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Notes

Diatom evidence for earthquake-induced subsidence and tsunami 300 yr ago in southern coastal Washington

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ABSTRACT

Fossil diatoms from four stratigraphic sections along the tidal Niawiakum River, southwestern Washington, provide an independent paleoecological test of a relative sea-level rise that has been attributed to subsidence during an inferred earthquake in the Cascadia subduction zone about 300 yr ago. Diatom assemblages in a buried soil and overlying mud indicate a sudden and lasting shift from marshes and forests near or above highest tides to mud flats and incipient tidal marshes, with a progressive return to high-level tidal marshes by sediment aggradation and, perhaps, gradual tectonic uplift. The amount of coseismic submergence required to generate the paleoecological changes observed at these sites could have ranged from a minimum of 0.8–1.0 m to a maximum of ~3.0 m.

Fossil diatoms also provide an independent test of previous inferences that the subsidence was shortly followed by a tsunami. The inferred tsunami deposit is a distinct sandy interval that widely overlies the buried marsh and forest soil. Diatoms from this interval consist of species observed on modern sand flats of the open bay, identifying a bayward source for the sand. Occurrences of the same sand-flat species above the buried soil in the farthest up-valley outcrop where a sandy interval is not recognizable suggest that the tsunami extended farther landward than was previously inferred from the stratigraphy.

These data rule out proposed alternatives to the coseismic subsidence model—that is, climatically induced sea-level rise, temporary submergence caused by storms—and support the hypothesis that a great earthquake struck southwestern Washington 300 yr ago.

INTRODUCTION

Differences in affinities for salinity, substrate, and intertidal exposure make coastal

and estuarine benthic diatoms extremely valuable in reconstructing paleo-sea-level changes (Palmer and Abbott, 1986; Kosugi, 1987, 1988; Vos and Wolf, 1988, 1993). The recognition that certain taxa dominantly occur in specific intertidal zones (tidal flats, low marshes, and high marshes) in the Pacific Northwest further suggests that diatoms can be used to identify small-scale sea-level changes of a few meters or less (Nelson and Kashima, 1993; Hemphill-Haley, in press). The purpose of this study was to use diatom biostratigraphy as an independent test of the hypothesis that a large earthquake in the Cascadia subduction zone (Fig. 1) caused sudden relative sea-level rise, or submergence, in southwestern Washington about 300 yr ago (Atwater, 1987, 1992; Atwater and Yamaguchi, 1991). Diatoms were collected from four stratigraphic sections on the east side of Willapa Bay along the Niawiakum River (Sites 1–4, Fig. 2), at closely spaced intervals below, within, and above a prominent buried soil that has been inferred to record a large subduction zone earthquake in the Pacific Northwest between A.D. 1680 and A.D. 1720 (Atwater et al., 1991). This soil may also be coeval with similar buried soils in estuaries of northern California and Oregon (Nelson and Atwater, 1993). The Niawiakum River was specifically chosen as the location for this study because it allowed a direct comparison with previous stratigraphic and sedimentological studies (Atwater, 1987, 1992; Reinhart and Bourgeois, 1987; Atwater and Yamaguchi, 1991) while excluding the possibility that the results of the diatom analyses included any different local ecological factors.

Stratigraphic evidence for coseismic submergence has been reported from numerous estuaries of the Pacific Northwest from northern California to British Columbia (Atwater, 1987, 1992; Grant and McLaren, 1987; Vick, 1988; Darienzo and Peterson, 1990; Nelson and Personius, 1991; Peterson and Darienzo, 1991; Nelson, 1992a, 1992b;

Clarke and Carver, 1992; Clague and Bobrowsky, 1994; Mathewes and Clague, 1994). Sequences of alternating wetland soils and estuarine mud attest to episodes of rapid sea-level rise and inundation of coastal lowlands, which is consistent with documented coseismic submergence during subduction-zone earthquakes (Plafker, 1969, 1972; Plafker and Savage, 1970). Contacts between the soils and overlying mud, as observed in outcrop or in cores, are usually sharp, but may appear more gradational in less well developed or poorly preserved soils, or where the remains of herbaceous plants protrude into the overlying mud (Atwater and Yamaguchi, 1991). However, gradational contacts may also indicate nontectonic processes such as eustatic sea-level rise or changes in tidal range within an estuary (Nelson, 1992b). As shown below, diatom analyses at closely spaced intervals across stratigraphic contacts can be used to differentiate sudden changes in sea level, as might occur during an earthquake, from slower or smaller changes that may imply nontectonic processes.

Atwater (1987, 1992) and Atwater and Yamaguchi (1991) used several lines of evidence to suggest that the uppermost buried soil along the Niawiakum River was consistent with submergence during a large earthquake. First, they argued that abruptness of the soil/mud contact, and the preservation of tree roots and plants in the soil, suggested that the submergence was sudden. Second, the occurrences of rhizomes of a salt marsh plant, *Triglochin maritima*, in mud a few tens of centimeters above the buried soil suggested lasting submergence to a lower intertidal level, rather than a temporary submergence as might be caused by a storm. The amount of submergence, based on the relative positions of fossil plants with their modern counterparts, was estimated at ~0.5–2 m. Finally, they presented anomalous fine sand laminae in a zone capping the soil that became finer and thinner up-valley as pos-

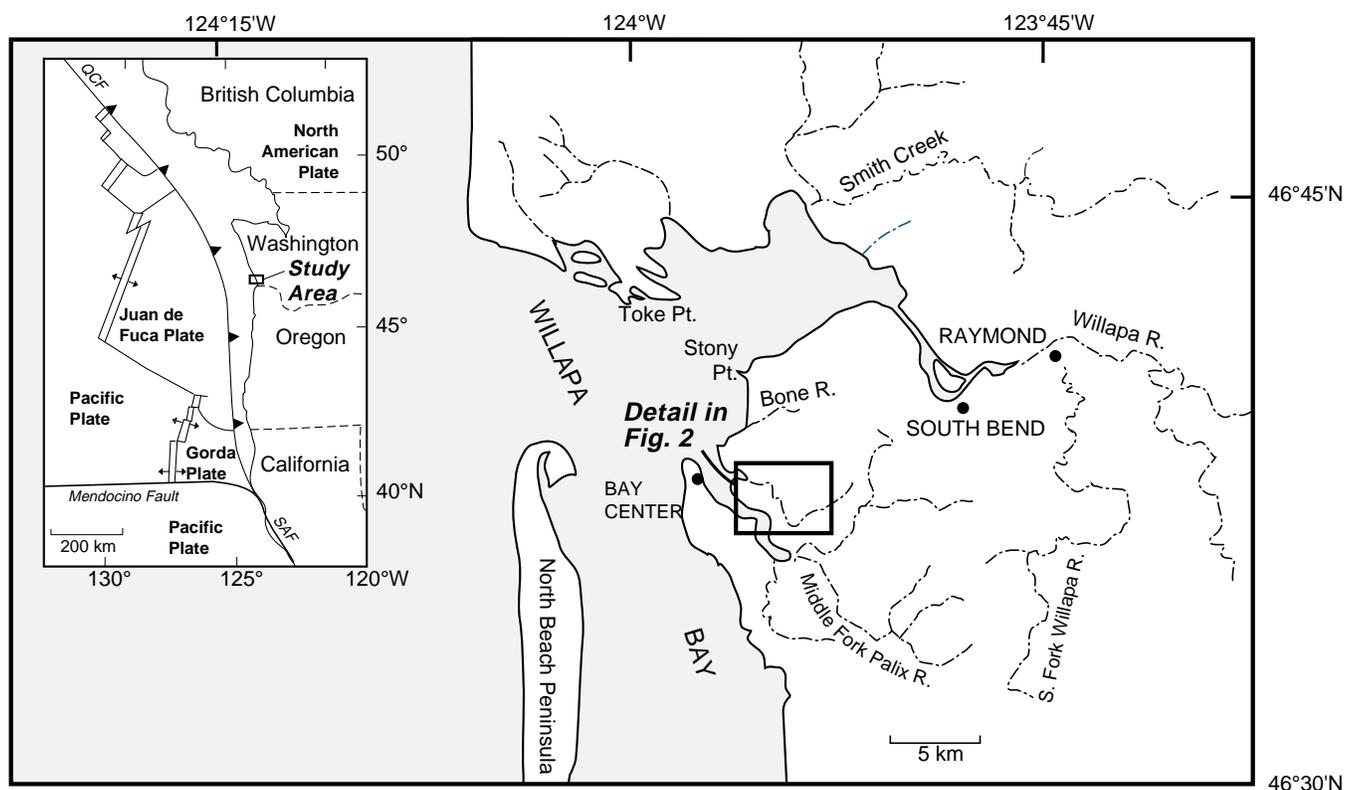


Figure 1. Location of Niawiakum River Valley, on eastern side of Willapa Bay. Inset shows position of the study area relative to the Cascadia subduction zone (barbed line), the boundary between North America and Juan de Fuca/Gorda plates that extends from northern end of San Andreas Fault (SAF) to the southern end of Queen Charlotte fault (QCF). Double lines with arrows are spreading ridges; single lines are transform faults.

sible evidence for a tsunami that may have been generated by an earthquake.

In this paper, the 300 yr B.P. submergence along the Niawiakum River is examined biostratigraphically to determine if it is best explained by tectonic or nontectonic processes. Changes in diatom assemblages are used to estimate (1) the preburial elevation of the 300 yr B.P. soil, (2) the rate and amount of submergence of the soil, and (3) the possible source and up-valley extent of the proposed tsunami sand. The conclusions of this report are based primarily on my observations of the distributions of modern diatoms at Willapa Bay (Hemphill-Haley, 1993a, 1993b, in press) but also build on other studies of modern estuarine diatom ecology in the Pacific Northwest (Riznyk, 1973; Rao and Lewin, 1976; Amspoker and McIntire, 1978; Whiting, 1983; Tynni, 1986; Nelson and Kashima, 1993) and elsewhere (Brockmann, 1950; Hendey, 1964; Kosugi, 1987, 1988; Vos and De Wolf, 1988). The results illustrate a powerful micropaleontological method for interpreting sea-level changes associated with subduction-zone tectonics.

STUDY AREA AND METHODS

The Niawiakum River is a tidal stream on the east side of Willapa Bay, a mesotidal estuary in southwestern Washington (Fig. 1). Tidal ranges in Willapa Bay vary from 2.3 m near the mouth of the estuary to 3.4 m at its southern reaches (Sayce, 1988) and are about 2.4 m at the Niawiakum River (Shotwell, 1977).

Four sections were analyzed for diatoms along Niawiakum River, on cutbanks with good exposures of the 300-yr-old soil (Fig. 2). Previous stratigraphic and chronological analyses for Sites 1 and 2 were reported by Atwater (1987, 1992), Reinhart and Bourgeois (1989), and Atwater and Yamaguchi (1991). Estimates for tidal datums at Sites 1–4 are based on comparisons of water levels measured at high and low tide during good weather, and compared with tidal charts corrected for tidal variation in Willapa Bay (Pacific County Planning Department, 1990, written commun.). These datums are estimated to be within ± 0.1 m for Sites 1–3, and ± 0.2 m in the upper part of the valley at Site 4, where

tidal changes are more difficult to determine.

For Sites 1 and 2, vertical slabs 60 cm long, 20 cm wide, by 8 cm thick were collected intact and subsampled in the laboratory. Samples from Sites 3 and 4 were collected directly from the outcrops in the field, after the surfaces were dug back to form a vertical face of unexposed sediment. Sample intervals ranged from 2 cm near visible lithologic boundaries, to 35 cm in more continuous muddy deposits.

Diatom-strewn slides were processed by the following method: (1) ~ 1 cc of sediment was dried and weighed; (2) organic debris was removed by gentle heating in concentrated nitric acid; (3) acid was removed and the sample was neutralized by repeated rinses in distilled water; (4) the total sample volume was reduced to 5 mL; (5) a 0.05 to 0.10 mL aliquot was transferred to a cover slip and allowed to dry; and (6) the cover slip was permanently fixed to a glass slide using Hyrax. An average of 410 diatom valves per sample were counted. Of these, the ecologically significant species used for this study (Fig. 3) accounted for an average of 110

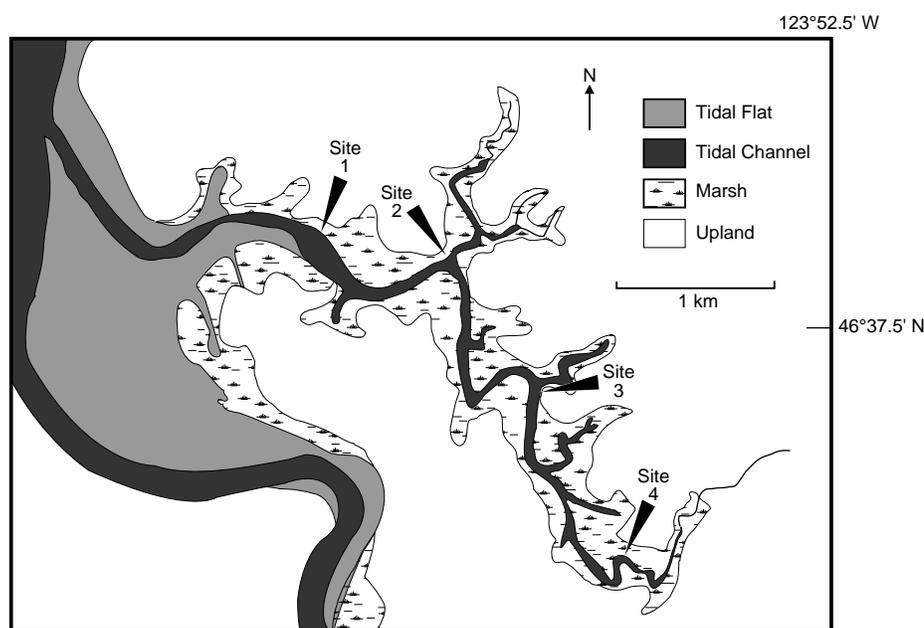


Figure 2. Locations of vertical sections sampled for diatoms in Niawiakum River Valley. Sites 1–4 are cutbank outcrops exposed during low tide. Floor of the valley is presently a broad brackish marsh dominated by *Distichlis* and *Deschampsia* in lower half of valley, and by *Deschampsia*, *Potentilla*, and *Carex* in vicinity of Site 4. Spruce forests, which covered the floor of upper part of valley prior to about 300 yr ago, are now restricted to upland surfaces at the edges of valley.

valves per sample excluding *Paralia sulcata*, and 322 including *P. sulcata* (Hemphill-Haley, 1993a).

BACKGROUND

The mixed tides of the Pacific Northwest typically generate a three-tiered intertidal zonation, with intertidal flats encompassing about the lower two-thirds of the tidal range, followed by regularly submerged (“low”) marshes, and less frequently submerged (“high”) marshes in the upper part of the intertidal zone (Fig. 3) (Macdonald, 1977; Macdonald and Barbour, 1977; Frey and Basan, 1985). The absolute elevations of the zones are dictated by local tidal range, and in some cases, river discharge. Transitions between intertidal zones are more or less gradational, a characteristic also noted for diatoms (Nelson and Kashima, 1993), benthic foraminifers (Jennings and Nelson, 1992), and marsh macrophytes (Macdonald, 1977; Macdonald and Barbour, 1977; Frey and Basan, 1985).

A variety of environmental factors influences the distribution of benthic estuarine diatoms, including nutrient supply, amount of irradiance, competition with other orga-

nisms, temperature, salinity, type of available substrate, and amount of intertidal submergence or sustained subaerial exposure (McIntire and Moore, 1977). Of these, salinity, substrate, and intertidal exposure figure prominently in paleo-sea-level studies. Most estuarine diatoms are strongly euryhaline (Admiraal, 1979), but obvious changes in populations above and below salinities of about 5‰ (Moore and McIntire, 1977; Amspoker and McIntire, 1978; McIntire, 1978; Hemphill-Haley, 1993a) make diatoms useful for identifying marine transgressions and regressions (Palmer and Abbott, 1986). The affinities of some diatom species for certain kinds of substrate (i.e., sand, mud, or solid surfaces such as rocks or larger plants) make diatoms useful for identifying paleoenvironments retained in the sedimentary record (Amspoker and McIntire, 1978; Whiting, 1983; Kosugi, 1987, 1988; Vos and Wolf, 1988; Hemphill-Haley, in press). It is the distribution of diatoms associated with the tide-controlled intertidal zonation that is particularly pertinent in studies of decimeter- to meter-scale sea-level changes (Nelson and Kashima, 1993; Hemphill-Haley, in press). A generalized scheme of the intertidal zones, and diatoms

associated with these zones (Fig. 3), is described below.

Upland areas are positioned above the extent of the highest tides, or extreme high water (EHW; Fig. 3), and support lowland forests. The elevation of this datum on the Niawiakum River is ~3.3–3.4 m above mean lower low water (MLLW). Diatoms from upland sites are represented by rare, allochthonous valves, deposited by wind and during storm surges.

The high marsh is positioned between mean higher high water (MHHW) and EHW (Fig. 3), or approximately between 2.9 and 3.3 m above MLLW along the Niawiakum River. The high marsh encompasses a relatively small vertical range and typically supports grassy marsh vegetation and prolific diatom populations. Because the high marsh is infrequently submerged and the diatoms must sustain long periods of exposure, many high-marsh diatoms have sturdy valves that fossilize well.

The low marsh is positioned between mean lower high water (MLHW), an approximate lower limit for marsh vegetation in many estuaries of western North America (Macdonald and Barbour, 1977), and MHHW (Fig. 3). In Willapa Bay, *Spartina alterniflora*, a cordgrass introduced during historical times (Sayce, 1988), extends lower in the intertidal zone than the native plants that would have been present 300 yr ago. The elevation of the low marsh ranges from ~2.2 to ~2.9 m above MLLW in the middle to lower part of the Niawiakum River valley. For marshes fringing the open bay, the low marsh typically grades into the high marsh, but along the Niawiakum River the low-marsh zone forms along the steep, sometimes vertical, river bank. Low-marsh diatoms require regular submergence by tides or are associated with fine-grained organic-rich sediment that accumulates between marsh plants. Whereas some diatom species are associated with either the high or low marsh, others may be found throughout the range of high and low marshes above MLHW, and particularly above mean high water (MHW, Fig. 3), where marsh plants grow thickest and trap sediment more efficiently.

The lower intertidal zone encompasses the channel banks of tidal rivers and the broad tidal flats of the open bay, between MLLW and MLHW (Fig. 3). Diatom assemblages consist of species that migrate to the surface of silty sediment during low tide or attach permanently to *Zostera* (eelgrass), either the broad-leaved *Z. marina* that

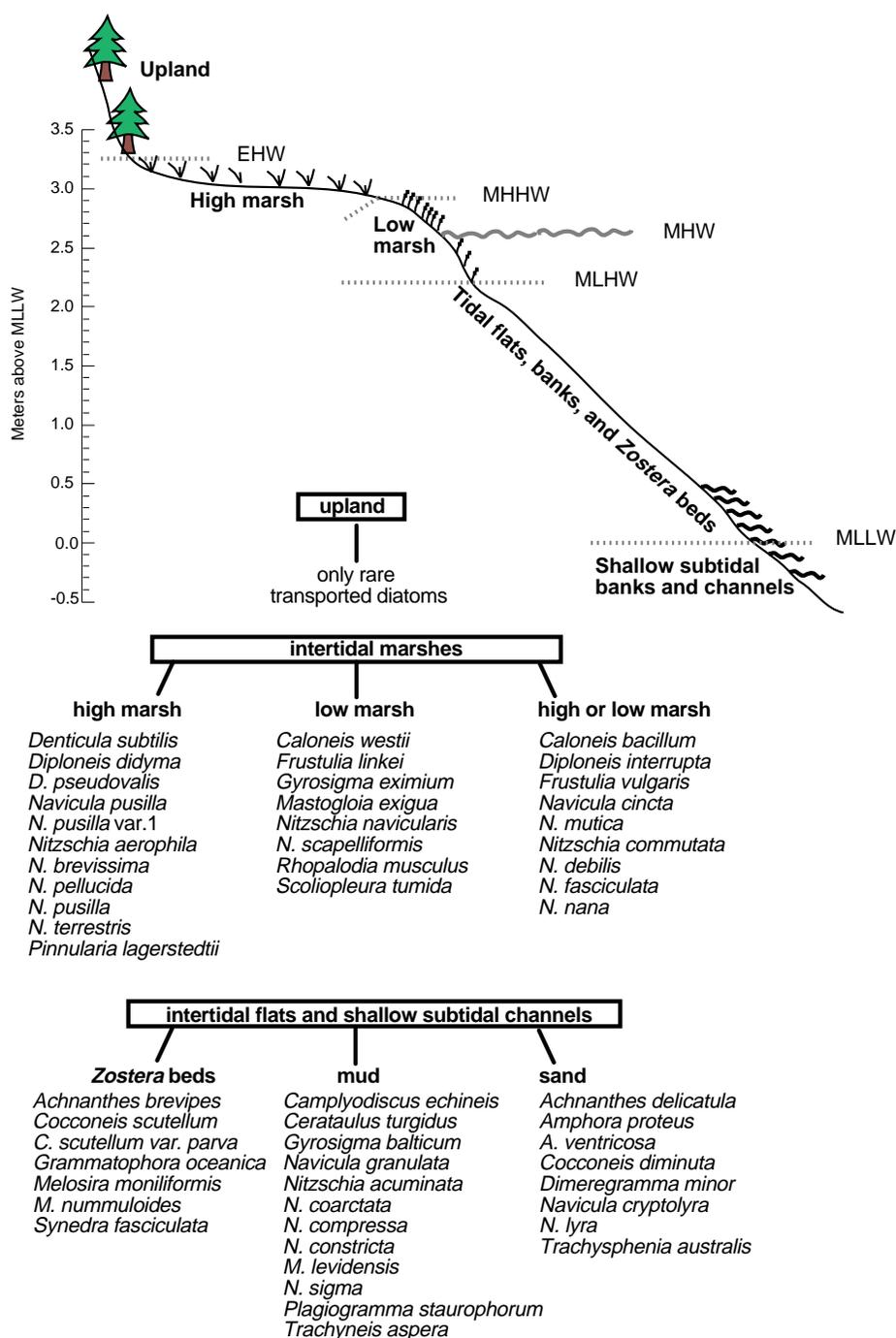


Figure 3. Diatom associations within intertidal zones. EHW, extreme high water; MHHW, mean higher high water; MHW, mean high water; MLHW, mean lower high water; MLLW, mean lower low water. Dry upland surfaces are barren of in situ diatoms; high marshes support aerophile diatoms that can withstand long periods of exposure; low marshes support species that prefer diurnal submergence; an intermediate group of diatoms is found on both high and low marshes, particularly above MHW, where marshes are best developed. Lower intertidal channel banks and tidal flats support species that prefer silty or sandy substrate or attach to eelgrass (*Zostera*). Shallow subtidal channels contain mostly allochthonous diatom valves from the lower intertidal zone.

grows near MLLW or the introduced *Z. noltii* found higher than *Z. marina* on flats and banks (Kozloff, 1973). Another distinct diatom assemblage is composed of species adapted to organic-poor sandy tidal flats.

The shallow subtidal zone, below MLLW (Fig. 3), includes shallow tidal rivers and channels in the estuary. Diatoms there consist largely of transported (allochthonous) intertidal diatoms, particularly from the lower part of the lower intertidal zone (Hemphill-Haley, 1993a, in press). Because of this mixing of diatom species, it is not feasible to use diatoms to subdivide the lower-intertidal and shallow-subtidal zones, which must be considered a single, broad ecological zone, ranging from near MLHW to several meters below MLLW (Vos and de Wolf, 1988). However, preliminary observations suggest that deep subtidal-channel deposits (>4 m below MLLW at the mouth of the Palix River near Bay Center) may be distinguished from shallow subtidal deposits by higher percentages of large planktonic species relative to all other diatoms.

General Comments on Using Estuarine Diatoms for Sea-Level Studies

Preservation. Preservation provides information both on syndepositional and post-depositional processes. Fractured or eroded valves may indicate intertidal exposure and abrasion, whereas intact valves may indicate either rapid burial or the presence of vascular plants that trap fine sediment and inhibit abrasion. Ecological interpretations will be hindered where finely silicified indicator species (e.g., *Gyrosigma* spp., *Frustulia* spp.) are removed by chemical dissolution. Conversely, where finely silicified species are well represented in an assemblage, they are indicative of superior diatom preservation. Diatom diversity in estuarine samples can range from several hundred species (e.g., Hustedt, 1955) to nearly monospecific assemblages (e.g., Eronen et al., 1987), but samples containing only a number of robust species, and lacking delicate forms, should be treated with suspicion as dissolution-biased assemblages.

Allochthonous diatoms. The problem of mixing allochthonous (transported) diatom species with autochthonous (in place) assemblages is not unique to estuarine studies and is probably important in all aquatic environments except for isolated small basins. Reworking of diatoms is prevalent in estuaries where the tides are capable of transporting cells on a diurnal basis, with high

spring tides or storm surges being especially proficient at mixing species from different environments. Various authors (Sullivan, 1975; Whiting, 1983; Hemphill-Haley, in press) have noted that although reworking is a predictable feature in estuaries, there is no evidence that allochthonous valves will necessarily outnumber autochthonous valves in an assemblage, or mask in situ assemblages. As noted above, robust valves may be reworked many times in a deposit, and observations on the overall preservation of an assemblage may provide evidence for transported valves.

The *Paralia* Problem. *Paralia sulcata* is one of the most common diatoms in coastal deposits (McIntire and Moore, 1977) and is sometimes dominant in Holocene samples from Willapa Bay. It usually lives on the bottom but is easily lifted into the plankton (Crawford, 1979) and is not uncommon in coastal planktonic samples (Hendey, 1964). At modern Willapa Bay it is ubiquitous where salinities typically exceed 5‰. Because it forms long chains, many valves may be transported in a single event, and it is not unusual to observe chains of a dozen or more small valves of *P. sulcata* resting on high marsh surfaces after elevated tides. Its superior resistance to dissolution may enhance the abundance of *P. sulcata* in coastal deposits. Reworked valves of *P. sulcata*, albeit rare and eroded, even occur as “background silt” in upland deposits, which are otherwise devoid of diatoms. Therefore, in samples containing few frustules other than *P. sulcata*, the assemblage may have been modified by dissolution.

There may be a linear correlation between the size of *P. sulcata* and salinity (Roelofs, 1984). In modern Willapa Bay, larger specimens (exceeding about 20 μm in diameter) were observed most frequently on silty tidal-flat sediments of the open bay, whereas smaller specimens were not indicative of any particular environment (Hemphill-Haley, 1993a, in press). Therefore, although large specimens of *P. sulcata* may be indicative of lower intertidal sediment, and possibly silty tidal-flat deposits in particular, caution should be used so as not to overestimate its significance. For this study, I used the ratio of large *P. sulcata* to all other diatoms counted as a possible indicator of open tidal-flat conditions.

RESULTS

Paleoecological interpretations for Sites 1–4 (Figs. 4–7) are based on the relative per-

centage of ecologically significant diatoms in five categories (Fig. 3), plus their quality of preservation and potential for transport, as noted in the previous discussion. Data from each of the four localities showed a dramatic ecological shift at the contact between the 300-yr-old soil and the overlying mud, suggesting a sharp increase in local water depth probably in excess of 1 m.

Site 1

Site 1 is located along a broad stretch of the lower Niawiakum River (Fig. 2). The 300-yr-old soil at Site 1 is 10–15 cm thick, with a gradational lower contact and sharp upper contact, and the top of the soil is presently positioned at ~2.4–2.5 m above MLLW (Fig. 4). Dominant high-marsh diatoms in the soil suggest that it represents a high marsh between former MHHW and EHW, similar to the modern high marsh at this location. This agrees with the plant fossil analysis of Atwater and Yamaguchi (1991, p. 708, Fig. 4). Sediment identified as a probable tsunami deposit (Atwater, 1987; Reinhart and Bourgeois, 1989; Atwater and Yamaguchi, 1991) is well exposed at this locality as a series of silty sand laminae, 2–10 mm thick, interbedded with mud in a mostly 5-cm-thick interval directly above the soil (Fig. 4; Atwater and Yamaguchi, 1991, p. 709, Fig. 5). These fine laminae contain well-preserved sand-flat diatoms, including *Cocconeis diminuta*, *Navicula lyra*, *N. cryptolyra*, *Opephora marina*, *Achnanthes delicatula*, and *Trachyneis australis*. Good preservation of these species and the laminae suggests rapid burial and little postdepositional disturbance.

Diatoms 10 cm above the soil (i.e., above the inferred tsunami deposit) are moderately preserved and dominated by tidal-flat species. Stratigraphically higher assemblages contain higher frequencies of low marsh diatoms. The mix of marsh and tidal-flat species and the relatively high ratio of large *Paralia sulcata* to total diatoms suggest the development of a patchy low marsh, and possible sediment reworking. Aggradation to the modern high marsh in the uppermost 10 cm of the section at this site is evident from the increase in diatoms that are found in both high and low marshes.

Site 2

Site 2 is located at the confluence of the Niawiakum River and a small slough, ~1 km upriver from Site 1 (Fig. 2). The 300-yr-old

soil, 15–20 cm thick, contains spruce roots in growth position (Fig. 5). The top of the soil, at ~2.4 m above MLLW, is in sharp contact with overlying mud. Sand probably deposited by a tsunami, which was a prominent feature at Site 1, is reduced to a single lamina of silty, very fine sand 1 mm thick embedded in mud 2–3 mm above the soil that similarly contains sand-flat diatoms.

The position of former EHW in the 300-yr-old soil is identified by the upper limit of high-marsh assemblages in the soil. At the soil-mud contact, visible examination showed that some of the overlying mud had worked downward into interstices in the coarse peaty soil. Rare, well-preserved intertidal diatoms associated with this injected mud were observed in the soil, but there was no indication for the establishment of in situ assemblages at the top of the soil.

Diatoms 5 and 10 cm above the soil consist dominantly of well-preserved tidal-flat diatoms. Aggradation of a low marsh is inferred for the middle part of the section, followed by transition to a high marsh. Diatoms 15 cm below the modern marsh surface are well preserved and consist of an anomalous mix of marsh diatoms (e.g., *Navicula mutica*, *N. pusilla*, *Nitzschia aerophila*) and species that live attached to eelgrass in the lower intertidal zone (*Melosira moniliformis*, *Synedra fasciculata*, and *Hyalodiscus scoticus*). During high-productivity periods, these species are easily torn from eelgrass beds and deposited on the outer edges of marsh surfaces by receding tides (Hemphill-Haley, 1993a, in press). This mixed assemblage is probably a result of sampling on the outer part of the marsh and recovering the in situ high-marsh assemblage mixed with allochthonous diatoms from the channel bank.

Possible evidence for a storm deposit in the 300-yr-old soil is suggested by the occurrence of anomalous subarctic planktonic diatoms (*Rhizosolenia hebetata* and *Denticulopsis seminae*) and rare benthic species in a silty zone about 10 cm below the top of the soil. It differs both stratigraphically and paleontologically from the proposed tsunami deposit. The tsunami deposit consists of a continuous sandy interval of fine-sand laminae, embedded in mud above the buried soil, that pinches out landward. Its stratigraphic position suggests that it was deposited soon after submergence of the 300-yr-old soil. In contrast, the possible storm deposit consists of a discontinuous silty zone within the soil and shows no evidence for association with coseismic submergence.

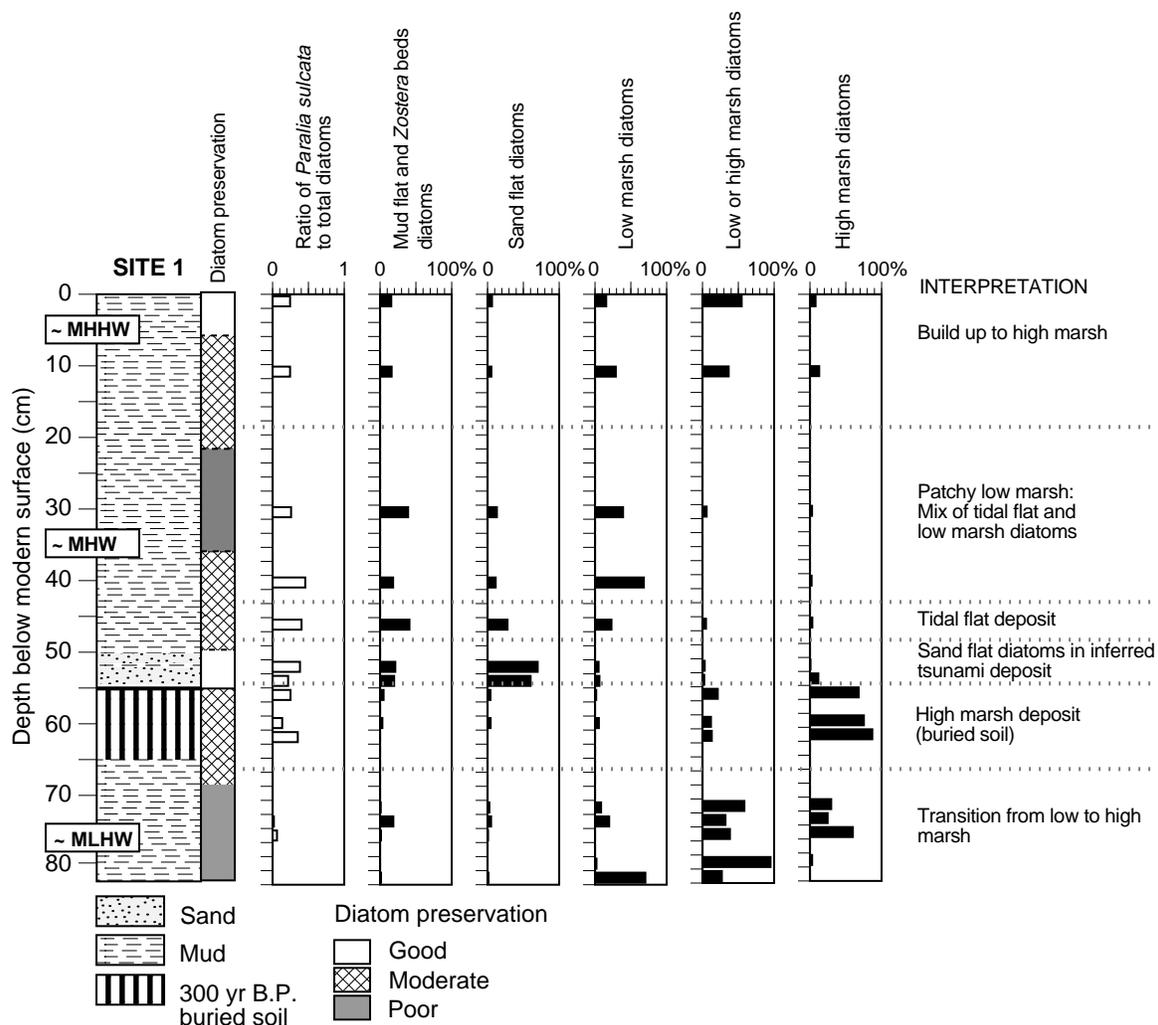


Figure 4. Diatom assemblages from Site 1, along the lower Niawiakum River. Sample depths are relative to the modern marsh surface; approximate positions of modern tidal datums are shown on the left.

Tsunami and storms would both bring estuarine and marine diatoms ashore, and it is unlikely that in most cases it would be possible to differentiate the type of deposit based on diatom assemblages alone. At this particular locality, however, diatoms are abundant in the proposed tsunami sand and consist of a dominantly benthic tidal-flat assemblage, whereas diatoms are rare in the proposed storm deposit and include planktonic species that normally live in the upper water column and, therefore, may have been more easily blown or washed ashore by high winds.

Site 3

Site 3 is located along a narrow stretch of the Niawiakum River, in the upper-middle

part of the valley (Fig. 2). The 300-yr-old soil is 15–20 cm thick and represents a spruce forest that existed at or above former EHW (Fig. 6). The top of the soil is positioned at ~2.2 m above MLLW. Diatoms are virtually absent from the upper part of the soil, as was the situation at Site 2 for a forest-soil deposited above EHW. Rapidly deposited mud 1–3 cm above the soil contains small black organic bodies, 0.5–1 cm thick and 5–15 cm long, which diatom analysis suggests are pieces of low marsh soil that were ripped up and deposited with the mud. They are unrelated to the buried upland soil and are overlain by a 0.5-cm-thick zone of very fine sand that contains sand-flat diatoms and is probably equivalent to similar sand layers at Sites 1 and 2. Therefore, the few centimeters of mud directly above the soil and

the anomalous pieces of low-marsh soil were rapidly deposited during or before the tsunami sand. Poorly preserved assemblages 15 cm above the soil may suggest a period of sediment abrasion and reworking, followed by aggradation of a low marsh. The transition from low to high marsh is suggested by a shift in dominance from low-marsh diatoms in the lower part of the column to species found in low and high marshes, but most commonly above MHW where vegetation is usually thickest.

Site 4

Site 4 is located on a meander along the upper reaches of the tidal Niawiakum River (Fig. 2). The river channel is steep and narrow at this locality, with the floor of the

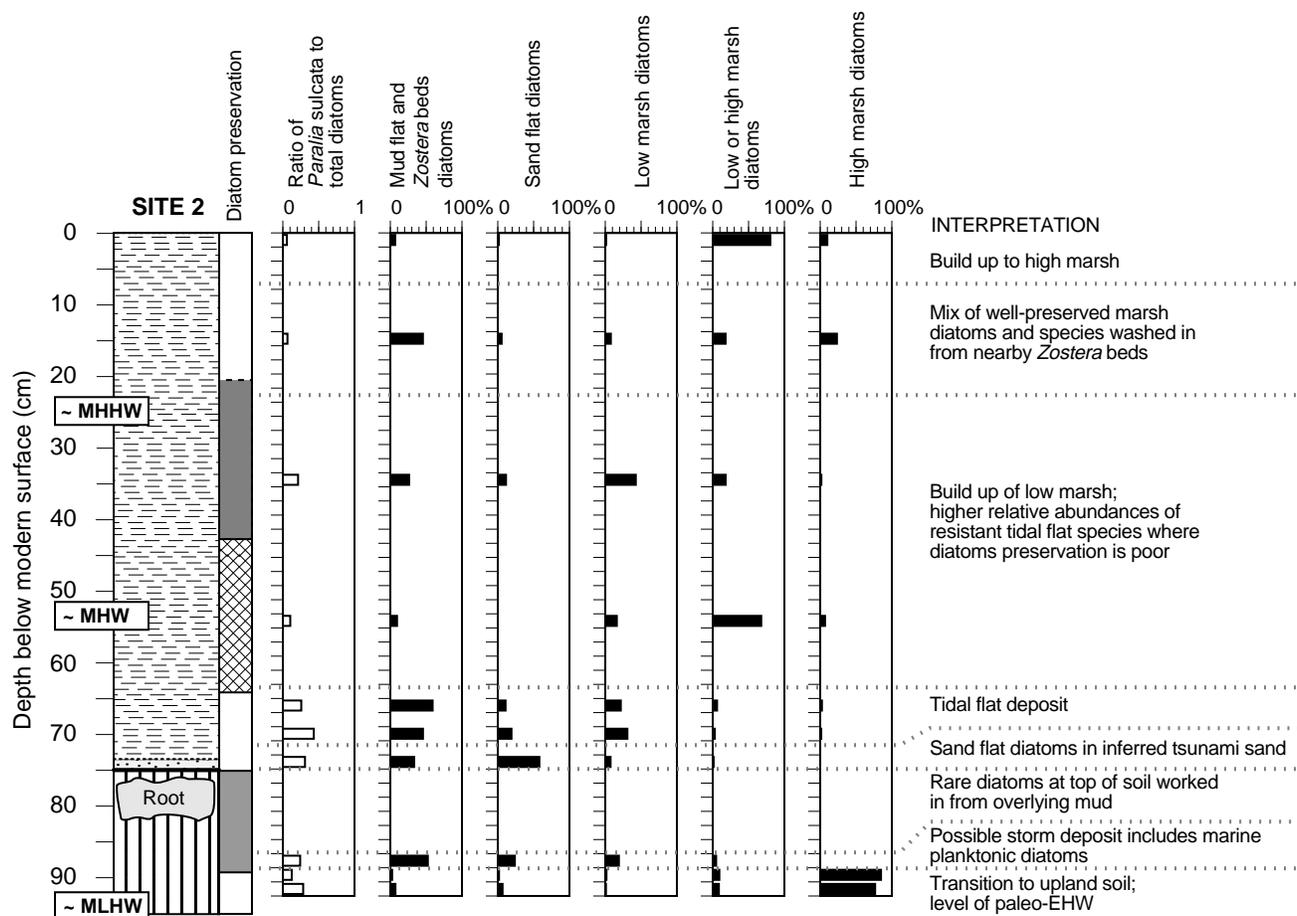


Figure 5. Diatoms from Site 2, along the middle Niawiakum River. Sample depths are relative to the modern marsh surface; approximate positions of modern tidal datums are shown on the left. Symbols are the same as for Figure 4.

channel close to MLLW. As at Sites 2 and 3, the 300-yr-old buried soil represents a former spruce forest that lined the river channel. The top of the soil, ~2.2 m above MLLW, forms a sharp contact with overlying mud. Discrete fine-sand laminae, visible above the 300-yr-old soil in the outcrops at Sites 1–3, were not observed at or near this locality (see also Atwater, 1987, Fig. 3e). However, sand-flat diatoms found 1 cm above the top of the buried soil are comparable to species found in sand laminae above the 300-yr-old soil at Sites 1–3. These silt-sized diatoms may have been deposited by a tsunami, beyond the up-valley extent of preservation of sand laminae. Overall good preservation of lower intertidal diatoms in this sample also suggests rapid deposition and burial of diatom valves from a bayward source. Aggradation of low-marsh deposits and minimal sediment reworking 10–20 cm above the soil is followed by a transition to high-marsh deposits in the upper part of the section.

DISCUSSION

The signature of coseismic subsidence of low-lying coastal areas, as documented during historic events in Chile and Alaska (Plafker, 1965, 1972; Plafker and Savage, 1970), is geologically instantaneous sea-level rise and submergence. The amount of submergence is variable over large areas (Plafker, 1965, 1969, 1972) and includes large-scale crustal deformation, as well as local deformation from liquefaction (McCulloch and Bonilla, 1970). Diatom assemblages representing this geologically instant sea-level rise should be fundamentally different from assemblages that accumulated during periods of slower submergence, if the amount of submergence is large enough to cause the stratigraphic juxtaposition of ecological zones that are not normally adjacent in coastal settings (e.g., uplands and low marshes, uplands and tidal flats, high marshes and tidal flats). In addition, because diatom populations become estab-

lished within days to weeks on moist surfaces and in shallow standing water, fossil assemblages would be expected to be found at the tops of soils that were inundated by rising sea level in even relatively short amounts of time.

Coseismic subsidence also implies lasting submergence due to land-level change, not temporary submergence and sediment burial caused by storms. Along the Niawiakum River, Atwater (1987) noted that plant fossils in the buried soil and overlying mud suggested that upland or high intertidal vegetation, once buried, failed to become re-established and were replaced by *Triglochin maritima*, a species that is most common in low salt marshes fringing the open bay, where it forms thick stands with *Salicornia virginica* (Hemphill-Haley, in press). Diatoms deposited by storms would be expected to include a mixture of transported valves, possibly including planktonic marine species, whereas diatoms accumulating in new habitats caused by lasting submergence

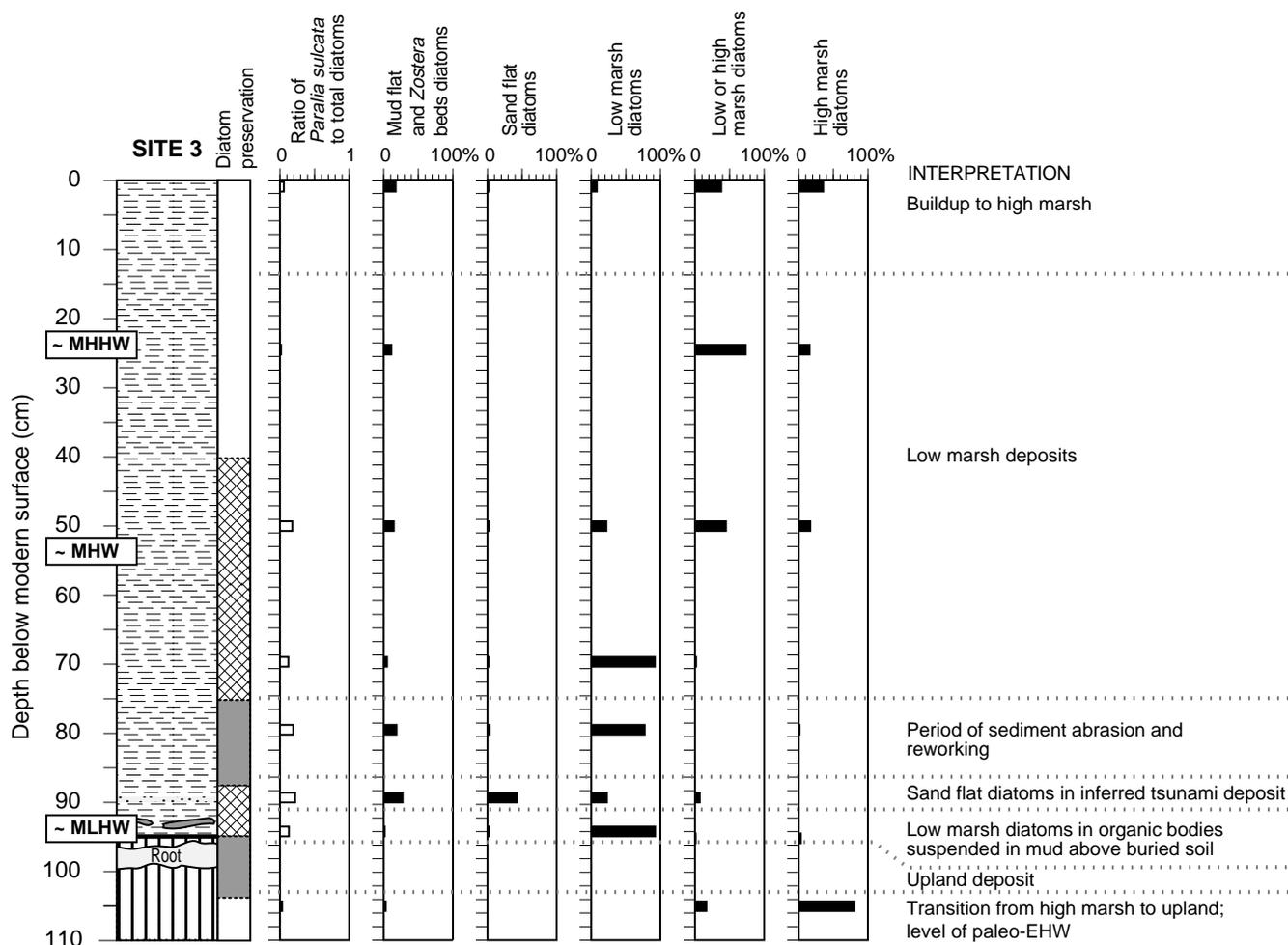


Figure 6. Diatoms from Site 3, along the middle Niawiakum River. Sample depths are relative to the modern marsh surface; approximate positions of modern tidal datums are shown on the left. Symbols are the same as for Figure 4.

should be dominated by species associated with the new habitat only.

The amount of land-level change as a result of subduction zone earthquakes is dependent on location relative to broad zones parallel to the trench where strain release allows flexing of the overriding plate (Plafker, 1972). A well-documented case of coseismic subsidence occurred near Portage, Alaska, where the land subsided a total of about 2.3 m (Plafker, 1969, 1972), including about 1.6 m of actual crustal subsidence plus an additional 0.8 m of settling related to liquefaction (McCulloch and Bonilla, 1970). If intertidal zones can be reconstructed based on fossil diatom assemblages, then the amount of coseismic submergence and elevational change that occurred may be broadly estimated. The errors involved with such an estimate for the Willapa Bay area are large, however, because (1) the in-

tertidal zones, particularly the tidal flat and low marsh zones, are relatively broad due to the relatively large tidal range; (2) the boundaries between intertidal zones are typically gradational, which may introduce some ambiguities into ecological assemblages; and (3) postseismic rebound, which may occur for months to years following an earthquake (Brown et al., 1977; Savage and Plafker, 1991), may modify the sedimentary unit overlying the buried surface and reduce the thickness of sediment accumulating at lower elevations. Although there will necessarily be large errors involved, diatom assemblages should nonetheless provide enough information to make inferences about minimum net elevational changes.

Tsunami commonly accompany subduction-zone earthquakes (Plafker, 1972). Along the Niawiakum River, Atwater

(1987) proposed that a tsunami generated by the earthquake 300 yr ago deposited anomalous layers of coarse silt and fine sand above the buried soil, and Reinhart and Bourgeois (1989) used sediment-transport analysis to conclude that the distribution of the sand laminae capping the soil was best explained by a tsunami moving up-valley, as opposed to deposition by a seiche or storm. Diatoms associated with an up-estuary tsunami surge could be expected to include estuarine and marine species associated with sandy shoals of the open estuary and would be easily differentiated from fresh-water species that might be associated with a downriver flood.

In the following discussion, rapid submergence, lasting submergence, estimate of amount of submergence, and tsunami deposition based on diatom paleoecology are presented and interpreted.

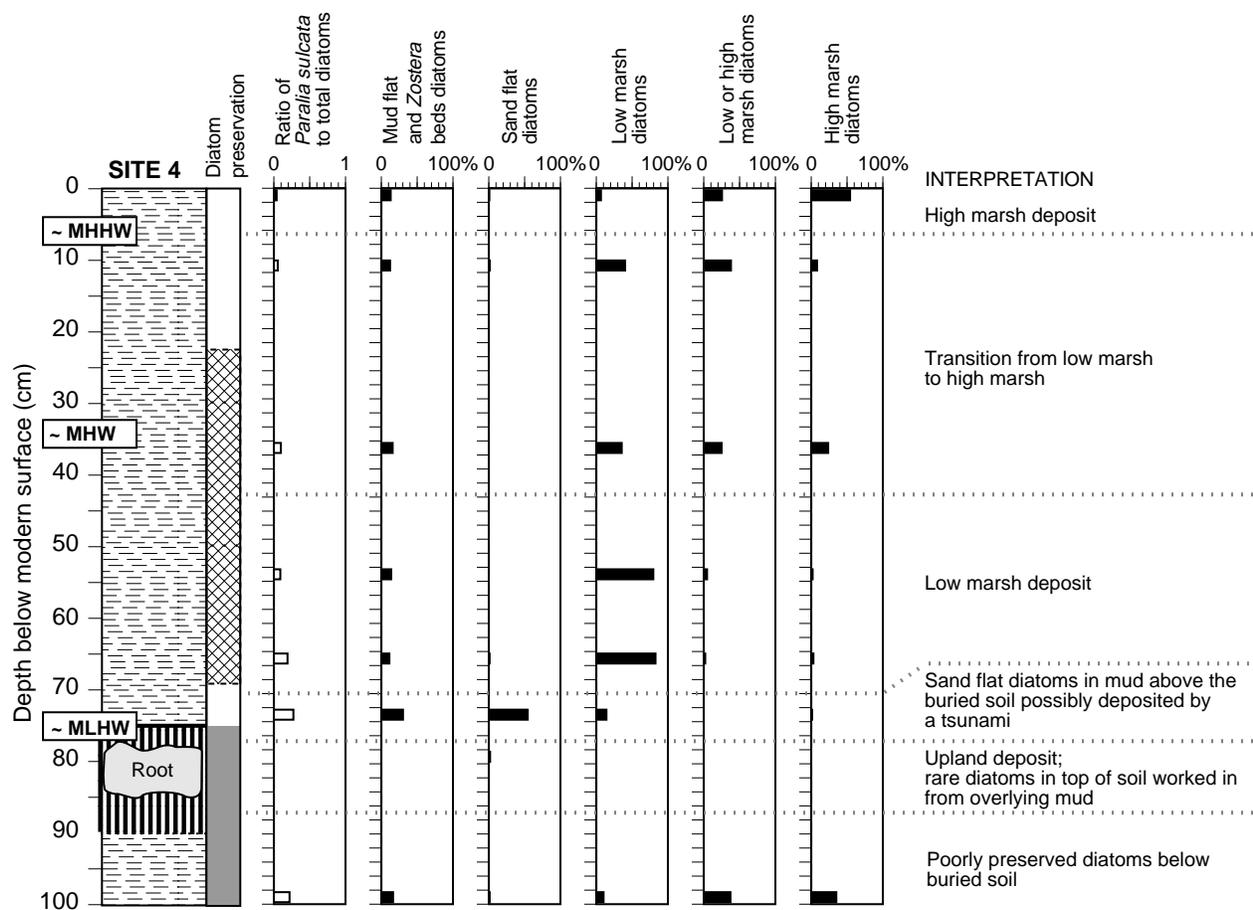


Figure 7. Diatoms from Site 4, in the upper Niawiakum River valley. Sample depths are relative to the modern marsh surface; approximate positions of modern tidal datums are shown on the left. Symbols are the same as for Figure 4.

Diatom Evidence for Rapid Submergence

Diatoms in the uppermost part of the 300-yr-old soil and the lowermost overlying mud provide straightforward evidence for a sudden sea-level change. Diatoms are fast-growing (life spans of days to weeks) and abundant on all intertidal surfaces, especially the surfaces of high marshes immediately below the elevation of adjacent forested uplands. Diatoms do not typically grow on dry upland surfaces of Willapa Bay but produce large populations in isolated places where water is ponded for days or weeks at a time (Hemphill-Haley, unpub. data). At Sites 2–4, where the 300-yr-old soil represents a former spruce forest, detailed sampling on either side of the contact between the soil and overlying mud shows a rapid change from upland deposits to tidal-flat or low-marsh deposits, bypassing the intervening high marsh. Had sea level taken only weeks to months to completely submerge the Niawiakum River Valley 300 yr

ago, instead of possibly minutes to hours following an earthquake, moistening and ponding of the forest floor would have provided ample habitats for diatom growth. However, there is no record for the accumulation of any high marsh or aquatic diatoms at the top of the soil before the deposition of the overlying intertidal mud. In addition, similarities among the diatom records for the farthest up-valley site (Site 4) and the other locations (i.e., occurrences of well-preserved sand-flat diatoms above the buried soil, progression from tidal-flat assemblages to marsh assemblages) further suggests that sea level did not progressively flood the valley.

Diatom Evidence for Lasting Submergence

Diatoms in the mud overlying the 300-yr-old soil suggest a lasting shift from a high-marsh or upland environment to a tidal-flat or low-marsh environment, rather than a

temporary submergence caused by a storm surge. This is in contrast to a potential storm-related deposit 15–20 cm below the top of the 300-yr-old soil at Site 2 (Fig. 2). Here, the presence of cold-water marine planktonic diatoms (*Rhizosolenia styliformis* and *Neodenticula seminae*; Akiba, 1985) in a silty zone within the soil (Fig. 5) suggests that open-marine deposits washed across upland surfaces, with diatom transport possibly supplemented by strong winds (e.g., Du Saar, 1967). Continued soil development stratigraphically above this level suggests that storm deposition had a positive effect on aggradation and did not impede the growth of the established plants or pedogenesis. In contrast, the mud that buries the 300-yr-old soil provides a consistent pattern based on diatoms of a sudden initial shift to tidal-flat or low-marsh elevations, followed by gradual aggradation to a high marsh. After 300 yr the surfaces at Sites 2–4, which were forested prior to submergence, have yet to build up out of the reach of the tides.

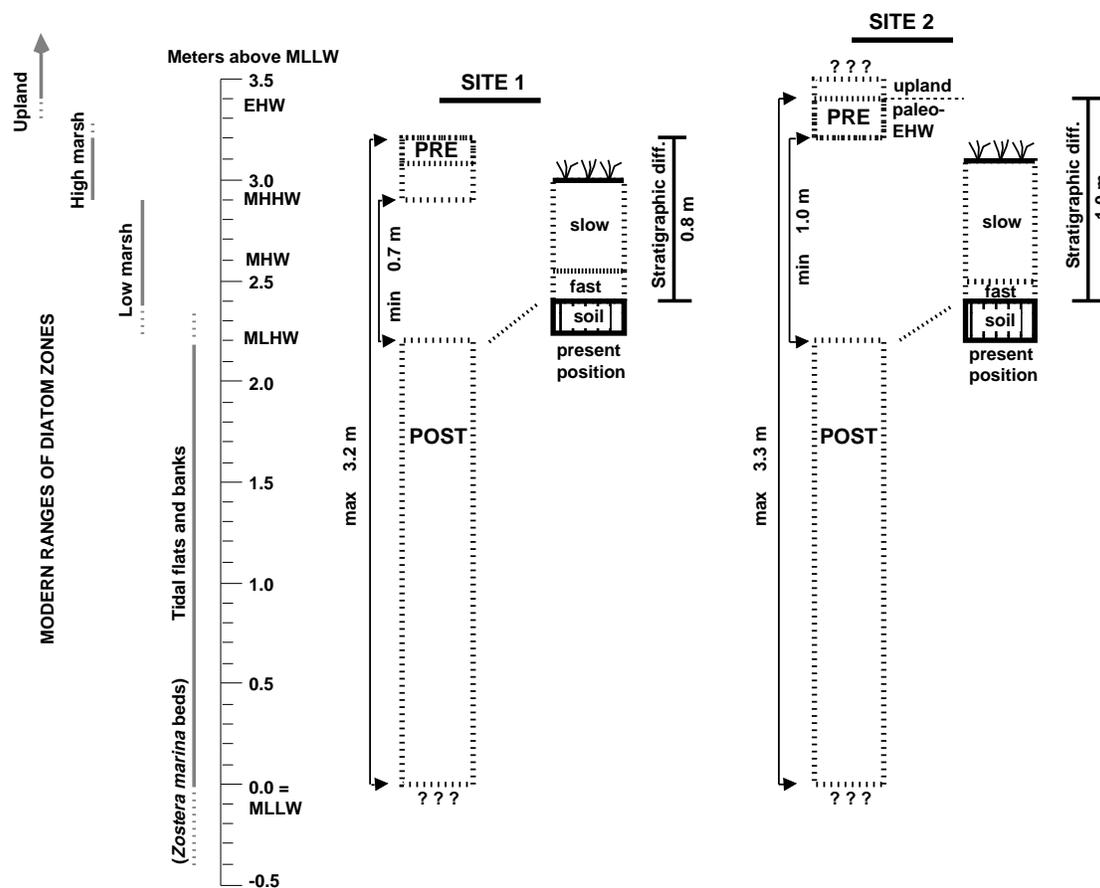


Figure 8. Possible minimum and maximum ranges of submergence of 300-yr-old soil at Sites 1 and 2 based on diatom assemblages, and present intertidal position of buried soil and overlying mud. The elevational ranges of diatom zones used in this study, relative to modern tide level, are shown on the left. PRE = range of elevations of surface before submergence 300 yr ago; POST = possible range of surface after submergence; slow = sediment that accumulated slowly, based on inferior diatom preservation; fast = sediment deposited rapidly, based on superior diatom preservation; soil = modern elevation of 300-yr-old buried soil; Stratigraphic diff. = apparent change in elevation based on present-day intertidal position and approximate elevation for marsh or upland soil development; ??? = upper or lower boundary imprecisely known.

Diatom Evidence for Amount of Coseismic Submergence

Diatoms may be used to make general inferences about absolute amounts of coseismic submergence, but estimates are limited by several important factors. First, the elevational ranges of the ecological zones used in this study (upland, high marsh, low marsh, tidal flat) are a function of local tidal range and cannot be estimated unless the tidal range is known. Furthermore, because the widths of intertidal zones will increase with increasing tidal range, larger tidal ranges will result in larger errors. Second, the boundaries between the zones are diffuse, probably in response to the regular fluctuations in tidal height, and cannot be precisely reconstructed (Frey and Basan, 1985; Nelson and Kashima, 1993). Third,

poor preservation of indicator species or dominance of transported valves will hinder paleoecological interpretations.

At the four sites studied along the Nia-wiakum River, the 300-yr-old buried soil is stratigraphically positioned ~0.8–1.1 m below the elevations of modern high-marsh or upland soils. Based on the diatom data, two general models could explain the stratigraphy as presently observed along the Nia-wiakum River: (1) the buried soil was submerged to the level of its present intertidal position, or (2) the buried soil was submerged to a level below its present intertidal position, but its intertidal elevation has been modified by postseismic uplift. Based on these models, submergence histories for Sites 1 and 2 (Fig. 2) can be inferred using diatom assemblages and the modern tidal range. Sites 3 and 4 are excluded from this

discussion because of greater uncertainties in estimating both tidal datums and the pre-earthquake elevation of the buried soil.

At both Sites 1 and 2, mud containing predominantly tidal-flat diatoms directly overlies the buried soil (Figs. 4 and 5). At Site 1, the pre-earthquake surface (PRE, Fig. 8) was a high marsh that would have been positioned between ~2.9 and 3.3 m above MLLW, and possibly in the range of 3.2–3.3 m above MLLW based on the predominance of diatoms found in the highest part of the modern high marsh at this location. The top of the buried soil is presently positioned at 2.4 m above MLLW. Using model 1, the soil would have been submerged to its present intertidal elevation (~0.7–0.8 m), with about 20 cm of tidal-flat mud rapidly deposited on top of it, followed by more gradual accumulation of mud in the low

marsh zone. Using model 2, the deposition of predominantly lower intertidal diatoms directly above the buried soil could suggest that the postearthquake surface (POST, Fig. 8) was submerged farther into the lower intertidal zone, equating to an elevational change from a minimum of 0.7 m to a maximum of >3.0 m (Fig. 8). By comparison, the maximum amount of subsidence documented in both the 1960 Chile and 1964 Alaska earthquakes was 2.3 m (Plafker, 1972).

At Site 2, in situ spruce roots in the upper part of the 300-yr-old soil suggest that it was formerly an upland forest, the upper limit of which is unknown. Because EHW ($\approx 3.3\text{--}3.4$ m above MLLW) is the approximate upper limit for diatom growth on the modern marsh surfaces in this area, however, it is possible to approximate the level of paleo-EHW by the upper limit of high-marsh diatoms in the buried soil. At Site 2, this level is observed $\sim 15\text{--}20$ cm below the top of the buried soil, at the transition to upland deposits (Fig. 5). Although the age of paleo-EHW exceeds that of the top of the soil by an undetermined amount of time (i.e., that required to produce $\approx 15\text{--}20$ cm of forest peat), the presence of paleo-EHW in the stratigraphy still provides a useful alternative pre-earthquake datum, because the upper limit of upland surfaces cannot be determined. The level of paleo-EHW in the buried soil is presently positioned at $\sim 2.2\text{--}2.3$ m above MLLW. Using model 1, the soil would have been submerged to its present intertidal position (a change of $\sim 1.0\text{--}1.1$ m), with rapid sedimentation of tidal-flat mud followed by slower accumulation of mud in the low-marsh zone, as was also observed at Site 1. Using model 2, the presence of tidal-flat diatoms in mud 10–15 cm above the buried soil could indicate submergence of the forest surface farther into the lower intertidal zone, suggesting an elevational change from a minimum of 1.0 m to a maximum of >3.0 m (Fig. 8).

Diatoms are useful for differentiating various types of intertidal depositional environments that may be difficult to discern directly from the stratigraphy, but if parts of the stratigraphic record are missing, then the diatom record will be incomplete. In general, the diatom record at Sites 1 and 2 can be best explained by model 1, that is, well-preserved tidal-flat diatoms rapidly deposited directly above the soil at its present intertidal elevation. Because of postseismic rebound, however, this record may be incomplete.

Postseismic rebound will result in a smaller amount of time for intertidal habitats to develop and gradually aggrade and, by raising the ground level, increase erosion and reduce the thickness of stratigraphic sections overlying submerged surfaces. For example, the effects of about 0.5 m of postseismic rebound for submerged areas near Portage, Alaska (measured 12 yr after the earthquake by Brown et al., 1977), has resulted in stratigraphic sections where the buried soil is overlain by a thinner unit of intertidal silt than would be expected from the documented amount of submergence. Similarly, postseismic rebound on Kodiak Island since the 1964 earthquake is creating more rapid transitions from lower to higher intertidal zones than would normally occur through gradual sedimentation and marsh buildup and is reducing the thickness of the sedimentary record above the buried 1964 soil (L. Gilpin, 1993, personal commun.). Postseismic rebound, therefore, could limit the amount of time for fossil diatom assemblages to accumulate at lower intertidal or subtidal levels and enhance the establishment of populations at higher intertidal levels. With or without the possibility that erosion may have removed part of the stratigraphic section during uplift, the result would be a biased biostratigraphic record suggesting a smaller amount of submergence than had in fact occurred.

Therefore, the diatom record at Sites 1 and 2 could support a model of ~ 1.0 m of submergence without postseismic rebound, or up to several meters of submergence if postseismic rebound occurred. Tide gauge and leveling measurement suggest that the Willapa Bay is presently experiencing little or no uplift (Mitchell et al., 1994), but because of the prevalence of postseismic deformation following subduction-zone earthquakes, the possibility of a greater amount of submergence than is suggested from the thickness of stratigraphic units along the Niawiakum River cannot be ruled out.

Diatom Evidence for Tsunami Deposition

Diatoms can be used to determine an estuarine, marine, or fresh-water source for suspected tsunami deposits, thereby distinguishing up-valley surges from downriver floods, but they cannot be used to determine the actual mechanism of transport, be it tsunami, storm, or seiche. The presence of open estuarine sand-flat species in sandy laminae capping the 300-yr-old soil suggests a bayward source for the sand, as opposed to

a downriver flood deposit. At the farthest up-valley site along the Niawiakum River, coherent sand laminae are not visible in outcrop, but rare occurrences of the same sand-flat species as found in down-valley sand laminae suggest that the tsunami extended at least as far up-valley as Site 4 (Fig. 2). Well-preserved diatoms in sediment 5–10 cm above the buried soil suggest that the diatoms were buried and protected from degradation at the sediment surface (e.g., Plater and Poolton, 1992). Therefore, diatoms may be useful for identifying rapidly deposited tsunami-related sediment that might otherwise be indistinguishable from the remaining sediment column.

CONCLUSIONS

Diatoms below, within, and above a buried soil support a model of coseismic subsidence to explain submergence 300 yr ago along the Niawiakum River in southwestern Washington.

(1) Sudden submergence is suggested by an abrupt shift from diatom-poor upland deposits to tidal-flat or low-marsh diatom assemblages, bypassing assemblages that are associated with the intervening, distinctive high marsh. Coseismic processes are favored over eustatic processes because the diatom record shows no evidence for gradual flooding of dry upland surfaces, and similarly abrupt biostratigraphic changes at all four sites suggest that the submergence did not progressively move up-valley.

(2) Lasting submergence, as opposed to a temporary storm surge and sediment deposition, is suggested by the slow aggradation of intertidal deposits overlying the buried soil, following a probable initial short, rapid pulse associated with tsunami deposition and rapid sedimentation immediately following submergence. Modern surfaces along the Niawiakum River have yet to return to elevations relative to tide level that they occupied prior to 300 yr ago.

(3) The amount of coseismic submergence along the Niawiakum River 300 yr ago, based on present-day tidal datums, could have ranged from a minimum of $\sim 0.8\text{--}1.0$ m to a maximum of >3.0 m. Uncertainties in determining absolute elevational changes based on diatoms arise from the associations of species with intertidal zones that are broad and have gradational boundaries, and from the indeterminate effects of postseismic rebound on the biostratigraphic record.

(4) Sand-flat diatoms associated with fine-

sand laminae interbedded with mud capping the 300-yr-old soil imply a bayward source for the sand and are consistent with deposition by a tsunami. Occurrences of the same sand-flat species in mud capping the soil at the farthest up-valley site where sand laminae are not visible suggest that the tsunami may have extended at least that far up-valley, and that it may be possible to use diatoms to estimate the landward extent of tsunami deposits beyond the range of distinct stratigraphic markers.

The results of this study show the usefulness of diatom paleoecology as a tool for reconstructing the ecological effects of paleo-sea-level changes, including those that may be associated with tectonic activity.

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