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Holocene Relative Sea Level Changes along the Seattle Fault at Restoration Point, Washington

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At a marsh on the hanging wall of the Seattle fault, fossil brackish water diatom and plant seed assemblages show that the marsh lay near sea level between ~7500 and 1000 cal yr B.P. This marsh is uniquely situated for recording environmental changes associated with past earthquakes on the Seattle fault. Since 7500 cal yr B.P., changes in fossil diatoms and seeds record several rapid environmental changes. In the earliest of these, brackish conditions changed to freshwater ~6900 cal yr B.P., possibly because of coseismic uplift or beach berm accretion. If coseismic uplift produced the freshening ~6900 cal yr B.P., that uplift probably did not exceed 2 m. During another event about 1700 cal yr B.P., brackish plant and diatom assemblages changed rapidly to a tidal flat assemblage because of either tectonic subsidence or berm erosion. The site then remained a tideflat until the most recent event, when an abrupt shift from tideflat diatoms to freshwater taxa resulted from ~7 m of uplift during an earthquake on the Seattle fault ~1000 cal yr B.P. Regardless of the earlier events, no Seattle fault earthquake similar to the one ~1000 cal yr B.P. occurred at any other time in the past 7500 years.

Key Words: **relative sea level; Holocene; earthquakes; diatoms; seeds.**

INTRODUCTION

The Seattle fault zone, which crosses central Puget Sound with few surface traces, poses a poorly understood hazard to the Seattle metropolitan area. A late Holocene earthquake, with a magnitude (M) of 7 or more, occurred on the northernmost fault of the zone between A.D. 900 and 930, or roughly 1000 cal yr B.P. (Bucknam *et al.*, 1992; Atwater, 1999). However, no other examples of large earthquakes have been identified for the Seattle fault. In this paper, we consider the recurrence of large earthquakes on the Seattle fault by reporting the paleoenvironmental history of a formerly coastal marsh at Restoration Point, Bainbridge Island (Fig. 1). Because the marsh is underlain largely by intertidal deposits spanning the past 7500 years and because it adjoins a wave-cut platform that was uplifted about 7 m during the earthquake ~1000 cal yr B.P. (Bucknam *et al.*, 1992), uplift from other Holocene earthquakes has the potential of being recorded there.

We focus on paleoenvironmental history because plants and other organisms that live in the upper part of the intertidal zone are sensitive to environmental factors that are related, in large measure, to elevation (Macdonald, 1977). Sudden changes in the elevation of coastal marshes produce abrupt environmental changes and shifts in the types and relative abundance of marsh organisms. Sediment accumulating in coastal marshes preserves a stratigraphic record of these environmental changes, as was first demonstrated for marshes that subsided during the 1964 Alaska earthquake (Ovenshine *et al.*, 1976).

In our paleoenvironmental reconstruction for the Restoration Point marsh, we see no abrupt change in relative sea level (RSL) nearly as large as the uplift during the Seattle fault earthquake ~1000 cal yr B.P. However, we do infer environmental changes that could represent smaller earthquakes or, alternatively, the opening and closing of a beach berm.

PREVIOUS WORK

Seattle Fault

Uplifted wave-cut marine platforms were identified a century ago at Restoration Point on the west side of Puget Sound

Supplementary data for this article are available on the journal homepage (http://www.academicpress.com/qr).

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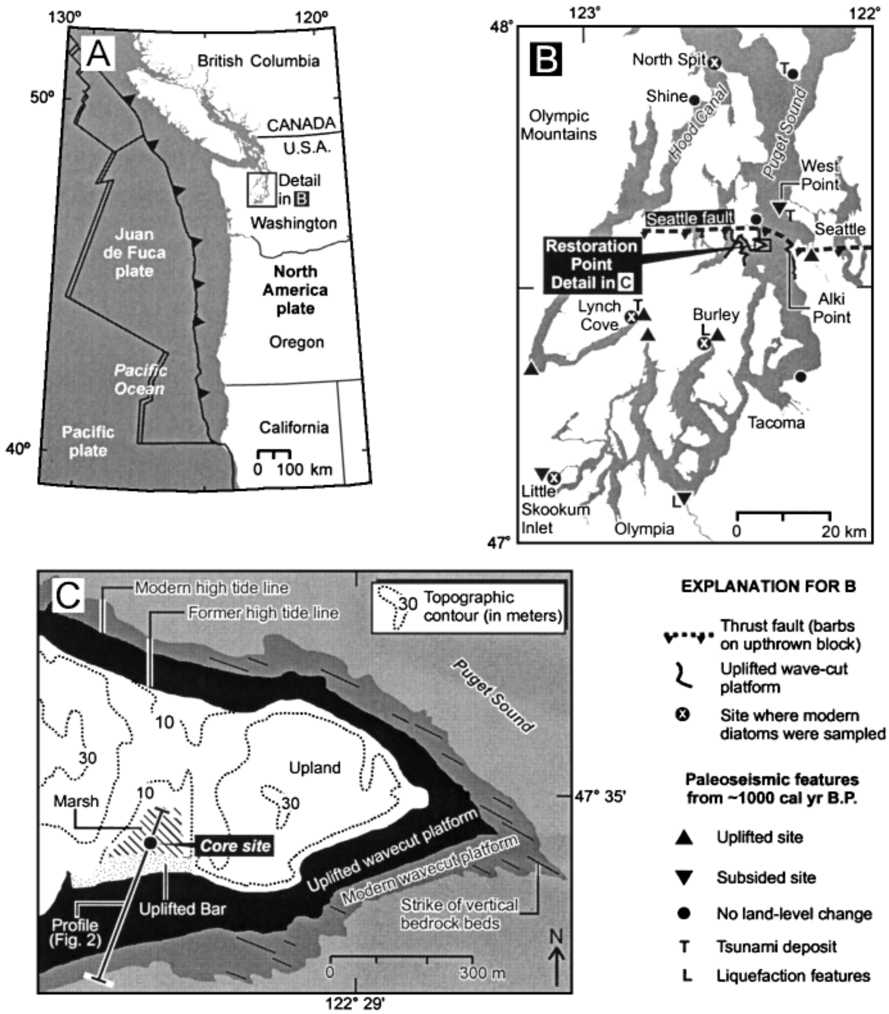

FIG. 1. Index maps. (A) Regional Setting. (B) Central Puget Sound. The trace of the Seattle fault is from Johnson *et al.* (1999). Paleoseismic features shown are from Bucknam *et al.* (1992) and Sherrod (1998). (C) Restoration Point.

and Alki Point on the east side of Puget Sound near Seattle (Kimball, 1897; Fig. 1). Geophysical studies in the late 1960s showed that a fault lies north of the uplifted platform (Danes *et al.*, 1965; Rogers, 1970). Uplifted shells of marine mollusks on the platform provided an early clue that this fault was active in the late Holocene (Yount, 1983; Gower *et al.*, 1985).

Restoration Point is now known to lie within a zone of faults having up to 900 m of Quaternary structural relief (Johnson *et al.*, 1999). The northernmost strand, the Seattle fault of Yount and Holmes (1992), projects to the surface about 3.5 km north of Restoration Point and dips to the south. Slip on this strand ~1000 cal yr B.P. produced 5–7 m of uplift in a band 6 km wide south of the fault, while areas to the north subsided as much as a meter (Bucknam *et al.*, 1992; Atwater and Moore, 1992; Jacoby *et al.*, 1992).

A scarp along a north-dipping fault within the Seattle fault zone, identified by airborne laser mapping, crosses Bainbridge Island about 2 km north–northwest of Restoration Point (Bucknam *et al.*, 1999). Stratigraphy and structure exposed in trenches excavated across the south-facing scarp indicate a long history of folding and faulting, the most recent event ~1200 cal yr B.P. (Nelson *et al.*, 1999). Because the scarp is not present on the uplifted wave-cut platform, Bucknam *et al.* (1999) inferred that the last movement on the north-dipping fault predates the Seattle fault earthquake ~1000 cal yr B.P.

Holocene Sea Levels

At Puget Sound and vicinity, RSL was near its present position throughout the late Holocene. By 5000 cal yr B.P., it had risen to within 2–3 m of its present position in northern Puget Sound and southern British Columbia (Beale, 1990; Clague *et al.*, 1982). At Shine along northern Hood Canal (Fig. 1B), RSL rose to within about 6 m of its present position by 6000 cal yr B.P. (Eronen *et al.*, 1987). No study shows that RSL in Puget Sound rose more than a meter in the past 1000 yr.

SETTING

Restoration Point

Restoration Point is the tip of a small peninsula at the southeast end of Bainbridge Island, 11 km west of downtown Seattle (Fig. 1B). Fringing the peninsula is an uplifted wave-cut platform composed of steeply dipping siltstone and sandstone of the Oligocene Blakeley formation (Waldron, 1967).

A marsh lies behind a berm of gravelly sand at the landward edge of the uplifted platform (Figs. 1B and 2A). This berm, which connects a bedrock hill at the eastern end of the peninsula to the remainder of the island, was an intertidal beach bar at the time of uplift ~1000 cal yr B.P. Deposits beneath the marsh evince a history of brackish and marine conditions prior to uplift (Fig. 2B). Although the marsh now has standing water most of the year, past landowners drained the marsh and plowed it.

Tidal Marsh Zonation

Following Macdonald (1977), we subdivide coastal marshes into three broad categories primarily based on salinity and tidal inundation, which the modern and fossil plants reflect. Freshwater marshes typically have surface salinities of 0–3 parts per thousand (‰) and occur at or above the extreme high tide line. Brackish-water marsh environments have salinities of 3–20‰ and are broken into two subenvironments: low marsh and high marsh. Low marshes typically lie between mean high water and mean higher high water, while high marshes fall between mean high water and extreme high water. Brackish-marine environments and tideflats have the highest salinities, of 20–35‰, lie below mean high water, and contain mixtures of brackish species and obligate marine taxa.

FIELD SAMPLING AND LABORATORY METHODS

Stratigraphy and Dating

A transect of borings, 2.5 cm in diameter, shows the general stratigraphy of the marsh (Fig. 2B). For paleoenvironmental details, we studied macrofossils and microfossils from cores collected by pounding plastic pipe (5 and 10 cm diameter) into the marsh deposits (Figs. 3–6). Core segments were correlated by a distinctive change from peat to mud (top of Brown Peat in Fig. 2B). A pit excavated into the marsh surface exposed a 30-cm-thick profile for sample collection, correlated with adjacent cores by depth. We accounted for compaction in the large-diameter cores by relating obvious stratigraphic contacts to the same contacts in small-diameter borings nearby. Extraction of diatoms and macrofossils from core samples followed procedures in Sherrod (1998). Diatom and macrofossil data used in this study are available at the Quaternary Research on-line data repository.

All core elevations are tied to mean lower low water (MLLW), a standard tidal datum. We determined local MLLW by equating measurements of local low tides and high tides at Restoration Point to heights of the same tides observed at Seattle by the National Ocean Survey (http://www.co-ops.nos.noaa.gov). Two determinations of calculated MLLW agreed within 2 cm. Because the tidal ranges at Seattle and a subordinate tidal station at Port Blakely, 2.5 km from Restoration Point, are very nearly the same, our estimate of MLLW is probably within a few centimeters of its true value.

We obtained three radiocarbon ages on peat and charcoal (Table 1). The ages were calibrated with OxCal ver. 3beta2 (Ramsey, 1995), the INTCAL98 data of Stuiver *et al.* (1998), and a laboratory error multiplier of 1. To estimate intervening ages, we used a linear regression of age vs depth (Fig. 3). In this regression, we did not include the age of the detrital charcoal sample at a depth of 30 cm because it gives only a limiting maximum age for deposition.

Inference of Salinity and Elevation from Fossil Diatom Assemblages

Diatoms from a training set of 39 surface sediment samples were collected at several Puget Sound coastal marshes (Fig. 1). The taxa were related to salinity and elevation using multivariate statistical techniques, which showed that diatom distribution is controlled primarily by salinity and secondarily by elevation (Sherrod, 1999). Because diatoms are distributed according to salinity and elevation, we use the term "equivalent elevation changes" in our paleoenvironmental reconstruction to emphasize uncertainty that a change in elevation caused the change in local environment.

Using the computer program WACALIB version 3.3, we created transfer functions to infer past changes in elevation and salinity (Line and Birks, 1990). WACALIB uses a two-step weighted averaging regression and calibration technique to generate transfer functions. The first step (regression) calculates the optimum salinity and elevation values for each taxon in the modern samples. A modern taxon's optimum (μ_k) is the average of all salinity or elevation values for sites where the taxon occurs, weighted by the taxon's relative abundance at each site. The second step (calibration) estimates salinity or elevation from a fossil assemblage. This is accomplished by averaging the μ_k for each environmental variable of interest, weighted by the relative abundance of each taxon in the fossil assemblage (see Birks, 1995).

We estimated error associated with the modern data set by removing one sample (test sample) from the modern data set, recalculating the transfer functions, and inferring the elevation and salinity of the test sample. These three steps are repeated for each sample in the modern data set. To estimate error associated with inferences, we compared the inferred values with the measured values for each test sample.

The largest source of error in the calibration process is lack of a close modern analog in the training set. We used a similarity measure (squared-chord distance) that compares relative percentages of species shared between fossil and modern

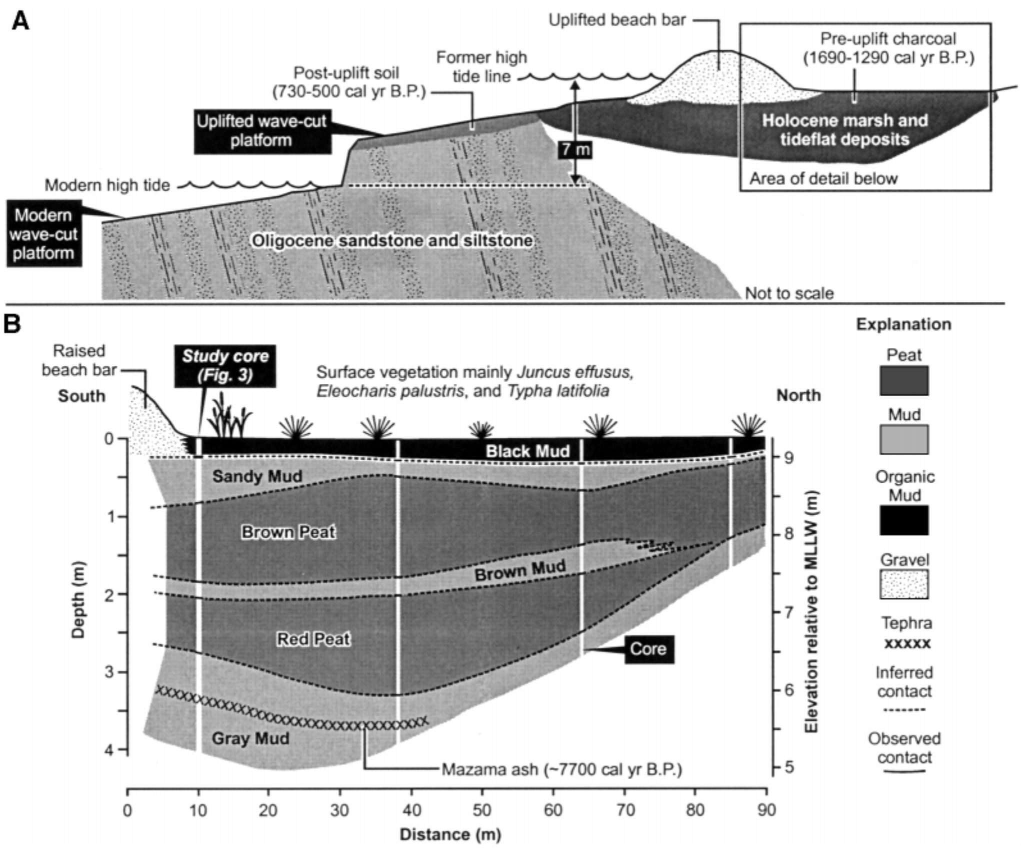

FIG. 2. Diagrammatic cross-section across uplifted wave-cut platform at Restoration Point and cross-section of marsh constructed from cores. Additional stratigraphic data are from Bucknam *et al.* (1994). Uplift at this site ~1000 cal yr B.P. was about 7 m, as measured by the difference in the elevations of the former shoreline angle and the present shoreline angle (Bucknam *et al.,* 1992).

samples to determine whether the assemblages in each sample are comparable. If a fossil assemblage resembles a modern one, the fossil assemblage is assumed to have an analog in the modern data set. We took the extreme upper and lower 5% of the similarity values calculated among all modern samples as threshold values to indicate whether a fossil sample has a modern analog (Birks, 1995, p. 208). Similarity analyses indicate that all but three samples (identified in Fig. 6) have modern analogs in the training set.

LITHO- AND CHRONOSTRATIGRAPHY OF MARSH DEPOSITS

Peat and mud beneath the marsh appear to fill a small basin that is deepest near the center and shallows gradually toward the edges (Fig. 2A). Some of these deposits underlie a meter-thick layer of sand and sandy gravel seaward of the former beach bar south of the marsh.

At least six stratigraphic units lie beneath the marsh surface. The oldest unit is a laminated to massive mud (informally called the Gray Mud) that contains a thin tephra identified as Mazama ash (Fig. 2B). Overlying the Gray Mud is peat composed mainly of coarse detritus (Red Peat). Massive organic-rich mud (Brown Mud) overlies the Red Peat, which is in turn overlain by peat containing coarse detritus (Brown Peat). A sharp contact separates the Brown Peat from overlying deposits of sandy mud containing rounded charcoal clasts (Sandy Mud). Organic mud caps the sequence (Black Mud).

Radiocarbon and tephra samples from the study core and from a nearby trench show that deposition began prior to deposition of Mazama ash (7790–7580 cal yr B.P.; Zdanowicz *et al.*, 1999) and continued through the latest Holocene (Fig. 3; Table 1). A centimeter-thick sample of peat from immediately above the contact between the Gray Mud and the Red Peat gave an age of 6670–6200 cal yr B.P. Peat from the upper centimeter of the Brown Peat dates to 1870–1530 cal yr B.P.; rounded charcoal clasts from near the top of the Sandy Mud date to 1690–1290 cal yr B.P.

Average sedimentation rates, estimated from a linear regression of age against depth, were ~0.5 mm/yr between ~7600 and ~1700 cal yr B.P. and ~1.5 mm/yr after ~1700 cal yr B.P.

BIOZONES

Changes in macrofossil concentrations, and in relative abundance of diatom taxa, define five biozones (Figs. 4 and 5). Each

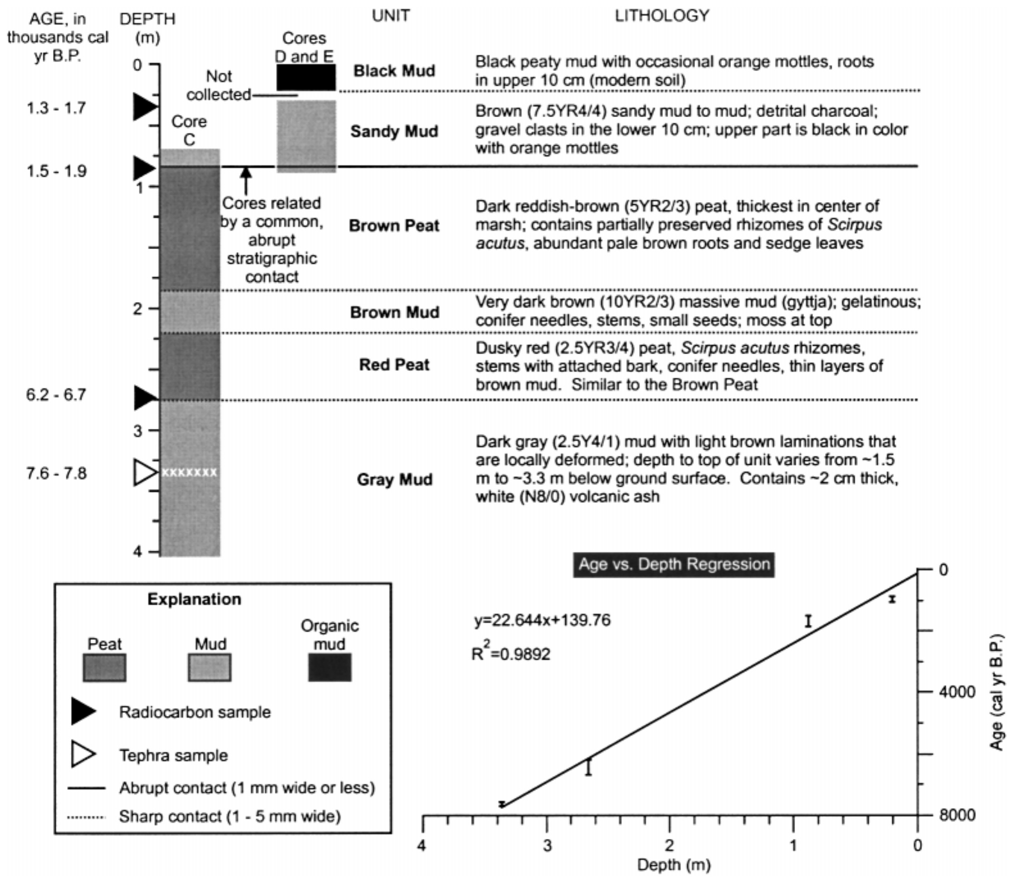

FIG. 3. Study core lithology and age vs depth regression.

biozone is a stratigraphic interval containing a distinctive set of diatoms and plant macrofossils.

Biozone BZ1 (4.04–3.10 m)

The macrofossils and diatoms found in BZ1 show that a small freshwater to slightly brackish water marsh occupied the site during deposition of the Gray Mud. The zone is dominated by abundant *Juncus* cf. *bufonius* seeds, *Typha latifolia* seeds, and *Aulacoseira islandica* (Figs. 4 and 5). *A. islandica* is characteristic of small freshwater lake and pond environments but can tolerate slightly brackish water (Laws, 1988; Pankow, 1971).

Biozone BZ2 (3.10–2.20 m)

Biozone BZ2 includes the upper part of the Gray Mud and extends to the top of the Red Peat (Figs. 4 and 5). It is notable for the first appearance of salt water fossils: foraminifera (*Trochammina* sp.) and seeds of salt marsh plants that include *Atriplex patula*, *Potentilla pacifica*, and *Scirpus* cf. *maritimus*. Also present are seeds of freshwater to low-salinity taxa including *T. latifolia*, *Carex* sp., and *Scirpus acutus* and rhizomes of *S. acutus*. The main diatoms from this zone are *Fragilaria construens*, *Aulacoseira italica*, and *Sellaphora pupula*.

The *Atriplex patula*, *P. pacifica*, *S.* cf. *maritimus*, foraminifera, and peaty deposits of biozone BZ2 together show that a brackish high marsh occupied the site between 7500 and 5000 cal yr B.P. Diatom assemblages observed in the zone are common in brackish water marsh assemblages at other coastal marshes in Washington (Hemphill-Haley, 1995; Sherrod, 1999). Mixtures of salt-tolerant taxa (*Melosira nummuloides*) and obligate freshwater taxa (*A. italica*) suggest that conditions in the marsh ranged from brackish water at low elevations to freshwater at high elevations.

Biozone BZ3 (2.20–0.84 m)

Biozone BZ3 begins at the base of the Brown Mud and extends upward to the top of the Brown Peat. Its base is marked by an increase in *Fragilaria* cf. *schulzii* and *Fragilaria virescens* and by the presence of *A. patula* seeds (Figs. 4 and 5). The rest of the zone contains seeds of *Carex* sp., *Triglochin maritima, A. patula, P. pacifica,* and small numbers of foraminifera (*Trochammina* sp.). Large numbers of ostracodes, *Daphnia* sp. ephippia (dormant brood sacs), and the diatom *Nitzschia frustulum* are found in several samples at the top of the zone. Small amounts of the diatoms *Navicula peregrina* and *Odontella aurita* are present as well.

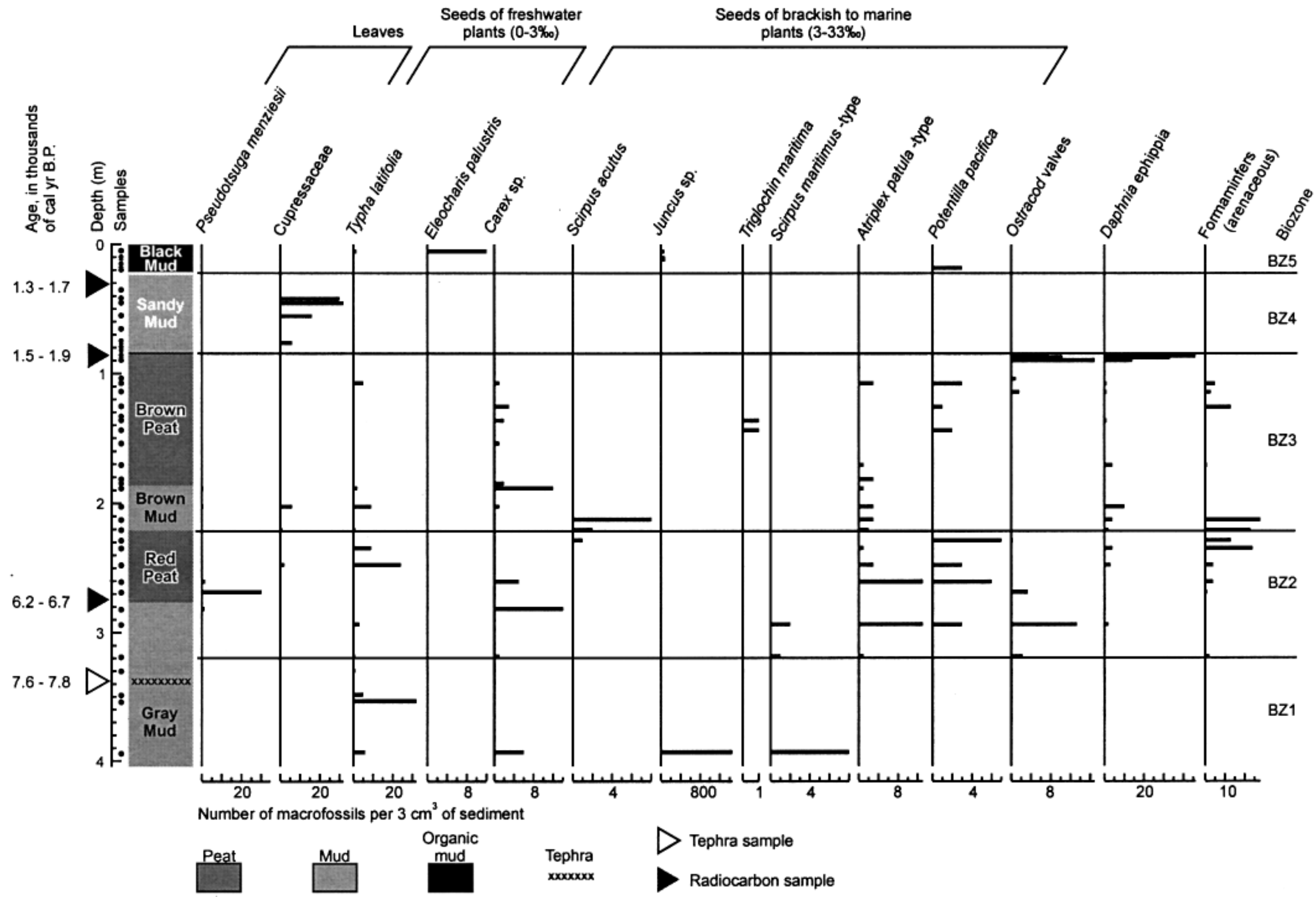

FIG. 4. Plant macrofossils and other common fossils from Restoration Point cores C–E.

BZ3 shows that a brackish marsh occupied the site from about 5000 cal yr B.P. to ~1700 cal yr B.P. This inferred environment best explains not only the sporadic occurrence of *T. maritima* and *A. patula* seeds and the presence of foraminifera, but also the diatoms *N. peregrina, O. aurita,* and several *Fragilaria* species. *F.* cf. *schulzii,* which dominates the lower part of the zone, is commonly found attached to sand grains in marine to brackish water environments around the world (Krammer and Lange-Bertalot, 1991). *F. construens* var. *venter,* a cosmopolitan taxon found high in the zone, lives in modern tidal flat sediments at False Bay, which borders San Juan Island in northern Puget Sound (E. Hemphill-Haley, written communication, 1992; Tynni, 1986).

Biozone BZ4 (0.84–0.40 m)

Biozone BZ4, which coincides with the Sandy Mud, contains fossil assemblages dominated by salt-tolerant diatoms. Samples collected immediately above the base of BZ4 contain large concentrations of *F. virescens* (~65% of the count). Marine diatoms in this zone include *Paralia sulcata, Opephora parva, Trachyneis aspera, Achnanthes delicatula, Cocconeis scutellum, Grammatophora oceanica, Fragilaria fasiculata, Melosira nummuloides,* and *O. aurita* (Fig. 5). *Thuja plicata* leaves, *Pseudotsuga menziesii* needles, and ostracodes are common in this zone.

We interpret BZ4 as tideflat deposits because the zone is composed of mud containing tidal flat diatoms. Modern tidal-flat diatom assemblages from Puget Sound typically contain ~2% of *T. aspera,* while marsh samples rarely contain this taxon (Sherrod, 1999). A sample from the upper part of BZ4 contains 3.5% of *T. aspera* and includes several other diatoms commonly found in tidal flat sediments. (*A. delicatula, C. scutellum,* and *O. parva*). The tree leaves and needles in BZ4 likely washed in from nearby forests (Fig. 4).

Biozone BZ5 (0.40–0 m)

Biozone BZ5 records freshwater conditions. The zone, which coincides with the Black Mud, lacks seeds of salt-tolerant plants except near the base where seeds of *P. pacifica* were found. Higher in the zone, seeds of freshwater plants such as *Eleocharis palustris* and *T. latifolia* are common (Fig. 4). Freshwater taxa also dominate the diatom assemblages: *Euno-*

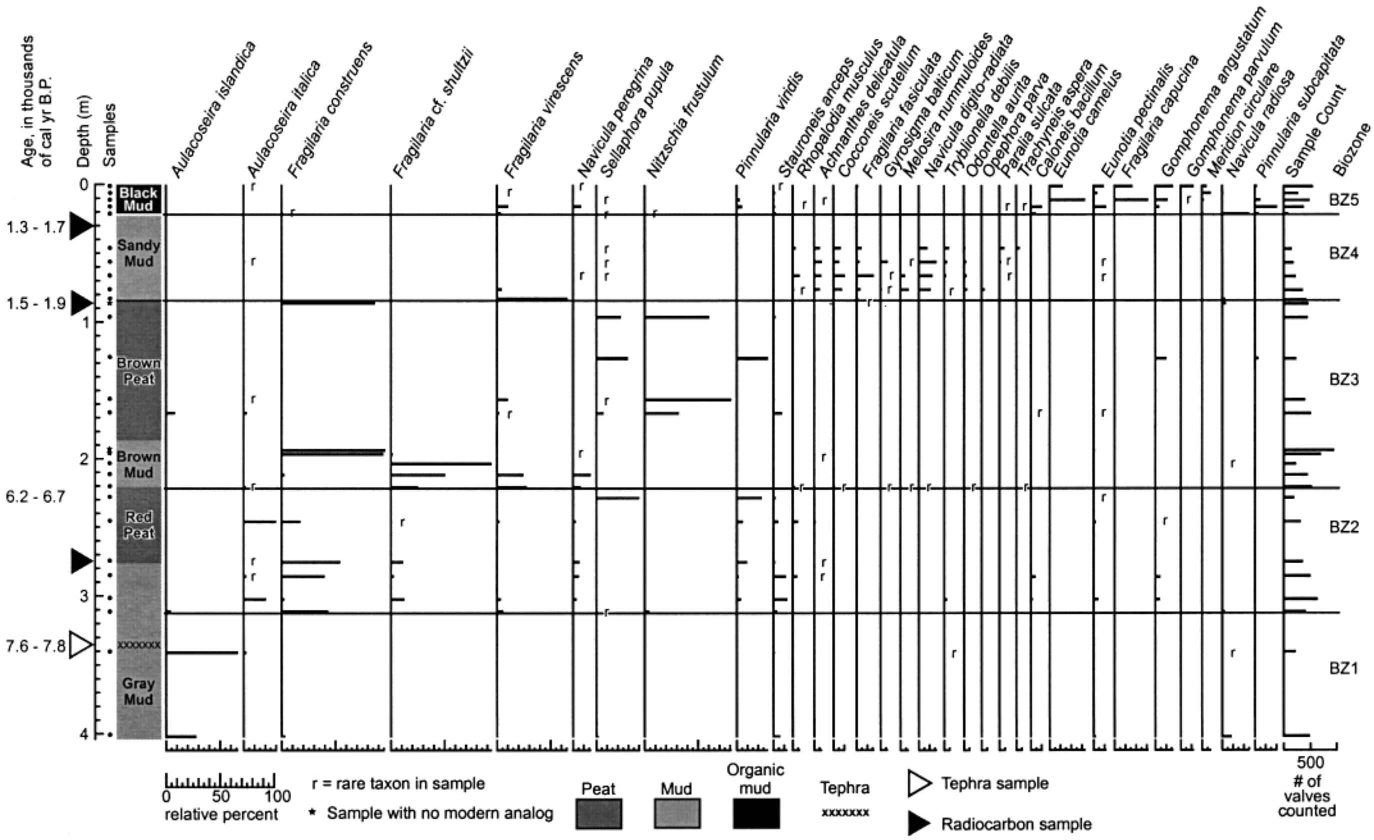

FIG. 5. Main diatom taxa from Restoration Point cores C–E.

tia camelus, Eunotia pectinalis, Caloneis bacillum, and species of *Gomphonema* and *Pinnularia.* Marine diatoms in this zone, mainly *P. sulcata* and *T. aspera,* are rare and possibly windblown.

ENVIRONMENTAL HISTORY

Fossil assemblages in the five biozones show that the site lay in the intertidal zone during most of the middle and late Holocene. The assemblages also show four prominent environmental changes, termed events A, B, C, and D (Fig. 6). We ascribe these changes in marsh biota to changes in salinity, elevation, or both, and we consider tectonic and nontectonic causes.

Event A—Probable Uplift or Berm Accretion ~6900 cal yr B.P.

During event A, a sudden decrease in salinity and a concurrent increase in equivalent elevation of 1.5 m produced a change in biota about 7200–6400 cal yr B.P. (Fig. 6). The site then returned gradually to conditions similar to those before event A. The equivalent elevation (relative to MLLW) of the site is +3.8 ± 0.6 m ~7200 cal yr B.P. and +5.5 ± 0.6 m ~6900 cal yr B.P. By about 6400 cal yr B.P., the site lay at an equivalent elevation of +3.9 ± 0.6 m. Inferred salinity during the same period changed from a high of ~25 ± 6‰ at ~7200 cal yr B.P. to a low of ~8 ± 6‰ at ~6900 cal yr B.P. and returned to ~25 ± 6‰ by ~6400 cal yr B.P.

Event A could have resulted from coseismic uplift of about 1.5 m. Alternatively, accretion of a beach bar bordering the brackish marsh could have isolated the marsh from more saline marine water, resulting in a freshening of the marsh. Neither cause is ruled out by the available information.

If event A resulted from a RSL fall of 1.5 m, this amount can be used to estimate the rate of RSL rise just after event A (Fig. 7). For this estimate, we assume that the tidal marsh aggraded about as fast as RSL rose (R) until event A raised the site above the reach of all tides. Following event A, marsh deposition ceased. After ~750 years (T), the site began to aggrade at rate R as high tides began to cover the site again. These figures imply a 2 mm/yr rate of relative sea level rise at Restoration Point between 7200 and 6400 cal yr B.P.

Event B—Apparent Environmental Changes ~3000 cal yr B.P.

Changes in fossil diatoms suggest a shift in elevation and salinity between 3500 and 2000 cal yr B.P. Samples at 1.6 and 1.0 m contain diatoms that indicate an equivalent elevation of

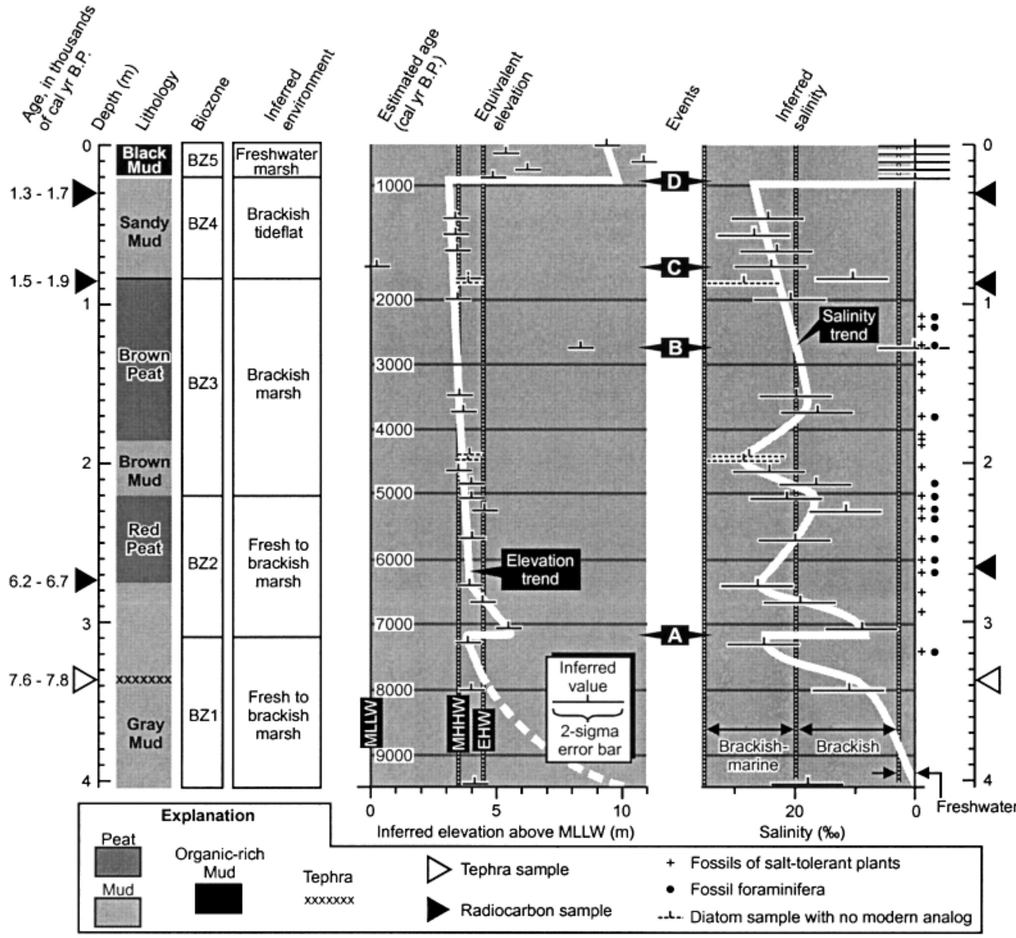

FIG. 6. Summary diagram of environmental changes at Restoration Point. Heavy white lines are visually fitted through inferred elevation and salinity data points in consideration of all available biostratigraphic and lithologic data.

~3.5 ± 0.6 m. A sample from 1.25 m in depth has diatoms suggesting an equivalent elevation of 8.3 ± 0.6 m. Taken at face value, these estimates imply a change in equivalent elevation of 4.8 ± 0.6 m between 3500 and 2700 cal yr B.P. and a shift in salinity of 20 ± 6‰ (Fig. 6).

Possible causes for the inferred change in equivalent elevation and salinity between 3500 and 2000 cal yr B.P. include tectonic uplift, berm accretion and erosion, and sampling and statistical artifacts. Small increments of uplift from several moderate earthquakes between 3500 and 2500 cal yr B.P. could have resulted in meters of net uplift at the site. However, if uplift caused a RSL fall of 4.8 m by ~2700 cal yr B.P., then

TABLE 1
Descriptions of Radiocarbon Samples and Tephra

Lab no.	Depth (cm)	Material dated	Age (^{14}C yr B.P.)	Age (cal yr B.P.)
Beta-36045	30	Detrital charcoal (rounded clasts)	1560 ± 90	1690–1290
Beta-29143	89	Peat collected from a 1-cm-thick slice immediately below abrupt contact between Brown Peat and Sandy Mud	1770 ± 70	1870–1530
Beta-29144	266	Peat collected from a 1-cm-thick slice immediately above contact between Gray Mud and Brown Peat	5630 ± 100	6670–6200
Tephra	336	Tephra from a ~2-cm-thick layer within Gray Mud. Identified as Mazama ash by D. R. Mullineaux (U.S.G.S., personal communication, 1994)	6850 ± 50 (Zdanowicz *et al.*, 1999)	7790–7580

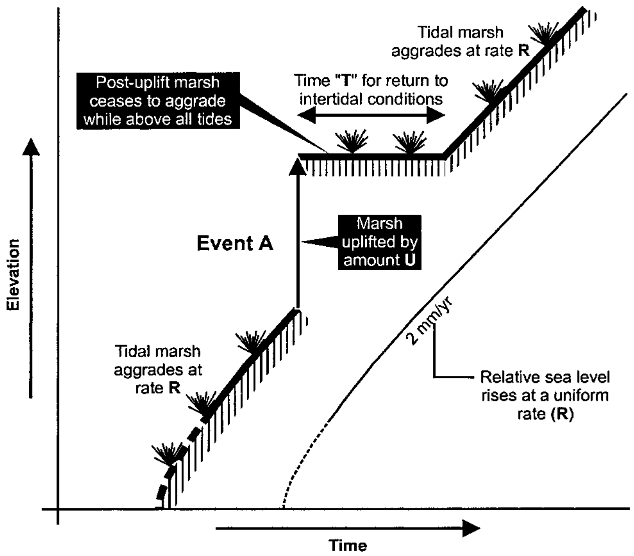

FIG. 7. Conceptual model of interaction between RSL rise, marsh accretion, and uplift for event A.

4.8 m of RSL rise between 2700 and 2000 cal yr B.P. is required to restore the site to intertidal conditions by 2000 cal yr B.P. Alternatively, accretion of the sandy berm could have isolated the marsh from the tides, resulting in a freshening of the marsh, and later erosion resulted in the marsh becoming brackish again. Perhaps the simplest explanation for the singular 4.8-m excursion in equivalent elevation ~2700 cal yr B.P. is the apparent elevation change is a statistical or sampling artifact. Our sparse sampling in this part of the section is not sufficient to delineate any related trend in uplift or subsidence.

Events C—Probable Submergence ~1700 cal yr B.P.

Shortly after 1900–1500 cal yr B.P., changes in lithology and marsh biota record a sudden increase in salinity and a decrease in equivalent elevation. Just above the contact between the Brown Peat and the Sandy Mud, equivalent elevation abruptly decreases 3.6 ± 0.6 m (Fig. 6) and soon returned to conditions similar to those prior to event C. Salinity also changed abruptly at the same time as the elevation change, from ~10 ± 6‰ before the event to ~24 ± 6‰ after the event.

In contrast to event A, the inferred elevation and salinity changes of event C were short-lived, in which case event C likely resulted from berm erosion rather than tectonic subsidence. However, the lithology of the Sandy Mud and the diatoms of Biozone BZ4 show that, following event C, the site remained a tideflat from ~1700 cal yr B.P. to ~1000 cal yr B.P. (Fig. 5). This persistence requires an open connection to Puget Sound for ~700 years. Perhaps tectonic subsidence both created tideflat conditions ~1700 cal yr B.P. and helped maintain them for centuries thereafter.

Event D—Abrupt Uplift ~1000 cal yr B.P.

The large earthquake ~1000 cal yr B.P. uplifted a tideflat out of the intertidal zone, resulting in the development of a freshwater marsh on the former tidal flat surface (Bucknam *et al.,* 1992). Between the Sandy Mud and the Black Mud, equivalent elevation increases about 6.0–7.5 m. The uppermost sample in the Sandy Mud, a tidal flat deposit, has an inferred elevation ~3.3 ± 0.6 m above MLLW. By contrast, the Black Mud (Biozone BZ5) is now 9.0–9.3 m above MLLW (Fig. 2B). Equivalent elevations for the Black Mud shown in Fig. 6 are likely in error because plowing in the early 1900's mixed freshwater diatoms from this unit with tideflat diatoms from the Sandy Mud below, resulting in a mixed diatom assemblage with little paleoecological meaning.

These findings are consistent with earlier estimates that the site rose 5–7 m ~1000 cal yr B.P. (Bucknam *et al.,* 1992). An abrupt decrease in salinity, from ~25 ± 6‰ to 0 ± 6‰, coincides with the change in equivalent elevation (Fig. 6).

IMPLICATIONS FOR EARTHQUAKE RECURRENCE

The paleoenvironmental record at Restoration Point suggests that the last complete recurrence interval for large earthquakes on the Seattle fault lasted at least 6500 years. The large earthquake on the Seattle fault ~1000 cal yr B.P. (event D) resulted in uplift at Restoration Point and caused a major environmental change at the marsh. We found no other environmental changes of comparable size in the RSL record for the past 7500 years (Fig. 6).

The sudden paleoenvironmental changes 7200–6400 cal yr B.P. (event A), 3500–2000 cal yr B.P. (event B), and 1900–1500 cal yr B.P. (event C) are smaller and less long-lasting than the changes ~1000 cal yr B.P. (event D). For event B, additional sampling is needed to show whether the changes are due to statistical aberrations or to actual environmental changes. For events A and C, more work will clarify their implications for the history of earthquakes on the Seattle fault.

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