Grain-size trends in a Holocene tsunami deposit from Cultus Bay, Puget Sound, Washington

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Abstract. Well-preserved evidence for a tsunami in Puget Sound is exposed in a series of marsh deposits at Cultus Bay. These deposits contain a 1 to 15 cm thick layer of sand that cuts across facies boundaries and drapes an area at least 150 m by 300 m. The sand rises from 145 cm below present-day MSL to the east, where it blends into tidal flat deposits, to 70 cm above MSL to the west, where it tapers against colluvium.

Grain size of the sand sheet diminishes westward and upward. The sand fines from $D_{50} =$ 0.010 mm in the east to $D_{50} = 0.006$ mm in the west. The sand also shows normal grading, with grading becoming less pronounced westward. This trend is consistent with a single westward-directed surge of water entraining tidal-flat sand and advecting it onto the marsh. A westward surge suggests that the tsunami washed around the end of a spit on the south side of the marsh, and swept into the lagoon formed behind the spit. No evidence for spit breaching was found, and the strong westward direction of the grain-size trend suggests that any wave that did breach the spit waned before it reached the study area.

1. Introduction

Sheets of marine sand are a common feature of tsunami-devastated lowlands. Such material has been noted for most modern tsunamis, including 1999 Vanuatu (Caminade *et al.*, 2000), 1998 Papua New Guinea (Goldsmith *et al.*, 1999), 1996 Irian Jaya (Imamura *et al.*, 1997), and 1992 Flores Island (Shi *et al.*, 1995). Ancient tsunamis have also been inferred based on sand sheets found in coastal lowlands, including those found in Scotland (Dawson *et al.*, 1988; Long *et al.*, 1989), Japan (Minoura and Nakaya, 1991), New Zealand (Chagué-Goff and Goff, 1999), the Mediterranean (Dominey-Howes *et al.*, 1999; Minoura *et al.*, 2000), and the Pacific coast of North America (Clague *et al.*, 2000). Sand sheets are important markers of ancient tsunamis, especially, and may serve as the only record of some prehistoric tsunamis.

There are, however, many other coastal phenomena that leave sand sheets. Similar sheets have been reported from storms, coastal floods, liquefaction, and seiches. Previous tsunami studies have involved a system of eliminating all other possibilities so that tsunami is the only remaining alternative. In order to make such distinctions, however, it is important to have detailed descriptions of tsunami sediments so that depositional models of the general features of tsunami deposits can be developed.

Here we describe a well-established prehistoric tsunami deposit from Cultus Bay, Washington (Fig. 1). The deposit was first described by Atwater and Moore (1992), as resulting from sudden movement 1000 years ago along a fault running under Puget Sound some 40 km to the south (Bucknam . *et al.*, 1992). We here extend the original deposit description to include trends

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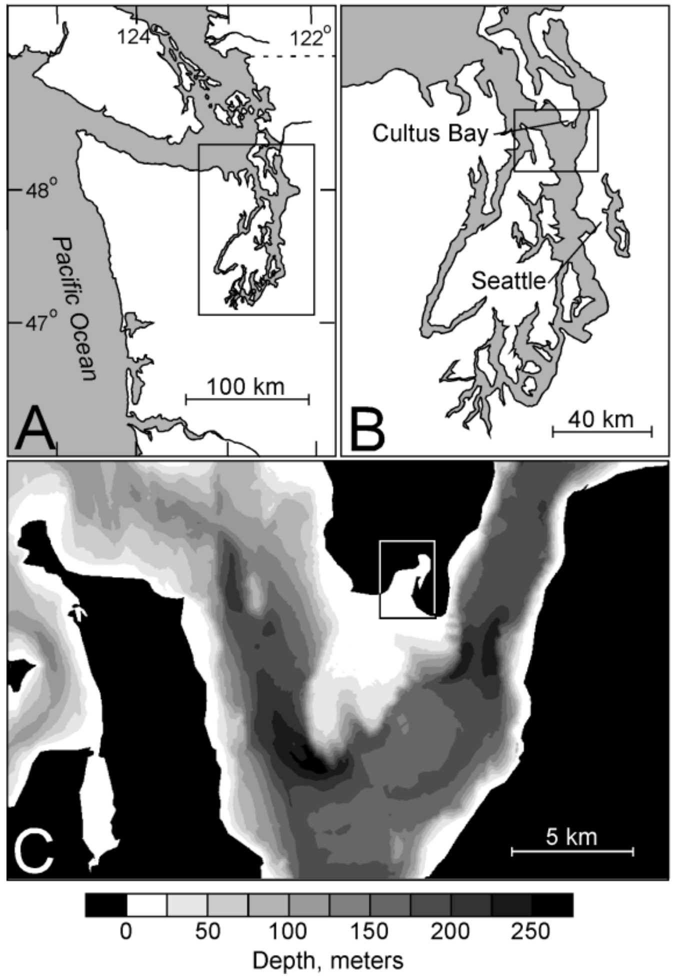

Figure 1: (a) Location of Puget Sound in western Washington. (b) Location of Cultus Bay in Puget Sound. (c) Bathymetry offshore Cultus Bay. Countour interval 25 m.

in grain size—we show that part of the depositional model of tsunamis should include landward fining of the deposit in the direction of tsunami flow.

2. Geologic Setting

Cultus Bay lies between two headlands of Pleistocene glacio-marine drift and at the foot of a small drainage formed in their trough (Fig. 2a). The bay itself rests on more than 150 m of Quaternary sand and mud and is elongated north–south, with a spit extending most of the way across the bay about halfway from the mouth to the back. Seaward of the spit, the bay is characterized by large sand waves (about 50 m between wave crests) that are exposed at low tide. Behind the spit, a salt march began to develop at least 2200 years ago, based on a 14C date of rhizomes of the marsh plant *Triglochin maritimum* found at the base of a sequence of salt marsh peat

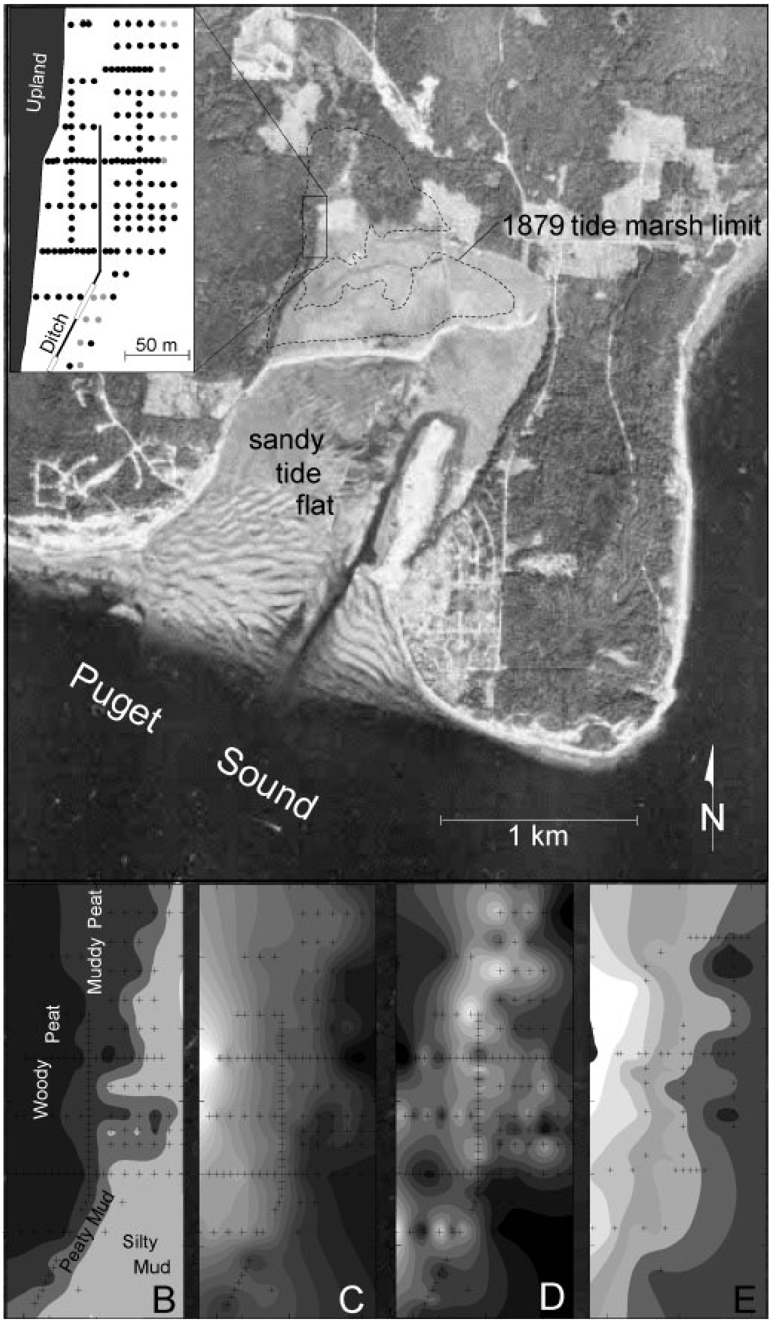

Figure 2: (a) Arial photo of Cultus Bay, with pre-dike marsh extent marked. Inset panel shows location of core holes and drainage ditch exposures in the study area. Black dots and solid black line show holes and ditch exposures where sand was present: light gray dots and open lines show holes and ditch exposures where sand was either absent or could not be distinguished. (b) Facies map showing the sediment type in contact with the base of the sand sheet. (c) Topography of the base of the sand sheet. Contour interval 10 cm. (d) Thickness map of the sand sheet. Contour interval 2 cm. (e) Median grain size of the sand sheet. Contour interval 0.05 mm.

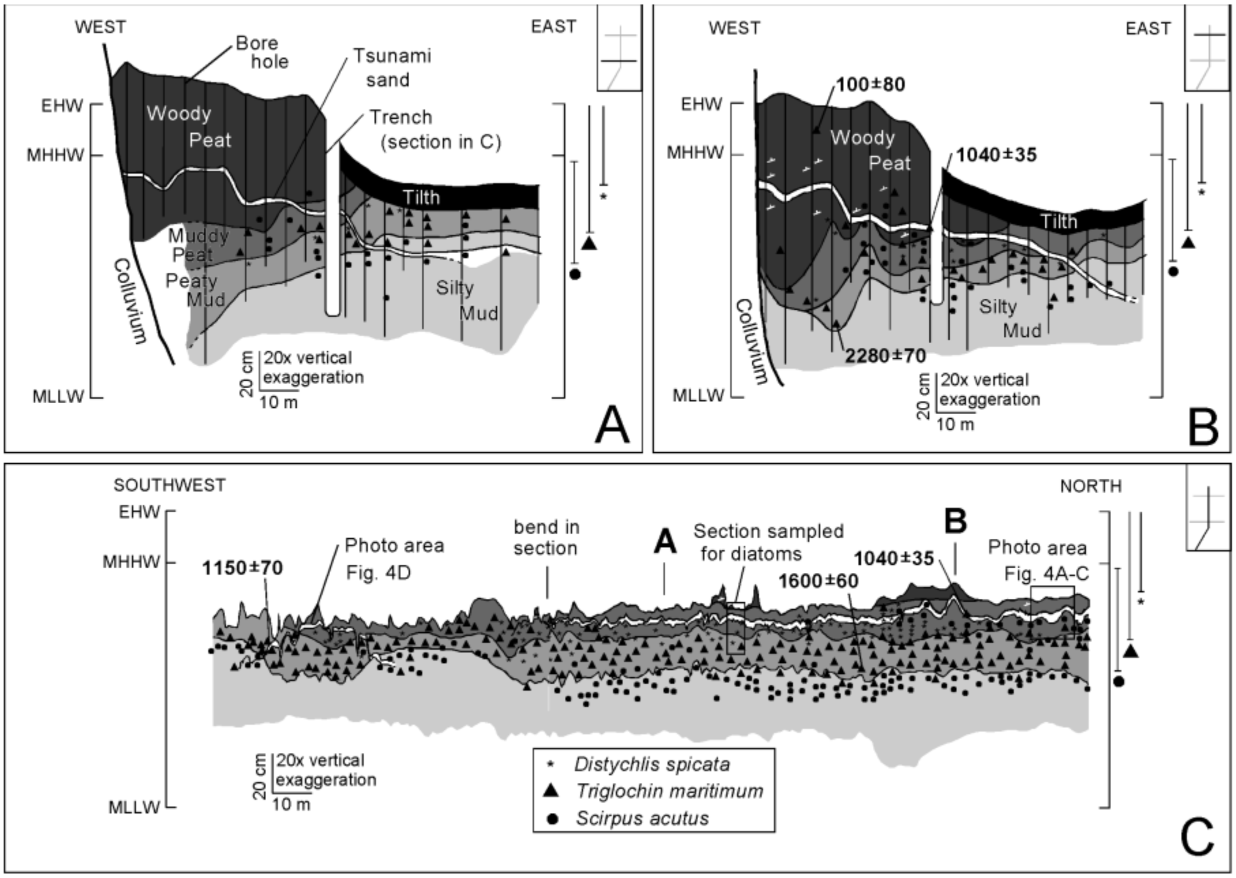

Figure 3: Transect cross sections. (a) Southern lateral transect, showing sand sheet climbing from tidal flat deposits onto a tidal marsh and finally pinching out in colluvium. (b) Northern lateral transect. (c) Drainage ditch transect. Interrupted deposition in the left center of the transect probably represents a distributary channel.

near the western hillside. The marsh expanded into the tidal lagoon formed behind the spit so that by 1879 most of the lagoon had been converted to marsh (Fig. 2a). The marsh was diked in 1909 to provide pasture, with a small patch of marsh left undiked—the diked area is now dry for most of the year.

The salt marsh stratigraphy at Cultus Bay shows that the marsh developed from a mud flat, first by pioneering *Scirpus californicus*, then by the marsh plants *Triglochin maritimum* and *Distichlis spicata*. Exposures of the marsh sediments show this transition as a change upward from tidal flat mud to woody peat (Fig. 3). The lowest exposed unit is a blue-gray, compact silty mud with common rhizomes of *S. californicus*. This unit is similar to the sediment found in the current seaward portion of the bay. Overlying the silty mud is a tannish-gray, peaty mud containing abundant below-ground stems of *T. maritimum* and rhizomes of *S. californicus*. This unit probably represents the low marsh, where marsh plants first begin to colonize the tidal flat. Overlying this is a tannish-brown muddy peat containing rhizomes of

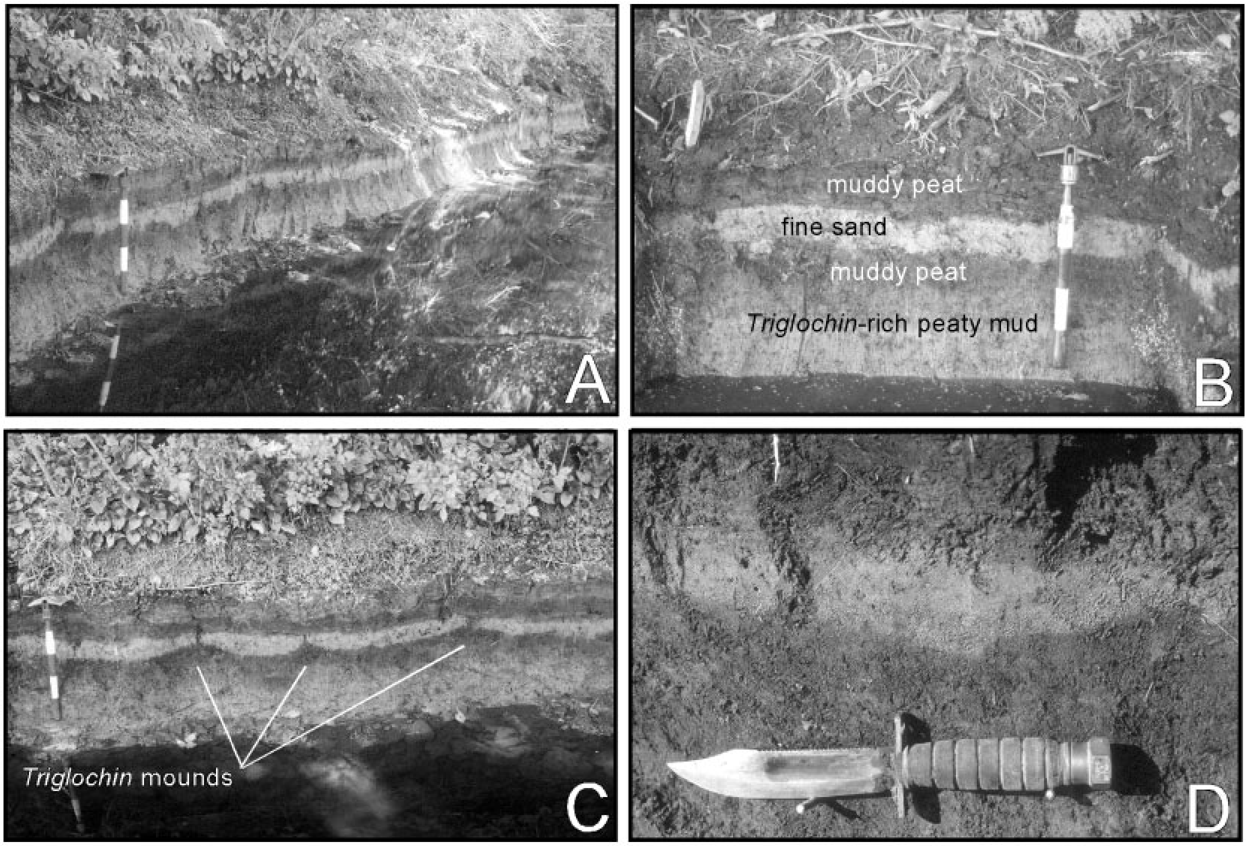

Figure 4: Transect photos. (a) Oblique view of the drainage ditch showing laterally continuous sand. (b) General stratigraphy of the drainage ditch. (c) Closeup of *Triglochin* mounds buried by the sand sheet. (d) Normal grading in the sand sheet.

D. spicata and *S. californicus*, together with below-ground stems of *T. maritimum*. This unit is similar to that found under the present-day high marsh (the platform of marsh above most high tides). The uppermost unit is a dark brown peat containing rhizomes of *D. spicata* and stems of *T. maritimum* together with abundant woody debris. This unit probably formed in a coastal swamp at or above the higher high tide line.

3. Architecture

The sand sheet at Cultus Bay is most readily seen as a layer of sand cutting through *Triglochin*-rich muddy peat exposed in 210 m of a drainage ditch on the west side of the marsh (Figs. 2 and 3). To establish areal trends in the deposit, the author took 150 2-cm-diameter cores on transects extending perpendicular to the drainage ditch. The transects were ended when the sand layer could no longer be distinguished from tide-flat mud (where the sand descended into tide-flat deposits) or when the transects hit the hillside to the west.

The core holes and drainage ditch exposures show that a sheet of sand

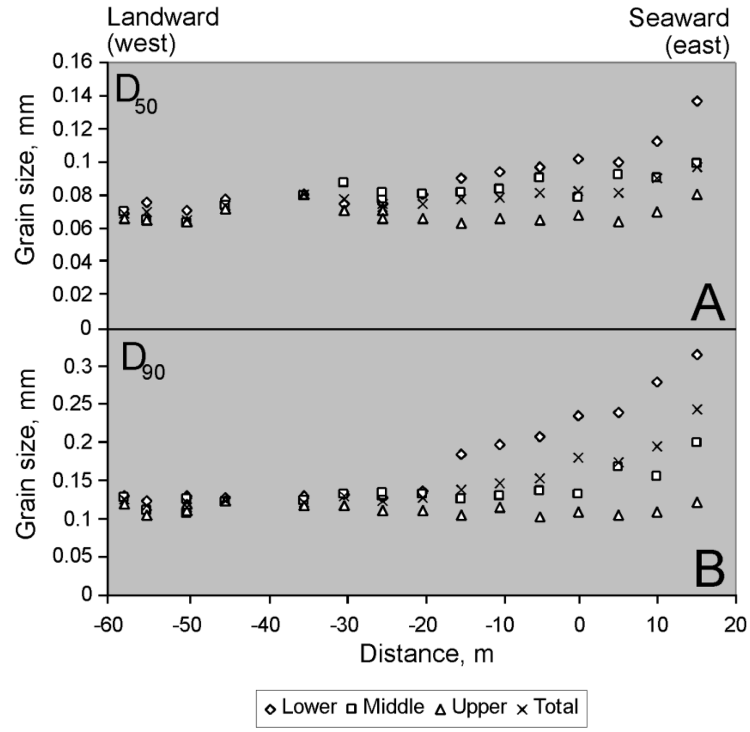

Figure 5: Grain size trends along the transect in Fig. 3b. (a) Change in median grain size with distance and elevation within the deposit. (b) Change in D_{90} with distance and elevation. For both figures, 0 is the location of the drainage ditch transect in Fig. 3C.

extends throughout an area at least 150 m by 300 m (Fig. 2a). The sand sheet ranges in thickness from a few grains to 15 cm, being thickest toward the middle of the deposit (Fig. 2d). Variability in thickness within the deposit is caused in part by burial of clumps of *Triglochin* under the sand sheet (Fig. 4). The deposit emerges from tidal deposits to the east (where it becomes indistinguishable from normal tidal flat deposition), climbs through marsh and coastal swamp deposits (which causes deposition to become more variable in thickness), and finally pinches out on the western hillside, some 4.5 m above present day low tide (Fig. 2a, b). The change in elevation of the sand sheet indicates that the sand forms a mantle covering what was primarily a marsh in the past.

4. Grain-Size Trends

The sand sheet fines from east to west over the area studied (Fig. 2). This is normal to the travel direction of a wave coming from the south, suggesting that at least part of the wave washed around the end of the spit and was traveling west when it reached the marsh. Ditch exposures of the sand sheet show it to consist of one normally graded unit (Fig. 4d), indicating that at least the bulk of sedimentation was accomplished by a single wave. These two trends show that the portion of the wave that washed over the spit had died out before reaching the study area, and that deposition so far from the spit was probably facilitated by a salient of the bay extending into the marsh, as existed prior to diking (Fig. 2).

To gather more detailed information on the grain-sized trends in the deposit, the author collected grain-size samples every 5 m along the cross section shown in Fig. 3b. Each sample was split into thirds, and dry sieved at $\frac{1}{4}$-Φ intervals. The resulting grain-size diagram (Fig. 5) shows that the changes in grain size shown in Fig. 2e are primarily caused by changes in the base of the deposit—upward the deposit becomes homogenous. The deposit also becomes homogenous landward so that the most landward portion shows little or no lateral fining.

This depositional pattern is consistent with advection of suspended sediment from a restricted source (the tide flat) onto the marsh. As the tsunami propagated across the tide flat, it suspended sediment—when the wave struck the marsh platform, it was deprived of its source of sediment and began to deposit as the flow decelerated. Grains settled differentially because of their different settling velocities, so that the coarsest grains ended closest to the source and finer grains farthest from the source. Vertical grading arises from the waning flow behind the passage of the main wave. Once deposited, sediment was probably kept from being reentrained by the mats of *Triglochin* present on the marsh surface.

5. Conclusion

The Cultus Bay sand sheet is a particularly well-exposed tsunami deposit. In addition to providing paleotopographic information for tsunami simulations, analysis of the sand sheet can suggest details of wave propagation that can also be used to constrain simulations. Grain-size changes in the deposit follow simple patterns, and raise the possibility of determining flow characteristics of the tsunami directly from the tsunami deposit.

6. References

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