UP-ESTUARY EXTENT AND LITHOLOGIC CHARACTERISTICS OF TSUNAMI DEPOSITS ATTRIBUTED TO THE 1700 CASCADIA EARTHQUAKE WITHIN ALSEA BAY, OR.

OREGON STATE UNIVERSITY

John T. Spruell[a], Andrew J. Meigs[a]

[a]Oregon State University, College of Earth, Ocean, and Atmospheric Sciences, Corvallis, OR 97331, USA

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John Spruell

Abstract

Cascadia's 1700 earthquake generated a tsunami and widespread subsidence along Pacific Northwest coastline. The tsunami deposited sandy sediments in many Oregon coastal estuaries, such as Alsea Bay. Although the recurrence of subduction-generated megathrust earthquakes and tsunami events in this region are recorded in the stratigraphy, knowledge of the full inland extent of inundation is limited. A series of eighty-one 25-mm gouge cores taken throughout Alsea Bay show a widespread distribution of buried gray sand at depths of 0.29 to 0.73 meters beneath the overlying tidal-influenced mixed alluvium. These fine-grained tsunami sands, ranging in thickness from 0.6 to 13.4-cm, demonstrate landward thinning from the Pacific Ocean at distances of seven kilometers inland along the Alsea River. The data gained in this study further fills the spatial gap in knowledge concerning tsunami sediment lithology and inundation extent along the central Oregon coast between the Salmon and the Coquille Rivers. Identification of tsunamigenic sediments and characteristics of their distribution within estuaries and bays constrain existing and future modeling of coastline inundation following rupture of the Cascadia Subduction Zone.

Introduction

The coastal areas of the Pacific Northwest have a long history of occupation prior to the arrival of the first European settlers. Many of these locales are centered near estuaries where freshwater sources such as the Alsea River meet the cold waters of the Pacific Ocean along the central Oregon coast (Fig. 1a-c). Despite the temperate climate and lush landscape, the Pacific Northwest holds a dark secret passed down through stories and whispers of indigenous populations such as the Coquille Indians (Byram, 2007; Younker, 2007). Oral traditions speak of a great earth shaking and angry tides that swallow villages. The repository of this earthquake history resides in not just the oral traditions, but in the stratigraphic and geomorphological record of the estuary.

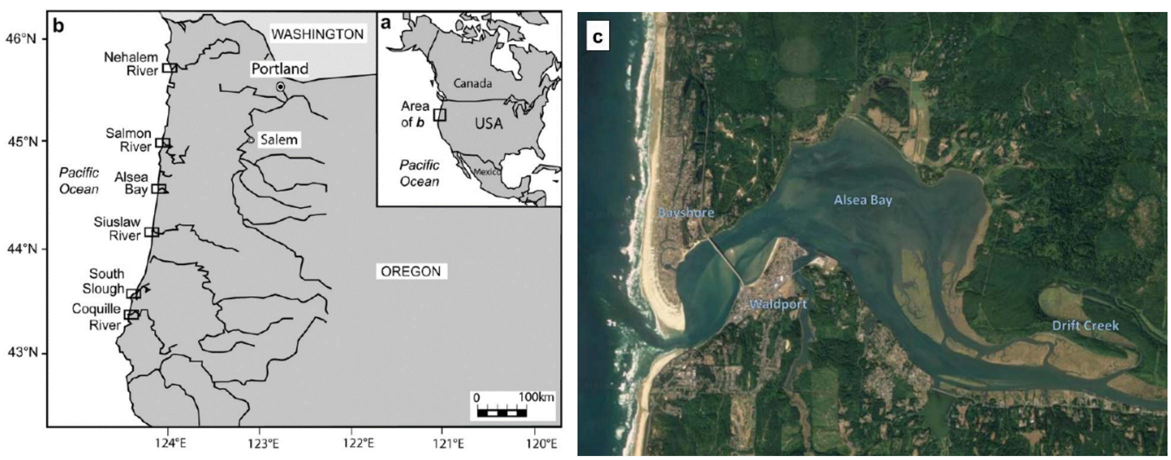

Figure 1 - (a) Alsea Bay's position within the United States and (b) its relative position to other major estuaries along the Oregon coast (Hawkes, et al, 2009); (c) Alsea Bay estuary in relation to Waldport and Bayshore along the central Oregon coast.

The deformation in a megathrust earthquake induced by slip along a locked portion of the Cascadia Subduction Zone (CSZ) generates tsunamis. The rupture of this coupled region releases accumulated strain in which the locked plates return to a state with a reduced coefficient of coupling or transitions to aseismic slip after the event (Wang, 2013; McCrory, 2012). The instantaneous release of stored strain generates uplift along the leading edge of the upper plate and subsidence in the landward direction. The combination of uplift and subsidence displaces a column of water above the region of uplift, which then seeks to re-achieve equilibrium with the surrounding ocean. This column of uplifted water spreads quickly in all directions as a tsunami. These tsunamis inundate the nearest coastlines within minutes while the other regions may not experience their effects until hours later.

Despite a lack of a written history of the previous earthquake and tsunami history in the Pacific Northwest, the events left evidence of their occurrence in the sequence of sediments in coastal estuaries. The record includes soil buried due to subsidence and sand carried in the turbulent waters as they flood areas of low relief. Estuaries chronicle the earthquake record, though the specific properties of tsunamis are oft debated (Priest, 2017; Peterson, 2015). The tsunamigenic sediments and their characteristics help to constrain the extent of inundation along the coastline and within bays. Alsea Bay, Oregon is one such estuary in which tsunami sediments attributed to the 1700 Cascadia earthquake and tsunami have been found. Previous studies of the Alsea Bay identified these buried sand sheets, the local subsidence, and fluid flow in and out of the bay, but none systematically explore the extent of tsunami inundation and deposition within the estuary (Peterson, et al, 1996; Nelson, et al, 2008).

I retrieved a series of eighty-one 25-mm gouge cores, which demonstrate that the buried 1700 tsunami sand ranges in thickness from 0.6 cm up to 13.4 cm and extended up to 7 kilometers inland from the mouth of the Alsea Bay estuary. This coring attempts to bridges the gap in knowledge between from the Salmon River Estuary to the Siuslaw River concerning tsunami inundation extent and sediment characteristics along the central Oregon coast. These new data combined with previous projects, such as Bradley Lake in southern Oregon, along the Salmon River, and at Ecola Creek place constraints on 1700 earthquake and tsunami (Witter, Kelsey, Nelson), which can serve to validate DOGAMI tsunami hazard maps (Priest, et al, 2010; 2017). Validation will enhance preparedness for future rupture events along the Cascadia Subduction Zone (Kelsey, et al, 2005).

Geologic Background

The Cascadia Subduction Zone, seen in Figure 2a, is characterized by the subduction of the Juan de Fuca (JdF) tectonic plate underneath the North American (NA) plate. This subduction occurs just off-shore and underneath a 1,000 kilometer stretch of the Pacific Northwest extending from Cape Mendocino in northern California northward through Oregon and Washington to Vancouver Island, British Columbia (McCrory, et al, 2012). Rates of convergence between the plates varies along the boundary as seen by the 45-mm/yr. in the northern section to a much slower convergence rate of 30-mm/yr. in the southern portion (Wang, et al, 2013).

Due to plate smoothness, sediment accumulation, asperities, and multiple other factors, the up-dip part of the plate boundary are treated as coupled in whole or in partially between earthquakes. This coupling between the Juan de Fuca and North American plate, which is shown systematically in Fig. 2b, generates strain in the upper plate. Response of the western edge of the North American plate includes northeastwardly contraction and slow uplift of the overriding plate (Hyndman, et al, 1995; Wang, et al, 2013). Full or partial rupture along the plate boundary occurs in great earthquakes and the convergent margin experiences elastic rebound to a state of reduced strain (McCrory, et al, 2012; Wang, et al, 2013). As strain along the upper plate is released it springs westward along the JdF-NA plate boundary and generates subsidence near the coastline in varying amounts (Leonard, et al, 2004; 2010). Subsidence is typically between 0.4 to 1.0 meters along the central Oregon coast although localized areas may deviate from the range (Nelson, et al, 2006). The combination of rebound on the plate boundary, which displaces the water column upward, and subsidence along the coastline generates an inequality in local ocean levels that gravity seeks to equalize. This equalization comes in the form of a tsunami or "harbor wave" that races both toward the coastline and across the Pacific Ocean to distant shores such as Hawaii and Japan (Atwater, 2005).

As the wave approaches shore, the turbulent water begins to lift sediment from local near-shore sources. As inundation of the coastline progresses additional sediment is lifted into transport from on-shore locations and carried landward in suspension. Figure 2c shows that as wave energy

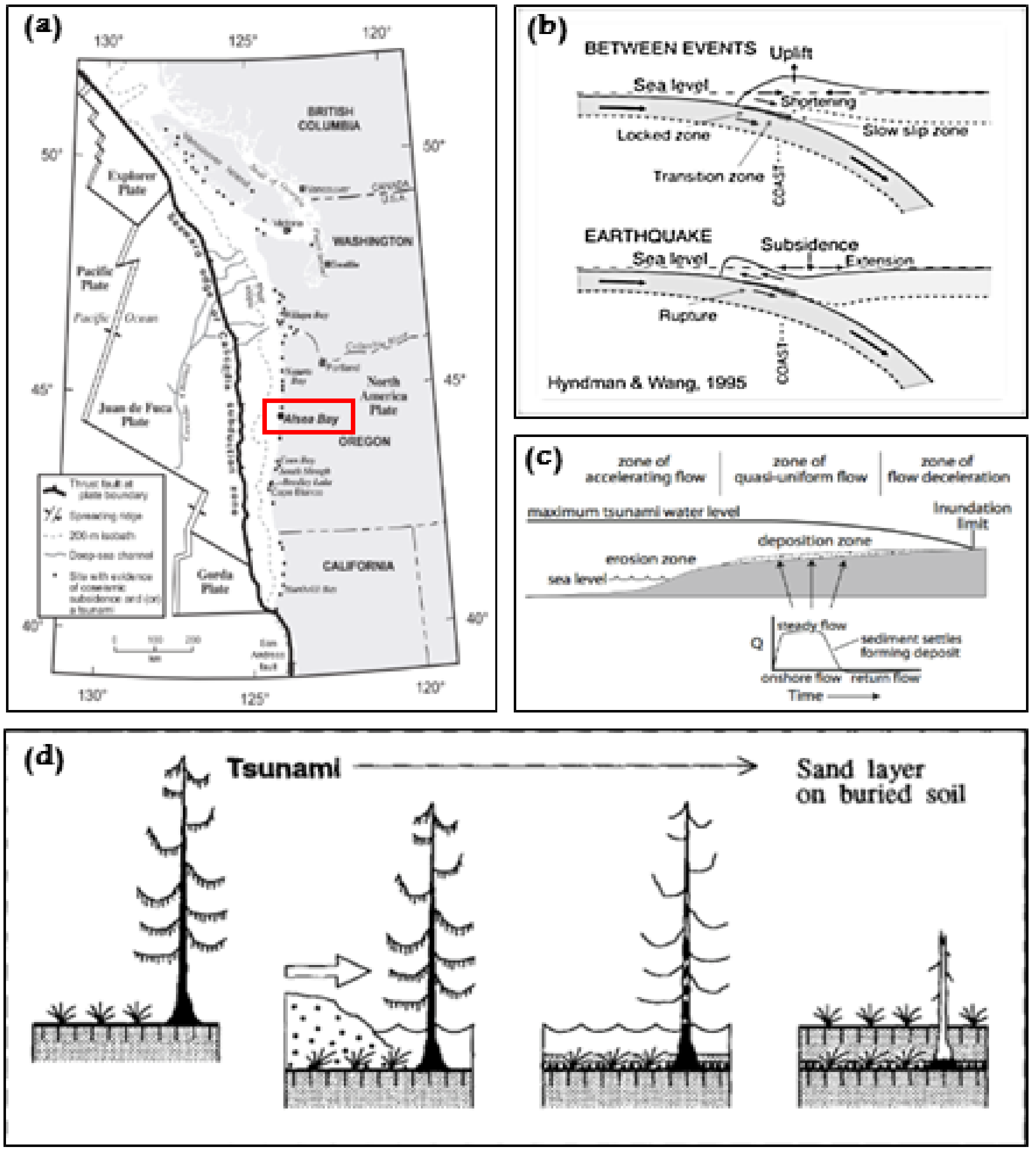

Figure 2 - (a) The tectonic setting of the Pacific Northwest features the convergence of the Juan de Fuca plate under the North American plate through subduction (Nelson, et al, 2008). (b) Uplift and shortening along the seaward edge of the overlying plate during interseismic periods are punctuated by during rupture of the locked portion resulting in extension and subsidence (Hyndman & Wang, 1995). (c) Displacement of the water column during rupture of the locked zone generates a tsunami that entrains near-shore and onshore sediments into the flow, which are subsequently deposited as flow wanes and the limit of inundation are reached (Jaffe, et al, 2007). (d) Deposition during coseismic subsidence followed by subsequent burial during the interseismic period provides evidence of paleotsunami recurrence (Atwater, et al, 1995).

begins to wane during the run-up process, the sediment load is deposited. The tsunamigenic sands along the coastline are then slowly buried by geomorphic processes during the subsequent interseismic period resulting in the stratified sequence seen in Figure 2d in estuaries throughout the

Pacific Northwest (Witter, 1998). The signature of the earthquake in the stratigraphic sequence is a dark organic rich layer overlain by a clean tsunami sand that grades slowly back into an organic rich layer.

The earliest known work within Alsea Bay, conducted by Peterson, C., Scheidegger, K., and Komar, P. in the early 1980s, focused on the distribution, texture, bedforms, and composition of alluvium and tidal-influenced sediments within the estuary (Peterson, et al, 1982; 1996). Later studies of the tsunami sediment lithology and coseismic subsidence (0.09 to 0.46-m) conducted within Alsea Bay evaluated the foraminifera within the buried sediments of previous tsunami events through coring, trenches, and outcrops (Nelson, et al, 2008). Later geodesic research estimates relative sea-level rise of 0.18-m within the Alsea Bay estuary as a result of coseismic subsidence during the 1700 rupture event (Hawkes, et al, 2011).

Methods

Initial site selection for coring was based on inspection of LiDAR data from the Oregon Department of Geology and Mineral Industries (DOGAMI) using ArcMap. This reconnaissance mapping an assessment of potential coring sites and their distribution around Alsea Bay prior to field work. A template for coring notes was then created to ensure annotation of core locations and tsunami sediment properties was consistent throughout the fieldwork process.

Figure 3 – Gouge cores with varying lengths and diameters allow the user to extract soil sediment profiles (Nelson, et al, 2015).

Each core location and site characteristics were annotated using latitude, longitude, and elevation in the template. Coring was conducted using a 25-mm gouge core (Figure 3) that is inserted vertically into the surface one-meter, rotated 180°, and extracted slowly to expose the soil profile within the corer. Upon identification of the Cascadia 1700 tsunami deposit, measurements were taken from the one meter mark to the sharp contact that denotes the bottom of the tsunami deposit. Deposit thickness and the thickness of both the lower and upper contacts were measured. Core were then photographed and analyzed on site. Lithological properties such as grain-size, color, sorting, roundness, and composition were recorded. Samples were gathered into sealable clear plastic bags and immediately labeled with the corresponding core name. Subsequent coring sites progressed eastward up the Alsea River from the estuary both on the high marsh islands and banks.

Data from all individual cores were logged into a spreadsheet. This information was then uploaded into ArcMap as a series of points and attributes. These points allowed the data to be viewed individually or as a whole based on chosen attributes such as depth, grain size, or thickness.

Results

A total of 81 cores were extracted from Alsea Bay (Figure 4) using the hand auger (gouge core) with a wide spread distribution up the Alsea River from the bay. Of the 81 cores, 56 contained readily identifiable sandy deposits that are attributed to the 1700 Cascadia earthquake and tsunami. The first buried tsunami sediment depth varied spatially within the bay, but work by Nelson, et al, 2008 and Peterson, et al, 1996 constrained the depth to an average of 0.45 to 0.50 meters below surface level. The remaining 25 cores showed either no deposit or were insufficiently distinct enough to properly identify. The soil profile cores in which the deposit was identified showed a characteristic stratigraphy of known buried tsunami deposits in which a sandy deposit interbeds the local soil horizons as seen in Figure 5.

Cores extracted from low, middle, and high marsh locations showed silt loam that is overlain by a distinct bed of sandy sediment. The underlying soil lower bed ranges in color (Munsel Color System) from a dark gray (5Y 3/1) when wet to a light brownish gray (2.5Y 6/2) when dry. The mucky silt loam horizons that overlay the tsunamigenic deposits correspond closely to the Oa and A horizons with a color scheme ranging from 2.5Y 3/2 when wet to 2.5Y 6/2 when dried. The texture is generally blocky with a number of irregular pores. Roots are common in the upper horizons, but are generally rare to non-existent in the lower beds.

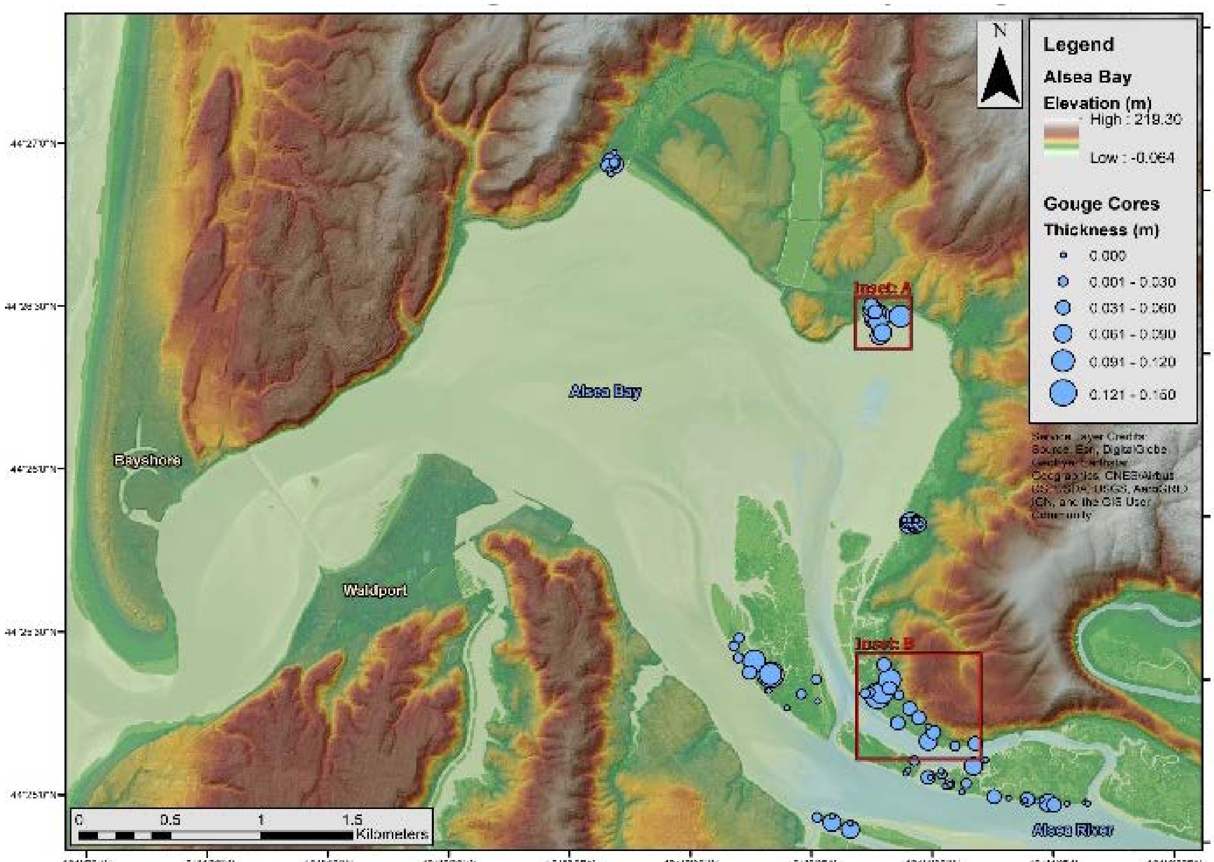

Figure 4 – Locations of 81 cores extracted from Alsea Bay with their distribution along the margin of the estuary and their extent up the mouth of the Alsea River. Inset A and B shown in greater detail in Figure 6a and b respectively. (Map generated by in ArcMap using LiDAR from DOGAMI at www.oregongeology.org)

The interbedded tsunami sediments, as seen in Figure 5, show a sharp lower contact from the soil C horizon that ranges from 1.0 to 4.0 millimeters (mm) thick, but averaged 1.8-mm. The upper contact is a gradational contact from the sandy deposit back into a mucky silt loam and peat. The average upper gradation contact is 8.4-mm with a range of 3.0-mm at a minimum to 2.9 centimeters at the maximum.

The thickness of the tsunami deposit, measured from the base of the sandy deposit upwards, varied greatly throughout the bay. The average tsunami deposit for Alsea Bay is 5.5-cm thick and found at a depth of 0.535 meters (m) relative to the modern surface. Coring along a north-south transect from the tidal flat to the shore in the northeastern quadrant of Alsea Bay produced an average deposit of 7.9-cm at an average depth of 0.50-m. Deposit thicknesses range from 3.7 to 13.4-cm beneath primarily anoxic mud flats. The high marsh islands where the Alsea River enters the estuary produced deposits in 69.4% of the cores. The average thickness of the sandy deposits within the tidal influence alluvium is 4.9-cm at an average depth of 0.54-m. Of minimums and maximums, thickness ranges from 0.6 to 13.1-cm, respectively. The sand is buried at a wide range of depths from 0.30 meters to 0.73-m.

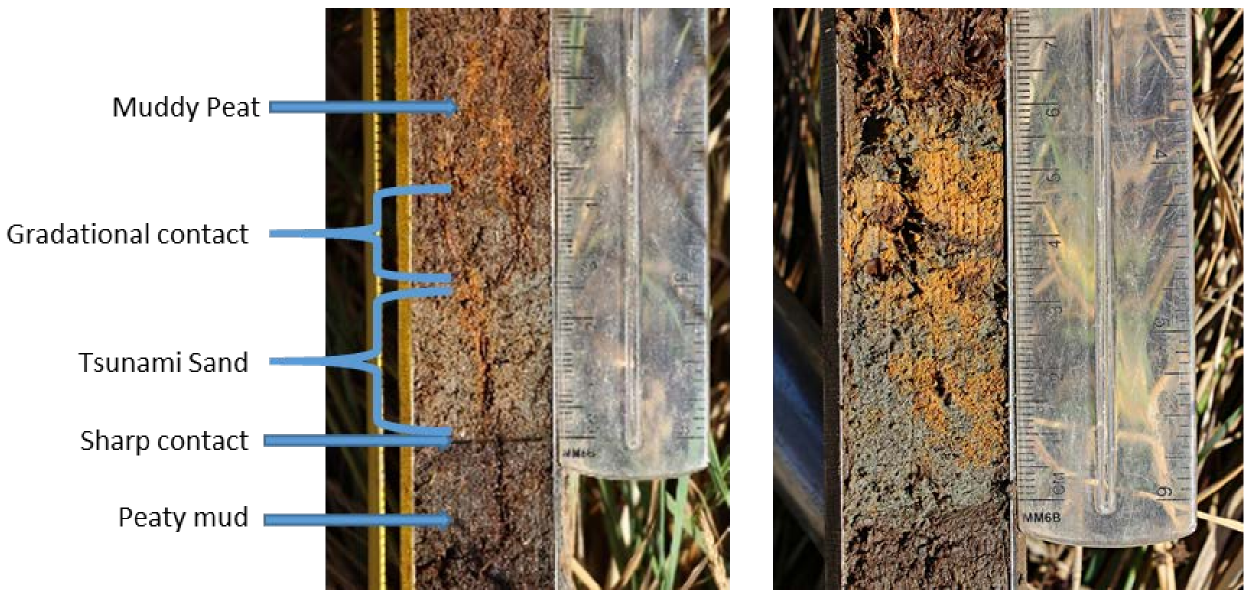

Figure 5 - Core IDs: AB-20170913-009 (left) and AB-20170913-004 (center) were extracted from the high marsh along the eastern boundary of the Alsea Bay estuary shows a grey sandy deposit bed atop a dark brown organic rich peaty mud.

The primary sand grains that comprised the tsunami deposits spanned the phi scale (ϕ) between 2 (medium/fine) to 4 (very fine/silt). Most beds show a grading from ϕ2 into the surrounding silty alluvium (~ϕ 4-6). Grains are rounded to sub-round with a high sphericity except for mica, which is plate-like. The composition of these sand grains are approximately 70% clear quartz sand, 20% grey/black lithics, 7% white feldspars, and 3% silver micas (mostly muscovite).

Within the tsunami deposit, organics were absent except for the rare root penetrating from the soil surface.

Tsunami deposits identified through gouge coring and located within the Alsea Bay estuary demonstrate the extent of inundation in the 1700 event. The coring locations labeled Inset A on Figure 4 show an inundation of ~5 kilometers (km) from the sandy spit that separates Alsea Bay from the Pacific Ocean (Fig. 6, Profile A). This distance is measured along the thalweg and to the closest core. The greatest inland extent of a tsunami deposit identified by this study lies at a distance of approximately 7-km inland from the Pacific Ocean as measured along the thalweg (Fig. 4; Fig. 6 Profile B).

Discussion

Spatial Distribution

The distribution of coring allows tsunami flow behavior to be inferred as a result of changing sediment thickness, depth, elevation, and stratigraphy. Figure 6 shows the elevation and inland extent of the sand sheet in a cross-bay profile (6a) and upstream transect (6b). Profile A shows an overall landward decrease of deposit thickness from about 8.5-cm to 6.0-cm over a distance of 195 meters and a gain of approximately 1.0 meters. This is expected due to bed roughness, the generated friction, and the change in elevation across the edge of the bay.

Profile B records the sand sheet thickness beneath the high marsh elevation of the southeastern estuary on a path of increasing distance up river relative to the mouth of Alsea Bay (Fig. 6). Despite a number of channels that cross-cut the both the islands and the banks, tsunami thickness shows a gradual decrease in average thickness. A nearest neighbor interpolation between cores of the transect shows thinning from 5.2-cm at point B to a thickness 2.9-cm at point B'. Profile B's transect provided the most complete record of coring data to allow interpolation of upstream thinning.

Both Profile A-A' and B-B' (Fig. 6) show thinning of sediment thickness as a function of cross-bay and upstream distance of the bay. Alsea Bay when viewed as a whole (Fig. 4) allows viewing of all 81 sediment cores and their thickness. The diameter of the blue circles correspond to deposit thickness in which a thinning sand sheet at depth is portrayed by an average decrease of marker diameters on the map.

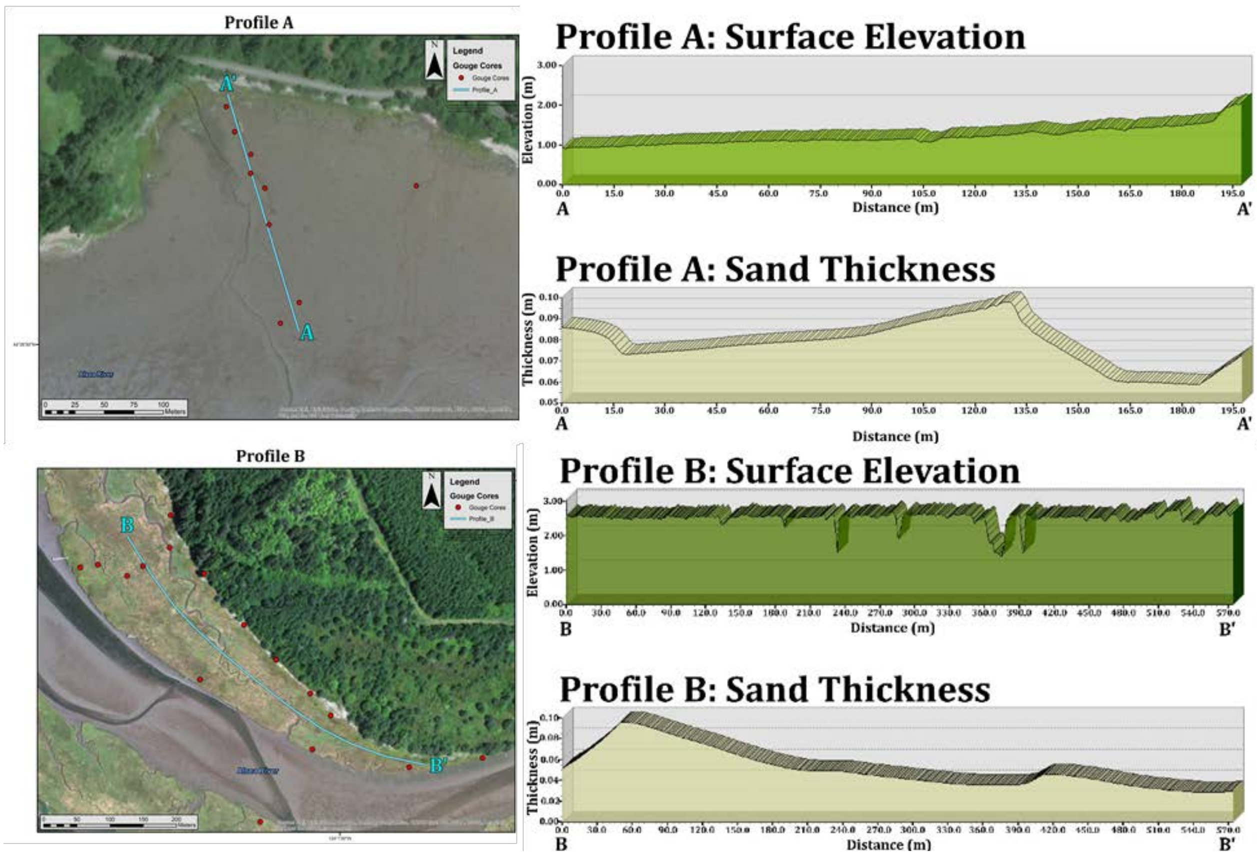

Figure 6 - Profiles A and B (located on Fig. 4) show sediment thickness taken from gouge cores (red) as a function of waning flow. This waning flow is generated through friction with the surface as well as increases in both elevation and inland extent.

These profiles when viewed in conjunction with the research on marine surge (Figure 7) by Peterson, et al (1996) within Alsea Bay, allow for additional hypothesis within the estuary concerning tsunami flow. The channelized flow due to the narrowing bay mouth may lead to erosion thus acting as a source of additional sediment during inundation. Flow propagation up-stream into the widening bay would lead to a loss of flow energy, decreasing velocity, and resulting in deposition of sediments. The location of profile A (fig. 6) would act as a possible eddy current in which velocity slows allowing

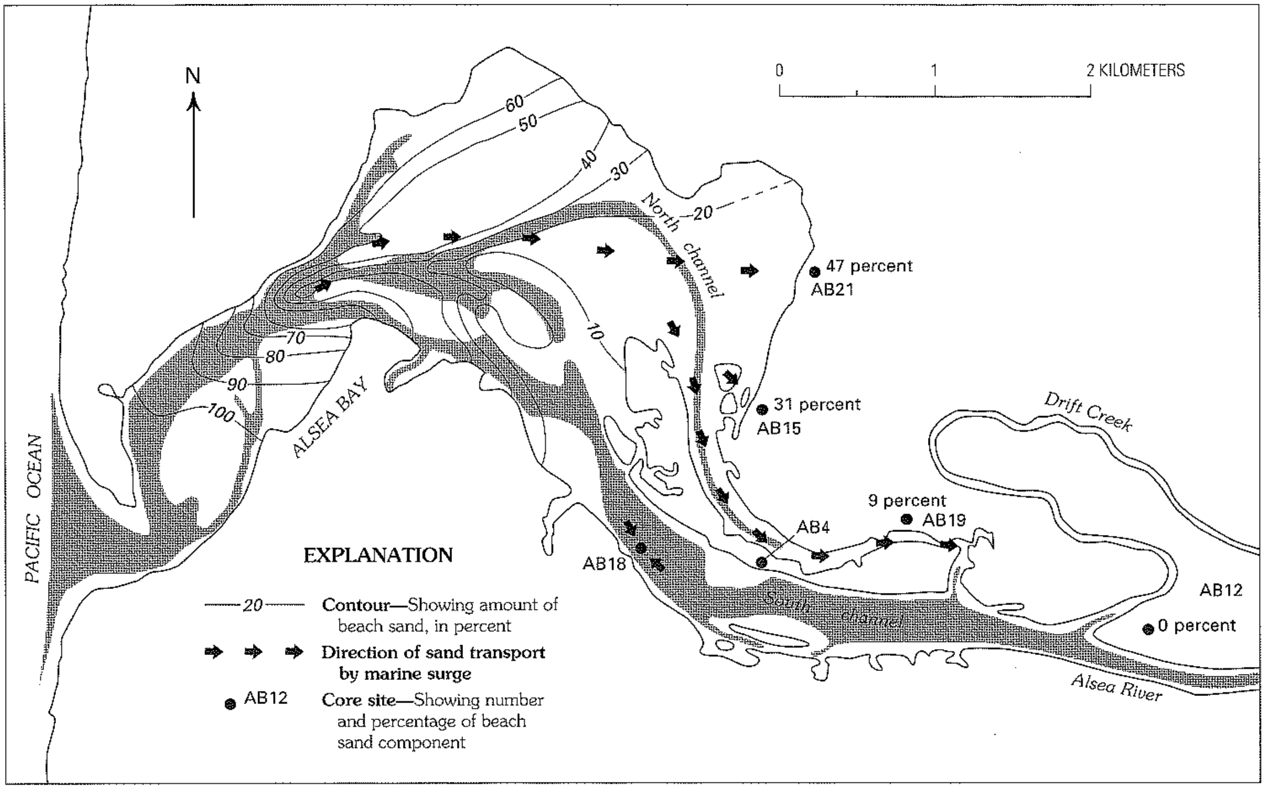

Figure 7 – Direction of sediment transport during periods of marine surge with in Alsea Bay, OR are indicated by the black arrows (Peterson, et al, 1996).

for additional deposition of suspended sediments. This northeastern transect also runs perpendicular to the inferred direction of inland flow during both marine surge and tsunami inundation.

Comparison with the Salmon River Estuary

Identification of a known site containing deposits of the 1700 Cascadia earthquake and tsunami was critical during the initial investigation of buried tsunami sediments within Alsea Bay. The Salmon River Estuary (Figure 8), north of Lincoln City, OR, contains a well-documented tsunami deposit shown in outcrops along the banks (Nelson, et al, 2004). Visitation provided a physical example in addition to literature in which the cores extracted from Alsea Bay can be compared. This literature review aided identification of the 1700 deposit from either other Cascadia rupture or storm events (Morton, et al, 2007). The tsunami deposit and its distribution in the estuary are documented in Nelson, et al (2004).

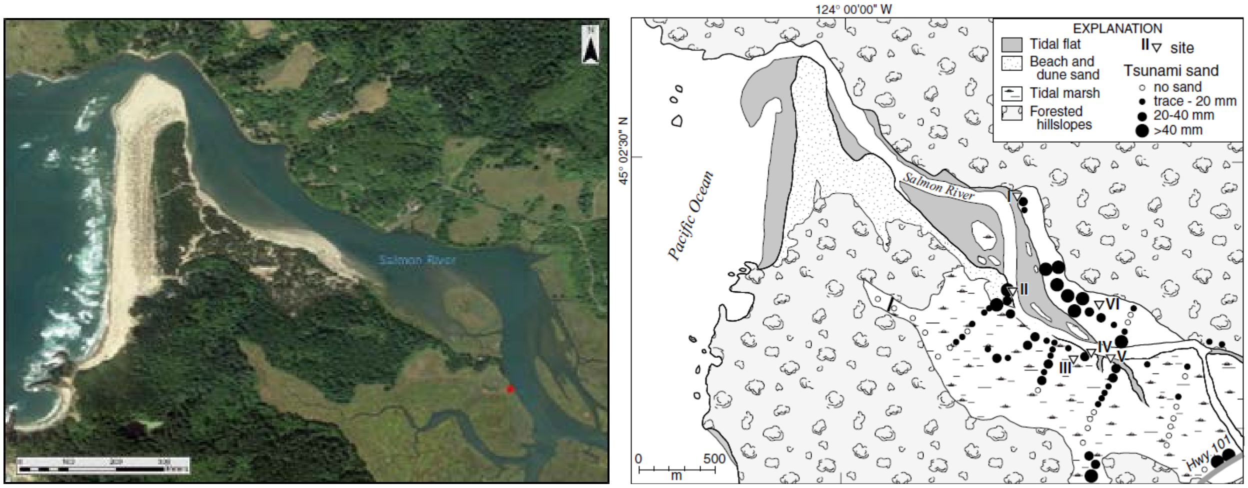

Figure 8 – (Left) The Salmon River Estuary holds evidence of the 1700 Cascadia earthquake and tsunami in the form of buried sandy sediments (Google Maps, 2018); (Right) Coring transects perpendicular to the Salmon River show evidence of tsunami sand deposits that decrease as a function of increasing inland distance (Nelson, et al, 2004).

The outcrop resides about 1.2-km inland along the banks of the Salmon River and show a distinct sandy sediment at depth. The light brown deposit, shown in Figure 9, consists of a medium grained quartz sand that overlays a dark brown organic-rich sandy loam at a sharp contact (<2-mm). The sub-rounded spherical grains that make up the tsunami deposit show a thickness of about 7-cm as their normally grade into a very fine sand along the upper contact. This upper gradational contact is approximately 1.0 to 2.0-cm thick and transitions into a silty/clayey brown tide-influenced mud. Thickness along the length of the outcrop varied as a result of localized topography resulting the bed to both increase in thickness at some locations while disappearing entirely at others. The occasional rip-up clast, not shown, provides an additional identifying feature that was seen during investigation of the Salmon River site (Morton, 2007). Overall, the comparison between the Salmon River Estuary and Alsea Bay demonstrates

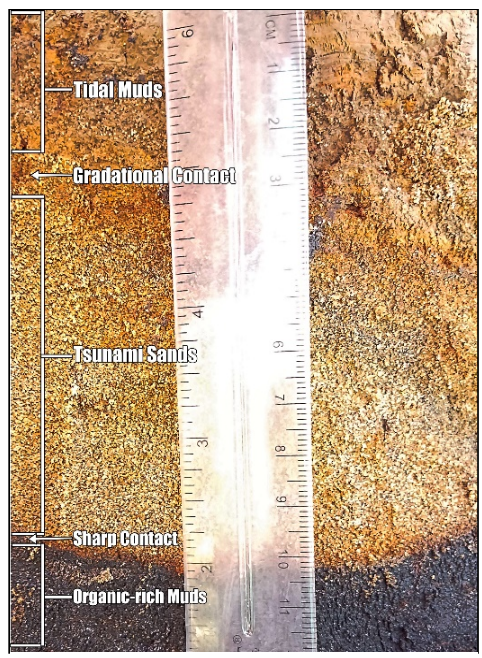

Figure 9 – An outcrop of the tsunami deposit generated during the 1700 event shows a fairly typical buried tsunami sediment profile in which a “clean” sandy sediment that grades upward overlays an organic-rich horizon.

the expected landward thinning of tsunami sediments as well as substantial inland inundation extent (Nelson, 2004; 2008).

Impact

Identification and comparison of deposits attributed to the 1700 Cascadia earthquake and subsequent tsunami provide a physical reference of inundation along the central Oregon coast. Many studies use physical stratigraphy and biostratigraphy as the means of calculating subsidence of individual bays and estuaries (Nelson, 2008). Displaced marine flora, sediment thickness, and radiocarbon dating of material in the tsunami deposits as well as the soil horizons above and below the event deposits inform models of tsunami generation.

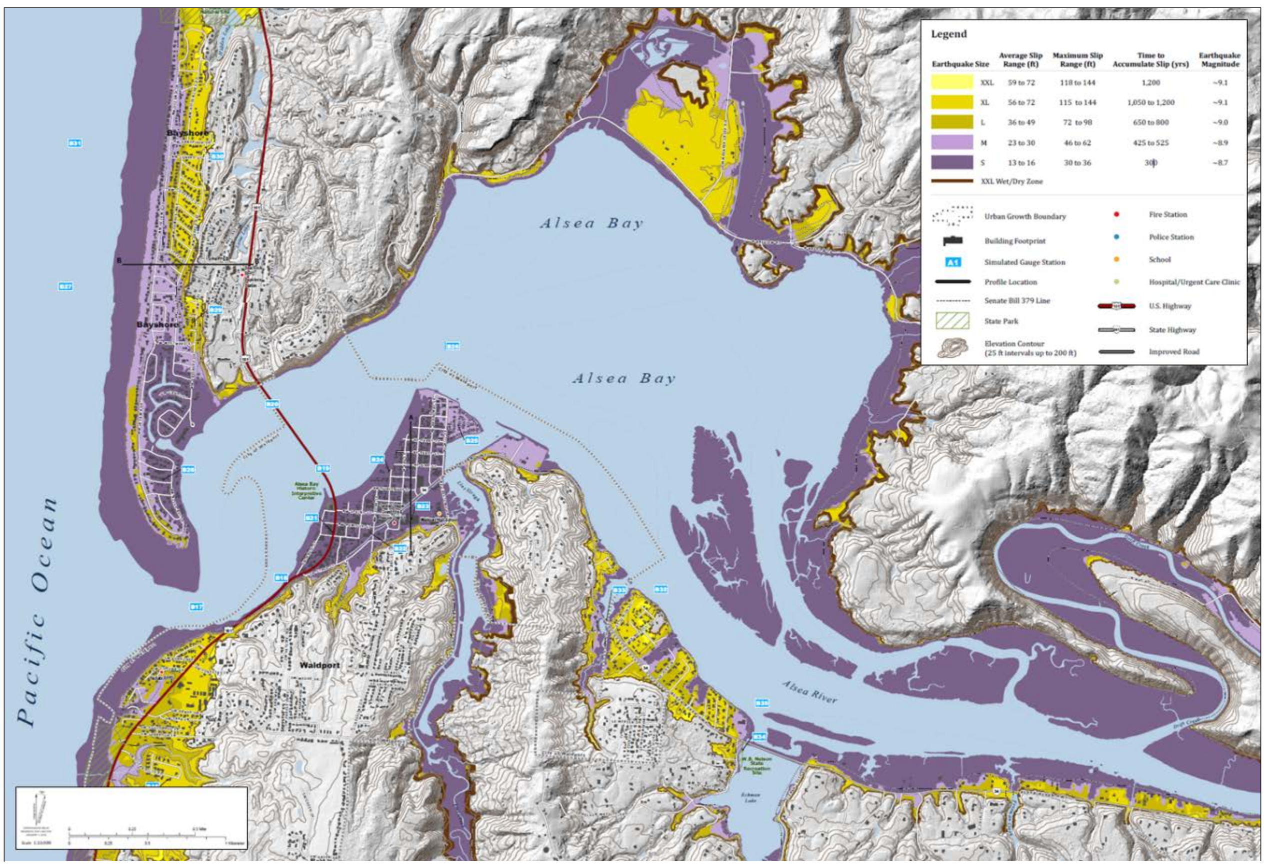

Figure 10 – The tsunami hazard map for Waldport, OR shows inundation scenarios based on varying tsunami heights generated as a result of rupture along the Cascadia Subduction Zone. (Modified from Priest, et al, 2003)

These models place constraints used by the Oregon Department of Geology and Mineral Industries (DOGAMI) to produce tsunami hazards maps (Fig. 10) for the numerous communities that inhabit the Oregon coastline of the Pacific Northwest. Whereas these maps do not predict the size of a future rupture and tsunami scenario, they do provide a context of inundation possibility. The 81 cores extracted from Alsea Bay add physical evidence that reinforce future Cascadia behavior. Inundation by tsunami within the estuary and river system, seen on the DOGAMI hazard map, does not infer buried sediments will be found at any specific location. Rather, the presence of tsunami sand at depth place constraints on prior inundation and possibly flow velocity. The location, thickness, and other lithological properties can be used validate inundation maps as well as possible rupture scenarios and magnitudes if flow capable of suspending sediments is directly related to uplift of the seafloor in earthquakes.

Conclusion

The sediments buried beneath tidal muds and Alsea River alluvium within Alsea Bay demonstrate a record of paleoseismicity and inundation by tsunami. These 81 gouge cores retrieved provide evidence of the tsunamigenic flow that carried sandy sediments a minimum of 7-km inland from the Pacific Ocean. The soil profile from each of these cores provides a familiar stratigraphic sequence seen in additional estuaries and lakes along the coastline. The sequence within Alsea Bay is identifiable as a dark brown organic-rich silty/sandy loam overlain by a primarily fine-grained quartz sand with an average thickness of 5.5-cm. This graded sandy deposit shares a gradational contact of ~1.8-cm that transitions to a brownish-grey muddy-peat.

The deposits show a sand sheet constrained topographically to the Alsea Bay estuary and river. Tsunamigenic sediments illustrate the result of waning flow in which a deposit thickness decrease from 8.5-cm to 6.0-cm as a result of increasing elevation as seen in profile A. They also provide evidence of waning flow that shows thinning of the sand sheet as a function of increasing upstream distance, reaching 2.9-cm at about 7.0-km from the bay mouth (Figure 4 and 6b).

The Cascadia Subduction Zone has not produced a great earthquake ($M_W > 8.0$) since the Japanese recorded an "orphan tsunami" on January 27th, 1700 (Atwater, 2005). In addition to the oral traditions passed down among the original inhabitants of the Pacific Northwest, buried sandy sediments reside in bays and estuaries of the terrestrial record and the turbidite sequences of the marine record (Goldfinger, et al, 2013). The stratigraphic record within Alsea Bay shows a history of at least 4 inundation events within the uppermost 2.0 meters of the stratigraphic column (Nelson, et al, 2008). Overall, Pacific Northwest Records shows a history of at least 23 megathrust earthquake events captured in the marine record during the last 10,000 years (Goldfinger, et al, 2013). These events are recorded by the estuaries as sand sheets. The sand sheet distribution recorded in Alsea Bay places constraints on past tsunami scale, models of inundation and public awareness.

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