soil U are dominated by *Salicornia virginica.*

Soil W probably represents a vegetated wetland transitional between low marsh and high marsh. This position is suggested by the high numbers of low-marsh species, particularly *Diploneis interrupta.* Although uncommon in modern samples from Willapa Bay, *D. interrupta* is a dominant constituent of *Salicornia* and *Distichlis* low marshes at Lynch Cove (E. Hemphill-Haley, unpublished data; location shown in Figure 1).

The tsunami deposit overlying soil Y at the Oyster locality (p. 15) contains many well-preserved sand-flat diatoms (sample depth 0.89 m in Table 4, 1.09 m in Table 5). Chief among these species are *Achnanthes delicatula* and *Cocconeis diminuta.*

The change in diatom assemblages across the top of soil W conceivably could record a tsunami rather than decades or centuries of submergence. Although the diatoms imply a change from tidal marsh (soil W) to a tidal flat (the overlying mud), the tidal flat apparently reverted to tidal marsh after aggrading merely 5 cm (Figure 12). However, compared with the tsunami deposit on soil Y, the mud on soil W contains few sandflat diatoms that might have been derived from the open bay.

Age and correlation

Radiocarbon ages have been measured on vascular-plant fossils associated with the burial of soils S and Y at the Oyster locality. The burial of soil S at the Oyster locality began shortly before 1300-1900 years ago, as shown by a radiocarbon age on rhizomes above the soil (Plate 1, Figure 8). The age supports correlation with soil S at the Redtail locality—a soil that began to be buried about 1500-2000 years ago

(Figure 8). Burial of soil Y began no earlier than A.D. 1660, as shown by radiocarbon ages of *Potentialla pacifica* and *Juncus balticus* rooted in soil Y and surrounded by the overlying tsunami deposit (Nelson and others, 1995). The individual ages are listed in Table 6, and ranges of calendric ages corresponding to their weighted mean (161 ± 15 ^{14}C yr B.P.) are plotted in Figure 8.

Several additional lines of evidence tend to confirm that the oldest and youngest buried soils exposed at the Oyster locality correlate with soils S and Y, respectively, at the nearby Redtail locality. (1) Both soils are characteristically bold at both localities. (2) The youngest buried soil is the only one covered by sand at either locality. (3) Vascular-plant fossils rooted in both soils at both localities imply lower soil salinity do the plants of the modern marshes. At the Oyster locality, *Salicornia* is common on modern high marsh near the river but is absent from soils S and Y. Similarly at the Redtail locality, Sitka spruce is absent from the modern marsh but abundant in soils S and Y. (4) Diatom assemblages at both localities suggest that soils S and Y formed higher in the intertidal zone than did the intervening soil or soils (p. 16).

The lower of the characteristically faint soils between soils S and Y at the Oyster locality (soil U) probably correlates with the only faint soil preserved between soils S and Y at the Redtail locality (soil U). The upper of the faint soils between soils S and Y at the Oyster locality (soil W) was probably destroyed altogether at the Redtail locality: soil U at the Redtail locality is as high in the profile of soil Y as it is at the northwest end of the Oyster locality (Plate 1), where soil W was probably destroyed by oxidation during the time that soil Y was at the ground surface (p. 14).

Twigs from the sand lens in the channel fill at the Oyster locality yielded radiocarbon ages that may be centuries greater than the age of the lens. Several tens of twigs collectively gave an age of about 500-1000 years ago, and a single twig gave an age of about 500-800 years ago. However, the lens accumulated only 300 years ago if it correlates with the sandy interval on soil Y. We infer that a tsunami along the Niawiakum River about 300 years ago exhumed and redeposited twigs that had first been deposited centuries before. Such recycling of twigs and sticks best explains discordant radiocarbon ages from a tsunami deposit about 300 years old at Port Alberni, British Columbia (Clague and Bobrowsky, 1994).

Pool locality

The Pool locality comprises 20 m of bank about 10 m from upland (Figure 5B). The bank is fully exposed at many low tides because the minimum level of river water at the Pool locality is about 1 m above the level of mean lower low water (Plate 1). The water cannot drop further because, in its upper tidal reaches, the bed of the Niawiakum River ascends upriver through the level of very low summer tides. During such tides the river is a trickle on an exposed bed where it passes beneath the South Bend - Palix River Road.

Though not tall, the bank exposes five buried soils. In addition, we noted two underlying soils in a gouge core near the southwest end of the outcrop, and we found Pleistocene deposits about 1 m below the lower of these soils (Plate 1).

The sequence of five soils resembles the sequence of the five uppermost buried soils at the Redtail locality: three bold soils contain tree roots in growth position; and these soils (L, S, and Y) alternate with faint soils (N and U). Most of the tree roots at the Pool locality belong to Sitka spruce, but soil S also contains roots of western redcedar (Plate 1, horizontal coordinate 3 m). Inner rings of the redcedar have been sampled for high-precision radiocarbon dating.

High-precision radiocarbon ages were previously reported for several samples from soil Y near the Pool locality (Atwater and others, 1991). The nearby samples are from Sitka spruce stumps rooted in the soil at locations plotted in Figure 5B and identified there by laboratory number (QL-). For one of these stumps, separate ages for inner and outer rings (QL-4405 and QL-4406) reduced ambiguity in converting radiocarbon ages to calendric ages; the ages limited the probable time of tree death to the first few decades of the 1700s (Nelson and others, 1995).

Willapa River

The Willapa River drains about 350 km^2 of mostly hilly country southeast of Raymond (Figure 5A). Its lower reaches are flanked locally by tidal marshes and, upstream of Raymond, by tidal spruce swamps. In 38 years between 1947 and 1993, discharge by the main branch of the river averaged 1.8 m^3/sec and ranged from 0.4 m^3/sec to about 335 m^3/sec at a gage about 5 km east of Raymond (Miles and others, 1994, p. 45).

Buried soils suggestive of coseismic subsidence along the Willapa River have been briefly described from the South Fork locality, on the east flank of the South Bend antiform (Figure 5). At least six buried soils are superposed in outcrop at this locality, and two underlying soils were found in boreholes (Hull, 1987; Atwater, 1992, Table 1). The South Fork locality closely resembles the Redtail locality in sequence of bold and faint soils and in radiocarbon ages on spruce roots, woody detritus, and peat associated with these soils (Hull, 1987) (Figure 8).

Buried soils have now been surveyed at several Willapa River outcrops on the South Bend antiform—the Jensen, Sewer, and Airport localities (Figure 5; Plate 1). None of these localities have been studied as thoroughly as have the Redtail and Oyster localities along the Niawiakum River. However, the sequence of eight buried soils at the Jensen locality probably spans as much time as does the sequence at the Redtail locality, and the shorter sequences of buried soils at the Sewer and Airport localities probably record most or all of the time represented in outcrop at the Oyster locality (Figure 8).

Jensen locality

The Jensen locality comprises part of the western end of Jensen Island. The main outcrop is an east-west dredge cut on the north side of the island. This outcrop, surveyed for 70 m, exposes a section of natural deposits 3.5 m tall at lowest tides (Figure 13A). Additional surveyed outcrop extends 40 m southward from the west end of the dredge cut. The bottom of this additional outcrop intersects a modern mudflat about 1 m above lowest tides.

Buried soils

Eight buried soils crop out at the Jensen locality. Four are typically bold enough to form horizontal ledges that extend without interruption for tens of meters along the dredge cut—especially soil S, which has a peaty surficial horizon 15-20 cm thick. A fifth soil, termed soil L, is bold only among spruce roots (Figure 13B). The other three soils are everywhere faint and have little topographic expression. We correlate each of the soils with a soil along the Niawiakum River. This correlation, discussed below under "*Age and correlation*" (p. 19), is based on the sequence of bold and faint soils, on the presence or absence of spruce roots, and on radiocarbon ages from soils H and L.

The horizontality and close vertical spacing of the buried soils at the Jensen locality reflect a shallow, almost horizontal foundation of Pleistocene deposits. These deposits consist of stiff yellowish mud that resembles weathered Pleistocene estuarine deposits elsewhere in the Willapa Bay area. They lie less than 3/4 m below the top of soil H and grade upward, through firm brownish gray mud, into the peaty surficial horizon of soil H (Plate 1).

Faint soils N and W are the least traceable of the buried soils at the Jensen locality. They fade laterally like soil W at the northwest end of the Oyster locality, where soil W becomes too faint to identify readily high in the profile of the succeeding bold soil Y (Figure 11E). Soils N and W at the Jensen locality are high in the profiles of succeeding bold soils S and Y, respectively.

Growth-position fossils of vascular plants

Soils H, J, L, S, and Y are associated with woody roots and (or) with herbaceous rhizomes (Plate 1). Soils H and Y contain woody roots indicative of conditions high in the intertidal zone or above highest tides; in addition, mud above each of these soils contains rhizomes of *Triglochin maritima*, an indicator of conditions lower in the intertidal zone. Soil L contains radiating roots attributable to a single Sitka spruce. Soil S lacks woody roots in growth position but is overlain by mud that contains rhizomes doubtfully identified as *Carex lyngbyei*. Soil J also lacks woody roots but mud above it contains rhizomes of *Triglochin maritima.*

Age and correlation

The sequence of soils and intervening mud at the Jensen locality spans the past 3500-4500 years. This estimate is based on the age of a stick associated with soil H—3640 ± 80 ^{14}C yr B.P. This stick was found undulating subhorizontally across the top of the soil. Its age shows that burial of the lowest soil began no later than 3500-4500 years ago. We correlate this lowest soil with soil H at the Redtail locality, where soil H was buried shortly before 3570 ± 70 ^{14}C yr B.P., the age of *Triglochin maritima* rhizomes above the soil (Table 6; Plate 1).

Three points suggest that typically faint soil L at the Jensen locality correlates with typically bold soil L at the Redtail locality, despite the greater abundance of peat in the latter. (1) The outer 25 rings of a spruce root in soil L at the Jensen locality gave a radiocarbon age—2820 ± 50 ^{14}C yr B.P.—similar to three of the four ages for soil L at the Redtail locality (Table 6; Figure 8). This age is geologically reliable because the outermost of the dated rings probably formed during the year before the tree died from earthquake-induced submergence: this ring adjoins bark; and, like several tens of preceding rings, it is wide enough to record ordinary growth of a healthy tree. (2) In containing spruce roots, soil L at the Jensen locality resembles soil L, but not the root-free soil N, at the Redtail locality. (3) The typical faintness of soil L at the Jensen locality can be explained by proximity to, and consequent oxidation beneath, soil S.

These correlations are consistent with overall similarities among the Jensen, Redtail, and South Fork localities in the sequence and age of bold and faint soils (Figure 8). The sequence at the Jensen locality differs only in the presence of a faint soil—soil W—not recognized at the Redtail and South Fork localities. But as inferred above (p. 14, 17), poor preservation limits the traceable extent of soil W at the Oyster locality and probably accounts for the absence of soil W at the Redtail locality. The survey of the South Fork locality was completed in 1987, before findings elsewhere—especially at Elliott Slough (Figure 4, Figure 8) (Atwater, in press) and the Oyster locality—called attention to possible destruction of soils high in the profile of soil Y.

Sewer locality

The northeast bank of the Willapa River displays buried soils for much of the 5-km distance between the South Bend sewer ponds and the Willapa Harbor airport. We surveyed outcrops near the South Bend sewer ponds (the Sewer locality) and near the airport (the Airport locality) (Figure 5). The buried soils at both these localities are exposed mainly in steep banks less than 2 m high. Additional outcrop below these banks slopes gently riverward and is commonly obscured by modern mud and (or) cut by bank-parallel fractures.

The surveyed outcrop at the Sewer locality extends 1/2 km northwestward from the pipe that carries effluent to the sewer ponds, which are situated on former tidal marsh north of the river. We noted an uppermost buried soil, termed soil Y, along the entire length of this outcrop, and we found a lower buried soil, termed soil S, along its northwestern half. Plate 1 depicts the outcrop's central 180 m, which contains representative stratigraphy and all the archaeological features noted at the locality.

Buried soils

The northwestern part of the Sewer locality contains four buried buried soils. Only the lowest of these, soil S, is characteristically peaty. Soil Y, the uppermost buried soil, is the next-most noticeable but mainly because the lowest 10-30 cm of the overlying mud is distinctively laminated with silt that etches on recently scraped, well-washed faces (Figure 14A,B). Both the remaining, intervening soils (soils U and W) are faint, particularly the upper one. Like soil S, soils U and W are probably not exposed in the southeastern 1/4 km of the outcrop.

We did not observe continuity of the buried soils as widely at the Sewer locality as at the Redtail, Oyster, and Jensen localities. In general, the soils at the Sewer locality cannot be seen where outcrop has not been scraped clean. None of the soils form widely visible breaks in the slope of the outcrop: soil S is commonly at or near the bottom of steep outcrop; none of the other soils are typically peaty; and steep outcrop is commonly cluttered by modern slumps and plants.

Soils S and Y have maximum relief of about 1/2 m. Between horizontal coordinates 360 and 290 m, soil Y rises southeastward to a crest on the northwest margin of a tidal creek. This crest may be a natural levee or it may mimic relief from underlying archaeological material. However, neither of these explanations accounts for the high level of soil Y between coordinates 260 and 180 m, where nearby tidal creeks are lacking and cultural deposits are scarce (Plate 1).

The surficial horizon of soil Y ranges from peaty mud 1-2 cm thick to dark mud as little as 0.5 cm thick, probably because of variable decomposition after burial. The soil is richest in peat at low altitude, where the lowest part of the overlying mud locally contains *Triglochin maritima* rhizomes. At high altitude the surficial horizon of the soil contains no peat (Figure 14A,B), the overlying mud lacks *Triglochin maritima* rhizomes, and mud both above and below the surficial horizon of the soil is commonly firmer and more oxidized (yellower and redder) than at low altitude. These differences imply that where soil Y is high and faint, oxidation has extended through the surficial horizon of the soil and destroyed any peat or overlying rhizomes that may have been present soon after burial.

Growth-position fossils of vascular plants

Growth-position fossils show that soil Y formed at higher altitude than did mud that overlies the soil. Whereas the soil contains sparse stumps of shrubs (perhaps western crabapple; Figure 14B), the overlying mud locally contains growth-position rhizomes of *Triglochin maritima.*

Vascular-plant fossils in growth position are absent within, and sparse or absent immediately above, the other buried soils. Mud above soil S contains rhizomes of *Triglochin martima* at several surveyed points, as does mud above soil U at one such point. However, we did not find remains of plants that had lived on either of these soils, nor did we find any vascular-plant fossils within or immediately above faint soil W. Like the widespread lack of preserved peat and vascular-plant fossils in overlying soil Y, and also in soil U at the Oyster locality (p. 14), this paucity or absence of vacular-plant fossils probably reflects decomposition after burial, not initial absence.

Cultural deposits

Cultural deposits locally underlie the surficial horizon of soil Y, from which they are separated by 5-20 cm of mud (Figure 14A,B; Plate 1, archaeological detail). The cultural deposits, in bodies as much as 18 m long and 0.4 m thick, consist of black carbonaceous mud and sand. Within this mud and sand are charcoal, cracked rock, and lenses of reddish-brown fire ash containing fish vertebrae. In places the carbonaceous deposits continue downward, into underlying mud, as filled holes about 5 cm in diameter (Figure 14A; Plate 1). The holes were probably left by stakes: we found laminae bent downward beside one of the holes, and we found the charred, nearly vertical lower tip of a stake about 3 cm in diameter near a probable fire pit (Plate 1, horizontal coordinates 298.5 and 295.5, respectively).

The Sewer locality also includes remains of two fish weirs (Figure 14C,D). The weirs are located on a tidal flat 10-25 m southwest of (riverward from) the steep riverbank outcrop and 25-100 m southeast of (upriver from) the cultural deposits. Their remains comprise hundreds of vertical sticks arrayed in v-shaped lines 5-15 m long. The sticks retain bark and sound wood below the soupy modern mud that veneers the flat, and they protrude as rotten, worm-bored stubs as much as 15 cm above the flat.

Collectively, these cultural features have been designated the "South Bend fishing weir and camp" and assigned, by the Washington State archaeologist, Smithsonian number 45PC103.

Fossil diatoms

Diatoms were studied from a vertical section across the top of soil Y near horizontal coordinate 299 m (Plate 1).

Changes in diatom assemblages across this stratigraphic boundary indicate that the soil formed at higher altitude than did the overlying mud. The faint surficial horizon of soil Y contains diatom fragments and abundant pollen grains suggestive of conditions near or above the level of highest tides. By contrast, mud above the soil contains many tidal-flat diatoms (e.g., *R. psammicola, Synedra fasciculata, Thalassionema nitzschioides, Nitzschia sigma*), consistent with the presence of *Triglochin maritima* rhizomes in this stratigraphic position 40 m to the northwest.

Diatom assemblages centimeters below the top of soil Y are too sparse to be diagnostic of any depositional environment. The few diatoms in mud between the cultural deposit and the top of soil Y are dominated by tidal-flat species (e.g., *Rhaphoneis psammicola, Delphineis* cf. *surirella, Dimeregramma minor*). The cultural deposit itself contains rare fresh to brackish soil diatoms, including *Hantzschia amphioxys* and *Navicula muticoides.*

Age and correlation

We correlate buried soils at the Sewer locality with four soils at the Niawiakum River on the basis of approximate similarity in stratigraphic sequence and radiocarbon age (Plate 1, Figure 8). Although generally fainter than soil Y along the Niawiakum River, the uppermost buried soil at the Sewer locality resembles that soil in recording an altitude higher than is represented by overlying mud. Moreover, a radiocarbon age of 90 ± 60 ^{14}C yr B.P. was obtained on outer rings of one of the shrub stumps rooted in soil Y at the Sewer locality (Plate 1). This age, which corresponds to A.D. 1650 or later, is indistinguishable from outer-ring ages of earthquake-killed spruce rooted in soil Y at the Niawiakum and Copalis Rivers (Figure 8). In addition, the age overlaps, at one quoted error, with the weighted-mean age of 161 ± 15 ^{14}C yr B.P. from the eight separately dated earthquake-killed herbs rooted in soil Y at the Oyster locality (Plate 1; Table 6).

The correlation of bold soil S is doubtful because of a difference in radiocarbon ages for *Triglochin maritima* rhizomes in overlying mud: 1990±70 ^{14}C yr B.P.at the Sewer locality, versus 1630±70 ^{14}C yr B.P. at the Oyster locality. However, old plant fragments may have contaminated the dated rhizomes from the Sewer locality. These rhizomes, collected rotten nearly beyond recognition, were not cleansed of interstitial mud, which may have contained older plant detritus. By contrast, the dated rhizomes from the Oyster locality were nearly as fresh as modern rhizomes, a condition that allowed vigorous cleaning under tapwater and verification that the dated material contained little or no old detritus.

The fishing camp recorded by the cultural deposits originated as early as A.D. 1100, and the weirs were built or repaired sometime between 1400 and 1650. These estimates are based on radiocarbon dating of the stake with the charred lower tip (710 ± 70^{14}C yr B.P.) and of a bark-bearing stave from one of the weirs (380 ± 50 ^{14}C yr B.P.) (Plate 1). The camp was abandoned years to centuries before burial of soil Y began at the Sewer locality, as shown by the 5-20 cm of mud that separates cultural deposits from the surficial horizon of the soil.

Airport locality

Two buried soils are widely exposed at the Airport locality and a third, intervening soil is exposed at the southeastern end of this locality (Plate 1). The uppermost soil, probably equivalent to soil Y at the other localities, is commonly overlain by mud that contains *Triglochin maritima* rhizomes. Such rhizomes also overlie the lowest soil at the edge of a filled channel. This lowest soil, probably equivalent to soil U, is typically faint but locally retains a peaty surficial horizon and rhizomes of the high-marsh plant *Juncus balticus*. The intervening soil is entirely faint and probably equivalent to soil W. These correlations are tentative because no radiocarbon ages have been obtained for the Airport locality.

DISTINCTION BETWEEN TECTONIC SUBSIDENCE DURING EARTHQUAKES AND OTHER WAYS OF PRODUCING THE BURIED SOILS

Buried soils at estuaries can serve as recorders of tectonic subsidence that accompanies earthquakes. Near Anchorage, Alaska, subsidence during the great 1964 Alaska earthquake lowered marshes and forests to the level of tidal mudflats. As a result of this subsidence, peaty soils of the marshes and forests became covered by 1-2 m of tidal-flat mud by the early 1970s (Ovenshine and others, 1976). This Alaskan example underpins the use of interbedded peat and mud as evidence for coseismic subsidence at the Cascadia subduction zone.

Such paleoseismic interpretation of interbedded peat and mud can be confounded, however, by similar interbedding produced without coseismic tectonic subsidence. The potentially confounding processes include cut and fill by migrating tidal streams, deposition by storms and floods, rise in sea level, breaching of bay-mouth barriers, settlement from earthquake-induced compaction, and rapid aseismic folding (Atwater, 1987, 1992; Nelson and others, in press b).

We found no evidence that alternatives to sudden tectonic subsidence better explain any of the buried soils that we surveyed. However, criteria for identifying sudden tectonic subsidence can be applied more securely to some buried soils than to others. We ruled out cut and fill for most buried soils in most of the surveyed outcrops. In many cases we also ruled out deposition by storms or floods; in some cases we ruled out rise in tide level from sea-level rise and barrier breaching; and in some cases we can also show that subsidence had a tectonic, probably coseismic component. Finally, we used similarities in stratigraphic sequence and radiocarbon age to extrapolate from these various cases to all soils correlated (named by letter, as in "soil Y") among the surveyed outcrops.

Cut and fill by tidal streams

Most of the buried soils have less relief and more lateral continuity than is likely for a mud-over-peat contact that represents cutting and filling. Relief on the buried soils resembles the typically low relief on modern tidal marshes. This low relief contrasts with the unconformities observed for modern and filled channels (Plate 1; Figure 11A-C). In addition, the preservation of herbaceous stems and leaves rooted in some of the soils—particularly in soils S and Y at the Oyster locality—show that the tops of those soils underwent little or no erosion before burial. The only soil that might record cut and fill is faint soil W at the Jensen locality, where the soil is so poorly preserved that its relief and continuity cannot be readily determined.

Lateral continuity has also been checked through drilling of boreholes away from modern tidal streams at several localities in southern coastal Washington. Most such work has been done to check for tsunami deposits on soil Y along the Niawiakum River—about 50 borings in reconnaissance (Atwater, 1987) and about 200 additional borings made by M.A. Reinhart and several coworkers (compiled by Atwater, in press). Tens of borings have also demonstrated continuity of buried soils beneath marshes along the Johns River, at Grays Harbor (Figure 4) (M.A. Reinhart, written communication, 1993; Shennan and others, 1994).

Deposition by storms or floods

Fossils show that storms or floods alone cannot account for the burial of many of the soils. Burial of a soil by storm or flood deposits builds land higher. By contrast, fossils in mud above many of the buried soils record conditions of *lower* altitude than do fossils within the soils (Figure 8). Such a contrast is shown by vascular-plant fossils in growth position associated with soil H at the Redtail locality; soils S, U, and Y at the Oyster locality; soils H and Y at the Jensen locality; soil Y at the Sewer locality; and soil U at the Airport locality. It is further is implied by diatom assemblages associated with soils J, L, N, S, U, and Y at the Redtail locality; by diatom assemblages associated with soils S, U, and Y at the Oyster locality; and, less certainly, by diatom assemblages associated with soil W at the Oyster locality (p. 16). Many additional soils provide partial evidence for subsidence: either they contain vascular-plant fossils indicative of conditions high in the intertidal zone, or they are overlain by mud with vascular-plant fossils indicative of conditions lower in the intertidal zone.

If the soils correlate as inferred in Figure 8, the storm and flood hypotheses can be ruled out for every buried soil shown in Plate 1, with the possible exception of soil W, which conceivably could have been buried by deposition without subsidence (p. 16). On the basis of preserved vascular-plant fossils alone, correlation would rule out the storm and flood hypotheses for soils H, J, S, U, and Y. Storm and flood can be further ruled out for these soils, and for soil N as well, by correlation with soils associated with contrasting diatom assemblages at the Redtail locality (soils J, L, N, S, U, and Y; Figure 10) and the Oyster locality (soils S, U, and Y; Figure 12). Similarly, the storm and flood hypotheses are precluded by changes in fossil diatom and pollen assemblages that Shennan and others (1994) found associated with soils at the Johns River (Figure 4) that probably correlate with soils L, N, S, U, and Y at Willapa Bay (Figure 8).

Fluctuations in sea level

Fluctuations in sea level have been implicated in the interbedding of lowland peat and tidal-flat mud in tectonically stable areas. Late Holocene peat layers intercalated with tidal-flat deposits are widespread in northwestern Europe (Jelgersma, 1961; Streif, 1972; Devoy, 1979) and the eastern United States (Johnson, 1925, his Figure 259B; van de Plassche, 1991;Varekamp and others, 1992; Fletcher and others, 1993a, 1993b). As at Willapa Bay, peat layers locally form soils of submerged forests (Reid, 1913, p. 6-8). Also as at Willapa Bay, peat layers can be correlated regionally by stratigraphic sequence (Jelgersma and others, 1979, p. 131-134) and radiocarbon age (Geyh, 1980; Shennan and others, 1983). Sea-level fluctuations are commonly invoked to explain the alternation between peat and mud, as illustrated by Meyerson (1972), Devoy (1979, p. 388), Behre and others (1979, p. 102-103), Shennan (1986), van de Plassche (1991), Varekamp and others (1992), and Fletcher and others (1993a, 1993b).

None of the buried soils in our surveyed outcrops, however, appear to result primarily from fluctuations in sea level. Such an origin for the soils tends to be ruled out by fossils and tsunami deposits in southern coastal Washington and by comparison with peaty tidal-marsh deposits of south-central Oregon and Puget Sound.

Only extremely rapid rise in sea level is likely to have allowed preservation of the herbaceous fossils that are rooted in soils S, U, and Y at the Oyster locality (Plate 1), in probable correlatives of soils L and S at the Johns River, or in soil Y at the Copalis River (Atwater, 1992, p. 1908-1909). These fossils, consisting of leaves and stems rooted in the buried soil and entombed in overlying tidal-flat mud, show that tidal submergence and consequent burial were completed before the stems and leaves had time to decompose. From casual inspection we estimate that such decomposition takes place within a few years on modern high marsh at Willapa Bay. The fossils thereby imply submergence too fast for most sea-level rise in the past few thousand years (Atwater and Yamaguchi, 1991; Jacoby and others, 1995). A possible exception has been reported from Delaware, where "stems and roots" and "rhizomes and stalks" are preserved at a mud-over-peat contact ascribed to a rise in sea level (Fletcher and others, 1993a, p. 123; Fletcher and others, 1993b, p. 185). Although not documented as formerly subaerial, some of these fossils may be comparable to the entombed stems and leaves in Washington.

Sea-level rise also appears inconsistent with abrupt changes in microfossil assemblages at the contact between buried soils and overlying mud at the Redtail, Oyster, and Johns River localities. These abrupt changes cannot have resulted from gradual rise in sea level unless gradual transitions in assemblages have been removed by widespread erosion. We recognized no widespread unconformities at the surveyed localities. Moreover, erosion can be ruled out where formerly subaerial stems and leaves of herbaceous plants are preserved in growth position on the soils. Such fossils are associated with diatom evidence for sudden submergence of soils S, U, and Y at the Oyster locality (Plate 1) and of soil L at the Johns River (Shennan and others, 1994; Atwater, 1992, his Table 1).

Tsunamis, which commonly result from sudden seafloor displacement, are more likely to coincide with coseismic subsidence than with gradual, aseismic rise in sea level. The sandy tsunami deposit on soil Y at the Niawiakum River demonstrates coincidence with subsidence because it rests on the soil and surrounds the remains of plants that had been living on the soil before it subsided (p. 12). The lack of sandy tsunami deposits above the other buried soils portrayed in Plate 1 need not indicate a lack of tsunamis if the surveyed sites are located too far inland to have received much sand from most tsunamis generated at the Cascadia subduction zone. The surveyed sites are much farther from the coast than are sites at which multiple buried soils are widely covered with probable tsunami deposits: the Copalis River, where a probable correlative of soil S is widely overlain by sand (Figure 8; Atwater, 1992); and several estuaries in northern Oregon where sand is common on such possible correlatives of soils S and U (Darienzo and others, 1994; Darienzo and Peterson, 1995).

If fluctuations in sea level produced buried soils in southern coastal Washington, they might also produce such soils along nearby coasts. Buried soils are locally absent, however, in tidal-marsh peat several meters thick along the south-central coast of Oregon (Nelson, 1992a; Nelson and others, in press b) and at Puget Sound (Eronen and others, 1987). Such peat implies sea-level rise gradual enough for marshes to avoid the kind of submergence that episodically changed tidal wetlands into tidal flats in southern coastal Washington. In classic examples in Massachusetts, tidal-marsh peat several meters thick is pervaded by growth-position roots and rhizomes of plants that thrive only near high-tide levels (Mudge, 1862; Redfield, 1972, p. 210). The presence of such deposits at the Cascadia subduction zone limits the extent of any sea-level fluctuations that might be implicated in the pronounced submergence and burial of late Holocene soils in southern coastal Washington.

Breaching of bay-mouth barriers

If Willapa Bay had a barrier at its mouth that limited the tidal range behind it, the breaching of such a barrier might cause high-tide levels to rise, thereby producing buried soils similar to those produced by subsidence during earthquakes. Such tide-level rise "has, for a long time, been the mechanism used to explain the intercalated peats and clays" of northwestern Europe (Shennan, 1986, p. 121)—as illustrated by Jelgersma and others (1979, p. 139). But fossils and historical records imply that barrier breaching played little or no role in the episodic late Holocene submergence and burial of wetland soils in southern coastal Washington.

Fossils preclude bay-mouth blockage complete enough to have turned Willapa Bay into a freshwater lake in the years just before buried soils were submerged and buried. Instead of freshwater plants like cattails and willows, soils S and Y at the Oyster locality supported the brackish-water tidal assemblage of *Deschampsia caespitosa*, *Potentilla pacifica*, and *Juncus balticus*. Moreover, soil U at the Oyster locality was largely covered by the halophyte *Salicornia virginica*. Inflow of seawater is further implied by diatom assemblages—in the surficial horizon of soils S, U, W, and Y at the Oyster locality; in the surficial horizon of soils J, L, and U at the Redtail locality; and just beneath the surficial horizon of soil N at the Redtail locality. None of the diatom assemblages studied at either of these localities are consistent with prevalence of standing fresh water.

Fossils similarly imply seawater inflow to the Copalis River and Grays Harbor just prior to the burial of one or more soils at these estuaries. *Deschampsia caespitosa*, *Potentilla pacifica*, and *Juncus balticus* were living along the Copalis River when a probable correlative of soil Y was suddenly submerged (Atwater, 1992, p. 1908-1909). These species also lived on probable correlatives of soils L and Y at Grays Harbor, along the Johns River (Atwater, 1992, localities 13 and 14 of his Table 1 and Figures 6 and 7). Moreover, the Johns River was also bordered by a *Triglochin maritima* low marsh at the time of submergence marked by a low-marsh soil probably correlative with soil Y (Atwater, 1992, locality 12 in his Table 1 and Figures 6 and 7). Annual freshwater inflow to Grays Harbor averages about 10 km^3 (Peterson and others, 1984, p. 88), ten times the high-tide volume of Grays Harbor (Barrick, 1975, p. A-6). If a barrier greatly limited seawater inflow to Grays Harbor before sudden submergence of soil Y, salinity along the Johns River should have been low enough to favor freshwater plants over *Triglochin maritima.*

In accord with such geologic evidence for past connections with the sea, historical records provide no basis for inferring past blockage of the largest estuaries in southern coastal Washington. Although associated with treacherous offshore bars, Willapa Bay, Grays Harbor, and the Columbia River have stayed fully open to the sea since Euro-Americans first entered them about 200 years ago. A likely explanation is that the estuaries exchange too much water with the sea to have been blocked by barrier sand. The tidal prisms are huge—about 1/2 km^3 for Willapa Bay and Grays Harbor, about 1 km^3 for the Columbia River (Johnson, 1973).

Settlement

Seismic shaking can produce localized submergence through compaction and consequent settlement of unconsolidated deposits. Such settlement from the 1964 Alaska earthquake widely affected estuarine and alluvial deposits (Plafker and Kachadoorian, 1966, p. D13-D18; Plafker, 1969, his Plate 4B and Figure 27) and locally doubled the total subsidence near Portage (McCulloch and Bonilla, 1970, p. D81). Settlement also may have contributed to coastal submergence in Chile during the 1960 Chile earthquake (Plafker and Savage, 1970, p. 1006 and thier Table 1 and Figure 5A).

Although settlement may have augmented tectonic subsidence in southern coastal Washington, it probably did not contribute much to subsidence where buried soils are underlain, at shallow depth, by well-consolidated Pleistocene deposits. One such site is the Jensen locality, where the entire late Holocene section rests on a shallow, subhorizontal foundation of stiff Pleistocene mud. At other sites, described previously from the Niawiakum and Copalis Rivers (Atwater, 1992, p. 1909), soil Y can be traced in outcrop into a hillside soil on Pleistocene deposits. Tidal mud on soil Y extends onto the hillside soil—evidence that the hillside participated in the subsidence of soil Y.

Aseismic folding

Rapid tectonic subsidence without seismic shaking can be shown unlikely for the submergence events marked by buried soils Y and S at northeastern Willapa Bay. These events probably correlate with liquefaction a few tens of kilometers to the south.

A buried soil probably correlative with soil Y is widely associated with liquefaction features along the lower Columbia River about 30-45 km east of the Pacific coast. The features, discovered by Obermeier (1995), are further documented in observations compiled by Atwater (1994). Although most of the liquefaction features are dikes that do not extend to the top of the soil, some of the intrusions appear continuous with sand lenses that rest directly on the soil. The stratigraphic position of the sand lenses, which resembles that of the tsunami deposits at the Oyster and Redtail localities, implies that the sand was vented during or soon after the land subsided.

A buried soil probably correlative with soil S is associated with several gravelly dikes along the Naselle River of southern Willapa Bay. These dikes, discovered in 1995 by Alan Mortimer, Judith Boughner, and Brian Atwater, are situated at locality 20 of Atwater (1992). At least one of them is low in a mud-filled crack that extends upward to, but not above, a buried tidal flat continuous with the probable corrrelative of soil S. This crack probably records lateral spreading that coincided with the sudden subsidence marked by soil S.

Enigmatic sand bodies mistakenly ascribed to liquefaction are present along the Copalis River, where they formed between 900 and 1300 years ago (Atwater, 1992). Although probably caused by an earthquake and perhaps correlative with submergence marked elsewhere by soil W and its correlatives, these sand bodies do not appear to record seismic shaking (p. 29).

DISTINCTION BETWEEN PLATE-BOUNDARY AND UPPER-PLATE SOURCES FOR THE EARTHQUAKES

Several geophysical arguments show that plate-boundary earthquakes provide a simple explanation for many of the buried soils at estuaries along the Pacific coast at the Cascadia subduction zone: (1) Plate-boundary earthquakes could have caused widespread, sudden subsidence by elastically thinning the North America plate. Possible analogs include the sudden subsidence of coastal areas hundreds of kilometers long during great historical earthquakes at subduction zones in Alaska, Chile, and Japan (Heaton and Hartzell, 1986). (2) The Cascadia plate boundary resembles, in age of subducting lithosphere and rate of convergence, some plate boundaries elsewhere on which great earthquakes have occurred historically (Heaton and Hartzell, 1987; Rogers, 1988). (3) Forces deduced from plate motions imply strong coupling between the Juan de Fuca and North America plates; a large fraction of the shallow slip between these plates should occur during earthquakes (Scholz and Campos, 1995, p. 22112). (4) The Cascadia subduction zone is likely to be accumulating energy for release in future plate-boundary earthquakes, according to interpretation of geodetic surveys and heat-flow models (Savage and others, 1991; Hyndman and Wang, 1993, 1995; Dragert and others, 1994; Mitchell and others, 1994).

The alternative of upper-plate earthquakes arises where sudden coastal subsidence may have been limited to areas along faults or folds in the North America plate. Such localized subsidence has been documented for a syncline in northern California that trends approximately parallel to nearby thrust faults having Holocene slip (Clarke and Carver, 1992). Further north, subsidence during the past few thousand years may have been localized along coastal synclines in south-central Oregon (Nelson, 1992a; Nelson and Personius, in press). In addition, upper-plate faults off the Pacific coast of Oregon and Washington have slipped in the past 10,000 years, and some of the estuaries having evidence for sudden subsidence are located along the eastward projection of such offshore structures (Goldfinger and others, 1992a, 1992b; McNeill and others, 1994; McCaffrey and Goldfinger, 1995). The subduction zone along the North Island, New Zealand, may contain analogs for land-level change during upper-plate earthquakes at the Cascadia subduction zone. Some of the prehistoric marine terraces on the North Island represent coseismic uplift that was not necessarily accompanied by seismic slip on the subduction boundary between the Pacific and Australian plates (Berryman and others, 1989).

Coastal geology provides at least two criteria for distinguishing between plate-boundary earthquakes and upper-plate earthquakes as causes of coseismic subsidence at the Cascadia subduction zone. One of these is the extent of subsidence of the same approximate age. Unlike a single plate-boundary rupture at the Cascadia subduction zone, a series of earthquakes on faults in the North America plate could be distributed through enough time for geologic detection of differences in dates of subsidence. Such differences have not been detected for the best dated and most recent of the prehistoric sudden subsidence (Nelson and others, 1995). Instead, high-precision radiocarbon dating shows that the most recent sudden subsidence at Willapa and Humboldt Bays, 625 km apart along the subduction zone (Figure 1), occurred during the same few decades in the early 1700s. Additional radiocarbon dating of lower resolution, employing subsidence-killed herbaceous plants, shows that the most recent coseismic subsidence postdates A.D. 1660 at the six estuaries where such plants have been dated: the Copalis River and Willapa Bay, Washington; and Netarts Bay and the Nehalem, Salmon, and Coquille Rivers, Oregon (localities shown by herb and tree symbols in Figure 1).

Here we use a second criterion for distinguishing between plate-boundary earthquakes and upper-plate earthquakes—the sense of coseismic land-level change on anticlines. The criterion is based on two assumptions: (1) An anticline can subside during a plate-boundary earthquake at a subduction zone by participating passively in the coseismic thinning of the upper plate. In a well-studied example, a magnitude-9.2 earthquake on the subduction zone in Alaska in 1964, was accompanied by subsidence throughout an Alaskan area 800 km long and more than 100 km wide (Plafker, 1969), apparently irrespective of many late Cenzoic folds and faults (Plafker and others, 1994). (2) An anticline is unlikely to subside during an upper-plate earthquake that causes localized subsidence along adjacent synclines of similar age and trend. Rather, the anticline may undergo uplift, as during the folding at Puget Sound during one or more earthquakes on faults in the North America plate about 1000-1100 years ago (Bucknam and others, 1992).

The Cascadia subduction zone contains at least two anticlines having buried soils indicative of coseismic subsidence. One of these, located near Cape Blanco, Oregon, deforms Pleistocene marine terraces that have been uplifted at net rates of nearly 1 m per 1000 years, which is among the highest rates of net Quaternary uplift along the Pacific coast at the Cascadia subduction zone (Kelsey, 1990; Kelsey and others 1994, their Figure 4). Despite this history of late Quaternary uplift, the anticline contains several successive buried soils suggestive of coseismic subsidence during the past 5000 years (Kelsey and others, 1993).

Buried soils further show that the South Bend antiform undergoes coseismic subsidence, and that coseismic uplift has not occurred on this structure in the past 3500 years or more. The soils are present not only in the Holocene deposits surveyed at the Jensen, Sewer, and Airport localities (Plate 1) but also in estuarine deposits of Pleistocene age (p. 5; Table 1). The Holocene soils imply that structural setting has had little effect on the amount or timing of coseismic subsidence in southern coastal Washington, except perhaps about 1000-1100 years ago. These findings, summarized below, show that most or all coseismic subsidence in southern coastal Washington results from plate-boundary earthquakes, not from earthquakes on faults in the North America plate.

Sense of land-level change

The South Bend antiform is similar to other parts of the Willapa Bay area in evidence of the sense of coseismic change in land level. Buried soils are present in estuarine deposits of Pleistocene age (Table 1) and Holocene age (Plate 1), both on and off the antiform (Figure 4). Where preserved, vascular-plant fossils in Holocene soils on the antiform show that lasting tidal submergence, not just storms or floods, caused burial of the soils (p. 23). The probable correlation between buried Holocene soils on and off the antiform (Figure 8) further implies that this submergence resulted from sudden tectonic subsidence, at least in the case of soils L, S, U, and Y; herbaceous fossils rooted in these soils off the antiform demonstrate sudden submergence followed by rapid burial (p. 23). Although we did not find such herbaceous fossils rooted in any buried soil on the South Bend antiform, neither did we find them rooted in any of the buried soils at the Redtail locality, which is off the antiform—nor did we find them on soils J, N, or W anywhere off the antiform. The routine lack of entombed herbs both on and off the antiform is probably due to decomposition after burial (p. 11), not to any lack of coseismic subsidence.

We recognized no evidence for coseismic uplift at Willapa Bay, either on or off the South Bend antiform. As little as 0.5 m of uplift would suffice to change tidal marshes into upland forests containing not only Sitka spruce but also other trees typical of uplands beside Willapa Bay: alder, maple, western redcedar, western hemlock. On the antiform, however, growth-position stumps of any species are sparse or absent in all buried soils at the Airport, Sewer, and Jenson localities, and where present they are limited to tidal-wetland species—Sitka spruce and an unidentified shrub, probably western crabapple. Off the antiform, soils S and Y were heavily wooded along the upper reaches of tidal streams (near the Pool locality, for example) and beside uplands (Redtail locality). But nearer the sea even these soils represent brackish-water tidal marshes, as at the Oyster locality.

Amount of land-level change

The South Bend antiform probably resembles adjacent areas not only in subsiding during earthquakes but also the amount of this subsidence. The amount is difficult to determine because the indicator fossils have large vertical ranges (Figure 6; Hemphill-Haley 1995a) and because local settlement can augment tectonic subsidence (p. 25). However, large differences in amount of tectonic subsidence would probably create consistent differences in vascular-plant assemblages and in the thickness of mud between soils. We found no such differences that consistently depend on location with respect to the South Bend antiform.

Where vascular-plant fossils are preserved in growth position both within a buried soil and in mud above the soil, the fossils show that a high marsh, or a forest near extreme high water, became a tidal flat or a low marsh—both on and off the antiform. Examples include soil Y on the antiform at the Jensen, Sewer, and Airport localities, and off the antiform at the Oyster locality; soil U at the Airport and Oyster localities; and soil H at the Jensen locality. Soil S at Oyster locality may record greater subsidence; several tens of centimeters of tidal-flat mud accumulated on this soil before *Triglochin maritima* became established (Plate 1). But the Oyster locality, which probably adjoins a former channel containing tens of meters of soft Holocene fill (p. 14), is especially subject to settlement during and (or) between earthquakes, as shown by tilting of buried soils (Plate 1).

The thickness of mud between buried soils at the surveyed localities varies mainly with the presence or absence of Pleistocene deposits at shallow depth beneath them. Mud between soils is thin where their Pleistocene foundation is shallow, both on the antiform at the Jensen locality and off the antiform at the Redtail locality. Conversely for sites probably underlain by tens of meters of soft Holocene mud, buried soils are more widely spaced at the Sewer, Airport, and Oyster localities. These comparisons are summarized simplistically in Figure 8 but are better viewed in Plate 1, which shows the variability of spacing between soils at each locality.

The thickness of intertidal mud above a buried soil can serve as a rough indicator of the amount of coseismic subsidence because subsidence makes room for tides to deposit mud on the soil. The thickness of mud is unlikely to equal the amount of coseismic subsidence, however, if tidal inundation subsequently decreases during interseismic uplift or increases during interseismic subsidence (Darienzo and Peterson, 1990). The most reliable indicator of the amount of coseismic subsidence is the paleobathymetric difference between the buried soil and the mud immediately above it, as can be inferred from contrasts in vascular-plant fossils and diatom assemblages (Figure 10, Figure 12) that are vertically zoned in modern tidal wetlands (Figure 6, Figure 7). This amount probably equals or exceeds 1 m for soils J, L, N, S, U, and Y at the Redtail locality (p. 12) and for soils S, U, and Y at the Oyster locality (p. 15).

Coevality of land-level change

Buried soils of the past 2000 years on the South Bend antiform do not appear to differ in stratigraphic sequence or radiocarbon age from buried soils at nearby sites off the antiform (Figure 8). All these soils appear to be part of a regionally correlative sequence previously reported from many estuarine localities along the southern 100 km of the Washington coast (Atwater, 1992). In this sequence, two bold soils (herein, soils S and Y) bracket one or two faint soils (U and W). Soils S and Y commonly contain more fossil tree roots than do soils U and W, and only soil Y is commonly covered by a tsunami deposit at Willapa Bay and Grays Harbor. Ages determined by radiocarbon dating (chiefly for soils S and Y; Atwater, 1992) and by tree-ring pattern matching (soil Y only; Yamaguchi and others, 1989) are consistent with correlations inferred from these various stratigraphic clues. Additional radiocarbon dating of soils in the stratigraphic position of soils S, U, and Y implies correlation between a typical southern-Washington sequence of buried soils at the Naselle River (Figure 4) and a sequence of buried soils at Netarts Bay, Oregon (Figure 1) (Nelson and others, in press b).

Buried soils 2000-3500 years old also show no major differences in stratigraphy or approximate age between the South Bend antiform and the handful of sites at which such soils have been dated in southern coastal Washington. Numerical age by itself cannot show differences smaller than a few centuries, but it strengthens correlations based on interbedding of bold soils and faint soils. The four lowest soils on the antiform at the Jensen locality probably correlate with soils H, J, L, and N off the antiform at the Redtail locality (p. 19). Soils low in the section at the Jensen locality probably also correlate with soils off the anticline at Willapa Bay (South Fork locality) and Grays Harbor (Johns River and Blue Slough localities) (Figure 8).

Possibly anomalous changes in land level 1000-1100 years ago

Soil W at northeastern Willapa Bay may represent a time of anomalous deformation from movement on faults in the North America plate. Such deformation probably occurred some 50 km to the north, at the Copalis River. There, vented sand covers a soil, possibly correlative with soil W (Figure 8), that underwent little or no subsidence at the time of venting. This lack of obvious subsidence implies localized deformation in the North America plate because the venting, which probably does not represent shaking-induced liquefaction, probably resulted from faulting or folding of an aquifer beneath the Copalis River (Atwater, 1992, p. 1917, "Note added in proof"). Such faulting or folding could have been part of widespread movement on structures high in the North America plate in western Washington 1000-1100 years ago. At that time, movement on one or more faults in the North America plate farther inland, in the Puget Sound area, generated 5-7 m of coseismic uplift near Seattle and several meters of coseismic uplift in an area 30-50 km to the southwest (Bucknam and others, 1992).

Despite this evidence for upper-plate seismicity, soil W at northeastern Willapa Bay probably represents an earthquake on the plate boundary. Radiocarbon-dated soils show that coseismic subsidence occurred elsewhere along the Washington coast between 900 and 1300 years ago (Atwater, 1992) at Neah Bay (location shown in Figure 1), at Grays Harbor along Elliott Slough, and at southern Willapa Bay along the Bear River (locations shown in Figure 4). We speculate that movement on faults and folds in the North America plate of western Washington accompanied—or shortly preceded or followed—one or more plate-boundary earthquakes 1000-1100 years ago, and that this plate-boundary seismicity is recorded at northeastern Willapa Bay by soil W.

SIZES OF THE EARTHQUAKES

Although their sizes are difficult to estimate, most or all of the earthquakes represented by buried soils H through Y were probably great earthquakes—of moment magnitude 8 or larger. Such magnitudes are suggested by geologic evidence for large ruptures and by a tradeoff between size and frequency.

Dimensions of plate-boundary ruptures

As shown above by coseismic subsidence irrespective of late Cenozoic structures, the earthquakes marked by the buried soils probably occurred on the boundary between the Juan de Fuca plate and the

North America plate. Ruptures on the Washington part of this plate boundary are likely to exceed 50 km, according to interpretation of geodetic and heat-flow data (Savage and others, 1991; Dragert and others, 1994; Hyndman and Wang, 1995). Ruptures this wide at the Cascadia subduction zone can be as short as 200 km and still have enough area to produce a magnitude-8 earthquake, if the magnitude-area correlation by Wells and Coppersmith (1994) applies to the Cascadia subduction zone.

The most recent coseismic subsidence, which probably dates to 300 years ago, struck estuaries as much as 625 km apart during the same few decades (Nelson and others, 1995). This degree of coevality implies either a single long rupture or a swift series of shorter ruptures.

Earlier coseismic subsidence, though not so precisely dated, may have also resulted from long ruptures. No statistical differences have been found between two stratigraphic sequences 110 km apart—at the Naselle River, Washington (Figure 4) and at Netarts Bay, Oregon (Figure 1)—for which multiple ages have been measured on earthquake-killed herbs or delicate plant detritus on probable correlatives of soils S, U, and Y (Nelson and others, in press b). Widespread subsidence marked the by lowest of these soils is further suggested by similarities among ages for soil S throughout southern coastal Washington (Figure 8). Moreover, a long apparent interval without buried soils, centered about 2100 years ago, is indicated by a gap in radiocarbon ages both in southern Washington (Figure 8, gap between ages for soils N and S) and in northern Oregon (Figure 4 of Darienzo and Peterson, 1995; gap between ages for their events 5 and 6).

Tradeoff between size and frequency

If plate-boundary earthquakes at the Cascadia subduction zone are typically smaller than moment magnitude (M_w) 8, the earthquakes probably should happen more often than is indicated by historical quiescence or implied by geologic estimates of recurrence intervals. This tradeoff between size and frequency of earthquakes can be viewed in terms of seismic moment, which is related to seismic energy and is defined as the product of rigidity, rupture area, and average displacement (Hanks and Kanamori, 1979). Given estimates of rigidity and rupture area, one can deduce combinations of earthquake size and frequency that produce average displacement consistent with plate convergence at the Cascadia subduction zone.

The combinations of size and frequency shown in Table 8 are based on several estimates that are treated here as constants and which were selected to understate seismic moment. For rigidity we use 3×10^{10} N/m^2, at the low end of the range used by Kanamori (1977, p. 2983) to calculate sizes of great earthquakes. For seismogenic area we use 50,000 km^2, well under the 90,000 km^2 estimated by Hyndman and Wang (1995, p. 22152) on the basis of geodetic and heat-flow data. For plate convergence we use 3.5 cm/yr, the component orthogonal to the strike of the plate boundary off Oregon and Washington; the component parallel to strike can be excluded because most or all of this component can be accounted for by permanent deformation in the North America plate (McCaffrey and Goldfinger, 1995). Orthogonal convergence probably exceeds 3.5 cm/yr off northern Washington and southern British Columbia, where the convergence direction is nearly orthogonal (Wilson, 1993, p. 16069), and off northern California, where the orthogonal component of plate convergence is increased by spreading of the Basin and Range (Pezzopane and Weldon, 1993, p. 1164-1165).

The combinations shown in Table 8 vary with the coupling ratio, which is the fraction of plate convergence that becomes seismic slip on the plate boundary. No coupling ratio has been measured for the Cascadia subduction zone, owing to lack of historical plate-boundary earthquakes. However, because of their motions with respect to the mantle, the Juan de Fuca and North America plates may be strongly coupled (Scholz and Campos, 1995, p. 22112). Such coupling is consistent with heat-flow and geodetic data (Savage and others, 1991; Hyndman and Wang, 1993, 1995; Dragert and others, 1994) and with the lack of small modern earthquakes that could indicate creep on the plate boundary (Heaton and Hartzell, 1987; Rogers, 1988).

The remaining variable in Table 8 is a recurrence interval for plate-boundary earthquakes, for which we use two average values. The larger average, of 500 years, is in the range that we estimate from the buried-soil record of plate-boundary earthquakes at northeastern Willapa Bay (p. 34) and within or near ranges estimated elsewhere at the Cascadia subduction zone (p. 3, Figure 2). Because the geologic records of recurrence may be incomplete, we also use a smaller value, of 300 years. Average intervals shorter than 300 years have not been inferred in most paleoseismic studies of the Cascadia subduction zone (p. 3, Figure 2), nor are they implied by the probable lack of plate-boundary earthquakes of M_w 7.5 or larger at the Cascadia subduction zone in the 150 years since Euro-Americans began to settle the region.

The two right-hand columns in Table 8 show that many M_w 8 earthquakes or scores of M_w 7.5 earthquakes correspond to the seismic moment calculated for 300-500 years of plate convergence at the Cascadia subduction zone. The M_w 7.5 earthquakes are so numerous that many such earthquakes should have occurred historically if plate-boundary earthquakes at the Cascadia subduction zone do not exceed M_w 7.5. The numbers of M_w 8 earthquakes can be considered, simplistically, in series of five; along 1000 km between Vancouver Island and Cape Mendocino (Figure 1), the Cascadia subduction zone can accomodate five adjacent M_w 8 ruptures each 200 km long, adjoined like sausage links. Average intervals of 300-500 years produce one such series of five M_w 8 earthquakes if seismic slip on the plate boundary accounts for one-quarter of the convergence. Stronger coupling implies M_w greater than 8 or average recurrence intervals shorter than 300 years.

RECURRENCE INTERVALS

In estimating recurrence intervals for plate-boundary earthquakes at northeastern Willapa Bay, we rely mainly on the buried-soil record of such earthquakes along the Niawiakum River. We assume that this record is representative of southern coastal Washington as a whole—an assumption supported by the evidence for correlation of buried soils throughout southern coastal Washington (Figure 8). We focus on the Niawiakum River because it has some of the best-dated, best-understood examples of buried soils in the region. We limit the estimates to the past 3500 years of earthquake history (soil J and younger soils) because evidence for earlier earthquakes has not been widely studied or dated in southern coastal Washington.

The recurrence intervals probably represent centuries of tectonic uplift and tidal sedimentation between instants of tectonic subsidence. We depict such history schematically for the Oyster and Redtail localities (Figure 15). In this figure the heavy sawtooth line for each locality represents approximate changes in the level of wetland at the locality, as inferred from vascular-plant fossils and diatom assemblages. We assume that the combined effect of post-earthquake uplift and sedimentation is rapid at first but slow later, in keeping with the high initial rates of post-earthquake uplift (Brown and others, 1977; Savage and Plafker, 1991) and sedimentation (Ovenshine and others, 1976; Bartsch-Winkler and Garrow, 1982) documented for parts of Alaska that subsided during the 1964 Alaska earthquake. Rapid post-earthquake sedimentation is further suggested by historical evidence from Willapa Bay (discussed below under "Incompleteness of buried-soil records"). The overall sawtooth shape is partly based on analogy with cyclic vertical deformation related to great earthquakes in southwest Japan (Thatcher, 1984). The gentler interseismic slope of the heavy line for the Oyster locality represents settlement from compaction of peat and mud (p. 10); we infer that such settlement has counteracted tectonic uplift and sedimentation more effectively at the Oyster locality, where soft underlying mud may be as much as 30 m thick (p. 11), than at the Redtail locality, where buried soils lap onto stiff Pleistocene deposits (Plate 1). The graph neglects sea-level change and permanent tectonic uplift.

Uncertainties in counting and dating of the inferred earthquakes

The recurrence intervals estimated below may contain errors from possible contamination and incompleteness of buried-soil records of great plate-boundary earthquakes, and from problems with dating the inferred earthquakes (Figure 3).

Contamination of buried-soil records by events other than great plate-boundary earthquakes

We evaluate possible contamination in sections above headed "Distinction between tectonic subsidence during earthquakes and other ways of producing the buried soils" and "Distinction between plate-boundary and upper-plate sources for the earthquakes". From these evaluations, we conclude that plate-boundary earthquakes probably account for all the buried soils in the surveyed outcrops, particularly along the Niawiakum River.

This general conclusion does not apply equally to every soil. The case for a great-plate boundary earthquake at northeastern Willapa Bay is strongest for soil Y: its shallow depth allows alternative explanations to be tested more readily than for less accessible soils; it is the only soil shown to be widely accompanied by evidence for tsunami and liquefaction in southern coastal Washington; and it is the only soil for which rupture length has been investigated through high-precision radiocarbon dating. The case is weakest for soil J, whose great depth limits its exposure and dating to a few outcrops, and for soil U, owing to faintness or absence in most outcrops.

Incompleteness of buried-soil records

Uncertainties from possible incompleteness probably exceed those from possible contamination. The buried-soil record of great plate-boundary earthquakes could fail to record intervals that are especially long; in addition, it could fail to record intervals that are very short.

Incompleteness from long intervals

Long recurrence intervals can lead to the destruction of buried soils, as shown by the absence of soil W in the northwestern part of the Oyster locality (p. 14) and throughout the Redtail locality (p. 13, 17). This kind of destruction could limit the geologic record of earthquakes that produce too little tectonic subsidence to occasion the deep burial of a soil. Such earthquakes could include events comparable to the 1944 and 1946 earthquakes in southwest Japan, which caused a maximum of about 1/2 m of tectonic subsidence (Ando, 1975, p. 122). These earthquakes were probably close to M_w 8.0 (Heaton and Hartzell, 1986, p. 693-694).

We doubt, however, that sequences of buried soils fail to record earthquakes where the earthquakes lowered well-vegetated land by 1 m or more. Such subsidence would likely permit tidal burial deep enough to protect soils—and their telltale diatom assemblages (Figure 10, Figure 12)—from total destruction.

Incompleteness from short intervals

Short recurrence intervals could leave too little time for tidal sediment to build up a marsh on which a peaty soil could form. This problem may contribute to the faintness and widespread absence of soil W, whose diatom assemblages at the Oyster locality imply conditions transitional between low marsh and high marsh (p. 16). However, nineteenth century writings and maps suggest that intervals of 150-170 years are probably long enough for reconstructing high marshes at Willapa Bay.

The writings come from one of the first Euro-American settlers of Willapa Bay, James G. Swan. Swan resided at the marshy mouth of the Querquelin (now Bone) River (Figure 5A) in the early 1850s, about 150 years after the most recent great earthquake in southern coastal Washington had changed Willapa Bay's marshes into tidal flats. Although their suitability for agriculture appears exaggerated, the tidal marshes ("prairie-land") described by Swan seem dominated by high marsh:

> "...all the rivers, large and small, run through fine prairie-land, exceedingly rich. That portion nearest the Bay is liable to be overflowed one or twice during the highest tides of winter, and are termed tide lands. This overflowing is, however, of no great detriment, although the water is salt, as, wherever the lands have been properly cultivated, they have yielded heavy crops. These prairies are all covered with grass of an excellent quality, making good grazing for stock, or a nutritious fodder when cut and made into hay." (Swan, 1857, p. 28).

Swan's account is consistent with depiction of tidal marshes on 1:10,000-scale plane-table maps of the bay's margins in the 1870s. These so-called T sheets, made by the U.S. Coast Survey, are on file with the National Oceanic and Atmospheric Administration in Rockville, Maryland; in addition they can be viewed and reproduced from microfilm at NOAA's library in Seattle. The maps show tidal marshes similar in extent to those of modern Willapa Bay. Moreover, the topographers drew a solid line beween marsh and mudflat except for a few small patches of marsh surrounded by mudflat. We assume that the solid line denotes high tide, and that the patches of marsh consisted of *Triglochin maritima* low marsh that was colonizing tidal flat in the 1870s. If these assumptions hold, 170 years is ample time for high marsh to rebuild from post-earthquake tidal flats at Willapa Bay.

Uncertainties in dating

Timing is least known for events marked by soils U and W, which are undated along the Niawiakum River, and for soils L and S, which are poorly dated along the Niawiakum River. For these soils we imported ages from probably or possibly correlative soils at other places, as described below. Such reliance on stratigraphic correlation adds uncertainty, which we do not quantify, to the estimation of earthquake-recurrence intervals at the Niawiakum River.

History of geologically recorded earthquakes

As recorded along the Niawiakum River, the great-earthquake history of the past 3500 years in southern coastal Washington probably contains at least seven events, each of which comprised a single rupture or multiple contiguous ruptures on the Cascadia plate boundary.

The first three events date between about 3500 and 2400 years ago (Figure 8, soils J, L, and N). The 95-percent confidence intervals for the ages of these events adjoin one another: 3300-3500 years ago for soil J; 2800-3300 years ago for soil L, as dated best by a spruce root at the Jensen locality (p. 19); and 2400-2800 years ago for soil N. The dating for soil N includes a high-precision age on forest-floor litter (2475 ± 23 ^{14}C yr B.P.; Table 6), but this age corresponds to a several-century range of calendric dates (Figure 8).

A long apparent hiatus preceded the next recorded event, represented by soil S. A broad range of 1400-1900 years ago is consistent with the abundant ages for soil S at the Redtail locality and for its probable correlatives elsewhere in southern coastal Washington (Figure 8). The age range vertically ruled for soil S in Figure 8—1600-1900 years ago—is based on data of Nelson and others (in press b), for a probable correlative of soil S at the Naselle River, an arm of Willapa Bay about 30 km south-southeast of the Niawiakum River (Figure 4). This range includes the 95-percent confidence interval corresponding to 1797 ± 21 ^{14}C yr B.P., the weighted mean of five radiocarbon ages each measured on a different herbaceous plant rooted in the soil. The mean is suspect, however, because the five consitutent ages (Table 7) are significantly different (at the 95-percent level) in the chi-squared test of contemporaneity of Ward and Wilson (1978).

The next recorded event, represented by soil U, is thus far undated along the Niawaikum River but has been dated to 1200-1400 years ago along the Naselle River. This range corresponds to 1364 ± 21 ^{14}C yr B.P., the weighted mean of six radiocarbon ages (Table 7) each measured on a different herbaceous plant rooted in a probable correlative of soil U in the same outcrop as the well-dated soil S at the Naselle

River (Nelson and others, in press b). The range of 1200-1400 years ago is mostly younger than the handful of ages for soil U at Grays Harbor and the Copalis River (Figure 8). These other ages, however, were measured on peat (Elliott Slough and Copalis River) and on an upright but possibly detrital stump (Blue Slough)—material that could be centuries older than the event recorded in the Grays Harbor area by probable correlatives of soil U.

Soil W represents a subsequent event whose buried-soil record is barely preserved at the Oyster locality and is absent, probably because of decomposition, at the Redtail locality. Diatom assemblages suggest that the event was accompanied by enough subsidence to change a low marsh into a tidal flat at the Oyster locality (Figure 12). As interpreted above on p. 29, this event may have occurred at or about the time of seismicity on faults in the North America plate in the Puget Sound area. High-precision dating of earthquake-killed herbs and trees shows that the Puget Sound seismicity occurred between 1000 and 1100 years ago (Bucknam and others, 1992; Atwater and Moore, 1992; Jacoby and others, 1992).

The most recent and best documented of the plate-boundary earthquakes at northeastern Willapa Bay occurred about 300 years ago (soil Y). The likely time of this earthquake is A.D. 1700-1720 (>95 percent confidence interval), as judged from high-precision dating of earthquake-killed spruce along the Niawiakum River, at nearby Bay Center, and at the Copalis River (Atwater and others, 1991; corresponding calendric ages revised by Nelson and others, 1995). The earthquake may have happened on January 26, 1700 (Satake and others, 1995). This date, from written records of a tsunami in Japan, does not coincide with documented earthquakes in Japan, Kamchatka, Alaska, or South America, and it just barely falls within the probable age range of the great Cascadia earthquake recorded by soil Y at northeastern Willapa Bay.

Average interval

We recognize evidence for six recurrence intervals between successive great earthquakes in southern coastal Washington between 3300-3500 years ago (soil J) and 300 years ago (soil Y). The resulting average recurrence interval is one-sixth of 3000-3200 years, or 500-535 years. This narrow range does not express uncertainties, discussed above, in the counting of earthquakes, particularly from possible incompleteness of the buried-soil record.

Average intervals of 500-535 years are near or within the ranges estimated from buried soils at other estuaries and from turbidites in deep-sea channels (Figure 2). The 550- to 630-year average estimated from the deep sea (Adams, 1990) may reflect incompleteness from non-deposition of turbidites. As noted by Adams (1990, p. 579), the deep-sea record could be incomplete if little unstable sediment accumulates at a submarine-canyon head between two successive earthquakes spaced closely in time.

Variability among individual intervals

Individual intervals between successive plate-boundary earthquakes recorded by buried soils along the Niawiakum River probably range from a few hundred years to perhaps 1000 years.

The shortest times between the recorded earthquakes are probably on the order of a few hundred years. The two intervals among the successive earthquakes marked by soils J, L, and N average 250-550 years. Similarly, the average is 250-450 years for two successive intervals represented by soils S, U, and W, provided that 1600-1900 and 1000-1100 years ago are the ages of earthquakes recorded by soils S and W, respectively.

The longest times between the recorded earthquakes are 500-1200 years between the earthquakes marked by soils N and S, and perhaps 700-800 years between the earthquakes marked by soils W and Y. These long intervals are consistent with vascular-plant fossils and diatom assemblages that place soils S and Y higher in the intertidal zone than most other soils (p. 17). Such height may have been attained, in part, by prolonged interseismic uplift, as shown schematically in Figure 15. The long intervals are also consistent with the typical faintness of soil N, and of soils U and W. This faintness implies oxidation from prolonged residence high in the active profiles of soils S and Y, respectively, as also shown schematically in Figure 15.

Despite this evidence for two long intervals, it remains possible that long intervals were divided by by earthquakes accompanied by just a few tenths of a meter of subsidence at northeastern Willapa Bay. Soil W probably represents such an earthquake for the roughly 1000-year-long interval between the earthquakes marked by soils U and Y. We could not have divided this interval, by means of soil W, had we relied solely on the buried-soil record at the Redtail locality, where soil W is invisible in outcrop (Figure 9C,D) and doubtful or destroyed in diatom assemblages (p. 13; Figure 10). If we similarly overlooked additional buried soils in the profiles of soils S and Y, and if these soils represent great earthquakes, we may may have overestimated the variability among recurrence intervals for great earthquakes at northeastern Willapa Bay.

REFERENCES CITED

Adams, J., 1990, Paleoseismicity of the Cascadia subduction zone--evidence from turbidites off the Oregon-Washington margin: Tectonics, v. 9, p. 569-583.

Ando, M., 1975, Source mechanism and tectonic significance of historic earthquakes along the Nankai Trough, Japan: Tectonophysics, v. 27, p. 119-140.

Ando, M., and Balazs, E.I., 1979, Geodetic evidence for aseismic subduction of the Juan de Fuca plate: Journal of Geophysical Research, v. 84, p. 3023-3028.

Atwater, B.F., 1987, Evidence for great Holocene earthquakes along the outer coast of Washington State: Science, v. 236, p. 942-944.

Atwater, B.F., 1992, Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington: Journal of Geophysical Research, v. 97, p. 1901-1919.

Atwater, B.F., compiler, 1994, Geology of liquefaction features about 300 years old along the lower Columbia River at Marsh, Brush, Price, Hunting, and Wallace Islands, Oregon and Washington: U.S. Geological Survey Open-File Report 94-209, 64 p.

Atwater, B.F., in press, Coastal evidence for great earthquakes in western Washington, in Rogers, A.M., Walsh, T.J., Kockelman, W.J., and Priest, G.R., eds., Earthquake hazards in the Pacific Northwest of the United States: U.S. Geological Survey Professional Paper 1560.

Atwater, B.F., Hull, A.G., and Bevis, K.A., 1987, Aperiodic Holocene recurrence of widespread, probably coseismic subsidence in southwestern Washington [abstract]: Eos, v. 68, p. 1468.

Atwater, B.F., and Moore, A.L., 1992, A tsunami 1000 years ago in Puget Sound, Washington Science, v. 258, p. 1614-1617.

Atwater, B.F., Nelson, A.R., Clague, J.J., 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.C., Nishenko, S.P., Palmer, S.P., Peterson, C.D., and Reinhart, M.A., 1995, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone p. Earthquake Spectra, v. 11, p. 1-18.

Atwater, B.F., Vita-Finzi, C. and Jiménez Núñez, H., 1992, Net late Holocene emergence despite earthquake-induced submergence, south-central Chile, *in* Ota, Y., Nelson, A.R., and Berryman, K.R., eds., Impacts of tectonics on Quaternary coastal evolution: Quaternary International, v. 15/16, p. 77-86.

Atwater, B.F., Stuiver, M., and Yamaguchi, D.K., 1991, Radiocarbon test of earthquake magnitude at the Cascadia subduction zone. Nature, v. 353, p. 156-158.

Atwater, B.F., and Yamaguchi, D.K, 1991, Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington State: Geology, v. 19, p. 706-709.

Barbour, M.G., and Davis, C.B., 1970, Salt tolerance of five California salt marsh plants: American Midland Naturalist, v. 84, p. 262-265.

Bartsch-Winkler, S.R., and Garrow, H.C., 1982, Depositional systems approaching maturity at Portage Flats, *in* Coonrad, W.L., ed., The United States Geological Survey in Alaska: accomplishments during 1980: U.S. Geological Survey Circular 844, p. 115-117.

Behre, K.-E., Menke, B., and Streif, H., 1979, The Quaternary geological development of the German part of the North Sea, in Oele, E., Schttenhelm, R.T.E., and Wiggers, A.J., eds, The Quaternary History of the North Sea: Acta Universitatis Upsaliensis, Symposia Universitatis Upsaliensis Annun Quingentesimum Celebrantis, v. 2, p. 85-113.

Berryman, K.R., Y. Ota, and A.G. Hull. 1989. Holocene paleoseismicity in the fold and thrust belts of the Hikuangi subduction zone, eastern North Island, New Zealand. Tectonophysics 163 p. 185-195.

Brown, L.D., Reiloinger, R.E., Holdahl, S.R., and Balazs, E.I., 1977, Postseismic crustal uplift near Anchorage, Alaska: Journal of Geophysical Research, v. 82, p. 3369-3378.

Bucknam, R.C., Hemphill-Haley, E., and Leopold, E.B., 1992, Abrupt uplift within the past 1700 years at southern Puget Sound, Washington: Science, v. 258, p. 1611-1614.

Cahoon, D.R., Reed, D.J., and Day, J.W., Jr., 1995, Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited: Marine Geology, v. 128, p. 1-10.

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

Clarke, S.H., Jr., and Carver, G.A., 1992, Late Holocene tectonics and paleoseismicity, southern Cascadia subduction zone: Science, v. 255, p. 188-192.

Clifton, H.E., 1983, Discrimination between subtidal and intertidal facies in Pleistocene deposits, Willapa Bay, Washington: Journal of Sedimentary Petrology, v. 53, p. 353-369.

Cole, S.C., Atwater, B.F., McCutcheon, P.T., Stein, J.K., and Hemphill-Haley, E., 1996, Effects of sudden submergence on archaeological sites along the southern Washington coast: Geoarchaeology (in press).

Cowan, D.S., and Potter, C.J., 1986, Juan de Fuca spreading ridge to Montana thrust belt: Geological Society of America Continent-ocean transect B3.

Darienzo, M.E., and Peterson, C.D., 1990, Episodic tectonic subsidence of late Holocene salt marshes, northern Oregon coast, central Cascadia margin, U.S.A: Tectonics, v. 9, p.1-22.

Darienzo, M.E., and Peterson, C.D., 1995, Magnitude and frequency of subduction-zone earthquakes along the Oregon coast in the past 3,000 years: Oregon Geology, v. 57, p. 3-12.

Darienzo, M.E., Peterson, C.D., and Clough, C., 1994, Stratigraphic evidence for great subduction-zone earthquakes at four estuaries in northern Oregon: Journal of Coastal Research, v. 10, p. 850-876.

Devoy, R.J.N., 1979, Flandrian sea level changes and vegetational history of the lower Thames estuary: Philosophical Transactions of the Royal Society of London, B, v. 285, p. 355-407.

Dragert, H., Hyndman, R.D., Rogers, G.C., and Wang, K., 1994, Current deformation and the width of the seismogenic zone of the northern Cascadia subduction zone: Journal of Geophysical Research, v. 99, p. 653-668.

Eronen, M., Kankainen, T., and Tsukada, M., 1987, Late Holocene sea-level record in a core from the Puget lowland, Washington: Quaternary Research, v. 27, p. 147-159.

Fletcher, C.H., III, Pizzuto, J.E., John, S., and van Pelt, J.E., 1993a, Sea-level rise acceleration and the drowning of the Delaware Bay coast at 1.8 ka: Geology, v. 21, p. 121-124.

Fletcher, C.H., III, van Pelt, J.E., Brush, G.S., and Sherman, J., 1993b, High-resolution stratigraphic framework, Holocene sea-level and climate history, and evoluation of a tidal wetland: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 102, p. 177-213.

Geomatrix Consultants, 1995, Seismic Design Mapping: Prepared for Oregon Department of Transportation, Salem, Oregon, Personal services contract no. 11688, Project no. 2442, various pagination.

Geyh, M.A., 1980, Holocene sea-level history: case study of the statistical evaluation of ^{14}C dates: Radiocarbon, v. 22, p. 695-704.

Goldfinger, C., Kulm, L.D., Yeats, R.S., Appelgate, B., MacKay, M., and Moore, G.F., 1992a, Transverse structural trends along the Oregon convergent margin: implications for Cascadia earthquake potential: Geology, v. 20, p. 141-144.

Goldfinger, C., Kulm, L.D., Yeats, R.S., Mitchell, C., Weldon, R., Peterson, C.D., Darienzo, M.E., Grant, W.C., and Priest, G.R., 1992b, Neotectonic map of the Oregon continental margin and adjacent abyssal plain. Oregon Department of Geology and Mineral Industries Open-File Report 0-92-4, scale 1:500,000.

Goodbred, S.L., Jr., and Hine, A.C., 1995, Coastal storm deposition: salt-marsh response to a severe extratropical storm, March 1993, west-central Florida: Geology, v. 23, p. 679-682.

Hanks, T.C., and Kanamori, H., 1979, A moment magnitude scale: Journal of Geophysical Research, v. 84, p. 2348-2350.

Heaton, T.H., and Hartzell, S.H., 1986, Source characteristics of hypothetical subduction earthquakes in the northwestern United States: Bulletin of the Seismological Society of America, v. 76, p. 675-708.

Heaton, T.H., and Hartzell, S.H., 1987, Earthquake hazards on the Cascadia subduction zone. Science, v. 236, p. 162-168.

Hemphill-Haley, E., 1995a, Intertidal diatoms from Willapa Bay, Washington: application to studies of small sea-level changes: Northwest Science, v. 69, p. 29-45.

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

Holdahl, S.R., Faucher, F., and Dragert, H., 1979, Contemporary vertical crustal motion in the Pacific Northwest, *in* Cohen, S.C., and Vanicek, P., eds., Slow Deformation and Transmission of Stress in the Earth: American Geophysical Union Geophysical Monograph 49, p. 17-29.

Hull, A.G., 1987, Buried lowland soils from Willapa Bay, southwest Washington: further evidence for recurrence of large earthquakes during the past 5000 years [abstract]: Eos, v. 68, p. 1469.

Hyndman, R.D., and Wang, K., 1993, Thermal constraints on the zone of major thrust earthquake failure: the Cascadia subduction zone: Journal of Geophysical Research, v. 98, p. 2039-2060.

Hyndman, R.D., and Wang, K., 1995, The rupture zone of Cascadia great earthquakes from current deformation and thermal regime: Journal of Geophysical Research, v. 100, p. 22133-22154.

Hyndman, R.D., and Weichert, D.H., 1983, Seismicity and rates of relative motion on plate boundaries of western North America: Geophysical Journal of the Royal Astronomical Society, v. 72, p. 59-82.

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

Jacoby, G.C., Williams, P.L., and Buckley, B.M., 1992, Tree ring correlation between prehistoric landslides and abrupt tectonic events in Seattle, Washington: Science, v. 258, p. 1621-1623.

Jelgersma, S., 1961, Holocene sea level changes in the Netherlands: Mededelingen van de Geologische Stichting, Serie C, VI, v. 7, p. 1-100.

Jelgersma, S., Oele, E., and Wiggers, A.J., 1979, Depositional history and coastal development in the Netherlands and the adjacent North Sea since the Eemian, in Oele, E., Schttenhelm, R.T.E., and Wiggers, A.J., eds, The Quaternary History of the North Sea: Acta Universitatis Upsaliensis, Symposia Universitatis Upsaliensis Annun Quingentesimum Celebrantis, v. 2, p. 115-142.

Johnson, D.W., 1925, The New England - Acadian Shorline: New York, John Wiley, 608 p.

Johnson, J.W., 1973, Characteristics and behavior of Pacific Coast tidal inlets: Journal of the Waterways, Harbors, and Coastal Engineering Division, Proceedings of the American Society of Civil Engineers, v. 99, p. 325-339.

Kanamori, H., 1977, The energy release in great earthquakes: Journal of Geophysical Research, v. 82, p. 2981-2987.

Kelsey, H.M., Engebretson, D.C., Mitchell, C.E., and Ticknor, R.L., 1994, Topographic form of the Coast Ranges of the Cascadia Margin in relation to coastal uplift rates and plate subduction: Journal of Geophysical Research, v. 99, p. 12245-12255.

Kelsey, H.M, Witter, R.C., and Polenz, M., 1993, Cascadia paleoseismic record derived from late Holocene fluvial and lake sediments, Sixes River valley, Cape Blanco, south coastal Oregon [abstract]: Eos, v. 74, no. 43, p. 199.

Kelsey, H.M., 1990, Late Quaternary deformation of marine terraces on the Cascadia subduction zone near Cape Blanco, Oregon: Tectonics v. 9, p. 983-1014.

Kunze, L.M., and Cornelius, L.C., 1982, Baseline inventory of rare, threatened and endangered plant species/communities along Washington's Pacific coast: Washington Department of Ecology, National Oceanic and Atmospheric Administration Coastal Zone Management Grant G68-029.

Mall, R.E., 1969, Soil-water-salt relationships of waterfowl food plants in the Suisun marsh of California: California Department of Fish and Game, Wildlife Bulletin 1, 59 p.

McCaffrey, R., and Goldfinger, C., 1995, Forearc deformation and great subduction earthquakes: implications for Cascadia offshore earthquake potential: Science, v. 267, p. 856-859.

McNeill, L.C., Goldfinger, C., Kulm, L.D., and Yeats, R.S., 1994, Tectonics of the Washington continental margin, Cascadia subduction zone [abstract]: Geological Socieity of America Abstracts with Programs, Annual Meeting 1994, p. A-523.

Miles, M.M., Wiggins, W.D., Ruppert, G.P., Smith, R.R., Reed, L.L., Hubbard, L.E., and Courts, M.L., 1994, Water resources data Washington water year 1993: U.S. Geological Survey Water-Data Report WA-93-1, 408 p.

Meyerson, A.L., 1972, Pollen and paleosalinity analyses from a Holocene tidal marsh sequence, Cape May County, New Jersey: Marine Geology, v. 12, p. 335-357.

Mitchell, C.E., Vincent, P., and Weldon, R.J., 1994, Present-day vertical deformation of the Cascadia margin, Pacific Northwest, United States: Journal of Geophysical Research, v. 99, p. 12257-12277.

Mudge, B.F., 1862, The salt marsh formations of Lynn: Proceedings of the Essex Institute, v. 2, p. 117-119.

Mumford, T.F., Jr., Peyton, P., Sayce, K.R., and Harbell, S.(eds.). 1990. *Spartina* workshop record. Seattle, Washington, University of Washington, Washington Sea Grant Program, WSG-WO 91-01, 73 p.

Nelson, A.R., and Kashima, K., 1994, Diatom zonation in southern Oregon tidal marshes relative to vascular plants, foraminifera, and sea level: Journal of Coastal Research, v. 9, p. 673-697.

Nelson, A.R., Atwater, B.F., Bobrowsky, P.T., Bradley, L.-A., Clague, J.J., Carver, G.A., Darienzo, M.E., Grant, W.C., Krueger, H.W., Sparks, R., Stafford, T.W., and Stuiver, M., 1995, Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone: Nature, v. 378, p. 371-374.

Nelson, A.R., Jennings, A.E., and Kashima, K., in press a, Holocene intertidal stratigraphy, microfossils, rapid submergence, and earthquake recurrence at Coos Bay, southern coastal Oregon, USA: Geological Society of America Bulletin.

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

Nelson, A.R., and Personius, S.F., in press, The potential for great earthquakes in Oregon and Washington—an overview of recent geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia subduction zone, *in* Rogers, A.M., Walsh, T.J., Kockelman, W.J., and Priest, G.R., eds., Earthquake Hazards in the Pacific Northwest of the United States: U.S. Geological Survey Professional Paper 1560 (released in preliminary form in 1991 as U.S. Geological Survey Open-File Report 91-441-A).

Nelson, A.R., 1992a, Holocene tidal-marsh stratigraphy in south-central Oregon—evidence for localized sudden submergence in the Cascadia subduction zone, *in*Fletcher, C.P., and Wehmiller, J.F., eds., Quaternary coasts of the United States: marine and lacustrine systems: Society for Sedimentary Geology Special Publication 48, p. 287-301.

Nelson, A.R., 1992b, Discordant ^{14}C ages from buried tidal-marsh soils in the Cascadia subduction zone, southern Oregon coast: Quaternary Research, v. 38, p. 75-90.

Ota, Y., and Umitsu, M., 1995, Stratigraphic, radiocarbon and diatom indicators of sudden submergence along the Nesselle [sic] River mouth, Washington, USA: Journal of Geography, v. 104, p. 107-112 (in Japanese).

Ovenshine, A.T., Lawson, D.E., and Bartsch-Winkler, S.R., 1976, The Placer River Silt—an intertidal deposit caused by the 1964 Alaska earthquake: Journal of Research of the U.S. Geological Survey, v. 4, p. 151-162.

Palmer, S.P., and Lingley, W.S., Jr., 1989, An assessment of the oil and gas potential of the Washington outer continental shelf: Washington Sea Grant Program, University of Washington, Seattle, 83 p.

Peterson, C.D., and Darienzo, M., 1989, Potential evidence of subduction zone tectonics from stacked peat horizons in late Pleistocene coastal terraces of the northern Cascadia margin [abstract]: Eos, v. 70, p. 1331.

Pezzopane, S.K., and Weldon, R.J., II, 1993, Tectonic role of active faulting in central Oregon: Tectonics, v. 12, p. 1140-1169.

Plafker, G., 1969, Tectonics of the March 27, 1964 Alaska earthquake: U.S. Geological Survey Professional Paper 543-I, 74 p.

Plafker, G., and Savage, J.C., 1970, Mechanism of the Chilean earthquakes of May 21 and 22, 1960: Geological Society of America Bulletin, v. 81, p. 1001-1030.

Plafker, G., Gilpin, L.M., and Lahr, J.C., 1994, Neotectonic map of Alaska, *in* Plafker, G., and Berg, H.C., eds. The Geology of Alaska: Geological Society of America, The Geology of North America, v. G1, Plate 12, scale 1:2,500,000 with 3 tables and text.

Redfield, A.C., 1972, Development of a New England salt marsh: Ecological Monographs, v. 42, p. 201-237.

Reid, C., 1913, Submerged Forests: Cambridge, University Press, 129 p.

Reinhart, M.A., and Bourgeois, J., 1987, Distribution of anomalous sand at Willapa Bay, Washington—evidence for large-scale landward-directed processes [abstract]: Eos, v. 68, p. 1469.

Reinhart, M.A., and Bourgeois, J., 1989, Tsunami favored over storm or seiche for sand deposit overlying buried Holocene peat, Willapa Bay, WA [abstract]: Eos, v. 70, p. 1331.

Rogers, G.C., 1988, An assessment of the megathrust earthquake potential of the Cascadia subduction zone: Canadian Journal of Earth Sciences, v. 25, p. 844-852.

Satake, K., Shimazaki, K., Tsuji, Y., and Ueda, K., 1995, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami record of January 1700: Nature, v. 378, in press.

Savage, J.C., Lisowski, M., and Prescott, W.H., 1991, Strain accumulation in western Washington: Journal of Geophysical Research, v. 96, p. 14493-14507.

Savage, J.C., and Plafker, G., 1991, Tide gage measurements of uplift along the south coast of Alaska: Journal of Geophysical Research, v. 96, p. 4325-4336.

Sayce, K, 1988, Introduced cordgrass, *Spartina alterniflora* Loisel. in saltmarshes and tidelands of Willapa Bay, Washington: Ilwaco, Washington, Willapa National Wildlife Refuge, U.S. Fish and Wildlife Service contract FWSI-87058(TS), 70 p.

Scholz, C.H., and Campos, J., 1995, On the mechanism of seismic decoupling and back arc spreading at subduction zones: Journal of Geophysical Research, v. 100, p. 22103-22115.

Shennan, I., 1986, Flandrian sea-level changes in the Fenland. I: The geographical setting and evidence of relative sea-level changes: Journal of Quaternary Science, v. 1, p. 119-154.

Shennan, I., Innes, J.B., Zong, Y., and Long, A., 1994, A litho- and biostratigraphic evaluation of the coseismic subsidence and interseismic strain accumulation in the Washington and Oregon part of the Cascadia subduction zone: U.S. Geological Survey Open-File Report 94-176, p. 649-657.

Shennan, I., Tooley, M.J., Davis, M.J., and Haggart, B.A., 1983, Analysis and interpretation of Holocene sea-level data: Nature, v. 302, p. 404-406.

Streif, H., 1972, The results of stratigraphical and facial investigations in the coastal Holocene of Woltzeten/Ostfriesland, Germany: Geologiska Foreningens i Stockholm Forhandlingar, v. 94, p. 280-299.

Stuiver, M., and Becker, B., 1993, High-precision decadal calibration of the radiocarbon time scale, AD 1950-6000 BC: Radiocarbon, v. 35, p. 35-67.

Stuiver, M., and Pearson, G.W., 1986, High-precision calibration of the radiocarbon time scale AD 1950-500 BC: Radiocarbon, v. 28, p. 805-838.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program: Radiocarbon, v. 35, p. 215-230.

Swan, J.G., 1857, The Northwest Coast or, Three Years' Residence in Washington Territory: Harper & Brothers, 435 p. (reprinted in 1972 by University of Washington Press, Seattle).

Thatcher, W., 1984, The earthquake deformation cycle at the Nankai Trough, southwest Japan: Journal of Geophysical Research, v. 89, p. 3087-3101.

Torresan, M.E., 1987, Review and comparison of hydrophotometer and pipette method in analysis of fine grained sediment: U.S. Geological Survey Open-File Report 87-514, p. 1-38.

van de Plassche, O., 1991, Late Holocene sea-level fluctuations on the shore of Connecticut inferred from transgressive and regressive overlap boundaries in salt-marsh deposits: Journal of Coastal Research, special issue 11, p. 159-179.

Varekamp, J.C., Thomas, E., and Van de Plassche, O., 1992, Relative sea-level rise and climate change over the last 1500 years, *in* Wezel, F.-C., ed., Global Change Special Issue: Terra Nova, v. 4, p. 293-304.

Wagner, H.C., 1967a, Preliminary geologic map of the Raymond quadrangle, Pacific County, Washington: U.S. Geological Survey Open-File Report 67-265, scale 1:62,500.

Wagner, H.C., 1967b, Preliminary geologic map of the South Bend quadrangle, Pacific County, Washington: U.S. Geological Survey Open-File Report 67-266, scale 1:62,500.

Walsh, T.J., Korosec, M.A., Phillips, W.M., Logan, R.L., and Schasse, H.W., 1987, Geologic map of Washington—southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, scale 1:250,000.

Ward, G.K., and Wilson, S.R., 1978, Procedures for comparing and combining radiocarbon age determinations: a critique: Archaeometry, v. 20, p. 19-31.

Weinmann, F., Boulé, M., Brunner, K., Malek, J., and Voshino, V., 1984, Wetland plants of the Pacific Northwest: Seattle, Washington, U.S. Army Corps of Engineers, 85 p. and others, 1984

Wells, D.R., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, p. 974-1002.

Wells, R.E., 1989, Geologic map of the Cape Disappointment - Naselle River area, Pacific and Wahkiakum Counties, Washington: U.S. Geological Survey Miscellaneous Investigations Map I-1832, scale 1:62,500.

Wilson, D.S., 1993, Confidence intervals for motion and deformation of the Juan de Fuca plate: Journal of Geophysical Research, v. 98, p. 16053-16071.

Yamaguchi, D.K., Woodhouse, C.A., and Reid, M.S., 1989, Tree-ring evidence for synchronous rapid submergence of the southwestern Washington coast about 300 years ago [abstract]: Eos, v. 70, p. 1332.

Table 1. Buried soils in Pleistocene deposits near Willapa Bay

Location	Diagnostic features
NE/4 NE/4 sec. 33 and SE/4 SE/4 sec. 28, T.14N., R.10W., Bay Center 7.5-minute quadrangle; lowermost 2 m of bayside cliff	Woody organic horizon 5-15 cm thick, ∼300 m long, abruptly overlain by mud; this mud contains a dark gray layer about ∼1 cm thick, perhaps the faint surficial horizon of a second buried soil
NW/4 SW/4 sec. 4, T.13N., R.10W., Bay Center 7.5-minute quadrangle (H.E. Clifton, oral commun., 1989); bayside cliff	Mud with many traces of roots and rhizomes, conformably overlain by lighter-colored mud that lacks such traces (Clifton, 1983, his fig. 9)
W/2 SW/4 sec. 1, T.13N., R.10W, South Bend 7.5-minute quadrangle; roadcuts along west side of South Bend - Palix River Road	At least two superposed carbonaceous layers 2-5 cm thick, separated from one another by mud
In sec. 37, T.13N., R.10W., 820 m SSE of Goose Point, Bay Center 7.5-minute quadrangle; lowermost 3 m of bayside cliff	Mud containing many rhizomes of *Triglochin maritima*, abruptly overlain by locally woody mud that lacks rhizomes
NE/4 NW/4 SW/4 sec. 3, T.12N., R.10.W., Nemah 7.5-minute quadrangle; lowermost 2 m of bayside cliff	Three dark, probably carbonaceous layers 2-4 cm thick and ∼0.5 m apart, separated from one another by mud. Horizontal laminations in the mud resemble those of the tidal-marsh deposits photographed by Clifton (1983, his figs. 9, 14); much of the mud also contains rhizomes of *Triglochin maritima*
SE/4 SE/4 SW/4 sec. 3, T.12N., R.10W., Nemah 7.5-minute quadrangle; 2-6 m above base of bayside cliff	Dark, probably carbonaceous layers, at least two of them below and another above a surface of non-deposition marked by a woody, probably upland soil. Lowest layer conformably overlies mud whose low-angle crossbedding implies intertidal or subtidal origin
NW/4 SE/4 sec. 10, T.12N., R.10W., Nemah 7.5-minute quadrangle; 5 m above base of bayside cliff	Two successive beds, each about 1/4 m thick, in which mud with rhizomes grades upward into peaty mud or peat whose upper contact is abrupt. Lower bed abruptly overlies the A horizon of an upland soil. Bioturbated mud, probably deposited on a tideflat, conformably overlies the upper bed

TABLE 2. Diatom taxa used for the Brackish Intertidal Diatom Index (BIDI)

Diatoms representative of high marshes
Cosmioneis pusilla (Wm. Smith) Mann and Stickle *in* Round and others, 1990
Denticula subtilis Grunow, 1862
Diploneis didyma (Ehrenberg) Ehrenberg, 1854
Navicula tenelloides Hustedt, 1937
Nitzschia brevissima Grunow in Van Heurck, 1881
Nitzschia pusilla (Kützing) Grunow, 1862
Nitzschia terrestris (Peterson) Hustedt, 1934
Pinnularia lagerstedtii (Cleve) Cleve-Euler, 1934
Tryblionella aerophila (Hustedt) Mann in Round and others, 1990

Diatoms representative of high or low marshes
Caloneis bacillum (Grunow) Cleve, 1894
Diploneis pseudovalis Hustedt, 1930
Frustulia vulgaris (Thwaites) De Toni, 1891
Luticola mutica (Kützing) Mann in Round and others, 1990
Navicula cincta (Ehrenberg) Ralfs in Pritchard, 1861
Nitzschia commutata Grunow in Cleve and Grunow, 1880
Nitzschia fasciculata (Grunow) Grunow in Van Heurck, 1881
Tryblionella debilis Arnott in O'Meara, 1873

Diatoms representative of low marshes
Caloneis westii (W. Smith) Hendey, 1964
Diploneis interrupta (Kützing) Cleve, 1894
Diploneis smithii var. *rhombica* Mereschkowsky, 1902
Frustulia linkei Hustedt, 1952
Gyrosigma eximium (Thwaites) Boyer, 1927
Mastogloia exigua Lewis, 1862
Navicula cryptotenella Lange-Bertalot in Krammer and Lange-Bertalot, 1985
Nitzschia bilobata W. Smith, 1853
Nitzschia scapelliformis Grunow in Cleve and Grunow, 1880
Rhopaloda musculus (Kützing) Müller, 1899
Scoliopleura tumida (Brébisson ex Kützing) Rabenhorst, 1864
Tryblionella navicularis (de Brébisson ex Kützing) Ralfs in Pritchard, 1861

Diatoms representative of muddy intertidal flats and shallow subtidal areas
Bacillaris paradoxa Gmelin, 1791
Campylodiscus echineis Ehrenberg, 1840
Catenula adhaerens Mereschkowsky, 1903
Cerataulus turgidus (Ehrenberg) Ehrenberg, 1843
Cocconeis scutellum Ehrenberg, 1838
Cocconeis scutellum var. *parva* Grunow ex Cleve, 1895
Gyrosigma acuminatum (Kützing) Rabenhorst, 1853
Gyrosigma balticum (Ehrenberg) Rabenhorst, 1853
Melosira moniliformis (Müller) Agardh, 1824
Melosira nummuloides Agardh, 1824
Navicula digitoradiata (Gregory) Ralfs in Pritchard, 1861
Navicula tripunctata (Müller) Bory, 1824
Nitzschia sigma (Kützing) W. Smith, 1853
Nitzschia socialis Gregory, 1857
Odontella aurita (Lyngbye) Agardh, 1832
Opephora parva Krasske, 1939
Plagiogramma staurophorum (Gregory) Heiberg, 1863
Rhaphoneis amphiceros (Ehrenberg) Ehrenberg, 1844
Rhaphoneis psammicola Riznyk, 1973
Synedra fasciculata (Agardh) Kützing, 1844
Trachyneis aspera (Ehrenberg) Cleve, 1894
Tryblionella acuminata W. Smith, 1853
Tryblionella apiculata Gregory, 1857
Tryblionella coarctata (Grunow) Mann in Round and others, 1990
Tryblionella levidensis Wm. Smith, 1856
Tryblionella littoralis (Grunow) Mann in Round and others, 1990
Tryblionella plana (W. Smith) Mann in Round and others, 1990
Tryblionella punctata W. Smith 1853
Tryblionella vexans (Grunow) Mann in Round and others, 1990

Diatoms representative of sandy intertidal flats and shallow subtidal areas
Achnanthes delicatula (Kützing) Grunow in Cleve and Grunow, 1880
Amphora proteus Gregory, 1857
Amphora ventricosa (Gregory) Hendey, 1951
Cocconeis diminuta Pantocksek, 1902
Cocconeis peltoides Hustedt, 1939
Dimeregramma minor (Gregory) Ralfs in Pritchard, 1861
Fallacia cryptolyra (Brockmann) Stickle and Mann in Round and others, 1990
Lyrellla lyra (Ehrenberg) Karayeva, 1978
Navicula cancellata Donkin, 1872
Petroneis granulata (Bailey) Mann in Round and others, 1990
Petroneis marina (Ralfs) Mann in Round and others, 1990
Trachyneis australis (Ehrenberg) Cleve, 1894

Table 3. Numbers of diatoms counted at the Redtail locality

	Depth below modern surface (m)	Diatom sample ID		**Benthic diatoms**	*Achnanthes hauckiana*	*Achnanthes cf. minutissima*	*Achnanthes delicatula*	*Achnanthes lanceolata*	*Achnanthes spp.*	*Achnathes brevipes*	*Amphora libyca*	*Amphora proteus*	*Amphora spp.*	*Amphora ventricosa*	*Amphora ventricosa*	*Biddulphia spp.*	*Biremis ambiqua*	*Caloneis bacillum*	*Caloneis permagna*	*Caloneis spp.*	*Caloneis westii*	*Campylodiscus bicostatus*	*Campylodiscus echineis*	*Catenula adhaerens*	*Cerataulus turgidus*	*Cocconeis diminuta*	*Cocconeis peltoides*	*Cocconeis placentula*	*Cocconeis sctutellum v. parva*	*Cocconeis scutellum*	*Cocconeis spp.*
	0.01	OS10x-75								4								2			1					4		4	2	1	1
	0.15	OS10x-60				11	22		4	4						1				2	4		2			4		2	5	1	
	0.35	OS10x-40				1	3	1													14		4		7	3					4
	0.55	OS10x-20			1															1	23				1						
	0.66	OS8-1				1	1												1	1	7		5		8	6		5		5	
	0.70	OS8-3					3			2						2				2	9		8		3	3			2		
	0.74	OS8-6					32					2				1				1	1				6	6		1			
Top of soil Y	0.76	OS8-8																													
	0.90	OS10-24																			2		1			2					
	0.99	OS10-32				1	2													3	1		5								
	1.09	OS10-42					1														17		10								
	1.14	OS7-10																			2		24			6		4			
Top of soil U	1.17	OS10-56																					0.5								
	1.22	OS10-61																					1								
	1.40	930718 B3-20					20									2		6		2	46		6	2		16	4	2			2
	1.50	930718 B3-30					12	2													10			2		20		4	2		
	1.54	OS6-4			4		17	1	8		4			1							6			1		8	16	2			1
Top of soil S	1.58	OS6-8					2																	1		3	2				
	1.68	OS6-18						1													3					1		1			
	1.80	930718 B4-25																			8										
	1.89	OS5-1			2		1					4									2			1		64	1		5		1
	1.95	OS5-7					18						3											5		39	19		1	1	
Top of soil N	1.97	OS5-9					1																			7					
	2.05	OS5-18					1											6			1					4					1
	2.10	OS5-22					1													2						5	2				6
	2.15	OS5-27					1			2	2							13			11		3			2		1	1		
	2.18	OS5-30			1	3												7			7			1			1	1			
	2.45	930718 B7-1					1			1								12			13		8			3			1		
	2.58	OS4-1					4						4								1		1			25	9		2	2	
Top of soil L	2.67	OS4-10																								7					2
	2.75	OS4-18			2	2	1	1	7									4								4					
	2.90	930718 B8-1					1							1				4			7		1					1			
	3.00	930718 B8-10			2		1					2						1			16		3						1		
	3.10	930718 B8-20								2								1			37										
	3.20	OS2-1				2	36		2	5		1	1					3			26			1		6	22		2	1	
	3.23	OS2-4			3		6		5	1			1	1							19	1	1		2		3		1		
	3.27	OS2-8			2	7	12		10	2			2								18		3		1	1	7		2		
	3.31	OS2-12					11		4												7				1	2	5	2	1	3	
	3.35	OS2-16			6		23		4				1								2					6	4	4	6		
	3.39	OS2-20			3		20	2		2			4				2	2		2	2		1			11	6	3	10	2	2
Top of soil J	3.41	930718 B9-23					1											10									3		1	1	
	3.45	OS2-26			1		4						1		2					4				1		1		2			

Table 3 (cont.). Numbers of diatoms counted at the Redtail locality

	Depth below modern surface (m)	*Cosmioneis pusilla*	*Cosmioneis pusilla var.*	*Craticula halophila*	*Cymbella spp.*	*Delphineis cf. karstenii*	*Delphineis cf. margaritalimbata*	*Delphineis cf. surirella*	*Delphineis surirella*	*Denticula subtilis*	*Dimeregramma minor*	*Diploneis didyma*	*Diploneis interrupta*	*Diploneis oblongella*	*Diploneis pseudovalis*	*Diploneis smithii v. rhombica*	*Diplonies stroemi*	*Endictya hendeyi*	*Epithemia spp.*	*Epithemia turgida*	*Eunotia pectinalis*	*Eunotia spp.*	*Fallacia cryptolyra*	*Fallacia forcipata*	*Fallacia pygmaea*	*Fragilaria construens v. venter*	*Fragilaria pinnata*	*Fragilaria spp.*	*Frickea lewisiana*	*Frustulia linkei*	*Frustulia vulgaris*	*Gomphonema parvulum*	*Gomphonema spp.*	*Grammatophora oceanica*
	0.01	10							1		1		2																			2	1	2
	0.15	10			1		8			2										1	1		3				1		2				2	4
	0.35		1		4		4		15		1		21					33		3							2	2						1
	0.55		2						5			2	125					8		3														1
	0.66	4			3	3	1		10		2		3					13	1	18										1				2
	0.70				2	9		1	7	1	14		1					9		3			1											
	0.74					9			5		3		1					11		4			8											
Top of soil Y	0.76																																	
	0.90	43	2		4		1		3	1								5									1							
	0.99	59			3								3																					1
	1.09				7								28					4		7							1							1
	1.14					6		6			9									4														2
Top of soil U	1.17	61	1						2									3	1															1
	1.22	39			3							2	3					2		3														1
	1.40				2	4		4					2				2				2		8		4									
	1.50					12		12		2	2		2					2		6			12											
	1.54						10	18			1		1							1		1	10			4	2					1		
Top of soil S	1.58						2	3			2												1				2							
	1.68	4					1						1		1			6					1		1			1						2
	1.80	10	12		2	4							60																				2	
	1.89					3	1	2										4					2	4										
	1.95	5				2	7	5															13			11								1
Top of soil N	1.97	1						9												1			1											
	2.05	25	5			4	2								2	1		1		2					2						5			
	2.10	35			1			5			2								1								20							
	2.15	16		2	2	5		2					3												1						1			
	2.18					2	3	1										2								1	4							
	2.45	10				6	1	3					8				1			2														
	2.58					9	8				4		2		2					3			2			1								
Top of soil L	2.67	36		2			2	3						1									2											
	2.75	14						2						10																3	10	2		
	2.90	24	9	1	2			2					5					1		2			2									1		
	3.00	5	6			7	1	4					7							6					1							1		
	3.10	25	61		2			1					16			1		5		3	1													
	3.20	1		8	2			3		4			2					1					4								1			
	3.23	1		3	1			12										3				1												
	3.27			3	1	6	1	43					2					1		6			5		1			1						
	3.31					2		30			3							2		1			3									1	1	
	3.35	1		1		10	4	53					2					1					11	1									1	
	3.39	6	2	2	1		2	16				1	1					3		3			4											
Top of soil J	3.41	41				4								1	5	2														2		10		
	3.45	60	5			2		8				1			14	5		2	1											1	5		2	

Table 3 (cont.). Numbers of diatoms counted at the Redtail locality

	Depth below modern surface (m)	*Gyrosigma acuminatum*	*Gyrosigma balticum*	*Gyrosigma eximium*	*Gyrosigma wansbeckii*	*Hannaea arcuatum*	*Hantzschia amphioxys*	*Hantzschia virgata*	*Hyalodiscus laevis*	*Hyalodiscus scoticus*	*Luticola mutica*	*Luticola muticoides*	*Lyrella lyra*	*Mastogloia exigua*	*Mastogloia smithii*	*Melosira moniliformis*	*Melosira nummuloides*	*N. peregrina v. kefvingensis*	*Navicula cancellata*	*Navicula cincta*	*Navicula cryptotenella*	*Navicula digitoradiata*	*Navicula directa*	*Navicula elginensis*	*Navicula gregaria*	*Navicula libonensis*	*Navicula peregrina*	*Navicula phyllepta*	*Navicula rhyncocephala*	*Navicula salinarum*	*Navicula spp.*	*Navicula tenelloides*	*Nitzschia bilobata*	*Nitzschia brevissima*	*Nitzschia cf. nana*
	0.01						1			3	18					8	8			197															2
	0.15									8	17		2			33	15			3		4													
	0.35								1											3	2														2
	0.55						1		3		2			1		1				1						1									2
	0.66	1	5	7				2	1				2		2	1																			
	0.70		1				2		1							2															1				
	0.74		3							1						1			1			2	1								1				
Top of soil Y	0.76																									1									
	0.90								8		8									2															1
	0.99								10		7									4														1	5
	1.09						1		4																										1
	1.14								10																										
Top of soil U	1.17						1		1		5									5											1				1
	1.22						4		1		2									6												2			2
	1.40	2	14											4		2				2	2	2									4				2
	1.50	2	2	2							4			2		4	2														8				2
	1.54	5	2	5								2		13			5														1		1		
Top of soil S	1.58			1								5																							
	1.68										4					4																			
	1.80								2																										
	1.89	3	5		3		5									1						1													
	1.95										4						7		1	11	1										4				
Top of soil N	1.97											1								2											2				
	2.05	2		1							10									2				1					4		2				
	2.10										3									35															2
	2.15	5	1	77							3			1						4							4								1
	2.18	1	1	10			1				1	9					2		37		1	5			2						2		14		3
	2.45		7	13					30		1			1					2	1		2			1		1		1						
	2.58	8	5	1								2		2			2				3	2							5		2				
Top of soil L	2.67											22								13		2							5						4
	2.75	6										17						3		14									31		10		4		10
	2.90	1		4					1		6									5		1							1				1		
	3.00	1	1	5																3		2									3				
	3.10		2				1		2		2		2						1	2											1				
	3.20	6	88	1	3						5	1		3			2		1	1		2							2	2	8				
	3.23		38	2					1		3	1		5		1	2				2	4									1				
	3.27	2	37											15		4					13										1				
	3.31	1	23			1								10		3	4				13	2									2				
	3.35	5	9								1			4			1				27	3									1				
	3.39		4								14			7		5	4			2	10										2				3
Top of soil J	3.41										4	4		1			7	6		4							1				4			1	
	3.45										43							11		10		1					8	5			2		2		2

Table 3 (cont.). Numbers of diatoms counted at the Redtail locality

	Depth below modern surface (m)	*Nitzschia commutata*	*Nitzschia fasciculata*	*Nitzschia lorenziana*	*Nitzschia perminuta*	*Nitzschia scapelliformis*	*Nitzschia sigma*	*Nitzschia socialis*	*Nitzschia spp.*	*Nitzschia terrestris*	*Odontella aurita*	*Odontella longicruris*	*Odontella obnuta*	*Opephora cf. parva*	*Opephora spp.*	*Paralia sulcata*	*Paralia sulcata (small form)*	*Petroneis granulata*	*Petroneis marina*	*Pinnularia borealis*	*Pinnularia lagerstedtii*	*Pinnularia spp.*	*Pinnularia viridis*	*Plagiogramma staurophorum*	*Pleurosigma salinarum*	*Rhabdonema arcuatum*	*Rhaphoneis amphiceros*	*Rhaphoneis psammicola*	*Rhoicosphenia abbreviata*	*Rhopalodia acuminata*	*Rhopalodia gibba*	*Rhopalodia musculus*	*Rhopalodia operculata*
	0.01					3			11	4	1					26	66				15						1	1	1	3			
	0.15					1			2		1					30	122	1			10	16						4	2	6		1	
	0.35			1		3	1		3							216	551	1	2			1					4	24		6		6	
	0.55			20		2	15		5		5					59	155				9							6		1		5	
	0.66			3			10		1		1	2	5		2	161	186	2	1			1		5		6	5	4	1	1	2		
	0.70		1				6		1		13					185	71	1						5		2	3	1		1			
	0.74						6		14		2			1		149	146	5	2			1	1			1	4	7	1				
Top of soil Y	0.76																5				1												
	0.90									13						30	23				42							1					
	0.99															38	88				17						1						
	1.09			1		3					1					75	77	4										1		2			
	1.14															26	96																
Top of soil U	1.17									9						56	147	2			102	1											
	1.22									4						66	198				41	4											
	1.40		2				4	1	2							30	106						2				2		2				
	1.50		2			2	10		2		2		4			60	110									4	2		8				
	1.54				1	1	3				2					16	83			1													3
Top of soil S	1.58					0.5										5	9																
	1.68															53	299				3						1						
	1.80															18	150	2			2					2							
	1.89						6.5	8			2	1				114	197	1	2								2						
	1.95				1		3		8	1	1			5		54	78				4	3					4	1		5			
Top of soil N	1.97					1										79	91				5	2											
	2.05	2	1				1.5		1		1			1		11	60				30								2			1	
	2.10						0.5		8	2	1	2	1			93	222	1		1	16	11							3			3	
	2.15				2	1	12		5							19	56		2		4						1					8	
	2.18		2		2		14		3					2		26	98		13	1	11						1					1	
	2.45						23		5					24		23	49				2						1						
	2.58						4	13	17						2	115	109													3			
Top of soil L	2.67				2		1.5		6	7.5	1					11	96				56	19							2				
	2.75		1		5				51	16						2	18				36	4											
	2.90		2				8.5		2		1					16	137				4	2					3		2				
	3.00	4	2				13.5				1					8	58				1					1	2						
	3.10						6									24	77		1						1								
	3.20						5		6					15		37	31								10					1		3	
	3.23						26.5		5					4		62	37				1									2			
	3.27						4	1								32	5									2	1			1			
	3.31						10	1						2	6	61	50	1								12	2					1	
	3.35						4	1	1					2	3	41	39	1									1		2	1			
	3.39						11	1	7	1	3			2	4	123	122				4					1	1						
Top of soil J	3.41		1		5		4									20	38				33									1			
	3.45		2		1		8		11							58	75				52					1							

Table 3 (cont.). Numbers of diatoms counted at the Redtail locality

	Depth below modern surface (m)	*Scoliopleura tumida*	*Stauroneis spp.*	*Surirella spp.*	*Synedra fasciculata*	*Synedra spp.*	*Tabellaria fenestrata*	*Terpsinoe americana*	*Trachyneis aspera*	*Trachysphenia australis*	*Tryblionella acuminata*	*Tryblionella aerophila*	*Tryblionella apiculata*	*Tryblionella coarctata*	*Tryblionella debilis*	*Tryblionella granulata*	*Tryblionella levidensis*	*Tryblionella littoralis*	*Tryblionella navicularis*	*Tryblionella plana*	*Tryblionella punctata*	*Tryblionella vexans*		**Planktonic diatoms**	*Actinocyclus curvatulus*	*Actinocyclus kutzingii*	*Actinocyclus spp.*	*Actinoptychus senarius*	*Actinoptychus spp.*	*Actinoptychus vulgaris*	*Aulacoseira spp.*	*Chaetoceros spp.*	*Coscinodiscus spp.*	*Cyclotella spp.*
	0.01				1									1	38						1					2	3			1	2	1	2	
	0.15	5			12							17	2		10	4	1		2									2			3	9	1	1
	0.35	4			2				1							18									1	11	1	9	2		11		7	8
	0.55					1			29							33										2			1		6		14	2
	0.66	10			13			2	2					2	2	10						1			3	9	2	7	1	2	22		18	6
	0.70	15		1	8			2		1	1					8		1		5		1			5	4		10	2		3		5	2
	0.74	5			6				3																3	3		5	1		8		5	3
Top of soil Y	0.76								1																						6			
	0.90												2													2		4	1		37		1	
	0.99					1										9										1	7	2	2		77		8	3
	1.09						2									2	1								1	1			7		40		2	3
	1.14	18			2		20		16							40													4					
Top of soil U	1.17															9										1					26			1
	1.22															6											1				56		1	2
	1.40	14		2	1				20				4			26									2	4					10	2		
	1.50	4		2					12				2			10	2				4					4		6	2		10	6	2	2
	1.54				2.5								3	1	2						2	1						1			1	2	1	
Top of soil S	1.58															2																		
	1.68			1				1	1						2	8										2		7	1		9		1	3
	1.80	3			1										2	14										1					18			2
	1.89	7			4											24												7			8		1	
	1.95	2		2	6.5							5			4	5															2		1	2
Top of soil N	1.97											1				3															1			
	2.05	1			3										5	2		1													2			
	2.10				3.5											8										1		1			10		1	1
	2.15	2			1								2		12	8	3		2	1		3			1	1							2	
	2.18				7							2			8	2										1					2			
	2.45	4		2	2				2				1	1	7	10	1		2	2	1				1	2		1			2			
	2.58	6	2		4.5								2				4			10								2			11		1	
Top of soil L	2.67				3					1		1			10																			
	2.75				1	5						1			18						1													
	2.90	4			2.5										2	17						1				1	1	1			5			
	3.00	15			1				1				4	1	1	5						1				2		2						
	3.10	3			3										2	2				1	1				1	4		3		1	2			2
	3.20	39	1	1	3								4		1	2	3				2	1			1		2						1	
	3.23	88	4		4.5				2				1			3	2	2			1	2				5	1	14			7		2	
	3.27	43	1	4	8				5							4	1								1		7	39				2	3	4
	3.31	20		1	20								2			27	1			4	1					3	1	19	1				8	1
	3.35	10			13								1	1		12	1			1					4		1	8			4	1	10	1
	3.39	3		2	10								1	2	1	14						2					3	15			5	2	5	3
Top of soil J	3.41				2.5								2		2	3				2														
	3.45	1		1	1						1				15	12	3											1			8			

Table 3 (cont.). Numbers of diatoms counted at the Redtail locality

	Depth below modern surface (m)	*Rhizosolenia hiemalis*	*Stephanodiscus spp.*	*Stephanopyxis spp.*	*Thalassionema nitzschioides*	*Thalassiosira eccentrica*	*Thalassiosira pacifica*	*Thalassiosira spp.*	Unidentified diatoms	Preservation	Total diatom valves counted	Total high marsh diatoms(1)	Total low/high marsh diatoms (1)	Total low marsh diatoms (1)	Total tidal flat diatoms (1)	Total diatoms used for index (BIDI)	BIDI value
	0.01		1			1		1		G	462	29	255	6	27	317	0.91
	0.15				5	5		10		G	464	39	30	13	112	194	0.39
	0.35		1			1	2	4		P	1034	1	3	50	46	100	0.29
	0.55				1		5	11		P	571	13	3	156	57	229	0.41
	0.66		1		5		3	13		M	655	4	2	28	67	101	0.20
	0.70	1	1		3	1		5		M	464	1	1	25	75	102	0.14
	0.74				2		1	1		G	487			7	94	101	0.03
Top of soil Y	0.76									P	14	1			1	✳	✳
	0.90		1		1					P	242	101	10	2	6	119	0.94
	0.99		4		1					M	364	77	11	4	8	100	0.90
	1.09		2							P	307			48	18	66	0.36
	1.14			4				6	4	P	309			20	57	77	0.13
Top of soil U	1.17									M	438	173	10		2.5	186	0.99
	1.22									M	450	88	8	3	1	100	0.98
	1.40							10		M	416		10	68	108	186	0.24
	1.50				3	2	2	8		M-G	419	2	6	22	94	124	0.15
	1.54				8.5	1		5	7	G	300		2	27	82.5	112	0.14
Top of soil S	1.58				0.5		1	1		P	43			1.5	11	✳	✳
	1.68					2				P	426	7	7	4	8	✳	✳
	1.80				1		2	2		P-M	320	24	2	71	3	100	0.62
	1.89		1		12			3	2	M	518			9	116	125	0.04
	1.95				4.5			3	4	M	367	15	19	3	125	162	0.22
Top of soil N	1.97									P	208	7	2	1	9	✳	✳
	2.05			1						G	211	60	33	5	12.5	111	0.86
	2.10								7	M	517	53	38	3	16	110	0.84
	2.15				2		4	1	4	M-G	323	20	33	105	33	191	0.55
	2.18				2.5			4	5	M-G	331	13	18	33	86	150	0.32
	2.45							4	1	M-G	303	12	21	41	81	155	0.35
	2.58				4			10	2	G	433		2	15	104	121	0.08
Top of soil L	2.67				1.5			1	1	M	322	101	23		17.5	141	0.88
	2.75				5	1		4	14	G	340	67	47	7	9	130	0.90
	2.90				2			3	1	M	302	37	19	21	23	100	0.67
	3.00			1	1			1		M	206	12	11	43	35.5	102	0.44
	3.10						1			P-M	303	86	7	57	17	167	0.73
	3.20				3		1	1	8	M	441	5	11	74	205	295	0.18
	3.23				3		2	22	3	M	431	2	3	116	105	226	0.28
	3.27		1		5	4	3	5	10	M	405			91	95	186	0.24
	3.31				6	3	4	19	4	M	428			51	104	155	0.16
	3.35				14		6	17	12	M	405	1	1	45	99	146	0.17
	3.39				11	4	5	23	7	M	564	14	19	23	101	157	0.28
Top of soil J	3.41						2	2		M	381	88	29	5	25	147	0.81
	3.45				1			6	7	M	471	118	89	9	21	237	0.89

(1) Individual taxa listed in table 5

KEY:		
	G	Good preservation
	M	Moderate preservation
	P	Poor preservation
	✳	Upland deposit inferred from rare reworked diatoms

TABLE 4. Numbers of diatoms counted at the Oyster locality (horizontal coordinates 15 m and 25 m)

	Depth below modern surface (m)	Diatom sample ID	Benthic diatoms	*Achnanthes brevipes*	*Achnanthes delicatula*	*Achnanthes spp.*	*Actinoptychus senarius*	*Actinoptychus spp.*	*Amphora coffaeiformis*	*Amphora proteus*	*Amphora spp.*	*Amphora ventricosa*	*Bacillaria paradoxa*	*Biddulphia sp.*	*Caloneis bacillum*	*Caloneis westii*	*Campylodiscus echineis*	*Catenula adhaerens*	*Cerataulus turgidus*	*Cocconeis diminuta*	*Cocconeis peltoides*	*Cocconeis placentula*	*Cocconeis scutellum*	*Cocconeis scutellum v. parva*	*Coscinodiscus spp.*	*Cosmioneis pusilla*	*Cosmioneis pusilla var. 1*	*Craticula halophila*	*Cymbella aspera*	*Cymbella silesiaca*	*Delphineis cf. karstenii*	*Delphineis cf. surirella*	*Delphineis margaritalimbata*	*Denticula subtilis*	*Dimeregramma minor*	*Diploneis didyma*	*Diploneis finnica*	*Diploneis interrupta*	*Diploneis oblongella*	*Diploneis pseudovalis*	*Diploneis smithii v. rhombica*	*Endictya hendeyi*	*Epithemia turgida*
	0.20	N2-1			1		14					1				14									3					2	2	18		1	1	2		2	12	2		7	7
	0.45	N2-10					9	2			2					18	3								17	2	11		1						3			36					7
	0.65	N2-30		2	1		9	7			1					14	19		19	6		2			1				5		11	1			2	1		7			1	16	19
	0.75	N2-40					3				4					10	5		5	2		1			8	2			1			9			4							15	5
	0.80	N2-45			13		8	2			4			1		14	11		10	10		2			12				2			11			6	3		3			1	12	10
	0.87	N2-52		1	37	4			2		6			3		1			1	32		1	3								4	7	1		4			1				2	1
	0.89	N2-54			40	3	4		2	4	10					3				31		3	3		2	7		2			2	15								1		7	5
Top of soil Y	0.90	N2-55			1	1	1															2				60	2				7	2			1			3				3	
	0.95	N2-60					2									5				1		2			2	49	1		2		24	1			1	3		4				9	1
	0.98	930712 B2-1					1.5						0.5			1						1	0.5	1	2	16	18				2	2.5	1		2	5		2		1		12	1
	1.08	930712 B2-10			1		2			1												2			1	25	6			1	2	6			1		1	30				2	2
	1.11	930712 B3-1					1								1	2										15	3				1							50					
	1.13	930712 B2-15																				2				16	14		2		2	2	2		2			62				2	4
	1.16	930712 B2-18		6			8									14	2			2		2	8	2	18		14		4		30	6			14			6				8	8
	1.18	930712 B3-8		4												2	2								2	2								2	26			10				2	2
	1.19	930712 B2-21		10			3	2								24	1					3	1		1		4		1						23			6				2	
Top of soil W	1.20	930712 B2-22														2										6	2								2			87				2	
	1.20	930712 B3-10		2											2	5						1			1	1	2				2							76					
	1.22	930712 B3-12																				2			2	2												90					
	1.23	930712 B2-25						1						1		2																						93					
	1.27	930712 B3-18					1							1		34							5	2	4						31	2			2			9			1	4	2
	1.28	930712 B2-29		1			8									23							3	1							4				2			2				6	1
	1.36	930712 B3-26														6		2				2	4		2						14	2			2			2				2	
	1.42	930712 B3-32					2					2				4				2			2	2	2	8					26	12			6						2	8	2
Top of soil U	1.44	930712 B3-34					2									4						4				14	14					2			2			26					
	2.21	930712 B1-1			27	5														4	16	5		2							3	3	1		2							2	
	2.27	930712 B1-7			19	15														4	11	2	1	1	2								2										
	2.32	930712 B1-12			14					3						4		2	1	4	6		4	1							3	5										4	1
	2.37	930712 B1-17			29		1	13			8	2		1		1				10	5	1	1								8	7	1					1					
Top of soil S	2.40	930712 B1-20													15	1							1			22	17				1							12		4			
	2.48	930712 B1-28		1	1			1							2	3		1				1				19	10				5	1						50		1		1	

TABLE 4 (cont.). Numbers of diatoms counted at the Oyster locality (horizontal coordinates 15 m and 25 m)

	Depth below modern surface (m)	*Eunotia spp.*	*Fallacia cryptolyra*	*Fallacia pygmaea*	*Fragilaria pinnata*	*Fragilaria spp.*	*Frustulia spicula*	*Frustulia vulgaris*	*Gomphonema angustum*	*Gomphonema parvulum*	*Gomphonema spp.*	*Grammatophora oceanica*	*Gyrosigma acuminata*	*Gyrosigma balticum*	*Gyrosigma eximium*	*Hantzschia amphioxys*	*Hyalodiscus laevis*	*Luticola mutica*	*Lyrella lyra*	*Mastogloia exiguua*	*Melosira moniliformis*	*Melosira nummuloides*	*Navicula cancellata*	*Navicula cincta*	*Navicula cryptotenella*	*Navicula digitoradiata*	*Navicula lanceolata*	*Navicula spp.*	*Navicula viridula*	*Nitzschia bilobata*	*Nitzschia communtata*	*Nitzschia fasciculata*	*Nitzschia pusilla*	*Nitzschia scapelliformis*	*Nitzschia sigma*	*Nitzschia socialis*	*Nitzschia spp.*	*Nitzschia terrestris*	*Odontella aurita*	*Odontella obnuta*	*Opephora cf. parva*	*Paralia sulcata*	*Paralia sulcata (small form)*	*Petroneis granulata*	*Petroneis granulata*	*Pinnularia borealis*
	0.20											3	1				2		1	1	2	3						4			13	20		1								94	44	2		
	0.45																6		2		12																					75	30			
	0.65		2											1			4																									275	107			
	0.75		3		2						1			7			1		1		1														1							214	125	1		
	0.80		4					1						2			1	1	1				3												1							165	65	6		1
	0.87		36								2			2				4		4	7		3		1										4						14	91	57			
	0.89		21		1							4		2					2	4	6			1		4		2										2			8	107	35			
Top of soil Y	0.90								1			1				1		22	3			1				1		1							1			7				32	38			
	0.95		1		1											4	2	3	1		3			2				2										4				329	315			
	0.98			1		1				1								16			1			1								2						5	2	2		51	384	1		
	1.08			2					1									10																				1	3			34	121		1	
	1.11																	4	1					1																		13	16	1		
	1.13				2					2																																28	65		4	
	1.16				2							6														4						1			1	2						59	114		2	
	1.18	2																4								2										15			2			192	372	4	2	
	1.19				2		1												4							10									2	6						88	190			
Top of soil W	1.20																																									10	28			
	1.20				1														2											3						2						38	70			
	1.22																	4																								32	52			
	1.23																																									9	22			
	1.27				1							5														3				1					0.5	3.5		0.5			1	68	75			1
	1.28																		1							18										11			3	1		22	38	1		
	1.36				2									4												8								10	2	2			2			74	150	2		
	1.42																	2								2				4				2	18	3			4			140	316		2	
Top of soil U	1.44																	12						2						2				2	3			2	2			90	228			
	2.21		1											5	1								2			1		7						0.5	3	1.5	1		10		2	21	38			
	2.27		1									1		10				3		2		12				2		10					1	1	7				3			9	15			
	2.32												1	3						12	5	2						19				1			4.5	0.5	2		3		6	14	31			
	2.37		6										6	4	1				1	3			3			6		20						4	1.5	0.5	10					12	41			
Top of soil S	2.40														1			7									1			2		3			6.5							10	23			
	2.48																	2								1								1	2.5				2	1		16	60			

TABLE 4 (cont.). Numbers of diatoms counted at the Oyster locality (horizontal coordinates 15 m and 25 m)

	Depth below modern surface (m)	*Pinnularia lagerstedtii*	*Pinnularia spp.*	*Rhabdonema arcuatum*	*Rhaphoneis amphiceros*	*Rhaphoneis psammicola*	*Rhoicosphenia abbreviata*	*Rhopalodia gibba*	*Rhopalodia operculata*	*Rhopolodia musculus*	*Scoliopleura tumida*	*Stephanopyxis dimorpha*	*Surirella fatuosa*	*Synedra fasciculata*	*Trachyneis aspera*	*Trachysphenia australis*	*Tropidoneis spp.*	*Tryblionella acuminata*	*Tryblionella aerophila*	*Tryblionella apiculata*	*Tryblionella debilis*	*Tryblionella granulata*	*Tryblionella levidensis*	*Tryblionella littoralis*	*Tryblionella navicularis*	*Tryblionella plana*	*Tryblionella punctata*	*Tryblionella vexans*		**Planktonic diatoms**	*Actinocyclus curvatulus*	*Actinocyclus ochotensis*	*Actinocyclus kutzingii*	*Aulacoseira spp.*	*Chaetoceros spp.*	*Cyclotella sp.1*	*Cyclotella spp.*	*Stephanodiscus spp.*	*Thalassiosira spp.*	*Thalassionema nitzschioides*	Preservation
	0.20			10	3	2	2		10		8			1	7						2	20			5		2	2				9	2	24				1	2		
	0.45			1	3						8											3			2						1	5		25			2	4			
	0.65	1			4	1			1		37					2		1				14									2	12	2	30			7	3	2		
	0.75		1	1	1						56		1		4			1				11									2	3		14			6	1			
	0.80			4	3	3	2				7			1	2			1				6		1							1	12	1	18			8		8	1	
	0.87				3	7			2	1	2			9						2		6	1								2			9	3		2		14	4	
	0.89	7		1	5	2			2		3			11					2	2		6	1								1	2		6					13	5	
Top of soil Y	0.90	14			1	1					2			2							1	4												10			1		6	1	
	0.95	13				4																20										7	1	93			7	3		1	
	0.98	19				2	1							0.5		0.5		0.5				26	1										1				1	2	1.5	0.5	
	1.08	18				3		2														15											3	2		3	2		2		
	1.11	22															1					2																	1		
	1.13					2						2										38															2	4	6		
	1.16		2	8	6	2					4			12	2							52			4						2		4				6		10	1	
	1.18				2	4					4			13		4						10													2						
	1.19		2	1	5	4					3			3	1	1		1				7											1				4	1	2		
Top of soil W	1.20													1								5															1				
	1.20									1	1	1		2	1			2				4																			
	1.22	2														2						6																	2		
	1.23	4												0.5								1																			
	1.27	2				1					9			9.5	6	1	4	1				36	1		7												4	1	2		
	1.28		1	1	1						15			8.5	9		13					5	1		0.5								1				1				
	1.36				6		2			8	4			28	4			4				16												2			34		6		
	1.42		2		2						4			21	2		2			2		16			2		2				2								2	5	
Top of soil U	1.44	10			2									1	2							22															8		2		
	2.21				3	2				1				9						5						1	1								1		1		21	3	
	2.27				4		1			2	1			7						4		8	2				1	1											26	3	
	2.32	2			4				3	1			1	9	1					5		10					2										1		34	2	
	2.37									1	1			11						2		5																	42	2	
Top of soil S	2.40				1					2				0.5				1			4	3															2		2		
	2.48				2					1				0.5	1							3															2				

TABLE 4 (cont.). Numbers of diatoms counted at the Oyster locality (horizontal coordinates 15 m and 25 m)

	Depth below modern surface (m)	Preservation	Total diatom valves counted	Total high marsh diatoms (1)	Total low/high marsh diatoms (1)	Total low marsh diatoms (1)	Total tidal flat diatoms (1)	Total diatoms used for index (BIDI)	BIDI value
	0.20	M	415	3	37	31	29	100	0.56
	0.45	M	295	13		64	23	100	0.45
	0.65	M	667	2		59	39	100	0.32
	0.75	M	542	2		66	32	100	0.35
	0.80	M	476	3	2	25	70	100	0.18
	0.87	M	423		5	10	155	170	0.06
	0.89	M	428	18	2	14	132	166	0.16
Top of soil Y	0.90	M	239	83	23	6	12	124	0.88
	0.95	M	936	72	5	9	14	100	0.82
	0.98	P	595	63	21	3	12.5	100	0.86
	1.08	M	306	50	10	30	10	100	0.75
	1.11	M-G	135	40	5	53	2	100	0.72
	1.13	M	265	30		62	8	100	0.61
	1.16	M	458	14	1	28	57	100	0.29
	1.18	M	688	4	4	16	76	100	0.16
	1.19	M-P	420	4		34	62	100	0.21
Top of soil W	1.20	M-G	146	8		89	3	100	0.53
	1.20	P	220	3	2	86	9	100	0.48
	1.22	P	196	4	4	90	2	100	0.53
	1.23	M-G	134	4		95	0.5	100	0.52
	1.27	P	342	2.5		61	36.5	100	0.33
	1.28	M-G	203			40.5	59.5	100	0.20
	1.36	P	408			30	70	100	0.15
	1.42	P	637	8	2	18	72	100	0.19
Top of soil U	1.44	P	458	40	14	34	12	100	0.71
	2.21	M	212			2.5	97.5	100	0.01
	2.27	M	194	1	3	6	90	100	0.07
	2.32	M	231	2	1	17	80	100	0.12
	2.37	M	272			12	88	100	0.06
Top of soil S	2.40	M	142	39	33	18	10	100	0.81
	2.48	M	192	29	5	55	11	100	0.62

(1) Individual taxa listed in table 5

Key:

G, good preservation

M, moderate preservation

P, poor preservation

TABLE 5. Numbers of diatoms counted at the Oyster locality (horizontal coordinate 165 m)

	Depth below modern surface (m)	Diatom sample ID	**Benthic diatoms**	*Achnanthes brevipes*	*Achnanthes delicatula*	*Achnanthes hauckiana*	*Achnanthes spp.*	*Actinoptychus senarius*	*Amphora coffaeiformis*	*Amphora proteus*	*Amphora spp.*	*Amphora ventricosa*	*Biddulphia sp.*	*Caloneis bacillum*	*Caloneis westii*	*Catenula adhaerens*	*Cerataulus turgidus*	*Cocconeis diminuta*	*Cocconeis pellucida*	*Cocconeis placentula*	*Cocconeis scutellum*	*Cocconeis scutellum v. parva*	*Coscinodiscus spp.*	*Cosmioneis pusilla*	*Cosmioneis pusilla var. 1*	*Craticula halophila*	*Cymbella pusilla*	*Delphineis cf. karstenii*	*Delphineis cf. surirella*	*Delphineis margaritalimbata*	*Denticula subtilis*	*Dimeregramma minor*	*Diploneis didyma*	*Diploneis interrupta*	*Diploneis oblongella*	*Diploneis smithii v. rhombica*	*Endictya hendeyi*	*Epithemia turgida*	*Eunotia spp.*	*Fallacia cryptolyra*	*Fallacia forcipata*	*Fallacia pygmaea*	*Fragilaria spp.*	*Frustulia spicula*	*Frustulia vulgaris*
	0.15	950521-6												12	3						4								1															5	
	0.60	950521-5		1							2	1			15														10						1										
	0.80	950521-4		2	1							1	1	2	6						1	1		1					42	1	1														
	0.95	950521-3		1	2					1		1			1			10	3	1		2				1			37													1			1
	1.09	950521-2		2	18					2				2		2		22	4		3	1							12								2								
Top of soil Y	1.11	950521-1						3						1	2		1	1		2			1	43	5			11				2	1	10	2		1								
	1.39	940713 Bx7-1		2	1	1								4	2			2		1				13	3			1						25	1	3	1								
	1.43	940713 Bx7-5		8				2								2			2		4			48								6		2	2										
	1.48	940713 Bx7-10			2										2	4	2	2										6				16					4		2						
Top of soil W	1.51	940713 Bx7-12			2						2			12	1			2						12	1			1				1		27	1		2								
	1.52	940713 Bx7-14				1								9	8	1								13				4						29	4										
	1.54	940713 Bx7-15			1	1				2				5	7	1					1			13				1		2				31	6										1
	1.55	940713 Bx7-17												4	6	2		2						10				6				4		48	10		2								
	1.63	940713 Bx6-1		19	1		2	4	1		1			4	4	1			1			1		2			1	2						9	1		2								
	1.69	940713 Bx6-7		1	3	1		1							4	1			5								2	3	1		2										1				
	1.76	940713 Bx6-14			21				1						1	1		2	12							2		5	3	2	4				1						2	1	2		
	1.81	940713 Bx5-1			12	4					2								7							4	61	9	2		4										1				
	1.83	940713 Bx6-21		1	9	2	20				4	1		1	25				2			2					14	2	2						1										
	1.86	940713 Bx4-1		5	25	8	3			1	9	6						1	12		1	4				5		2		5								4			5				
	1.92	940713 Bx4-7			22	5		1			2					1		3	19		2	7				1		4	1												2				
	1.99	940713 Bx4-14		2	25	6	1				2	2							17	1		4		1		4		1	1	5		1									2				
Top of soil U	2.01	940713 Bx4-16			2									8					2					13				1							2							4		2	4
	2.07	940713 Bx4-22		1	6		12							7	3			1				1		3		1								8	4			2				3			
	2.55	940713 Bx1-1		4	12	2					2				2			4	20	2						14		4		4											4				
	2.61	940713 Bx1-7			16	4					4	4							14							14		4	2	4															
	2.69	940713 Bx1-15			22	17						1			2			1	17	3						7		4	9			4								3	2				
	2.78	940713 Bx1-24		2	23	13				2	1	2			1			1	8		1		1			14		2	6	1	2	1								5					
Top of soil S	2.80	940713 Bx1-26				6								5	1			1	5					14				3		1				8	2						1	4		4	

TABLE 5 (cont.). Numbers of diatoms counted at the Oyster locality (horizontal coordinate 165 m)

	Depth below modern surface (m)	*Gomphonema parvulum*	*Gomphonema spp.*	*Grammatophora oceanica*	*Gyrosigma acuminata*	*Gyrosigma balticum*	*Gyrosigma eximium*	*Luticola mutica*	*Mastogloia exiguua*	*Mastogloia smithii*	*Melosira moniliformis*	*Melosira nummuloides*	*Navicula cancellata*	*Navicula cari*	*Navicula cf. digitoradiata*	*Navicula cincta*	*Navicula cryptotenella*	*Navicula digitoradiata*	*Navicula gregaria*	*Navicula lanceolata*	*Navicula margalithii*	*Navicula meniscus*	*Navicula normalis*	*Navicula normaloides*	*Navicula radiosa*	*Navicula spp.*	*Navicula tenneloides*	*Navicula veneta*	*Navicula viridula*	*Nitzschia bilobata*	*Nitzschia brevissima*	*Nitzschia communtata*	*Nitzschia fasciculata*	*Nitzschia nana*	*Nitzschia perminuta*	*Nitzschia pusilla*	*Nitzschia scapelliformis*	*Nitzschia sigma*	*Nitzschia socialis*	*Nitzschia spp.*	*Nitzschia terrestris*	*Odontella aurita*	*Odontella obnuta*	*Opephora cf. parva*	*Paralia sulcata*	*Paralia sulcata (small form)*	*Petroneis granulata*
	0.15			3			8	1	2		2		2			3																	6					14							2	20	
	0.60			2		1	39	1	1		1					1	1	2								3				1				4				7.5	3	1					1	14	
	0.80			2	19	5			26		6							15								5											1	11	1			1			9	20	
	0.95			2	8	9	1	1	14			6	1			1		3	1							21											4	4	5					3	7	7	
	1.09				3	1	1		14		3															6											3	1.5	2	2				2	12	15	
Top of soil Y	1.11		1					6												1											2	2					1	2			1				65	213	
	1.39							19								3										2				3								0.5					1		14	12	2
	1.43							6								2																											2		26	10	
	1.48																	12		4						2												5	1					8	108	26	
Top of soil W	1.51					1		6	2								3	3																				2		1				2	46	7	
	1.52							7								1				1		1				3				2								3.5							65	27	
	1.54	1		1			5	3								1		3		3		2								6								1.5							74	17	1
	1.55																								2					2								2						2	78	12	
	1.63					1	7	5													2					4		1		5							1	7.5		2		3		1	72	5	
	1.69					3		3	1								28	10		1			1		1	3								1				10.5						6	15	3	
	1.76				1	4		2	6			6					9				5	1	1			8		2						2	1		1	3	0.5	1				17	9	1	
	1.81						1		16							2		14						1		13		2									2.5	5	1	2				27	13	1	
	1.83				2	4			6								2	4					1			18											5	5	1			1		8	13		
	1.86				1	3			3	1			1					4						5		21													5.5					11	20	1	
	1.92				2				1						81			12					8	2		12											1	1	0.5			1		19	26		
	1.99							5	4		1	5											2			3							1	5	1	1	1	1.5						17	21	5	
Top of soil U	2.01						14	17								2										5								9	9			1		8				1	8	2	
	2.07						9	6										10	4		10					11		1	4	1				1	4			10		1				10	14	1	
	2.55						8	2				2				2	2	2					4			24				2					2			1	4			2		12	68	20	
	2.61				4	2							4				8	8							2	18				2								2						22	18	2	
	2.69							1	1		2		2			1	4	4					2			8												1.5	1					25	18	5	
	2.78				4	9			1				1				1	7					2			24									5				1					16	5	5	
Top of soil S	2.80				1		0.5	15	1					2		1	11	1	3		1	1				6		6		1					10			3.5		4		1		1	4	6	

TABLE 5 (cont.). Numbers of diatoms counted at the Oyster locality (horizontal coordinate 165 m)

	Depth below modern surface (m)	*Pinnularia borealis*	*Pinnularia lagerstedtii*	*Pinnularia spp.*	*Plagiogramma staurophorum*	*Rhaphoneis amphiceros*	*Rhaphoneis psammicola*	*Rhoicosphenia abbreviata*	*Rhopalodia operculata*	*Rhopolodia musculus*	*Scoliopleura tumida*	*Stauroneis producta*	*Stephanopyxis dimorpha*	*Surirella fatuosa*	*Surirella ovata*	*Synedra fasciculata*	*Trachyneis aspera*	*Trachysphenia australis*	*Tryblionella acuminata*	*Tryblionella apiculata*	*Tryblionella debilis*	*Tryblionella granulata*	*Tryblionella levidensis*	*Tryblionella littoralis*	*Tryblionella navicularis*	*Tryblionella plana*	*Tryblionella punctata*	*Tryblionella vexans*		**Planktonic diatoms**	*Actinocyclus curvatulus*	*Actinocyclus ochotensis*	*Chaetoceros spp.*	*Cyclotella spp.*	*Stephanodiscus spp.*	*Thalassiosira spp.*	*Thalassionema nitzschioides*	Unidentified diatoms	Preservation
	0.15				1	2			1							4.5					2				27	1										4			
	0.60					5			4	7						10				1		2			2											16	2		
	0.80			1		3	3			1	2			1		6				3		5														6			
	0.95					3	6		1	3	2					11			2				1				1						2			18	5		
	1.09					1	5		2	1	1					6.5					1	2				2										8	1		
Top of soil Y	1.11		13			2	3									2		1				14														2	3		
	1.39		17			1										1						2														1	1	2	
	1.43		4			2	8	4								11				2		2			2									2	2	4	5	6	
	1.48				6	8			2		16					12			2			2				4										6	6		
Top of soil W	1.51		20						1							1				1		6						1						2		1	0.5		
	1.52		20			2			1				1			1						4						3									1.5	7	
	1.54		12			2	1									1				1		6												3			0.5	7	
	1.55		8			4			2							6						4										2		4					
	1.63			1		1			1	3	1				1	6	1		2	21	1	5		3	4			5				1				1	0.5	1	
	1.69								3	1	2					3.5	4			8	2	1		2	1										1	7	2.5	1	
	1.76					2			7			1				1.5				3	2	2						1								3	1	2	
	1.81		1						11							4			2			1						1								5		12	
	1.83								4		4					1.5	6			4		4					2	4								4		16	
	1.86						3				1					9.5			2			7				5	1					1	3			21	2.5	11	
	1.92					1			2		2					6.5															1	1	1	1		31	4	4	
	1.99		7			2										5.5					1	1										1			1	45	1	5	
Top of soil U	2.01	1	23	1						4											16							2					2			2	0.5	8	
	2.07		3							5	1										7						1	8								2		5	
	2.55	4				4	2	2								9			2		2						4									38	7	14	
	2.61										6											4					8							2		22	4	10	
	2.69					1										3.5				1		2				2								1		4	2.5	10	
	2.78				1	1					2					6			3			6					2							1		24	2.5	3	
Top of soil S	2.80		11							1						0.5				1	7							4						1		3	1.5	14	

TABLE 5 (cont.). Numbers of diatoms counted at the Oyster locality (horizontal coordinate 165 m)

	Depth below modern surface (m)	Preservation	Total diatom valves counted	Total high marsh diatoms (1)	Total low/high marsh diatoms (1)	Total low marsh diatoms (1)	Total tidal flat diatoms (1)	Total diatoms used for index (BIDI)	BIDI value
	0.15	G	131		12	57	30.5	100	0.41
	0.60	G	163		2	66	31.5	100	0.35
	0.80	G	212	2		38	65	105	0.20
	0.95	M	215		3	25	82	110	0.14
	1.09	M	166		1	22	77	100	0.12
Top of soil Y	1.11	P	420	65	8	14	13	100	0.80
	1.39	M	142	33	22	37	7.5	100	0.74
	1.43	P-M	176	52	8	4	37	101	0.61
	1.48	P	270			18	82	100	0.09
Top of soil W	1.51	P-M	171	33	6	45	16	100	0.62
	1.52	P-M	220	33	8	48	10.5	100	0.65
	1.54	P	224	25	5	54	15.5	100	0.57
	1.55	P	222	18		60	22	100	0.48
	1.63	P	232	2	6	38	53.5	100	0.27
	1.69	P	151	2	5	37	56	100	0.26
	1.76	P	166	4	4	17	75	100	0.17
	1.81	M	244	5	2	19.5	73	100	0.17
	1.83	P	206			43	56.5	100	0.22
	1.86	P-M	240			4	96	100	0.02
	1.92	P-M	291			4	96	100	0.02
	1.99	G	218	9	7	5	81	102	0.18
Top of soil U	2.01	G	174	36	39	28	8	111	0.80
	2.07	G	181	6	13	34	47	100	0.36
	2.55	P	319		6	14	80	100	0.13
	2.61	P	214			16	84	100	0.08
	2.69	P	195		2	7	91	100	0.06
	2.78	P	219	2		5	94	101	0.04
Top of soil S	2.80	P	179	25	23	32.5	19	100	0.65

(1) Individual taxa listed in table 5

Key:

G	Good preservation
M	Moderate preservation
P	Poor preservation

Table 6. Radiocarbon ages for samples from the Oyster, Redtail, Pool, Jensen, and Sewer localities, northeastern Willapa Bay

Age and quoted error[1]		Material	Soil	Stratigraphic setting[2]	Locality[3]	River[4]	Lab number[5]		Field number
90	60	Outer part of bark-bearing root 10 cm in diameter without conspicuous rings; probably western crabapple	Y	10 cm below top of soil; root attached to bark-bearing trunk about 15 cm in diameter that extends into silt above soil	Sewer	Wil	Beta	76289	J13A
120	41	Leaf base of *Potentilla pacifica*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17927	ARN91-37
135	42	Leaf base of *Potentilla pacifica*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17852	ARN91-36
139	40	Leaf base of *Potentilla pacifica*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17946	ARN91-40
155	47	Leaf base of *Potentilla pacifica*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17846	ARN91-34
156	43	Leaf base of *Potentilla pacifica*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17838	ARN91-32
162	49	Culm base of *Juncus balticus*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17828	ARN91-31
174	43	Leaf base of *Potentilla pacifica*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17942	ARN91-39
230	70	Spruce root 1.0-1.5 cm diameter	Y	Uppermost 1 cm of soil; from same tree as Beta-19840?	Redtail	Nia	Beta	19839	SL86-106O
250	60	Spruce root 1.0-1.5 cm diameter	Y	Uppermost 1 cm of soil; from same tree as Beta-19839?	Redtail	Nia	Beta	19840	SL86-106P
250	60	Charcoal	Y	Fire pit that extends to top of soil	Redtail	Nia	Beta	63220	F14B
272	47	Culm base of *Juncus balticus*	Y	Rooted in soil and entombed in overlying tsunami deposit	Oyster	Nia	GX	17933	ARN91-38
360	70	Spruce root 3.5 cm diameter, containing about 15 rings	Y	Top of root 1 cm below top of soil	Redtail	Nia	Beta	22368	A1F

Table 6, *continued*

Age and quoted error[1]		Material	Soil	Stratigraphic setting[2]	Locality[3]	River[4]	Lab number[5]	Field number
380	50	Stave. Dated portion—consisting of branched, bark-covered stick—was 4 cm in maximum diameter and contained about 15 annual rings	--	Weir on mudflat	Sewer	Wil	Beta 74541	J4A
601	55	Bark-free twig	--	Probable tsunami deposit in channel fill	Oyster	Nia	GX 20307-AMS	J10A2
630	90	Charcoal	Y	Fire pit 10-20 cm below top of soil	Redtail	Nia	Beta 49195	A1
710	70	Stake 5 cm in diameter; lower end charred, hard, and sharp	--	Vertical in mud to depth of 1.0 m below top of soil Y; charred end down	Sewer	Wil	Beta 76290	J14A
720	70	Bark-free twigs	--	Probable tsunami deposit in channel fill	Oyster	Nia	Beta 76685	J10A1
		Salicornia virginia stems and attached roots	U	Stems in mud 0-3 cm above top of soil; roots in peaty mud 0-2 cm below top of soil	Oyster	Nia	QL 4795	J9C
		Triglochin maritima rhizomes	U	In mud about 20 cm above top of soil	Oyster	Nia	QL 4798	J9D
		Triglochin maritima rhizomes; split into more or less identical sample for Beta-76633	S	In mud 45-55 cm above top of soil	Oyster	Nia	QL 4797	J9B
		Thuja plicata (western redcedar) root; rings number 60-69, where ring number 1 adjoins bark	S	One of a forked pair of redcedar roots high in soil	Pool	Nia	QL 4796	J12A
1630	70	*Triglochin maritima* rhizomes; split into more or less identical sample for QL-4797	S	In mud 45--55 cm above top of soil	Oyster	Nia	Beta 76633	J9B1
1720	40	Root or stick 3 cm diameter; split into more or less identical sample for Beta-19837	S	Top of soil	Redtail	Nia	USGS 2540	SL86-106K2
1740	70	Root or stick 2 cm diameter	S	Top of soil	Redtail	Nia	Beta 19838	SL86-106L
1800	70	Root or stick 3 cm diameter; split into more or less identical sample for USGS-2540	S		Redtail	Nia	Beta 19837	SL86-106K1
1830	40	Root or stick	S	Uppermost 1 cm of soil	Redtail	Nia	USGS 2541	SL86-106M
1990	70	*Triglochin maritima* rhizomes	S	Mud 20-30 cm above top of soil	Sewer	Wil	Beta 76291	J18A
2258	75	Rotten stick 0.5-1.0 cm diameter	N	Uppermost 0.5 cm of soil	Redtail	Nia	RIDDL 686	SL86-106I
2475	23	Spruce cones	N	Resting on top of soil; probably part of forest-	Redtail	Nia	QL 4715	F19A1

Table 6, *continued*

Age and quoted error[1]		Material	Soil	Stratigraphic setting[2]	Locality[3]	River[4]	Lab number[5]		Field number
				edge litter at time of subsidence					
2510	80	Stick	N	Mud 1-2 cm above top of soil	Redtail	Nia	Beta	22371	A-1N2
2530	100	Sticks and spruce cones	N	Uppermost 1 cm of soil	Redtail	Nia	Beta	21826	A-2A+B
2590	80	Sticks	N	Top of soil	Redtail	Nia	Beta	19836	SL86-106H
2590	60	Stick	N	Mud 1-2 cm above top of soil	Redtail	Nia	Beta	22370	A-1N1
2780	45	Peat	N	Uppermost 1 cm of soil	Redtail	Nia	USGS	2539	SL86-106J
2790	120	Peat	L	Uppermost 1-2 cm of soil	Redtail	Nia	Beta	21824	A-1D
2820	50	Spruce root, outer 25 rings	L	Part of a large root system in soil (Figure 13B)	Jensen	Wil	Beta	81551	J8A
2840	70	Root	L	In soil	Redtail	Nia	Beta	19835	SL86-106G
2945	30	Peat	L	Uppermost 1 cm of soil	Redtail	Nia	USGS	2538	SL86-106E
3063	80	Bark-free twig 0.2 cm diameter	J	Top of soil	Redtail	Nia	RIDDL	684	SL86-106B
3165	17	Spruce cones	J	Resting on top of soil; probably part of forest-edge litter at time of subsidence	Redtail	Nia	QL	4718	F16A1
3166	18	Twigs	J	Identical to QL-4718	Redtail	Nia	QL	4717	F16A2
3180	30	Stick	J	Identical to QL-4718	Redtail	Nia	QL	4716	F16C
3190	110	Root	L	In soil	Redtail	Nia	Beta	19834	SL86-106F
3230	60	Stick	J	Top of soil	Redtail	Nia	Beta	21822	A-1B
3262	80	Bark-free twig 0.5 cm diameter	J	Uppermost 0.5 cm of soil	Redtail	Nia	RIDDL	685	SL86-106C
3320	80	Rhizomes	J	Mud 20-40 cm above top of soil	Redtail	Nia	Beta	21823	A-1C
3570	70	Rhizomes	H	Mud 20-30 cm below top of soil J and about 30 cm above top of soil H	Redtail	Nia	Beta	21825	A-1E
3640	80	Bark-free stick	H	In upper few centimeters of soil and in lower few centimeters of overlying mud	Jensen	Wil	Beta	76288	J8E1
3730	210	Peat	J	Uppermost 1-2 cm of soil	Redtail	Nia	USGS	2537	SL86-106A

---

[1] Ages in radiocarbon years before A.D. 1950 (yr B.P.). Ages from laboratories GX, QL, and RIDDL calculated with measured $\delta^{13}C$; other ages calculated with assumed $\delta^{13}C$ of -25 parts per thousand. Quoted errors do not necessarily equal one standard deviation of age measurement

Table 6, *continued*

---

[2] Plate 1

[3] Fig. 3

[4] Nia, Niawiakum; Wil, Willapa

[5] Beta, Beta Analytic, Inc., Coral Gables, Florida. GX, target prepared by Geochron Laboratories, Cambridge, Massachusetts; age measured by accelerator mass spectrometry in Lower Hutt, New Zealand. QL, Quaternary Isotope Lab, University of Washington, Seattle, Washington. RIDDL, Radioisotope Direct Detection Laboratory, McMaster University, Hamilton, Ontario.

Table 7. Radiocarbon ages on herbaceous fossils rooted in two successive buried soils along the Naselle River, southeastern Willapa Bay

[Samples collected by Alan R. Nelson at outcrop described by Ota and Umitsu (1995); this outcrop is equivalent to locality 20 of Atwater (1992, his Table 1). Ages measured by accelerator mass spectrometry (AMS); methods are those of Nelson and others (1995, their Table 1). Weighted mean of ages listed below for soil S is 1797 ± 23 ^{14}C yr B.P., for soil U 1364 ± 21 ^{14}C yr B.P.; The mean for soil S is suspect because the constituent ages are significantly different at the 95-percent level; in the chi-squared test of Ward and Wilson (1978) their test statistic of 14.33 exceeds χ^2 of 9.49. A additional AMS age of 1287 ± 49 ^{14}C yr B.P. (GX-16139) was measured on a stick immediately above soil U at this outcrop. Ota and Umitsu (1995) mistakenly applied this age to a faint overlying soil that may correlate with our soil W.]

Soil[1]	Species of herbaceous plant	Height of stem or leaf, in millimeters[2]	Age and quoted error, in radiocarbon years before A.D. 1950	Laboratory number (GX-)
U	*Potentilla pacifica*	20	1290 ± 50	19631
U	*Potentilla pacifica*	5	1300 ± 50	19635
U	*Juncus balticus*	3	1360 ± 50	19638
U	*Potentilla pacifica*	20	1360 ± 60	19644
U	*Juncus balticus*	3	1420 ± 50	19627
U	*Potentilla pacifica*	10	1450 ± 50	19641
S	*Potentilla pacifica*	0.5	1680 ± 40	19636
S	*Potentilla pacifica*	1	1780 ± 50	19632
S	*Juncus balticus*	1	1800 ± 50	19628
S	*Potentilla pacifica*	1	1880 ± 50	19642
S	*Potentilla pacifica*	1	1910 ± 50	19639

---

[1] Letter name of probable correlative elsewhere in southern coastal Washington (Figure 8). Our soil U at the sampled outcrop was called soil C by Ota and Umitsu (1995), and our soil S is their soil D.

[2] Height measured from top of buried soil to highest part of stem or leaf in mud above soil

Table 8. Numbers of earthquakes corresponding to seismic moment deduced for 300 and 500 years of plate convergence at the Cascadia subduction zone.

[Assumptions described in text under heading, "Tradeoff between size and frequency"]

Coupling ratio	Seismic moment, in 10^{29} dyne-cm	Corresponding number of M_w 8 earthquakes per average recurrence interval	Corresponding number of M_w 7.5 earthquakes per average recurrence interval
		Average recurrence interval 500 years	
1	2.63	23	132
3/4	1.97	18	99
1/2	1.31	12	66
1/4	0.66	6	33
		Average recurrence interval 300 years	
1	1.56	14	79
3/4	1.18	11	59
1/2	0.79	7	39
1/4	0.39	4	20

FIGURE CAPTIONS

Figure 1. Cascadia subduction zone. Symbols explained at lower left depict plate boundaries, some of the faults active or probably active in the Quaternary, and some of the evidence bearing on occurrence of prehistoric earthquakes. Modified from maps compiled by Atwater and others (1995) and, for the Puget Sound area, by Bucknam and others (1992).

Figure 2. Comparison among average recurrence intervals estimated from geologic evidence for prehistoric earthquakes at the Cascadia subduction zone. In middle graph, narrow lines denote total age range of the inferred earthquakes, and wide lines denote age ranges of latest and earliest of the inferred earthquakes. For details see sections entitled "Previous work" and "Average interval". Sources: Willapa Bay, this report; Cascadia channel, Adams (1990); northern Oregon, Darienzo and Peterson (1995); Coos Bay, Nelson and others (in press a); Humboldt Bay, Clarke and Carver (1992).

Figure 3. Sources of error in using stratigraphic records to estimate recurrence intervals for plate-boundary earthquakes at the Cascadia subduction zone. ***A***, One-for-one correspondence between plate-boundary earthquakes and stratigraphic markers. ***B***, ***C***, Records contaminated by stratigraphic markers for events other than plate-boundary earthquakes. ***D***, Record lacking stratigraphic marker for one of the earthquakes. ***E***, Complete record having large uncertainties in dating. ***F***, Complete record of periodic, characteristic earthquakes. ***G***, Complete record of aperiodic earthquakes for which passage of interseismic time promotes change in vegetation and decomposition of soils; see Figure 15 for inferred examples.

Figure 4. Cenozoic folds in relation to some of the sites having evidence for coseismic subsidence of Quaternary age in southern coastal Washington. Most sites plotted on the map comprise at least one outcrop tens of meters long that widely displays one or more successive buried soils. Many additional sites not plotted, mainly in areas of modern tidal wetlands. Folds in Tertiary rocks and limits of Crescent Formation are from compilation by Walsh and others (1987).

Figure 5. Index maps for northeastern Willapa Bay. ***A***, Geology generalized from Wagner (1967a, 1967b). ***B***, Setting of outcrops surveyed along the Willapa and Niawiakum Rivers.

Figure 6. Vertical zonation of vascular plants in six tidal marshes and swamps at Willapa Bay. Zonation measured at surveyed outcrops and also, along the Niawiakum River, at transects plotted in Figure 5B. Topographic profiles schematic. Datum for each profile is mean lower low water estimated from tabulated tides.

Figure 7. Diagrams showing the benthic intertidal diatom index (BIDI) for modern samples from western Washington. ***A***, Samples from Willapa Bay (localities identified in explanation for Figure 4) and from Puget Sound (chiefly from Lynch Cove; Figure 1). ***B***, ***C***, Variation along leveled transects from high marsh to channel at the Niawiakum River. Transect Nl coincides with the vegetation transect at the Oyster locality (Figure 5B). Transect Nu is located about 0.5 km northwest of the Pool locality, just north of the South Bend - Palix River Road and on the east side of the Niawiakum River.

Figure 8. Inferred correlations among buried Holocene soils at estuaries in southern coastal Washington and at Puget Sound. Individual age ranges calculated from radiocarbon ages in Atwater and others (1991), Atwater (1992), and Table 6 of this report. Vertically ruled bands denote likely age ranges explained in the section entitled, "History of geologically recorded earthquakes". Age range for soil Y at Oyster locality corresponds to weighted mean age of 161 ± 15 ^{14}C yr B.P. (Plate 1).

Figure 9. Redtail locality, Niawiakum River. ***A***, Overview to north, across the Niawiakum River; tributary creek enters at right. Trees in background are rooted on upland, above level of highest tides. Tidal marsh high in intertidal zone (high marsh) forms meadow in foreground and in front of trees. Scale given by people at center, low on far bank of river. June, 1987. ***B***, Closer view of outcrop along Niawiakum River. Soils J and L dip eastward, away from firm substrate of Pleistocene deposits onto which they lap. Buried soil S is prominent because of its peaty surficial horizon, abundant spruce roots, and lack of concealment by modern vegetation. Soil Y is mostly concealed by modern plants. Landward end of soils J and L marked by spruce stumps (st) rooted in them at left. August, 1986. ***C***, Contrast between faint soil U and bold soils S and Y. Shovel at horizontal coordinate 42 m; handle is 0.5 m long. ***D***, Black peaty horizon of soil Y, containing reddish-brown lens (light tone, in right half of photo) of probable fire ash and a mammal bone (white dot at center). Soil U faint, as in *C*. Shovel handle near horizontal coordinate 21 m; stripes on handle are 0.1 m long.

Figure 10. Summary of diatom assemblages at Redtail locality, Niawiakum River. Samples collected from section at horizontal coordinate 18 m (Plate 1).

Figure 11. Oyster locality, Niawiakum River. ***A***, Overview to the southeast (upvalley), showing tidal marsh at left and tidal flat at right. Trees in background are rooted on upland, above level of highest tides. August, 1987. ***B***, Closer, eastward view of surveyed outcrop. Buried soil S, which has apparent dip to the southeast, is interrupted by channel fill (c) centered near horizontal coordinate 60 m (Plate 1). May, 1995. ***C***, Closer view of channel fill shown in *B*. Horizontal layer at man's feet is sandy bed probably correlative with tsunami deposit on soil Y (Plate 1). Difference in lighting makes area of channel fill appear lighter toned than in **B**. Sp, *Spartina foliosa*, an introduced salt-marsh grass, on accretionary bank. July, 1994. ***D***, Buried soils S and Y downstream from channel fill. Rhizomes of *Triglochin maritima* account for resistant layer (r) just above water line. Stakes on top of bank are 10 m apart; middle stake denotes horizontal coordinate 10 m (Plate 1). View across Niawiakum River; upstream to right. ***E***, Tsunami deposit on soil Y at horizontal coordinate 10 m. Deposit contains sandy laminae that appear dark from shadow in recess etched by water. Above 15-cm-long scale at center the upper several laminae turn upward against tuft of *Deschampsia caespitosa*, whose leaves are flopped over to the right, upvalley. Faint soil W, which is noticeable between soils U and Y farther upstream at the Oyster locality (Plate 1), is too faint to show in the photograph. Shovel and centimeter scale are in same position as in *D*.

Figure 12. Summary of diatom assemblages at Redtail locality, Niawiakum River. Samples collected from sections at horizontal coordinates 20 m and 165 m (Plate 1).

Figure 13. Jensen locality, Willapa River. ***A***, Overview from northeast. The most extensive, resistant layer visible in the outcrop is soil S. ***B***, Horizontal bedding from buried soils L, N, and S. Soil L in foreground contains roots of Sitka spruce centered near horizontal coordinate 45 m (Plate 1). View to the east.

Figure 14. Sewer locality, Willapa River. ***A***, ***B***, Faint soil Y and associated cultural deposits. Top of soil Y marked by shovel blade at left in *A* and at right in *B*; mud above soil contains distinct laminae of silt. Modern tidal marsh at top. Darkest deposit in both photographs is carbonaceous mud and sandy mud containing charcoal, cracked rock, and (in *A*) a reddish-brown lens probably made largely of ash from wood fires. These cultural deposits form a bed 25 cm thick in *A*, a lens as much as 15 cm thick in *B*, and the fill of stake holes (sh) in *A*. Roots of a shrub, perhaps western crabapple, protrude from soil Y below left-hand shovel in *B*. Centers of photographs near horizontal coordinates 299 m (*A*) and 228 m (*B*). ***C***, ***D***,

Weirs on tidal flat adjacent to outcrop. View in *C* is to the southeast, upriver; outcrop is vertical bank at left, weirs are lines of stakes at center and right. View in *D* is to the southeast, across river toward South Bend (piers visible at top), along long arm of weir centered near horizontal coordinate 205 m (Plate 1).

Figure 15. Diagrammatic history of land-level change, vegetation, and decomposition inferred from buried soils at Redtail and Oyster localities, Niawiakum River. Diagram displays land-level changes associated only with sedimentation, settlement, and tectonic uplift and subsidence directly related to earthquakes. Diagram ignores changes in sea level and permanent crustal uplift or subsidence. For details see second paragraph under heading, "Recurrence intervals".

Figure 1

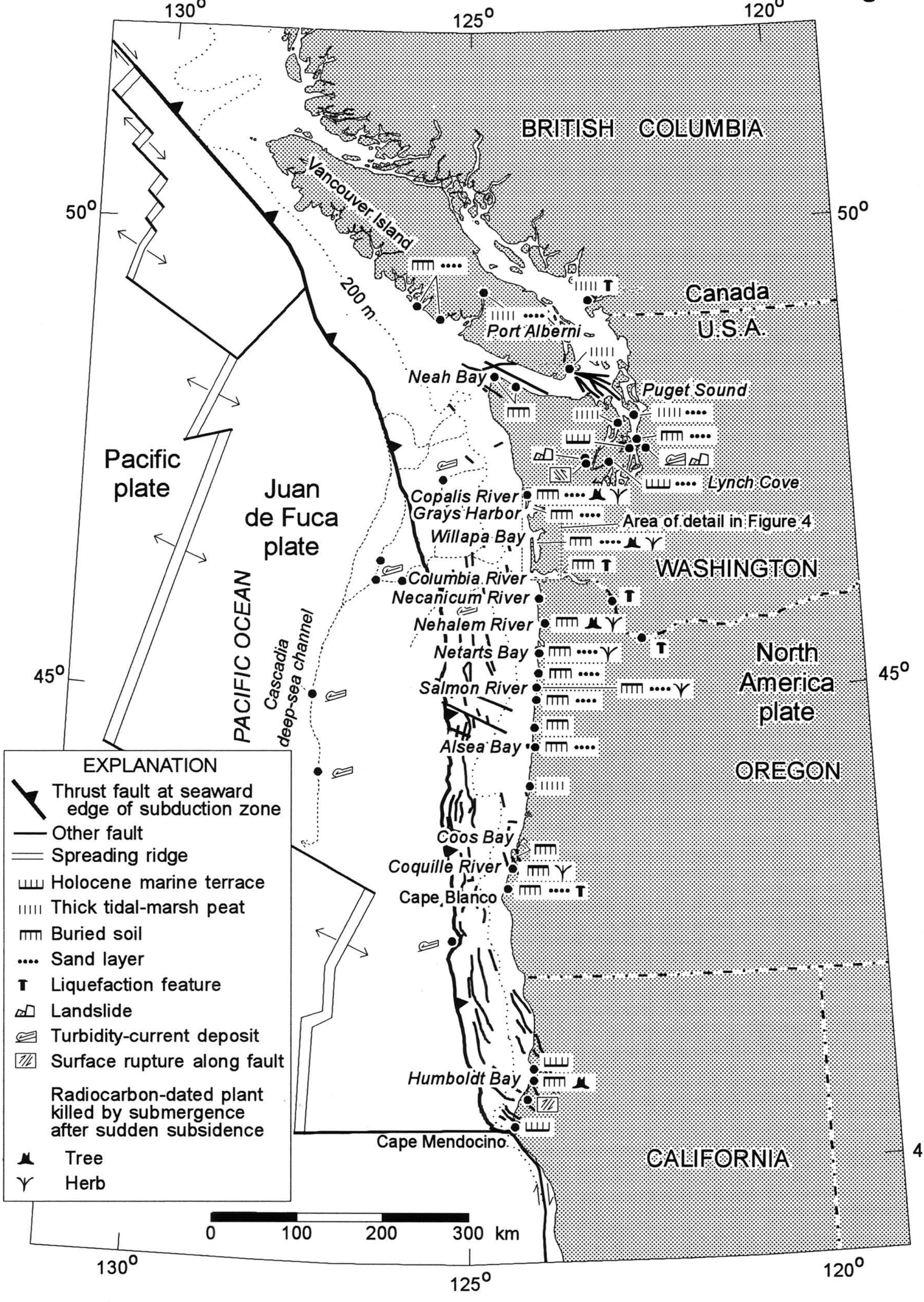
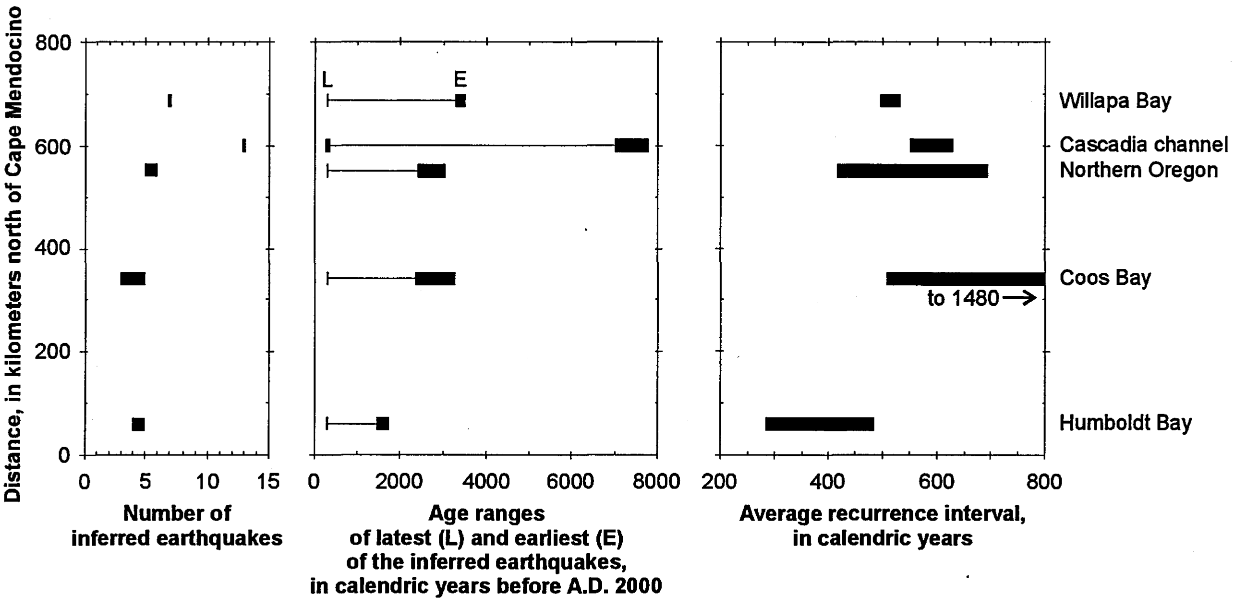
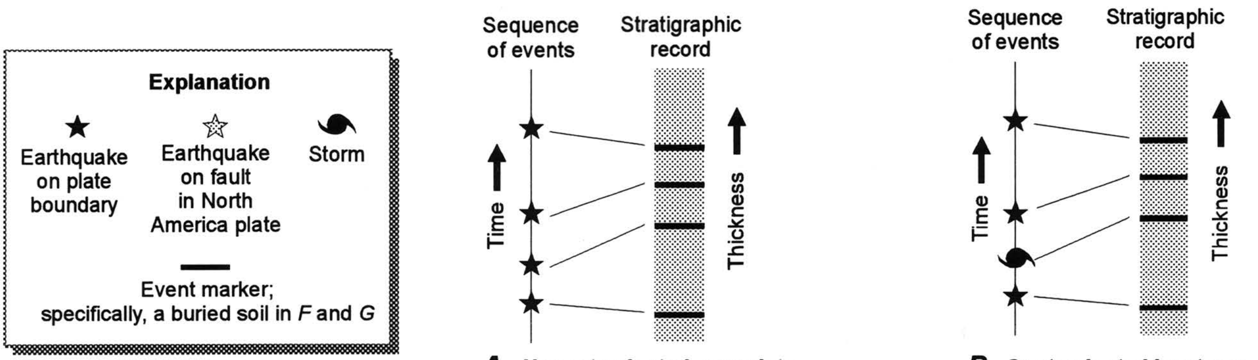

130°
125°
120°
50°
45°
40°
BRITISH COLUMBIA
Vancouver Island
200 m
Canada
U.S.A.
Port Alberni
Neah Bay
Puget Sound
Lynch Cove
Pacific plate
Juan de Fuca plate
Copalis River
Grays Harbor
Willapa Bay
Area of detail in Figure 4
WASHINGTON
Columbia River
Necanicum River
Nehalem River
Netarts Bay
Salmon River
Alsea Bay
PACIFIC OCEAN
Cascadia deep-sea channel
North America plate
OREGON
Coos Bay
Coquille River
Cape Blanco
Humboldt Bay
Cape Mendocino
CALIFORNIA
EXPLANATION
Thrust fault at seaward edge of subduction zone
Other fault
Spreading ridge
Holocene marine terrace
Thick tidal-marsh peat
Buried soil
Sand layer
Liquefaction feature
Landslide
Turbidity-current deposit
Surface rupture along fault
Radiocarbon-dated plant killed by submergence after sudden subsidence
Tree
Herb
0
100
200
300 km

Figure 2



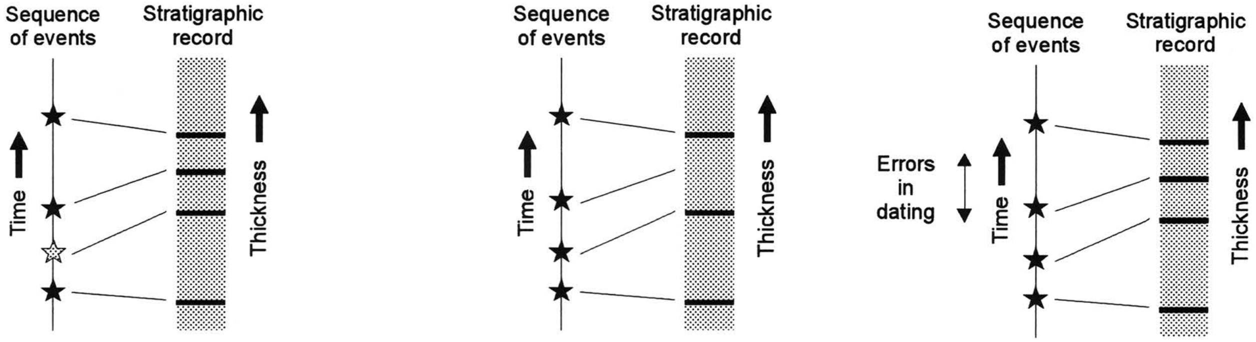
Distance, in kilometers north of Cape Mendocino
800
600
400
200
0
0
5
10
15
Number of inferred earthquakes
L
E
0
2000
4000
6000
8000
Age ranges of latest (L) and earliest (E) of the inferred earthquakes, in calendric years before A.D. 2000
200
400
600
800
Average recurrence interval, in calendric years
to 1480
Willapa Bay
Cascadia channel
Northern Oregon
Coos Bay
Humboldt Bay

Figure 3



A **Uncontaminated, complete**

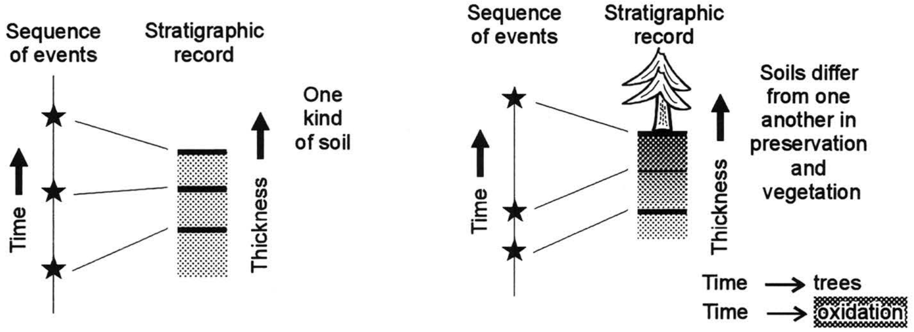
B **Contaminated by storm**



C **Contaminated by intraplate earthquake**

D **Incomplete**

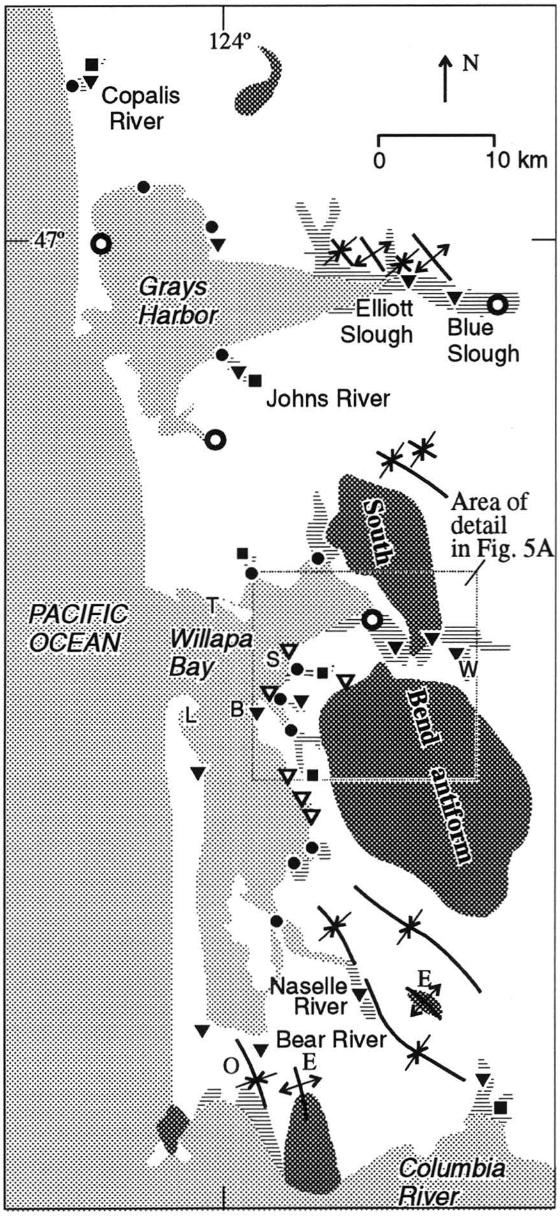
E **Ages poorly known**



F **Periodic**

G **Not periodic**

Figure 4



EXPLANATION

MAP UNITS

▤ **Tidal-wetland deposits** (Holocene)

▩ **Crescent Formation** (Eocene)

FOLDS

Anticline

Syncline

Age of youngest rocks mapped as folded--Miocene unless labelled O (Oligocene) or E (Eocene)

EVIDENCE FOR COSEISMIC SUBSIDENCE

Buried soil or soils in Holocene estuarine deposits

▼ **Dated by radiocarbon methods--**Chiefly from Atwater (1992)

■ **Dated by matching of ring-width patterns--**Western redcedar snags (Yamaguchi and others, 1989)

● **Uppermost soil covered by tsunami deposits--**Reinhart and Bourgeois (1987)

○ **In large outcrops far from buried soils that have been dated or are covered by tsunami deposits--**B.F. Atwater and M.A. Reinhart (unpublished data)

▽ **Buried soil or soils in Pleistocene estuarine deposits--**Table 1

MODERN DIATOM SAMPLE

S **Locality sampled by Hemphill-Haley (1993, 1995, and unpublished data)--**B, Bay Center; L, Leadbetter Point; S, Stony Point; T, Toke Point; W, Willapa River. Additional samples from Querquelin locality and Niawiakum River (Fig. 5)

Figure 5A

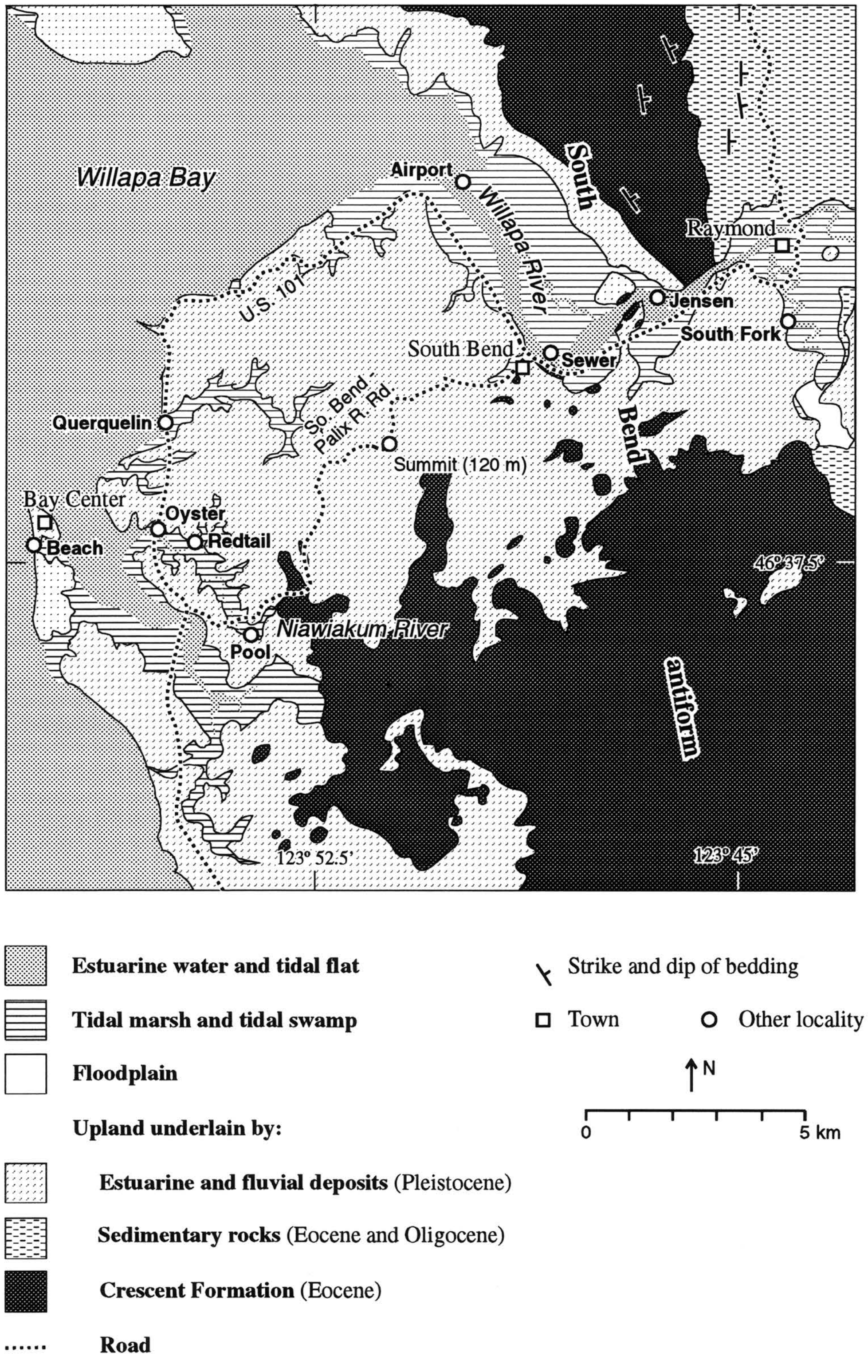

Willapa Bay
Airport
Willapa River
South
Bend
antiform
Raymond
Jensen
South Fork
South Bend
Sewer
U.S. 101
So. Bend - Palix R. Rd.
Querquelin
Summit (120 m)
Bay Center
Oyster
Redtail
Beach
Niawiakum River
Pool
46° 37.5'
123° 52.5'
123° 45'
Estuarine water and tidal flat
Tidal marsh and tidal swamp
Floodplain
Upland underlain by:
Estuarine and fluvial deposits (Pleistocene)
Sedimentary rocks (Eocene and Oligocene)
Crescent Formation (Eocene)
Road
Strike and dip of bedding
Town
Other locality
N
0
5 km

Figure 5B

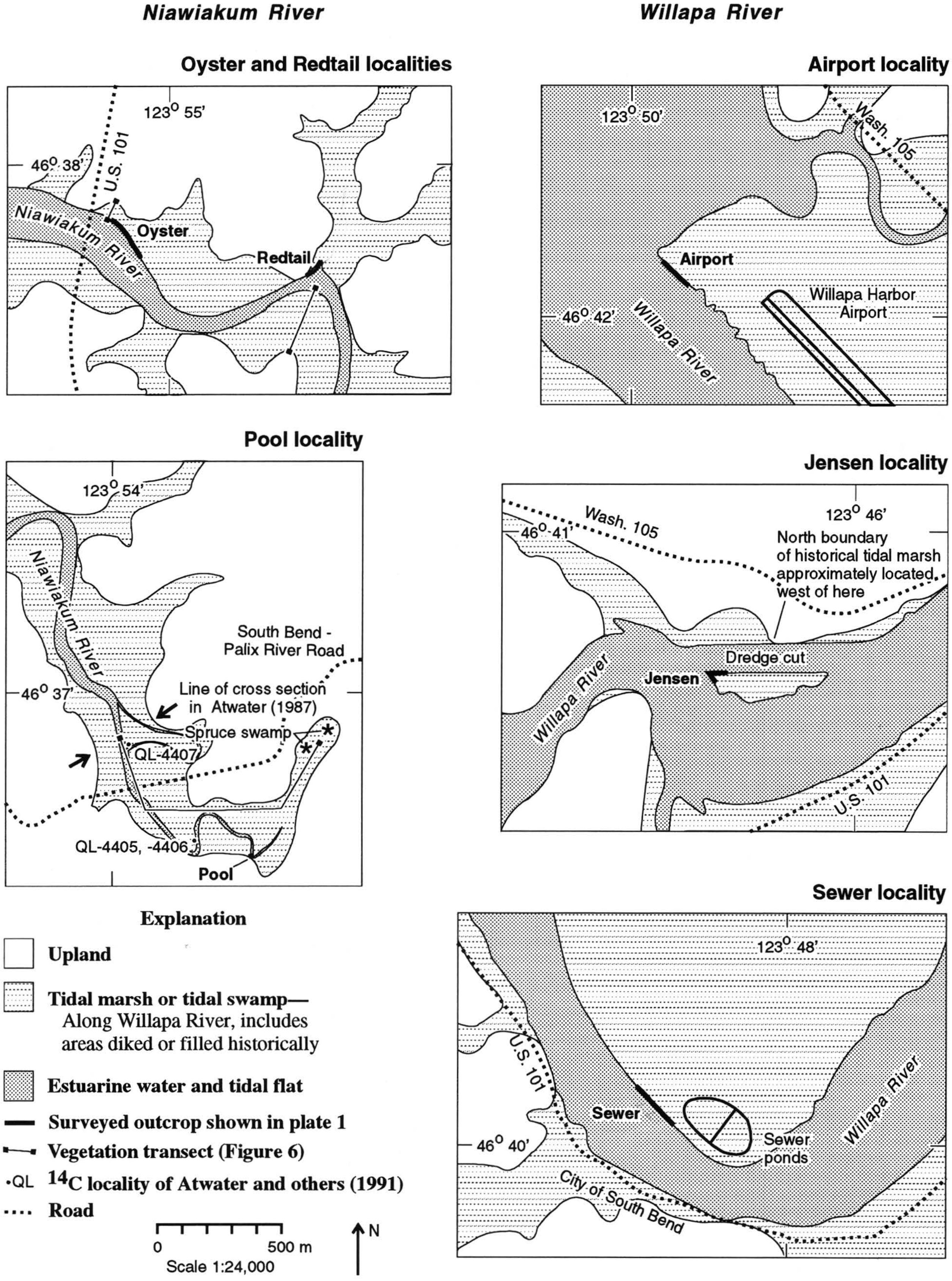

Niawiakum River
Oyster and Redtail localities
123° 55'
46° 38'
U.S. 101
Niawiakum River
Oyster
Redtail
Pool locality
123° 54'
46° 37'
Niawiakum River
South Bend - Palix River Road
Line of cross section in Atwater (1987)
Spruce swamp
QL-4407
QL-4405, -4406
Pool
Willapa River
Airport locality
123° 50'
46° 42'
Wash. 105
Airport
Willapa River
Willapa Harbor Airport
Jensen locality
Wash. 105
123° 46'
46° 41'
North boundary of historical tidal marsh approximately located west of here
Dredge cut
Jensen
Willapa River
U.S. 101
Sewer locality
123° 48'
46° 40'
U.S. 101
Sewer
Sewer ponds
Willapa River
City of South Bend
Explanation
Upland
Tidal marsh or tidal swamp— Along Willapa River, includes areas diked or filled historically
Estuarine water and tidal flat
Surveyed outcrop shown in plate 1
Vegetation transect (Figure 6)
•QL ¹⁴C locality of Atwater and others (1991)
Road
0
500 m
Scale 1:24,000
N

Figure 6

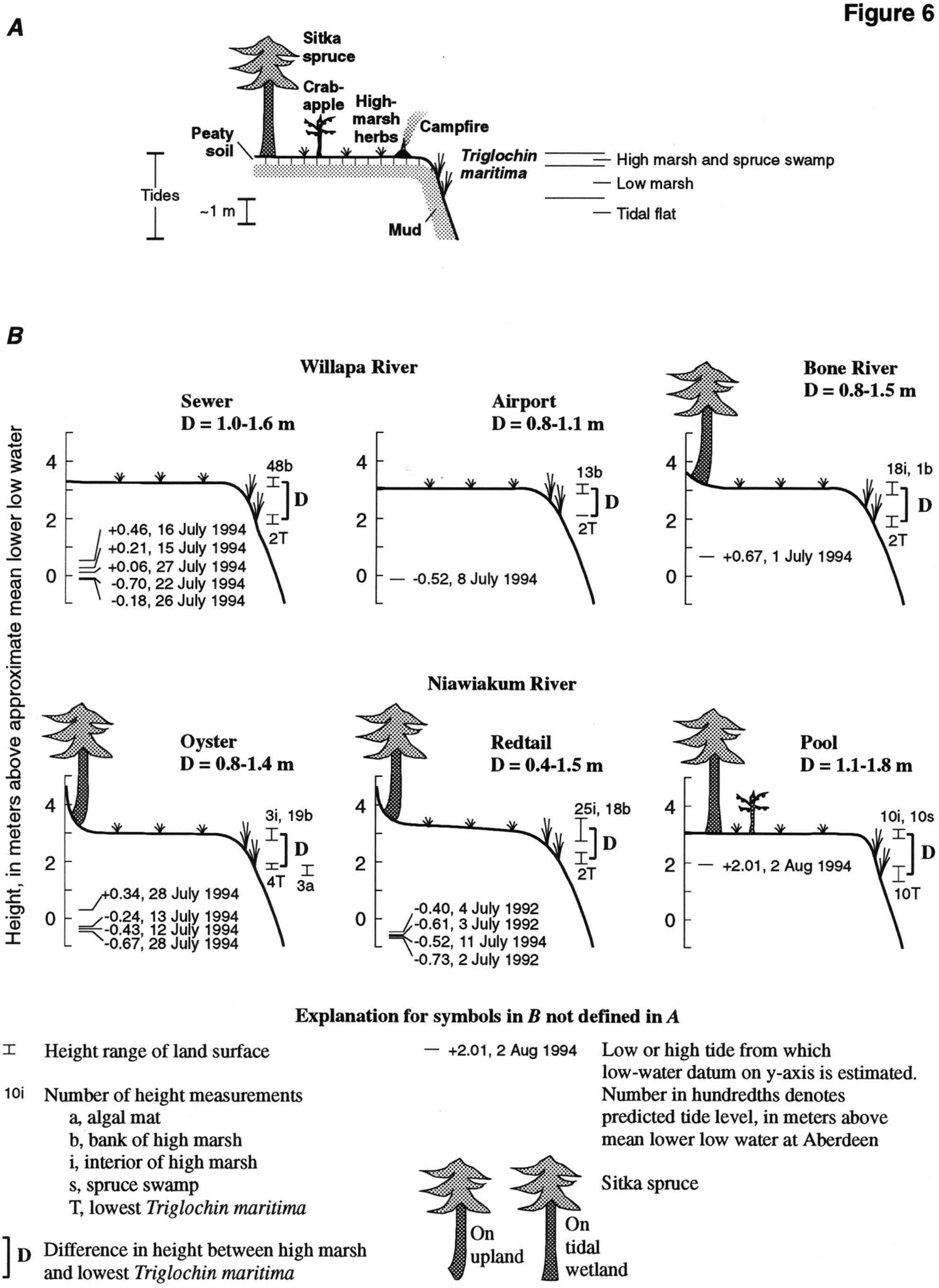

A
Sitka spruce
Crab-apple
High-marsh herbs
Campfire
Peaty soil
Triglochin maritima
High marsh and spruce swamp
Low marsh
Tidal flat
Tides
~1 m
Mud
B
Height, in meters above approximate mean lower low water
Willapa River
Sewer
D = 1.0-1.6 m
48b
D
2T
+0.46, 16 July 1994
+0.21, 15 July 1994
+0.06, 27 July 1994
-0.70, 22 July 1994
-0.18, 26 July 1994
Airport
D = 0.8-1.1 m
13b
D
2T
-0.52, 8 July 1994
Bone River
D = 0.8-1.5 m
18i, 1b
D
2T
+0.67, 1 July 1994
Niawiakum River
Oyster
D = 0.8-1.4 m
3i, 19b
D
4T
3a
+0.34, 28 July 1994
-0.24, 13 July 1994
-0.43, 12 July 1994
-0.67, 28 July 1994
Redtail
D = 0.4-1.5 m
25i, 18b
D
2T
-0.40, 4 July 1992
-0.61, 3 July 1992
-0.52, 11 July 1994
-0.73, 2 July 1992
Pool
D = 1.1-1.8 m
10i, 10s
D
10T
+2.01, 2 Aug 1994
0
2
4
Explanation for symbols in B not defined in A
Height range of land surface
10i Number of height measurements
a, algal mat
b, bank of high marsh
i, interior of high marsh
s, spruce swamp
T, lowest Triglochin maritima
D Difference in height between high marsh and lowest Triglochin maritima
— +2.01, 2 Aug 1994 Low or high tide from which low-water datum on y-axis is estimated. Number in hundredths denotes predicted tide level, in meters above mean lower low water at Aberdeen
Sitka spruce
On upland
On tidal wetland

Figure 7A

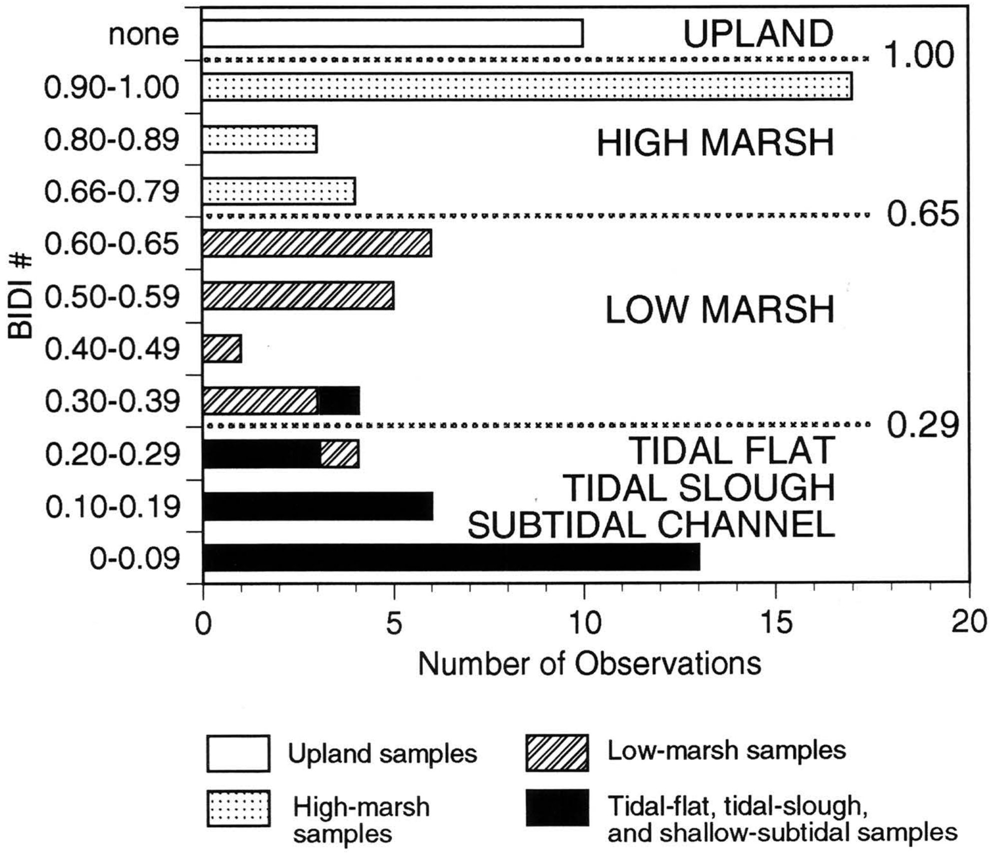

none
0.90-1.00
0.80-0.89
0.66-0.79
0.60-0.65
0.50-0.59
0.40-0.49
0.30-0.39
0.20-0.29
0.10-0.19
0-0.09
BIDI #
UPLAND
1.00
HIGH MARSH
0.65
LOW MARSH
0.29
TIDAL FLAT
TIDAL SLOUGH
SUBTIDAL CHANNEL
0
5
10
15
20
Number of Observations
Upland samples
Low-marsh samples
High-marsh samples
Tidal-flat, tidal-slough, and shallow-subtidal samples

Figure 7B,C

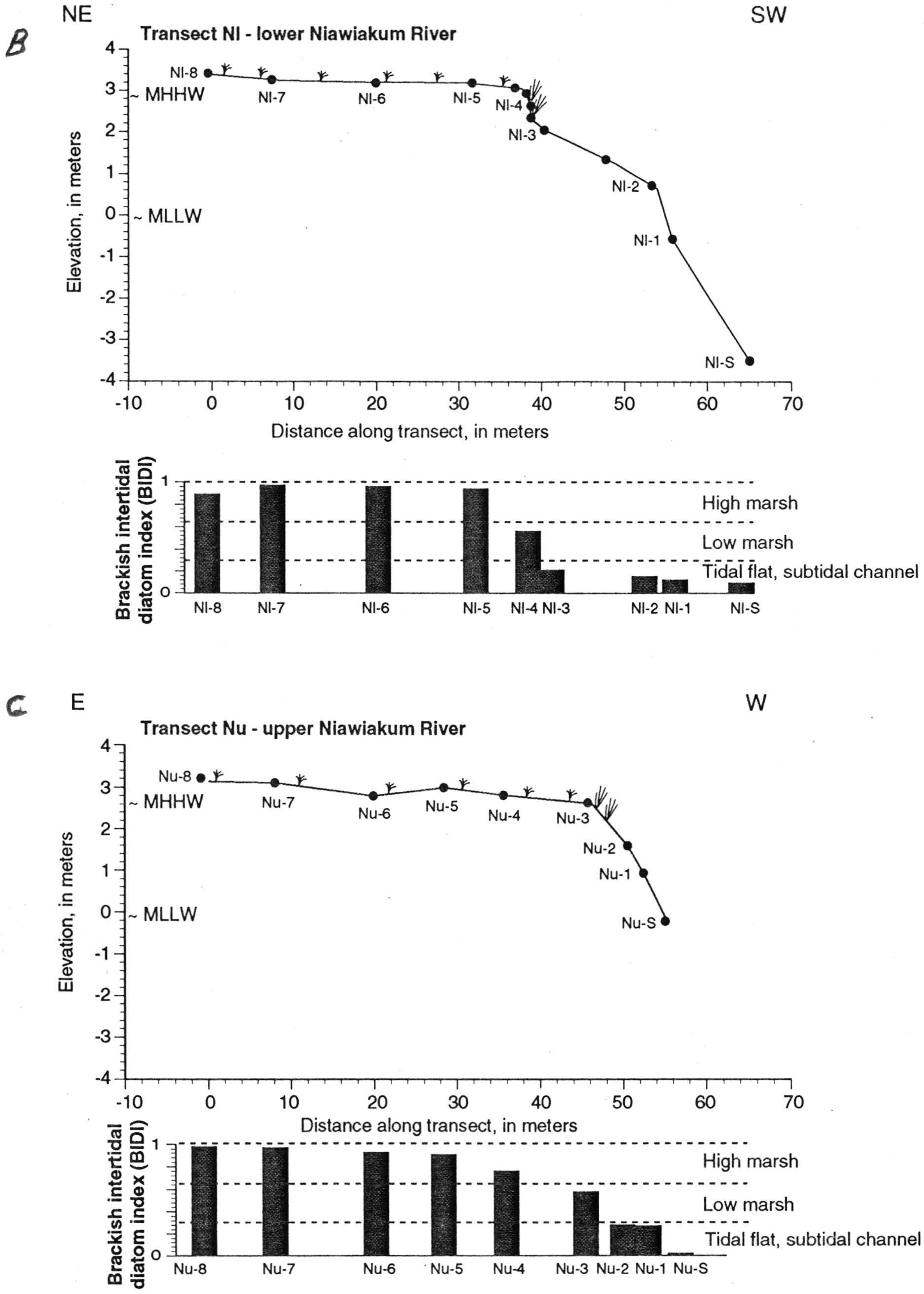

B
NE
SW
Transect NI - lower Niawiakum River
Elevation, in meters
4
3
2
1
0
-1
-2
-3
-4
~ MHHW
~ MLLW
NI-8
NI-7
NI-6
NI-5
NI-4
NI-3
NI-2
NI-1
NI-S
-10
0
10
20
30
40
50
60
70
Distance along transect, in meters
Brackish intertidal diatom index (BIDI)
1
0
High marsh
Low marsh
Tidal flat, subtidal channel
NI-8
NI-7
NI-6
NI-5
NI-4
NI-3
NI-2
NI-1
NI-S
C
E
W
Transect Nu - upper Niawiakum River
Elevation, in meters
4
3
2
1
0
-1
-2
-3
-4
~ MHHW
~ MLLW
Nu-8
Nu-7
Nu-6
Nu-5
Nu-4
Nu-3
Nu-2
Nu-1
Nu-S
-10
0
10
20
30
40
50
60
70
Distance along transect, in meters
Brackish intertidal diatom index (BIDI)
1
0
High marsh
Low marsh
Tidal flat, subtidal channel
Nu-8
Nu-7
Nu-6
Nu-5
Nu-4
Nu-3
Nu-2
Nu-1
Nu-S

Figure 8

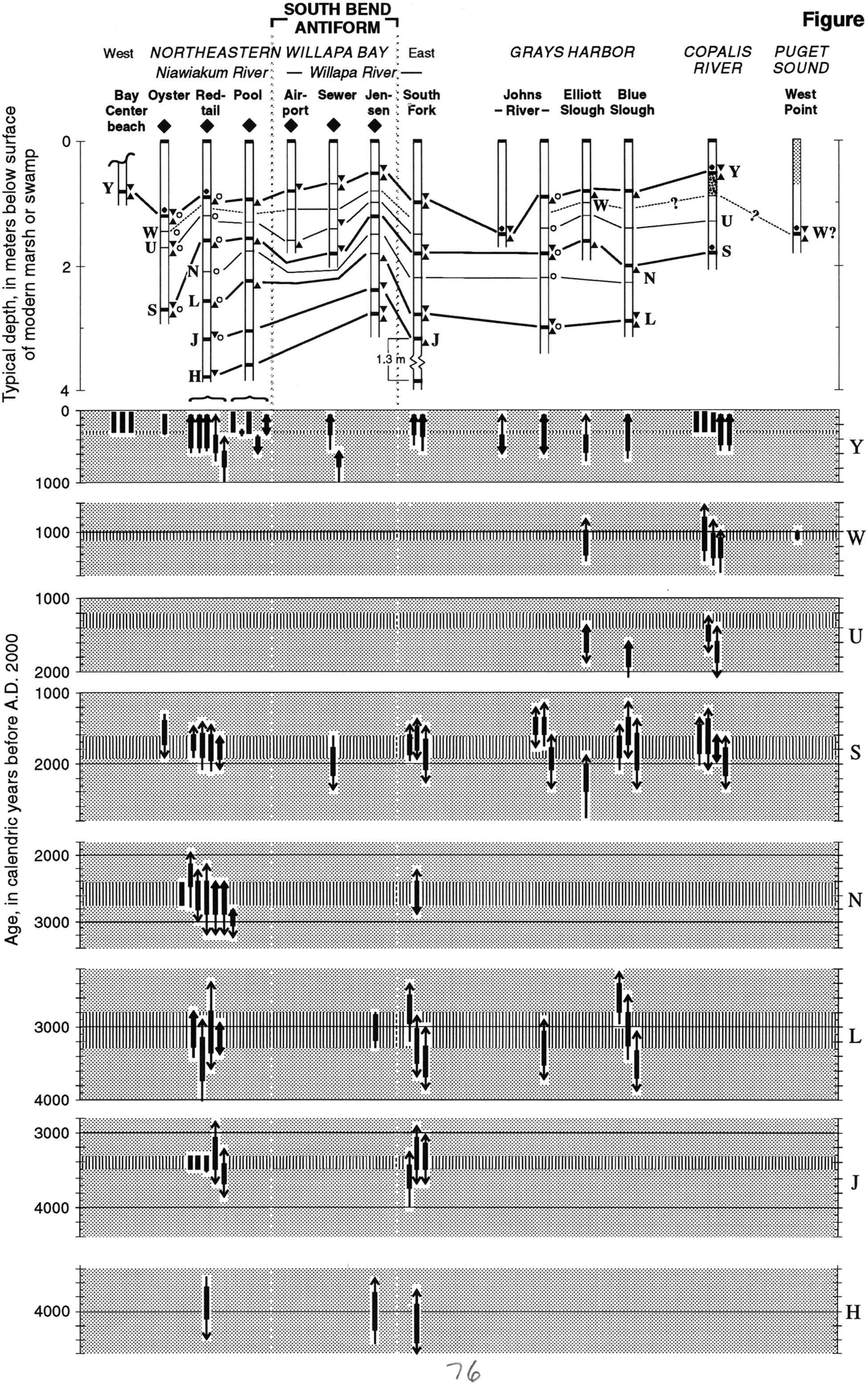

SOUTH BEND ANTIFORM
West
NORTHEASTERN WILLAPA BAY
East
Niawiakum River
— Willapa River —
GRAYS HARBOR
COPALIS RIVER
PUGET SOUND
Bay Center beach
Oyster
Red-tail
Pool
Air-port
Sewer
Jen-sen
South Fork
Johns – River –
Elliott Slough
Blue Slough
West Point
Typical depth, in meters below surface of modern marsh or swamp
0
2
4
Y
W
U
S
N
L
J
H
W?
?
1.3 m
Age, in calendric years before A.D. 2000
0
1000
2000
3000
4000
Y
W
U
S
N
L
J
H

Figure 8, continued

EXPLANATION

COLUMNAR SECTIONS

Soil—Categorized by surficial horizon

▯ **Bold**—Peaty mud or peat
  Faint—Dark mud

Deposits between successive soils

□ **Mud**

● **Probable tsunami deposit on soil**

▨ **Vented sand on soil**—Erupted from >35 m below land surface (Atwater, 1992)

▦ **Muddy peat**—>1/4 m thick; records gradual submergence in past 1000 years (Atwater and Moore, 1992)

Vascular-plant fossils in growth position

▼ **Rhizomes in mud above soil**—*Triglochin maritima* or, at South Fork, *Carex lyngbyei*

▲ **Plant remains rooted in buried soil**—Herbs, shrubs, or trees

○ **Microscopic fossils**—Diatoms at Redtail and Oyster localities (Figures 10, 12), diatoms and pollen at Johns River (Shennan and others, 1994). Differences between soil and overlying mud suggest sudden subsidence of soil

~ **Unconformity on modern beach**

Correlations—Dashed where drawn through section in which soil is not recognized; queried where speculative; letter is name for soils inferred to correlate with one another

Y — **Soil typically bold**

W — **Soil typically faint**

AGES OF INFERRED EARTHQUAKES

Each superimposed pair of lines gives calibrated-age range that incorporates large (thin line) and small or no (thick line) increase in error quoted by laboratory; see text for details

▮ **Closely limiting age**—Obtained from high-precision dating of earthquake-killed plants (soils W, Y) or of forest litter from uppermost 0.5 cm of buried soil (soils N, J); ages for soils W and Y denote inferred time of tree death

↓ **Minimum age**—Measured on rhizomes of *Triglochin maritima*

↑ **Maximum age**—Measured on woody root, plant detritus, or archaeological charcoal in buried soil

↕ **Minimum or maximum age**—Measured on peat in soil or on plant detritus in mud less than 20 cm above soil

||||||| **Likely age range for inferred earthquake or earthquakes**—Inferred from ages discussed in text under heading, "History of geologically recorded earthquakes"

Figure 9

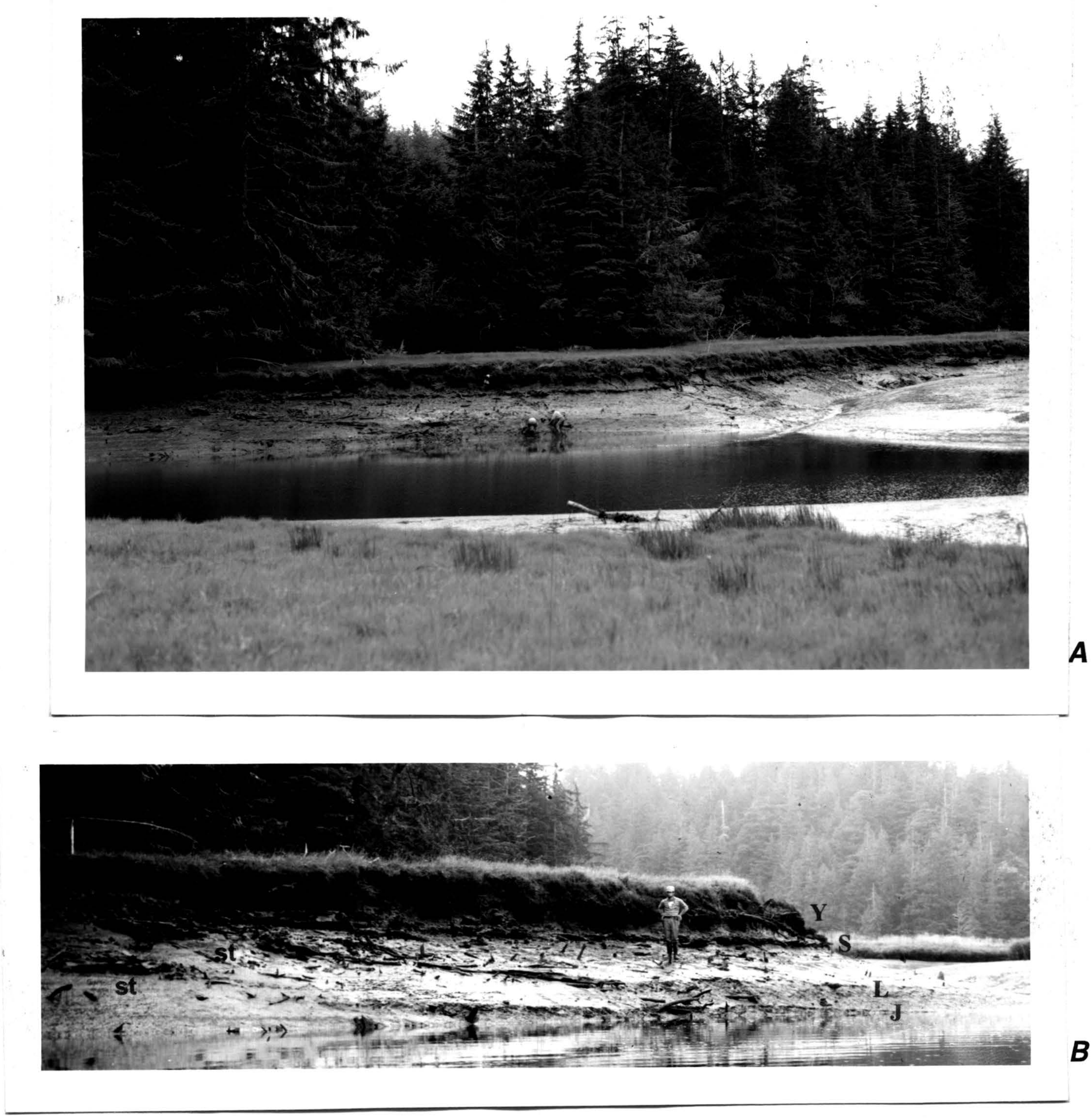


Figure 9, continued

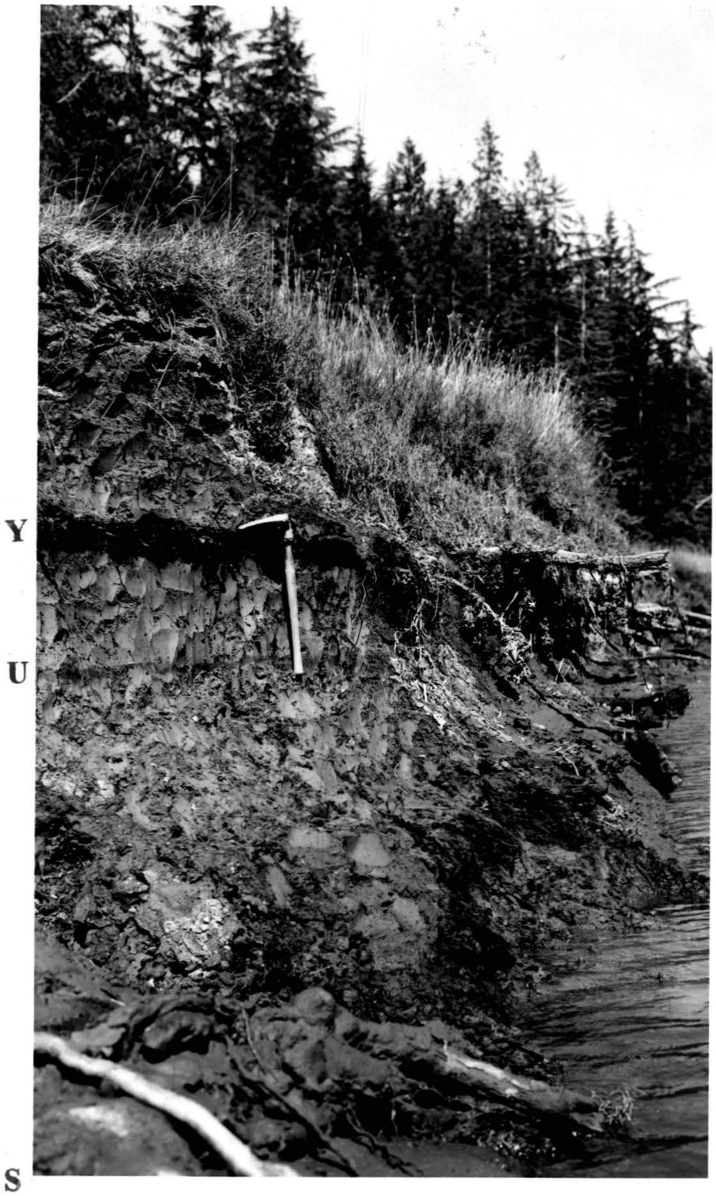


Figure 9, continued

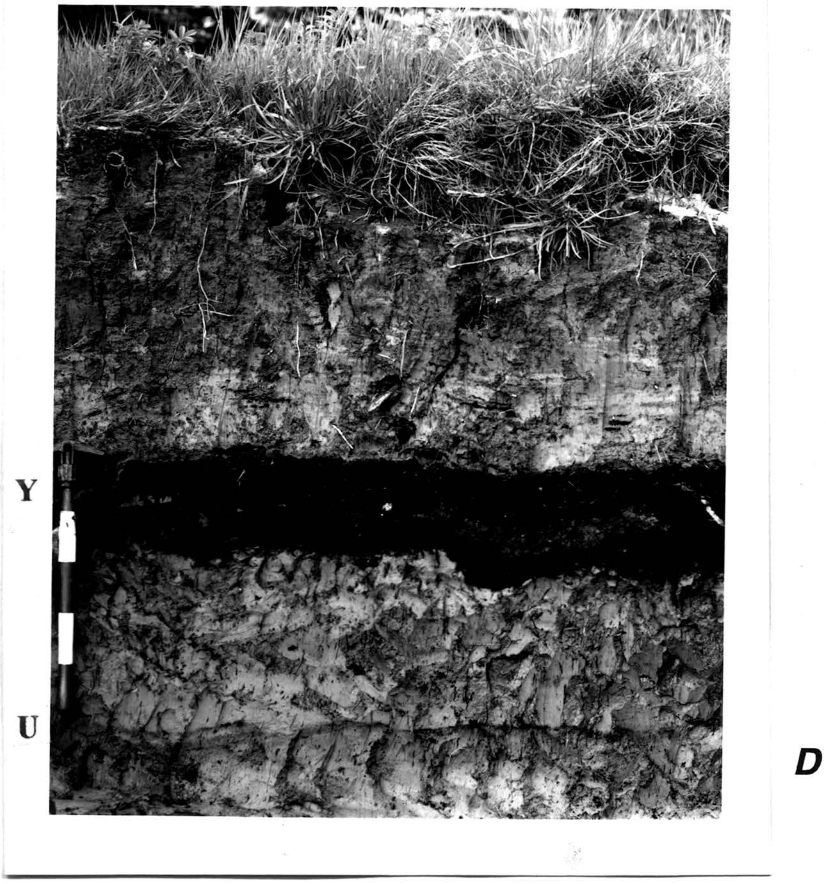
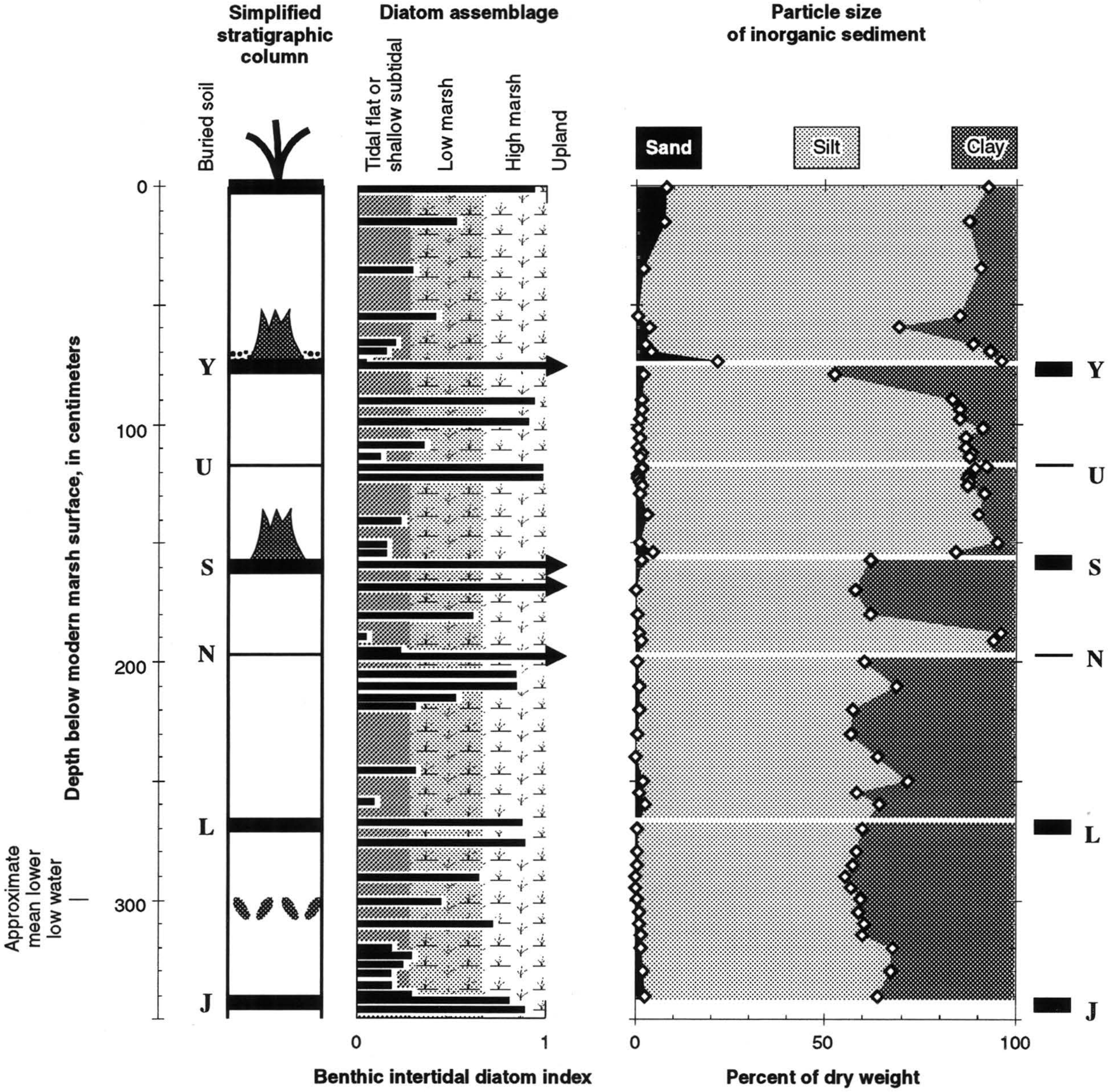


Figure 10


Simplified stratigraphic column
Diatom assemblage
Particle size of inorganic sediment
Buried soil
Tidal flat or shallow subtidal
Low marsh
High marsh
Upland
Sand
Silt
Clay
Depth below modern marsh surface, in centimeters
0
100
200
300
Approximate mean lower low water
Y
U
S
N
L
J
0
1
Benthic intertidal diatom index
0
50
100
Percent of dry weight

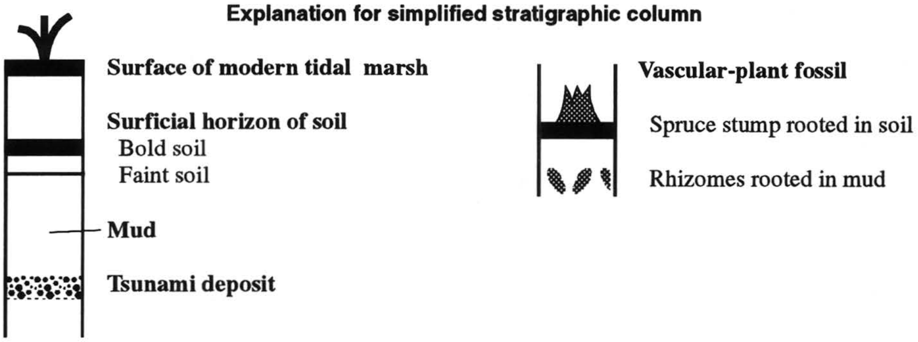

Explanation for simplified stratigraphic column
Surface of modern tidal marsh
Surficial horizon of soil
Bold soil
Faint soil
Mud
Tsunami deposit
Vascular-plant fossil
Spruce stump rooted in soil
Rhizomes rooted in mud

Figure 11

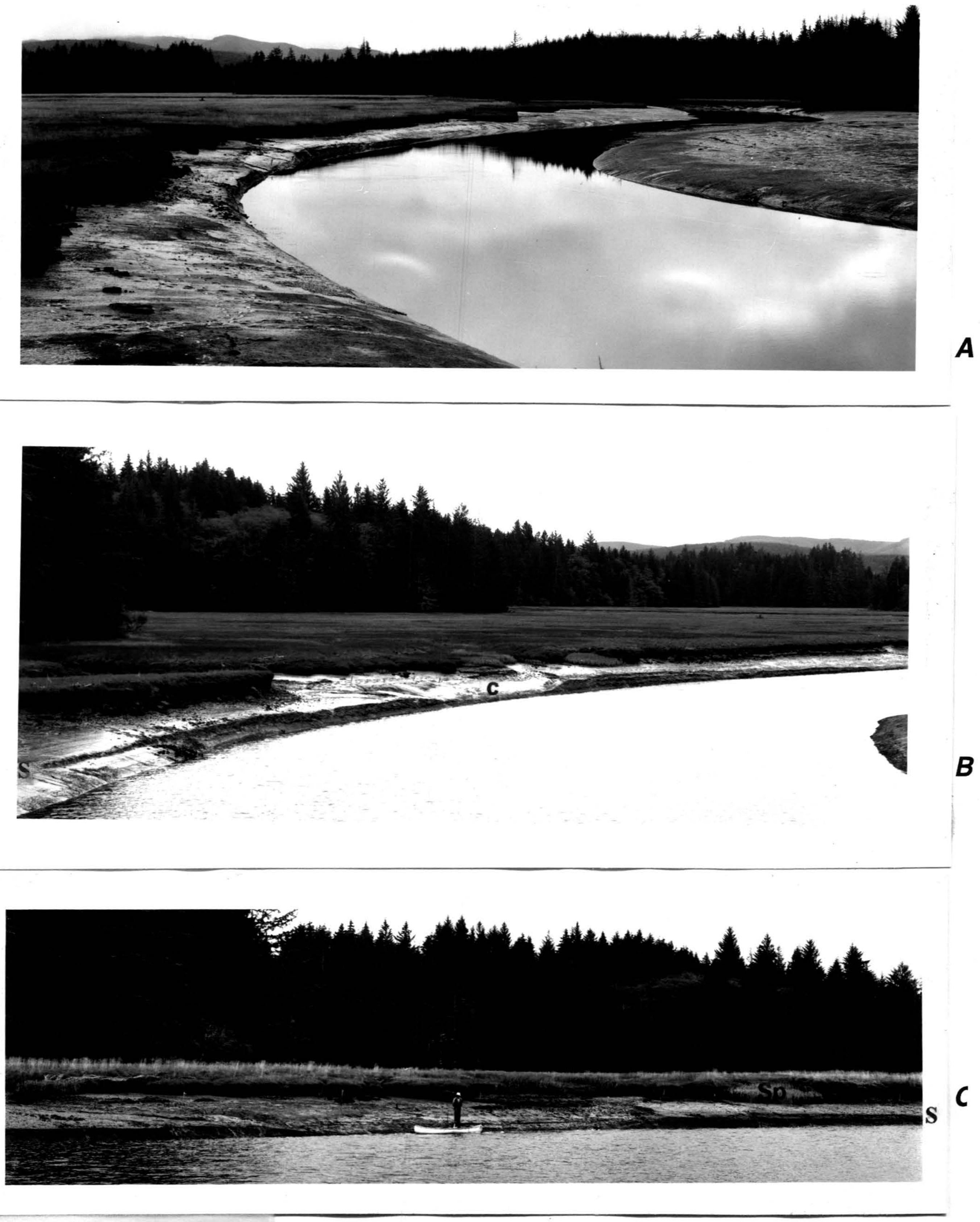


Figure 11, continued

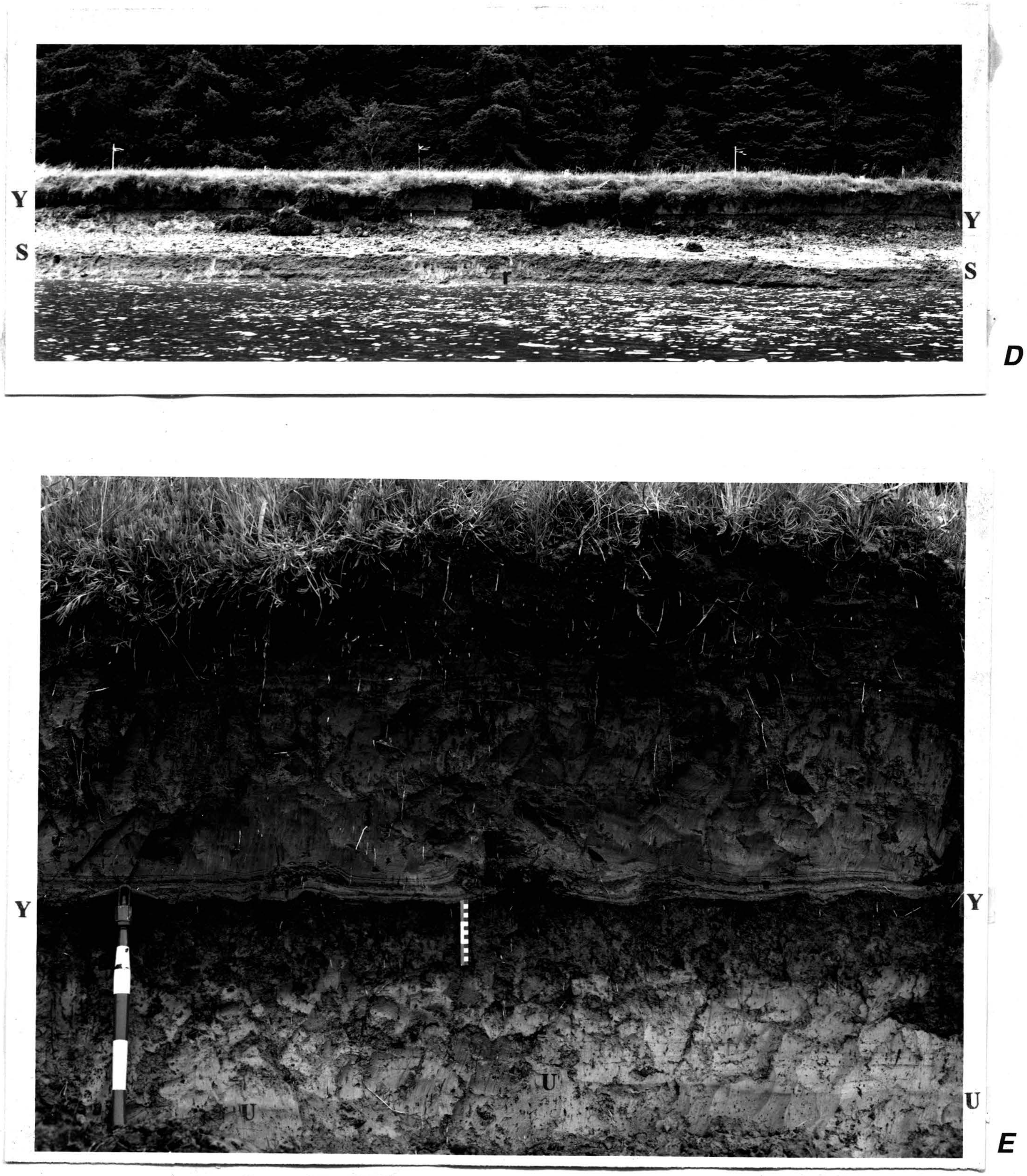


Figure 12

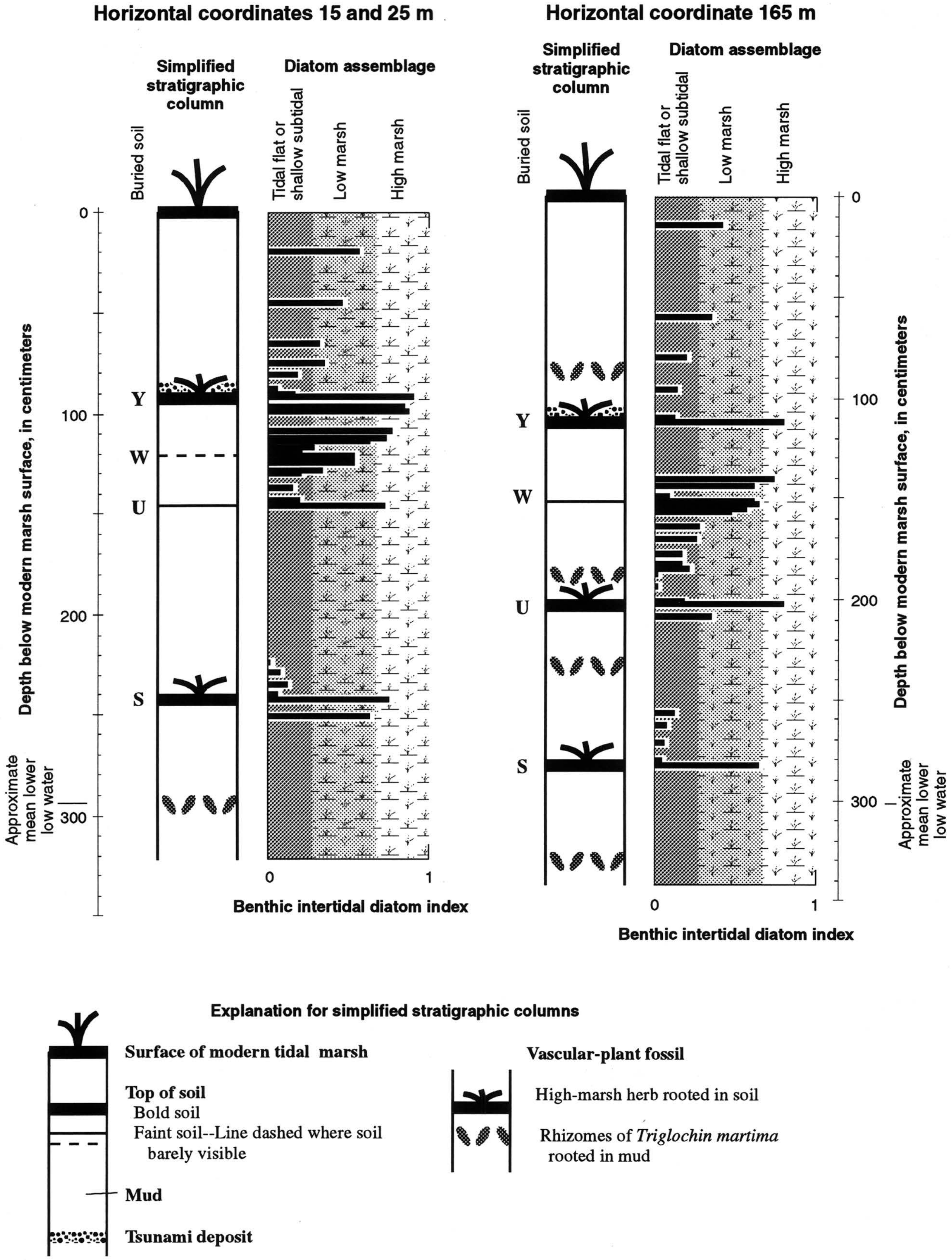

Horizontal coordinates 15 and 25 m
Simplified stratigraphic column
Diatom assemblage
Buried soil
Tidal flat or shallow subtidal
Low marsh
High marsh
Y
W
U
S
0
100
200
300
Depth below modern marsh surface, in centimeters
Approximate mean lower low water
0
1
Benthic intertidal diatom index
Horizontal coordinate 165 m
Simplified stratigraphic column
Diatom assemblage
Buried soil
Tidal flat or shallow subtidal
Low marsh
High marsh
Y
W
U
S
0
100
200
300
Depth below modern marsh surface, in centimeters
Approximate mean lower low water
0
1
Benthic intertidal diatom index
Explanation for simplified stratigraphic columns
Surface of modern tidal marsh
Top of soil
Bold soil
Faint soil--Line dashed where soil barely visible
Mud
Tsunami deposit
Vascular-plant fossil
High-marsh herb rooted in soil
Rhizomes of Triglochin martima rooted in mud

Figure 13

Figure 14

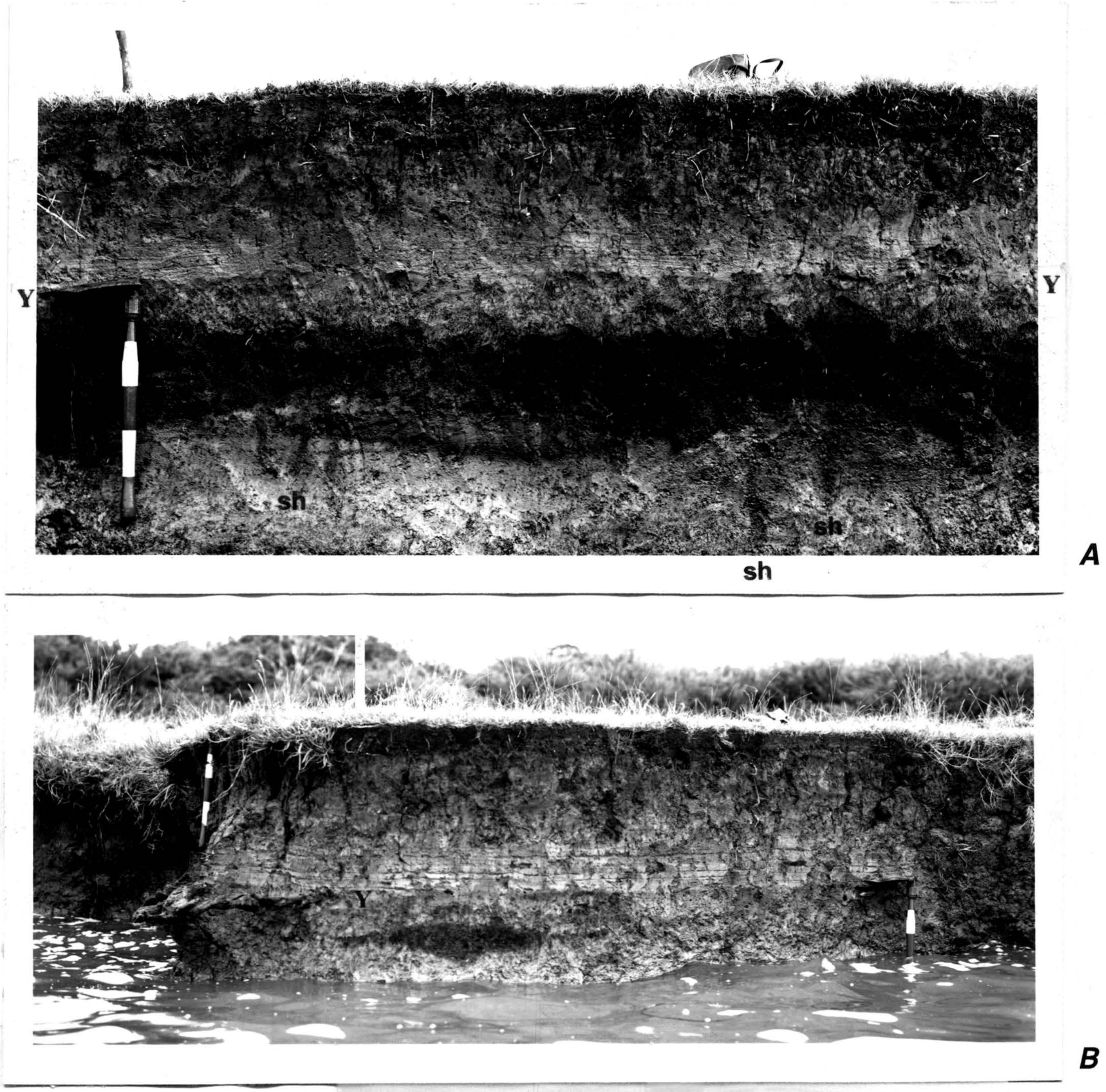
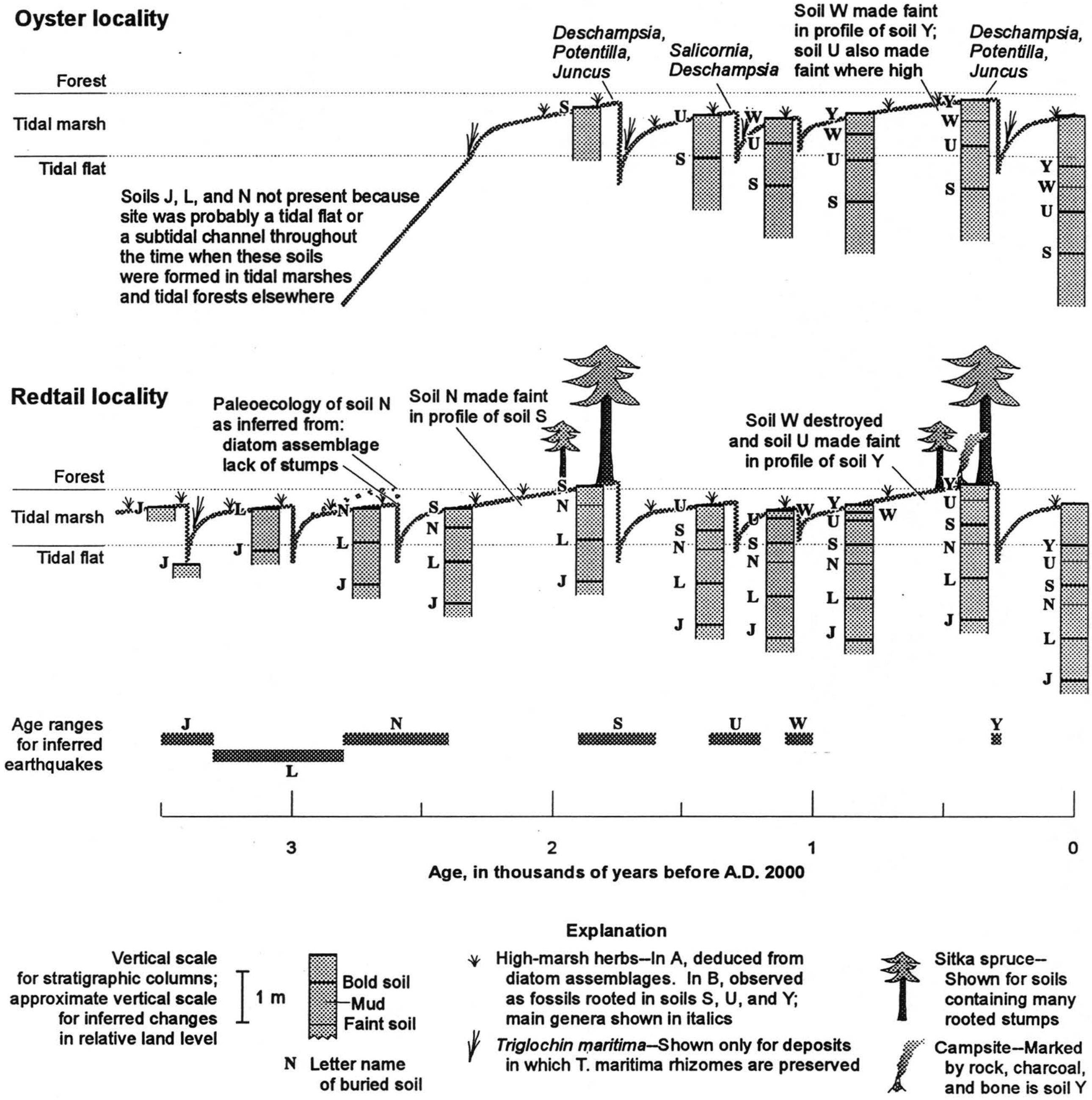


Figure 14, continued

C

D

Figure 15


Oyster locality
Forest
Tidal marsh
Tidal flat
Deschampsia, Potentilla, Juncus
Salicornia, Deschampsia
Soil W made faint in profile of soil Y; soil U also made faint where high
Deschampsia, Potentilla, Juncus
Soils J, L, and N not present because site was probably a tidal flat or a subtidal channel throughout the time when these soils were formed in tidal marshes and tidal forests elsewhere
S
U
S
W
U
S
Y
W
U
S
Y
W
U
S
Y
W
U
S
Redtail locality
Forest
Tidal marsh
Tidal flat
Paleoecology of soil N as inferred from: diatom assemblage lack of stumps
Soil N made faint in profile of soil S
Soil W destroyed and soil U made faint in profile of soil Y
J
L
N
S
U
W
Y
Age ranges for inferred earthquakes
J
L
N
S
U
W
Y
3
2
1
0
Age, in thousands of years before A.D. 2000
Explanation
Vertical scale for stratigraphic columns; approximate vertical scale for inferred changes in relative land level
1 m
Bold soil
Mud
Faint soil
N Letter name of buried soil
High-marsh herbs--In A, deduced from diatom assemblages. In B, observed as fossils rooted in soils S, U, and Y; main genera shown in italics
Triglochin maritima--Shown only for deposits in which T. maritima rhizomes are preserved
Sitka spruce--Shown for soils containing many rooted stumps
Campsite--Marked by rock, charcoal, and bone is soil Y