(*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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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

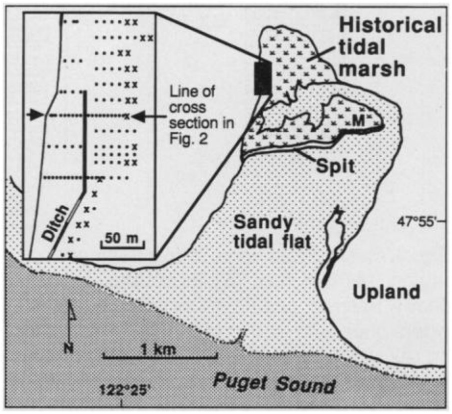

Fig. 1. Index maps of Cultus Bay. M, marsh surveyed for vertical ranges of plants plotted on right side of Fig. 2. Inset shows extent of sand sheet in peat or peaty mud, as seen in auger borings (•, sand present; **x**, absent) and in ditch (filled, present; open, absent).

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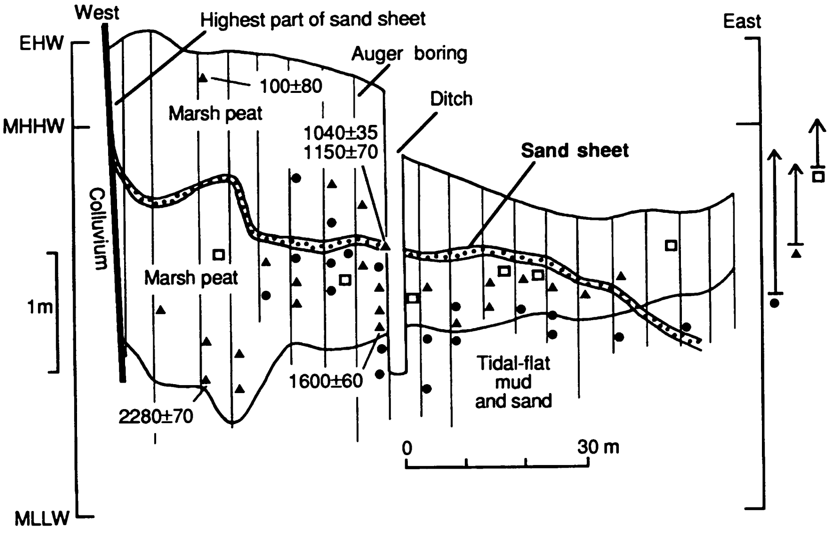

Fig. 2. Cross section along line of auger borings near Cultus Bay (vertical exaggeration ×20) (Fig. 1). Fossil rhizomes: (□), saltgrass *Distichlis spicata*; (▲), arrowgrass *Triglochin maritimum*; (●), tule *Scirpus acutus* or *S. californicus*. Radiocarbon ages (in ^{14}C yr before A.D. 1950) all measured on arrowgrass rhizomes (*25*). Vertical control from third-order leveling. Tidal datums (MHHW, mean higher high water; MLLW, mean lower low water) estimated by measuring a low slack tide on a windless sunny day, relating this tide to tide-table predictions, and extrapolating tidal datums from Hansville, which is 12 km west of Cultus Bay. EHW, extreme high water in winter of 1991–1992; denotes upper limit of flotsam in sheltered embayment. Lines at far right show vertical zonation of tule, arrowgrass, and saltgrass on tidal wetlands near M (Fig. 1): species denoted by rhizome symbol; horizontal line shows lower limit of marsh surface on which species was found living; tip of arrow shows upper limit.

Puget Sound, not a flood from the land. The lack of other sand beds distinguishes this surge from most or all storms at Cultus Bay in the past 2000 years. Because it occurred sometime between 850 and 1250 years ago, the surge may correlate with events that could have common cause with a tsunami in Puget Sound: abrupt uplift south of the Seattle fault between 500 and 1700 years ago (*1*), a landslide at Lake Washington between 1000 and 1100 years ago (*16*), rock avalanches in the Olympic Mountains between 1000 and 1300 years ago (*17*), a ground-water eruption along the Pacific coast of Washington between 900 and 1300 years ago (*11*), and abrupt subsidence at West Point between 1000 and 1100 years ago [see figure 1 of (*1*)].

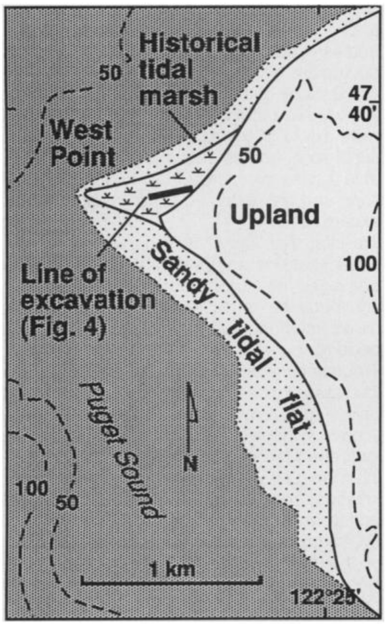

Fig. 3. Index map of West Point. Depth and elevation contours in meters.

The tsunami deposit at West Point punctuates a sequence of mostly intertidal deposits exposed in a sewer excavation 150 m long (Fig. 3). Sand and gravel low in the excavation represent a beach (*18*) on which people built fires and discarded shells before 2000 years ago (unit A, Fig. 4). The beach was eventually buried by silty debris flows from an adjacent hillside and by intertidal mud, peat, and sand. The first phase of intertidal burial, marked by unit B, lasted about 1000 years and concluded with a marsh dominated by saltgrass (*Distichlis spicata*) and bulrush (*Scirpus maritimus*). Next came the tsunami, which deposited the only widespread, tabular body of sand in the excavation (*19*). At that point the marsh and the toe of a debris flow became a short-lived tidal flat. This tidal flat, recorded by unit C, aggraded rapidly until it became a saltgrass marsh, recorded by unit D (*20*). The marsh of unit D persisted about 1000 years until it was covered by artificial fill several decades ago.

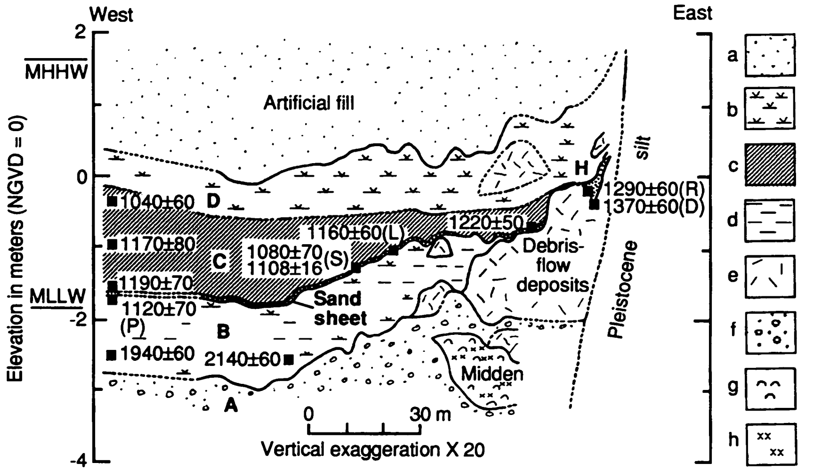

Fig. 4. Cross section along south wall of excavation for effluent pipe at West Point. Contacts solid where observed, dashed where inferred. A, B, C, and D denote stratigraphic units discussed in text. Kinds of deposits: a, stratified sand and basal mud pumped onto site in middle 1900s; b, peaty mud and peat with growth-position rhizomes of tidal-marsh plants; c, well-bedded, woody but rhizome-free mud and sand; d, nonbedded gray mud; e, sandy silt with scattered pebbles; f, sandy gravel and subordinate sand, organic in uppermost 0.1 to 0.5 m; g, disarticulated shell with minor charcoal, cracked rock, and mammal bone; h, lenses containing wood ash. Vertical control by third-order leveling from construction bench marks. Tidal datums (abbreviated as in Fig. 2) extrapolated from 10 km to southeast, at downtown Seattle, where tied by the National Ocean Survey to the National Geodetic Vertical Datum of 1929 (NGVD). Radiocarbon ages (in ^{14}C yr before A.D. 1950) on individual detrital sticks except where labeled P (peat), S (bulrush culms entombed in sand sheet and in overlying mud), L (Douglas fir log, outer 15 rings), R (shrub root in growth position), and D (multiple sticks from duff) (*26*). Location of cross section in treatment-plant coordinate system (*18*): north 850 to 900 feet, east 1365 to nearly 1900 feet.

Properties of the sand sheet at West Point vary with the kind of land that the sand covered. Where deposited on a marsh, the sheet ranges from 4 to 6 cm thick, shows little or no evidence of basal scour, grades stratigraphically upward from 0.5-mm sand to 0.1-mm sand, locally contains a basal lamina of 0.1- to 0.2-mm sand, includes sparse transported bivalves and barnacles, and surrounds culms (aboveground stems) of saltgrass and bulrush that are rooted just below the sand and extend vertically into tidal-flat mud as much as 10 cm above the top of the sand. On debris flows, the sand thickens to 40 cm in swales, disappears on rises, and contains angular clasts of debris-flow silt and rounded pebbles. The highest deposit that we assign to the sand sheet (below H, Fig. 4) contains microscopic marine fossils (*21*). Present-day relief on the sand-mantled marsh and debris flows totals 1.5 m, but this value exceeds initial relief if unit B has been compacted by its overburden.

Land at West Point underwent at least 1 m of abrupt, largely tectonic subsidence that coincided, within months, with deposition of the sand sheet. The subsidence sufficed to make room for the 1 to 1.5 m of tidal-flat deposits that widely accumulated on the sand-mantled marsh (*22*). Both the subsidence and some of the consequent tidal-flat deposition happened too abruptly for the saltgrass and bulrush culms to decompose before being buried by tidal-flat mud. Having initiated rapid tidal-flat deposition, the subsidence cannot have preceded deposition of the sand sheet by many months, for the sand accumulated on a marsh, not on a tidal flat. Nor did the subsidence follow sand-sheet deposition by more than one growing season: None of the marsh plants survived long enough after subsidence to grow rhizomes or tubers into the sand sheet, toward the aggrading tidal flat. We doubt that much of the subsidence resulted from landsliding or compaction because none of the subsided land appears to have been rotated toward the hillside and because the subsided hillside consists of scarcely compressible diamict and silt (Fig. 4).

The probable age of the sand sheet at West Point is between 1000 and 1100 years ago. This century contains the 95% confidence interval for the time of deposition, as shown by a high-precision radiocarbon age on standing, rooted bulrush culms (S, Fig. 4) (*23*) and as further shown by radiocarbon ages and matched ring-width patterns of Douglas fir. A Douglas fir log (L, Fig. 4) was deposited with the sand sheet: it rests on patches of the sand and on toppled, flattened bulrush culms. Bark on the trunk and on flexible limbs suggests that this fir died close to its time of deposition. A conventional radiocarbon age (Fig. 4) brackets the time of death between 850 and 1350 years ago. Matching of ring-width patterns shows that death of the West Point fir coincided, to the half year or less, with a landslide into Lake Washington (*16*). High-precision radiocarbon ages show that this landslide occurred between 1000 and 1100 years ago (*16*).

A tsunami explains the sand sheet at West Point because the sand contains marine fossils, mantles a former tidal marsh, ascends and incorporates hillside deposits, and dates to within months of subsidence and landsliding in the Seattle area. The tsunami probably originated in Puget Sound: Not only does the tsunami correlate closely with local subsidence and landsliding, it also left abundant deposits at sites that show no obvious sign of the largest tsunamis that probably struck the Pacific coast of Washington in the past 2000 years (*24*). We equate the tsunami at West Point with the one at Cultus Bay because the sand sheets at Cultus Bay and West Point resemble one another in graded bedding and radiocarbon age and because we recognized no evidence for any other tsunami in the past 2000 years at either site.

A large earthquake on the Seattle fault probably generated the tsunami by causing abrupt uplift south of the fault and complementary subsidence to the north (*1*). Such movement would have caused water in Puget Sound to surge northward across the fault. As it approached the West Point and Cultus Bay marshes, the tsunami probably encountered sandy shallows ancestral to modern tidal flats (Figs. 1 and 3). Sand thus suspended could have settled onto the marshes as the tsunami slowed across them. If tsunami deposits at West Point and Cultus Bay record every large earthquake on the Seattle fault in the past few thousand years, only one large earthquake has occurred on that fault since 2000 years ago.

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3. We use "years ago" to denote age in calibrated (approximately calendric) years before A.D. 1990. We converted from radiocarbon years to calibrated years with the bidecadal calibration data of M. Stuiver and G. W. Pearson [*Radiocarbon* **28**, 805 (1986)] and a recent version of the calibration program of M. Stuiver and P. J. Reimer (*ibid.*, p. 1022). We multiplied the laboratory-quoted error by 1.6 [high-precision age (*23*)] or by 2.0 (all other ages) because the quoted error may be smaller than one standard deviation of the age measurement [E. M. Scott *et al.*, *ibid.* **32**, 309 (1990)]. Treating the multiplied error as one standard deviation, we then calibrated at two standard deviations. While guarding against underestimation of analytical errors, this approach may also obscure differences in age between noncorrelative events.
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12. At its lowest the sand overlies peaty mud with rhizomes (below-ground stems) only of the tule *Scirpus californicus* or *S. acutus*, a pioneer colonist of modern brackish-water tidal flats of Cultus Bay. At higher levels it overlies peat with rhizomes of saltgrass (*Distichlis spicata*), which does not live as low as the tules at Cultus Bay (Fig. 2).
13. Samples containing the entire thickness of the sand bed showed a westward decrease in median grain size from 0.09 to 0.07 mm along the line of the cross section shown in Fig. 2.
14. *Isthmia nervosa* and *Arachnoidiscus ehrenbergii*, diatoms that live attached to rooted or floating seaweed in Puget Sound [H. H. Gran and E. C. Angst, *Publ. Puget Sound Biol. Sta.* **7**, 417 (1931); E. E. Cupp, *Bull. Scripps Inst. Oceanogr. Tech. Ser.* **5**, 1 (1943)], and *Trochammina*, a dominant genus of salt-marsh foraminifera in the northwestern United States [A. E. Jennings and A. R. Nelson, *J. Foraminiferal Res.* **22**, 13 (1992)].
15. Locally the peat is muddier above than below the sand. This contrast, along with a scarcity of saltgrass rhizomes above the sand, may mean that slight subsidence attended deposition of the sand sheet [A. L. Moore, *Eos* **72**, 315 (1991)].
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19. Unlike the peat at Cultus Bay, the tidal deposits above unit A at West Point contain many sand bodies in addition to the sand sheet. These sand bodies are low in unit B and high in unit C and in unit D. None of them, however, show the conformable base, tabular shape, graded bedding, or wide extent of the sand sheet. Rather, the additional sand bodies above unit A are disconformable lenses of interbedded fine to very coarse sand and are restricted to the western half of the excavation.
20. We infer that unit C was deposited rapidly because it shows no upward decrease in radiocarbon ages measured on individual sticks (Fig. 4) and because, in contrast to the probably bioturbated intertidal mud in unit B, unit C is distinctly bedded.
21. *Trochammina* sp. (*14*).
22. Our assumptions are that (i) the marsh deposits below and above unit C represent similar positions high in the intertidal zone and (ii) relative sea level changed little during deposition of unit C. We interpret unit C as having formed low in the intertidal zone because it contains many transported shells of mussels (*Mytilus edulis*), clams (*Macoma* sp.), and barnacles in the western half of the excavation and because it abounds in well-preserved leaves and sticks yet lacks growth-position rhizomes. This fossil assemblage signifies salt water too deep for the growth of tidal-marsh plants.
23. *Scirpus maritimus* culms surrounded by the sand

yielded a high-precision age of 1108 ± 16 ^{14}C yr before A.D. 1950 (QL-4623), which corresponds to a 95% confidence interval between A.D. 885 and 990 (3). This interval probably includes the time when the dated culms lived. Culms of modern *S. maritimus* at Puget Sound live less than 1 year and rarely stand dead for more than 2 years. By analogy, the dated culms lived within 3 years of the abrupt subsidence that killed the *S. maritimus* and that coincided, within months, with deposition of the sand sheet.

24. Oceanic tsunamis produced sand sheets along the southern Washington coast 300 and 1400 to 1900 years ago (*10, 11*)—times when little or no sand accumulated at our Cultus Bay and West Point sites.
25. Laboratory numbers, from greatest to least age: Beta-51806, -48232, and -48231; USGS-3090; Beta-51805. Ages calculated with an assumed δ^{13}C value of −25 per mil except for USGS-3090 (1040 ± 35 ^{14}C yr B.P.), which was calculated with a measured value of −26.8 per mil. Use of this measurement reduced the age by about 30 ^{14}C yr relative to the age that would have been obtained for a value of −25 per mil.
26. As in (*25*): Beta-50841, -49193, -52626, -52627, -52625, -49614, -49196, -52539, and -49194; QL-4623; Beta-51890 and -49615. Only ages for peat (P) and bulrush stems (S) were adjusted for the measured δ^{13}C value.
27. We thank D. Drake, K. Sharp, I. Khilfeh, and T. Gunstone for hospitality; B. Benson, S. Palmer, J. Bourgeois, L. Amidon, P. Atwater, P. Bierman, R. Bucknam, D. Clark, A. Eipert, B. Eipert, E. Eipert, C. Graff, B. Hallet, K. Hoppe, K. Nimz, D. Perkins, M. Reinhart, J. Shulene, R. Waitt, K. Whipple, and T. Yelin for field help; E. Hemphill-Haley and S. Cooke for fossil identifications; P. Reimer, M. Stuiver, and P. Wilkinson for high-precision radiocarbon dating; F. Bardsley for drafting; and R. Bucknam, D. Swanson, J. Bourgeois, A. Dawson, R. Waitt, and two anonymous referees for reviews.

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Paleoearthquakes in the Puget Sound Region Recorded in Sediments from Lake Washington, U.S.A.

Robert E. Karlin and Sally E. B. Abella

Holocene sediments in Lake Washington contain a series of turbidites that were episodically deposited throughout the lake. The magnetic signatures of these terrigenous layers are temporally and areally correlatable. Large earthquakes appear to have triggered slumping on the steep basin walls and landslides in the drainage area, resulting in turbidite deposition. One prominent turbidite appears to have been deposited about 1100 years ago as the result of a large earthquake. Downcore susceptibility patterns suggest that near-simultaneous slumping occurred in at least three separate locations, two of which now contain submerged forests. Several other large earthquakes may have occurred in the last 3000 years.

Recently, there has been increasing concern that the Pacific Northwest may be subject to infrequent great earthquakes caused by subduction of the Juan de Fuca plate under North America (*1–3*). The Puget Sound region itself is also seismically active, and occasional large earthquakes have occurred in recent times, such as the magnitude 7.1 Olympia earthquake in 1949 and the magnitude 6.5 Seattle earthquake in 1965 (*4, 5*).

The history of earthquake activity in Puget Sound has been difficult to decipher because the area lacks traditional morphologic indicators such as well-defined fault scarps from which the timing and areal extent of past earthquakes can be interpreted. Perhaps one of the most promising ways of assessing paleoseismicity is to study continuously deposited sedimentary sequences in lakes and fiords, where basin topography might be conducive to slumping and associated turbidite activity during a major earthquake. In addition to slumping from the sides, such bodies of water might also contain evidence of large changes in sediment input caused by earthquake-induced landslides in the drainage basin. Of course, seismically induced changes must be differentiated from changes due to climatic influences (floods, lake level variations) and nonseismic geotechnical effects (delta overloading and slope failure).

Lake Washington, bounding the eastern side of Seattle, lies in a steep-sided glacially sculpted valley. The oligotrophic lake averages about 34 m deep and has a subdued W-shaped cross section with marginal elongate troughs 3 to 4 m deeper than in the center of the lake (*6*). The lake sediments consist of a thick sequence of blue glacial clay of indeterminate thickness that is overlain by 7 to 17 m of Holocene limnic peat or gyttja with a basal radiocarbon age of 13,400 years before the present (yr B.P.) (*6, 7*). The limnic section contains the Mazama ash with a radiocarbon age of ~6850 yr B.P. and distinctive post-1916 A.D. laminations that serve as key marker beds. The sediments are anoxic (*8*), so sediment disturbance due to bioturbation is minimal. The lake contains three sunken forests (Fig. 1) that were emplaced by massive block slides with trees still in growth position. The submergence of the forests, lying at the north and south ends of the lake, was originally dated at about 1160 ^{14}C yr B.P. (*9*), and more recently, by high-resolution dates on rings of standing drowned trees (*10*).

Sediments from a series of gravity and piston cores taken throughout the lake contain a record of quasi-periodic sedimentary disturbances that may represent turbidity flows or rapid changes in mass flux from the drainage area. Here we report sedimentologic and paleomagnetic analyses of a suite of ten 3-m-long gravity cores that span the last 3000 years and discuss spatial and temporal patterns of sedimentation that constrain the timing, sources, and causes of these disturbances.

Because the magnetic properties of sediments are sensitive to small changes in the concentration and grain size of magnetic minerals, measurements of magnetic susceptibility (χ) are an extremely useful remote sensing technique for correlating cores and rapidly identifying lithologic and textural changes. As shown in Fig. 1, susceptibility profiles (*11*) of the cores show a high degree of intercore correlation. The shape, position, and magnitudes of the χ peaks are in close agreement for all cases, and several features can be traced across the lake. The magnetic spikes appear to define terrigenous clay and silt layers, which signify short, intense periods of rapid mud accumulation. One interval at 10 to 30 cm is probably the clay and silt layer deposited as a result of the 3 m lowering of the lake level and opening of the Lake Washington Ship Canal in 1916 A.D. (*6, 12*).

Another dominant susceptibility peak at 80 to 110 cm is present in all cores. The peak is sharp at the base and gradational toward the top, a pattern suggestive of a turbidite because hydraulic sorting causes upward fining and concentration of the heavy magnetic minerals in the coarse basal layer. X-radiographs show a distinctive opaque layer 8 to 10 cm thick at this depth. Visual examination and detailed grain-size analyses on TT195 cores 8, 14, and 15 confirm that the layer shows graded bedding and thus has the characteristics of a distal turbidite.

The χ intensities for the horizon at 80 to 110 cm shows a distinctive dependence on location. Magnitudes are highest in the northern and southern cores and lowest in the central cores. A lone exception to this trend is in the core (TT195-5 gc) taken on the western edge of the central basin by Madison Park. This overall pattern suggests that there were multiple detrital sources for

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