Hazards Inferred from Tsunami Deposits in Washington and Oregon.

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Project Summary

Our findings show that evidence for Puget Sound paleotsunamis is not as widespread as was previously suspected, while evidence for liquefaction near Puget Sound is more common than has been reported. Thus the original focus of this project on tsunami sedimentology has been expanded to use tsunami deposits, liquefaction features, and facies changes as earthquake proxies and thereby for implications of source area, magnitude, and recurrence. The initial aim of this project was to explore the Holocene earthquake history in Puget Sound through a detailed study of tsunami deposits and to use that information to refine tsunami models for Puget Sound. Through more detailed sedimentology than had been done previously, however, four locations classified as having tsunami deposits were reclassified to having liquefaction and other types of deposits, whereas only one site has clear evidence of a tsunami. While the relative paucity of tsunami deposits is a significant finding in itself the new evidence found for liquefaction and land-level change is another opportunity to understand in more detail the nature of the Seattle and nearby fault systems Four marshes studied near the Seattle, Tacoma, and Saddle Mountain East faults show evidence environmental changes suggestive of earthquake-induced uplift. A Tacoma-area marsh at Dumas Bay, by contrast, may have undergone gradual submergence in the last 2000 years or more.

Introduction

Puget Sound presents an important area for earthquake and tsunami research. With a population of over 3.5 million, two large ports, and two military shipyards, earthquakes and tsunamis could devastate socio-economics of the sound. Historical landslides have triggered tsunamis (e.g. the 1949 landslide near Tacoma which occurred after and earthquake), and deep earthquakes, occur about every 20 years in the Puget Sound region. However it is only with paleo-seismological evidence that we are able to understand the seismic threat to the Puget Sound metropolitan area.

No large (> M 7), shallow earthquakes have occurred in Puget Sound during historical times (Ludwin, 1991), but evidence for two shallow earthquakes and subsequent tsunami(s?) about 1100 years ago has been documented in the region (Figure 1). Evidence for earthquakes includes land-level change (Bucknam et al., 1992; Ota et al., 2006), tsunami deposits (Atwater and Moore, 1992), surface rupture (Nelson et al., 2002; Sherrod et al., 2004; 2005), turbidites in and landslides into Lake Washington (Karlin and Abella, 1992; Jacoby et al., 1992). One earthquake about 1000 years ago and estimated to be of magnitude 7+ (Bucknam et al., 1992), accompanied widespread uplift of up to 7 m along the Seattle fault zone (Bucknam et al., 1992; Ota et al., 2006). The Tacoma fault, with a surface trace recognized on laser topographic maps (Light

Detection And Ranging (LiDAR)), produced an earthquake between A.D. 770 and 1160 (Sherrod et al., 2004). A tsunami associated with the Seattle earthquake of about 1000 years ago best explains sand sheets documented from coastal lowlands in localities north of the Seattle fault (Atwater and Moore, 1992) and possibly on the Snohomish delta near Everett (Bourgeois and Johnson, 2001).

Vented and intruded sand from liquefaction has been reported from some the same marshes as the tsunami deposits (Bucknam et al., 1999; Bourgeois and Johnson, 2001). However, no detailed studies of the location and extent of liquefaction features have been carried out in southern Puget Sound. Liquefaction features are well studied in other areas (e.g. Obermeier et al., 1985; see also Obermeier, 1996, Galli, 2000). For large earthquakes in the expected magnitude for Puget Sound faults (Mw 7.0-7.5), most liquefaction should occur within 50 km of the fault (see Galli, 2000, for review of prior graphic analyses). However, in the geologic record, there is no method for determining if a liquefaction feature was driven by the main shock or an aftershock.

In most paleotsunami studies, storms are the most reasonable alternative for method of deposition, but in Puget Sound liquefaction and other processes are more likely culprits. Due to smaller storm potential than many regions with tsunamis, in the Puget Sound region we are usually able to exclude storms as a method of deposition. Therefore we can focus on differentiating among other processes that generate these sand bodies.

Methods

We have mapped and studied the thickness, extent, and sedimentary characteristics of tsunami deposits and liquefaction features at several localities in the Puget Sound region (Figure 2). Working in this metropolitan area requires significant effort to obtain permissions and comply with regulations. We made reconnaissance surveys to locate deposits, and also used a website generated by the USGS (Bucknam et al., 1999). We focused on Hood Canal and southern and western Puget Sound. These locations offer the potential to address important questions in tsunami-deposit research while also providing better knowledge of the earthquake and tsunami hazard in Puget Sound

Field methods. At each field locality, we surveyed in sites where we examined the stratigraphy exposed in outcrop or open excavation where possible, and in cores across marshes; we used hand-dug pits, backhoe trenches, outcrops, gouge cores, and soil-auger holes. There are currently a total of 197 sites, with some representing more than one core or outcrop description:

Locality	Gorst	Dumas	Hylebos	Burley	Lynch	Skok	Shine
Sites	72	25	4	3	15	60	18

Each site is numbered and has a GPS location, currently plotted onto Google Earth images (see Figures). At each site, we measured and described the stratigraphy and sedimentology, including grain size and sedimentary structures. For about 15-20 sites where the stratigraphy was exposed by outcrop of trenching, we took monoliths and/or made peels, which bring out details of the

sedimentary structure. We sampled some sand layers for grain-size analysis, and subsampled some for vertical-trend grain-size analysis, in 1-cm vertical increments.

Lab methods: In the one site with a plausible tsunami deposit [Gorst], we have performed three sets of detailed grain-size analyses using a settling column to look for grain size trends in the deposit (e.g., Figure 7) and to attempt correlation between sites. Samples from the field were dried and organic material removed with tweezers. The samples were then run in a settling column.

Preliminary diatom analysis was performed on several samples, with the help of Dr. Yuki Sawai, using his laboratory techniques.

Results by Field Locality (Figure 2)

Gorst (Figure 3) - The Gorst locality and sites comprise remnant salt marshes and an alder swamp beside upper Sinclair Inlet, as well as a cleared park surrounded by forest, along the banks of Gorst Creek in a city park 0.5 km inland. Much of the adjoining land has been covered with fill, pavement, or buildings. In the park and upstream of the park in stream bank outcrops, we have searched for sources of an uncommonly thick sand present beneath the salt marshes, as described below.

Outcrops, pits and cores in the remnant wetlands reveal an abrupt upward change from tidal flats to freshwater forest (Figures 4, 5) that probably resulted from uplift during the Seattle fault earthquake or on the Tacoma fault. Forest peat is in turn overlain by salt marsh peat of the modern depositional environment.

A puzzlingly thick sand unit (Figures 5, 6) formed at or about the time of uplift. We found the sand unit, along 0.5 km of the upper inlet's shoreline, beneath modern tidal marshes and alder swamps. The unit consists of silty fine sand up to 1 m in thickness. It has a sharp contact with shelly mudflat deposits below and a sharp to gradational contact with overlying peat. The unit contains at least three parts: a basal subunit that fines upward from medium and coarse sand to fine sand and silt; a thin, discontinuous (less than 1 cm thick) clay bed, commonly with flame structures; and a capping subunit up to 50 cm thick that is dominated by silty, fine to medium sand. Overall, the entire unit fines upward, but with some finer layers (Figure 7). The basal subunit is reasonably interpreted as a tsunami deposit, but the upper subunit's origin is uncertain. Preliminary diatom analysis shows the capping subunit contains diatoms from a brackish environment.

A possibly related sand body lies up to 1 3/4 km inland, up the valley of Gorst Creek (sites 310-316 on Figure 3). Its thickness is in the range 0.2-1.0 m as observed in creek banks and in backhoe trenches at a nearby park (Figure 8). Unlike the sand unit described above, this sand body contains multiple indistinctly graded beds and an unconformably overlying cross-bedded unit that shows silty laminae at cross-set boundaries. Preliminary diatom analysis revealed no diatoms in this deposit. We are investigating its relationship to the silty sand deposit above the mud layer in the tide flats.

The graded-bed subunit at the base of the sand body in Gorst marsh (Figure 7) is most likely a tsunami deposit. With permission, we will make vibracores inland of the marsh to map this sand, while undergraduate David Sullivan is conducting grain-size analyses on collected samples. This work will allow us to model tsunami runup by refining existing models (e.g., Koshimura et al., 2002).

The events at this locality remain to be dated, pending identification of appropriate materials.

Dumas Bay (Figure 9) - Dumas Bay consists of small fresh water cattail marsh and alder swamp in Federal Way. The freshening of the marsh appears to be a recent phenomenon as thick marsh peat containing *Disticlis* and *Triglochin* fragments (Bucknam et al., 1999), over 5 m in some areas, indicates subsidence possibly related to splays of the Tacoma fault. The bottom of the peat gives an age of 1930+/-60 C^{14} years B.P from *Triglochin maritima* leaf bases (Bucknam et al., 1999).

Bucknam et al. (1999) reported two sand layers found across most of the marsh, one sand layer near the base of the peat section and another with an age of ~1000 C^{14} years B.P *if* deposition rates have remained constant. These layers have been hypothesized to be linked be from a tsunami or storm (Bucknam et al., 1999).

Based on our coring (13 sites, Figure 9,10) we are not convinced that tsunami deposits are clearly preserved in the Dumas Bay marsh. Several sand and silt layers are present within the peat (Figure 10), but these sand layers are not widespread and they tend to thicken toward the steep slopes that bank the south and east sides of the marsh. These characteristics cause us to favor landslide runout and flooding as probable sources for many of the layers.

Although we have not found convincing evidence of tsunami deposits in the Dumas Bay locality, tsunami hazards modeling by NOAA shows tsunamis generated by earthquakes of magnitude 7.3 on the Seattle and Tacoma faults would both cause several meters of run-up in Dumas Bay, of which Seattle fault earthquakes drive the largest tsunamis in Dumas Bay (Venturato, 2007).

Further work might elucidate paleoseismic evidence at the Dumas Bay locality, but logistics of coring are difficult due to high water table and park regulations. Furthermore, if this site is subsiding, any tsunami runup reconstruction must account for the rate of subsidence.

Shine (Figure 11) – Shine is a small fresh water marsh located in Squamish Harbor near the northern end of Hood Canal. Peat almost 8.5 meters thick in some locations in Shine marsh indicates that after a lowstand in relative sea-level at about 6000 ybp there has been a relative rise in sea-level over the last 5000 years with subtle fluctuations (Eronen et al., 1987). We interpret this trend to indicate subsidence.

We found no widespread candidate for a tsunami deposit in Shine marsh. However, two muddy layers were traceable over tens of meters but were not continuous farther upstream (Figure 12).

We doubt they could be storm surge deposits because of the protected nature of this locality. These muddy layers could represent runout of debris flows from adjacent uplands (not in the upstream direction), tsunamis from Cascadia earthquakes, or local tsunamis. For example, at nearby Discovery Bay there are nine muddy sand beds that Williams et al. (2000) interpret as tsunami deposits; and at Swantown Marsh on Whidbey Island, Williams and Hutchinson (2004) similarly interpret up to four muddy sand layers.

The Shine locality deserves further investigation to map and analyze these muddy sand layers.

Skokomish delta – (Figure 13) The delta of the Skokomish River consists of salt- and fresh-water marshes that are pristine in some areas, while other portions of the delta were diked and used for farming. These altered portions are in the process of having the dikes removed and the land restored to wetland habitat.

Most of the previous work done on the Skokomish river system has looked at changes in sedimentation and erosion due to emplacement of a hydroelectric dam in 1930 and logging (Jay and Simenstad, 1996; Stover and Montgomery, 2001). Less work has been done looking at the longer Holocene history of the river and delta. However, a tsunami- deposit candidate was seen in reconnaissance (B. Sherrod, personal communication).

Potential sources for a tsunami on the Skokomish delta include uplift associated with the Tacoma fault or other faults, and landslides. Two potential landslide sources have been identified on Hood Canal. One is a large scallop-shaped scarp along the submarine toe of the Skokomish delta. The other is a subaerial scarp to the east of the delta near Lynch Cove dated to be younger than 1300 years (Sarikhan, et al., 2007).

The delta's late Holocene history includes coseismic uplift and later subsidence. Based on our study of nearly 60 sites on this delta (e.g., Figures 14-16), the stratigraphy of the Snohomish delta is characterized by tide flat or fluvial deposits overlain by a forest peat (Figure 14). The abrupt upward change from tideflat sand and mud to cedar forest peat we interpret as evidence of co-seismic uplift. Subsequent subsidence changed the forest into today's grassy salt marsh.

In three different streambank outcrops, a sand lenses lie between the lower layer and the forest peat (Figure 15). These lenses are up to 25 cm thick but less than 20 m in lateral extent -- a geometry suggestive of liquefaction, although we have not yet found sand dikes. The patchy nature of these deposits is not suggestive of tsunami deposition. We correlate these liquefaction bodies with the abrupt co-seismic uplift discussed above. We plan to make a more detailed study of the liquefaction features, including mapping and detailed description of internal structure.

On the landward side of the delta, a thick mud (over 1 m in some sites) lies below the peat (Figure 16). The stratigraphy below the mud and the mud's mode of origin remain to be determined.

The uplift event at Skokomish needs to be dated to see how it relates to other marshes in Puget Sound. This is an intriguing question as the Seattle and Tacoma faults have not been traced as

far west as the Skokomish delta, and the delta could possibly be influenced by east-side up faults along the eastern flank of the Olympic Mountains. Movement on splays of the Saddle Mountain fault system has been dated as <1,700 ybp from detrital charcoal from a trench on the Saddle Mountain West fault (Witter et al., 2008) and 1,240 to 1,235 yr B.P. from organics in sediment from ponds formed by movement on the Saddle Mountain East fault (Wilson et al., 1979).

Lynch Cove-- Lynch Cove is a salt marsh at the termination of Hood Canal (Figure 17). Marsh stratigraphy shows tideflat moods abruptly overlain by forest peat and finally saltmarsh peat. The uplift event in Lynch Cove has been dated to 1170+/-90 ^{14}C yr B.P. (Bucknam et al., 1992). Commonly, but not everywhere, there is a sand layer up to 80 cm thick with between the tideflat mud and forest peat. This sand contains marine diatoms (Hemphill-Haley, 1996). On part of the marsh, Jovanelly (2006) mapped this deposit using cores, noting thickness but not sedimentary structure. She concluded the deposit was of tsunami origin, with a small influence of liquefaction, based on a general landward trend of grain size fining and deposit thinning; she ruled out storms because of locally small amplitude of storm waves.

Our work in Lynch Cove over a broader area calls Jovanelly's tsunami interpretation of the sandy layer into question; we currently favor a liquefaction interpretation, but we plan more work, particularly mapping and describing the deposit over a broad area. The layer is highly variable in thickness (Figure 18, 19) and contains a variety of sedimentary structures. Though these characteristics do not discount tsunami origin, further work is necessary at this site to determine the origin of this deposit more conclusively.

Burley–The Burley site is located in a marsh at the termination of Carr Inlet (Figure 20). Down inlet from where we worked, uplift from tideflat to cedar forest is dated to 1130+/-50 ^{14}C yr B.P. (Bucknam et al., 1992). Our work here comprises one day of reconnaissance.

Between the tideflat mud and peat there is a discontinuous sand layer (Figure 21). This layer thickens and thins within meters and contains entrained peat and clay clasts and laminae. In some locations, a pebble layer lies between the tideflat deposits and the sandy layer. Liquefaction best explains the sandy deposits in Burley due to the highly variable thickness and stratigraphy of the deposit.

This site might be a good one to study liquefaction features. The work could be hampered by the multiple small-land ownership of the site.

Hylebos- Hylebos is the northernmost waterway in the Port of Tacoma (Figure 22). The former creek path was heavily modified including dredging and straightening for ship passage. Many sections of the bank have been covered in cement or rip-rap for stabilization purposes. On the unreinforced banks we cleared and described sections in one day of field work. In several outcrops there was rhythmic bedding possibly from high sedimentation input from lahars upstream from Mt. Rainer (Figure 23). We found no sandy tsunami deposits though there is one site with evidence of subsidence of a saltmarsh below tide range in one location.

Recommended work to be done in Hylebos includes tracing the evidence for subsidence and dating the event. Also, more detailed work might show more paleoseismic evidence such as liquefaction.

Summary

Among four candidates for tsunami deposits along and south of the Seattle fault zone, only one indicates clear tsunami origin while some others are clearly from liquefaction or possibly other origins such as landslide runout. Along Hood Canal, despite evidence for rapid uplift (Bucknam, 1992), we found no preserved evidence for tsunamis associated with the uplift. Also, we found no evidence for Puget Sound tsunamis since the events about 1,000 ybp though there have been several tsunami in historical times.

As part of Martin's Ph.D. project, she plans to continue work at Gorst, Skokomish and Lynch Cove. Other sites deserve further study, and all sites require more age control from radiocarbon dating.

This study has contributed and will contribute to better understanding of the shallow crustal fault systems in the Puget Sound region, and their paleoseismic history.

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Table 1: Field localities and both current [this study] and past interpretations of event deposits in marsh stratigraphy.

Locality	**Interpretation**					
	Tsunami		**Liquefaction**		**Other****	
	Previous	This study	Previous	This study	Previous	This study**
Burley	√ USGS*	Ø	√ USGS*	√		
Dumas	√ USGS*	Ø				√
Lynch Cove	√ USGS*	Ø	√ Jovanelly	√		
Skokomish	√ Sherrod^	Ø		√		
Shine	√ Atwater^	Ø?				√
Gorst	new site	√				√

*Bucknam et al. 1999, http://earthquake.usgs.gov/regional/pacnw/paleo/atlas.html

^Atwater, USGS, pers. communication

^Sherrod, USGS, pers. communication

Jovanelly, 2006 [see references]

**debris flow, fluvial, landslide runout

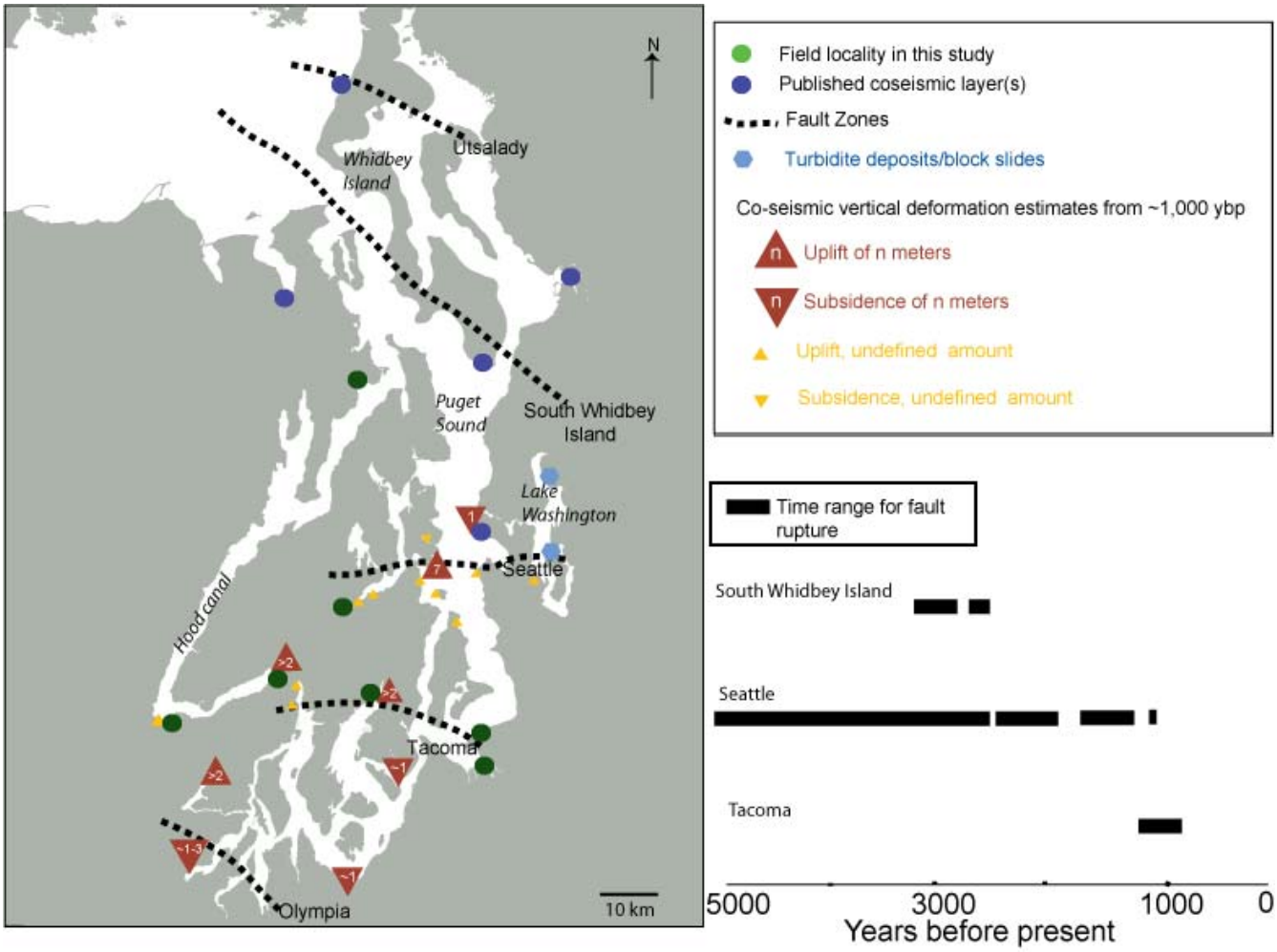

Figure 1: Summary of previous paleoseismic work in Puget Sound including the field areas looked at in this project. Paleotsunami deposits (Atwater and Moore, 1992; Bourgeois and Johnson, 2001; Williams and Hutchinson, 2000; Williams et al., 2005), abrupt land level change (Bucknam et al., 1992; Ota, 2006), landslides (Jacoby et al., 1992) and trenching across shallow faults (Nelson et al., 2002; Sherrod et al. 2004; 2005) are some of the multiple proxies for large earthquakes in Puget Sound.

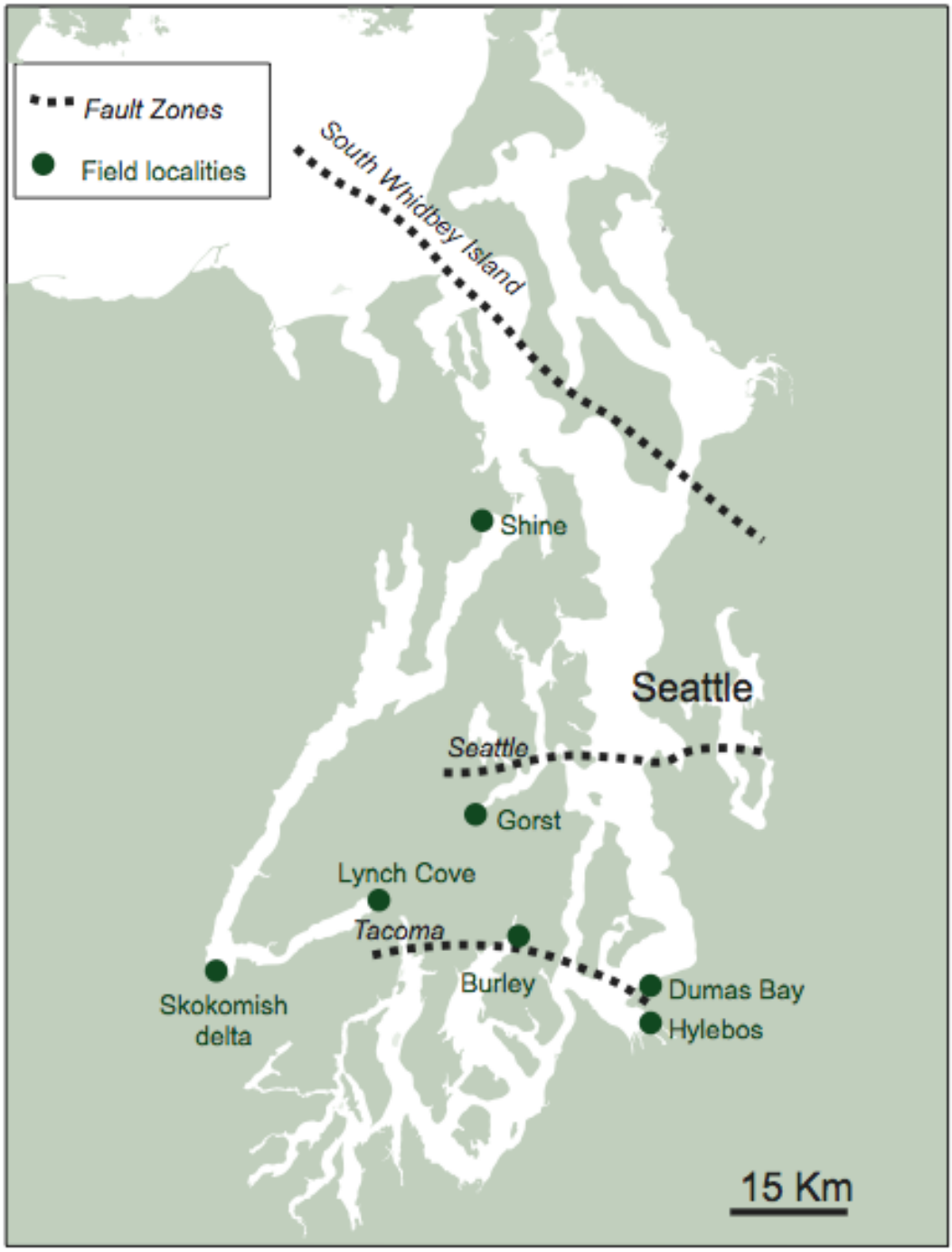

Figure 2: Field localities in this study.

Figure 3: Gorst locality (see Figure 2) -- locations of cores and excavations.

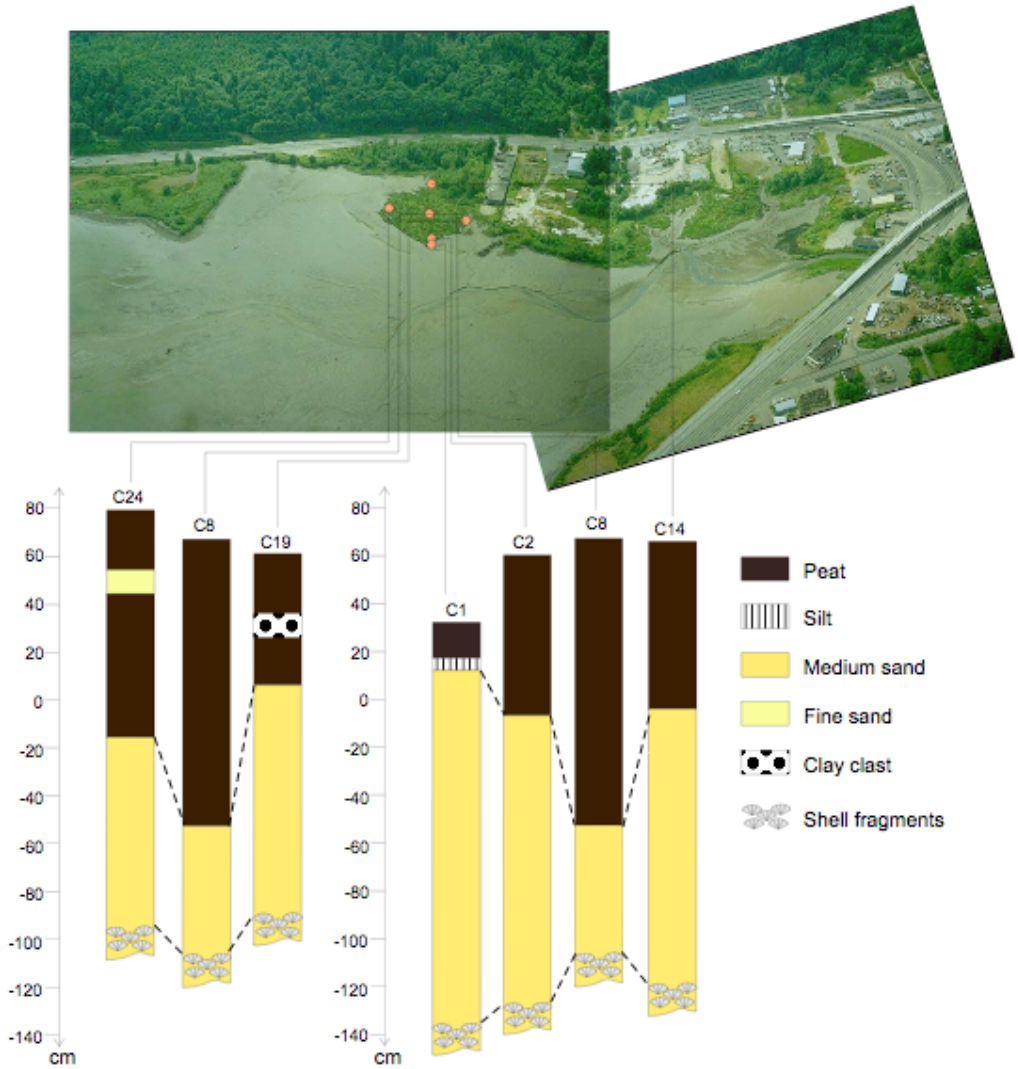

Figure 4: Cores from Gorst marsh (see Figure 3) showing thickness of sand layer and variations in the marsh stratigraphy.

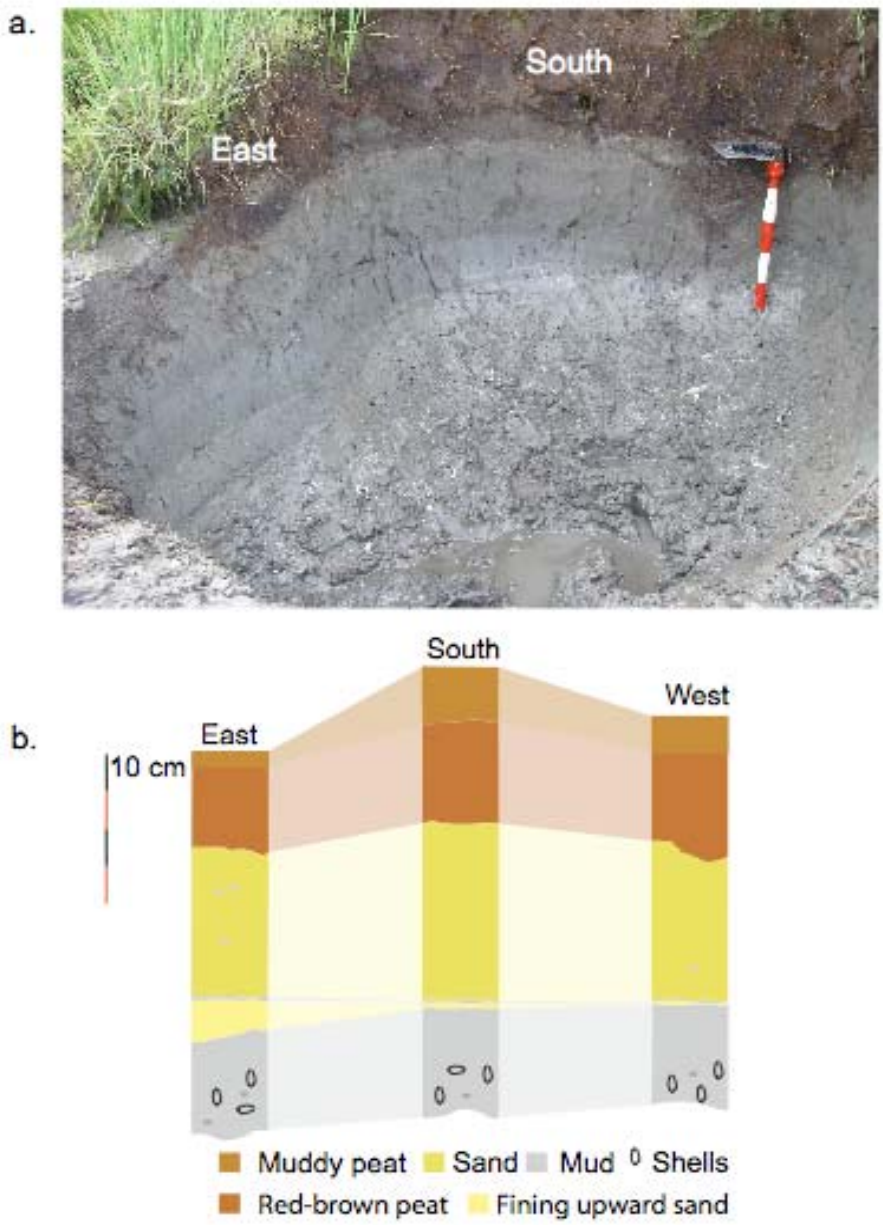

Figure 5: Three walls of an excavation at Gorst site 3 (see figure 3) showing fining upward sand capped by a mud lamina with flame structures, in turn overlain by a thick sand. We interpret the sand below the mud to be a tsunami deposit. This sand unit is situated stratigraphically between marine mudflat facies and forest peat.

a.

b.

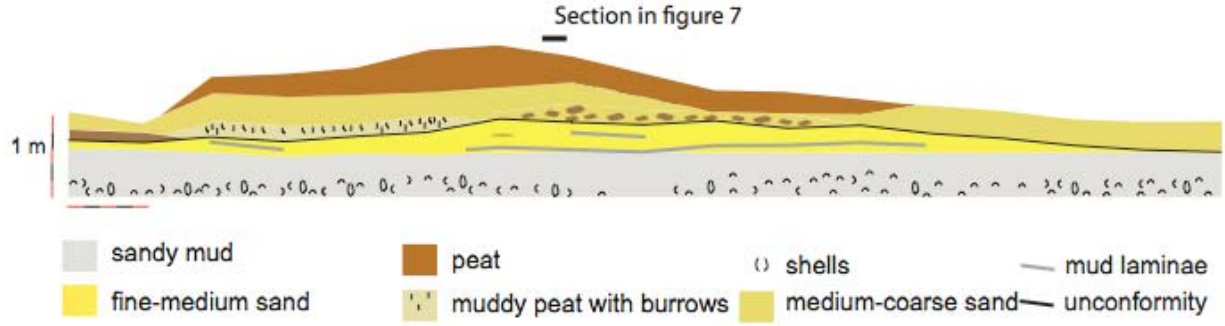

Figure 6: Outcrop along creek channel at site 168 in Gorst (see figure 3). a.) Photo of outcrop. b.) drawn section of outcrop. Ripup clasts of peat within the upper sand and cedar roots within the outcrop are evidence that peat which once overlay the fine-medium event deposit was eroded, possibly after the subsidence event ~ 300 ybp. Along much of the outcrop, a mud lamina caps a fining upward sand that we interpret as a tsunami deposit.

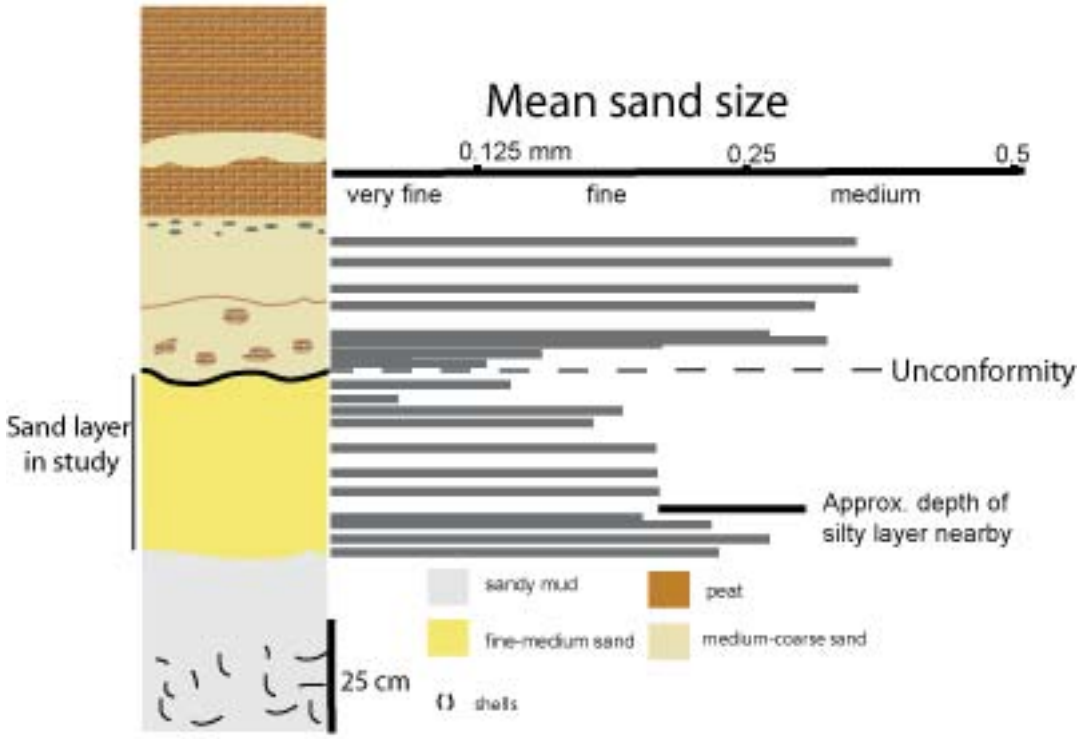

Figure 7: Section from site 168 in Gorst (see figure 3) with grain size analysis. The strata above fine-medium sand in this section was eroded, and the medium sand was deposited over an unconformity.

a.

b.

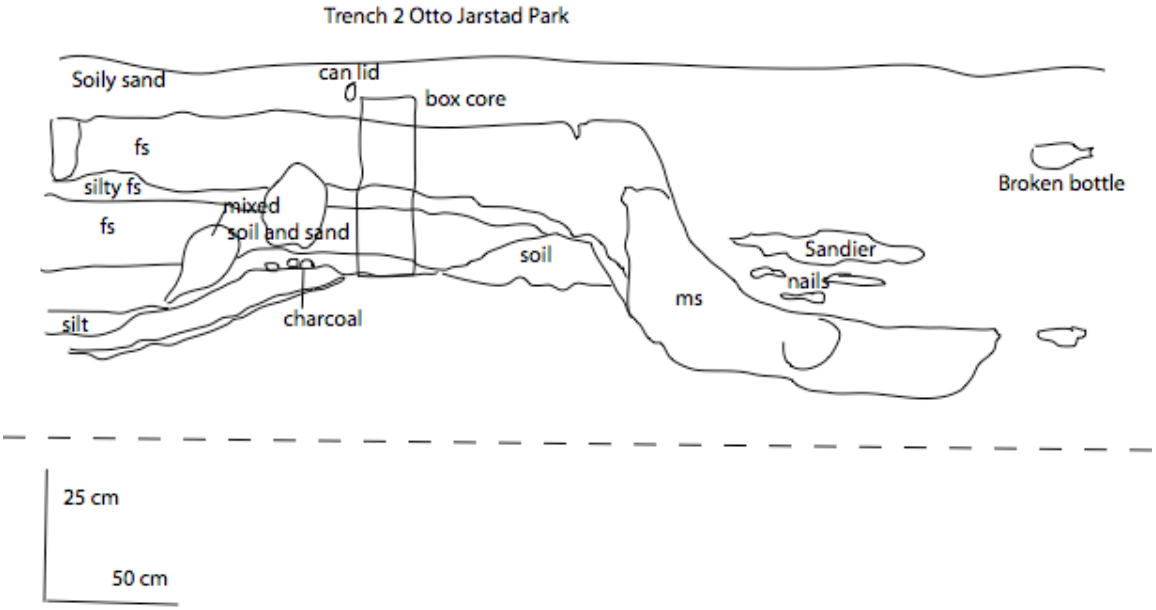

Figure 8: Sand layer upstream of Sinclair Inlet in Gorst from backhoe trench in a city park (see figure 3). a. photo of trench showing a basal soil overlain by a sand deposit and modern fill. This sand layer is present in outcrop along creek banks further upstream to at least point 314 (figure 3). Red and white stick is one meter in length and red flagging tape is at one-meter horizontal increments. b. fs – fine sand, ms- medium sand.

Figure 9: Location of cores in Dumas Bay (see figure 2 for location).

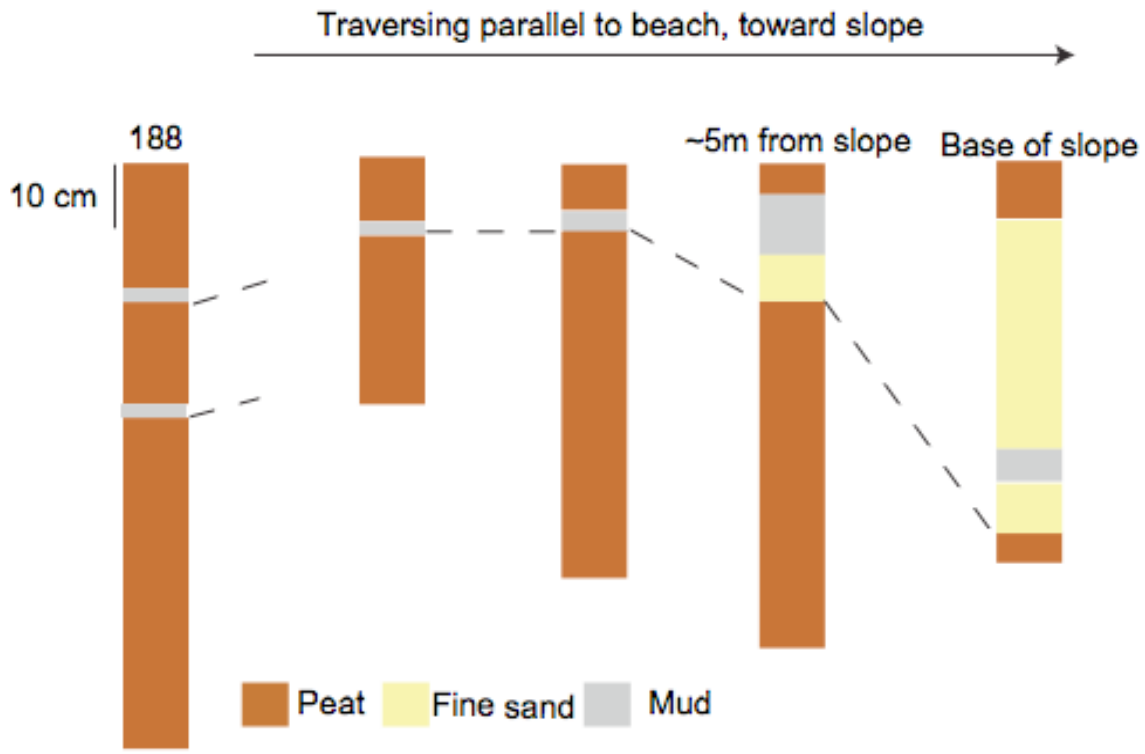

Figure 10: Cores from Dumas Bay (see figure 9 for location) taken from the center of the marsh to the western edge of the alder swamp. Note the sand and mud layers thickening toward the slope.

Figure 11: Location of cores in Shine marsh (see figure 2 for location on basemap).

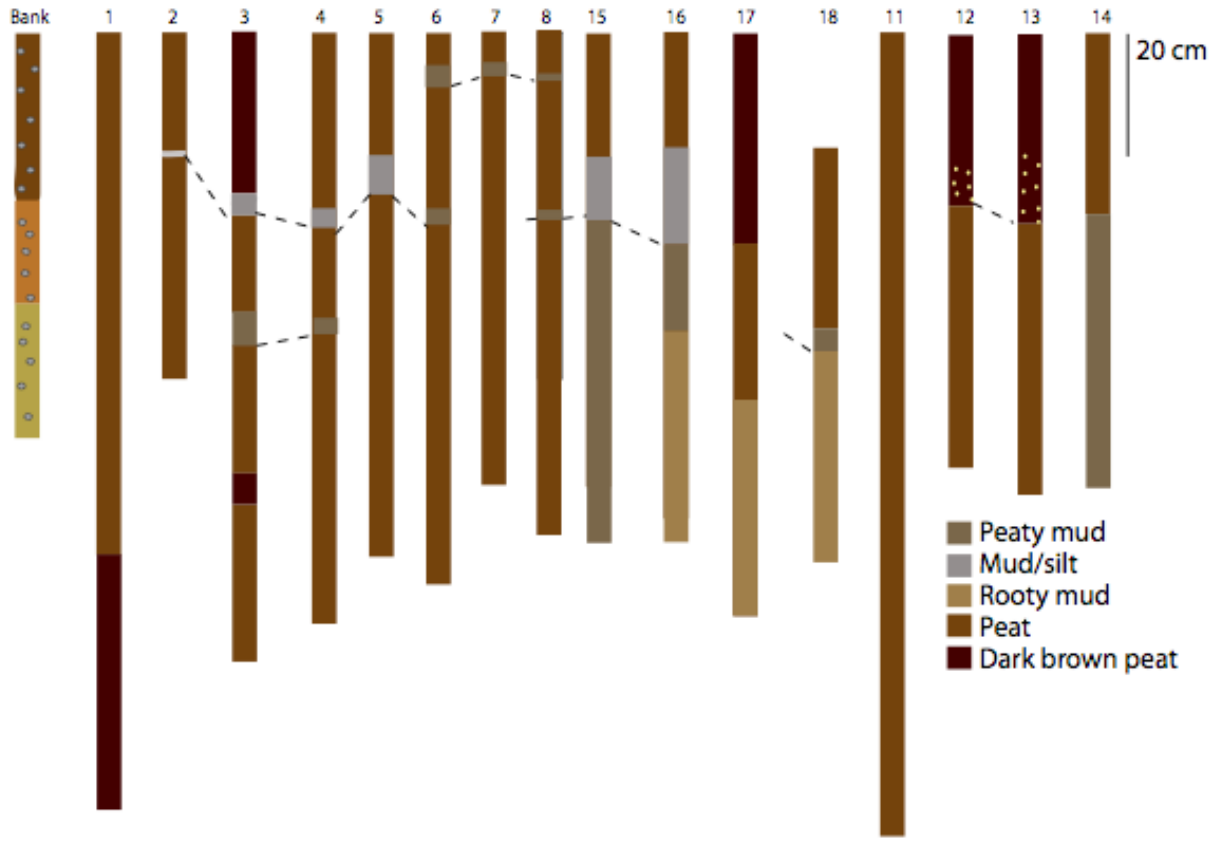

Figure 12: Cores from Shine marsh (see figure 11 for location). Cores 1-8, 15-18 were taken near the road, cores 11-14 were taken upstream with core 11 taken closest to the road and core 14 taken the furthest upstream. Mud layers traceable near the road are not found further upstream.

Figure 13: Locations of cores and excavations on the Skokomish Delta (see figure 2 for location).

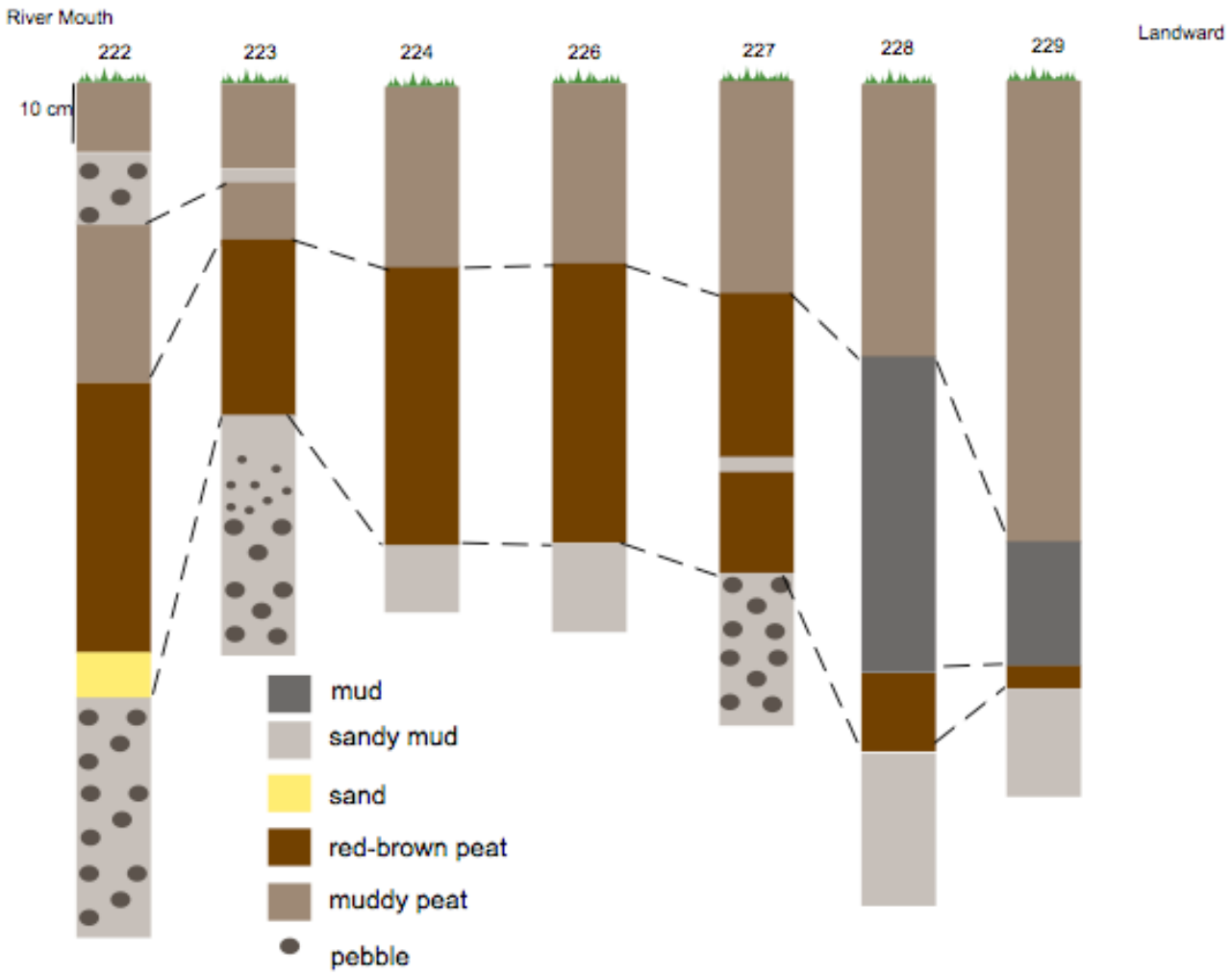

Figure 14: Excavations along the banks of the western channel of the Skokomish River (see figure 13 for locations). These excavations show the abrupt change from gravel to forest peat and from forest peat to marsh peat indicating two episodes of land-level change.

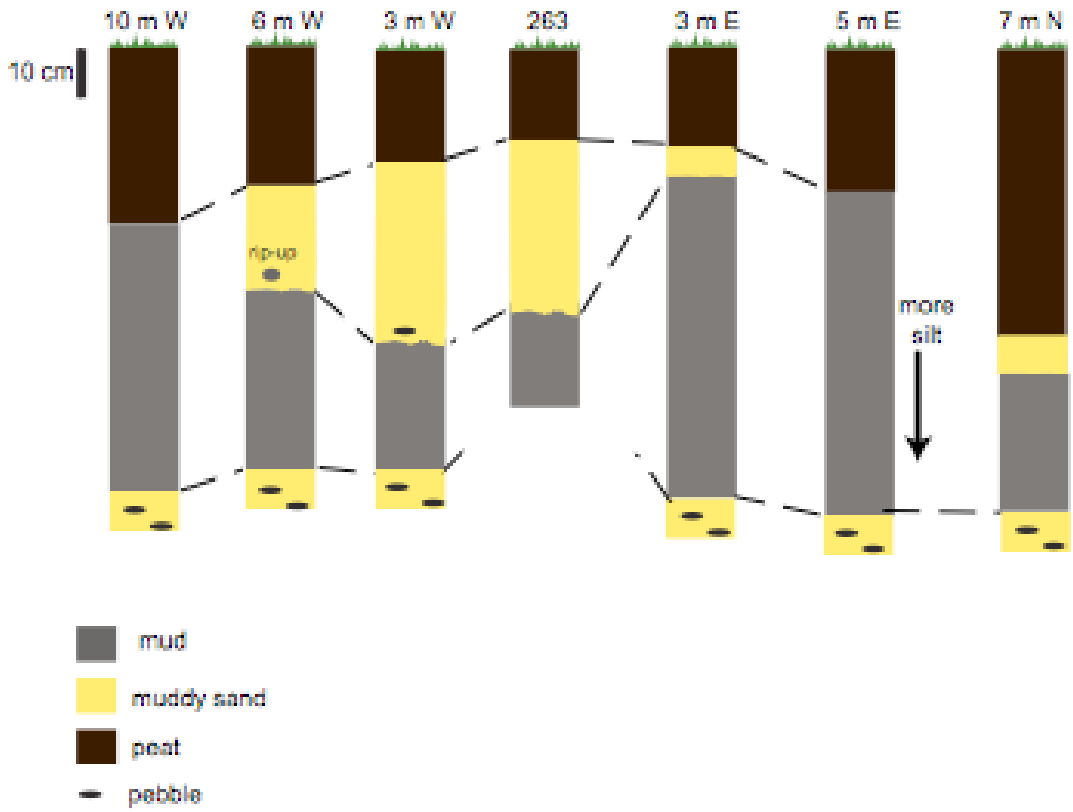

Figure 15: Excavations from tidal creek bank at the Skokomish delta point 263. We interpret the sand between the mud and peat as liquefaction.

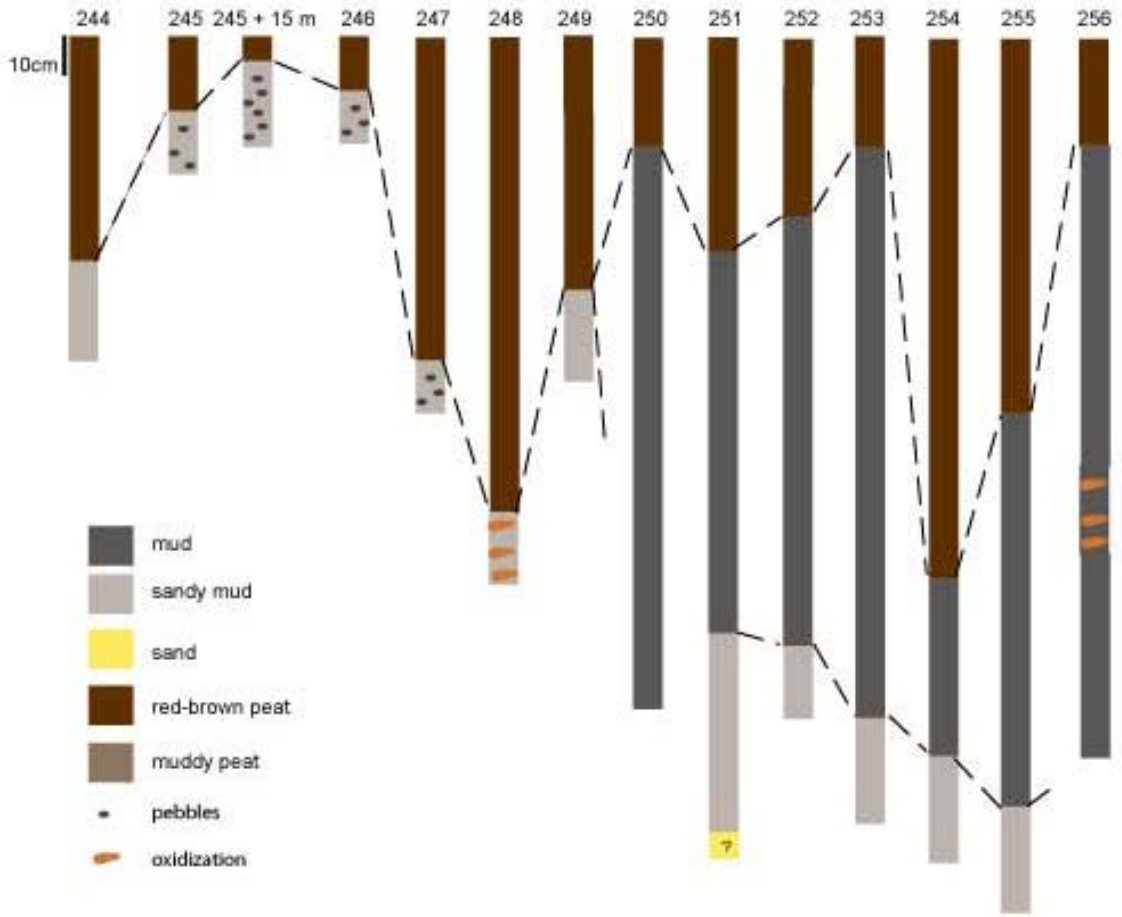

Figure 16: Cores from the back marsh at the Skokomish delta (see figure 14 for locations). The back marsh is a fresh water marsh.

Figure 17: Location of cores and excavations in Lynch Cove (See figure 2 for location).

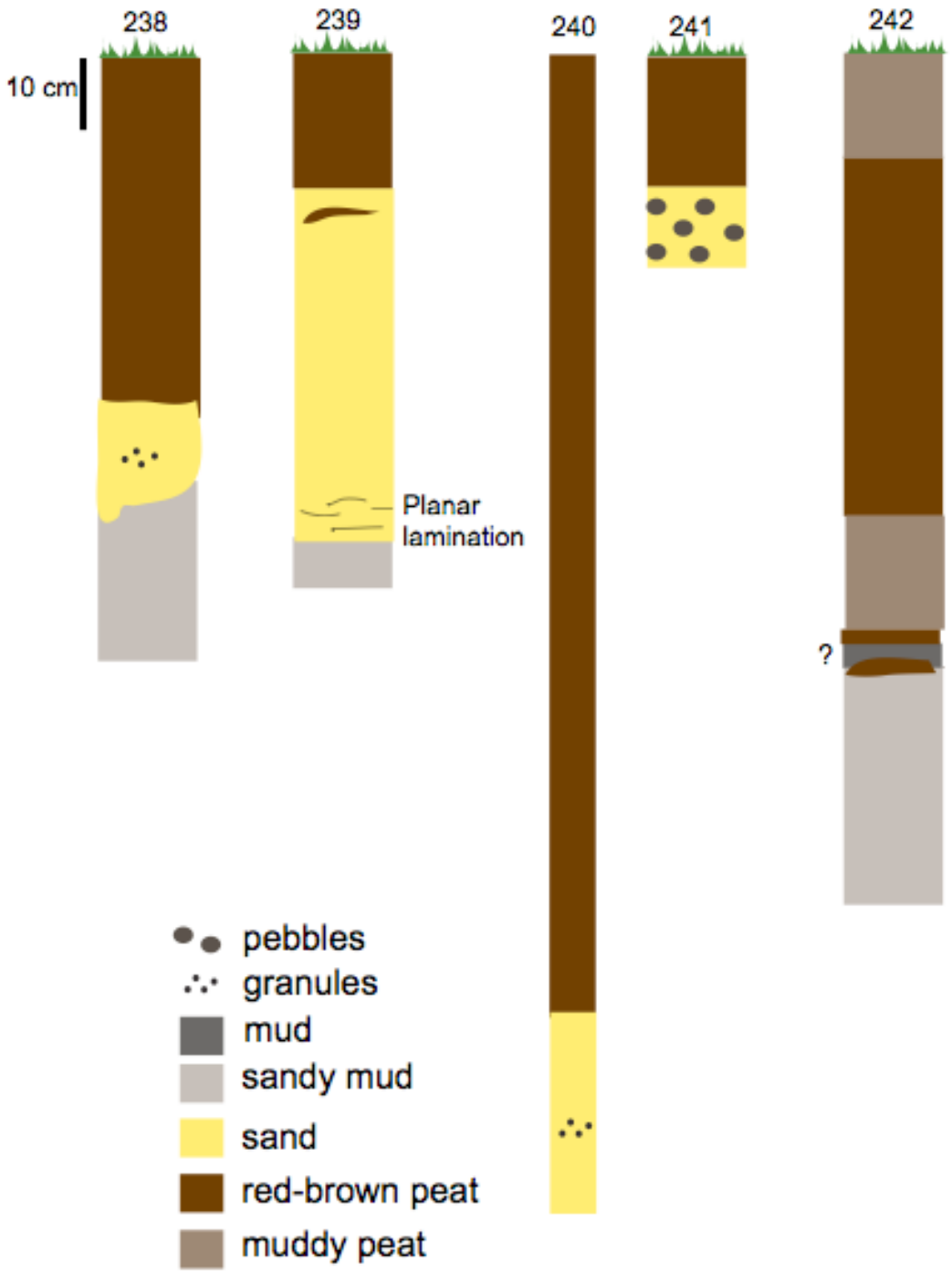

Figure 18: Excavations and a core (site 240) from the northwestern side of the Union River in Lynch Cove (see figure 17 for locations) showing the variability in thickness of the sand layer.

Figure 19: Tidal channel bank at site 287 in Lynch Cove showing the tapering of the sand deposit and its stratigraphic location between mud and forest peat.

Figure 20: Location of outcrops cleaned in Burley (see figure 2 for location).

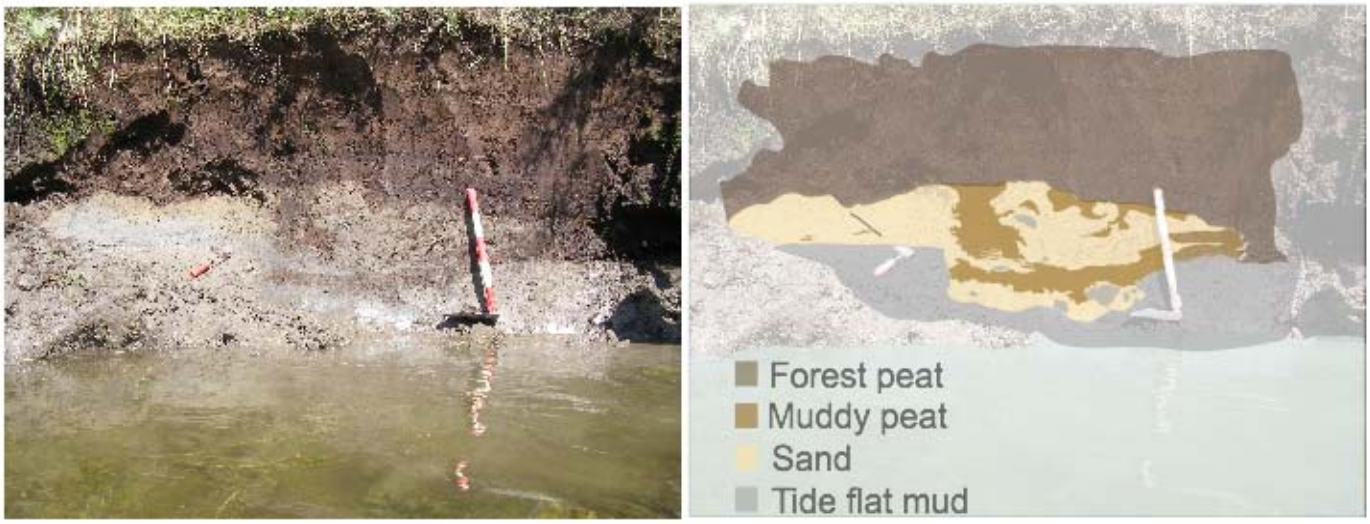

Figure 21: Outcrop at site 3 (see figure 20 for location) in Burley showing liquefaction sands with rip-ups of clay and peat. Note the highly variable thickness.

Figure 22: Port of Tacoma overlain with 1877 shoreline in red. The Hylebos waterway is the northernmost channel (see figure 2 for location).

Figure 23: Rhythmic bedding in outcrop along the Hylebos waterway. Branching structure is the remains of rhizomes of the saltmarsh plant *Triglochin maritima.*