Abrupt Uplift within the Past 1700 Years at Southern Puget Sound, Washington

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Shorelines rose as much as 7 meters along southern Puget Sound and Hood Canal between 500 and 1700 years ago. Evidence for this uplift consists of elevated wave-cut shore platforms near Seattle and emerged, peat-covered tidal flats as much as 60 kilometers to the southwest. The uplift was too rapid for waves to leave intermediate shorelines on even the best preserved platform. The tidal flats also emerged abruptly; they changed into freshwater swamps and meadows without first becoming tidal marshes. Where uplift was greatest, it adjoined an inferred fault that crosses Puget Sound at Seattle and it probably accompanied reverse slip on that fault 1000 to 1100 years ago. The uplift and probable fault slip show that the crust of the North America plate contains potential sources of damaging earthquakes in the Puget Sound region.

Western Washington State has at least three dissimilar sources of earthquakes that could damage metropolitan areas near Puget Sound. The best documented of these sources, the interior of the subducted Juan de Fuca plate, has released several 20th-century earthquakes of magnitude (M) 6 or 7 from depths of 50 to 60 km beneath Puget Sound (*1*). A second source, the offshore part of the boundary between the Juan de Fuca and North America plates, lacks historical seismicity but may produce infrequent earthquakes as large as M = 8 or 9 (*2–4*). In this report we present evidence for a third source—historically quiescent faults within the North America plate. We propose that one or more large earthquakes on such faults account for uplift that occurred in the southern Puget Sound region between 500 and 1700 years ago. Accompanying reports present evidence that one of these earthquakes generated a tsunami (*5*) and may also account for landslides (*6*), rock avalanches (*7*), and turbidity currents (*8*) (Fig. 1).

The most conspicuous evidence for earthquake-induced uplift at Puget Sound is a raised wave-cut platform at Restoration Point (*9*), the easternmost part of a peninsula 5 km west of Seattle (Fig. 1). The raised platform extends discontinuously along the coast nearly 3 km to the northwest and 7 km to the west of the peninsula (*10*). The peninsula is fringed by the raised platform (Fig. 2), which is expressed as a seaward sloping, nearly planar bedrock surface as much as 7 m above high tide (*11*). Organic-rich sand 20 to 40 cm thick overlies much of the platform, which is cut on steeply dipping Tertiary siltstone and sandstone. Much thicker deposits of sand and gravel cover the platform 2.5 km northwest of Restoration Point; these deposits contain shallow-water marine mollusk shells in growth position (*12*).

The raised platform at Restoration Point, which resembles the adjacent modern platform at sea level, records about 7 m of uplift. Erosion at the seaward edge of the raised platform has produced a low bedrock scarp as much as 3 m high. High tide coincides approximately with the foot of the scarp. The corresponding part of the raised platform lies 7 m higher. Because the type of rock and exposure to waves are similar on the modern and raised platforms, we assume that the landward edge of the raised platform similarly formed at about the level of high tide, in which case the net uplift is 7 m (*13*).

The nearly planar form of the raised platform indicates that it was uplifted suddenly. Low linear ribs of the most resistant of the Tertiary beds can be traced from the modern platform onto and across the raised platform. Postuplift weathering has subdued these features on the raised platform, but

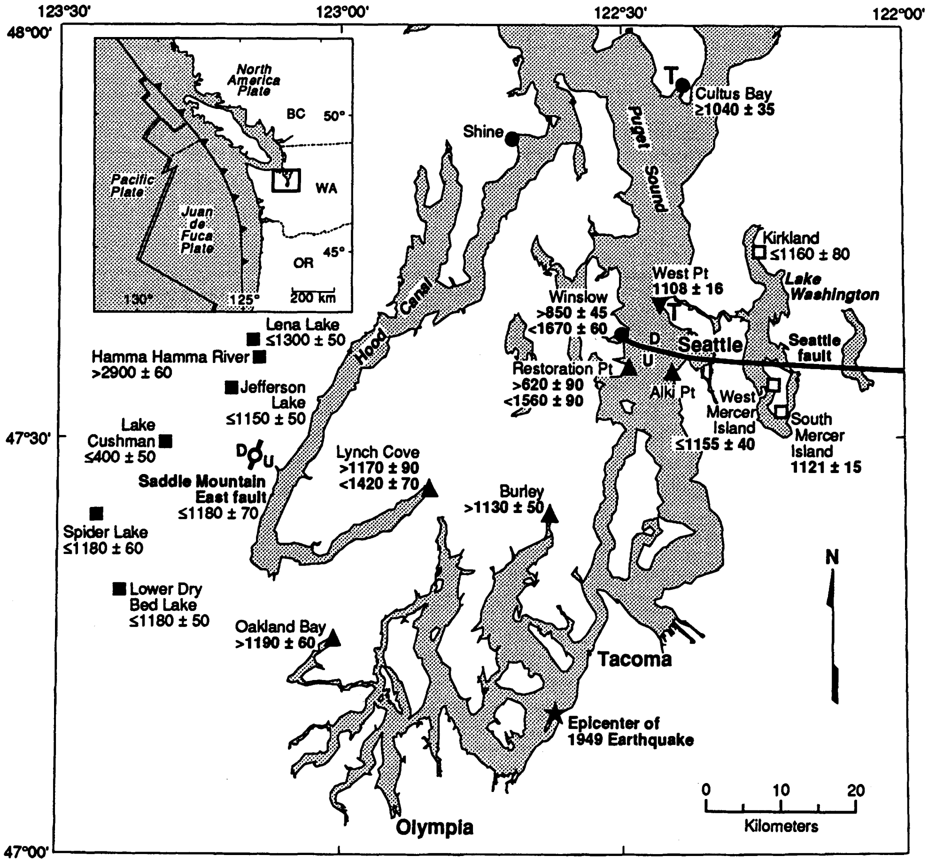

Fig. 1. Location and radiocarbon age of features bearing on seismic events in the Puget Sound region of Washington between 500 and 1700 years ago. Features: uplifted tidal flat or wave-cut marine platform (this paper) (▲); subsided tidal marsh or swamp (*5*) (▼); tidal-marsh deposit showing little or no abrupt change in level in past 2000 years (Cultus Bay, Winslow) (*5*) or in past 3000 years (Shine) (*26*) (●); probable tsunami deposit (*5*) (T); rock avalanche (*7*) (■); landslide (*6*) (□); ponds impounded along fault scarp (*6, 24*) (O). Radiocarbon ages in ^{14}C years before A.D. 1950, with 1 standard error quoted by laboratory; ages shown in boldface were adjusted for measured ^{13}C/^{12}C ratio. Age of feature relative to average age of dated material: identical within 10 years (no prefix); older (≥) or younger (≤) by as much as decades; older (>) or younger (<) by as much as centuries. Where multiple limiting ages are available, only the youngest limiting maximum or oldest limiting minimum ages are shown. Ages are not shown for landslides distinctly older than 900 to 1300 years at Lake Washington. Relative movement on fault: U, up; D, down.

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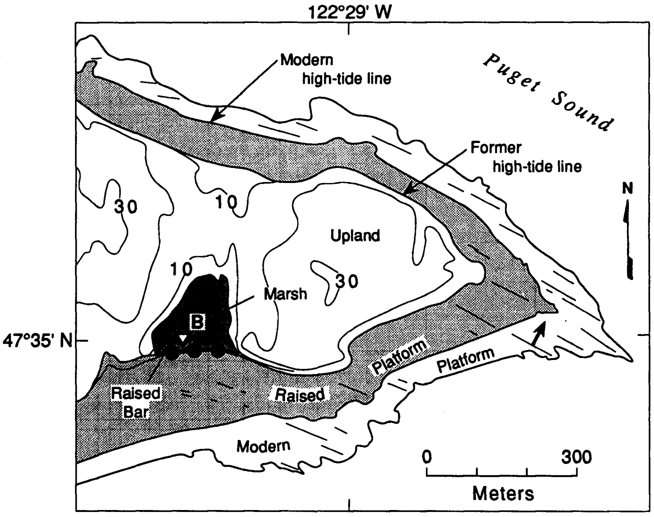
Fig. 2. Map of Restoration Point, showing relative elevation contours (in meters); datum is approximate mean sea level. Fine straight lines are bedrock ribs of resistant sedimentary rock that dip steeply in direction shown by arrow. Inverted triangle at B is location of the columnar section shown in Fig. 3B.



ribs with as little as 20 to 30 cm of relief are conspicuous. This preservation suggests that slow uplift would have left recognizable patterns of intermediate shoreline features on the uplifted surface, such as bars of beach gravel or small erosional scarps. In a careful search we found no such features, with one doubtful exception (*14*). This lack of intermediate shorelines is inconsistent with slow (aseismic) uplift, which would have taken at least a decade at the highest known aseismic uplift rates (*15*). Therefore, we suspect that the uplift accompanied an earthquake.

Radiocarbon ages show that the abrupt uplift occurred between 500 and 1700 years ago. A concentrate of humus from the basal 4 cm of the organic sand that overlies the bedrock of the raised platform gave a minimum time for the uplift of 500 to 800 years ago (620 ± 90 ^{14}C yr B.P.) [*16, 17*]. Beach gravel and tidal flat mud, now 6 to 7 m above high tide, underlie a small marsh in the isthmus west of the peninsula (Fig. 2). Rounded fragments of detrital charcoal from the uplifted tidal flat mud (Fig. 3B) gave a maximum time for the uplift of 1300 to 1700 years ago (1560 ± 90 ^{14}C yr B.P.).

A marine platform also stands a few meters above high tide at Alki Point in Seattle, 5 km east of Restoration Point. Although that platform is mostly obscured by houses and roads, a recent excavation exposed a planar sand-covered bedrock surface 4 m above present high tide. Uplift of this surface was greater than 4 m because the landward edge of the platform was not exposed in the excavation.

Deposits at a small marsh at Winslow (Fig. 1), just 5 km north of Restoration Point, give evidence that the amount of vertical displacement was quite variable locally. The marsh at Winslow is underlain by peat that was deposited during the past several thousand years (Fig. 3A), that is, including the time of the uplift at Restoration Point. Diatom assemblages from mud directly beneath the peat indicate that the site was a freshwater bog or swamp 1600 to 2100 years ago. Peat about 30 cm higher in the section (1400 to 1700 years ago) contains diatoms characteristic of freshwater bogs or swamps but tolerant of slightly brackish water. The peat also contains a few fossil diatoms characteristic of brackish to marine environments. They presumably were blown or washed into the peat; thus, the site was near marine water and may have been only slightly above the level of the highest tides. Tidal marine water inundated the site more frequently by 700 to 900 years ago as shown by radiocarbon-dated leaf bases of *Triglochin maritimum*, a common plant of brackish and saltwater tidal marshes in Washington (*18*).

The deposits at the Winslow marsh lack clear-cut evidence of an abrupt change in relative sea level in the past 2000 years. If the Winslow marsh changed level at the time of the uplift at Restoration Point, it probably subsided as shown by the change from mostly freshwater wetland to tidal marsh. Such subsidence could have accompanied the uplift at Restoration Point, as inferred for a site 9 km to the northeast at West Point (*5*). Alternatively, the tidal marsh at Winslow could have originated from a gradual rise in relative sea level.

In any case, the lack of uplift at Winslow implies that the amount of vertical displacement was variable—at least 7 m over the 5 km between Restoration Point and Winslow. A similar difference exists to the east between Alki Point (uplift >4 m) and West Point [subsidence ≥ 1 m (*5*)]. Both Restoration Point and Alki Point are on the south side of the Seattle fault [Fig. 1; (*19*)], a major east-trending structure that has been inferred from depth-to-bedrock data (*10*), gravity anomalies (*12*), and seismic reflection profiles (*20*). The long-term sense of offset inferred on this fault is south side up. The coincidence of the pattern of vertical displacement in the marshes and terraces with the same sense of late Cenozoic displacement on a major fault nearby suggests that the uplift occurred in conjunction with slip on the Seattle fault. Because no surface rupture is apparent, fault slip at depth may have been accommodated by folding or warping at and near the surface.

Large uplift south of the Seattle fault and small subsidence north of the fault suggests that reverse slip occurred on a south-dipping fault, rather than normal slip on a north-dipping fault. For dipping normal faults, subsidence is large and uplift is small. The ratio of subsidence to uplift suggests that dip of the fault is less than about 70° (*21*).

Our radiocarbon ages only broadly limit the time of this fault slip and associated uplift to between 500 and 1700 years ago. A narrower range between 1000 and 1100 years ago is suggested by radiocarbon dating and tree-ring correlation of tsunami and landslide deposits near Seattle, provided that these deposits are coeval with the uplift (*5*).

There is also evidence for uplift between 1000 and 1500 years ago at the heads of three bays in southwest Puget Sound and Hood Canal, 30 to 55 km southwest of Restoration Point. The strongest case for uplift in these other areas comes from Lynch Cove, at the landward end of Hood Canal (Fig. 1). We also found evidence of uplift at Oakland Bay, 25 km southwest of Lynch Cove, and at Burley, 15 km southeast of Lynch Cove (Fig. 1).

Tidal flat sediment overlain by freshwater peat provides the evidence of abrupt uplift at Lynch Cove. Fossil diatoms (Fig. 3C) show that the sediment accumulated below high tide, on a tidal flat. By contrast, woody roots, diatoms, and seeds of plants characteristic of moist upland meadows and freshwater marshes show that the overlying peat formed above the highest tides. The sharp contact at the base of the peat and the lack of intervening salt-marsh deposits suggests that the change from tidal flat to upland meadows and marshes was abrupt (*22*). A rise in relative sea level subsequent to the uplift allowed high tides to submerge the upland meadows and marshes many centuries later, as shown by salt marsh peat that overlies the freshwater peat.

Relief of the former tidal flat beneath the peat shows that the uplift at Lynch Cove exceeded 2 m. The former tidal flat surface buried beneath the peat descends gently toward the central part of the cove. Before uplift, the highest point on the former tidal flat was below high tide, and after uplift the lowest point on that surface beneath the freshwater peat was above high tide. The relief between these two points is at least 2 m.

The oldest age determined thus far for the lowermost several centimeters of the peat at Lynch Cove is 900 to 1300 years (1170 ± 90 ^{14}C yr B.P.), which is a minimum for the time of the uplift. Upland shrubs had become established on the surface by 800 to 1100 years ago (1050 ± 70 ^{14}C yr B.P.) as shown by the age of a woody root in growth position in the sediment beneath the peat (Fig. 3). A well-rounded detrital fragment of wood from the sediment beneath the peat gave an age of 1300 to 1500 years (1420 ± 70 ^{14}C yr B.P.), which is a maximum for the time of uplift.

As at Lynch Cove, peat containing abundant wood overlies mud at Oakland Bay and Burley, and roots of woody shrubs are also present locally in the uppermost several decimeters of the mud at both sites. Radiocarbon ages of the lowermost few centimeters of the peat at Oakland Bay and Burley are similar to those at Lynch Cove—1190 ± 60 ^{14}C yr B.P. at Oakland Bay and 1130 ± 50 ^{14}C yr B.P. at Burley (*23*). Also, as at Lynch Cove, a rise in relative sea level since the uplift has resulted in the formation of salt-marsh deposits on the freshwater peat at both sites.

Uplift of tidal flats in the Lynch Cove–Oakland Bay areas, uplift adjacent to the Seattle fault, and formation of an 8-m-high fault scarp along the Saddle Mountain East fault [Fig. 1; (*24*)] probably reflect slip on several faults in the crust of the North America plate. The slip may have occurred either as a series of events closely spaced in time (up to several centuries apart) or as synchronous coordinated events. We implicate more than the Seattle fault because uplift of the Lynch Cove–Oakland Bay area appears too distant (35 to 60 km from the Seattle fault) and too large (locally at least 2 m) to be solely the result of slip on that fault. Alternative, but less likely, origins for uplift in Puget Sound are earthquakes within the subducting Juan de Fuca plate or at the boundary between the Juan de Fuca and North America plates. Earthquakes in the subducted plate are unlikely sources of widespread uplift, as judged from the lack of recognized uplift from a M = 7.1 earthquake in the Juan de Fuca plate deep under southern Puget Sound (epicenter in Fig. 1). However, we cannot rule out coeval slip on faults in the North America plate and on the Juan de Fuca plate boundary because ^{14}C ages for the uplift resemble ages for abrupt subsidence and unusual ground-water eruption along the Pacific coast of Washington (*4*).

The size of the smallest earthquake compatible with the uplift between Seattle and Oakland Bay can be estimated by comparison of the uplift produced by the magnitude 7.3 earthquake of 1980 near El Asnam, Algeria, with that at Puget Sound. The El Asnam earthquake produced 5 m of uplift along a high-angle reverse fault (*25*), comparable to the amount of abrupt uplift near the Seattle fault. We conclude that faults in the North America plate can produce damaging earthquakes, probably of magnitude 7 or larger, in the Puget Sound region.

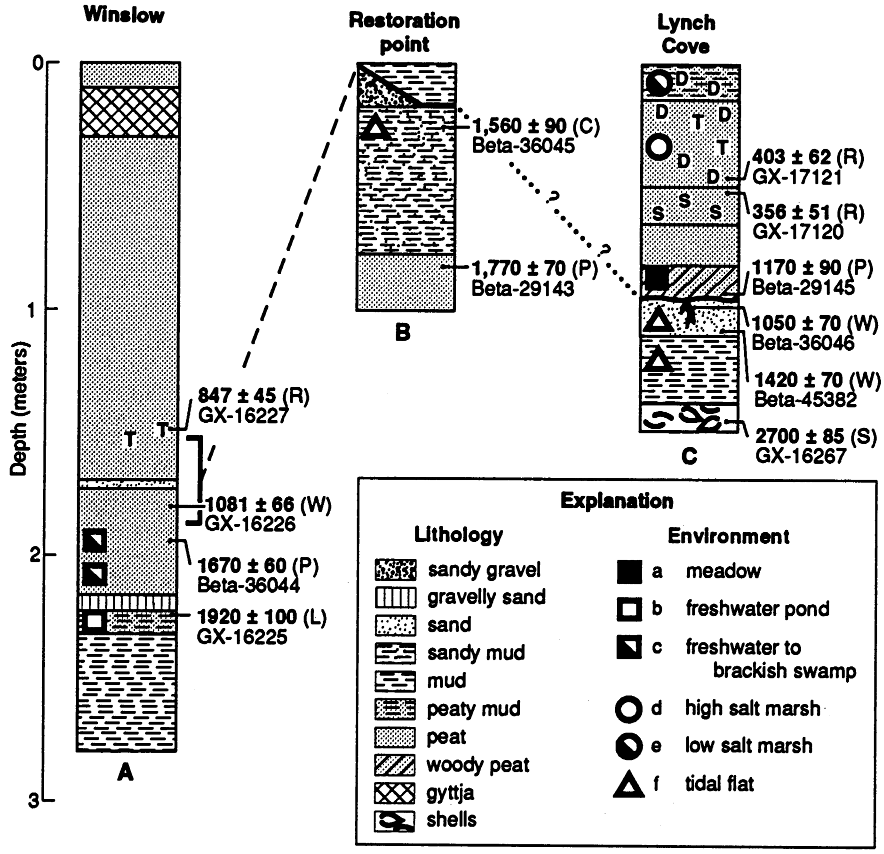


Fig. 3. Generalized composite columnar sections at uplift sites in central and southern Puget Sound region. (**A**) Winslow, (**B**) Restoration Point, and (**C**) Lynch Cove. Dashed line between sections shows inferred correlation of uplift event (shown by heavy line in sections), dotted and queried where uncertain, and time interval of Restoration Point uplift at Winslow site within bracketed interval on (A). (C) represents the stratigraphy in the seaward part of the Lynch Cove marsh. Radiocarbon ages on right side of columns are conventional radiocarbon ages (*17*), corresponding analytical laboratory numbers, and abbreviations for material dated: C, charcoal; L, leaf; P, peat; R, rhizome or leaf base; S, marine shell; W, wood. Abbreviations in explanation: a to e, representative diatom species for environments (*27*); a (A), *Fragilaria virescens*; b, *Navicula radiosa*; c, low salt marsh, *Gyrosigma eximium*; d, *Pinnularia lagerstedtii*; e (B), *Gyrosigma balticum*; and (C), *Dimeregramma minor*. Representative plant species for environment from fossil seeds: f (C), *Vaccinium* sp. or *Gaultheria* sp., and *Urtica* sp. Fossil rhizomes and inferred environments (*18*): D, *Distichlis spicata*; T, *Triglochin maritimum* (high salt marsh); S, *Scirpus acutus* (freshwater to brackish marsh).

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13. The abrupt uplift could have differed by several meters from 7 m because of subsequent uplift, subsidence, or regional rise in sea level of 1 to 2 m.
14. Faint lineations of unknown origin parallel the coast on the southeast part of the raised platform. They lack relief and are defined by variations in the tone of grass on the platform during the dry season.
15. At vertical uplift rates on the high end of those that have been observed for tectonic uplift (for example, 70 mm/yr) [A. R. Nelson and W. F. Manley, in *Impacts of Tectonics on Quaternary Coastal Evolution*, Y. Ota, A. R. Nelson, K. Berryman, Eds.

(*Quat. Int.* **15/16**, special issue, 1992), p. 61], aseismic uplift of Restoration Point would have required 100 years. Even at the highest known rates of uplift of about 200 to 800 mm/yr, which have only been observed on the flanks of active volcanoes [K. R. Lajoie, in *Active Tectonics: Impact on Society* (National Academy Press, Washington, DC, 1986), pp. 95–124], 7 m of uplift would have required at least a decade.
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28. We thank B. Atwater, T. Barnhard, B. Benson, and J. Suhy for their help with this study, and property owners who generously provided access to critical sites on their land. P. Bierman reported the Alki Point excavation. The manuscript was improved by reviews by B. Atwater, A. Nelson, K. Berryman, and C. Weaver.

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A Tsunami About 1000 Years Ago in Puget Sound, Washington

Brian F. Atwater and Andrew L. Moore

Water surged from Puget Sound sometime between 1000 and 1100 years ago, overrunning tidal marshes and mantling them with centimeters of sand. One overrun site is 10 kilometers northwest of downtown Seattle; another is on Whidbey Island, some 30 kilometers farther north. Neither site has been widely mantled with sand at any other time in the past 2000 years. Deposition of the sand coincided—to the year or less—with abrupt, probably tectonic subsidence at the Seattle site and with landsliding into nearby Lake Washington. These findings show that a tsunami was generated in Puget Sound, and they tend to confirm that a large shallow earthquake occurred in the Seattle area about 1000 years ago.

A large earthquake probably happened between 500 and 1700 years ago on the Seattle fault (*1*), which has been inferred to extend westward across Puget Sound from downtown Seattle (*2*). The main evidence for the earthquake consists of terraces that record meters of abrupt uplift at Puget Sound (*1*). If abrupt enough to have accompanied an earthquake, such uplift should have generated a tsunami in Puget Sound. In this report, we show that a tsunami originated in Puget Sound between 1000 and 1100 years ago (*3*) and that it probably was generated by an earthquake on the Seattle fault.

Tsunamis can deposit sand on coastal lowlands. Modern examples have been reported from Chile (*4*, *5*), Japan (*6*), and British Columbia (*7*), and ancient examples have been inferred for Chile (*5*), Japan (*6*), Scotland (*8*), Alaska (*9*), and the Pacific coast of Washington and Oregon (*10*, *11*). In most of these examples, an onshore sheet of marine or estuarine sand dates to the time of an event known or inferred to have generated a tsunami.

We found tsunami deposits at two sites north of the Seattle fault [see figure 1 in (*1*)]. One of these sites borders Cultus Bay, which opens southward from Whidbey Island, 40 km north of the fault. The other site is West Point, which juts into Puget Sound 7 km north of the fault.

The tsunami deposit at Cultus Bay forms a sheet of sand mostly 5 to 15 cm thick in an area at least 100 by 200 m (Figs. 1 and 2). There, wetland peat has built upward and bayward since a tidal marsh began to supplant a tidal flat about 2000 years ago. This peat contains the sand sheet, which we found in scores of auger borings and followed as a continuous bed along more than 100 m of a drainage ditch. Neither the auger borings nor the ditch revealed any other sand bed in the peat. The surface covered by the sand shows 2 m of relief: 1.5 m where the sand mantled a sloping marsh (*12*) and another 0.5 m where the sand covered colluvium of an adjacent hillside (Fig. 2). The median grain size, mostly about 0.1 mm, decreases landward and stratigraphically upward (*13*). The sand contains microscopic marine fossils (*14*).

Deposition of the sand sheet at Cultus Bay occurred sometime between 850 and 1250 years ago, and it happened while the site probably underwent little or no subsidence. We dated the sand sheet by obtaining radiocarbon ages on plant remains in growth position in the sand (Fig. 2, in ditch). The dated remains are rhizomes (below-ground stems) and attached leaf bases of arrowgrass (*Triglochin maritimum*), which at modern Cultus Bay thrives only in a 1-m range high in the intertidal zone. Because additional arrowgrass rhizomes lie both below and above the sand, we suspect that the dated rhizomes grew upward through the sand sheet within years of its deposition. Such maintenance of arrowgrass would mean that deposition of the sand attended little or no subsidence of the Cultus Bay marsh (*15*).

The sand sheet at Cultus Bay is better explained by a tsunami than by a flood or storm. The landward fining and salt water fossils of the sand implicate a surge from

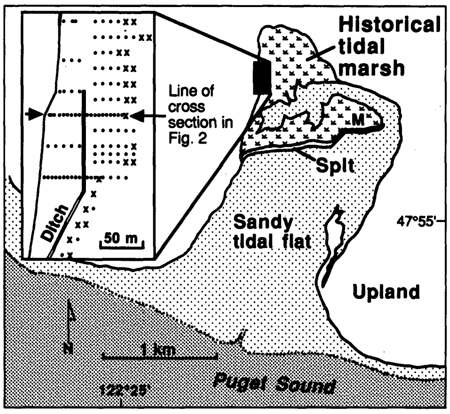

Fig. 1. Index maps of Cultus Bay. M, marsh surveyed for vertical ranges of plants plotted on right side of Fig. 2. Inset shows extent of sand sheet in peat or peaty mud, as seen in auger borings (•, sand present; **x**, absent) and in ditch (filled, present; open, absent).

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