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Tsunami Deposits beneath Tidal Marshes on Northwestern Vancouver Island, British Columbia

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Two sand sheets underlying tidal marshes at Fair Harbour, Neroutsos Inlet, and Koprino Harbour on the northwestern coast of Vancouver Island, British Columbia, were probably deposited by tsunamis. The sand sheets become thinner and finer-grained landward, drape former land surfaces, contain marine microfossils, are locally graded or internally stratified, and can be correlated with earthquakes that generated tsunamis in the region. ^{137}Cs dating and historical accounts indicate that the upper sand sheet was deposited by the tsunami from the great Alaska earthquake in 1964. Radiocarbon ages on plant fossils within and on top of the lower sand sheet show that it was deposited sometime after about A.D. 1660. We attribute the lower sand sheet to a tsunami from the most recent plate-boundary earthquake on the Cascadia subduction zone about 300 yr ago, extending the documented effects of this earthquake north of the Nootka fault zone. The 1964 tsunami deposits differ little in thickness and continuity among the three marshes. In contrast, the lower sand sheet becomes thinner and less continuous to the north, implying a tsunami source south of the study area.

INTRODUCTION

There are no written accounts of earthquakes along the offshore boundary between the North America plate and subducting Juan de Fuca and Gorda plates (Cascadia subduction zone, Fig. 1). The lack of historical seismicity has been attributed to aseismic creep (Ando and Balazs, 1979) or to a locked plate boundary that is storing elastic strain to be released in a future earthquake, as is happening at subduction zones off Chile and Alaska (Heaton and Hartzell, 1986). Geophysical models and geodetic measurements (Heaton and Hartzell, 1987; Rogers, 1988; Savage *et al.*, 1991; Hyndman and Wang, 1993, 1995; Dragert *et al.*, 1994) suggest that strain now accumulating on this 1000-km-long plate boundary may be released either in a series of great, magnitude-8 earthquakes or a single giant, magnitude-9 earthquake.

In the late 1980s and early 1990s researchers identified in coastal wetlands three types of geologic evidence best explained by earthquakes at the Cascadia subduction zone (Atwater *et al.*, 1995, and references therein): (1) buried soils that were submerged suddenly, consistent with coseismic subsidence; (2) sand sheets, interpreted to be tsunami deposits, which overlie buried soils, thin and fine landward, and contain marine microfossils; and (3) intruded and extruded sand bodies produced by liquefaction resulting from intense ground shaking. Studies of this geologic evidence have shown that intervals between successive earthquakes range from less than a few centuries to perhaps more than 1000 yr (Atwater *et al.*, 1995; Atwater and Hemphill-Haley, in press). The most recent earthquake or series of earthquakes occurred between about A.D. 1700 and 1720 (Atwater and Yamaguchi, 1991; Nelson *et al.*, 1995), probably in January 1700 (Satake *et al.*, 1996).

The purpose of this paper is to characterize tsunami deposits in Holocene peat at tidal marshes on northwestern Vancouver Island, British Columbia. We studied the architecture, stratigraphy, and sedimentology of two sand sheets at Fair Harbour, Neroutsos Inlet, and Koprino Harbour (Fig. 1) to understand their deposition, preservation, identifying charac-

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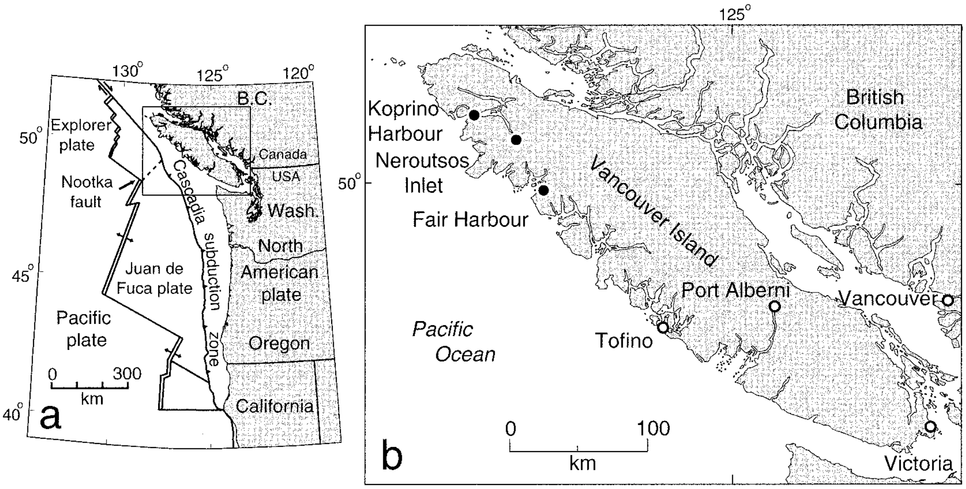

FIG. 1. (a) Lithospheric plates and the seaward edge of the Cascadia subduction zone (study area outlined in box). (b) Study area; solid circles are study sites.

teristics, and paleoseismic significance. The two sand sheets are similar in age, stratigraphic position, and morphology to tsunami deposits farther south that have been attributed to the 1964 Alaska earthquake and to the last great earthquake on the Cascadia subduction zone about 300 yr ago.

SETTING

The study area is situated at the north end of the Cascadia subduction zone, a 1000-km-long area of plate convergence and subduction (Fig. 1). The Nootka fault zone, just south of the study area, may mark the northern limit of the Cascadia subduction zone (Rohr and Furlong, 1995). The small Explorer plate, which is separated from the Juan de Fuca plate by the Nootka fault, is probably a broad deformational zone where convergence on the Cascadia subduction zone to the south changes into strike-slip motion along the North America–Pacific plate boundary to the north (Rohr and Furlong, 1995). The subducting Juan de Fuca plate, south of the Nootka fault, is currently locked against the overriding North America plate (Dragert *et al.,* 1994; Hyndman and Wang, 1995). Evidence for locking and for the buildup of strain at the plate boundary includes geodetic measurements that reveal uplift and crustal shortening in coastal British Columbia and Washington (Savage *et al.,* 1991; Dragert *et al.,* 1994).

Tidal marshes at Fair Harbour, Neroutsos Inlet, and Koprino Harbour were chosen for study because they are extensive, easily accessible, and north of the area previously shown to have been affected by earthquakes on the Cascadia subduction zone. The three marshes are underlain by about 1 m of peat containing two unique sand sheets. This peat is underlain by Pleistocene glaciomarine clayey silt or by Holocene sand and gravel deposits similar to those found elsewhere on the coast of Vancouver Island (Friele and Hutchinson, 1993; Clague and Bobrowsky, 1994a). This sand and gravel may have been deposited during a transgression about 6000 to 7000 yr ago and then reworked during a late Holocene regression. The marshes, characterized by salt-tolerant plants, are situated within the upper half of the intertidal zone between unvegetated tidal flats and supratidal grass and forest. The mean tide range at the three study sites is about 2.9 m, and the maximum range is 4.5 m (Fisheries and Oceans, 1995).

METHODS

We studied sediments at the aforementioned marshes in channel-bank outcrops, pits, and cores. Gridded transects with data points 5 m apart were installed by tape and Brunton compass in areas of minimal fluvial influence. The elevation of each grid point, relative to a temporary benchmark, was measured with an automatic leveling instrument or a hand level. Benchmarks were linked to high tide levels which were determined from regional tide gauge data corrected for local differences in time and magnitude (Fisheries and Oceans, 1995). Depths of stratigraphic contacts, sediment types, colors, and textures were recorded at each grid point from continuous cores retrieved with a 2.5-cm-diameter gouge corer. Stratigraphic cross sections and three-dimensional fence diagrams were constructed from these data.

Block samples of the sand sheets and enclosing peat were collected for laboratory study of sedimentology, internal stratigraphy, and microfossils. Samples of sand were collected from the two sand sheets at each grid point at the Fair Harbour marsh for grain-size analysis. Particle-size trends in the sand-sized fraction were determined with a semiautomatic visual settling tube (Inter-Agency Committee on Water Resources, 1958).

FIG. 2. (a) View north–northwest across Fair Harbour marsh; study site in the foreground. Bridges (B) were rebuilt after their destruction by the 1964 Alaska tsunami. (b) Bank of tidal channel at Fair Harbour; scale = 30 cm.

Fossil plant material for radiocarbon dating, including sticks, conifer cones, bark, and leaf bases of growth-position herbaceous plants, was retrieved from near and within the lower sand sheet and at the base of the peat sequence. Eight samples were radiocarbon dated at IsoTrace Laboratory, the Geological Survey of Canada Radiocarbon Laboratory, and the Quaternary Isotope Laboratory of the University of Washington. Calendric ages were calculated from the radiocarbon ages using the decadal tree-ring dataset of Stuiver and Becker (1993).

Ten samples from the upper 24 cm of the peat sequence at Fair Harbour were analyzed for ^{137}Cs using an X-ray spectrometer at the Pacific Geoscience Centre (Geological Survey of Canada). The samples provided coverage from the marsh surface to a depth of 12 cm below the upper sand.

STRATIGRAPHY AND SEDIMENTOLOGY

Two thin, stratigraphically unique sand sheets occur in similar peat sequences at the Fair Harbour, Neroutsos Inlet, and Koprino Harbour marshes. The sand sheets are similar to seismogenic tsunami deposits at Port Alberni and Tofino farther south on Vancouver Island described by Clague and Bobrowsky (1994b).

Both sand sheets at each marsh become thinner and finer-grained landward and blanket paleosurfaces with relief like that of the present-day marshes. Each sheet is commonly no more than 2 cm thick and consists of moderately sorted silt and very fine to very coarse sand composed of quartz, feldspar, and lithic fragments. The sand also contains sticks, cones, bark, sparse shell fragments, foraminifera, and diatoms. In grain size and lithology the sand resembles adjacent tidal-channel sediments.

The sand sheets range from massive through normally graded to internally stratified. Locally, they consist of two or three couplets of sand and mud. Each sand–mud couplet comprises a layer of normally graded, sharply based, fine to coarse sand abruptly overlain by a layer of sandy mud.

Fair Harbour

Fair Harbour, the southernmost of the three study sites, is located 30 km north of the Nootka fault zone. The 30-ha marsh at the east end of Fair Harbour (Figs. 2a and 3a) is protected from the open ocean, 20 km away, by numerous

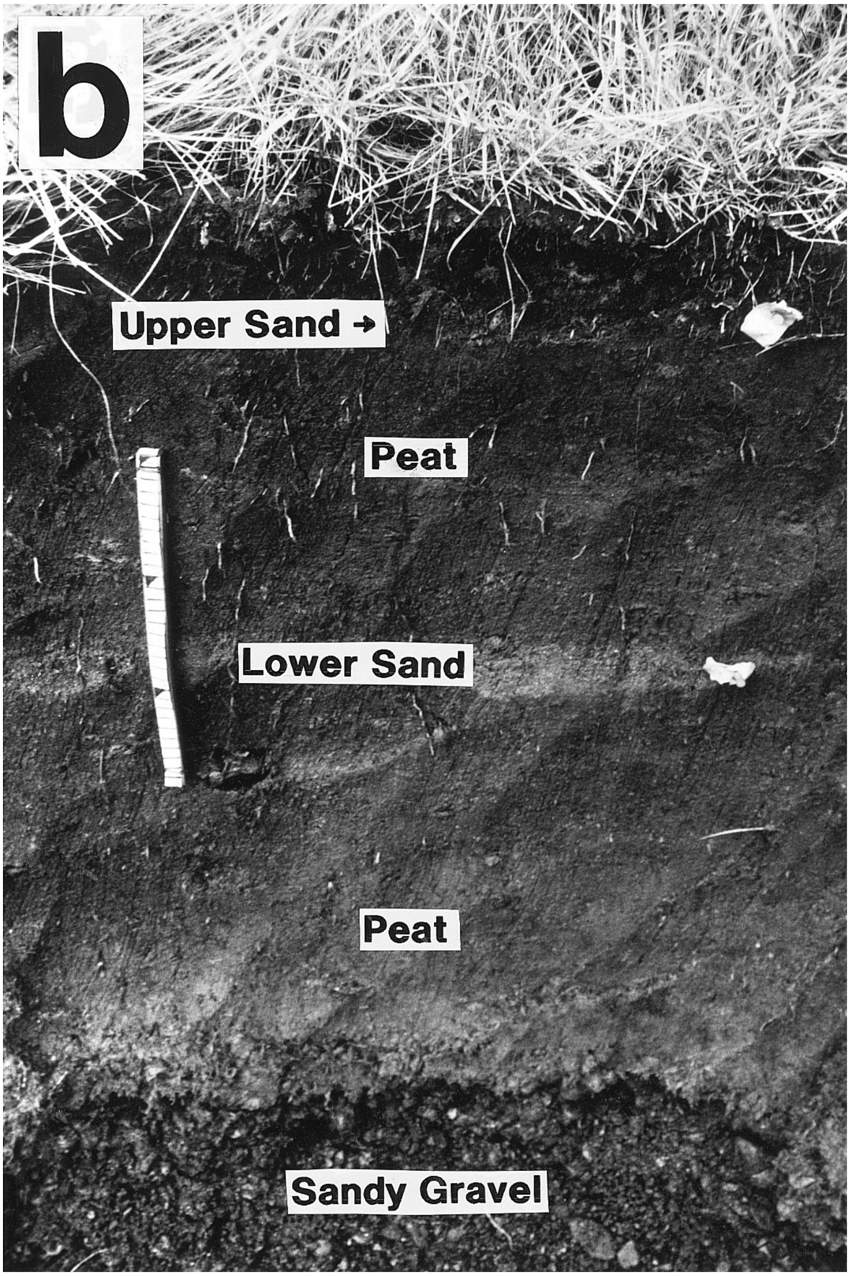

FIG. 2—*Continued*

islands and a narrow inlet. The tsunami from the great Alaska earthquake of March 27, 1964 destroyed two bridges that crossed the marsh and moved buildings at a nearby logging camp (Glen Griffiths, B.C. Ministry of Forests, personal communication, 1995).

We made 215 borings in a 50 $\times$ 90-m grid in the tidally dominated, southeastern part of the marsh, far from fluvial influences to the north and open water to the west (Figs. 2a and 3a). The marsh in this area is underlain by about 1 m of peat that contains the sand sheets (Fig. 4). The peat is uniform in texture and color to within 20 cm of its base, where it grades down into a peaty mud; the peaty mud, in turn, overlies up to at least 3 m of sand and gravel of probable intertidal origin (Fig. 2b). The sand and gravel overlie a thick sequence of clayey silt (AGRA Earth and Environmental Group, 1993), probably a glaciomarine deposit.

The two sand sheets thin and fine landward and away from tidal channels. Fair Harbour Mainline transect (Fig. 4) is interrupted by two 15-m-wide tidal channels. Sediment is coarsest adjacent to both channels and fines away from them (Fig. 5). The sand sheets also thin inland away from these channels and pinch out near the forest edge. Similar trends

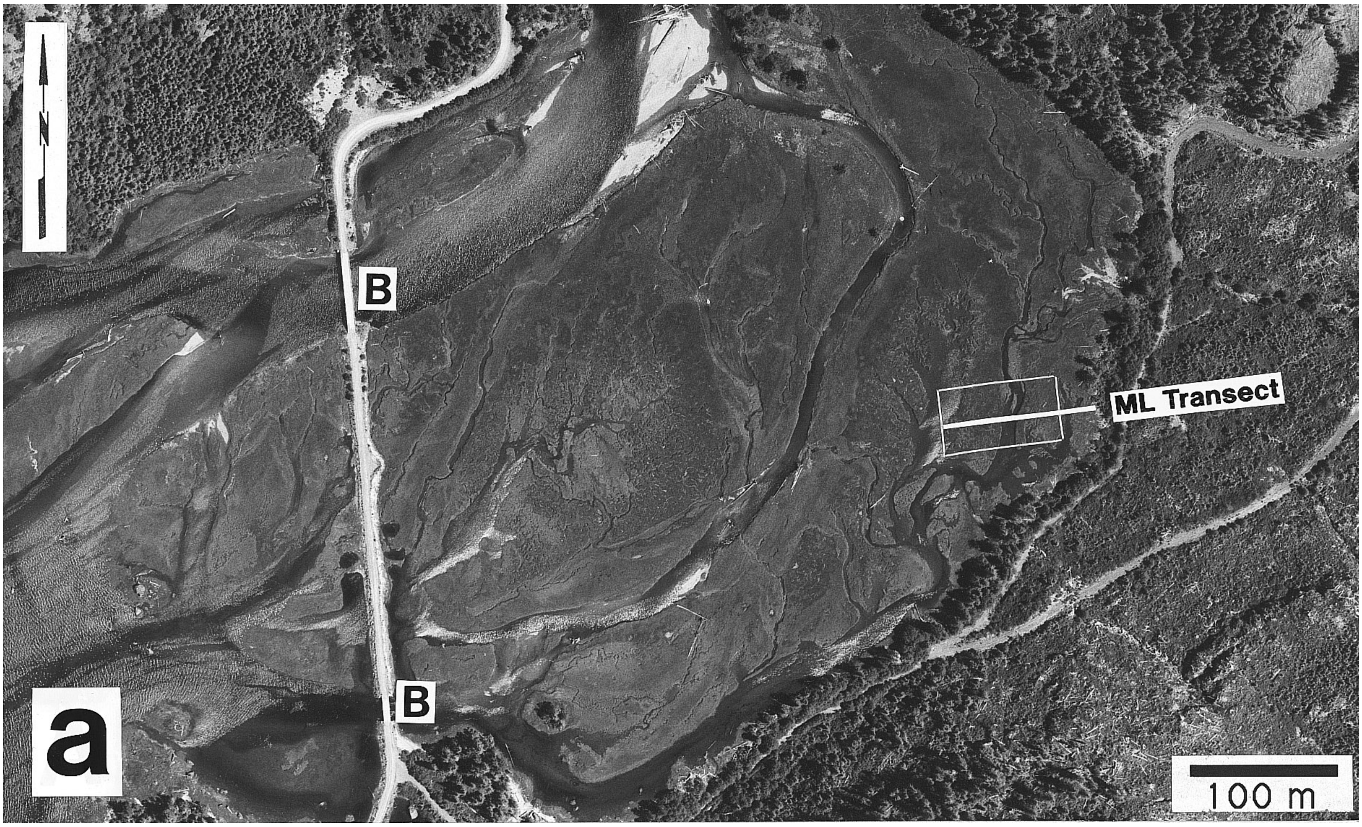

FIG. 3. (a) Fair Harbour marsh; study site outlined in white box. Bridges (B) near the seaward edge of the marsh were rebuilt after being destroyed by the 1964 Alaska tsunami (see also Fig. 2a). Province of British Columbia airphoto BC87033-195. (b) Neroutsos Inlet marsh; white square with an asterisk indicates the study site. The upper sand sheet extends into forest near the site of a cabin (C) that was destroyed by the 1964 Alaska tsunami. Province of British Columbia airphoto BC80092-37. (c) Koprino Harbour marsh, showing locations of transects. The stratigraphy along the transect parallel to the axial channel is shown in Figure 8. Province of British Columbia airphoto BC80092-190.

FIG. 3—*Continued*

were seen elsewhere at Fair Harbour and in outcrops at Neroutsos Inlet and Koprino Harbour.

The lower sand sheet consists of fine to very coarse sand; some gravel is present near the banks of tidal channels facing open water. The sand sheet averages 1.5 to 2.5 cm in thickness, but is locally up to 10 cm thick. It is commonly 60 to 70 cm below the marsh surface. Though typically massive or normally graded, the lower sand sheet locally comprises up to three couplets of basal clean coarse to fine sand overlain by muddy fine sand and silt (Fig. 6). Sticks, conifer cones, and bark are common in the sand. Leaf bases of marsh plants that had been growing prior to sand sheet deposition are entombed in the sand. The lower sand sheet rises topographically 1.4 m from the open marsh to the forest edge.

Diatoms in the peat directly above and below the lower sand sheet are typical middle marsh species (Ian Hutchinson, written communication, 1996). However, the sand itself contains marine diatoms that are absent on the modern marsh, including *Navicula marina* (Ian Hutchinson, written communication, 1996). The presence of marine diatoms in the sand indicates landward transport of the sand from the sea (Hemphill-Haley, 1996).

The upper sand sheet is composed of fine to medium sand. It averages 0.5 to 1 cm thick, has a maximum thick-

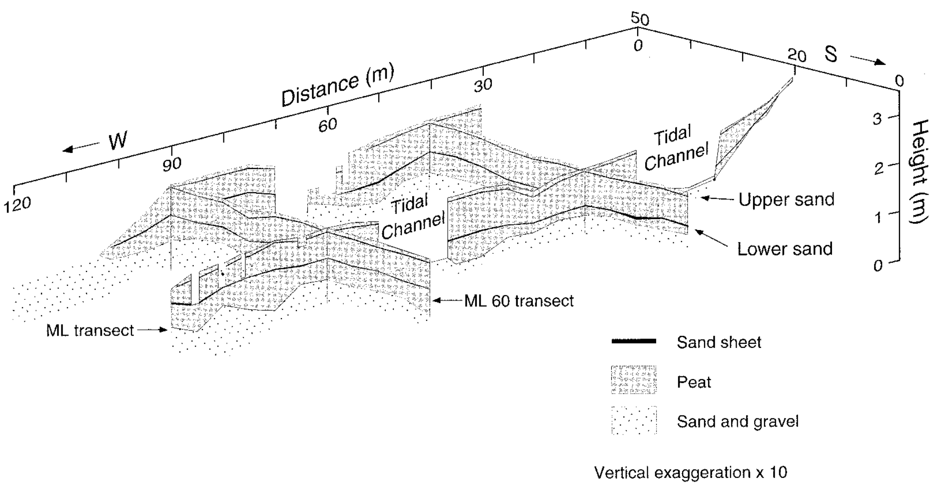

FIG. 4. Fair Harbour marsh stratigraphy. The peat contains two sand sheets. See Figure 3a for location of Mainline (ML) transect. Vertical datum is lower low water.

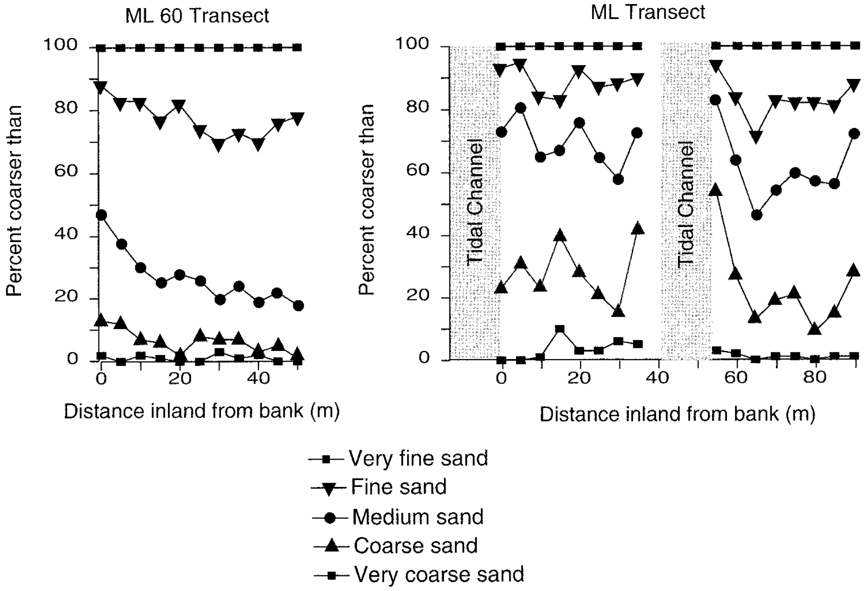

FIG. 5. Particle-size trends in the sand-size fraction of the lower sand sheet along two Fair Harbour transects (see Fig. 4 for location). The sand sheet fines away from tidal channels, which are probably the primary sediment source.

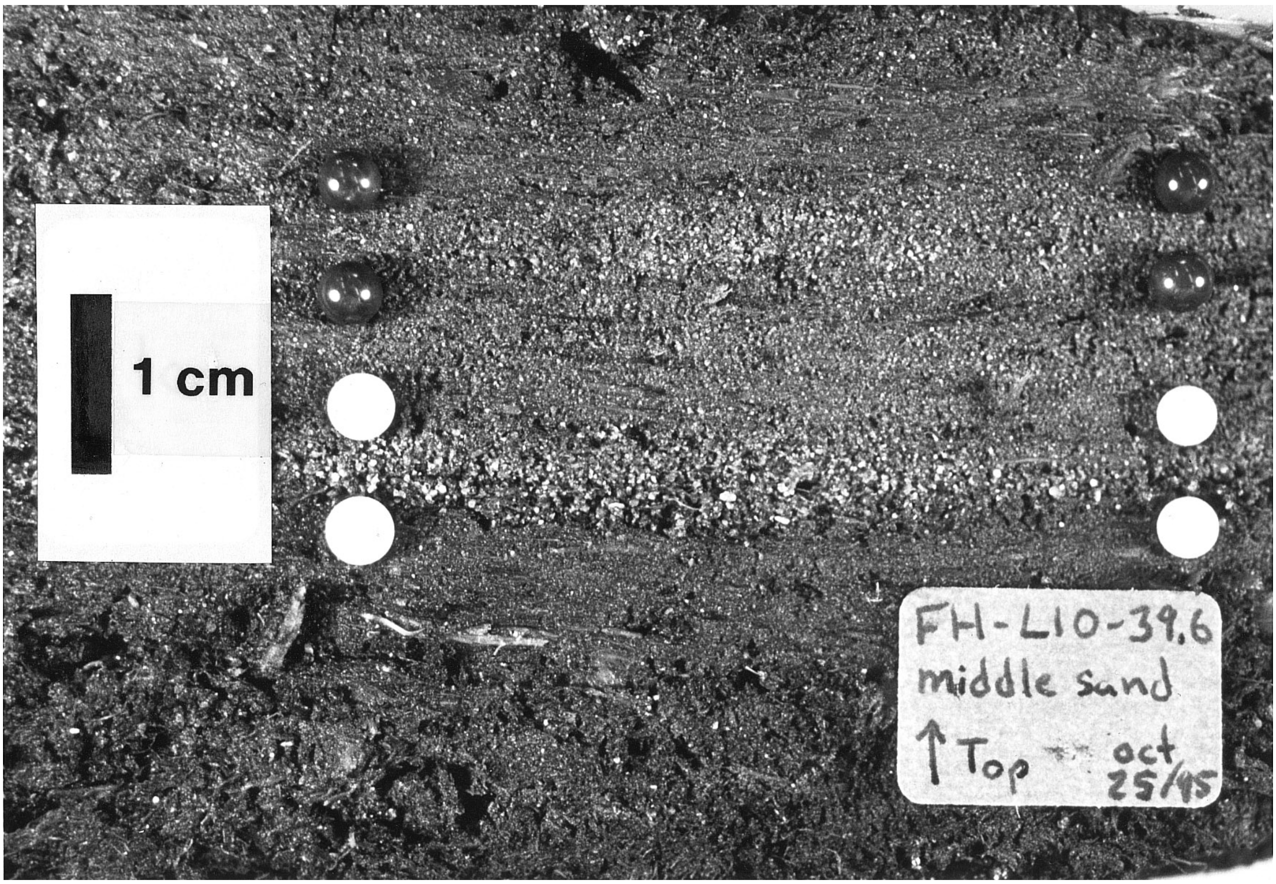

FIG. 6. Couplets in the lower sand sheet at Fair Harbour. Each couplet is composed of a coarse basal layer and an overlying finer layer; the two coarse basal layers in this sample are bracketed by pins. Each couplet may record a separate surge of water in a tsunami wave train.

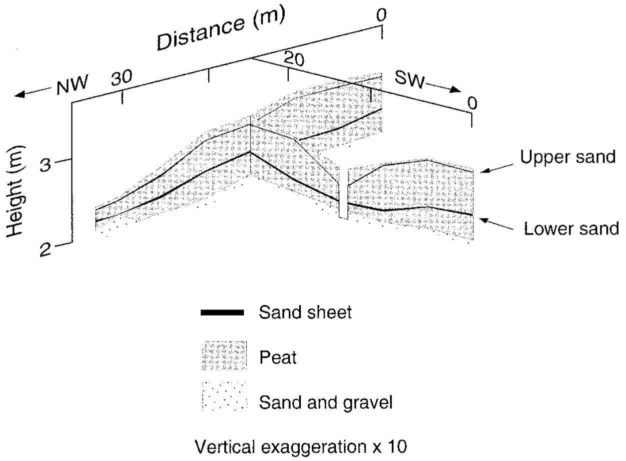

FIG. 7. Neroutsos Inlet marsh stratigraphy (see Fig. 3b for location). Vertical datum is lower low water.

ness of 2 cm, and is commonly 6 to 10 cm below the marsh surface. This sand sheet is generally massive, but in some places it consists of up to three couplets of coarse to fine sand and mud.

Neroutsos Inlet

Neroutsos Inlet is a 2.5-km-wide fjord that branches off Quatsino Sound and penetrates 30 km south into the mountainous interior of northern Vancouver Island (Fig. 1). A 17-ha marsh at the head of the inlet (Fig. 3b) is protected from the open ocean by approximately 50 km of narrow waterways and by islands. According to Fred Lind, a veteran tug boat captain, log booms in the inlet and a hunting cabin at the head of the inlet (Fig. 3b) were destroyed by the 1964 Alaska tsunami (personal communication, 1995). Jetsam from the cabin was found suspended in tree branches 1.5 m above the ground and a small wood stove was carried 20 m into the forest by the tsunami (Lou Walker, personal communication, 1995). The jetsam is about 2 m above tide height at the time that the largest wave from the 1964 Alaska tsunami probably arrived in Neroutsos Inlet (Spaeth and Berkman, 1967).

A 30 × 30-m grid was established in the tidally dominated northeastern portion of the marsh, away from fluvial influences to the west (Figs. 3b and 7). At the grid site the marsh is underlain by 0.8 m of peat which is uniform in texture and color to within 20 cm of its base, where it grades downward into peaty mud. The peaty mud abruptly overlies at least 2 m of cobble gravel exposed in the banks of tidal channels. Two sand sheets are present throughout the grid site, but they occur only discontinuously within thinner peat near the back of the marsh to the southeast.

The lower sand sheet at the grid site is 1 to 2 cm thick, consists of medium to very coarse sand that is massive to normally graded, and lies 40 to 60 cm below the marsh surface (Fig. 7). The sand contains growth-position leaf bases of the marsh plant *Triglochin maritimum.*

The upper sand sheet at the grid site is 0.5 to 2 cm thick, is composed of very fine to coarse massive sand, and lies 4 to 12 cm below the marsh surface. In the forest, near the site of the cabin that was destroyed by the 1964 tsunami, stratified coarse sand and granules up to 17 cm thick underlie 2 cm of forest duff. This sediment probably correlates with the upper sand sheet at the grid site.

Koprino Harbour

Koprino Harbour is located on the northern side of Quatsino Sound about 50 km from the northern end of Vancouver Island and 15 km from the open Pacific Ocean (Fig. 1). A 10-ha tidal marsh (Fig. 3c) is protected by a small island within the harbor and by a large fan delta that almost isolates the marsh from the open water of Quatsino Sound. A small tidal channel runs the length of the marsh. Boats and dock facilities at Winter Harbour, 10 km to the northwest, were damaged by the 1964 Alaska tsunami (Fred Lind, personal communication, 1995).

We studied cores and outcrops along a 330-m-long axial transect in the eastern part of the marsh (Figs. 3c and 8). Seven shorter transects extend from forest edge to forest edge perpendicular to the axial transect.

A 60- to 70-cm-thick peat unit containing two sand sheets (Fig. 8) is uniform in texture and color to within about 10 cm of its base, where it grades into peaty mud. These sediments overlie less than 20 cm of gravelly sand, which in turn overlies clayey silt containing bivalve shells. Both sand sheets thin and fine away from open water and from the axial tidal channel.

The lower sand sheet is continuous only within about 15 m of the axial tidal channel (Fig. 8), along which it rises 10 cm topographically toward the forest. It is composed of fine to very coarse sand, is 0.1 to 1 cm thick, and commonly lies 60 to 70 cm below the marsh surface. Possibly correlative, discontinuous lenses of sand up to 12 cm thick are present near the forest edge.

The upper sand sheet rises 0.4 m topographically away from the tidal channel toward the forest, but only locally reaches it. It is composed of fine sand, is 0.5 cm thick on average, and lies 5 to 8 cm below the marsh surface.

CHRONOLOGY

Clayey silt at the base of the succession at Koprino Harbour and in boreholes at Fair Harbour is probably correlative with similar late Pleistocene glaciomarine sediments at Tofino and Ucluelet to the south (Friele and Hutchinson, 1993; Clague and Bobrowsky, 1994a). Bivalve shells collected from the Tofino sediments yielded a radiocarbon age of 13,780 ± 110 ^{14}C yr B.P. (TO-2365; Clague and Bobrowsky, 1994a).

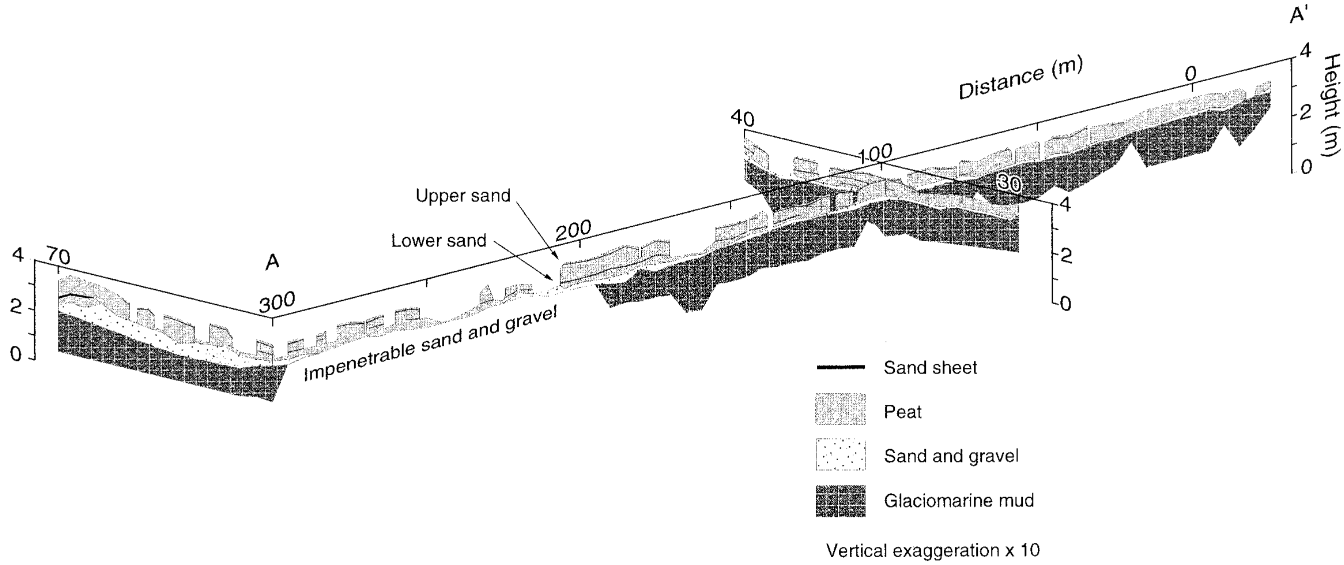

FIG. 8. Koprino Harbour marsh stratigraphy (see Fig. 3c for location). The two sand sheets are continuous only near the axial tidal channel. Vertical datum is lower low water.

A stick from the base of the peat at Fair Harbour gave ages of 290 ± 80 and 300 ± 80 ^{14}C yr B.P. (sample 8, Table 1), indicating that peat accumulation began there less than 550 cal yr ago. Sand and gravel below the peat are probably a lag deposit that spans much of Holocene time (Clague and Bobrowsky, 1994a).

The age of the lower sand sheet is constrained by seven radiocarbon ages (Table 1, Fig. 9). Radiocarbon ages of leaf bases of *T. maritimum*, which were living on the marsh and most closely date the time of sand deposition, correspond to calendric ages younger than A.D. 1659 (samples 5 and 6 in Table 1). Radiocarbon ages of sticks, bark, and other detrital material associated with the sand sheet provide only maximum dates for sand deposition. The youngest of the ages on detritus (sample 4) corresponds to calendric ages more recent than A.D. 1653 and is compatible with the *Trig-*

TABLE 1
Radiocarbon Ages

No., Fig. 10	Location	Radiocarbon age[a] (^{14}C yr B.P.)	Calendar age range[b] (yr A.D.)	Laboratory number[c]	Dated material and stratigraphic position
1	Fair Harbour	510 ± 80, 420 ± 80[d,f]	1331–1628[e]	GSC–6006	Stick, 6–10 cm above lower sand
2	Fair Harbour	6930 ± 80	6115–5599 B.C.	TO–5317	Stick, 0.5 cm above lower sand
3	Neroutsos Inlet	230 ± 50	1444–1950	TO–5314	Bark fragment on lower sand
4	Fair Harbour	60 ± 50	1653–1950	TO–5316	*Tsuga heterophylla* cone on lower sand
5	Koprino Harbour	40 ± 50	1659–1950	TO–5315	Growth-position *Triglochin* in lower sand
6	Koprino Harbour	161 ± 16	1670–1950	QL–4806	Growth-position *Triglochin* in lower sand
7	Fair Harbour	270 ± 80[g]	1444–1950	GSC–6018	Stick, 2–3 cm below lower sand
8	Fair Harbour	300 ± 80[h], 290 ± 80[d,i]	1449–1950[e]	GSC–6030	*Juniperus* stick at base of peat

[a] Laboratory-reported uncertainties are 2σ for GSC ages and 1σ for all others. Ages normalized to δ ^{13}C = −25.0‰ PDB.
[b] Radiocarbon ages were calibrated using the decadal tree-ring dataset of Stuiver and Becker (1993). The range represents the 95% confidence interval based on the 2σ error limits of the radiocarbon age (error multipliers = 1.6 (QL age) and 2.0 (GSC and TO ages) to expand laboratory-quoted errors to cover uncertainties in reproducibility and systematic bias; see Stuiver and Pearson, 1993).
[c] Laboratories: GSC, Geological Survey of Canada; TO, Isotrace Laboratory; QL, University of Washington Quaternary Isotope Laboratory.
[d] The same sample was dated twice.
[e] Calibrated age range calculated from the weighted mean of the two radiocarbon ages.
[f] δ ^{13}C = −24.18.
[g] δ ^{13}C = −28.25.
[h] δ ^{13}C = −24.47.
[i] δ ^{13}C = −26.14.

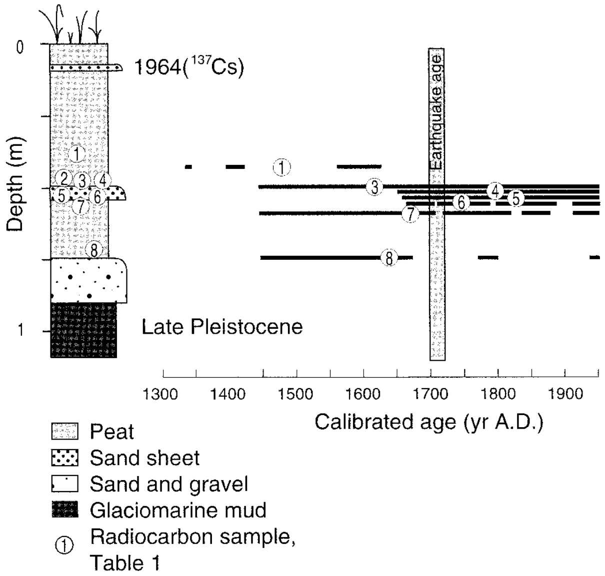

FIG. 9. Calibrated radiocarbon ages of dated plant material. The stratigraphic section is generalized from observations at the three studied marshes. Horizontal lines are 2σ calibrated age ranges (see Table 1). The vertical bar represents the probable age range of the most recent plate boundary earthquake(s) at the Cascadia subduction zone (Nelson *et al.,* 1995).

lochin ages. The stick dated at 6930 ± 80 ^{14}C yr B.P. (sample 2) is much older than the enclosing sediment and must have been recycled from an older deposit.

Peat just below the upper sand sheet at Fair Harbour has a high concentration of ^{137}Cs (Fig. 10), related to atmospheric nuclear testing which began in 1953 and peaked around 1964 (Clague *et al.,* 1994). The cesium data show that the upper sand sheet dates to the late 1950s or early 1960s and support the conclusion that this sand was deposited by the 1964 Alaska tsunami (see Discussion).

DISCUSSION

Origin of Sand Sheets

Two sand sheets preserved in coastal marshes at Fair Harbour, Neroutsos Inlet, and Koprino Harbour are best explained as tsunami deposits. The upper sand sheet probably was deposited by the tsunami of the 1964 Alaska earthquake. The lower sand sheet is similar in stratigraphic position, sedimentology, and age to other sand layers on the Pacific coasts of Oregon, Washington, and southern Vancouver Island that have been attributed to the tsunami of a large earthquake on the Cascadia subduction zone about 300 yr ago (references in Atwater *et al.,* 1995). The stratigraphic position and age of the lower sand sheet are similar at the three studied marshes; thus the deposit likely records a single tsunami that affected all three sites.

Many stratigraphic and sedimentological observations from our study sites are consistent with tsunami deposition (Fig. 11): (1) the sand layers are landward-thinning sheets that blanket paleo-marsh surfaces; (2) the sand sheets rise toward the forest edge; (3) the sediment fines landward away from tidal channels; (4) the sands contain marine microfossils; (5) some sands are normally graded or locally comprise two or more couplets consistent with deposition by multiple waves of a wave train; (6) the sand sheets are similar in age and stratigraphic position to identified tsunami deposits farther south along the Cascadia subduction zone (Clague and Bobrowsky, 1994b; Atwater *et al.,* 1995; Nelson *et al.,* 1995).

Other processes, such as floods and storm surges, do not account for all these characteristics. The deposit of a river flood should fine toward the sea and contain few or no marine microfossils. By contrast, the lower sand sheet at Fair Harbour fines inland and contains marine diatoms, showing that it was deposited by a landward-directed surge of water. Furthermore, all three study sites are distant from fluvial influences. The presence of only two sand sheets at the study sites, the lack of sedimentary structures indicative of prolonged inundation, and the remoteness of the sites from open water and Pacific storms argue against storm surges as the agent of deposition for the sand sheets.

Both sand sheets at Fair Harbour are locally layered (Fig. 6). Three couplets in the upper sand sheet may record the flood and return flows of successive discrete waves of the 1964 tsunami. Tide gauge records from Tofino show that the 1964 tsunami arrived on the west coast of Vancouver Island as three 1- to 3-m-high waves over a period of about 3 hr (Spaeth and Berkman, 1967).

Age of Sand Sheets

Radiocarbon ages on fossil plant material associated with the lower sand sheet show that it was deposited after about

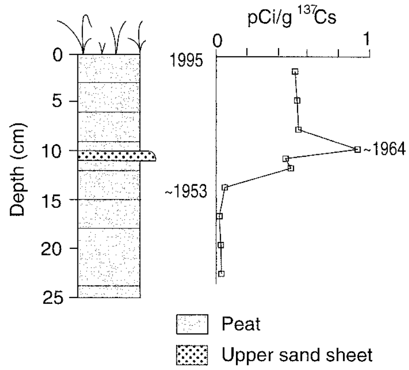

FIG. 10. Cesium activity (pCi/g) in the upper part of the peat at Fair Harbour. The increase in ^{137}Cs activity between 15 and 12 cm marks a major increase in atmospheric nuclear testing in the early 1950s (Anderson *et al.,* 1957; Rankama, 1963, pp. 439–441); the peak in testing and ^{137}Cs activity occurred around 1964. The rectangles represent samples used for ^{137}Cs analysis.

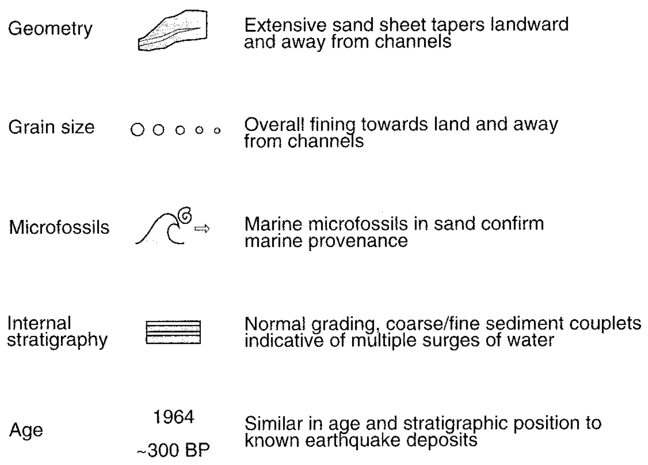

FIG. 11. General characteristics of tsunami deposits in our study areas.

A.D. 1660. The lack of any written record of a tsunami prior to 1964 since the first significant European settlement on Vancouver Island in about A.D. 1850 further limits the age of the sand sheet to before 1850. This age control allows correlation with a plate-boundary earthquake, or a series of such earthquakes, that produced very similar deposits in coastal Oregon, in Washington, and on central Vancouver Island about 300 yr ago (Atwater *et al.,* 1995; Nelson *et al.,* 1995). This correlation is strengthened by the absence of stratigraphic evidence for more than one sand sheet of about this age at the three study sites and at other sites on Vancouver Island where similar deposits have been found (Clague and Bobrowsky, 1994b).

^{137}Cs data (Fig. 11) and eyewitness accounts of wave damage at or near all three study sites indicate that the upper sand sheet was deposited by the 1964 Alaska tsunami. The similarity of this sand sheet to well-dated deposits of the 1964 tsunami at Port Alberni (Clague *et al.,* 1994) further supports this conclusion.

High-precision radiocarbon ages show that the most recent Cascadia plate-boundary earthquake occurred between A.D. 1700 and 1720 (Nelson *et al.,* 1995). Unavoidable imprecision in this numerical dating allows for two interpretations of the seismicity: multiple magnitude-8 earthquakes may have affected different parts of the subduction zone during this 20-yr period, or one magnitude-9 earthquake may have ruptured the entire plate boundary. The singularity of the lower sand sheet and the lack of peat laminae within the sand preclude a hiatus of more than a few years between any successive tsunamis ca. 300 yr ago at our sites.

The presence of only two tsunami deposits at the three study sites is due to the youthfulness of tidal marshes on northern Vancouver Island. Late Holocene emergence at net rates of up to a few millimeters per year (Clague *et al.,* 1982; Friele and Hutchinson, 1993), which has continued into the 20th century (Dragert, 1995; Hyndman and Wang, 1995), probably accounts for this short record.

Comparison of 1964 and 300-Yr-Old Tsunamis

Although local bathymetry, shoreline aspect, onshore topography, and other factors affect wave amplitude and run-up (Van Dorn, 1965), the deposit of the 1964 Alaska tsunami can be used as a modern analog to evaluate the 300-yr-old event. Site comparisons can be made between the two tsunamis because the local bathymetry and topography are not likely to have changed by much over the past 300 yr. These comparisons ignore differences in tidal conditions, wave directions, and tsunami source characteristics. Differences in the amount of sediment available for transport and the depositional and erosional characteristics of the tsunamis also complicate these comparisons, but cannot be resolved at present.

We compared the sand sheets at the three marshes and found that the 1964 sand sheet is similar in thickness at each marsh, whereas the 300-yr-old sand sheet is thicker and more continuous at the southernmost site than at the two northern sites. At Fair Harbour, the southernmost site, the lower sand sheet has an average thickness of 2 cm and is as continuous as the 0.75-cm-thick upper sand sheet. This comparison implies that the 300-yr-old tsunami was larger there than the 1964 tsunami (Fig. 12). In contrast, at Koprino Harbour, the northernmost site, the 300-yr-old deposit has an average thickness of less than 0.5 cm and is not as continuous as the 0.5-cm-thick 1964 deposit (Fig. 12). This suggests that the 300-yr-old tsunami was smaller there than the 1964 tsunami. These observations collectively suggest that the 300-yr-old tsunami may have attenuated to the north. The tsunami of a far-field earthquake or an earthquake directly off northern

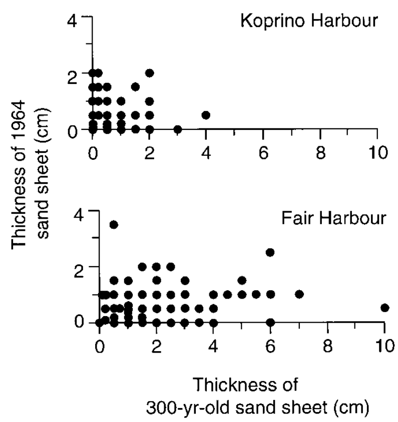

FIG. 12. Thickness of the 1964 and 300-yr-old sand sheets at Fair Harbour and Koprino Harbour. The 300-yr-old sand sheet is thicker and more continuous than the 1964 sand sheet at Fair Harbour. In contrast, the 300-yr-old sand sheet is about the same thickness as the 1964 sand sheet at Koprino Harbour.

Vancouver Island would probably not attenuate in this fashion. We infer that this tsunami came from south of the Nootka fault zone.

CONCLUSIONS

Peat beneath three marshes on northwestern Vancouver Island contains sand sheets deposited by the 1964 Alaska tsunami and by an older tsunami that we attribute to the most recent plate-boundary earthquake(s) on the Cascadia subduction zone about 300 yr ago. The sand sheets are stratigraphically unique, landward-thinning, and landward-fining deposits that blanket paleomarsh surfaces. The deposits are commonly massive, but in places are normally graded or consist of couplets that probably record the surge and return flows of successive waves in a tsunami wave train. The sands contain marine microfossils, indicating that they were deposited by landward-directed flows.

The discovery of ca. 300-yr-old tsunami deposits on northwestern Vancouver Island extends the documented effects of Cascadia subduction zone seismicity to north of the Nootka fault zone. The presence of only one sand sheet of this age at the studied marshes and at other sites farther south is consistent with a single, very large (moment magnitude-9) Cascadia earthquake or with two or more smaller earthquakes separated by no more than a few years.

Relative to the 1964 sand sheet, the 300-yr-old deposit is thinner and less continuous to the north. This indicates a southerly tsunami source, probably south of the Nootka fault, as opposed to a source directly off northern Vancouver Island.

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