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Validation of Predicted Tsunami Inundation for the Inland Coast of the Salish Sea Associated with Cascadia Subduction Zone Earthquakes

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**Validation of Predicted Inundation for the Inland Coast of the Salish Sea Associated with
Cascadia Subduction Zone Earthquakes**

By

Paige Morkner

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

ADVISORY COMMITTEE

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Master's Thesis

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Paige Morkner

8/8/2019

**Validation of Predicted Inundation for the Inland Coast of the Salish Sea Associated with
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A Thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by
Paige Morkner
August 2019

Abstract

The Cascadia subduction zone is understood to produce large, Mw 9.0, earthquakes every 300-1000 years. As a result of large ruptures along the fault, Washington, Oregon and Northern California, are susceptible large tsunamis along the coast. Recent earthquakes in Indonesia, Japan, and Chile, and resultant tsunamis, have helped constrain potential slip along large subduction zone margins, such as Cascadia. Accurate slip parameters, such as sea floor deformation and upper plate subsidence, are essential for accurate tsunami modeling. Hazard modeling and mapping along the Cascadia subduction zone has concluded that large tsunamis are able to travel through the Strait of Juan de Fuca and inundate coastal regions of the Salish Sea and Puget Sound. However, to improve modeling efforts, field validation of models is required. Tsunamis can move material from the near shore and beach and deposit in low-laying coastal marshes and ponds, acting as a proxy for past tsunami inundation. This research focuses on two locations in the northern Puget Sound, Ship Harbor marsh Anacortes, and Eliza Island. Using gouge auger cores and vibracores, subsurface features of each marsh were reconstructed to look for laterally continuous sand sheets indicative of tsunami inundation. Magnetic methods were used to correlate between cores, and look at sedimentary depositional fabrics within stratigraphic beds. Potential Cascadia tsunami origin for a deposit at Ship Harbor was confirmed with the use of ^{14}C dates and magnetic paleosecular variation dates. This research has implications for validation of the L1 seismic-scenario-based tsunami models, currently being produced by the Washington Geological Survey for hazard planning, and may indicate that L1 based tsunami models are valid regarding the inundation threat along the inland coast for future Cascadia earthquakes.

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I. Introduction

Natural hazard impact prediction is increasingly important in the built environment as population grows, as we gain better understanding of the extent and recurrence of hazards, and as certain types of hazards are impacted by climate change. The limited ability to predict and mitigate the effects of natural hazards, such as large earthquakes and tsunamis, has historically led to catastrophic consequences and loss of life. Tsunami hazard prediction and mitigation have been unsuccessful in places where risk was not well understood; the Chile 1960 tsunami, Papua New Guinea 1998 tsunami, the 2004 Indonesia tsunami, and the Japanese Tohoku earthquake and tsunami in 2011, resulted in severe damage, and loss of life. The lack of understanding of displacement in recent subduction zone earthquakes and resultant larger-than-expected tsunamis has forced growth within all tsunami related science. As an example, the Tohoku earthquake had mitigation planning in place for the subduction zone earthquake – however, rupture width extended well beyond expected, causing an extension of rupture to the toe of the accretionary wedge. The extension of the rupture through the wedge caused a much larger than expected vertical displacement and the resultant tsunami was much larger than models predicted (Ozawa et al., 2012; Koshimura et al., 2014). Understanding model accuracy is essential for future hazard mitigation efforts.

Past Cascadia subduction zone (CSZ) earthquakes are understood to have a recurrence interval of 300-1000 years over the last 10,000 years (Atwater and Hemphill-Haley, 1997; Atwater et al., 2003; Goldfinger, 2012; Gica and Arcas, 2016; Eungard et al., 2018). CSZ earthquakes are recorded in local Native American history, but have all occurred prior to the advent of instrumental seismology, and so the spatial extent and event sizes are modeled based on geological constraints, and are thought to be similar to events recorded in other subduction

zone settings. CSZ earthquakes are large (Mw 7+) and present a hazard to the West Coast as both seismic shaking, and as a resultant tsunami inundation (flooding). Specifically, CSZ megathrust events present significant known tsunami hazard to the outer coast of Washington (Figure 1), where inundation may be greater than 4m and warning times less than 30 minutes (Cherniawsky et al., 2007).

While the risks for large-scale tsunami inundation of the outer Pacific coast of Washington and Oregon are better understood, possible tsunami inundation hazards for the inland coast of the Salish Sea and Puget Sound (Figure 1) are less understood. Fault dislocation models have been produced to try to estimate how slip along the CSZ has occurred in the past and predict how it will occur in the future (Satake et al., 1996; Flück et al., 1997; Wang et al., 2003). Fault dislocation models produce slip parameters which can be applied to sea floor deformation. With an estimate of sea floor deformation, inundation predictions are made and tsunami modeling can be executed. Priest et al. (1997) and Witter et al. (2013) produced several potential deformation models to use as initial boundary conditions for tsunami modeling, which have been applied to models for the outer coast of Washington and Oregon, and for the inner coast of the Puget Sound. One such scenario, the L1 (Mw 9) simulates wave propagation into the inland waters of the Puget Sound, with inundation depths of low-elevation coastal areas of the north Puget Sound varying from 0.5 to 5.6m (Gica and Arcas, 2016; Eungard et al., 2018). Because the predicted inundation risk to the inner coast of the Puget Sound is spatially varied, poorly understood, and model dependent, field verification to identify past inundation locations is important to validate and refine model predictions of tsunami processes and coastal responses, and to better constrain timing and spatial extent of events in the geological record and future.

Deposits potentially created by CSZ tsunami events have been identified in several

protected local marshes in the Puget Sound (Figure 2) (Atwater and Hemphill-Haley, 1997; Williams and Hutchinson, 2000; Atwater et al., 2003; Williams et al., 2005; Hutchinson et al., 2013). Evidence of tsunami run-up from a site with significant modeled inundation also allows for analysis of the tsunami inundation distance while considering tide, sea level, and roughness of the coastal surface, all commonly used as initial parameters in tsunami modeling. Using models produced from the recent seismic modeling of the CSZ to choose field locations for paleotsunami studies will aid in validation of the newer L1 model, which is currently being considered for use in future hazard modeling in Washington (Eungard et al., 2018).

Identification of predicted deposits with coring, radiometric dating, anisotropy of magnetic susceptibility, and magnetic paleosecular variation dating, will help constrain the spatial distribution of tsunami run-up associated with past tsunami events, and test methods not yet used on Puget Sound tsunami deposits in the published literature. The purpose of this research is to test for evidence of past tsunami inundation in a new location, correlate any deposits found to other deposits in the Puget Sound predicted to be from CSZ sources, and test the L1 scenario-based model as an explanatory mechanism.

II. Background

2.1 Tectonic Setting

The CSZ is a convergent boundary between the subducting Juan de Fuca plate and the North American plate, extending approximately north-south from British Columbia, Canada to Northern California. The CSZ presents a clear earthquake hazard, with megathrust earthquake events predicted to be Mw 8-9 recurring ~550 years (Atwater et al., 2003). Geodetic measurements suggest that the CSZ is currently locked and that inter-seismic strain accumulation

is creating shortening and uplift along a majority of the outer coast, and decoupling of the plates will result in large rupture events in the future (Atwater et al., 2003; Kelsey et al., 2012).

Uplift and subsidence of the outer coast is determined by interseismic and coseismic periods of CSZ megathrust events. During an interseismic period the outer coast of Washington, because it is located over the locked, or coupled, section of the plate interface, experiences elastic uplift from building stress. During an earthquake, this uplift is accommodated as coseismic subsidence which occurs in a matter of seconds to minutes during the earthquake (Atwater, 1987). Because the inland coast of Washington is located east of this coupled zone, there is less interseismic uplift and thus a lesser amount of coseismic subsidence. For the western Puget Sound lowlands 0-50cm of subsidence is predicted to be possible (Leonard et al., 2004).

Accommodating movement along the CSZ on the overriding plate are a series of faults that extend through Whatcom and Skagit counties, and these present their own earthquake and tsunami hazard to the Puget Sound coastal areas (Johnson et al., 1996, 2004; Kelsey et al., 2012; Personius et al., 2014). Movement of these faults in the offshore environment could act as additional tsunami sources that should be considered. Seismic activity underwater along these smaller faults could potentially produce a tsunami large enough that its deposit is preserved in the sediment record nearby (Williams and Hutchinson, 2000; Kelsey et al., 2012). Submarine landslides and delta collapse are also potential causes of tsunamis. However, the history of all these events, their size, and locations, are even less well constrained than the large CSZ events.

2.2 Seismic modeling

Potential rupture scenarios for future CSZ events establish boundary conditions for tsunami modeling. However, the modeling of these boundary conditions has evolved as new research has been published. Variability of potential seismic scenarios presents a challenge when

modeling for hazard prediction and mitigation planning. Priest et al. (1997) describe a rupture scenario, referred to as 1A, modeled after the 1700 event, based on a fault dislocation model and paleoseismic data. The 1A scenario predicts a Mw 9.1 earthquake and explores a N-S full rupture length of ~1050km and a narrow E-W rupture width of ~70km, with a total estimated average slip along the fault of 17.5m propagating through the fault zone and to the surface. Based on the Hyndman and Wang, (1995) finite element model of the thermal regime, Priest et al. (1997) calculated a dislocation model of megathrust rupture for tsunami modeling with proposed bathymetric vertical uplift up to 6m along the length of the subduction zone. Coseismic coastal subsidence is variable in this scenario from North to South along the subduction zone. This seismic scenario has been used in older tsunami models of the Salish Sea (Priest et al., 1997; Cherniawsky et al., 2007), however it is based on outdated rupture parameters which have been expanded upon in the last 10 years.

Witter et al. (2013) published a set of 15 different modeled ruptures, ranging in size and fault dynamic parameters. The seismic scenarios produced were used to model tsunami inundation in Bandon OR, located on the outer coast. Turbidite records from Goldfinger et al. (2012) were used as a basis to calculate recurrence intervals and seismic strain accumulation between events. The modeled results produce three variations of each size SM, M, L, XL, and XXL scenario: the #1 iterations are modeled using splay faulting, which diverts some of the slip to a hypothetical splay fault in the accretionary wedge, increasing seafloor deformation (Witter et al., 2013). The #2 and #3 iterations of each size slip model are based on two buried rupture models which used different up-dip limits of coseismic slip, suggesting that the up-dip section of the fault will act to prevent slip from reaching the seafloor; these scenarios produce a smaller amount of sea floor deformation. The likelihood of splay faulting seems high, as other major

subduction zones have exhibited splay faulting in recent ruptures – such as Japan, Sumatra, and Chile (Witter et al., 2013).

When evaluating the statistical likelihood of the models, Witter suggests that the M1 and L1 scenarios, which factor splay faulting, to be good scenarios for building planning. The L1 scenario predicts 0-2.1m of coseismic subsidence along the outer coast of Washington and Oregon (Witter et al., 2013). Due to the short interseismic period since the 1700 event, the L1 is determined statistically possible but not likely to occur soon, as the slip deficit (the amount of stress created along the locked boundary) is not yet large enough (Witter et al., 2013). The L1 scenario has been and likely will continue to be used as the seismic source for hazard-prediction related tsunami modeling in Washington because it predicts a full rupture CSZ event and likely represents a maximum near-future event and risk (Cherniawsky et al., 2007; Witter et al., 2013; Gica and Arcas, 2016; Eungard et al., 2018). There is very little subsidence predicted for the inland coast when using the L1 to model tsunamis in the Puget Sound, but is variable in coastal subsidence along the outer coast (Witter et al., 2013, 2013).

2.3 Cascadia Turbidite Records

Goldfinger et al. (2012) describe a set of turbidite deposits found off the coast of Oregon and Washington which are used to estimate a long-term sequence of Holocene CSZ ruptures. Age estimate for each turbidite is based on the datum of Mazama ash as well as ^{14}C dates from organic material found in these cores (Goldfinger, 2012). Witter et al. (2013) use the turbidite record and ^{14}C dates from related marsh record tsunami deposits as the basis for reoccurrence intervals to calculate the slip parameters necessary to create the Bandon, OR seismic sources.

There are 19 turbidite events recorded, T 1-18, which range between 170-10,000 years B.P. This record is considered the most extensive way to determine the previous earthquake

record of the CSZ, since marsh records only span the late Holocene (Atwater and Hemphill-Haley, 1997). The turbidite record ages have been commonly used to determine if marsh stratigraphic records are from CSZ rupture, or from other tsunamigenic sources.

Atwater et al., (2014) bring into question the turbidite record interpretation by Goldfinger et al. (2012). They suggest that the turbidite record, due to simplified assumptions about flow paths, stratigraphic correlation, and record completeness are not a perfect record of the history of rupture along the CSZ. Combining the late Holocene record from marshes with the turbidite record provides a higher resolution set of potential dates for the most recent CSZ tsunamis.

2.4 Tsunami Hazards and Modeling

Current hazard evacuation in Skagit and Whatcom counties are based on older tsunami models produced from the Priest et al. (1997) seismic scenarios. Walsh et al (2004) used the Method of Splitting Tsunamis (MOST) to model run-up through different parts of the Puget Sound. MOST is a modeling method which uses the chosen parameters of tide gauge levels and wave propagation as the basis for output cells containing flow depths (inundation). Walsh et al (2004) base the MOST parameters on the 1A Priest et al. (1997) scenario for the rupture geometry of a Cascadia subduction zone earthquake and using the thermal constraints of Hyndman and Wang (1995) and model the outer coast to subside 1-2m. This causes a predicted inundation from 0.5-5.0m along sections of the inland coast, while some areas are predicted to have no inundation. Because this older tsunami model is based on an older seismic rupture scenario and low-resolution topographic data, this model may not predict maximum tsunami inundation for hazard planning purposes.

The L1 scenario from Witter et al. (2013) has been recently used to produce several published tsunami models for Washington and Oregon. Gica and Arcas (2016) produced a high-

resolution model using MOST based on the L1 scenario (Witter et al. 2013), and predicts inundation to 5.6m in Anacortes and other coastal areas in the Puget Sound. This model uses updated bathymetric data and digital terrain models to calculate tsunami run up. Similar modeling was completed by (Eungard et al., 2018), in a joint effort to bring Washington Department of Natural Resources together with NOAA to produce standard models for hazard planning purposes in the Puget Sound. Though the L1 does not represent the largest modeled inundation from Witter et al. (2013), it does predict a significant amount of inundation compared to models produced by Walsh et al. (2004), and this is clear in the amount of spatial variation between the older 1A based models and the newer L1 based models.

All the tsunami inundation models described here were simulated with either mean high-water level (MHW) or mean high higher water level (MHHW), tidal datums representing higher tides and conditions appropriate to assess the greatest hazard and risk for planning purposes. Modeling based on MHW or MHHW likely underestimates the total potential tsunami inundation that would be accentuated by higher tides (e.g., king tides), storm surges that can range 2-3 ft, and future sea level rise, and potentially overestimates inundation during low tides (Gica and Arcas, 2016; Walsh, et al. 2004). Sea level local to Bellingham Bay is modeled to rise 0.5-1 m by 2100, indicating that MHW could increase by 25cm in less than 50 years (Board on Earth Sciences, 2012; Pollard and DeConto, 2016). By evaluating the effects of high tides, storm surge, and sea level rise on inundation, the full range of risk scenarios can be assessed.

2.5 Depositional Processes of Tsunamis and Storms

Tsunamis are typically erosional near the shoreline, redistributing sediment further inland and producing a deposit. Tsunami deposits have certain characteristics that help distinguish them from storm or other coastal marsh deposits: they are spatially extensive, conform to landscape,

are generally <25cm thick, and consist of one or a few homogeneous graded beds, from material settling out of the flow, potentially with rip-up clasts and mud intraclasts or laminae (Morton et al., 2007). The high energy depositional wave can overtop beach berms and enter coastal marshes, depositing sediment in a wedge shape thinning and fining inland, 100s of meters from the beach (Morton et al., 2007). Studies in Chile and Japan have shown that deposits are generally thicker in low-lying areas (such as marshes), and thinner on topographical highs (Morton et al., 2011; Richmond et al., 2012). The deposits are commonly preserved in low lying, marshy or ponded areas, as they provide a means of capturing the sediment between plants and roots, protecting it from wave erosion at the beach front, and ultimately preserving it in the geologic record (Morton et al., 2007).

There are three main settings in Cascadia where deposits are preserved: estuaries, coastal lakes and back-barrier wetlands. All these environments are low energy, with deposits above and below a tsunami deposit distinctly different than the tsunami deposit itself (Peters et al., 2007). In a tidal marsh setting, tsunami deposits will consist of sandy mud overlaying peat or organic-rich mud (Peters et al., 2007). If the peat is not well developed at the time of deposition, the tsunami deposition over the marsh substrate may result in a less obvious deposit between overlaying and underlaying materials (Peters et al., 2007). A layer of organic debris or massive mud may overlie the sand layer (Peters et al., 2007). All published Cascadia tsunami deposits in the Puget Sound have consisted of silty and clayey sand layers found within the top 3m of the coastal marshes (Williams and Hutchinson, 2000; Williams et al., 2005; Hutchinson et al., 2013).

The morphology of a tsunami deposit is distinguishable from thick storm deposits which do not extend much laterally beyond beach berms (typically 1-3 meters) and consist of thick (>25cm) muddy sand beds between peat layers (Williams and Hutchinson, 2000; Williams et al.,

2005; Morton et al., 2007; Hutchinson et al., 2013). Even though storm waves can run up significant distances, they do not typically have enough power to deposit material as far inland as a tsunami and generally are characterized by an abruptly-ending thick, massive, wedge (Morton et al., 2007). Tsunami deposits generally have a sedimentary fabric created by a single flow direction from initial inundation, potential secondary direction of flow from the backwash outflow, and settling from suspension preserved in the stratigraphy as normal grading (Morton et al., 2007; Wassmer et al., 2010, 2015; Wassmer and Gomez, 2011; Kain et al., 2017). Storms typically display a degree of organization containing multiple sets of laminae and cross-beds, due to back and forth swash movement and inconsistent flow (Morton et al., 2007; Wassmer et al., 2010, 2015; Wassmer and Gomez, 2011; Kain et al., 2017).

2.6 Previous Tsunami Deposits in Oregon and Washington

2.6.1 Oregon and Washington Outer Coast

Marshes on the outer coast of Washington and Oregon provide the highest resolution record of past CSZ tsunami inundation, due to susceptibility from CSZ tsunami inundation. Tsunami deposits are preserved and correlate to turbidite events (Goldfinger, 2012; Witter et al., 2013). The buried soils at Willapa Bay and surrounding area are generally used as a proxy for the late Holocene marsh tsunami record for the CSZ, with each buried soil representing a coincident tsunami event. As an example, soil S correlates to earthquake event S. Willapa Bay likely contains at least 6 CSZ tsunami events, preserved as buried soils that were heavily inundated during tsunami genesis and coastal subsidence (Atwater and Hemphill-Haley, 1997).

These buried soils are as follows (Atwater and Hemphill-Haley, 1997):

Soil J: Occurred between 3320-3500 years B.P.

Soil L: Likely dates to 2800-3300 years B.P.

Soil N: Dates well to 2400-2780 years B.P.

Soil S: Exposed in Willapa Bay and Grays Harbor, and other marshes with smaller tidal ranges. Likely occurred between 1500-1700. This could also possibly be between 1600-1900 years B.P. from additional ^{14}C dates which are not statistically well constrained.

Soil U: Widespread in WA state, likely occurred between 1130-1350 years B.P.

Soil W: Likely 900-1300 years B.P.

Soil Y: Likely associated with 1700AD event

2.6.2 Along the Strait of Juan de Fuca

Over 60 localities from N. California to Southern Vancouver Island have been determined to have paleotsunami evidence from Cascadia earthquakes (Peters et al., 2007). Local to the Puget Sound, CSZ tsunami deposits have been identified in cores taken from Discovery Bay, Salt Creek and Swantown marsh (Figure 2). This suggests that historic, low-lying coastal marshes have high likelihood of preservation of CSZ tsunami deposits (Williams and Hutchinson, 2000; Williams et al., 2005; Peters et al., 2007; Bourgeois, 2009), due to the morphology of tsunami run-up and sediment transport inland. These were identified as tsunami deposits based on their micro sediment structures, presence and classification of marine microfossils (diatoms), ^{14}C dating, and lateral run-up extent from the beach inland. Used as a proxy for comparing dates of these deposits is the record from Willapa Bay, OR which contains buried soils that correlate to the longer-term turbidite record off the coast of Washington and Oregon (Atwater and Hemphill-Haley, 1997; Goldfinger, 2012).

2.6.2.1 Salt Creek, WA

Located on the southern shore of the strait of Juan de Fuca, Salt Creek Marsh is a estuarine marsh, which contains two thin sand layers interpreted to be the product of Cascadia tsunami propagation and inundation (Hutchinson et al., 2013). These layers extend approximately 60m along one edge of the creek, and 800m from the mouth of the creek. Evidence of marine diatoms suggest tsunamigenic origin. ^{14}C dating of the two sand sheet ages, with an estimated age for the upper sand dating 1560 ± 30 (2 sigma range), with an estimated upper limit of 1790 ± 30 . The lower sand layer has a maximum limiting age is 2440 ± 30 years B.P. They correlate the upper sand to buried soil S (and CSZ earthquake event S) found in Willapa Bay (Atwater and Hemphill-Haley, 1997).

2.6.2.2 Discovery Bay, WA

Discovery Bay is an inlet near Sequim, WA, just west of Port Townsend, located on the southern coast of the Strait of Juan de Fuca (Site B, Figure 2). This bay consists of a tidal flat that is ponded at high tide and exposed at low tide, and fed by freshwater from a fluvial outlet (Williams et al., 2005). A local home was flooded at this location from the tsunami produced by the Alaskan earthquake in 1964, suggesting that this location is particularly sensitive to tsunami inundation, even from distant sources (Williams et al., 2005).

Nine distinct sandy deposits are found in Discovery Bay up to 3m below the surface, suggesting a rich paleotsunami history. Many of these deposits date to inferred CSZ event from turbidites and the record in Willapa Bay. The top 4 beds are interpreted to be CSZ tsunamis, with beds 5 and 6 being likely tsunamis and beds 7, 8 and 9 being possible tsunamis (Williams et al., 2005). All sand beds identified at Discovery Bay contain marine diatoms (Williams et al., 2005). However, the oldest of the deposits, beds 8-9, are unclear in age constraints, making them more

difficult to correlate to turbidite events and other local marsh paleotsunami deposits. Beds 6 and 7 can both potentially be correlated to Soil S (and earthquake S) at Willapa bay.

These beds are radiocarbon dated as follows:

Bed 1: Likely dates to the 1700 event, 310-0 cal. years BP.

Bed 2: 300-500 cal. years B.P.

Bed 3: 790-540 cal. years B.P.

Bed 4: 1270 – 960 cal. years B.P

Bed 5: 1300-1060 cal. years B.P, inferred to likely overlap with inundation producing buried Soil U from CSZ Earthquake U from Willapa

Bed 6: 1820-1560 cal years B.P. or 2120-1930 cal. years B.P.

Bed 7: 1710-1330 cal. years B.P., inferred to likely overlap with the buried soil S from CSZ earthquake S.

Bed 8: 2100-1400 cal. years B.P.

Bed 9: 2750-2150 cal. years B. P.

2.6.2.3 Swantown Marsh, WA

Swantown marsh is on the west coast of Whidbey Island at the eastern end of the Strait of Juan de Fuca (Site C, Figure 2). The marsh faces WNW, meaning it is directly exposed to incoming influences of the Pacific Ocean (Williams and Hutchinson, 2000). Swantown has at least two CSZ tsunami depositional layers, dated with radiocarbon to be 1160-1350 cal. years B.P. and 1400-1700 cal. years B.P. The authors also concluded two more potential age ranges for tsunamis, around 1810-2060 cal. years B.P. and 1830-2120 cal years B.P., but these are potentially from sources other than the CSZ (Williams and Hutchinson, 2000). Within 25km of the marsh are three local fault traces: Darrington-Devils Mountain, Southern Whidbey Island,

and Leech River faults, and these could be responsible for these two older deposits (Williams and Hutchinson, 2000).

2.6.3 Terrell Creek estuary

The Birch Bay upper crustal fault is believed to be the source of a very thin (1mm) tsunami deposit found in Terrell Creek estuary, WA (Kelsey et al., 2012). This deposit is believed to be caused by the Birch Bay fault where it traces off shore, adjacent to the Terrell Creek estuary (Kelsey et al., 2012). Though this is not a CSZ tsunami deposit, it is an example of a tsunamigenic source along an upper crustal fault, which exist locally to the north Puget Sound.

2.7 Current Mitigation planning in Whatcom and Skagit Counties

The 2015 Whatcom county hazard mitigation plan uses the Walsh et al. (2004) tsunami models as the basis for planning. The 2004 models predict grounding of ships in the harbor at low tide and, at higher tides, up to three meters of inundation into lower elevation downtown areas (“Whatcom County Natural Hazards Mitigation Plan,” 2015). However, this prediction is based on older tsunami modeling, and newer models suggest the potential for inundation in Bellingham and other populated is actually greater and more spatially varied (Eungard et al., 2018). Large subduction zone earthquakes in the last 15 years have refined our understanding of splay faulting, and the potential for propagation of the fault through the accretionary wedge and to the sea floor, increasing tsunami height. Further developments in research and data sets factored into tsunami models for the CSZ events calls for revised models to be used in mitigation planning, such as the models produced by Eungard et al. (2018).

Skagit county’s most recent natural hazard mitigation plan was updated in 2014 and claims “there is no written historical record of a damaging tsunami occurring in or affecting Skagit County” but does report that “geologic evidence of tsunamis has been found in Cultus

Bay on Whidbey Island and at West Point in Seattle” (“Skagit County Natural Hazard Mitigation Plan,” 2014). They claim that tsunamis still pose a hazard to coastal areas such as the San Juan Islands and Anacortes. Skagit County uses the Walsh et al. (2004) models to make hazard assessment and mitigation plans and as a basis to suggest that there would be minimal effect from tsunami inundation along Skagit County coastal areas. The city of Anacortes, specifically, ranks tsunami hazard as a low risk, low probability issue currently facing the residents. While tsunamis may pose a less likely threat relative to other natural disasters such as flooding, which has a shorter recurrence interval and better understood effects, (“Skagit County Natural Hazard Mitigation Plan,” 2014), the assessment of inundation risk is made based on older tsunami models (Walsh et al., 2004) which predict less spatial extent of inundation than more recent models (Gica and Arcas, 2016; Eungard et al., 2018). In addition to tsunami hazard, the Skagit County Hazard Mitigation Plan mentions the possibility of a “seiche”, a large surge of water by earthquake waves forms a set of standing waves and causes the much larger than normal waves to arrive on shore, even where tsunami inundation is not expected (“Skagit County Natural Hazard Mitigation Plan,” 2014). Though it is only mentioned in Skagit County’s plan, likely due to the small inlets within Skagit County, it is possible that seiches are a threat to a number of communities along the coast of the Puget Sound where a many constrictions can retard the flow of water out to the sea and promote development of a seiche.

2.8 GeoCLAW Tsunami Modeling

GeoCLAW software is used for modeling tsunami propagation and inundation (Gonzalez et al., 2011), by solving the depth averaged, non-linear shallow water wave equations (Leveque et al., 2010; Gonzalez et al., 2011; Mandli et al., 2016). For this model, sea floor deformation, calculated using Okada’s 1985 method for slip on rectangular faults is used as an input and

models inundation produced from that fault-slip source. The parameters chosen, such as initial sea level, and earthquake initial boundary conditions, specify sea floor deformation and define the incoming wave (Gonzalez et al., 2011; Mandli et al., 2016). To calculate these factors, depth of undisturbed water before the wave arrives is chosen as a model input, and sea level/larger storm swells/high tides can be used to define these initial conditions. Based on water depth, the flow velocity of the propagating wave can be determined (Gonzalez et al., 2011). Tsunami waves, once onshore, do not act linearly and are less predictable; so direct changes in inundation flow depth will vary spatially (Gonzalez et al., 2011). However, changes in tidal level can be used as a proxy for different sea level rise scenarios. GeoCLAW was used in this study to produce high resolution (1/3 arc second resolution) models for the field areas of focus, and the Witter et al. (2013) Bandon, OR sources were used to assess the different potential tsunami scenarios possible.

2.9 Magnetic Fabrics of Tsunami Deposits

Sedimentary fabrics reveal information about the hydrodynamic conditions during deposition (Wassmer et al., 2010; Wassmer and Gomez, 2011; Kain et al., 2017). A flow direction may be detected in the tsunami beds if the current for the tsunami is high (Wassmer et al., 2010; Kain et al., 2017). This flow regime could manifest as three potential sedimentary fabrics. If current was slow, then grains will be aligned in the direction of flow, with the grain long axis ($K_{\max}$) aligning in a dominate flow direction (Taira and Masuda, 1989; Boggs, 2011). If current was fast, than grains may be aligned perpendicular to the direction of flow, and will have varied inclination angles due to viscous collisional (turbulent) flows (Boggs, 2011). With turbulent flow, the $K_{\max}$ axes will be oriented perpendicular to the expected direction of flow (Taira and Masuda, 1989), indicating how the tsunami moved inland as it inundated the marsh. If

inundation was followed by ponded water, the deposits could have a fining upper sequence deposited from settling, producing a fabric with random orientations of the long axes and minimum axes perpendicular to the settling surface (Taira and Masuda, 1989; Boggs, 2011). The grain short axis ($K_{\min}$) orientations are referred to here as imbrication angles, which is the difference between the $K_{\min}$ inclination reported and 90 degrees.

Fluvial deposition will preferentially orient grains with flow; alignment of grains can produce mineral fabrics that are characteristic of sediment transport mechanisms (Taira and Masuda, 1989), which can be measured as magnetic fabrics. When placed in a weak field, the grain long axis orientation, commonly the long axis of an oval shaped grain, produces a maximum ($K_{\max}$) susceptibility, producing the strongest response to the field. The intermediate axis (K_{int}), the second longest grain axis, and minimum axis ($K_{\min}$), the shortest grain axis, produce less intense responses to the field than the $K_{\max}$, as they are not as magnetically susceptible in response to a magnetic field. Due to the differences in the depositional flow regimes of storm and tsunami deposits anisotropy of magnetic susceptibility (AMS) fabric analysis can be used to differentiate the axis orientations, if a clear flow regime is detectable (Wassmer et al., 2015). Tsunami deposits will generally have a clearer flow direction retained in the sediment fabric due to the alignment of the long axes with or perpendicular to flow and little expected backwash to alter grain alignment. However, the general expectation that a flow regime is preserved can be complicated by local obstacles or fast, collisional flow. In previous studies (Wassmer et al., 2010, 2015; Wassmer and Gomez, 2011) tsunami deposit AMS results show a clustering of the AMS axes, with the $K_{\min}$ s being clustered perpendicular to the settling surface (flat or imbricated), and $K_{\max}$ magnetic grain orientation commonly spread in orientations parallel or perpendicular to flow and parallel to the bedding plane, or presenting in random

orientations parallel to the bedding plane, suggesting deposition from settling (Taira and Masuda, 1989; Wassmer et al., 2010). In contrast, storm wave AMS fabrics are typically more collisional due to multidirectional flow from the back and forth swashing motion, and highly collisional flows show less clustering of the $K_{\min}$ perpendicular to the settling surface, and less clustering of $K_{\max}$ and K_{int} directions making a flow direction more difficult to detect (Taira and Masuda, 1989). Magnetic fabrics in deposits from the 2004 Indonesian tsunami corroborated with the eyewitness accounts, suggesting this could be a feasible method for measuring flow direction for tsunami deposits (Wassmer et al., 2010).

2.10 Paleo Secular Variation Dating

The global magnetic field directions and paleointensity varies geographically but has been measured and documented by instruments for the last 150 years in North America, and paleosecular variation (PSV) records from igneous and sedimentary rocks are available in detail for older periods of time (Hagstrum and Champion, 2002). Based on geographical location, the paleosecular variation of the geomagnetic field can be used to determine the age of a section of sedimentary strata. Hagstrum et al., (2004) used this method to determine the regional PSV record for the Pacific NW from sediments that span 2000 years of Cascadia tsunami deposits in Discovery Bay (top 5 beds), and obtained PSV records from the Snohomish River which are believed to have preserved a Seattle Fault earthquake from ~900 cal. years B.P. Paleosecular variation dating can be used as a compliment to the ^{14}C dates and may provide both a higher-resolution age of the cores when factored into a sequence model, and be directly compared with the geomagnetic field directions recorded in other sections that contain deposits from tsunami events locally.

2.11 Field Sites

2.11.1 Ship Harbor, Anacortes, WA

Ship Harbor marsh faces NNW on the north-western tip of Fidalgo Island, WA, in the city of Anacortes (Figure 1 and 3). This marsh is bordered to the west by the Anacortes Ferry terminal and bordered on the north side by the Anacortes Interpretive Preserve and beach, which contains the old foundations and docks of the cannery built in the mid to late 1800s (“Intro to Anacortes History”). Although Fidalgo Island has been home to the Samish and Swinomish people for thousands of years it was settled in the early 1800s by westerners, and by 1890 a cannery and railroad system was built on the north side of the marsh. The marsh is primarily fresh water fed by rain, and has no major source of surface fluvial input. The barrier beach extends the entire width of the marsh with no tidal channels, separating the marsh from the ocean. The western most part of the marsh is likely the most “historical” long standing marsh area, as suggested by the 1889 T-sheets available (Gilbert, 1885) . The building of the railroad berm along the north-west edge of the marsh likely separated the marsh completely from the beach, causing a potential shift in the dominate vegetation in the marsh. Pilings where built throughout the marsh in order to dry nets, and aerial photos show images of a ditch having been dug through the marsh at some point before it was left to return to its natural state. Today, the pilings stand about .5m high, and were observed in the field.

Ship Harbor marsh has an average elevation of 3-4m, based on LiDAR produced using the NAVD 88 vertical datum (“North Puget USGS 2006 DTM 43”). The typical tidal range for Ship Harbor, according to a permanent tide gauge at Friday Harbor, WA, can be -2m to +1.5m change from mean sea level (“Tide Predictions - NOAA Tides & Currents”).

The L1 based model predicts inundation at this site of up to 3.4m, extending approximately 330m inland, with inundation predicted throughout the marsh (Gica and Arcas, 2016; Eungard et al., 2018). Based on the stratigraphy of nearby marshes, peaty intertidal sediments beneath this marsh are thin <0.5m, and thicker sediment layers likely exist near the middle/back part of the marsh or in the pond (MacInnes, 2018).

The current marsh surface is seasonally ponded for most of the year (October – July), and dries in the summer. The plants, year-round, consist mainly of cattails and bulrushes which cover the entire marsh and stand around 2-2.5m in height. Duckweed is present covering areas where soils are saturated most of the year. The front part of the marsh consists of shrubby trees, blackberry and rose hip bushes.

2.11.2 Shannon Point/Cannery Lake, Anacortes

Cannery Lake is a coastal lake located in north-west Anacortes, adjacent (west) to the Anacortes ferry terminal. The area is mapped in the 1889 T-sheets as an estuary, prior to the build of the railroad berm, inducing ponding and likely formation of the lake (Gilbert, 1885). There is predicted inundation of the lake up to 1.5m, with potential for preservation of the intertidal flat materials under the current reservoir/lake. We attempted to core with the gouge auger and the vibracorer here but were unsuccessful at retrieving anything below 1m depth. This field site was eliminated from this study.

2.11.3 Eliza Island

Eliza island is located off the southwest tip of Lummi Island, Whatcom County, WA. It has a total land area of 158 acres (“Eliza Island plan”) and consist of 139 property subdivisions owned by private families and the Eliza Island Beach Club, which is a board of land owners. The site of interest on Eliza is located in the middle, low-elevation part of the island, just west of the

airstrip which runs roughly NW-SE on the east side of the marsh (Figures 1 and 4). The marsh itself is ponded seasonally and located around a pond which is wet year-round.

Average elevation of the marsh is 1.8-2.5m (“San Juan 2009 DTM 12”). There is a large beach berm, approximately 3m in height (“San Juan 2009 DTM 12”), on the north and south sides of the middle of the island. Tidal range for Eliza are typically -2m to +1.5m above mean sea level (“Tide Predictions - NOAA Tides & Currents”). There are no channels connecting the marsh to open water. The beach berm is approximately 30m from the closest collected core (Figure 4). The north side of the marsh is approximately 145-190m from the beach.

The marsh has at least 1.5m of predicted inundation based on the Walsh et al. (2004), Gica et al. (2016) and Eungard et al. (2018) models. The marsh is present in the 1889 T-sheets, suggesting a good environment for paleotsunami deposit preservation (Gilbert, 1885). The area of interest on Eliza Island is a federal jurisdiction wetland, and the island’s shorelines are protected by the county due to eelgrass populations and other protected plant communities. Eliza Island is considered a known geologic hazard tsunami zone in Whatcom County (“Whatcom County Natural Hazards Mitigation Plan,” 2015).

Plants identified in the immediate area consist of *Salicornia Virginica* (slender pickleweed), a succulent segmented grass which inhabits the areas closest to the central pond, *Oenanthe sarmentosa* (water parsley), *Eleocharis acicularis* (needle spike-rush), and *Carex aperta* (Columbia sedge) (Guard et al., 2010). These plants cover the entirety of the marsh.

III. Field methods

3.1 Gouge auger transects

Data collection consisted primarily of gouge auger coring and vibracoring to characterize and subsample subsurface features and reconstruct paleoenvironments at both field sites. All field work was completed between mid-August 2018 and late September 2018. During the summer months, both field sites are substantially drier, making it easier to core and easily traverse each site. Prior to collecting vibracores, a 1m x 60mm diameter Elijakemp gouge auger with two 1m extensions and handle with beating head was used for most of the exploration and transect data for both field sites. A 1m soil probe with up to 4m of extensions was used for initial exploration of depths and presence of sand layers. Field exploration consisted of collecting auger pushes in 5-15m spaced points along several transects spanning through parts of the marsh, especially focused on areas that showed potential tsunamigenic deposits (Figures 3 and 4). In total, 33-36 auger cores were collected at each site, and for each core sediment type, size, color, grain size, rounding, clay content, and visual organic content was documented (Appendix 1). Field photos were taken of most auger cores.

A Trimble explorer 6000 or a Garmin 64s was used to mark points and waypoints in the field. When possible, a topographic profile was also completed (only in Ship Harbor).

3.2 Vibracore collection

A vibracorer was used to collect nine cores: three from Eliza Island, and six from Ship Harbor. Vibracores were collected using 3" aluminum irrigation tube. The aluminum tube was cut into 8ft, 10ft and 13ft segments, based on desired sampling depth and vibrated to depth by mounting a customized, heavy vibrating head at the top of the pipe.

The inside of the core pipe was wetted before collection to minimize compaction. Cores were oriented and marked with magnetic North during collection using a Brunton compass. Cores were oriented for magnetic data correction. A large clamp is positioned around the core pipe and connected to a cement mixing cable, which is connected to a modified gas-powered motor. When the motor is started, a mechanism spins the inside of the cable, effectively vibrating the clamp and the pipe and using the operators' body weight, driven into the ground until desired depth or refusal. Inner and outer measurements of the remaining core pipe are taken before retrieval to calculate compaction for each core (Table 1).

To retrieve the core, the pipe is filled with water to the top, capped with a plumber's cap to create a pressurized seal, wrapped with carpenters wrapping and retrieved with a jack. In the field, core tubes were then marked with name and orientation, labeled, and some were cut into segments ranging from 1-1.5m for transport.

3.3 Field Methods

Initial exploration was spent surveying as much of the marsh as possible with the gouge auger. Subsequent days were spent focusing on locations of interest within each marsh, found to have preferentially preserve the long-term stratigraphic record.

Several transects were completed in Ship Harbor (Figure 3): a large transect spanning approximately NW to SE, and several smaller transects extending to the SE, SW, and from East to West. Vibracores were collected at several different locations throughout the marsh, in locations representative of the overall stratigraphy seen in the gouge auger data.

On Eliza Island, cores were collected around the central pond in the wetland (Figure 4), adjacent to a well-sorted gravel-dominated mixed-sediment beach directly south. The central pond is armored on the bottom with gravels between 1-5cm in diameter, sub-rounded to well

rounded. Along the north side of the pond is a slope, which leads away from the pond into a grassy field. Eliza island had four transects completed using a gouge auger: two spanning East-West and two, one of which was short (30m), spanning North-South. Points for auger collection were chosen based on location and ability to collect. Most cores were collected in the marsh around a pond that remains saturated year-round, and is the topographic low in the marsh. Using published inundation models and gouge auger data, three vibracores locations were selected for Eliza Island, one on the North side of the pond, in a predicted inundation zone, and two at a lower elevation on the South side of the pond.

IV. Lab Methods

4.1 Sediment vibracore analysis

Vibracores were split at WWU for analysis. The North mark on the core pipe, made in the field, was used as a reference to measure and mark East, West, and South directions, running a line up either side of the core. Using a set of metal shears, two opposite sides were split, along the east and west marked lines, removing a ribbon of aluminum from the cores. A thin stainless-steel wire was used to separate the halves, and when difficult, a knife was used. Immediately after splitting a core, each half was photographed using a Nikon DSLR camera and a stage with lights, as well as a reference measuring tape.

The cores, once photographed, were then described to characterize sediment type, based on color using a Munsell color book, grain size and visual sand and mud %, textures and interpreted stratigraphic contacts and subdivisions (Appendix 2). Cores were stored in a refrigerator, with each half wrapped in plastic wrap and placed back together, capped on each end, and taped.

To calculate compaction, the inner measurement and outer measurements made in the field are subtracted from one another and the difference, divided by the total core length minus the outer field measurements, calculating the amount of compaction per centimeter present within the core (Table 1). If material was removed prior to coring, this was subtracted from the inner field measurement before calculating compaction. These compaction factors were used to calculate the actual subsurface depths of each bed identified in the core (Appendix 2).

4.2 Organic Content

Four vibracores were analyzed for organic content using LacCore standard organic content loss on ignition (LOI) procedure (Myrobo et al., 2013). Samples were collected at 10cm intervals down the length of the cores (VCS2, VCS6, VCEI2, VCEI3), starting stratigraphically below the peat (almost 100% organic) sections. Crucibles were cleaned with deionized (DI) water and left to dry overnight in a 150°C oven. The crucible dry weight was measured, and then a wet sample from the core was placed in the crucible. The crucible was weighed again, and then left in a 100°C oven overnight. The samples were then weighed for pore water percent. They were then placed in a 550°C oven, held at temperature for four hours, and then cooled in the oven. The samples were weighted again to calculate organic content percent. Organic content was calculated using $\text{organic content} = \frac{(\text{dry sample weight}) - (\text{final post-550 weight})}{\text{dry sample weight}} * 100$ to get a percentage organic content.

4.3 Particle size analysis

4.3.1 Fine grained fraction, <0.5mm

Grain size distribution was measured on the WWU Geology Department Malvern Mastersizer instrument. Samples within cores VCS2, VCS6, VCEI2 and VCEI3 in were analyzed in 3-15cm sections within each stratigraphic unit present.

To prepare sediments for analysis, extensive pre-treatment was involved to remove organics and biogenic silica (diatoms). LacCore standard operating procedure (SOP) (Triplett and Heck, 2013) and SOPs from previous users of the Mastersizer were used as a reference for how to complete these pretreatments. Samples were digested for organics using 35% hydrogen peroxide and a warm sonicating bath. The samples were then left to complete digestion for 4 or more days under a fume hood. Samples were centrifuged and decanted several times with new DI water additions each time to dilute the hydrogen peroxide until very dilute. Samples were treated next with 1M sodium hydroxide to remove biogenic silica, using a warm sonicating bath. The reaction was halted with hydrochloric acid, and samples were centrifuged and rinsed several times till dilute. Samples were filled with DI water and fixed with sodium hexaphosphate dispersant to prevent clay flocculation prior to and during analysis.

Samples were run using a Fraunhofer model SOP (“Mastersizer 2000 User Manual MAN0384 Issue 1.0,” 2007) taking three measurements from an aliquot ranging between 1-50mL. The pots were mixed for 20 seconds, and treated with pre-measurement ultrasonic for 10 seconds to reduce flocculation of clays. Results are an average of the three measurements, and used to determine a grain size distribution within a section of stratigraphy.

4.3.2 Median grain size >0.5mm

For samples which are dominantly sand and gravels, the Mastersizer is not appropriate as it cannot accurately measure any materials greater than 0.5mm in diameter. Settling tests were instead used as a simple way to accurately measure the percent of sand, silt and clay within a deposit. The soil settling procedure from the University of California, Agriculture and Natural Resources was used (“Sedimentation Test of Soil Texture”), which bases the sediment size fall

velocities on Stokes law related to the size and Reynolds number of spherical particles in a slurry (Howard, 1983; Zhiyao et al., 2008).

Approximately 6-10 cubic cm of material were used for each settling test, sampled from core intervals that could not be analyzed using the Mastersizer, except those comprised of mostly organics. Materials were placed in a 6oz container, filled with 180mL of water, shaken, and left to settle for 24 hours. The total thickness of settled sediment was measured, then container shaken again. A ruler was used to measure the thickness to .5mm precision. After 30 seconds of settling, the sand measurement is taken. After 30 minutes, the depth of silt was measured. The containers were then shaken a last time, and left to settle for another 24 hours. This give the clay measurement height. These measurements were subtracted from one another to produce percentages of sand, silt and clay, and a USDA soil triangle was used to estimate the sediment soil types present.

4.4 ^{14}C radiometric dating subsampling

One core from each site with interpretable stratigraphy and present sand sheet(s) was chosen for ^{14}C dating. Because of the clear presence of a potential tsunami-related deposit at Ship Harbor, dating was primarily focused on this site.

For Ship Harbor, eight detrital plant macrofossils where selected from core VCS2: 61.8cm and 12.85cm above, 41.2cm and 68.3cm below, and four from within the sand-sheet between 230.7-254.5cm corrected depth (156.5-175cm compacted depth) (Table 2), further labeled as Ship Harbor bed 1, or sand-sheet SHb1. This deposit contains shells, abundant sand, with an organic-rich section approximately 10cm thick at the top (from 156-166cm compacted depth, Figure 5). This organic rich debris layer is referred to in notes as the “trash layer”.

Samples were prepared for analysis at WWU by rinsing each sample with DI water and leaving to air dry within glass vials with caps set on top to prevent dust contamination, and left under a heat lamp for 3-5 days. Samples were examined under a dissecting microscope and cleaned with tweezers to remove unwanted organics, sand, mud, and surface debris. The samples were weighed to ensure a minimum 1mg sample weights, and sent to Woods Hole Oceanographic Institute, NOSAMS for analysis.

OxCal was used to calibrate the radiocarbon dates reported from NOSAMS for cores VCS2 and VCEI2. An age range for sand-sheets SHb1 and E1b2 was calculated by placing radiocarbon dates into OxCal sequence model, which makes no assumptions about relative stratigraphic depth within a single bed assumed to be deposited as a single event.

4.5 AMS analysis

After the initial split of the vibracores, oriented samples were collected for magnetic studies. Ten cubic centimeter sample cylinders were used to collect magnetics samples at 5cm intervals. If collecting at such an interval was not possible due to the presence of large gravels, organic fragments, or signs of alteration or oxidation, samples were collected in alternate locations close by.

A KYL3-S Kappabridge Susceptometer was used with a rotating arm sample holder. The Kappabridge produces a low intensity magnetic field, and measures the response of the induced magnetization of the sample. The arm spins the sample in 360 degrees in three orthogonal positions and measures to determine the strongest signal direction. AMS measures the induced magnetization of the entire sample, paramagnetic, diamagnetic, and ferromagnetic constituents, to determine the bulk magnetic orientation of grains. Empty holders and background noise were measured prior to each analysis to ensure no major source of error were present.

4.6 Rock Magnetism Experiments

Three types of rock magnetism experiments were performed: hysteresis loops, isothermal remnant magnetization (IRM) backfield measurements, and temperature vs susceptibility (high and low), to determine the magnetic constituents present throughout the cores at each site. Magnetic mineral constituents are important to identify prior to paleosecular variation dating to determine ability to complete demagnetization using alternating field (AF) demagnetization and the steps necessary during demagnetization.

4.6.1 Hysteresis

Hysteresis experiments measure the remnant and saturation magnetizations and the coercivity values of an unoriented portion of sample (Tauxe, 2018). This analysis used a Princeton Magnetics 4500 vibrating sample magnetometer (VSM) capable of producing a field up to 2.2 Tesla (T). Hysteresis experiments were made using a peak field of 1.0 T, and between 50-60 field steps. The hysteresis data were corrected for high-field slope (due to the paramagnetic and diamagnetic phases in the sample) before determination of saturation moment (M_s), saturated remnant moment (M_r), and coercivity (H_c), and these results were mass-normalized to determine magnetization values for M_s and M_r . These variables reveal the types of magnetic minerals present and the field steps of AF demagnetization necessary to demagnetize the sample.

To prepare samples for hysteresis and IRM, a small portion of sample weighed and placed in a gelatin capsule and compressed to be used in the VSM. Samples were prepped for all depths in the cores where AMS samples were collected.

4.6.2 Isothermal Remnant Magnetization (IRM)

IRM is a measurement of the magnetization of a sample during increased step-wise field, but immediately after exposure to the field while the field is off. IRM measures the remanence of the ferromagnetic constituents, including those with short relaxation times. As the sample is exposed to a higher field, it will reach saturation if the coercivity is low (Tauxe, 2018). The field is then switched in direction starting from zero field, and the back field is measured. The backfield provides information about the coercivity of remanence of the sample (H_{cr}), providing further insight into the type and size of the magnetic minerals present, which can affect the demagnetization process during paleo secular variation dating (Tauxe, 2018). IRM is completed using the same sample prepped for hysteresis, and a demagnetization of the sample is completed before IRM if the sample was previously measured for hysteresis with the VSM.

4.6.3 Temperature vs Susceptibility

The KLY-3 Kappabridge was used to measure the temperature vs susceptibility curve for key samples, representing the different overarching stratigraphic units, from cores VCS2, VCS6, VCEI2 and VCEI3. To prepare samples for temperature vs susceptibility, samples were dried in a 100°C oven overnight, crushed with a mortar and pestle and weighed. The powdered sample is placed in a glass tube, inserted with a temperature probe, and set into a specific attachment for the Kappabridge. The empty holder was measured, and the curve produced is smoothed and applied as a background noise correction for the temperature vs susceptibility curve, to account for noise from the sample holder. The data for high and low temperature samples was bulk susceptibility normalized for analysis.

Low temperature vs susceptibility measurements were taken for key samples from VCS2 and VCEI2. Liquid nitrogen is used to cool the sample to -174°C, and measured over time as the

sample warms to room temperature. Low temperature experiments provide information about the strength of the paramagnetic constituent(s) present, to justify the use of an automatic correction for the paramagnetic constituents in the hysteresis loop correction. If a strong paramagnetic signature is not present, a hysteresis correction may not be the correct course of action, as the lack of saturation than is caused by the magnetic minerals present instead of the paramagnetic constituents.

High temperature vs susceptibility is diagnostic of the ferromagnetic minerals in the sample, providing information about the necessary steps for demagnetization during paleo secular variation dating data collection. As a sample is heated, the ferromagnetic constituents will continue to maintain a consistent susceptibility until reaching the Curie temperature, where susceptibility decreases drastically. The Curie temperature is characteristic of the ferromagnetic constituents present within a sample. The sample tube is connected to Argon gas, which creates an Argon atmosphere to minimize oxidation and mineral neoformation during heating. The sample is incrementally heated to 700°C and then incrementally cooled using DI water surrounding the tube. Measurements are conducted at a regular interval through the entire process.

4.7 Paleosecular variation dating (PSV)

To determine the orientation of the geomagnetic field recorded by these sediments, each sample that was collected for AMS from cores VCS2 and VCEI2 was then was demagnetized in steps and measured to observe the demagnetization behavior. Alternating field (AF) demagnetization was performed in 6 or more steps, up to 60mT or greater (up to 200mT), in three orthogonal positions. Samples were measured between demagnetization steps using the 2G DC-SQUID Magnetometer. AF demagnetization was performed in three positions, in the same

order each time: +XYZ. This was done for all samples from VCS2 and for all but six samples from VCEI2 which were demagnetized in a set of 6 different orders to limit potential bias from the AF demagnetizer: +XYZ, +YZX, +ZXY, -XYZ, -YZX, -ZXY. Notable differences in the data results are not observed between these methods.

A pilot study was completed for VCS2 and VCEI2 to understand the response to demagnetization of each unit present from the cores at each site. The pilot study focused on areas that are clay rich, sand rich and gravel rich to differentiate the behaviors within the overarching stratigraphic units and observe viability of PSV dating. Samples were kept in a shielded room during demagnetization to prevent an overprint of magnetization from the Earth's magnetic field.

4.8 GeoCLAW Tsunami Modeling for Ship Harbor and Eliza Island

Since no CSZ megathrusts earthquakes have occurred in the modern, instrumented era, it is difficult to determine source parameters of characteristic CSZ megathrust events. Tsunami inundation models are used to assess the likelihood of any sandy deposit being the product of a CSZ earthquake tsunami. The rupture parameters produced in Witter et al. (2013) are some of the most recent set of potential earthquake parameters to apply to tsunami models. GeoCLAW was used to run some basic tsunami wave height models using Witter et al. (2013) L1, L2, M1, M2 and SM1 earthquake scenarios, and the Seattle Fault earthquake scenario at mean sea level. This differs from the L1 model plots produced from Gica and Arcas (2016) and Eungard et al. (2018) which are based on mean higher high water (MHHW). Models were run using ClawPack 5.4.1 run on Linux through an Ubuntu virtual machine.

Slip parameters used as inputs are from the Witter et al. (2013). Peak slip is assumed at 42.94° latitude. L1 assumes splay faulting, with 22m of peak slip, 5.8m maximum offshore uplift, 3.5m of offshore subsidence. L2 assumes shallow faulting producing 21.8m peak slip,

4.9m max offshore uplift and 3.3m maximum offshore subsidence. M1 assumes splay faulting with 14.4m peak slip, 3.8m max offshore uplift and 2.4m maximum offshore subsidence. SM1 assumes splay faulting with 9.5m peak slip, 2.6m max offshore uplift, and 1.6m max offshore subsidence.

GeoCLAW outputs are produced as time frame images and predicted total water level change. Each model scenario was run by defining locations for outputs of the model, such as water level and wave height, based on latitude and longitude observation points placed along the near-shore. For Ship Harbor, a single point measurement location was placed in front of the marsh, while for Eliza a tide gauge was placed in the bays to the North and South of the island to observe spatial differences in the change of water height as the simulated tsunami moved into Bellingham Bay on either side of the island. Mean sea level is used in these model scenarios, so tides are not considered for the basic model outputs. Open source bathymetry and topographic data was used as a base parameter for all models, with the coarser resolution being used for earlier time intervals, prior to tsunami propagation into areas of interest using etopo1, and the finer resolution after about 1.5 hours of run time being porttownsend_nadv88_2011 available at <https://catalog.data.gov/dataset/port-townsend-washington-coastal-digital-elevation-model>. Six levels of resolution were chosen for different time intervals, with each step producing 18 frames for a total of 7 hours, with the first hour being modeled at the coarsest resolution, since tsunami arrival at the field sites of interest does not happen in this initial first hour. Subsequent steps are run with the higher resolution topography to monitor land-fall of the tsunami and to better resolve the spatial extent of inundation.

Tidal variability in the Puget Sound can be quite large, on the magnitude of 0.5-3m daily variations, according to the harmonic tide gauge positioned by NOAA Co-ops at Port Townsend,

and secondary (temporary) gauges positioned around Anacortes. Models of the L1 and M1 scenarios were run to determine the effect of tidal variation on inundation into Ship Harbor and Eliza Island. Initial sea level parameters are default set to mean sea level, then manipulated to +/- 1m increments to evaluate response to tidal variations. L1 scenario was run with a -1m and -2m tidal variation, while M1 was run with a +1m tidal variation. Each run produces outputs at specified time steps set in the modeling parameters, as well as plots of water height above the chosen sea level prior to arrival on land at designated observation points in the model.

V. Results

5.1 Sedimentary core results and particle size analysis results

Stratigraphic units were classified based on position within the stratigraphy of the core(s), grain size, color, texture, and presence of macroscopic features. Particle size analysis results were used to classify the dominant sediment or soil grain sizes present (Tables 3 and 4). Particle size, thickness of units and presence of shells/sand/gravels were used to correlate units between cores.

5.1.1 Particle Size analysis results

Both methods of particle size analysis produced a percentage of sand, silt and clay for each section of stratigraphy (Table 3 and 4). One result was omitted from VCEI2 due to a mechanical error during Mastersizer analysis (detachment of the feeder tube from the instrument arm to the prep tank), marked in yellow in Table 4. Homogeneity of the upper part of core VCEI2 suggests that this omitted sample, core VCEI2 depths 102-112, is similar to the section above and is also likely a silt loam.

Grain size distribution from the Mastersizer shows a bimodal distribution, with a mean peak distribution in the silt/clay/fine sand fraction and a smaller peak in the medium to coarse sand fraction. This secondary peak is due to diatom presence and is not representative of the overall grain size distribution. Smear slides confirm the presence of diatoms, typically between 25-50 micrometers in size within samples, indicating that there was an incomplete diatom digestion during preparation. This second, larger particle size peak is not considered in the overall particle size classification, as it does not represent the bulk of the sample.

5.1.2 Ship Harbor Data Assessment

There is a consistent stratigraphy to the western-most part of the marsh. The top of each core collected along transects T1a and T1b (Figure 3) consists of peat ranging from H1-H9 humification. The peat extends through the entire marsh and ranges from 60-120cm thick. On the west side of the marsh, the peat gradually transitions to grey-green clay-rich mud (Figure 5), with generally less than 5% of fine to very fine sand. The clay is stratigraphically extensive and thickens to the south (Figure 6). The mud is composed primarily of silt (~50-60%) and clay (~30-40%), suggesting a history of ponded water (lagoon) or intertidal marsh. Thickening of subsurface mud southward suggests long-standing ponded water at the land-ward extent of the marsh, similar to present-day conditions.

The northern most part of the marsh surveyed in this study has a uniform stratigraphy both north and south of the railroad berm, well represented by core VCS3 (Appendix 2). The top 80cm consist of peat, above clay-rich mud around 42cm thick (Figure 6). Below the peat and mud is a thick section of sand and gravels from 145.1cm to 225.6cm depth. Stratigraphically below 225.6cm depth is a 33cm thick mud to 258.9cm depth. From 258.9 to the bottom is sand.

It is unclear if the bottom sand here is discrete, or extends further down, as there are no data collected from lower depths.

One well-defined sand-sheet SHb1, is present though the western edge of the marsh, thinning inland and primarily composed of sand, with a lateral extent of 50+m (Table 5, Figures 5 and 6). The sand-sheet is first detected closest to the beach as a discrete unit in gouge auger core S13 (Figure 3) as a clear stratigraphic unit, 26cm thick between 233-259cm depth within mud, and is traceable south in cores VCS2 (Figure 5), VCS6 and VCS4 (Figure 6), as well as gouge auger cores that reach a depth of at least 2.5m. The sand commonly contains shell fragments, with core VCS2 containing a whole mollusk shell, and a few conular mollusk shells (Figure 5 and 7). Sand-sheet SHb1 in core VCS2, from depths 230.7-254.5cm is a massive sand bed containing 40% fine sand, 10% shell fragments and coarse sand, 20% organics (concentrated into the top 10cm of the deposit) and 40% silt-rich mud, with an abrupt lower contact (Figure 5). Particle size analysis reveals that the mud in units above and below sand-sheet SHb1 contains 4-5% fine sand in silt and clay (Table 3).

Moving south along transect T1a and T1b (Figure 3), VCS6 contains sand-sheet SHb1 from 214.5-234.0cm, as a discrete bed with graded sand and organics present, containing 55% sand, between silt loam beds containing 3.5-5.8% sand (Table 3). To collect core VCS6, 45.7cm of material was first removed from the top of the marsh, necessary for the vibracoring process to be successful. The difference in stratigraphic depth between the position of sand-sheet SHb1 in cores VCS2 and VCS6 could be due to the variation of the amount of peat and modern rooting systems of the marsh plants; the difference in stratigraphic depth could also be due to paleotopography differences, with VCS6 being ~15m closer to the edge of the marsh.

Identification of the conular shells from within the VCS2 (Figure 7) appears to be *Neostylidium eschrichtii* or *Lirobittium attenuatum*, both within the *Cerithiidae* family and *Bittinae* subfamily, due to the number of shell grooves, tiers, smoothness, color, and size. Both gastropods have been found along Anacortes beaches by the Pacific Northwest Shell Club (“Pacific Northwest Marine Mollucan Biodiversity,” 2019). Though uncommon, they are present in the Pacific Northwest and Puget Sound, and have been seen on recent beaches near Ship Harbor (“Pacific Northwest Marine Mollucan Biodiversity,” 2019). Both organisms live in intertidal and subtidal waters up to 55m depth, but are commonly found under rocks and the shells are commonly inhabited by hermit crabs (“Pacific Northwest Marine Mollucan Biodiversity,” 2019). Intertidal mollusk shells suggest inundation from the beach or intertidal region as a potential source of deposition of SHb1.

At the most landward extent of sand-sheet SHb1 to the south, along transect T1b (Figure 3, Table 5), gouge auger core S33 contains shells in mud at the depth that correlates to sand-sheet SHb1, however, did not contain a higher sand percentage detectable in the field, indicating that it may or may not correlate with SHb1.

Correlation of sand-sheet SHb1 can potentially be extended north along transect T1a (Figure 3) through gouge auger cores S17, S18 and S19, and core VCS3 (Table 5), though gouge auger cores collected in this area end with unconsolidated and poor recovery, making correlation difficult. Gouge auger core S18, from 121-211cm and S19, from 186-245cm, contain a massive sand bed with abundant organics and an abrupt lower contact with sand-poor mud. This may correlate with the bed in core VCS3 from 145.1-225.6 cm, and potentially connect with sand-sheet SHb1 in gouge auger core S13 to the south (Figure 3). The sand units in gouge auger cores S18, S19 and core VCS3 (Figure 6) are significantly thicker than sand-sheet SHb1 in VCS2 and

start stratigraphically higher, but end at a similar depth. Presence of shell fragments, graded sand and gravels, stratigraphic depth, and an abrupt contact at the base, suggest that sand-sheet SHb1 could be the larger bed within these core VCS3, or at the base of the larger bed of from 197.4-225.6cm.

Interpreting stratigraphy eastward of VCS2 presents a challenge for several reasons. The stratigraphy to the east of VCS2, along transect T2 (Figure 3), through cores S29, S25, VCS5, S28, and S27 is more convoluted and difficult to correlate, due to the presence of sand and gravel beds that are not clearly stratigraphically continuous. Moving east from core VCS2, gouge auger core S29, closest to VCS2, contains peat and sand-poor mud overlaying sand from 241-261cm, with an unconsolidated return from 262-270cm and unconsolidated clay-rich material at the base. If there were difference in paleotopography this bed could be sand-sheet SHb1. Continuing east, S25 is more convoluted, as there was a loss of material within the barrel between 197-204 and 214-220. Gouge auger core S26 contains several beds of sand and organics, from 98-104.5, 114-139.5, and 167-176cm, with poor return beyond 176cm depth. The presence of a sand beds from 114-139.5 and 167-176cm could correlate to the higher sand percentage of core VCS2 between 151.4-168cm and 181.1-188.8cm respectively. Within core VCS5, a discrete sandy section from 170.1-190.6cm is followed by a section of mud from 190.6-197.4cm, above sand and gravels at the base (Figure 6). Due to similarities in stratigraphy, the section in core VCS5 from 170.1-190.6cm could correlate to sand-sheet SHb1, or to the sandier bed from 181.1-188.8 in VCS2, and an upper sandy bed from VCS5 from 151-155.8cm could correlate to the sandier bed in VCS2 from 151.4-168cm. The upper two beds described here may be laterally continuous to the east, suggesting the presence of more than one sand-sheet, though poor return on gouge auger pushes make this correlation less clear.

Gouge auger core S27, the easternmost point along transect T2, contains a graded sand bed directly below peat, similar to gouge auger core S26, starting at 87cm depth and extending to 104.5cm depth, followed by sand from 104cm downward, and 40% organics. Lack of return beyond 185cm depth makes it unclear if this bed is discrete or continues further. Other gouge auger pushes in the eastern portion of the marsh (S1-S4) consisted of peat directly above sand (Appendix 1).

5.1.3 Eliza Island Data Assessment:

South of the pond (Figure 4), stratigraphy of gouge auger and vibracores consists of peat between 60-72cm thick above silt loam, which dominates below the peat except in sand-rich sections between 155-188cm depth (Appendix 1 and 2). In stratigraphic sections rich in sand, the sediment type transitions from silt loam to a loam or sandy loam, and is further labeled sand-sheet EIb2 (Table 6). This lower sandy section appears to be laterally extensive across the marsh from the south extending to the north (Table 6). Below the silt-loam, there is a transition to a very light blue mud, high in clay content, which commonly made up the base of the gouge auger cores and vibracores.

On the north side of the pond, the top of the marsh is organic rich soil (such as in core VCEI3, Appendix 2) approximately 49cm thick. The topsoil contains 30-50% gravels, which made collecting vibracores and gouge auger pushes difficult in the field, limiting collection locations. Below the topsoil, the stratigraphy is dominated by silt loam, with sections of higher sand percentage being loam or sandy loam.

East of the pond, the stratigraphy furthest north (gouge auger core EI7, Figure 4) is similar to core VCEI3, consisting of topsoil from 0-30cm, followed by alternating sections of sand-poor mud and sandy loam, with abundant gravels throughout. An upper sand-sheet EIb1 is

detectable through this portion of the marsh (Table 6). Moving south, with gouge auger core EI24, the lower section of core consist of a light blue-grey clay. Gouge auger and vibracores show pockets of sand present throughout the marsh, consisting of angular well sorted coarse sand, white and black in color.

5.2 Organic Content

In reporting the organic content (Table 7 and Table 8) corrected depths are reported. For sections of stratigraphy between two organic content results, percentages were averaged to assume the organic content for the section (Table 7 and Table 8).

5.2.1 Results Ship Harbor

Organic content is consistent between cores VCS2 and VCS6. Both cores have a generally higher organic content at the top, where peat transitions to clay. Organic content within clay sections (~100-215cm and ~252-289cm) range from 10-14% organics (Table 7). Within sand and gravel dominated stratigraphic beds, organic content decreases to 2-9%. Just above sand-sheet SHb1 in core VCS2, the organic content increases to 22-23%. The increase is likely due to the organic-rich layer associated with the top of sand-sheet SHb1.

5.2.2 Results Eliza Island

Eliza Island cores VCEI2 and VCEI3, taken on opposite sides of the pond (Figure 4) range between 1-11.8% organics (Table 8). In core VCEI2 there is a high percentage of organics at 171.7cm, similar to the base depth of the laterally extensive sand-sheet EIb2. Organic content increases in VCEI3 around 114.1cm depth, which does not correlate to either sand-sheet EIb1 or EIb2.

5.3 C¹⁴ dating

Because wood can persist in an environment and may be older than a deposit it is found in, and all samples selected were wood and plant macrofossils, all samples likely represent maximum ages.

5.3.1 Ship Harbor Results

Materials were selected to constrain the age of sand-sheet SHb1 within core VCS2. Four samples were dated from sand-sheet SHb1: three dates are from the organic-rich layer of wood and sticks at the top of sand-sheet SHb1 and one 20cm lower, from within the sand-rich section of the deposit (Figure 5). Stratigraphically, the reported dates vary sequentially with respect to depth in the cores (Tables 9). Within the organic-rich top of sand-sheet SHb1, a variation of about 600 years between dates from samples stratigraphically close to one another suggest that older material was likely transported with younger material during deposition. Four dates, two above and two below sand-sheet SHb1, were selected to better constrain the age of the bed within the core. Dates predict the age of sand-sheet SHb1 to be 1802-1730 cal. yrs BP (Table 10).

5.3.2 Eliza Island

For Eliza Island, VCEI2 has a single bed, EIb2, which consist of graded sand overlaying an organic-rich section (Appendix 2). Dates from VCEI2 were much older than expected (Table 9 and 11), with the youngest date at 143.1cm depth being 4248 years B.P., and the oldest calibrated date for the bottom (176.2cm) of the core ranging between 5274-4980 years B.P. (Table 11). The sequence model results suggest that the date of EIb2 ranges between 4820-4669 cal. years BP (Table 11).

5.4 AMS analysis

Magnetic fabrics are coaxial to sedimentary fabrics, as commonly in sedimentary minerals crystal habit and grain shape determine the maximum, intermediate and minimum susceptibility axes (long grain axis commonly is parallel to $K_{\max}$, short-axis or basal-plane of phyllosilicates is parallel to $K_{\min}$). Susceptibility values of the mean tensors can be compared to determine the dominate fabric type present within a deposit. Triaxial fabrics typically represent fabrics with three distinct axes orientations for $K_{\max}$, K_{int} , and $K_{\min}$, with $K_{\max}$ having the strongest susceptibility, K_{int} having the second strongest, and $K_{\min}$ the weakest. Prolate fabrics have a high susceptibility in the $K_{\max}$ direction with susceptibilities along the K_{int} and $K_{\min}$ axes being similar (making them more difficult to distinguish from one another, and producing a higher error along those axes during measurement). Oblate fabrics have similar susceptibilities in the $K_{\max}$ and K_{int} directions, with lower susceptibility of the $K_{\min}$ typically perpendicular to the settling surface produced when material settles out of suspension. Mean susceptibility axes, or mean tensors, are reported as declinations and inclinations, and represent the mean orientation of each axis within the grains, corrected for the geographic orientation of the sample in space. Errors recorded from the AMS data provided initial insight into the strength of the fabric during analysis, and were used to determine data accuracy during analysis (Tables 12 and 13).

AMS results were grouped by stratigraphy, so an overall fabric could be determined for each unit present, and reported as both equal angle stereonet projections of the $K_{\max}$, K_{int} and $K_{\min}$ (Figure 8a-d) and as mean tensors (Tables 14 and 15). Anisoft (AGICO) was used to calculate parameters related to the AMS ellipsoid shape: lineation (L , $K_{\max}/K_{\text{int}}$), foliation (F , $K_{\text{int}}/K_{\min}$), corrected degree of anisotropy (P_j) relating to the strength of the magnetic fabric, and

shape parameter T ($0 < T < 1$ the fabric is oblate and dominated by settling, $-1 < T < 0$ than the fabric is prolate and dominated by traction or flow) (Table 16).

5.4.1 Ship Harbor AMS results

Ship harbor AMS results from core VCS2 and VCS6 are grouped for analysis by stratigraphic designations of peat, sand-poor silt loam (Clay Upper and Clay Lower, upper for above SHb1 and lower for below SHb1), sand-sheet SHb1, and basal gravel/sand in Figure 8a-b. Sample locations are displayed in Figure 8e and 8f. Combined results from sand-sheet SHb1 are presented to analyze if a flow regime is detectable. Clay-rich beds above and below sand-sheet SHb1 are grouped together, as they are interpreted to be the same paleoenvironment pre and post sand-sheet SHb1 deposition.

AMS parameters of lineation ($1.00 < L < 1.04$), foliation ($1.002 < F < 1.08$), corrected degree of anisotropy ($1.02 < P_j < 1.11$), and alignment parameter ($-0.7 < T < 0.94$) vary vertically within the core and between stratigraphic designations, but also have some variability within stratigraphic sections. The L , F and T values suggest that there are both prolate and oblate fabrics present within the stratigraphy, with sand-poor silt loam sections being generally oblate ($T > 0$) and peat and sand-sheet SHb1 sections being generally prolate ($T < 0$). A generally high L value, around one, suggests the sand sheet SHb1 has a triaxial fabric.

Low L values and poor grouping of the K_{int} and K_{max} (Figure 8a and Figure 8b), suggest a weak depositional fabric within the peat sections. The values for the peat sections should be questioned, as there is high error ($\sim 100\%$) recorded for these samples (Table 12) suggesting that no real fabric is detectable.

Within the sand-poor silt-loam sections above and below sand-sheet SHb1 (Figure 8a and 8b), K_{mins} , with a few exceptions, have low imbrication between 0-20 degrees, and distribution of

$K_{\max}$ and K_{int} with variable declinations and low inclination angles generally between 0-20 degrees (Figure 8a and 8b). When grouped, the silt loam sections produce an oblate fabric, with a grouping of K_{mins} at 90 degrees inclination, suggesting that these samples have mostly likely formed as a depositional fabric. The T values for these samples are generally between 0 and 1, however several samples are between 0 and -1. Most T values are positive, suggesting an oblate fabric.

Sand-sheet SHb1, in both cores, presents as a commonly triaxial fabric when plotted on a Flinn diagram (Figure 8g), with some samples plotting as more oblate or prolate. Three samples fall near the 1:1 line on the Flinn diagram, suggesting that there are some strongly triaxial samples from within sand-sheet SHb1. Seven of the thirteen samples from VCS2 and VCS6 identified as being from sand-sheet SHb1 have T values between -1 and 0, suggesting that more than half the samples present a prolate fabric, meaning likely deposition from flow. Combined result for sand-sheet SHb1 (Figure 8h) produced a general grouping of K_{mins} with imbrication between 0-30 degrees, with some outliers.

The lower section of sand-sheet SHb1 in core VCS2 (samples 174, 172.5, 168.5, and 166) shows varied K_{mins} with high imbrication angles (Figure 8h). Above these, sample 163.5 shows ~35 degrees of imbrication in the southern direction. The top of sand-sheet SHb1 in core VCS2 shows almost 0 degrees imbrication.

Samples from sand-sheet SHb1 in VCS6 (samples 168.8, 167, 161.8) show 0-20 degrees imbrication in the northern direction (Figure 8b and 8h). Above these, samples 163s, 161s, 160s and 157s have high imbrication angles between 30-50 degrees but not in any one direction.

5.4.2 AMS mean tensor results Eliza Island

VCEI2 and VCEI3 were grouped into different stratigraphic sections similar as for Ship Harbor: soil/peat, clay-rich sand-poor sections (green) and sand-sheet deposits (blue) (Figure 8a-d). The peat in VCEI2 had a very high error, between 29-500%, suggesting very weak anisotropy. Mean tensors for each stratigraphic unit was calculated (Table 15).

Clay-rich section $K_{\min}$ have imbrication from 0-25 degrees (Figure 8c and 8d). $K_{\max}$ and K_{int} declinations are variable, and have low inclinations (Figure 8c and 8d), forming an oblate fabric. An oblate fabric is supported by the T values which are generally higher than 0 (Table 16). Both cores sampled were collected close to the pond, in areas that are seasonally ponded, depositing material from suspension, supported by the dominantly oblate fabric.

AMS results from sand-sheet EIb2 from cores VCEI2 and VCEI3 show a grouping of $K_{\min}$ approximately around the origin, but varying in imbrication from 5-20 degrees, with a few outliers having imbrication ~ 50 degrees. Combined results from sand-sheet EIb2 (Table 15) $K_{\max}$ directions appear to be well grouped to the Southwest, between 200-270 degrees. EIb2 in VCEI2 generally has T values greater than 0, however, in VCEI3, the T values are generally less than zero. Core VCEI2 has clear normal grading at the top of sand-sheet EIb2, however normal grading is not visually present within core VCEI3 for the sand-sheet.

5.5 Rock Magnetism Results

5.5.1 Bulk Susceptibility

5.5.1.1 Ship Harbor

Cores VCS2 and VCS6 have similar susceptibility values from $-9.82\text{E-}06$ to $7.05\text{E-}04$ throughout (Figure 9a, Table 17). Peat sections have very low, close to zero, susceptibility. At the transition to clay, there is an increase in susceptibility to $\sim 0.25\text{E-}04$. This is consistent until

sand-sheet SHb1, where susceptibility increase to $\sim 2.0\text{E-}04$ in both cores. At the base of VCS2 the susceptibility increases rapidly in the basal section of gravels. Core VCS6 does not have an increase in susceptibility towards the bottom extent, but is also missing the lower basal gravels layer.

5.5.1.2 Eliza Island

Cores VCEI2 and VCEI3 vary in bulk susceptibility by a factor of 10 (Table 18, Figure 9b), ranging from close to zero to $2.0\text{E-}03$. Bulk susceptibility for both cores increases from $\sim 0.5\text{E-}04$ to $2.0\text{E-}04$ between 110-120cm depth, and around 150cm depth to $2.0\text{E-}04$, near the top of Elb2. VCEI3 has a generally very low susceptibility, between 73-175cm, increasing around 175cm depth up to $2\text{E-}03$.

5.5.2 Hysteresis

The corrected H_c value for each sample is important when demagnetizing samples for PSV dating. Corrected hysteresis loops show low coercivity and saturation within a 1T field (Figure 10). Corrected coercivity values from both field sites are generally low, typically less than 150mT, but for most samples less than 60mT (Table 17 and 18). The low coercivity suggests that the main magnetic constituent is magnetite at both field sites (Tauxe, 2018). The presence of magnetite is also confirmed by the temperature vs susceptibility experiments completed. Hysteresis loops from core VCS2 contain a fairly high level of error, likely due to presence of water within the samples.

5.5.3 IRM

IRM was completed on select samples, and at least one sample from each stratigraphic unit was measured for the four cores VCS2, VCS6, VCEI2 and VCEI3. The IRM was saturated for all samples measured (Figure 11, Tables 17 and 18), suggesting that the samples have a

saturation magnetization below 1T, which is the maximum field applied in the IRM experiments. Saturation during IRM determines the magnetic saturation value (M_s), which helps identify the type and size of the magnetic minerals present. The IRM saturation and coercivity values further suggest that magnetite, which has a very low coercivity typically between 30-120mT (but up to 300mT), is the main ferromagnetic constituent for both Ship Harbor and Eliza Island (Tauxe, 2018).

5.5.4 Temperature vs Susceptibility

Two to three samples from representative deposits were selected from cores VCS2, VCS6, VCEI2, and VCEI3 each to measure the Curie temperature. Samples from cores VCS2 and VCEI2 were selected to complete low temperature susceptibility experiments, as these cores were the focus for PSV dating.

All samples, except VCEI2n at 80cm show a Curie temperature ranging from 550-600°C (Figure 12, Table 19). The 80cm sample for VCEI2 has an ambiguous result, as there is a very weak signal. A Curie temperature between 550-600°C suggests the main magnetic constituent is magnetite for both field sites (Tauxe, 2018). This corroborates the IRM and hysteresis data.

Low temperature vs susceptibility experiments show a dramatic decrease in susceptibility between -200 and -170 °C (Figure 13). This dramatic decrease is related to increase in susceptibility of paramagnetic constituents at low temperatures. The decrease suggests that there are strong paramagnetic constituents present in cores from both sites, and that a paramagnetic correction can acceptably be made for hysteresis data.

5.6 Paleosecular variation dating results

PSV dating was performed with the intention of refining the age sequence models produced from ^{14}C dates to better constrain the dates for sand-sheets SHb1 and Elb2. Examples

of demagnetization Zijderveld diagrams are displayed in Figure 14. Reported declinations, inclinations, and ^{14}C dates were all used to match declinations and inclinations reported from demagnetization data (Tables 20 and 21) with the PSV curves from Hagstrum and Champion (2002) (Figure 15). The regional reference curve was calculated from the latitude and longitude of the field sites using the highest quality data with the lowest error from volcanic flows in the western US, reported as years before 2000A.D. (Hagstrum et al., 2004). For Eliza Island, the dates from Hagstrum et al. (2004) were supplemented with later dates and virtual geomagnetic poles (VGPs) from Hagstrum et al. (2002) to create a longer predicted record (Figure 16). The virtual geomagnetic poles (VGPs) reported were converted to expected declinations and inclinations for each field site using Butler (1992) equations for the expected magnetic field direction (Appendix 4). Alpha 95% confidence envelopes were calculated equations from Butler (1992) for calculating the 95% confidence envelopes (Appendix 4), labeled delta-I and delta-D for inclination and declination respectively. Puget Sound tsunami buried soil VGPs from Hagstrum et al. (2004) were also converted to inclinations and declinations for both field site latitudes and longitudes, to directly compare to the regional reference curve and field data in this study. Date ranges for each sample were estimated using an OxCal sequence model for each site, with error bars to represent the range of dates reported along the y-axis and the mean absolute deviation (MAD) reported for each component as the error along the x-axis (Figures 15 and 16). Because OxCal reports dates as years B.P. using the datum of 1950, estimated ages had 50 years added to them to match the PSV dates reported as years before 2000B.C. Samples which intersect the PSV expected curve were used to estimate dates for those core locations, based on inclination or declination of the sample.

5.6.1 Ship Harbor

Sample results show vertical variability in declinations and inclinations of the primary components throughout the cores (Table 20). Each sample is estimated to represent ~50 years of deposition, based on calculated rates of deposition (~.15 cm/year) and rates of compaction for the vibracores (Table 1), so each sample was treated as a single PSV component.

Samples are plotted in Figure 15 with the Hagstrum (2004) soil samples and the Hagstrum (2002) PSV calculated curve. Six samples intersect with the declination or inclination PSV expected curve, all within the upper clay unit above sand-sheet SHb1.

To account for inclination shallowing from vibracore compaction in core VCS2, an inclination correction was done, using equation 1 from (Tauxe et al., 2008): $\tan(I_r) = (1/f)\tan(I_0)$ where I_r is corrected inclination, f is the flattening factor for magnetite, and I_0 is the sampled inclination.

5.6.2 Eliza Island

Results show vertical variability in declinations and inclinations of the primary components throughout the cores. Table 21 reports declinations and inclinations calculated. Figure 16 shows that of the samples plotted, five intersect with the PSV declination or inclination curves.

Some issues with demagnetization data arose during the demagnetization process within the lower section of VCEI2. Demagnetization plots (Figure 14) show a curving of the component away from the origin for VCEI2 reference depth: 152cm. Work by Snowball (1997) suggests that this effect could be due to the presence of greigite or another sulfide mineral gaining a gyroremanent magnetization from the AF demagnetization process, creating a secondary component. However, the H_c values for these samples are not higher than others, which

contradicts the potential for sulfide minerals, which should have a higher Hc value (Tauxe, 2018). Due to the odd demagnetization behavior and potential for sulfides, these results have been omitted from the PSV dating analysis for this site.

5.7 GeoCLAW Modeling results

The L1 scenario (Table 22), the largest earthquake scenario considered in this study, predicts an increase in water height above mean sea level greater than 4m at the tide gauge in front of Ship Harbor, and almost 2m at the tide gauges placed near Eliza Island (Figure 17). The L1 scenario produces the largest inland extent of inundation within Ship Harbor, up to 325m inland during the initial wave (Figure 17). L1 only inundates the outer sections of Eliza Island, varying greatly from the MHHW simulation produced from Walsh et al. (2004), Gica and Arcas (2016), and Eungard et al. (2018), which predicts inundation large enough to overtop the beach berm and inundate the central marsh and pond. Spatial variations in modeling could also be due to the use of a MHHW datum run in the models using MOST relative to MSL used with GeoCLAW, or from different assumptions of surface roughness and wave physics parameterized for modeling. An L2 scenario was also run, which predicts a 3m tidal gauge increase, and inundation into Ship Harbor less extensive than the L1, but still approximately half the lateral extent of the marsh (~150m), and no inundation into Eliza Island marsh.

The moderate M1 scenario (Table 22), considered the most statistically likely scenario (Witter et al., 2013), was modeled to compare to the L1 hazard planning models (Figure 18). At Ship Harbor, the M1 scenario predicts a maximum water level at the observation point just under 3m, producing inundation into the northern part of the marsh to at least 1m, with a lateral extent inland around 130m, and predicts several smaller waves through the 5 hours following the slip event and propagation into the Puget Sound (Figure 18). At Eliza Island, the M1 scenario

registered to 1.5m height at the tide gauges for the initial wave, as well as for a secondary wave just before hour 5. The M1 inundates outer parts of Eliza Island, but does not predict overtopping the beach berm or inundation of the central marsh and pond.

The M2 scenario (Table 22) was also run to look at differences between the two most statistically likely scenarios (Witter et al., 2013). M2 does not factor in splay faulting, and thus produces a smaller amount of sea floor displacement and inundation. M2 model results are summarized in Figure 19, and show a similar inundation as the M1 scenario, only varying in the water height change. The M2 scenario predicts just under 2m of water height change, and ~100m of lateral extent landward, at Ship Harbor, and just over 1.5m of change south of Eliza Island. Inundation at both locations is similar to M1, with just over a meter of inundation in the northern 100m of Ship Harbor marsh, and along outer sections of Eliza Island.

The small SM1 scenario (Table 22) is considered one of the most historically common scenarios according to Witter et al. (2013). This was important to consider, as it is one of the smaller potential scenarios for CSZ events. For Ship Harbor, the tide gauge registers just over 1.5m increase in water column height, producing up to 1m of inundation along the beach and northern-most extent of the marsh, with ~100m of landward extent (Figure 20). The SM1 predicts no inundation at Eliza Island.

A Seattle Fault scenario from Koshimura et al. (2002) was run to see what the effect of a well understood upper crustal fault would have for producing inundation for both field sites. Based on seismic reflection data, the Seattle Fault is interpreted as a south-dipping thrust fault, with a potential total rupture area of 4420km², and produces $M_w = 7.6$ to 7.7 earthquakes (Koshimura et al., 2002). The model separates the fault into 12 total segments varying in length and width, six along the upper steeper dipping section, and six below in the more gently dipping

fault zone. Total slip along each segment is predicted to be 2-8m total, with greater slip along the upper portion of the fault. Based on model results, minimal inundation is predicted for both Ship Harbor and Eliza Island (Figure 21). At Ship Harbor, the Seattle Fault scenario produces just more than a 20cm increase in the water column height, while Eliza Island only produces 10cm at the south observation point, and less than 10cm at the north observation point.

5.7.1 Tidal Variations on the L1 and M1 scenarios

The L1 run with -1.0m tide at the time of tsunami propagation (Figure 22) predicts a total increase in water level height of the first wave to 3.5m and a landward extent of inundation to 324m. This results in inundation of Ship Harbor marsh the entire extent of the marsh, with lingering water in the marsh for a number of hours after the initial wave (Figure 22). Model results for Eliza Island are similar to the M1 scenario results.

The L1 run with -2.0m low tide (Figure 23) predicts an increase of water height at the observation point at Ship Harbor for the first wave of 2.5m and inundation is limited to the northern 94m of Ship Harbor marsh. This appears to be similar to the mean sea level prediction for the M1 scenario.

The M1 was run with a high tide (+1m) variation (Figure 24), as it does not inundate the full extent of Ship Harbor marsh at mean sea level. With a +1m tide (Figure 24), the observation point at Ship Harbor predicts almost 4m of water height increase, and an inundation extent of 300m landward in Ship Harbor marsh. Eliza Island is still not effectively inundated.

VI. Discussion

6.1 Interpreting Ship Harbor Stratigraphy, AMS and Modeling

6.1.1 Stratigraphy

Ship harbor is a marsh primarily fed by fresh-water run-off and rain, with no modern tidal channels (Figure 3). The marsh consists of the beach barrier and central pond; the barrier beach extends E-W along the front of the marsh, protecting the entire extent of marsh from regular tidal or wave influences (Figures 1 and 3), and the marsh is seaward (north) of a pond, which likely formed in response to the sandy barrier beach. There are no large streams feeding into the marsh, so fluvial sediment supply is limited. Though the front of the marsh has been heavily impacted by human modification in the last 160 years, including ditching and drainage for building of a railroad berm, the marsh appears generally undisturbed in the subsurface, and this is reflected in the stratigraphy and ages from the cores that were collected (Figure 5).

Simplified stratigraphic sections (Figure 5 and 6 and Appendix 2) show that the stratigraphy of the back-marsh transitions from a gravel-rich sand at the base of 2.5-3m, grading upwards to silt loam, which gradually transitions into peat, marking a gradual infilling of Ship Harbor marsh over the late Holocene. The color of the mud and humification of peat, suggests a water-logged anoxic subsurface. The silt loam is thickest in the south above and below sand-sheet SHb1 and thins to the north both above and below sand-sheet SHb1 (Figure 25). The mud is occasionally interbedded with sand lenses, but is generally sand-poor, consisting mostly of massive silt loam. The silt loam is interpreted to be a low marsh or lagoon paleoenvironment due to lithology, texture, color, organic content, and current marsh conditions (Nichols, 2009). The modern marsh surface is dominated by peat formation, with minimal discernable sediment deposition occurring within the marsh today.

From stratigraphy (Figure 5, Figure 6, Figure 25a), lateral extent (Table 5, Figure 25a and 25b), and presence of intertidal mollusk shells (Figure 5 and Figure 7), sand-sheet SHb1 was likely created during inundation of ocean water. Sand-sheet SHb1 has a lateral extent of at least 50m south of VCS2 (Table 5), and potentially extends another 50+m north along transect T1a (Figure 25b and Figure 3). An organic rich layer of twigs and bark at the top of SHb1 is interpreted to be organic debris carried from the beach and front marsh and deposited during inundation. SHb1 contains shell fragments in cores VCS2, S14, S15, including half a bivalve mollusk shell, and multiple whole conular mollusk shells (Figures 5 and 7). The presence of intertidal mollusk shells further suggests that materials were transported during inundation from the intertidal or beach.

SHb1 is first clearly detected 200m south of the modern beach berm, with 50m lateral extent to the south (Table 5 and Figure 25a). A tsunami has the energy to drive water inland for several hundred or more meters when coastal topography is relatively flat, and as a consequence inland sediment transport distances can be 200+m. Storm waves typically limit sediment transport to a few hundred meters at most, ending abruptly, and have a higher degree of internal stratification and sets of mud laminae (Morton et al., 2007). Though both storms and tsunami processes theoretically can drive materials the distance of the marsh, it is unlikely with the beach barrier and lack of tidal channels that lateral extent of inundation into the marsh by storm waves would deposit this far into the marsh. Terrestrial fluvial origin of sand-sheet SHb1 can be ruled out due to lateral extent and land-ward thinning, and lack of fluvial sources into the marsh.

Presence of mollusk shells from intertidal areas, general thickness less than 26cm (potentially up to 90cm) and thinning landward (to the south), high percentage of sand, abrupt lower contact, massive and graded sand structures, and detectable extent of 50m but potentially

up to 100m, are all stratigraphic evidence that suggest that sand-sheet SHb1 is likely the result of tsunamigenic inundation in Ship Harbor marsh.

Sand-sheet SHb1 can possibly be correlated to the north along transect T1a (Figure 25b). Because maximum thicknesses reported for tsunami deposits globally is 1m, but typically most are less than 25cm thick (Morton et al., 2007), and the presence of intertidal mollusk shells, the whole bed from 145.1-225.6cm within core VCS3, and the similar-depth beds in gouge auger cores S18 and S19 could be correlated to sand-sheet SHb1. However, an alternative interpretation is that the large sand bed present in cores S18, S19 and VCS3 could be the remains of a historic barrier beach that was positioned further south in the marsh, located approximately in the location of VCS3. Lateral migration of the beach front to the north over time could account for this. However, this is unlikely, as lateral migration seaward is common with sea level fall, which has not occurred in the Puget Sound over the late Holocene, except by potential means of isostatic rebound. Even if this is true, sand-sheet SHb1 would still represent inundation into the marsh from the ocean, and require toppling of the paleo-beach berm and inundation to a lateral extent greater than 50m.

6.1.2 Peat accumulation in Ship Harbor marsh

Stratigraphy in Ship Harbor is covered with, on average, a meter of peat. 106cm of peat is present at the marsh surface at VCS2, and 127cm of peat has accumulated at VCS6. Peat accumulation is understood to occur at a maximum rate of 2mm/year globally (Borgmark, 2016), and in the Puget Sound is measured to be closer to 0.62mm/year (Kulzer et al., 2001). Even at 2mm/year, a meter of peat should represent ~500 years of accumulation. Based on the calibrated ¹⁴C dates, the difference in depth between samples VCS2n_RC28 and VCS2n_RC28 is 48.9cm, with a maximum age difference of 450 years, and a minimum age difference of 184 years. Based

on the ^{14}C dates, the sedimentation rate within the silt and clay dominated beds likely ranges between 0.11cm/year and 0.27cm/year, with an average of 0.19cm/year, or 1.9mm/year. ^{14}C dates indicate that at 168.2m depth the core is 1546-1414 cal. years B.P. Because ^{14}C dates are reported as years B.P. from the datum of 1950, this location in the core is likely closer to 1614-1482 years prior to the sampling date. Assuming 1.9mm/year of for 62.2cm of clay, and 2mm/year for 106cm of peat, the base of the peat should have started forming around 530 years ago, prior to the first western settlers arrived. The cause of a shift in the environment at Ship Harbor from a lagoon or low marsh environment to a peat marsh is unclear. Lateral migration of the front of the marsh could have occurred with sea level fall, or isostatic rebound (uplift).

6.1.3 AMS results

Sand-poor silt loam beds above and below SHb1 show an overall oblate fabric, representative of clays and silts settling out of suspension (Figures 8a and 8b). Most samples represented in this set have a T value above 0 (Table 16), supporting a dominantly oblate fabric. The oblate fabric and grain size distribution together support a low energy lagoon-like paleoenvironment, with clay and silts settling out of suspension. Oblate fabrics above and below sand-sheet SHb1 support that the environment was a calm depositional environment pre and post sand-sheet SHb1 deposition.

K_{max} and K_{mins} from sand-sheet SHb1 are highly varied, making a definitive flow regime difficult to interpret. Collision of grains can vary the K_{max} direction greatly, as the strength of flow and the amount of grain collisions that occur effect the alignment of the grain long-axis with flow (Taira and Masuda, 1989; Tauxe, 2018). K_{max} s are highly varied for samples throughout sand-sheet SHb1, but have some grouping oriented in the 90-degree plane or around the 0-degree plane. Flow direction of inundation, based on models and geography of the marsh,

is expected to be from the north/north-east direction, flowing toward south/south-west. If the run-up phase had a strong enough current, some sections of the bed could be aligned with flow from the north, while some are oriented to the east, perpendicular to flow, during collision or rolling. Core VCS2 shows $K_{\min}$ imbrication to the SW, suggesting a possible flow direction to the SW (Figure 8a). The projection of AMS data for sand-sheet SHb1 in core VCS6 shows a much clearer flow regime than core VCS2, with most samples from the north half of the core reporting a mean tensor of $K_{\max} \sim 108$ degrees, $K_{\text{int}} \sim 200$, and a $K_{\min}$ imbrication between 0-25 degrees (Table 14, Figure 8b). This could indicate a flow to the south, or a strong back-wash phase to the north. However conclusive flow direction cannot be made due to the scatter for the $K_{\max}$ and $K_{\min}$ s when data is combined from both cores by depth (Figure 8i). The massive bedding of sand-sheet SHb1, and lack of stratified bedding structures, supports viscous collisional flow as a sediment transport mechanism.

6.1.4 GeoCLAW modeling and potential of CSZ source for SHb1

The presence of a tsunami deposit in Ship Harbor marsh helps validate the L1 based models used for hazard planning, as the L1 model parameters predict enough inundation in Ship Harbor marsh to produce a tsunami deposit such as the one identified in this study.

Using models at Ship Harbor to predict future inundation may be more accurate than for past inundation predictions due to a shift in the environment and topography over the last few hundred years from human modification to northern extent of marsh. The current barrier beach berm is approximately 2.4m above sea level and the typical marsh elevation is less than 3m. GeoCLAW models of tsunami inundation predicted for the L1 and L2 earthquake scenarios easily overtop the beach berm and inundate the marsh to the full lateral extent of 325m (Figure 17). However, the smaller seismic scenarios with initial parameters at mean sea level, such as the

M1 and M2, do not (Figures 18 and 19). Current topographic data of the marsh includes the railroad berm, which is 3m above local surface elevation and could prevent future inundation from reaching the back part of the marsh. The modern railroad berm may act as a topographical barrier for modern models, and may cause an underprediction of inundation for the past, prior to the build of the railroad.

Tsunami inundation and impacts appear sensitive to water level from tidal changes and storm surge, made clear by the tidal variations of the L1 and M1 models. (Figures 22, 23, and 24). The L1 modeled at -2m low tide only inundates the most northern part of the marsh (Figure 23). The M1 with a +1m high tide does inundate the entire lateral extent of Ship Harbor marsh (Figure 24). These models suggest that typical tidal ranges in the Puget Sound (between 1-3m) can greatly affect the potential of tsunami inundation at Ship Harbor, and may explain why only one clear sand-sheet can be detected.

6.2 Interpreting Eliza Island marsh

6.2.1 Stratigraphy

The typical stratigraphy of Eliza Island, at the base consists of clay-rich blue mud, which has a sharp transition to lithic fragments, below a large bed of graded gravels and sands, followed by sand-poor grey-green mud, with soil or peat at the top (Appendix 2). Skagit county soil surveys labels the marsh as Sharlcar mud, which consists of deep, very poorly drained soil, formed in herbaceous deposits above alluvium and glaciofluvial deposits. The basal unit here could be interpreted to be part of glaciomarine drift plane soils formed during glacial retreat, but the origin is unclear.

Overall, Eliza Island stratigraphy suggests that there has been a shift in the environment sometime between 4500-6000 years ago and has been relatively steady since then. The modern

marsh environment has abundant gravels covering the floor of the pond and present in pond outcrop exposures, suggesting that gravels and sands can enter the marsh regularly from the beach, despite the large and extensive beach berms present. Anthropogenic sources may also be a reason for the presence of gravels and pebbles in the pond. Two sand sheets appear to be laterally extensive throughout the marsh (Figure 26), and from the grading of the sand and presence of gravels suggest deposition during ocean water inundation. EIb2, present in VCEI2 and VCEI3 between depths 142.5-174cm and 155.6-166.8cm respectively is not conclusively of tsunamigenic origin; however, because of lateral extent and presence, it is possible that the sand was deposited during inundation events.

6.2.2 AMS data Eliza Island

The sand-poor silt-loams from Eliza Island, according to the plots of Figure 8a and 8d, as well as the T values, suggest settling from suspension (Figure 8c and 8d, Table 16) and may suggest deposition in the pond adjacent to the cores collected.

T values larger than 0, and visual grading of EIb2 in VCEI2 suggests settling from suspension, which is supported by the generally oblate fabric in Figure 8c and 8d. The grouping of the K_{mins} in VCEI2 (Figure 8c) suggest that there is a lack of clear imbrication, and no clear fabric indicating flow. The generally oblate fabric suggests that sands and gravels were carried into the marsh and then deposited out of suspension.

6.2.3 GeoCLAW modeling and Eliza Island inundation potential

Tsunami modeling for Eliza Island makes it unclear if inundation from CSZ tsunamis can breach the beach berm and inundate the central marsh. Of all GeoCLAW models run, no models predict toppling of the beach berm, even the largest L1 scenario. However, though inundation predictions are high, future inundation could be prevented due to the large beach berm present on

the south and north sides of Eliza Island. Despite current height, the beach berm may not have been historically as tall. According to DTMs from Washington DNR, the south berm is 4.3m above mean sea level (based on the NAVD88 vertical datum), lowering on the north side to an average marsh elevation of 2.4m above sea level. On the north side of the marsh, the elevation of the beach berm is around 3.0m elevation. If these beach berms have been modified by human action, which field observations suggest, then these berms may not have always been as high, meaning the potential for inundation into the marsh may have been more likely in the past.

6.3 OxCal sequence modeling using PSV dates and C¹⁴ dates, other Paleotsunami deposits dated in the Puget Sound and potential sources for inundation other than the CSZ plate-boundary earthquakes.

Seven PSV dates from Ship Harbor and five PSV dates from Eliza Island, were used to compare to the calibrated ¹⁴C dates and were used as additional dates within the OxCal sequence model to predict a depositional age for SHb1 and EIb2 (Table 23a and 23b).

6.3.1 Ship Harbor

The OxCal sequence model with PSV dates incorporated reports a maximum age of SHb1 between 1804-1731 cal. years B.P. (Table 23a). Including supplemental dates from PSV analysis does not considerably change the dates of sand-sheet SHb1, suggesting that the PSV dates support the ¹⁴C dates measured for core VCS2.

The most likely scenario of deposition is inundation from a tsunami event, and SHb1 modeled dates are close to the maximum ages of many of the sand sheets correlated to Earthquake S in the Puget Sound. Atwater et al. (1997) identified several soil sequences along the Oregon and Washington coast believed to be buried during past CSZ events. Soil S is widely exposed in a Willapa Bay, Grays Harbor, and several other estuaries with low tidal ranges

(Atwater and Hemphill-Haley, 1997). Earthquake S, marked by the burial of soil S, is predicted to have occurred between 1500-1700 years B.P. based on two precise radiocarbon ages collected along the Niawiakum River (Atwater and Hemphill-Haley, 1997). However, dates from Nelson et al. (1996) suggest the age of earthquake S had a weighted mean of 1797 $\pm$ 23 years B.P., corresponding to 1600-1900 years ago; however, statistical differences suggest that these later dates are problematic (Atwater and Hemphill-Haley, 1997). Earthquake S is potentially correlated with Bed 7 in Discovery bay, dated to 1330-1710 years ago (Williams et al., 2005). Hutchinson et al (2013) correlate the upper sand sheet deposited in Salt Creek marsh to earthquake S, dated 1560 $\pm$ 30 years B.P. with a maximum limiting age for the upper sand being 1790 $\pm$ 30 years B.P. In Swantown Marsh, earthquake S is correlated to the deposition of layer E2, with ^{14}C dates from *S. maritimus* tubers, which predict a calibrated minimum age of 1400-1700 years B.P (Williams and Hutchinson, 2000).

Earthquake S is calculated to have occurred after a long inter-seismic period, estimated to be 700-1300 years, due to spruce root fossils indicating prolonged high marsh and depth of soil formation (Atwater and Hemphill-Haley, 1997). The long interseismic period that preceded earthquake S, and the presence of earthquake S dated deposits along the coasts of Oregon, Washington, the Puget Sound and Vancouver Island, suggest that earthquake S spurred a large tsunami able to inundate many areas of the Salish Sea. Based on the age of sand-sheet SHb1, the dates of other beds in the Puget Sound similarly dated to sand-sheet SHb1 and associated with earthquake S, and the potential that earthquake S created a large tsunami, it is possible that sand-sheet SHb1 was created during inundation from the tsunami produced by earthquake S along the CSZ plate boundary. Earthquake S is commonly associated with Goldfinger's turbidite T5 event,

dated 1400-1740 cal. years B.P. which is modeled to be large with up to a 1000 year interseismic period prior to the full rupture (Goldfinger, 2012; Witter et al., 2013).

6.3.2 Other potential sources tsunamis in the Puget Sound

Though CSZ earthquakes are predicted to produce large tsunamis, there are many potential upper crustal faults in the Puget Sound lowlands with off-shore fault traces including the Darrington-Devils Mountain fault zone, South Whidbey Island fault zone, Seattle Fault, Sandy Point fault, and Leech Creek fault. Though these faults do not have reported earthquakes that are directly dated to sand-sheet SHb1, and because we cannot easily model the potential tsunamis from these faults, the possibility still exists that one or more of these faults could be the source of a tsunami that could produce inundation in Ship Harbor marsh.

The Darrington-Devils mountain fault zone (DDMFZ) is located approximately 25km south of Ship Harbor (Figure 2), on the border between Fidalgo and Whidbey islands. Trenching along the DDMFZ identifies the fault as having dominantly right-lateral strike slip movement along a NW-SE strike, however, the deep dip of the fault around 90° makes it difficult to determine if the vertical component is reverse or normal (Personius et al., 2014). ¹⁴C dates from the trench suggests that the most recent earthquake to happen along the fault was 1,900 +/- 400 years B.P. Connecting to the DDMFZ is the Leech River fault system (LRF), located on Vancouver Island and tracing to the east offshore. The LRF is 130km long and has dip-slip motion and trenching reveals three rupture events (greater than Mw 6.0) in the last 9000 calendar years before present (Morell et al., 2018). Trench ¹⁴C chronology reveals the most recent rupture likely occurred ~1700 +/- 100 years before present (1630 +/- 100 cal. years BP) (Morell et al., 2018). Though the dates from the DDMFZ and LRF overlap with the dates of SHb1, Ship Harbor faces away from both fault systems limiting direct propagation into the marsh; however, though

not well constrained, diffraction around the islands is possible, and constriction of water in the Puget Sound between islands could increase wave velocity and height.

The Seattle Fault is approximately 100km south of Ship Harbor (Figure 2). Tsunami modeling done for this study suggests that the maximum increase in water level at Ship Harbor would be 20cm (Figure 21). This would not be enough increase in the water column to overtop the beach berm at either field site, and is an unlikely source for sand-sheets SHb1 or EIb2.

The Southern Whidbey Island fault system (SWF) is located approximately 30km south of Ship Harbor and strikes NW, tracing offshore west of Whidbey Island (Figure 2). Magnetic measurements, gravity anomalies, and borehole data all suggest that the fault has a transpressional history and has experienced strike-slip and thrust or reverse offsets (Johnson et al., 1996). Seismic reflection profiles and boreholes suggest that there has been displacement along the fault within the Quaternary, confirmed by identified liquefaction structures cross-cutting Quaternary deposits. The SWF to the west and northwest is inferred to connect to the southern extent of the Leech River fault on Vancouver Island. It is possible that slip along these faults could produce tsunami inundation to local areas (Johnson et al., 1996). The timing of the most recent earthquake events along these faults are not well constrained (Johnson et al., 1996).

The Sandy Point fault (SPF) is approximately 35km north of Ship Harbor marsh and has inferred slip which has offset Holocene landforms/deposits (Figure 2) (Kelsey et al., 2012). Kelsey et al. (2012) predict that there have been three coseismic uplift events in the last 6,000 years, with the most recent event occurring several centuries after 2060-2320 years B.P.

It is possible that one or more of these faults created a tsunami during a Holocene slip events. However, it is unclear if any of these faults could generate enough vertical sea floor deformation to produce the observed inundation and deposit thickness of SHb1. All fault traces

mentioned here except the Sandy Point fault are to the south of Ship Harbor marsh, limiting direct tsunami propagation into the north-facing Ship Harbor marsh. However, it is possible that wave propagation through the Puget Sound diffracts around the islands, and constriction of water in the Puget Sound between islands could increase wave velocity and height.

6.3.3 Limited records of CSZ tsunamis in Ship Harbor

It is problematic that earthquake Y (associated with buried soil Y in Atwater and Hemphill-Haley (1997)) representing the most recent 1700 AD CSZ earthquake, and other CSZ tsunami event deposits are not recorded in the stratigraphy at Ship Harbor. Over the last 4300 cal. years B.P. nine potential full-rupture CSZ events have occurred (Goldfinger, 2012; Witter et al., 2013). Of these nine events, only one event is modeled, based on recurrence interval, to have been a large event, while the rest are modeled to have been SM or M size events (Witter et al., 2013). Assuming mean sea level, this may explain why only one tsunami event is detectable within Ship Harbor marsh.

Earthquake Y (~300 years ago) is understood to have been large, and likely comparable to earthquake S. Tidal differences in the models show that the L1 with -2.0m tide does not produce inundation further than the northern, seaward 100m of the marsh at Ship Harbor (Figure 23). Daily tidal fluctuations around Anacortes range between 1.3-2.35m (“Tide Predictions - NOAA Tides & Currents”), and models suggest that tide changes this size can influence the possibility of overtopping of the beach berm and inundation of the marsh. Tides may play a role in the potential and extent of inundation into the marsh during the most recent 1700 event, and could account for the absence of these deposits in Ship Harbor marsh. Tide hindcasting from the eastern Strait of Juan de Fuca predict that neap tides occurred during the inferred time of tsunami arrival in the Puget Sound (Mofjeld et al., 1997; Williams and Hutchinson, 2000). At low tides,

as confirmed by modeling, it is possible that a tsunami may not have sufficient height to effectively overtop the beach berm- in this case this provides a viable explanation for lack of tsunami deposits from the last large CSZ event at Ship Harbor marsh. The most northern beachward extent of the marsh, were not surveyed in this study, due to limited access. Furthermore, the Skagit County soil survey from 1989 suggests that the whole area has been heavily altered by human development and fill, likely when the cannery and railroad were built in the 1800s. It is possible that the seaward marsh has preserved more deposits than found in the back of the marsh, if not too heavily disturbed from human modification.

6.3.4 Eliza Island

EIb1 and EIb2 are interpreted as potential inundation events into Eliza Island marsh. Dating of VCEI2, and the refined sequence model incorporating PSV dates, suggests that sand-sheet EIb2 was deposited 4669-4820 years B.P (Table 23b). The dates for sand-sheet EIb2 do not correlate to the modern marsh record preserved on the outer coast or in the Puget Sound. However, it does relate to a large, full rupture event predicted by the turbidite record. Goldfinger et al. (2012) and additional ^{14}C dates from Witter et al. (2013) suggests that T10 occurred between 4590-4950 years B.P. T10 is predicted to have occurred after a very long post-seismic interval, and is estimated to be large. This evidence is the best to suggest that EIb2 may have been the result of CSZ tsunami inundation into Eliza Island marsh.

6.4 Future work

There are many areas of research, field work, and data collection that could be expanded upon to answer some lingering questions related to the conclusions made here.

Confirmation of SHb1 as a paleotsunami deposit requires additional study. Stratigraphy of the subsurface at the front of Ship Harbor marsh would be helpful for looking at the northern

extent of the deposit and how the thickness varies spatially through the front 200m of marsh between VCS4 and the modern beach, and if it is detectable within the modified marsh environment. Presence of a large section of sands and gravels in VCS3 could represent a paleo beach environment, present at the historic marsh front, or a larger deposit of beach berm over wash, or the deposition of multiple inundation events (be it storm or tsunami) which accumulated to produce a larger column of sand and gravels. More field work would be an ideal way to answer the lingering questions about spatial extent and detect other deposits not identified in this study.

Smear slides show that abundant diatoms are present within the cores. Diatom smear-slide analysis and identification would be a great way to confirm ocean inundation caused the deposition of sand-sheet SHb1. Diatoms can be traced to their source when identified from within specific sections of the cores collected. An abundance of marine diatoms from within sand-sheets SHb1, Elb1 and Elb2 would confirm that ocean inundation created these sand sheets. Terrestrial diatoms, and general diatom make-up from beds above and below these sand-sheets would help confirm the past environments pre/post sand-sheet deposition.

Puget Sound upper crustal fault tsunami modeling is important to assess the potential of the faults to produce inundation at Ship Harbor. In order to provide the parameters for these models, trenching and other paleoseismic analyses need to be done to constrain the timing of the Holocene slip events along the faults. Large submarine landslides could also be a tsunamigenic source in the Puget Sound. Constraints on timing of collapses and slumps from the Fraser, Nisqually, Skokomish and Hood River canal deltas would provide better timing constraints on potential submarine landslides in the Puget Sound.

Further AMS analysis of Ship Harbor data would help to constrain the flow regime for sand-sheet SHb1. Lack of tidal channel exposures made in situ AMS collection impossible, and compaction from coring could have impacted interpretation of sedimentary fabrics. Digging trenches/benches/holes within the marsh from which samples can be directly collected in situ would be a good solution to this, though potentially difficult do to the saturated subsurface of the marsh.

Work Cited

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Figure 1. Context image of Washington State, Bellingham Bay, and field sites considered for this study. a: Image of western Washington state. CSZ appears as green line on left side of image, outer and inland coasts are labeled. b: Image of northern Puget Sound lowlands with current speed overlay from Gica and Arcas (2016). Labeled boxes are field sites of interest for this study: i. Eliza Island with predicted maximum inundation to 1.67m. ii. Cannery Lake, Anacortes. iii. Ship Harbor Marsh, Anacortes with predicted maximum inundation to 3.4m.

Figure 2. Map of North-west Washington, and images of Puget Sound marsh locations where CSZ tsunami deposits have been identified. Top left image is adapted from Kelsey et al. (2012) and displays the general outline of the Puget Sound and upper crustal fault locations in red with field locations of CSZ identified deposits are in blue boxes, labeled with letter or corresponding image. A: Salt Creek, B: Discovery Bay, C: Swantown Marsh. Key for shorthand: SPF: Sandy Point Fault, DMF: Darrington-Devils Mountain Creek Fault (which connects to the Leach River fault system off Vancouver, BC), UPF: Utsalady Point Fault. Imagery acquired from ArcGIS REST Services Directory. PugetSound_2009_30cm_color_wsps_83h_img.

Figure 3. Image of Ship Harbor marsh, Anacortes, WA. Gouge-auger core locations in yellow, vibracore locations in red. Vibracores VCS1 and VCS2 are located under S30 and S12 respectively. Gouge auger cores are named relative to Appendix 2, and vibracores are labeled relative to Appendix 1. To the NE is the beach front, and to the SW is landward. Landsat aerial image from USGS public access.

Figure 4. Image of Eliza Island Marsh, Eliza Island, WA. Gouge-auger core locations in yellow, vibracores locations in red. All points labeled with core name relative to appendix 1 and appendix 2. Beach fronts are located approximately south and NW of the central pond. A 2m high beach berm borders the marsh to the south. Aerial imagery acquired from USGS public access global imagery site.

Figure 5. VCS2 core summary. Full image mosaic of core on right, with A. Upper transition from peat to mud. B. Sand-sheet SHb1 containing woody debris at top and mollusk shells within deposit. C. Lower section of gravels and organics. Left: Stratigraphic section of VCS2 with ^{14}C dates in cal. years BP given with +/- error.

Figure 6. Stratigraphic sections of vibracores from Ship Harbor, described in appendix 2. Peat is generally >80% organic material, ranging from H1 to H9 humification. Mud with some sand, and sand-poor mud are generally grey-green in color, and contain less than 30% sand, and ~10% organics. Sand sections are greater than 40% sand, and sections of sands and gravels are >40% gravels. Name of vibracore is at the top, and depth in centimeters is on the y-axis.

Figure 7. Left: Image of shell from sand-sheet SHb1 core reference depth: 165cm, with mm/centimeter measure below, Right: image of VCS2 layer SHb1 from which this shell was retrieved.

Figure 8a. Vibracore Ship Harbor 2 (VCS2) AMS results. Strat column displays depth in cm on the y-axis. Samples are organized by sediment type, indicated by color classifications of stratigraphic section. Brown: peat, Green: sand-poor silt and clay rich unit, yellow: sand, pink: gravels and sand. Lower hemisphere equal-area projections for sections display K_{max} , K_{int} and K_{mins} from AMS measurements, plotted in Anisoft. Circles are 95% confidence ellipses. A. Peat samples. B. Clay samples. C. Sand Samples. D. Lower gravel samples

Figure 8b. Right: diagram of stratigraphic section for VCS6. Strat column displays depth in cm on the y-axis. Samples are organized by sediment type, indicated by color classifications of stratigraphic section. Brown: peat, Green: sand-poor silt and clay rich unit, yellow: sand, pink: gravels and sand. Lower hemisphere equal-area projections for sections display $K_{\max}$, K_{int} and $K_{\min}$ from AMS measurements, plotted in Anisoft. Circles are 95% confidence ellipses. A. Peat samples. B. Clay samples. C. Sand sample interpretation 1. D. Sand sample interpretation 2.

Figure 8c. Right: diagram of stratigraphic section for VCEI2. Strat column displays depth in cm on the y-axis. Samples are organized by sediment type, indicated by color classifications of stratigraphic section. Brown: peat, Green: sand-poor silt and clay rich unit, yellow: sand, pink: gravels and sand. Lower hemisphere equal-area projections for sections display $K_{\max}$, K_{int} and $K_{\min}$ from AMS measurements, plotted in Anisoft. Circles are 95% confidence ellipses. A: Peat samples (brown). B: Clay/Mud samples (green). C: Sand sheet samples (yellow).

Figure 8d. Right: diagram of stratigraphic section for VCEI3. Strat column displays depth in cm on the y-axis. Samples are organized by sediment type, indicated by color classifications of stratigraphic section. Brown: peat, Green: sand-poor silt and clay rich unit, yellow: sand, pink: gravels and sand. Lower hemisphere equal-area projections for sections display $K_{\max}$, K_{int} and $K_{\min}$ from AMS measurements, plotted in Anisoft. Circles are 95% confidence ellipses. A. Soil samples. B. Clay samples (green). C. Sand samples (yellow). D. Basal ravel samples (lower pink unit)

Figure 8e. AMS analysis sample locations of SHb1 from cores VCS2 and VCS6. Stratigraphy from VCS2 with oriented sampling locations, inset is portion of core identified as sand-sheet SHb1 with reference core depths labeled for samples collected. Reference depths correlate with the name of each sample. Y-axis is the corrected depth for compaction in centimeters, specific sample labels are core reference depths (not corrected for compaction, but used in nomenclature for sample names).

Figure 8f. Stratigraphy from VCS6 with oriented sampling locations for AMS and paleomagnetic data collection, inset is portion of core identified as sand-sheet SHb1. Y-axis is the corrected depth for compaction in centimeters. Within inset, specific sample labels (right) are core reference depths (not corrected for compaction, but used in nomenclature for sample names). Reference depths correlate with the name of each sample. Samples on right are from the south marked half of the core, and samples on the right are from the north marked half of the core. These two sets of samples are not collected in the same half but are depicted in such a way here.

Figure 8g. Flinn diagram of samples from sand-sheet SHb1 in cores VCS2 and VCS6 plotted based on L and F parameters calculated in Anisoft. Y-axis is labeled L for lineation ($K_{\max}/K_{\text{int}}$) and X-axis is labeled F for foliation ($K_{\text{int}}/K_{\min}$). Samples which plot above the orange line have measured prolate fabrics, suggesting a direction of flow is recorded, and samples below the line are measured as oblate fabrics, meaning they have less well defined K_{int} and $K_{\min}$ susceptibility axes.

Figure 8h. Equal area stereonet northern-hemisphere projections of AMS results from SHb1, organized by depth within sand-sheet SHb1. Samples from the base of sand-sheet SHb1 reference depths: VCS2: 168.5cm, 172.5cm, 174cm, VCS6: 167cm, 168.8. Middle referenced depths: VCS2: 163.5cm, 166cm. Top reference depths: VCS2: 160.6cm, VCS6: 154.4n, 157s, 160n, 161.8n, 161s. D. Combined equal area stereonet projections of all samples from VCS2 and VCS6 for SHb1. E. Combined equal area stereonet projections with only $K_{\max}$ plotted.

Figure 9a. Mass normalized bulk susceptibility results plotted with mass normalized corrected saturation magnetization (Ms) on secondary axis for Ship Harbor. Left is VCS2, right is VCS6. Top x-axis is volume normalized bulk susceptibility, secondary x-axis at bottom is mass normalized magnetization. Both cores have an increase in susceptibility and magnetization within the (yellow) sand bed to $\sim 2 \text{ Kg/m}^3$.

Figure 9b. Mass normalized bulk susceptibility results plotted with mass normalized saturation magnetization (Ms) on secondary axis for Eliza Island Left: core VCEI2, Right: core VCEI3. Both have an increase in susceptibility and magnetization within the (yellow) sand bed, identified as Elb2.

Figure 10. Figure of typical hysteresis for Ship Harbor and Eliza Island. Left is uncorrected, and right has a correction for the paramagnetic signal applied. A correction is only applied when saturation is present in the IRM data.

Figure 11. IRM results. IRM Data Examples from Ship Harbor and Eliza Island

Figure 12. Typical temperature vs susceptibility curves. Y-axis is normalized bulk-

Figure 13. Graphs of typical low temperature vs susceptibility curve for VCS2 and VCEI2, corrected for the holder and room temperature bulk susceptibility, labeled with corrected depths in cores. Y-axis displays bulk corrected susceptibility, and x-axis displays temperature in Celsius.

Figure 14. PSV Zijdeveld examples from core VCS2 and VCEI2. Zijdeveld diagrams are two dimensional displays of declination and inclination vector measurements made during the demagnetization process. The natural remnant magnetization is the point furthest from the origin, and as the sample is demagnetized the vector should continue towards the origin. Green dots are inclination projected in the X-Z plane, and blue dots are declination in the X-Y plane.

Figure 15. Figure of Ship Harbor PSV curves and plotted samples. Calculated delta-I and delta-D (Appendix 4) in pink displaying a 95% confidence envelope, while the calculated (Appendix 4) regional reference curve is blue, is calculated based on the high-resolution PSV dates reported in Hagstrum et al. (2004) and the latitude and longitude of each field site. X-axis error bars based on MAD from calculated component, y-axis displays age errors determined by an OxCal sequence model. Inclinations are shallow (lower than expected) likely due to compaction during vibracoring.

Figure 16. Eliza Island PSV curves and plotted samples. Calculated delta-I and delta-D (Appendix 4) in tan displaying a 95% confidence envelope, while the calculated (Appendix 4) regional reference curve is blue, is calculated based on the high-resolution PSV dates reported in Hagstrum et al. (2004) and the latitude and longitude of each field site. X-axis error bars based on MAD from calculated component, y-axis displays age errors determined by an OxCal sequence model. Inclinations are shallow (lower than expected) likely due to compaction during vibracoring.

Figure 17. Model results from GeoCLAW, L1 scenario (Witter et al. 2013). First figure is of the northern Puget Sound showing how multiple pulses of waves move through the area in the five hours after initial wave propagation, with A-F representing different times during tsunami propagation. Field sites shown in next images are in boxes here, with tide gauges labeled. Tide gauge 1000 is used to predict wave height at Ship Harbor, and tide gauges 1001 and 1002 are used for Eliza Island. Latitude is displayed on the y-axis and longitude is displayed on the x-axis. Image A is a course resolution, while images B-F are higher resolution, showing more features of the coast. The gauge on the right shows wave height, with a maximum of one meter displayed.

Figure 17. Continued from previous page. Ship Harbor L1 scenario. Tide gauge on top right displays the wave height just prior to landfall, and is labeled with corresponding field site predictions. Initial wave (B) has a maximum amplitude of 4.5m and inundates the clear extent of the marsh.

Figure 17. Continued from previous page, Eliza Island field site

Eliza Island L1, mean sea level

Figure 18. Model results scenario M1 (Witter et al. 2013). First figure is of Bellingham bay area, second is Ship Harbor, and third is Eliza Island.

Figure 18. Continued from previous page

Ship Harbor, M1, mean sea level

Figure 18. Continued from previous page

Eliza Island, M1, mean sea level

Figure 19. M2 model results (Witter et al. (2013)) scenario. Location shown in figures 17 and 18.

Ship Harbor, M2, mean sea level

Figure 19. Continued from previous page

Eliza Island, M2, mean sea level

Figure 20. Model Results SM1 (Witter et al. 2013). First image of Ship Harbor, second is Eliza Island.

Ship Harbor, SM1, mean sea level

Figure 20. Continued from previous page

Eliza Island, SM1, mean sea level

Figure 21. Model tide gauge results for the Seattle Fault Koshimura (2002) modeling parameters

Seattle Fault Scenario

Figure 22. Model results L1 with -1m low tide

Figure 22. Continued from previous page, Eliza Island field site.

Figure 23. Model results L1 with -2.0m tide.

Ship Harbor, L1, -2m tide

Figure 23. Continued from previous page

Eliza Island, L1, -2m tide

Figure 24. Model results from M1 scenario with +1.0m high tide

Ship Harbor, M1, +1m tide

Figure 24. Continued from previous page

Eliza Island, M1, +1m tide

Figure 25a. Figure of simplified stratigraphic correlation for SHb1. Y-axis is depth below the surface in centimeters. X-axis based on latitude and longitudinal profile created in the field with a Trimble DGPS unit, y-axis is based on depth above sea level in meters. Left side of image is the landward (south-east) direction, right is seaward (northwest) direction.

Figure 25b. Figure of alternate stratigraphic correlation for SHb1, extending north sand-sheet SHb1. Y-axis is depth below the surface in centimeters. X-axis based on latitude and longitudinal profile created in the field with a Trimble DGPS unit, y-axis is based on depth above sea level in meters. Left side of image is the landward (south-east) direction, right is seaward (northwest) direction.

Figure 26a. Figure of Eliza Island Stratigraphic Correlation for EIb2, extending east-west along the southern extent of marsh **Figure 26b.** Figure of Eliza Island Stratigraphic Correlation for EIb2 extending north to south across the central pond

Table 1. Vibracore inner and outer measurements, taken in the field. Diagram to the right displays how compaction is calculated based on field measurements. Total outer field measurement is subtracted from the inner field measurement, producing a total amount of compaction. This is divided by the compacted core length to produce compaction per centimeter in the core. This factor is then used to calculate the total uncompacted length of the core.

Core	Inner Field (IF) Measurement (cm) (minus material removed if done so)	Total Length of pipe (cm)	Outer Field (OF) (cm)	Si: IF-OF = (cm)	Penetration depth (cm): Total length – OF	Depth, uncorrected core (Du) (cm)	Compaction Factor: (IF-OF)/(Total length-OF)
VCS1	180.9	322	55.7	125.2	267.2	142	0.4686
VCS2	160.5	409.5	59.7	100.8	349.8	249	0.2882
VCS3	159.4	405.4	132.7	26.7	272.7	246	0.0978
VCS4	223.5	408.5	156.2	67.3	252.2	160.8	0.2668
VCS5	53.7	309.1	46.9	6.7	262.1	225	0.0254
VCS6	60.3	311.6	38.1	22.2	273.5	205.6	0.0812
VCEI1	78.9	315.6	38.4	40.5	277.1	210	0.1460
VCEI2	59.2	280.8	32.7	26.5	220.1	189	0.1414
VCEI3	91.8	312.2	60.6	31.1	251.5	220.4	0.1237

Table 2. Radiocarbon sample list sent to NOSAMS. Samples listed by site and stratigraphic depth.

Name and Site Location	Depth (cm) uncorrected for compaction	Depth, corrected for vibracore compaction (cm)	Sample type/ Comments	Weight (mg)	Note of likely max/minimum	Type
Ship Harbor						
VCS2n_RC28	108	168.20	Twig	5.97	Maximum	Plant/Wood
VCS2n_RC6	146	217.15	Pinecone needle or very small twig	1.57	Maximum age	Plant/Wood
VCS2n_RC14	160.5	235.83	Twig	4.84	Maximum age	Plant/Wood
VCS2n_RC12	161	236.47	Twig	2.43	Maximum age	Plant/Wood
VCS2n_RC13	162.5	238.41	Wood fragment	29.22	Maximum age	Plant/Wood
VCS2n_RC17	170	248.07	Twig, in tsunami deposit	3.55	Maximum age	Plant/Wood
VCS2n_RC23	207	295.73	Twig - small	3.63	Maximum below age	Plant/Wood
VCS2n_RC25	228	322.78	Potentially bark	4.05	Oldest sample	Plant/Wood
Eliza Island						
VCEI2n_RC28	124.5	143.1	Bark	2.4	Max age	Plant/Wood
VCEI2n_RC19	135	154.9	Twig, inside normally graded sand	14	Max of sand above	Plant/Wood
VCEI2n_RC1	143.5	164.4	Twig trash layer top	68.98	Maximum age, 7 growth rings counted	Plant/Wood
VCEI2n_RC8	154	176.2	Twig - below trash	12.59	Max age, down section from "sand sheet EIb2"	Plant/Wood

Table 3. Particle size analysis results for Ship Harbor. Grey indicates measurement was collected with a settling test, white samples were completed with the Melvern Mastersizer instrument. Texture is based on the USDA soil texture triangle. Percent organics is based on LOI data, and if taken between two measurements from LOI an average is taken from samples above and below.

Core name and Uncorrected Sampling depths (cm)	Top Depth (cm)	Bottom depth (cm)	Result % 0.01µm- 3.90µm Clay	Result % 3.91µm- 15.60µm Lower Silt	Result % 15.61µm- 62.50µm Silt	Silt %	Result % 62.51µm- 250.00µm (vfs to fs)	Result % 250.01µm- 2500.00µm	Obscuration %	Texture	% Organics
VCS2											
70-80	119.2	132.1	24.1	38.8	33.0	71.8	4.0	0.0	6.33	Silty Clay Loam	13.03
80-90	132.1	145.0	24.8	38.7	28.4	67.0	4.2	3.9	6.33	Silty Clay Loam	10.95
90-95	145.0	151.4	24.3	40.1	30.3	70.4	3.6	1.7	7.26	Silt Loam	11.50
95-108	151.4	168.2	7.0			51.2	41.9			Silt Loam	12.00
108-118	168.2	181.1	24.3	38.0	29.4	67.5	3.5	4.7	5.67	Silt loam	10.59
118-124	181.1	188.8	0.0	72.7		72.7	27.3			Silt Loam	11.00
124-134	188.8	201.7	26.0	40.0	29.9	70.0	3.7	0.3	6.76	Silt Loam	11.67
134-144	201.7	214.6	24.2	38.3	30.9	69.2	3.3	3.2	7.23	Silt Loam	11.59
144-146	214.6	217.1	0.0			69.0	31.0			Silt Loam	11.00
146-154	217.1	227.5	23.0	35.4	30.7	66.1	4.0	6.8	6.65	Silt Loam	10.99
154-176	227.5	255.8	5.0			55.0	40.0			Silt Loam	7-22
176-186	255.8	268.7	22.7	35.1	37.3	72.4	4.8	0.0	7.31	Silt Loam	10.20
186-195	268.7	280.3	23.4	35.3	33.0	68.4	4.3	3.9	6.70	Silt Loam	10.10
195-226	280.3	320.2	7.1			40.5	52.4			Silt Loam	2-4
226-245	320.2	344.7	20.7			6.9	72.4			Sandy Clay Loam	2.00
VCS6											
85-92	139.4	147.0	24.0	39.5	32.7	72.2	3.7	0.0		Silt Loam	10.00
92-100.6	147.0	156.3	24.4	39.5	30.4	69.9	3.5	2.1		Silt Loam	10.60
100.6-110	156.3	166.4	20.2	31.8	37.6	69.4	5.5	4.8		Silt Loam	11.72
110-116	166.4	172.9	20.4	32.4	37.9	70.3	5.4	3.8		Silt Loam	12.24
116-121	172.9	178.3	21.9	35.3	37.8	73.1	4.9	0.0		Silt Loam	13.74
121-129	178.3	187.0	7.0			55.8	37.2			Silt Loam	12.00
129-135	187.0	193.5	23.0	37.0	31.3	68.3	5.1	3.5		Silt Loam	11.50
135-160	193.5	220.5	11.8			32.4	55.9			Sandy Loam	11.50
160-170	220.5	231.3	23.4	36.7	31.7	68.4	3.5	4.6		Silt Loam	14.17
170-178	231.3	240.0	25.2	37.7	29.5	67.2	4.3	3.2		Silt Loam	23.52
178-185	240.0	247.5	22.1	33.8	27.2	61.0	8.9	8.0		Silt Loam	6.56
190-205.6	252.9	269.8	25.1	38.6	28.9	67.4	4.0	3.4		Silt Loam	10.95

Table 4. Particle Size Analysis results for Eliza Island. Grey indicates measurement was collected with a settling test, white samples were completed with the Melvern Mastersizer instrument. Texture is based on the USDA soil texture triangle. Percent organics is based on LOI data, and if taken between two measurements from LOI an average is taken from samples above and below. Yellow indicates sample was lost during analysis. Bold are % sand silt and clay used to determine texture.

Core name and Uncorrected Sampling depth (cm)	Corrected Top Depth (cm)	Corrected bottom depth (cm)	Result 0.01µm- 3.90µm Clay	Result 3.91µm- 15.60µm Lower Silt	Result 15.61µm- 62.50µm Silt	Silt %	Result 62.51µm- 250.00µm (vfs to fs)	Result 250.01µm- 2500.00µm	Obscuration %	Texture	% Organics
VCEI2											
49-57	58.3	67.3	14.2	19.4	37.6	57.0	22.8	6.0	5.49	Silt Loam	6.71
57-62	67.3	72.9	10.0			65.0	25.0			Silt Loam	6.00
62-72	72.9	84.1	12.1	20.0	41.0	61.0	19.6	7.3	4.85	Silt Loam	7.16
73-82	85.2	95.3	17.8	25.5	41.6	67.2	13.0	2.0	8.00	Silt Loam	8.20
82-92	95.4	106.6	19.6	26.7	40.0	66.7	9.9	3.7	9.20	Silt Loam	6.36
92-102	106.6	117.8	16.5	22.9	38.7	61.6	13.6	8.3	7.57	Silt Loam	5.86
102-112	117.8	129.0									6.74
124-136	142.5	156.0	9.5			45.2	45.2			Loam	2-4
136-142.6	155.9	163.4	2.4			42.9	54.8			Sandy Loam	3.80
142.6-157.5	163.4	180.1	6.7			66.7	26.7			Silt Loam	4-11
157.4-182	180.0	207.6	2.6			71.1	26.3			Silt Loam	1.7-3.3
VCEI3											
15-26	20.7	33.1	0.0			69.6	30.4			Silt Loam	2.40
26-40	33.1	48.8	20.0			34.3	45.7			Loam	1.6-2.4
40-58	48.8	69.0	9.7			54.8	35.5			Silt Loam	1.60
64-70	75.8	82.5	11.8	17.0	31.2	48.2	27.0	13.0	4.70	Loam	4.12
70-77	82.5	90.4	13.0	22.3	38.3	60.6	12.8	13.5	3.47	Silt Loam	7.07
77-82	90.4	96.0	10.0	16.7	30.3	47.0	14.9	28.1	3.70	Loam	7.00
82-89	95.9	103.9	15.3	24.2	35.9	60.1	9.9	14.6	4.33	Silt Loam	8.33
89-93	103.9	108.4	12.3	22.6	45.0	67.6	11.9	8.2	4.33	Silt Loam	9.66
98-101	114.0	117.3	18.9	24.7	37.9	62.6	14.7	3.8	7.81	Silt loam	11.85
103-107	119.6	124.1	19.8	26.4	39.4	65.9	10.8	3.4	7.61	Silt Loam	7.67
121.6-135	140.5	155.6	4.5			63.6	31.8			Silt Loam	4.6-5.2
135-145	155.6	166.8	7.1			52.4	40.5			Silt Loam	4.40
154-166	176.9	190.4	5.9			35.3	58.8			Sandy Loam	2.1-3.7
166-173	190.4	198.3	10.0			10.0	80.0			Loamy Sand	1-2
178-183	203.9	209.5	9.1			12.1	78.8			Loamy Sand	1.00
194-200	217.7	228.6	30.6	31.2	23.4	54.6	9.7	5.1	9.77	Silty Clay Loam	1.88
200-210	224.3	239.8	37.4	35.5	20.4	55.9	3.5	3.1	8.20	Silty Clay Loam	2.37
212-217	237.61	247.7	27.1	27.6	24.3	51.9	12.6	8.3	9.85	Silty Clay Loam	2.42

Table 5. Lateral extent of sand-sheet SHb1 from north (closest to beach) to south (landward) along transect T1a and T1b (Figure 3b), gouge auger core name (Appendix 1) or vibracore name (Appendix 2) are listed in the far-right column, depths given are corrected for compaction as described in Figure 1. If sand sheet is not apparent, in “Sand-sheet name or comment of observation” column a comment of a potential correlating factor is made from field observations. Age here is based on the OxCal sequence model from ^{14}C dates (Table 10).

N-S	Sand-sheet name or comment of observation	Depth (corrected) (cm)	Thickness (cm)
S19	SHb1	124-134, 186-245, 251+	26+
S17	SHb1	187-212+	25+
S13	SHb1	233-259	26
VCS2	SHb1	230.7-254.7	24
VCS6	SHb1	214-234	20
S14	SHb1	240-253	13
S15	SHb1	190-205	15
VCS4	SHb1	213.1-217.2	5
S34	SHb1	246-253	7
S33	High Organics Content	220	<1
S32	Shell fragments	221	<1

Sand-sheet	Distance between cores	Age (B.P.)	Maximum Thickness	Minimum Lateral Extent	Landward Thinning	Number of laminae	Average Grain Size	Organic Content %
SHb1	5-10m	1802-1730	26cm	50m	yes	unclear	Sandy loam (sand and silt)	22.02% at top 8.93% at bottom

Table 6. Table of lateral extent of sand and gravel sheets, Eliza Island. Gouge auger core name (Appendix 1) or vibracore name (Appendix 2) are listed in the far-right column, depths given are corrected for compaction as described in Figure 1. N-S indicates north to south transects, while W-E indicates west to east facing transects. If sand sheet is not apparent in “Sand-sheet name or comment of observation” column, a comment of a potential correlating factor is made from field observations. Age here is based on the OxCal sequence model from ^{14}C dates (Table 10).

N-S, to the east of the pond. Name of cores along transect	Name	Depth below surface (cm)	Thickness (cm)		W-E South of pond. Name of cores	Sand-sheet name	Depth below surface (cm)	Thickness (cm)
EI7	EIb1	53+?	-		EI17	EIb2	Refusal at 175	
EI6	EIb1	62-83	21		EI12	EIb2	147.5-171	23.5
EI8	EIb1	63-73+?	10+		VCEI2	EIb2	142.5-174	32
EI24 *	EIb1	73-90	17		EI28	EIb2	145-156	11
EI25*	EIb1	71-88	17		EI29	EIb2	133-180	47
EI19B	EIb1	73-128	55		VCEI1	EIb2	176.9-188.7	12
EI26	EIb1	77-98+	21+		EI32	EIb2	176-?	?
VCEI2	EIb1	60-72	12		EI33	EIb2	185-193	8
N-S, across pond. Name of cores along transect					W-E North Side Pond. Name of cores			
EI22	EIb2	164-187	23		VCEI3	EIb2	140.5-166.8	27
EI1	EIb2	Only reached 163.5			EI3	EIb2	139-157	18
VCEI3	EIb2	140.5-166.8	27		EI4	EIb2	139-143	4
Pond								
EI12	EIb2	147.5-171	23.5					
VCEI2	EIb2	142.5-174	32					
EI13	EIb2	143-167	24					
EI14	EIb2	156-174+	18+					
EI15	EIb2	Final depth 140cm						
EI11	EIb2	135-140, 153-167	32					
EI16	EIb2	Final depth 133cm						

Name of Bed	Sand Bed Depth below surface (cm)	Thickness (cm)	Distance between cores	Lateral Extent (m)	Landward Thinning	Number of laminae	Average Grain Size	Organic Content
EIb1	62-98cm	17-55cm	10m	94.4m	None	None	Silt Loam	3.5-5%
EIb2	140-178cm	4-47cm	10m	86.3m	Unclear	0-2	Sandy Loam	4-11%

Table 7. Organic content calculated from loss of ignition for Ship Harbor cores VCS2 and VCS6. Samples collected at 10cm intervals throughout cores, starting below top peat bed.

Sample name and uncorrected core depth (cm)	Sample Corrected Depth (cm)	Organic Content %	Sample name and uncorrected core depth (cm)	Sample Corrected Depth (cm)	Organic Content %
VCS2_N			VCS6N		
60	106.4	23.95	70	123.2	32.93
70	119.2	15.65	80	134.0	12.28
80	132.1	10.40	90	144.8	10.00
90	145.0	11.50	100	155.7	11.20
100	157.9	12.39	110	166.5	12.24
110	170.8	10.59	120	177.3	13.74
120	183.7	10.98	130	188.1	11.50
130	196.5	11.67	140	198.9	11.49
140	209.4	11.59	150	209.7	9.96
150	222.3	10.99	160	220.5	4.83
160	235.2	22.02	170	231.3	23.52
170	248.1	7.67	180	242.2	6.56
180	260.9	10.20	190	253.0	10.36
190	273.8	10.10	200	263.8	10.95
200	286.7	4.10			
210	299.6	2.06			
220	312.5	2.07			
230	325.4	0.83			
240	338.2	2.35			

Table 8. Organic content calculated from LOI for Eliza Island cores VCEI2 and VCEI3. Samples collected at 10cm intervals throughout cores, starting below top peat bed.

Sample Name	Sample Corrected Depth (cm)	Organic Content %	Sample Name	Sample Corrected Depth (cm)	Organic Content %
VCEI2N			VCEI3N		
50	59.4	6.71	20	26.3	2.38
60	70.6	5.76	30	37.6	1.58
70	81.9	8.55	40	48.8	2.40
80	93.1	7.84	50	60.0	1.61
90	104.3	4.88	60	71.3	1.16
100	115.6	6.84	70	82.5	7.07
110	126.8	6.64	80	93.7	7.00
120	138.0	4.23	90	105.0	9.66
130	149.3	1.97	100	116.2	11.85
140	160.5	3.81	110	127.5	3.48
150	171.7	11.82	120	138.7	5.21
160	182.9	2.56	130	149.9	4.57
170	194.2	1.72	140	161.2	4.25
180	205.4	3.32	150	172.4	3.68
			160	183.6	2.10
			170	194.9	0.96
			180	206.1	1.00
			190	217.4	1.40
			200	228.6	1.88
			210	239.8	2.85
			220	251.1	1.98

Table 9. Uncalibrated dates from NOSAMS ^{14}C dating analysis and OxCal calibrated dates using a simple OxCal C_Date calibration.

Name	Depth, corrected for vibracore compaction (cm)	Age, radiocarbon years	Age Error (radio carbon years) +/-	Calibrated OxCal cal. years BP		% Confidence
				from	to	
Ship Harbor						
VCS2n_RC28	168.20	1,600	25	1546	1414	95.4
VCS2n_RC6	217.15	1,860	15	1864	1730	95.4
VCS2n_RC14	235.83	1,820	15	1815	1714	95.4
VCS2n_RC12	236.47	1,840	15	1821	1722	95.4
VCS2n_RC13	238.41	2,610	15	2759	2739	95.4
VCS2n_RC17	248.07	2,470	15	2705	2464	95.4
VCS2n_RC23	295.73	3,290	20	3567	3462	95.4
VCS2n_RC25	322.78	3,920	20	4424	4291	95.4
Eliza Island						
VCEI2n_RC28	143.1	4,250	25	4862	4726	95.4
VCEI2n_RC19	154.9	4,420	20	5213	4878	95.3
VCEI2n_RC1	164.4	4,160	20	4825	4615	95.4
VCEI2n_RC8	176.2	4,480	20	5287	5039	95.4

Table 10. OxCal sequence model results for Ship Harbor. Left if calibrated dates, right is sequence modeled age. Age of sand-sheet SHb1 is bold.

Name	Calibrated cal. years B.P.		Confidence	OxCal Sequence Modelled cal. years BP		Confidence
	from	to	%	from	to	%
Boundary Top VCS2				1122	-713	95.4
C_Date Peat Bottom	984	144	95.4	1134	265	95.4
R_Date VCS2n_RC28	1546	1414	95.4	1546	1414	95.4
R_Date VCS2n_RC6	1864	1730	95.4	1782	1717	95.4
Bed SHb1				1802	1730	95.4
R_Date VCS2n_RC14	1815	1714	95.4	1820	1751	95.4
R_Date VCS2n_RC12	1821	1722	95.4	1825	1744	95.4
R_Date VCS2n_RC13	2759	2739	95.4	2759	2738	95.4
R_Date VCS2n_RC17	2705	2464	95.4	2705	2465	95.4
Phase Max Ages SHb1						
R_Date VCS2n_RC23	3567	3462	95.4	3568	3462	95.4
R_Date VCS2n_RC25	4424	4291	95.4	4424	4288	95.4
Boundary Bottom VCS2				5623	4266	95.4
Sequence Ship Harbor B						

Table 11. OxCal sequence model results for Eliza Island.

Name	Calibrated cal. years B.P.		% Confidence	OxCal Sequence Modelled cal. years B.P.		% Confidence
	from	to	%	from	to	%
Boundary Top				4756	4248	95.4
R_Date VCEI2n_RC28	4862	4726	95.4	4758	4652	95.4
Bed EIb2				4820	4669	95.4
R_Date VCEI2n_RC19	5213	4878	95.3	5049	4880	95.4
R_Date VCEI2n_RC1	4825	4615	95.4	4830	4724	95.4
Phase Bed EIb2 Eliza						
R_Date VCEI2n_RC8	5287	5039	95.4	5274	4980	95.4
Boundary Base				5611	4985	95.4
Sequence Eliza Island						

Table 12. Table of Error for Ship Harbor AMS results. AMS error is reported in % error, calculated by the Kappabridge software during analysis. AMS error relates directly to the instruments ability to easily measure a susceptibility in one direction in the presence of the low field produced. A1, A2 and A3 all refer to axis positions used to do analysis with the KYL-3 Kappabridge for AMS analysis. Color indicates stratigraphic designation, with pink being peat, green being sand-poor silt-rich mud, and blue being sand-sheet beds sample from within the core. Sample name indicates which vibracore samples were collected in followed by T or B indicating top (T) or bottom (B) portion of core, and N or S indicating which half of the core was sampled, with N being for North out of the core barrel and S being for South out of the core barrel.

Core Name	Sampling Depth Top (cm), Corrected for compaction	Sampling depth top, core reference (uncorrected)	AMS Error A1 %	AMS Error A2 %	AMS Error A3
VCS2_TN	50.5	16.6	100	100	100
VCS2_TN	60.2	24.2	100	100	100
VCS2_TN	69.5	31.4	100	100	100
VCS2_TN	88.1	45.8	100	100	100
VCS2_TN	97.3	53	100	100	100
VCS2_TN	114.3	66.2	5-11%	5-11%	5-11%
VCS2_TN	125.4	74.8	34.63	9.28	16.84
VCS2_TN	134.4	81.8	62.31	12.32	No Record
VCS2_TN	143.7	89	33.06	4.54	No Record
VCS2_TN	151.7	95.2	7.02	3.74	5.27
VCS2_TN	162.3	103.4	20.24	4.65	9.3
VCS2_TN	171.5	110.6	19	8.62	7.79
VCS2_TN	180.8	117.8	No Record	No Record	No Record
VCS2_BN	190.1	125	116.96	10.8	5.93
VCS2_BN	199.8	132.5	98.61	2.93	6.24
VCS2_BN	209.4	140	45.87	5.27	No Record
VCS2_BN	224.9	152	11.48	12.02	26.58
VCS2_BN	236.0	160.6	7.68	6.76	7.63
VCS2_BN	239.7	163.5	9.09	4.56	~7
VCS2_BN	242.9	166	12.65	17.58	1.35
VCS2_BN	246.1	168.5	3.24	3.24	28.84
VCS2_BN	251.3	172.5	10.98	7.32	No Record
VCS2_BN	253.2	174	10.1	2.74	1.59
VCS2_BN	260.9	180	37.8	10.5	6.79
VCS2_BN	270.6	187.5	9.61	10.01	29.02
VCS2_BN	280.3	195	1.61	3.29	3.96
VCS2_BN	309.3	217.5	1.24	6.6	0.75

VCS2_BN	316.3	223	0.31	0.92	0.95
VCS2_BN	334.4	237	0.54	2.93	1.25

Core Name	Sampling Depth Top, Corrected for compaction	Sampling depth top, core reference (uncorrected)	AMS Error A1	AMS Error A2	AMS Error A3
VCS6_TN					
VCS6_TN	58.3	10	48.6	30.5	113.68
VCS6_TN	63.7	15	37.69	27.67	82.7
VCS6_TN	71.5	22.2	36.29	48.86	108.97
VCS6_TN	79.3	29.4	71.4	54.75	57.06
VCS6_TN	87.1	36.6	43.41	56.38	100.11
VCS6_TN	94.9	43.8	49.4	29.17	83.46
VCS6_TN	102.7	51	70.75	31.49	
VCS6_TN	110.5	58.2	74.63	55.38	
VCS6_TN	118.2	65.4	65.62		
VCS6_TN	125.4	72	64.15		
VCS6_TN	131.6	77.8	122.54	52.34	53.99
VCS6_TN	139.2	84.8	12.32	16.35	5.15
VCS6_TN	147.0	92	41.24	34.57	7.59
VCS6_BN	152.4	97	16.09	24.03	
VCS6_BN	160.0	104	55.58	32.29	24.47
VCS6_BN	167.8	111.2	49.29	11.66	21.92
VCS6_BN	175.5	118.4	33.19	5.86	14.24
VCS6_BN	183.3	125.6	20.57	10.23	4.81
VCS6_BN	191.1	132.8	63.4	10.25	9.39
VCS6_BN	198.9	140	147.5	9.43	9.36
VCS6_BN	207.6	148	63.83	14.08	7.12
VCS6_BN	214.5	154.4	2.9	3.74	2.23
VCS6_BN	222.3	161.6	4.17	1.52	1.45
VCS6_BN	220.5	160			
VCS6_BS	217.3	157			
VCS6_BS	221.6	161			
VCS6_BS	224.3	163.5			
VCS6_BS	228.1	167			
VCS6_BN	230.0	168.8	67.56	5.64	6.15
VCS6_BN	239.3	177.4	1.96	5.05	6.15
VCS6_BN	245.6	183.2	25.06	17.17	25.31
VCS6_BN	253.4	190.4	38.1	8.97	19.62
VCS6_BN	262.7	199	56.05	62.95	34.7

Table 13. Table of error for Eliza Island AMS results. AMS error is reported in % error, calculated by the Kappabridge software during analysis. A1, A2 and A3 all refer to axis positions used to do analysis with the KYL-3 Kappabridge for AMS analysis. Color indicates stratigraphic designation, with pink being peat, green being sand-poor silt-rich mud, and blue being sand-sheet beds sample from within the core. Sample name indicates which vibracore samples were collected in followed by T or B indicating top (T) or bottom (B) portion of core, and N or S indicating which half of the core was sampled, with N being for North out of the core barrel and S being for South out of the core barrel.

Core Name	Sampling Depth Top, Corrected for compaction (cm)	Sampling depth top, core reference (uncorrected) (cm)	AMS Error Axis 1 %	AMS Error Axis 2 %	AMS Error Axis 3 %
VCEI2_TN	25.7	20	45.27	165.21	40.67
VCEI2_TN	37.0	30	500.35	132.23	36
VCEI2_TN	48.2	40	46.72	29.45	30.59
VCEI2_TN	59.4	50	27.68	4.89	4.76
VCEI2_TN	67.8	57.5	16.48	5.92	7.44
VCEI2_TN	76.3	65	18.55	16.6	No Record
VCEI2_TN	84.7	72.5	41.98	15	12.26
VCEI2_TN	93.1	80	71.79	34.59	14.66
VCEI2_TN	104.3	90	16.36	11.83	17.5
VCEI2_TN	109.9	95	1.78	2.61	2.11
VCEI2_BN	118.4	102.5	2.93	6.59	3.31
VCEI2_BN	126.8	110	42.18	25.22	5.1
VCEI2_BN	135.2	117.5	40.79	13.12	8.67
VCEI2_BN	138.6	120.5	23.42	7.32	6.3
VCEI2_BN	143.6	125	11.37	11.93	7.44
VCEI2_BN	147.6	128.5	17.45	11.19	8.39
VCEI2_BN	152.1	132.5	4.39	13.77	7.75
VCEI2_BN	156.0	136	19.94	13.92	10.25
VCEI2_BN	160.5	140	26.97	11.34	11.36
VCEI2_BN	171.1	149.5	7.47	7.53	15.13
VCEI2_BN	179.6	157	3.23	1.05	1.36
VCEI2_BN	189.7	166	4.15	3.47	1.91
VCEI2_BN	196.4	172	54	84.05	45.88
VCEI2_BN	205.4	180	50.88	32.01	15.7

Table 13. Continued from previous page

Core Name	Sampling Depth Top, Corrected for compaction	Sampling depth top, core reference (uncorrected)	AMS Error A1	AMS Error A2	AMS Error A3
VCEI3_TN	36.4	29	1.63	0.6	low
VCEI3_TN	56.7	47	1.18	0.26	0.59
VCEI3_TN	74.6	63	11.45	4.6	7.81
VCEI3_TN	79.1	67	19.85	5.17	4.96
VCEI3_TN	85.3	72.5	16.1	9.44	8.61
VCEI3_TN	93.7	80	9.49	2.91	1.01
VCEI3_TN	102.2	87.5	163.17	16.96	29.04
VCEI3_TN	110.6	95	7.25	2.09	3.93
VCEI3_TN	121.8	105	68.57	8.14	7.59
VCEI3_BN	126.3	109	38.68	8.42	13.09
VCEI3_BN	135.9	117.5	27.46	7.81	27.88
VCEI3_BN	144.3	125	7.57	4.85	2.14
VCEI3_BN	152.7	132.5	4.29	15.72	7
VCEI3_BN	161.2	140	16.02	9.03	3.74
VCEI3_BN	169.6	147.5	12.76	4.44	3.23
VCEI3_BN	183.6	160	3.99	7.7	7.17
VCEI3_BN	205.0	179	0.47	0.35	2.49
VCEI3_BN	211.7	185	2.58	0.98	10.41
VCEI3_BN	220.2	192.5	0.76	0.78	0.79
VCEI3_BN	228.6	200	2.1	0.47	0.41
VCEI3_BN	237.0	207.5	1.24	0.23	0.25

Table 14. Table of AMS mean tensors for Ship Harbor. Declinations (Dec) and inclinations (Inc) are the mean grain orientations reported for each axis measured within the sample, corrected for geographic orientation in space. $K_{\max}$, K_{int} and $K_{\min}$ refer to the maximum, intermediate, and minimum susceptibility axes respectively. N is number of samples included in average.

Core	Unit Type	N	Mean $K_{\max}$ Dec	Mean $K_{\max}$ Inc	Mean K_{int} Dec	Mean K_{int} Inc	Mean $K_{\min}$ Dec	Mean $K_{\min}$ Inc	Notes
VCS2	Peat	5	333.3	52	170	36.7	74	8.3	
	Clay	13	282.6	82	92.5	7.9	182.7	1.4	
	SHb1	6	34.5	33.8	275.2	36.1	153.4	35.8	Kmins appear imbricated
	Basal (bottom)	3	89.2	41.2	289.3	47	188.2	10.2	

Core	Unit Type	N	Mean $K_{\max}$ Dec	Mean $K_{\max}$ Inc	Mean K_{int} Dec	Mean K_{int} Inc	Mean $K_{\min}$ Dec	Mean $K_{\min}$ Inc	Notes
VCS6	Peat	8	3.1	19.5	226.2	64.2	99	16.3	
	Clay	15	281.9	9.8	12.9	5.9	133.4	78.5	
	SHb1	3	108	11.2	200.1	10.6	332.4	74.5	

Table 15. Table of AMS mean tensors for Eliza Island. Declinations (Dec) and inclinations (Inc) are the mean grain orientations reported for each axis measured within the sample, corrected for geographic orientation in space. $K_{\max}$, K_{int} and $K_{\min}$ refer to the maximum, intermediate, and minimum susceptibility axes respectively.

Core	Unit Type	N	Mean $K_{\max}$ Dec	Mean $K_{\max}$ Inc	Mean K_{int} Dec	Mean K_{int} Inc	Mean $K_{\min}$ Dec	Mean $K_{\min}$ Inc	Notes
VCEI2	Soil	3	2.8	19.2	93.7	2.7	191.5	70.6	
	Clay	15	296.8	6.8	206.6	1.7	102.8	83	Kmax and Kint distribution suggests settling
	Elb2	6	204.6	9.5	296.1	8.8	67.9	77	General grouping of Kmax and Kints, potential imbrication of sands

Core	Unit Type	N	Mean $K_{\max}$ Dec	Mean $K_{\max}$ Inc	Mean K_{int} Dec	Mean K_{int} Inc	Mean $K_{\min}$ Dec	Mean $K_{\min}$ Inc	Notes
VCEI3	Soils, Gravely	3	224.5	24.8	126.5	16.7	5.9	59.5	
	Clay, Gravely	3	170.2	28.4	60.3	32.2	292.2	44.5	
	Clay	12	248	4.1	338.2	2.2	95.8	85.4	Grouping of Kmins suggest settling
	Elb2	3	314.2	1	223.9	14.4	47.9	75.6	Potential flow direction Kmax

Table 16. AMS calculated parameters, with parameters described on pg. 41-42. Equations for parameter calculations are described in Appendix 4, page 3.

Sampling Depth Top, Corrected for compaction	Sampling depth top, core reference (uncorrected)	L	F	P	Pj	T	U	Q	E
VCS2									
50.5	16.6	1.02	1.00	1.02	1.02	-0.76	0.76	0.13	0.99
60.2	24.2	1.02	1.01	1.03	1.03	-0.53	0.54	0.26	0.98
69.5	31.4	1.01	1.03	1.04	1.04	0.69	-0.68	1.45	1.02
88.1	45.8	1.01	1.01	1.02	1.02	-0.33	0.34	0.40	0.99
97.3	53	1.01	1.00	1.02	1.02	-0.45	0.45	0.32	0.99
114.3	66.2	1.03	1.00	1.03	1.04	-0.76	-0.76	1.57	0.98
125.4	74.8	1.01	1.02	1.03	1.03	0.30	0.29	0.43	1.01
134.4	81.8	1.01	1.04	1.04	1.04	0.73	0.72	0.15	1.03
143.7	89	1.01	1.03	1.04	1.04	0.41	0.41	0.35	1.01
151.7	95.2	1.01	1.03	1.04	1.04	0.55	0.54	0.26	1.02
162.3	103.4	1.01	1.03	1.04	1.05	0.51	0.51	0.28	1.02
171.5	110.6	1.02	1.04	1.06	1.06	0.26	0.25	0.46	1.02
180.8	117.8								
190.1	125	1.00	1.04	1.05	1.05	0.94	0.94	0.03	1.04
199.8	132.5								
209.4	140	1.01	1.06	1.07	1.08	0.82	0.81	0.10	1.06
224.9	152	1.01	1.01	1.02	1.02	0.19	0.18	0.51	1.00
236.0	160.6	1.03	1.02	1.04	1.04	-0.20	-0.21	0.87	0.99
239.7	163.5	1.01	1.02	1.03	1.03	0.17	0.16	0.53	1.01
242.9	166	1.02	1.01	1.03	1.03	-0.12	-0.13	0.79	1.00
246.1	168.5	1.01	1.04	1.05	1.05	0.76	0.76	0.13	1.04
251.3	172.5	1.04	1.02	1.06	1.06	-0.38	-0.39	1.06	0.98
253.2	174	1.01	1.00	1.01	1.01	-0.17	-0.17	0.83	1.00
260.9	180	1.01	1.03	1.03	1.04	0.52	0.51	0.28	1.02
270.6	187.5	1.02	1.01	1.03	1.03	-0.19	-0.20	0.86	1.00
280.3	195	1.03	1.02	1.05	1.05	-0.23	-0.25	0.90	0.99
309.3	217.5	1.02	1.02	1.04	1.04	-0.14	-0.15	0.81	0.99
316.3	223	1.04	1.08	1.12	1.12	0.30	0.28	0.44	1.03
334.4	237	1.01	1.02	1.03	1.03	0.59	0.59	0.23	1.02
VCS6									
58.3	10								
63.7	15								
71.5	22.2								

79.3	29.4	1.03	1.01	1.04	1.04	-0.36	0.37	0.37	0.99
87.1	36.6	1.02	1.02	1.03	1.04	0.11	-0.10	0.76	1.00
94.9	43.8	1.03	1.05	1.08	1.08	0.25	-0.24	0.89	1.02
102.7	51	1.01	1.05	1.06	1.07	0.66	-0.65	1.40	1.04
110.5	58.2	1.03	1.02	1.06	1.06	-0.16	0.18	0.52	0.99
118.2	65.4	1.02	1.04	1.07	1.07	0.35	-0.33	1.00	1.02
125.4	72	1.01	1.01	1.03	1.03	0.00	-0.01	0.67	1.00
131.6	77.8	1.00	1.02	1.02	1.02	0.76	0.75	0.13	1.01
139.2	84.8	1.02	1.03	1.05	1.05	0.19	0.17	0.52	1.01
147.0	92	1.01	1.02	1.03	1.03	0.19	0.18	0.51	1.01
152.4	97								
160.0	104	1.01	1.01	1.02	1.02	0.35	0.35	0.39	1.01
167.8	111.2	1.01	1.01	1.01	1.01	-0.07	-0.08	0.74	1.00
175.5	118.4	1.01	1.02	1.03	1.03	0.61	0.60	0.22	1.02
183.3	125.6	1.02	1.06	1.09	1.09	0.44	0.42	0.34	1.04
191.1	132.8	1.00	1.03	1.04	1.04	0.78	0.77	0.12	1.03
198.9	140	1.00	1.03	1.04	1.04	0.81	0.80	0.10	1.03
207.6	148	1.01	1.00	1.01	1.01	-0.48	-0.48	1.18	1.00
214.5	154.4	1.02	1.00	1.02	1.02	-0.59	-0.60	1.33	0.99
222.3	161.6	1.01	1.01	1.02	1.02	0.46	0.46	0.31	1.01
220.5	160	1.01	1.09	1.09	1.11	0.83	0.83	0.09	1.08
217.3	157	1.02	1.01	1.02	1.03	-0.58	-0.58	1.31	0.99
221.6	161	1.02	1.01	1.02	1.02	-0.49	-0.49	1.19	0.99
224.3	163.5	1.02	1.04	1.06	1.06	0.33	0.32	0.41	1.02
228.1	167	1.01	1.01	1.02	1.02	0.01	0.01	0.66	1.00
230.0	168.8	1.00	1.06	1.06	1.07	0.88	0.88	0.06	1.05
239.3	177.4	1.02	1.02	1.04	1.04	-0.06	-0.07	0.73	1.00
245.6	183.2	1.01	1.02	1.03	1.03	0.08	0.07	0.60	1.00
253.4	190.4	1.01	1.02	1.04	1.04	0.34	0.33	0.40	1.01
262.7	199	1.01	1.02	1.03	1.03	0.55	0.55	0.25	1.02
VCEI2									
25.7	20	1.06	1.05	1.11	1.11	-0.06	0.09	0.59	0.99
37.0	30	1.02	1.02	1.05	1.05	0.02	0.00	0.67	1.00
48.2	40	1.27	1.23	1.56	1.57	-0.06	0.17	0.52	0.97
59.4	50	1.01	1.05	1.06	1.06	0.53	0.52	0.27	1.03
67.8	57.5	1.01	1.04	1.05	1.06	0.75	0.75	0.14	1.04
76.3	65	1.03	1.02	1.05	1.05	-0.13	-0.14	0.79	0.99
84.7	72.5	1.01	1.03	1.04	1.04	0.41	0.41	0.35	1.02
93.1	80	1.01	1.02	1.03	1.03	0.39	0.38	0.37	1.01

104.3	90	1.01	1.01	1.02	1.02	-0.22	-0.23	0.89	1.00
109.9	95	1.01	1.05	1.06	1.06	0.59	0.58	0.24	1.04
118.4	102.5	1.02	1.02	1.04	1.04	-0.09	-0.10	0.76	1.00
126.8	110	1.01	1.02	1.03	1.03	0.24	0.23	0.48	1.01
135.2	117.5	1.01	1.03	1.04	1.04	0.40	0.39	0.36	1.02
138.6	120.5	1.01	1.01	1.03	1.03	-0.01	-0.01	0.68	1.00
143.6	125	1.01	1.01	1.02	1.02	0.22	0.21	0.49	1.00
147.6	128.5	1.01	1.00	1.01	1.02	-0.65	-0.65	1.41	0.99
152.1	132.5	1.01	1.01	1.02	1.02	0.15	0.14	0.54	1.00
156.0	136	1.00	1.02	1.02	1.02	0.63	0.62	0.21	1.01
160.5	140	1.01	1.02	1.02	1.02	0.47	0.46	0.31	1.01
171.1	149.5	1.01	1.01	1.02	1.02	-0.20	-0.21	0.87	1.00
179.6	157	1.01	1.03	1.04	1.04	0.38	0.37	0.37	1.01
189.7	166	1.01	1.01	1.02	1.02	0.17	0.17	0.53	1.00
196.4	172	1.00	1.00	1.01	1.01	0.08	0.07	0.60	1.00
205.4	180	1.01	1.00	1.01	1.02	-0.60	-0.60	1.34	0.99
VCEI3									
36.4	29	1.05	1.02	1.07	1.07	-0.39	-0.41	1.08	0.97
56.7	47	1.03	1.15	1.19	1.21	0.62	0.60	0.22	1.12
74.6	63	1.01	1.02	1.03	1.03	0.44	0.43	0.33	1.01
79.1	67	1.01	1.05	1.05	1.06	0.72	0.72	0.15	1.04
85.3	72.5	1.01	1.01	1.03	1.03	0.01	0.01	0.66	1.00
93.7	80	1.01	1.10	1.11	1.12	0.89	0.89	0.06	1.10
102.2	87.5	1.01	1.01	1.02	1.02	0.35	0.34	0.39	1.01
110.6	95	1.04	1.01	1.05	1.05	-0.61	-0.61	1.35	0.97
121.8	105	1.00	1.03	1.03	1.04	0.87	0.87	0.07	1.03
126.3	109	1.00	1.02	1.02	1.02	0.75	0.75	0.13	1.02
135.9	117.5	1.02	1.01	1.03	1.03	-0.07	-0.08	0.74	1.00
144.3	125	1.03	1.02	1.05	1.05	-0.25	-0.27	0.93	0.99
152.7	132.5	1.02	1.01	1.03	1.03	-0.14	-0.14	0.80	1.00
161.2	140	1.01	1.02	1.03	1.03	0.08	0.07	0.60	1.00
169.6	147.5	1.03	1.01	1.04	1.04	-0.66	-0.67	1.43	0.97
183.6	160	1.01	1.01	1.02	1.02	-0.22	-0.23	0.89	0.99
205.0	179	1.02	1.00	1.02	1.02	-0.86	-0.86	1.74	0.98
211.7	185	1.01	1.01	1.02	1.02	0.20	0.20	0.50	1.00
220.2	192.5	1.01	1.01	1.02	1.02	0.05	0.04	0.63	1.00
228.6	200	1.01	1.02	1.03	1.03	0.59	0.59	0.23	1.02
237.0	207.5	1.02	1.07	1.08	1.09	0.62	0.61	0.22	1.05

Table 17. Table of hysteresis and IRM data results for Ship Harbor

Core Name	Sampling Depth Top, Corrected for compaction	Sampling depth top (cm), core reference uncorrected	Bulk Susceptibility	Mass normalized magnetization Ms	Hysteresis Saturation (Ms)(T)	Hysteresis Remanence (Mr)	IRM Coercivity (mT) (Hcr)
VCS6_TN	58.3	10	-7.97E-06		-3.11E-07	9.62E-09	73.03
VCS6_TN	63.7	15	-6.70E-06		5.85E-08	2.17E-09	
VCS6_TN	71.5	22.2	-8.18E-06	-1.79E-03	-1.44E-07	2.59E-09	
VCS6_TN	79.3	29.4	-6.38E-06	9.49E-05	7.67E-09	5.04E-09	
VCS6_TN	87.1	36.6	-9.62E-06	-1.71E-03	-1.41E-07	3.43E-09	
VCS6_TN	94.9	43.8	-8.57E-06	-3.49E-03	-1.97E-07	1.41E-09	29.95
VCS6_TN	102.7	51	-9.60E-06	-3.07E-03	-2.28E-07	2.22E-09	
VCS6_TN	110.5	58.2	-8.85E-06	-1.71E-03	-1.06E-07	-3.75E-10	
VCS6_TN	118.2	65.4	-8.58E-06	5.32E-05	-1.37E-08	-4.48E-09	
VCS6_TN	125.4	72	2.02E-05	2.02E-03	1.98E-06	4.54E-08	43.55
VCS6_TN	131.6	77.8	3.29E-05	9.81E-03	3.51E-06	4.44E-07	48.80
VCS6_TN	139.2	84.8	8.86E-05	3.00E-03	1.90E-06	3.36E-08	44.61
VCS6_TN	147.0	92	5.39E-05	2.34E-03	2.87E-06	5.29E-08	47.46
VCS6_BN	152.4	97		1.24E-02	3.16E-06	4.10E-07	44.42
VCS6_BN	160.0	104	3.26E-05	2.42E-03	2.40E-06	4.87E-08	43.32
VCS6_BN	167.8	111.2	3.51E-05	2.58E-03	2.33E-06	4.82E-08	
VCS6_BN	175.5	118.4	3.36E-05	2.63E-03	2.63E-06	6.84E-08	46.08
VCS6_BN	183.3	125.6	3.40E-05	2.82E-03	2.13E-06	4.85E-08	44.86
VCS6_BN	191.1	132.8	3.02E-05	2.21E-03	2.52E-06	5.48E-08	
VCS6_BN	198.9	140	2.54E-05	2.01E-03	2.06E-06	4.47E-08	
VCS6_BN	207.6	148	6.10E-05	6.88E-03	3.13E-06	7.34E-08	
VCS6_BN	214.5	154.4	1.44E-04	1.46E-02	5.44E-06	1.40E-07	37.72
VCS6_BN	222.3	161.6	2.02E-04	1.30E-02	4.56E-06	1.87E-07	47.85
VCS6_BN	230.0	168.8	2.84E-05	1.86E-03	2.12E-06	3.65E-08	
VCS6_BN	239.3	177.4	5.55E-05	1.29E-02	3.57E-06	1.81E-07	42.93
VCS6_BN	245.6	183.2	3.46E-05	5.90E-03	2.75E-06	6.82E-08	
VCS6_BN	253.4	190.4	3.10E-05	2.52E-03	2.74E-06	5.81E-08	42.17
VCS6_BN	262.7	199	1.44E-05	1.01E-02	2.77E-06	5.34E-08	

Table 17. Continued from previous page

Core Name	Sampling Depth Top, Corrected	Sampling depth top, core reference	Bulk Susceptibility	NRM Intensity	Mass normalized Ms	Hysteresis Coercivity (mT) (Hc)	Hysteresis Remanence (Mr)	IRM Coercivity (mT) (Hcr)
VCS2_TN	50.5	16.6	-1.03E-05		-3.93E-03	3.84	-5.72E-10	51.90
VCS2_TN	60.2	24.2	-9.82E-06					
VCS2_TN	69.5	31.4	-9.41E-06		-4.87E-03	-26.56	-1.59E-09	52.35
VCS2_TN	88.1	45.8	-9.82E-06					
VCS2_TN	97.3	53	-7.75E-06	1.15E-03	-1.18E-03	-37.06	8.04E-09	45.79
VCS2_TN	114.3	66.2	3.70E-05	9.51E-02	2.32E-03	20.66	8.42E-08	45.69
VCS2_TN	125.4	74.8	3.85E-05	8.26E-02	2.69E-03	39.98	5.61E-08	44.58
VCS2_TN	134.4	81.8	3.12E-05	1.25E-01	3.08E-03	14.19	2.22E-07	44.79
VCS2_TN	143.7	89	3.14E-05	4.97E-02	1.95E-03	7.06	2.99E-08	47.47
VCS2_TN	151.7	95.2	3.60E-05	3.94E-02	2.62E-03	11.81	5.82E-08	46.28
VCS2_TN	162.3	103.4	3.68E-05	6.51E-02	2.83E-03	7.58	4.42E-08	45.52
VCS2_TN	171.5	110.6	3.29E-05	8.66E-02	2.45E-02	13.63	1.58E-07	45.24
VCS2_TN	180.8	117.8			2.73E-03	7.53	4.12E-08	43.64
VCS2_BN	190.1	125	2.64E-05	7.95E-02	2.43E-03	9.84	3.36E-08	0.00
VCS2_BN	199.8	132.5	2.70E-05	7.25E-02	4.27E-03	8.94	4.62E-08	43.20
VCS2_BN	209.4	140	2.65E-05	8.02E-02	2.48E-03	10.30	3.81E-08	45.08
VCS2_BN	224.9	152	3.56E-05	7.11E-02	3.01E-03	10.00	3.19E-08	46.62
VCS2_BN	236.0	160.6	6.41E-05	9.86E-02	9.34E-03	9.12	9.91E-08	40.50
VCS2_BN	239.7	163.5	1.44E-04	9.62E-02	1.26E-02	7.54	1.31E-07	36.92
VCS2_BN	242.9	166	1.14E-04	1.65E-01	1.28E-02	6.37	7.88E-08	37.86
VCS2_BN	246.1	168.5	9.97E-05	1.24E-01	8.28E-03	7.20	8.04E-08	38.51
VCS2_BN	251.3	172.5	1.06E-04	6.69E-02	4.97E-02	3.38	1.11E-07	35.88
VCS2_BN	253.2	174	1.74E-04	1.45E-01	6.21E-03	9.63	1.34E-07	35.18
VCS2_BN	260.9	180	3.47E-05	1.12E-01	2.95E-03	10.62	4.40E-08	48.46
VCS2_BN	270.6	187.5	3.28E-05	1.65E-01	3.68E-03	13.49	4.54E-08	42.97
VCS2_BN	280.3	195	1.67E-04	1.26E-01	2.14E-02	6.56	1.52E-07	32.06
VCS2_BN	309.3	217.5	4.87E-04		1.70E-01	2.98	5.64E-07	18.19
VCS2_BN	316.3	223	3.98E-04	3.25E-01	9.03E-03	6.26	6.79E-08	36.59
VCS2_BN	334.4	237	7.05E-04	1.03E+00	3.37E-03	9.45	6.16E-07	35.34

Table 18. Table of hysteresis and IRM data results for Eliza Island

Core Name	Sampling Depth Top, Corrected for compaction	Sampling depth top, core reference (uncorrected)	Bulk Susceptibility	NRM Intensity	Hysteresis Coercivity (mT)	Mass normalized Ms	Hysteresis Remanence (Mr)	IRM Coercivity (mT) (Hcr)
VCEI2_TN	25.7	20	-4.17E-06		-0.02	-0.002	-4.40E-10	
VCEI2_TN	37.0	30	-7.52E-06		56.18	-0.002	7.98E-09	56.18
VCEI2_TN	48.2	40	-1.15E-06		0.029	0.001	8.59E-09	
VCEI2_TN	59.4	50	5.15E-05		48.39	0.003	1.07E-07	48.39
VCEI2_TN	67.8	57.5	7.07E-05		15.70	0.004	1.01E-07	
VCEI2_TN	76.3	65	4.28E-05		52.13	0.003	7.03E-08	52.13
VCEI2_TN	84.7	72.5	5.62E-05		16.55	0.003	1.04E-07	
VCEI2_TN	93.1	80	5.69E-05		81.99	0.004	1.30E-07	81.99
VCEI2_TN	104.3	90	7.86E-05		22.00	0.003	1.15E-07	
VCEI2_TN	109.9	95	1.83E-04		47.09	0.003	1.18E-07	47.09
VCEI2_BN	118.4	102.5	1.61E-04		23.38	0.025	1.27E-06	
VCEI2_BN	126.8	110	5.98E-05		47.57	0.004	5.26E-08	47.57
VCEI2_BN	135.2	117.5	8.25E-05		49.27	0.003	5.45E-08	49.27
VCEI2_BN	138.6	120.5	1.07E-04				n/a	
VCEI2_BN	143.6	125	1.14E-04		11.96	0.005	6.88E-08	41.94
VCEI2_BN	147.6	128.5	1.51E-04				n/a	
VCEI2_BN	152.1	132.5	2.08E-04		39.89	0.018	1.62E-07	39.89
VCEI2_BN	156.0	136	1.10E-04					
VCEI2_BN	160.5	140	8.20E-05		11.79	0.007	1.09E-07	
VCEI2_BN	171.1	149.5	7.82E-05		41.83	0.001	9.76E-08	41.83
VCEI2_BN	179.6	157	4.04E-04		23.20	0.005	2.15E-07	
VCEI2_BN	189.7	166	4.09E-04		27.45	0.005	2.23E-07	63.15
VCEI2_BN	196.4	172	7.22E-05		9.08	0.012	1.56E-07	
VCEI2_BN	205.4	180	9.02E-05		22.36	0.004	1.31E-07	

Table 18. Continued Table of hysteresis and IRM data results for Eliza Island, continued from previous page.

Core Name	Sampling Depth Top, Corrected for compaction	Sampling depth top, core reference (uncorrected)	Bulk Susceptibility	Hysteresis Coercivity (T)	Mass normalized (Ms)	Hysteresis Remanence (Mr)	IRM Coercivity (mT) (Hcr)
VCEI3_TN	36.4	29	1.64E-03	1.43E-02	0.006	2.17E-07	37.30
VCEI3_TN	56.7	47	2.97E-04	6.60E-03	0.003	6.16E-08	
VCEI3_TN	74.6	63	1.17E-04	5.99E-03	0.020	2.02E-07	
VCEI3_TN	79.1	67	8.27E-05	8.67E-03	0.007	1.14E-07	44.86
VCEI3_TN	85.3	72.5	7.19E-05	6.66E-03	0.011	1.04E-07	
VCEI3_TN	93.7	80	1.30E-04	1.11E-02	0.008	1.29E-07	45.23
VCEI3_TN	102.2	87.5	6.41E-05	7.84E-03	0.006	6.59E-08	48.86
VCEI3_TN	110.6	95	2.32E-04	1.01E-02	0.004	8.55E-08	
VCEI3_BN	121.8	105	8.30E-05	9.76E-03	0.004	9.33E-08	
VCEI3_BN	126.3	109	7.80E-05	8.55E-03	0.003	1.04E-07	45.93
VCEI3_BN	135.9	117.5	7.51E-05	1.16E-02	0.003	1.08E-07	11.15
VCEI3_BN	144.3	125	1.06E-04	1.24E-02	0.006	1.96E-07	
VCEI3_BN	152.7	132.5	1.92E-04	1.71E-03	0.081	1.47E-07	0.00
VCEI3_BN	161.2	140	1.54E-04	8.91E-03	0.006	1.27E-07	
VCEI3_BN	169.6	147.5	1.13E-04	1.09E-02	0.006	1.43E-07	
VCEI3_BN	183.6	160	2.12E-04	6.86E-03	0.022	2.52E-07	36.02
VCEI3_BN	205.0	179	1.47E-03	3.66E-03	0.095	5.23E-07	
VCEI3_BN	211.7	185	1.13E-03	6.96E-03	0.130	1.42E-06	
VCEI3_BN	220.2	192.5	9.14E-04	7.84E-03	0.082	7.63E-07	30.99
VCEI3_BN	228.6	200	1.93E-03	7.61E-03	0.232	1.63E-06	
VCEI3_BN	237.0	207.5	9.14E-04	1.12E-02	0.089	1.15E-06	

Table 19. High temperature vs susceptibility for samples analyzed

Core Name	Sampling Depth Top, Corrected for compaction (cm)	Sampling depth top, core reference (cm)	Temp vs susceptibility weight (g)	Temperature Vs Susceptibility Curie Temperature
VCS2n	114.3	66.2	0.0905	575
VCS2n	199.8	132.5	0.0815	575
VCS2n	242.9	166.0	0.1642	575
VCS2n	316.3	223.0	0.1084	575
VCS6n	131.6	77.8	-	-
VCS6n	222.3	161.6	0.2632	575
VCS6n	253.4	190.4	0.0900	550-575
VCEI2n	93.1	80.0	0.1221	unclear
VCEI2n	171.1	149.5	0.2189	575
VCEI2n	196.4	172.0	0.2619	575
VCEI3n	56.7	47.0	0.2345	575
VCEI3n	102.2	87.5	0.0875	575
VCEI3n	183.6	160.0	0.2549	550-575
VCEI3n	220.2	192.5	0.1775	575-600

Table 20. Table of PSV declinations and inclinations, other important data

Ship Harbor	OxCal (years before 2000CE)	Age Error (+/-)	MAD	Inclination	Inclination correction degrees	Declination	Core Depth	Age from PSV Inclination before AD 2000	Age from PSV Declination before AD 2000	Years since 2019	Error	
UC1	415.5	250	2.2	52.9	63.82	8.5	66.2		440	1560	185	UC1
UC2	550	352	5.6	32.6	44.53	57	74.8					UC2
UC4	849.5	431	9.3	38.1	50.34	35.4	89					UC4
UC5	1004.5	413	3.8	39.9	52.14	18	95.2		1010	990	35	UC5
UC6	1148	367	5.1	35.3	47.45	11.7	103.4		1100	900	10	UC6
UC7	1307	274	9.1	49.3	60.79	14.6	110.6		1310	690	100	UC7
UC8	1591	116	3.7	61.9	70.86	9.8	125	1580	1520	420	100	UC8
UC9	1653	125	4.6	55	65.53	8.2	132.5		1575	425	100	UC9
UC10	1707.5	106	6.6	59.7	69.20	24.3	140	1720		280	100	UC10
S2	1824.5	34.5	17	50.6	61.90	54.4	152					S2
LC1	3101	256	3.6	53	63.90	37.7	180					LC1
LC2	3275.5	273	6.6	52.6	63.57	41.8	187.5					LC2
S1	1824.5	34.5	12.1	54.1	64.80	34.9	168.5					S1
Omitted												
UC3	694.5	412		40	52.24	90.9	81.8					
UC11	1811	34		22.9	33.02	122.8	152					
S1	1824.5	34.5		28	39.28	312.1	160.6					
S1	1824.5	34.5		20.9	30.43	293.3	166					
S3	1824.5	34.5		51.9	62.99	316.9	172.5					
BS1	4618	252		46.6	58.42	288.1	237					

Table 21. Table of Eliza Island declinations (Dec) and inclinations (Inc) measured

Component	Estimated Age	Error	Dec	Inc	MAD	Limit 1	Limit 2	Core Depth	Bulk Susceptibility	NRM intensity	PSV Estimated age, inclination	PSV estimated age, Declination	Years before 0CE
C1	1542	61	19.3	55.6	2.2	5	25	50	5.15E-05	7.28E-02			
C2	2221	165	142.3	65.7	8.5	2.5	20	57	7.07E-05	8.47E-02	2200		-200
C3	2819	376	55.3	66.9	4	10	70	72.5	5.62E-05	1.68E-01	2575		-575
C4	3359	695	47.6	69.3	3.2	7.5	60	80	5.69E-05	2.41E-01			
C5	3810	1088	25.8	60.7	2.6	7.5	65	90	7.86E-05	3.07E-01			
C6	4218	1563	57	66.4	3	5	55	95	1.83E-04	5.68E-01		4050	-2050
C7	4526	2093	26.1	52.4	4.1	7.5	35	102.5	1.61E-04	2.39E-01			
C8			345.2	75.4	3.8	12.5	35	110	5.98E-05	2.07E-01			
C9	4731	2698	118.2	74.2	11.3	10	25	120.5	1.07E-04	2.56E-01			
S1	5291	4935	323.4	70.2	2.7	5	35	149.5	7.82E-05	2.65E-01	5500		-3500
S2	6186	5051	49.1	72.9	4.4	10	60	166	4.09E-04	2.32E+00	6000		-4000

Table 22. Table of GeoCLAW Modeling parameters, adapted from Witter et al. (2013)

CASCADIA EARTHQUAKE SOURCE PARAMETERS USED TO DEFINE 13 RUPTURE SCENARIOS							
Earthquake size	Intersevent time (yr)	Fault geometry	Slip range (m)		M_w	Scenario name	Total weight
			Max.	Avg.			
Extra-extra-large (0.026)	1200	Splay fault (0.8)	35–44	18–22	~9.1	XXL1	0.02
		Shallow buried rupture (0.1)	38–44	18–22	~9.2	XXL2	0.0026
		Deep buried rupture (0.1)	38–44	18–22	~9.1	XXL3	0.0026
Extra-large (0.025)	1050–1200	Splay fault (0.8)	35–44	17–22	~9.1	XL1	0.02
		Shallow buried rupture (0.1)	35–44	17–22	~9.2	XL2	0.0026
		Deep buried rupture (0.1)	35–44	17–22	~9.1	XL3	0.0026
Large (0.16)	650–800	Splay fault (0.8)	22–30	11–15	~9.0	L1	0.128
		Shallow buried rupture (0.1)	22–30	11–15	~9.1	L2	0.016
		Deep buried rupture (0.1)	22–30	11–15	~9.0	L3	0.016
Medium (0.53)	425–525	Splay fault (0.6)	14–19	7–9	~8.9	M1	0.318*
		Shallow buried rupture (0.2)	14–19	7–9	~9.0	M2	0.106
		Deep buried rupture (0.2)	14–19	7–9	~8.9	M3	0.106
Small (0.26)	300	Splay fault (0.4)	9–11	4–5	~8.7	SM1	0.104
		Shallow buried rupture (0.3)	9–11	4–6	~8.8	SM2	0.078
		Deep buried rupture (0.3)	9–11	4–6	~8.7	SM3	0.078

Note: Logic tree branch weights are shown in parentheses in third column. Total scenario weight is listed in far-right column.
 *Scenario M1 carries the highest weight and represents the “most-likely” event in our analysis.

ESTIMATED EARTHQUAKE MAGNITUDES FOR CASCADIA RUPTURE SCENARIOS

Rupture scenario	Length (km)	Width* (km)	Intersevent time (yr)	Maximum slip† (m)	Average slip‡ (m)	Seismic moment§ (x10 ²² N m)	Moment magnitude** (M _w)
XXL1	1000	83	1200	41	20	8.8	9.1
XXL2	1000	105	1200	41	20	8.4	9.2
XXL3	1000	83	1200	41	20	8.8	9.1
XL1	1000	83	1200	41	20	8.8	9.1
XL2	1000	105	1200	41	20	8.4	9.2
XL3	1000	83	1200	41	20	8.8	9.1
L1	1000	83	800	27	13	4.4	9.0
L2	1000	105	800	27	13	5.8	9.1
L3	1000	83	800	27	13	4.4	9.0
M1	1000	83	525	18	9	2.9	8.9
M2	1000	105	525	18	9	3.7	9.0
M3	1000	83	525	18	9	2.9	8.9
SM1	1000	83	300	10	5	1.7	8.7
SM2	1000	105	300	10	5	2.1	8.8
SM3	1000	83	300	10	5	1.7	8.7

*Equivalent fault width; modeled fault width varies with latitude.

†Maximum slip estimates are the product of the intersevent times and the convergence rate in southern Oregon (34 mm yr⁻¹).

‡Average slip estimate is 0.48 of maximum slip estimate.

§Seismic moment (M_s) = Fault area × slip × rigidity, where rigidity = 4×10^{10} Pa.**Moment magnitude (M_w) = (log M_s – 8.1)/1.5.

Table 23a. OxCal Sequence Model incorporating PSV dates and C¹⁴ dates to determine the age of SHb1. Estimated age for sand-sheet SHb1 is in bold.

Name	Unmodelled cal. years B.P.		Confidence	Modelled cal. years B.P.		Confidence
	from	to		from	to	
Boundary Top VCS2				151	-558	95.4
C_Date Western Settling	151	111	95.4	152	111	95.4
C_Date UC1_66.2	761	21	95.4	718	133	95.4
C_Date UC5_89	1031	891	95.4	1030	892	95.4
C_Date UC6_95.2	1071	1031	95.4	1071	1031	95.4
C_Date UC7_103.4	1461	1061	95.4	1345	1064	95.4
C_Date UC8_110.5	1461	1061	95.4	1448	1165	95.4
R_Date VCS2n_RC28	1546	1414	95.4	1540	1412	95.4
C_Date UC9_125	1726	1326	95.4	1665	1439	95.4
C_Date UC10_132.5	1871	1471	95.4	1755	1543	95.4
R_Date VCS2n_RC6	1864	1730	95.4	1783	1718	95.4
Bed SHb1				1804	1731	95.4
R_Date VCS2n_RC14	1815	1714	95.4	1820	1753	95.4
R_Date VCS2n_RC12	1821	1722	95.4	1825	1745	95.4
R_Date VCS2n_RC13	2759	2739	95.4	2759	2738	95.4
R_Date VCS2n_RC17	2705	2464	95.4	2705	2465	95.4
Phase Max Ages Bed A						
R_Date VCS2n_RC23	3567	3462	95.4	3568	3462	95.4
R_Date VCS2n_RC25	4424	4291	95.4	4423	4259	95.4
Boundary Bottom VCS2				5052	4265	95.3
Sequence Ship Harbor B						

Table 23b. OxCal sequence model incorporating PSV dates from VCEI2 samples. The estimated age for sand-sheet EIb2 is in bold.

Name	Unmodelled (BP)			Modelled (BP)			A	C
	from	to	%	from	to	%		
Boundary Top				2746	730	95.4		96.2
C Date C2 57	2730	1530	95.4	2774	1724	95.4	101	99.7
C Date C3 72.5	3105	1905	95.4	3157	2134	95.4	102	99.6
C Date C6 95	4180	3780	95.4	4180	3780	95.4	99.9	99.8
R Date Min Age Bed 2 Eliza VCEI2n RC28	4862	4726	95.4	4755	4650	95.4	4.8	99.9
Bed 2 Eliza				4815	4667	95.4		100
R Date VCEI2n RC19	5213	4878	95.3	5048	4879	95.4	100	100
R Date VCEI2n RC1	4825	4615	95.4	4830	4707	95.4	96.6	100
Phase A Bed EIb2								
C Date S1 149.5	6030	4830	95.4	5261	4978	95.4	81.3	100
R Date VCEI2n RC8	5287	5039	95.4	5289	5050	95.4	107	100
C Date S2 166	6330	5530	95.4	6219	5410	95.4	91.2	99.7
Boundary Base				7239	5428	95.4		97.5
Sequence Eliza Island a								

APPENDIX 1 GOUGE AUGER DESCRIPTIONS

S1	
Depth	Description
P1	P1
	Peats, possibly compacted due to pushing the auger in
0	deeper than 1m
60	Muddy peat
63	63 – 66cm Sand with high organics content
66	66 – 77cm Mostly sand, with some mud content
77	

S2	
Depth	Description
P1	P1
0	Peat, possibly compacted 10-20cm
58.8	58.8cm Small layer, appears to contain some sand and consists of darker colored peat
59	59 – 63cm Peat
63	63.5 – 76+ Sand
76+	

S3		
Depth	Description	
P1	P1	
0	0 – 60cm Peat, alternating in colors	
60	60 – 61cm Transition from peat to sand	
		~98 is another peat layer
61	61 – 100cm Sand, silty and grey/blue in color	
100	100 – 109cm mud with some peat present	
109		

S4	
Depth	Description
P1	P1
0	cm Peat (was compacted into 60-130cm)
130	130 – 132cm Muddy sand
132	132- 160cm Sand
160	

S5	
Depth	Description
P1	P1
0	Peat
100	Sand, contains various colored sand, sub angular to sub rounded clasts present at lower depths
140	

S6	
Depth	Description
P1	P1
0	0-83cm Peat
83	83 – 101cm Blue/grey mud
101	101 – 125cm Peat (possibly squished there? Might not be natural)
125	125 – 176cm mud, similar to what is above
176	176 – 200cm Sand
200	

S7	
Depth	Description
P1	P1

S8	
Depth	Description
P1	P1
0	Lost return
50	Peat
60	Sand with angular clasts, unconsolidated
100	

S9	
Depth	Description
P1	P1
0	Lost return
30	Peat – slightly muddy, produces turbulent water
67	Grey mud, with 10% organics, roots etc
133	blue/grey mud
173	Muddy sand, about 90% sand, medium grained, some pockets of black and white, angular sand which contains >50% quartz sand. Some small gravels present
190	

S10	
Depth	Description
P1	P1
0	Peat
60	Peaty mud, mostly mud with ~50% organics
75	Blue/grey mud
100	Mud w/several pinecones? And other organics, ~10%
130	sandy mud, produces a 1in ribbon (sandy loam?)
155	Lost end of the push, but residue in barrel suggests sand
200	

S11	
Depth	Description
P1	P1
0	Lost return
29	Peat
91	Lost return
104	Peat
109	Mud, with 10% organics, no gravels
130	Gritty mud, likely has some sand grains present
170	Sandy mud, with minor amounts of sand present
204	Muddy sand
	Muddy sand with about 3-5 "pockets" of more pure sand, which are well sorted and contain black and white sands.
230	Some gravel clasts present, subangular to subrounded, and poorly sorted.
270	

S12	
Depth	Description
P1	P1
0	Peat, when squeezed produces turbulent water
84	84 – 87cm Muddy, clayey peat, brown
87	87 – 104cm clayey mud, grey in color, contains about 10% organics
104	Silty clay mud, produces a 1.5in ribbon, smells very sulfurey, abundant organics ~20%
183	Peat (perhaps scraped from sides on way down?)
185	Mud – silty, grey and contains about 20% organics
	Sand – poorly sorted, with some organics, white organic “flakes” present, possibly some white small shell pieces??
220	Some bits of charcoal present as well. Roots exist in top 4-5cm. Some larger gravel clasts to 1cm in size. Some larger wood fragments to 1cm in size.
238	Mud with some sand “pockets” present
240	Clay/Mud, blue/grey similar to above sand, gritty
284	

	S13	
	Depth	Description
	P1	
34	0	0 – 34cm Lost return – maybe peat
57	34	34 – 91cm Peat – lighter in color down section
102	91	91 – 193cm grey mud with abundant organics, no gravels
40	193	193 – 233cm Mud
5	233	233 – 238cm mixed sand and mud
13	238	238 – 251 mostly sand mixed with some mud, sub rounded, various colors
8	251	251 – 259cm Mud, mixed with some sand
35	259	259 – 294cm Mud, with some sand, poorly sorted, some large clasts to 2cm in size, subangular to sub rounded
	294	

	S14	
	Depth	Description
	P1	
97	0	0 – 97cm peat
7	97	97 – 104cm grey mud, slightly gritty
8	104	104 – 112cm Peat, possibly scraped from sides on way down
93	112	112 – 205cm Mud, organics 10%
35	205	205 – 240cm Mud, no gravels, 5-10% organics
		240 – 251cm Sand, one wood chunks present 2cm, clayey on top, grades to sand (normal grading), sand and some mud, sand appears subrounded, gravels at base of section
13	240	<1cm
47	253	251 – 300cm Pure mud, slightly grainy
5	300	300 – 305cm Gravely mud, gravels to 2cm diameter
	305	

	S15 Depth P1	Description
16	0	Lost – potentially peat
88	16	16 – 104cm Peat
86	104	104 – 190cm Clay/mud, grey, 10% organics
2	190	190 – 192cm Sand, micas present, subangular, poorly sorted, >50% sand
7	192	192 – 199cm Sandy mud (mostly mud)
2	199	199 – 201cm Sand, poorly sorted, >50% sand
4	201	201 – 205cm sandy mud, contains pebbles to .7cm
56	205	205 – 261cm Mud with one gravel 1cm in diameter
14	261	261 – 275cm Sandy mud, >50% mud
5	275	275 - 280cm Muddy sand, >50% sand, some gravels <1cm and subangular
24	280	280 – 304cm is muddy sand, bad return, soupy
	304	

S16	
Depth	Description
P1	P1
0	Lost – likely peat
40	40 – 105cm Peat
105	105 – 110cm Peat
110	110 – 206cm Grey mud, slightly gritty, some gravels <.5cm @165cm, ~5% organics present
206	206 – 232cm Sandy grey mud
232	232 – 240 muddy sand, sand >50%, high quartz content, subangular to subrounded
240	240 – 250cm Sand, sand >80%, subangular to subrounded, high quartz content (lots of white sand present), abundant small gravels and several wood chips throughout. Gravels include larger quartz gravels
250	250 – 252cm muddy sand similar to 232-240cm section
252	252 – 307cm Mud with some sand around 252 some gravels 0.4-1cm diameter.
307	

	S17 Depth P1	Description	
44	0	Lost return	
7	44	44 – 51cm Peat	
2	51	51 – 53cm Lost return	
42	53	53 – 95 Peat	
5	95	95 – 100 Transition from peat to grey brown mud, very muddy peat >50% organics	
5	100	100 – 105cm Mud, 20% organics, grey brown color	
15	105	105 – 120cm Peat – may be artificial due to collection on way down hole	
43	120	120 – 163cm Mud, gritty (some sand content), 10- 20% organics	
24	163	163 – 180cm ~10% sand in mud	@176cm large gravel clast 2cm diameter
3	187	180 – 194cm >50% sand in mud, 10% organics throughout	
4	190	@190-194cm >80% sand	
18	194	194 – 212cm similar to 190-194	
46	212	Sand, unconsolidated and soupy, poorly sorted, white and mixed colors, >80% sand with gravels throughout	
	258	194 – 215 sand >80%	
		@221cm gravel 1.5cm	
		@227cm large gravel clast	

	S18 Depth P1	Description	
10	0	Peat	
7	10	10 – 17cm Lost return	
53	17	17 – 70cm Peat	
5	70	70 – 75cm transition, lighter brown peat	
18.5	75	70 – 93.5cm mud, 20% organics, very smooth <1% sand, brown grey color	
27.5	93.5	93.5 – 121cm Mud, brown 30-40% organics, very soupie and unconsolidated	
42	121	121 – 163cm Sand >80% with some mud, gravels present starting at 150cm	
30	163	163 – 193cm Lost return, unconsolidated and soupie sand	
18	193	193 – 211cm sand >90%, poorly sorted fine to coarse, various colors ranging from black to white, mixed with mud, brown/black, white large organic present	
		Sharp, distinct contact here	
59	211	211 – 270cm Mud, smooth, slightly gritty, very well consolidated	@266 large gravel clast 1cm
9	270	270 – 279cm Soupy unconsolidated sand, poorly sorted up to 3mm, >80% sand	
21	279 300	279 – 300cm soupie sand with >50% organics	

	S19 Depth P1	Description
22	0	lost return
59	22	22 – 81cm peat
13	81	86 – 94cm Muddy peat, 50% organics
5	94	94 – 99cm >50% organics
25	99	99 – 124cm 20-30% organics
10	124	124 – 134cm Muddy sand, ~50% sand
36	134	134 – 170cm >80% sand, various colors black to white, white quartz grains, poorly sorted fine to coarse
16	170	170 – 186cm Peat
26	186	Sand, >80%, organics 10%, mud present, sand poorly sorted
23	212	212 – 235cm 50/50% sand and mud, sand similar to above
10	235	235 – 245cm Sand, poorly sorted >80%
		Abrupt transition here
6	245	245 – 251cm Mud, 5-10% sand
7	251	251 – 258cm Sand, >80% poorly sorted
		258 – 266cm soupie unconsolidated mud with some sand
8	258	“pockets” concentrated within
	266	

S20	
Depth	Description
P1	P1
0	0 – 67cm Peat
67	67 – 71cm Gradual transition from peat to mud
71	71 – 101cm mud, 20% organics
101	101 – 130cm mud, grey brown, 20% organics
130	130 – 135cm sandy mud, appears well sorted with sand in “pockets” concentrated
135	135 – 150cm regular graded from mud at top to sand at bottom. Sand is poorly sorted and abundant
150	150 – 156cm sand, poorly sorted, contains pinecone parts or wood chips
156	156 – 178cm Sand, some organics, >90% sand with some mud
178	178 – 208cm Sand, poorly sorted, contains gravels to .7cm
208	208 – 215cm Gradual transition to mud ~50% sand
215	215 – 260cm Mud with 10-30% sand, sand % increases down section, abundant gravels throughout ~25% and up to 1.5cm in size. Contains some spiral shell fragments
260	176-208cm contains many shell fragments @200 small shell piece @220 large shell piece

	S21 Depth P1	Description
83	0	0 – 83cm Peat, variable n color, darker at top. Lighter in middle, darkens again at bottom
5	83	83 – 88cm transition from peat to mud
9	88	88 – 97cm Mud wih ~10% organics
8	97	97 – 105cm Mud with sand, coarsens down section, ~30-50% sand at bottom. Mud is grey brown
10	105	105 – 115cm Mud
2	115	115 – 117cm Peat
8	117	117 – 125cm transition, coarsens down section to gravels <1cm
73	125	125 – 198cm Sand, >80%, 10-20% organics with gravels to 1.8cm, sand poorly sorted, fine to coarse
	198	
	Refusal	

	S22		
	Depth	Description	
	P1		
104	0		
4	104	104 – 108cm Peat	
97	108	108 – 205cm Mud, <5% sand, slightly gritty, grey brown color, Top half ~10% organics, ~5% organics in bottom half	Large organics @138cm and @180cm
29	205	205 – 234cm Mud with ~5% sand	
3	234	234 – 237cm diagonal, small sand layer – perhaps smeared due to core barrel sides?	
3	237	237 – 240cm Mud with ~50% sand	
7	240	240 – 247cm Sand, poorly sorted	
3	247	247 – 250cm Mud with ~50% sand	
5.5	250	250 – 255.5cm Peat with large gravels to 2m	
9.5	255.5	255.5 – 265cm sand with gravels to 2cm, poorly sorted >80% sand	
19	265	265 – 284cm Soupie unconsolidated mud, smooth with ~10% sand content	
20	284	Lost return	
	304		
	25		

S23		
Depth	Description	
P1	P1	
0	0 – 19cm Lost return	
19	19 – 85cm Peat	
85	85 – 97cm Transition from peat to mud, >50% organics throughout but less towards bottom	
97	97 – 104cm Mud, brown grey with ~20-30% organics	
104	104 – 122cm Peat	
122	122 – 129cm Transition from peat to mud	
		large organic
129	129 – 205cm Mud, grey/blue in top 30cm, grey brown throughout, produces a 2in ribbon	@156cm, appears to be a pinecone seed/part
205	205 – 222.5cm Mud	
	Abrupt transition to Sand	
222.5	222.5 – 231cm Sand with gravel 1cm at bottom, grades normally, organics present throughout	
231	231 – 244cm Sandy clay with gravels to .5cm	
244		
257	257 – 305cm lost return – soupy sand	
305		
Alternative:		
134	134 – 214cm Mud	
214	214 – 223cm Sand, poorly sorted, gravels throught to 1cm, organics present	
223	223 – 232cm mud with ~30% sand	
232		

S24	
Depth	Description
P1	P1
0	0 – 79cm Peat
79	79 – 94.5cm Mud with 30-40% organics
94.5	94.5 – 193cm Mud, grey brown, <1% sand, large organic at 70-75cm, 30% organics throughout
193	
127	127 – 134cm Peat
134	134 – 209cm Mud, some sand towards the bottom, gravels to .5cm
209	209 – 223cm Sand, poorly sorted
223	223 – 229cm Mud, with sand mixed
229	

S25	Description	
Depth	P1	
P1	P1	
0	0 – 64cm Peat	
64	64 – 72.5cm Transition to mud from peat	
72.5	72.5 – 104cm Mud, some mica flakes, ~30% organics	
		104 –
104	104 – 177cm Mud with some large organics, grey	125 some mottling of clay
177	177 – 198cm Sand with some mud, large gravels to 1cm at 178 and 185cm	
188	188 – 197cm sand, poorly sorted, with gravels to 2cm	
197	197 – 204cm no return	
204	204 – 214cm mud and sand 50/50% only part of barrel is full	
214	214 – 220cm lost return	
220	220 – 242cm poorly sorted sand, black to white, with gravels to 2cm at base and throughout	
242	242 – 247.5 Mud with some sand, bad return, soupey and unconsolidated, ~10% organics	
247.5	247.5 – 288cm soupey bad return, with large gravel 2.5cm	
288		

S26		
Depth	Description	
P1	P1	
0	0 – 17cm lost return	
17	17 – 98cm Peat	
98	98 – 104.5cm Sand, ~50% sand with mud, abundant organics 20%	At base at 104.5cm large organic, pinecone piece
Abrupt transition to next unit		
104.5	104.5 – 114cm Mud, smooth, grey brown, large organic, gritty	
114	114 – 118cm 50/50% mud and sand, mottled dark and light in color	
118	118 – 139.5cm Sand >70% with some mud, ~20-30% organics	
139.5	139.5 – 167cm Mud, gritty <5% sand, 20% organics	
167	167 – 176cm sandy >50%, with large gravels to 1cm, matrix supported	
176	167 – 198cm Sandy mud, no good return, ~40% organics, 30- 40% sand in mud,	
198		

S27 Depth P1	Description P1
0	0 – 33cm lost return upon come up, some large organics left in barrel
33	33 – 87cm Peat, block layer 4mm thick at 70cm and 78cm
87	87 – 104cm Sand, ~40% organics, >90% sand, large gravel at base, sand is poorly sorted, ranging from medium to coarse
104	104 – 185cm Sand >90% with some mud, gravels throughout to 2.5cm, matrix supported, organics ~20% throughout in small tufts
185	185 – 204cm lost return, appears as soupie unconsolidated sand and mud, sand is poorly sorted medium to coarse colors white to black
204	

S28	
Depth	Description
P1	P1
0	0 – 23.5cm lost return
23.5	23.5 – 98cm Peat
98	98 – 105cm Peat
	105 – 114cm Sand, poorly sorted, medium to coarse
105	>90%, contains small charcoals throughout, 10-20% organics
	Distinct contact
114	114 – 116cm Mud, ~50% sand
	Distinct contact
116	116 – 118cm sand >80% in mud, poorly sorted medium to coarse, organics 5-10%.
118	118 – 119cm mud ~50% sand
119	119 – 160cm Sand, poorly sorted medium to coarse, 3mm biggest, mixed quartz and other sand
160	160 – 197cm lost return
197	

S29

Depth	Description
P1	P1
0	0 – 16cm lost return (peat?)
16	16 – 80cm Peat, lightens in color downsection
80	80 – 106cm Peat
106	106 – 110cm transition, appears “smeared” up and down section
110	110 – 181cm Mud, <5% sand, ~10% organics
181	181 – 230cm Mud, <1% sand, grey brown, ~5-10% organics, 2in ribbon (mostly clay)
230	230 – 241cm Peat >50% organics, mixed with mud with pinecone bits @ top of section
	Abrupt transition
241	241 – 262 Sand >90% organics ~10% very solid top 10cm, unconsolidated/soupie below that
262	262 – 270cm Soupie, lost return, mostly sand in barrel
270	270 – 281cm Clay at base of barrel, bad return
281	

S30	
Depth	Description
P1	P1
0	0 – 96cm Peat
96	96 – 103cm transition to mud from peat – gradual
103	103 – 106cm peaty mud, ~60% mud, 40% organics and <1% sand
106	106 – 111cm Peat
111	111 – 208cm Mud, contains <2% sand, slightly gritty, and typically 10-20% organics throughout
208	208 – 229.5cm Mud, ~10% organics, <1% sand
229.5	229.5 – 233cm Sand, poorly sorted, >70% sand, fine to coarse, ~10% organics throughout
233	233 – 236cm Mud and sand 50/50%
236	236 – 238cm Sand >80%, poorly sorted
238	238 – 249cm Mud, <5% sand, smooth to touch Sharp, abrupt contact
249	249 – 253cm Sand >90% poorly sorted fine to lower coarse, inset in some mud, some organics ~10%
253	253 – 263cm Mud with sand ~30%, poorly sorted and produces 1.5in ribbon
263	263 – 309 – lost return for most part, large organic at 288-290cm
309	
189	189 – 223cm Mud, normally graded and with sand at the bottom Abrupt transition
223	223 – 230cm Sand in mud, sand poorly sorted, white to black, subrounded fine to coarse. Abrupt transition
230	230 – 250cm Mud
250	250 – 260cm Sand concentrated into “pockets” within mud, sand size is poorly sorted.
260	

@159-163cm large wood fragment organics make up most of barrel

S31	
Depth	Description
P1	P1
0	Peat, lighter downsection and more mud content
104	downsection
P2	
104	Peat, gradual transition below
127	Mud with <5% sand, ~20% organics. Sand increases at
205	bottom. Lighter color at top, mottled color from 140-160,
P3	dark from 160 to bottom
205	
306	Blue/grey mud, ~5-10% organics throughout
	end push 3

S32	
Depth	Description
P1	P1
0	
104	
P2	
104	Lost most of push - top is 10cm of peat with 20cm of clay below that.
P3	Tape lined up to top of push
206	Blue grey mud with <5% sand, produces a 1in ribbon
at 221	Shell fragments with 60% organics
at 283	Shell fragment
at 260	decomposed shell fragmetns, ~10% shells

S33	
Depth	Description
P1	P1
0	Peat, soupey at top and base
104	
P2	
	Grey green mud, <5% sand, around 160-165cm very
104	soupey
205	
P3	
	Mud, organics content ranges from 5-60%, mica sands can
	be seen throughout but no grit indicates very low sand
205	content
at 220	Organics are the most, at 60%
280-282	shell fragments present
306	

Thickness	S34 Depth	Description
	P1	
104	0	Peat
	104	end
	P2	
102	104	Grey mud with <5% sand, organics throughout, sand increases to 5% at bottom of section
	206	end
	P3	
41	205	~5% sand in mud, organics ~20-30%, gradual transition to layer below
5	246	Sand ,normally graded at tjop from fine sand and mud
2	251	Coarse sand 100%, subangular
2	253	Muddier, with ~60% sand
25	255	90+% sand in some mud, sand is fine to coarse, poorly sorted
0	280	Large organics and shell fragments
27	280	Mud, brown/grey, no sand <5%, organics ~10%
	307	

S35	
Depth	Description
P1	P1
P2	
104	Mud, gritty at bottomw ith few small gravels Top 5cm ~10% sand, rest below that is <5% sand throughout, grey clay rich mud, well consolidated wth
176	~20% organics
at 194	~5-10% sand
276	

	El_1	Field Description
	P1	
#VALUE!	P1	Mud, wet, with some large gravels
18	28	Mud, grey and brown mixed, gravels throughout to 1.5cm
3	46	Large pocket of sand next to gravels, sand >90% total
23	49	Grey mud with gravels to 1.5cm, sand poor
5	72	High organic content soil mixed with grey mud, small wood-looking fragments
11	77	Brown mud with no sand, some gravel clasts throughout
17	88	Grey mud, some grit <5% coarse sand, few small gravels
	105	End Push
		Push full but did not completely get auger in ground, matched tape to top of push on auger then recorded depth based on that. Perhaps did not get into hole straight for second push
	P2	
16	63	Mud, matrix supported gravels within
24	79	Grey mud with occasional gravels
16	103	Brown organic rich mud
3.5	119	Grey mud
1	122.5	Two large gravels
3.5	123.5	Smooth, sand poor mud
2	127	Gravelly grey mud, some grit (~5% sand), mud is compact at bottom
34.5	129	Concentration of gravels within section
	163.5	End push

El_2
Depth

P1 P1

0 Organic rich top soil, some large gravels present

14 Gravely mud, some sand clast supported

at 68 Some small shell fragments

88 Sandy mud with few large gravels

at 91-93 Imbricated gravels to 1cm

103 End push

El_3
Depth

P1

P1

0

Coarse sand with gravels to 1.5cm

45

Clayey, silty sandy mud, fine to coarse sand, occasional gravel, most small to 1cm, matrix supported. Soil ribbon is 1in

76

End push 1

P2

76

Coarse sand and gravels, sand >80% with some mud

83

Dark grey, mud with ~50% sand, >1in ribbon

96

Mud with <20% sand, some gravels throughout to 1cm

108

Gravelly sandy mud, coarser sand ~50% total

at 128

2cm thick pocket of sand, sand >80%

139

Sand >80% with mud, whole shell at 131cm

147

Mud with ~50% sand, some small gravels

152

Sand ~80%, grey color, mixed with mud, large gravel at base 1.5cm

157

Clay, grey, with fine sand ~20% throughout, produces 3in ribbon, more sand at top and decreases downsection

174

End Push 2

El_4	
Depth	
P1	P1
0	Coarse, gravelly sand
	Mud with ~50% sand, gravels to
55	1cm
	Grey mud, clay rich, produces
	2in ribbon, some coarse sands
102	but no large gravels
105	End push
P2	
75	Coarse sand mixed with gravels,
90	~50% sand in mud
97	<30% sand in grey mud
103	~50% sand in mud
	Organic rich, brown mud with
125	some organics present
132-133	Large gravel fills core barrel
135	Sandy layer
	Brown mud with clay and
137	organics
	Sand 95%, including quartz
	sand, subrounded, white and
139	black
	Compact, hard clay, occasional
	gravel to .5cm. @64cm some
	more sand, clay has areas of
	grey and brown, sand content
	increases at bottom, produces a
143	5in ribbon, charcole can be seen
	throughout
167	End P2

El_5	
Depth	
P1	P1
0	Top soil
15	Brown sand >80% sand, occasional gravels to .75cm
24.5	Mottled sand, grey mostly with some light brown color mottled throughout
78	Blue grey mud, some light brown organics, but mostly mud, basically no sand, occasional small wood fragments. Dark streaks throughout - perhaps charcoal
105	End push
Unable to collect P2	

El_6	
Depth	
P1	P1
0	Top soil, modern roots
16	Transition, gradual to sand
23	Sand >90%, grey, varies from fine to coarse
52	Coarser sand >90%, grey with small gravels to .5cm
58	Brown/red mud, grainy with a little sand ~5%
62	Sand, coarse, slanted due to barrel? >90% sand, coarse, small gravels
63	Mud - clay rich, grey blue, few coarse sands, produces 4in ribbon
79	Sandy clay, grey with ~40-50% sand
83	Mud, <40% sand, less sand further down section
87	End push
Refusal	

El_7
Depth

P1

P1

0

Top soil

Brown sandy soil with some light brown motteling in
color

30

50

Clayey, light tan

53

Coarse sand in mud, sand >50%

62

End push

EI8
Depth
P1

P1

0 Top soil

Sandy soil, large gravel at 33cm 2.5cm

13 large

Mottled grey with light brown sandy

42 soil

Mud/clay rich, grey blue with some
brown organics and mottled area,
varies in color from grey blue to
brown, last 5cm are crumbly, dry and

54 hard

~50% sand above 100% mud, some

63 gravels to 1cm

73 End push

El_9	
Depth	
P1	P1
0	Lost
17	Top soil
	Grey sand with organics and occasional gravels to
25	1.5cm
	Dark ~50% sand mostly clay/mud, at 80cm there
74	are many roots around gravel clasts
83	Sand in mud, sand ~50-60%, fine to coarse
89	Dark brown, same as above
91	Grey sand similar to 83-89
	Crumbly blue clay, super compact, block texture,
95	no sand, no gravels
104	End push

El_10	
Depth	
P1	P1
0	Top soil
37	Large gravel 2cm
38	Sand >90% fine to coarse, brown
44	Lost return
63	Clay mud with coarse sand, some gravels to 1cm, organic rich
74.5	lost return, some roots present
105	
Refusal	

	El_11	
	Depth	
	P1	
37	0	Top soil
31	37	Grey mud with ~10% organics
		Mud, dark grey/blue, gravel to .75cm
		@183cm, <5% sand, some grit but not
25	68	much
	93	End push
	P2	
		Mud, grey/brown with some ravel to
42	93	.5cm <1% sand, no grit
		Sand, quartz sand white and black,
		medium to coarse grained, some organics
5	135	present throughout
		Dark brown clay mud, very little sand,
13	140	large gravel @150 to 1cm
14	153	Sand >80% mixed with some mud
		Mud, with <10% sand, dark brown,
23	167	organics and wood chips present
		end push - bottom lost, sounded like
	190	gravel/sand at the bottom

	El_12 Depth P1	
28	0	Top soil, O horizon, Organic rich brown soil with high clay content
17	28	
1	45	small pocket of sand
		Grey blue clay, no grit, nos and, exept sand conentrated into pockets at 47cm and 60- 61cm. Sand is coarse and have some gravels o .5cm
17.5	46	
	47	Small pocket of sand
	at 60-61	Pocket of sand
		Organic rich clay, some areas of concentrated organics with roots present, some mica sands seen throughout, basically no grit/sand
20.5	63.5 84	End push, lost bottom
	P2	went to 1.5m depth
20	84	Clay, grey with areas of brown concentarted organics Grey clay, <5% sand, some grit from coarse sand, sub- angular
34.5	104	
	at 138.5 at 143	Small sand layer, sand is subangular to subrounded, Coarse, and contains quartz Same as 138.5
9	138.5	Mud, grey/brown, with some mica sands, <5%
23.5	147.5	Silty sand, sand starts around 5% and increases downsection to >50% Abrupt transition
2	171 173	Mud, brown, with ~5% sand End push

El_13	
Depth cm	
P1	P1
	Top soil, organic rich, brown, abundant roots, gradual transition to clay
0	
27.5	Grey clay, organics throughout
At 56	Small line/pocket of sand and gravel to 1.5cm
57	Grey and brown mud, sand <5%, some grit, some organics throughout
66.5	Sand pocket
68	Brown silty clay, breaks apart into blocky chunks
69	Grey and brown mud with <5% sand
73	Sand, poorly sorted, fine to lower coarse
74	Brown grey mud with <5% sand
at 80	Large gravel 2cm
82	Compacted grey mud with organics throughout, charcole present
86	end push
Lost end of push	
P2	
	Mud <5%, some grit, mostly unconsolidated, organics present throughout, gradual lower transition
86	Silty brown mud with ~10% sand, micas and quartz grains, subangular to subrounded
109	
121	Brown mud with sand increasing downsection, sand is white and black, quartz and micas
at 137	large wood fragment
143	Soubey sand-rich brown mud, ~50% sand, organics ~40% total
	Mud, clay rich, grey with sand and some organics throughout, sand is generally coarse
167.5	
188	end push 2

P3	
188	lost top
193	Grey brown clay
198	Blue grey mud with ~50% gravel and sand
218.5	Grey blue clay
	Pocket of coarse sand and gravels
From 221-224	~50%+
244	End push 3

	El_14	
	Depth	
	P1	
40	0	Top soil, o horizon, brown
		Transition from soil to clay, gradual
8	40	and light brown
		Clay rich mud, mottled in color, light
		brown and grey <5% sand, roots and
		wood throughout, gravel to 1.3cm at
26	48	68cm
		Large pocket of coarse sand, white
		and quartz rich, within similar clay as
2	74	above, gravels to .3cm
10	76	Same as above 48-74
		Dark brown organic rich clay, >50%
9	86	organics, some sand <5%
		Mottled grey and brown colored
9	95	mud with <5% sand
	104	End push
	P2	
		Mud, clay rich, with ~20% organics,
		mottled colors of grey and light
		brown, mostly well compacted, but
52	104	less consolidated from 141-144
		~50% coarse sand in some grey clay-
2	156	rich mud
		Brown mud/clay with <5% sand,
		which appear as micas, very smooth,
		produces 1.5in ribbon, silty and
12	158	crumbly
		Sand >50%, content increases
		downsection, sand is poorly sorted
		fine to Lco, >90% at bottom, with a
20	170	few gravels throughout to .5cm
	190	End push 2

El_15
Depth
0

P1

34

Transition to clay/mud, light brown
Grey and brown clay with gravels to
.9cm, ~5% sand, with coarse sand

45

seen throughout
Similar to above with ~50% sand,
sorted into "pockets" but also
throughout in matrix, sand is coarse
and has abundant quartz. Organics
throughout and gravels to 1.3cm
throughout, making up ~10% of
composition

56

At 81

Pocket of sand

85

End push 1

P2

85

Grey mud/clay, well consolidated,
some sand at 90cm some large
organic fragments throughout

at 90 within section

Sand

101

Mud in 1/2 of barrel, rest is same as
above with large pocket of sand
~80% in mud, sand is poorly sorted,
medium to coarse and has some
small gravels

105

Same as 85-100 section
Abrupt transition

108

Brown, organic rich material, with
sand concentrated at 112cm, sand is
medium to coarse, gravels to .8cm
throughout

at 112

Sand within section

118

Soupey brown mud with gravels to
1.1cm

124.5

Brown silty soil, compact, crumbly,
some organics, produces a 1in
ribbon

125

Half of barrel is fine sand in the same
material as above

128-129

Fine sand well sorted into brown
silty soil

El_16

Depth

P1

P1

Top soil, dark brown, from 15-20 is a
lighter brown color and gradual

0

transition

20

Large gravel 2cm

>50% sand and gravels in
grey/brown mud, abundant organics

20

~30-40%

Grey mud with ~30% sand and

30

gravels

36

>50% sand and gravels in grey mud

Grey brown mud with gravels
throughout to 1.4cm abundant
organics (10-20%) and coarse sand
(10-20%)

41

End Push 1

63

P2

63

Unconsolidated mud and organics

67

Soupey mud, ~30% organics

79

lost return

Grey mud, clay rich, with 20-30%
coarse sand and gravels ~10% and to
1.6cm, sand contains quartz and
micas, some roots

82

at 113

concentration of sand

at 120

concentration of sand

127

Mud with ~80% sand, sand is poorly
sorted, fine to lower coarse, roots
and organics present

133

End p2

	El_17 Depth	
	P1	
31	0	Top soil, dark brown to black
5	31	Transition from to clay
14	36	grey clay rich mud with ~5% sand, gritty with gravel to .5cm
		Pocke of sand in grey mud, sand is coarse, 100% sand, mixed composition with quartz and sand
1	50	
4	51	Gritty mud similar to 36-50
2	55	sand and gravels to .5cm
		Grey /brown mud, clay rich with sand concentrated into areas listed below. Whole section is generally ~30% sand, with small gravels present throughout, mostly grey mud.
6	57	
2	63	coarse sand >50%
14	65	Sandy mud (similar to above)
20	79	>50% sand
	80	Large gravel
	84	large gravel
	99	End of section and push
	P2	
8	99	Dark grey mudw ith ~30% sand, large 2.2cm gravel at 105cm
		Grey and brown mud with ~20-30% sand, organics ~10-20%, and occasional gravels 5-10% to 1cm.
30	107	Lost end of push
	137	Hard at end, hitting refusal about 1.75m depth, possibly super hard clay?

El_18	
Depth	
P1	P1
	14cm at top of barrel empty
0	Top soil - dark brown
26	Transition to clay, light brown
30	Brown/greyh mud, sand >50%, gravels throughout to 1.2cm
	Mud, grey brown, with ~30-40% sand, poorly soted coarse, with fine .5cm or less gravels
43	
53	Lost end of push
90	End

El_19b	
Depth	
0	P1
26	Transition to clay - light brown
31	Sand >50%, gravels throughout to 2cm, some organics present
38	lost return
52	Same as 31-38
63	Mud, <50% sand, sand is coarse
67	Same as 52-63cm, sand is coarse >50% (>80%), gravels abundant to .5cm
73	Lost end of push, sounded like sand/gravels at bottom of push
104	End of barrel
P2	
73	Mud, soupey, with >80% sand, mostly coarse and sub-angular, some gravels to 1.6cm
128	Light blue/grey clay, super compact, <5% sand contains some organics, crumbly, can see glimmer of mica sands present throughout
157.5	End Push 2

EI_20

Depth

0

P1

28

Clay, grey, with ~5% sand, compact

32

Sand rich >90%, poorly sorted, fine to coarse, subrounded to rounded

44

Mud, grey with ~30% sand

47

Sand >90%, fine to coarse, subangular, in mud

50

same as 44-47

53

Sand >80%, some areas are light brown in color, rest is grey, sand contains quartz

sand ~60-80%, brown mud, organics throughout

60

67

Light blue/grey mud, very compact, some charcoal

84

Mush, unconsolidated, black and light brown mud, contains organics

87

Blue/grey mud

at 89

Large 2cm gravel

94

End push

El_21	
Depth	
0	P1
	Mud, compact, grey with fine micas
27	seen throughout
31	>80% sand, coarse, organics present ~10% in grey mud
39	Mud with ~40-50% sand
42	Coarse sand >80% like 31-39 with ravels to 1cm, angular to subangular
46.5	Mud with ~40-50% sand
49	Sand >80%
51.5	Sand ~50% in grey mud, with organics (roots)
58	Sand >50%, coarse
	Light blue/grey clay, color is mottled with light brown, some dark soupier mud at 83-85, some small gravels at top
63	
From 83-85	Soupier/unconconsolidated
89.5	End push

	El_22 Depth P1	
20	0	no return
10	20	top soil
		Soupey gravelly mud, contains rock
35	30	3cm
		abrupt transition
		Grey mud with gravels and ~5% sand
	65	including mica sand
1	68	Sand rich black layer, sand is coarse
		Soupey gravelly sand, with large
8.5	69	gravels to 2.5cm at base, gravels at
		base are imbricated
		Mud, grey with gravels throughout
24.5	77.5	to .5cm
#VALUE!	at 90	Large shell fragment
#VALUE!	at 93	Large shell fragment
0	102	End P1
	P2	
7	102	Gravelly soupey - artificial?
		Mud, grey with gravels, matrix
10	109	supported
		Mud, well consolidated, grey/brown,
		gravels throughout to 1.1cm, ~5-10%
21	119	sand
		Dark brown mud with <5% sand,
		gravels throughout concentrated
10.5	140	@144
		Grey mud, some gravels to .5cm,
8.5	150.5	<5% sand
		Soupey mud with clast supported
5	159	gravels
3	164	Sand >80%, small gravels <.5cm
4.5	167	Mud, grey with ~30% sand
		Mud with gravels ~40%, and ~30%
10.5	171.5	sand
		>80% sand, coarse, poorly sorted in
5	182	mud, subangular
16	187	Brown grey mud, some gravels
	at 194	Sand >50%
	at 197	Small shell fragment
	203	end of push 2

EI_23

Depth

0

P1

36

Top soil

46

Mixed dandy soil + top soil

Sandy organic rich soil, produces
<1in ribbon, some clay content,
abundant organics. Clay content
increases to 100% clay grey/green at
bottom, last 2-3cm. Some micas can

67

be seen within

96

End push

El_24	
Depth	
0	P1
14	Top soil
	Sand >90% in clay, sand is fine to coarse, occasional small gravels.
22	From 43-57 there is a mottled section, light brown and grey
at 64	Clay rich section ~1cm thick
68	Clay rich, sand ~30-40%
70	Large light brown sand pocket
70	Brown mud, with ~30% coarse sand
73	Light grey/blue mud with 80% coarse sand
76	light grey mud with less sand, sand concentrated into pockets
	Sand >80% fine to coarse in light grey mud, roots and organics present. Unconsolidated and very gravelly at base
78	
90	Mud with <30% coarse sand. Some gravels to .5cm
	Sooth mud, grey with large sand pocket running vertically through middle
93	
98.5	sand layer, >80% sand
99	Same as 93-98
	Summer compact light blue mud, contains charcoal, crumbly, no sand, mottled in color, light brown and light blue/bre.
101.5	
105	End push
	Refusal beyond this point.

El_25	
Depth	
0	P1
10	top soil
37	Grey brown clay with ~20% sand
at 40	Large gravels and roots
40	sandy clay, sand >80%, poorly sorted
48.5	clay rich, sand ~50%
50	sand ~90%
54	Sand ~80% in grey clay with areas of light brown mottled color
62	Sand >90%, same mottled color, more clay and gravel to 1cm at base
66	Grey clay with 20-30% sand
71	Sand >80% in grey mud with mottled light brown throughout
76	~50% sand in mud/clay, grey with mottled color of light brown
88	Grey green mud with some concentrated sand @90 and @93, otherwise ery little sand, some gravels to .5cm
94	Mud, light grey and green, super compact, no sand
98	Light grey sand with mud, sand >80%, fien to coarse grained
101	Mottled light grey/blue and green, super compact mud, no sand
104	end push

El_26	
Depth	
0	P1
34	Top soil
	Dark brown clay rich with ~30-40% coarse sand throughout, some large gravels within, large gravel @66cm,
53	@70cm, @72cm
	Gravelly sand >80% in grey mud.
77	Sand is subangular and coarse,
98	gravels throughout to 1cm.
	End push
Lost P2	

EI_27

Was not able to collect or penetrate
below 10cm with auger. Sounds like
gravel

P1

#VALUE!	El_28 Depth P1	Top soil
		Sand >80%, concentrated in grey mud, sand is subangular to rounded, fine to coarse, gravel at base to 1cm
2	62	
6	64	Grey mud, ~10% sand
		Pocket/line of sand >50%, fine to coarse
1	70	
5	71	Sooth grey mud
		Organic rich dark brown mud with <5% sand
10	76	
		Grey mud, <1% sand, basically no grit at all
18	86	
	104	
	P2	
		Grey mud with <5% sand, some micas can be seen throughout, produces a 2in ribbon
28.5	104	
	at 132	Concentration of medium to coarse sand
		Organic rich grey and light brown mud <5% sand
12.5	132.5	abrupt transition
		Grey mud with ~50% sand, grades into layer below
6	145	
		Sand >90%, fine to lower coarse, mixed with grey mud, gravel at botom to 1cm
5	151	
		abrupt transition
10	156	Mud, dark grey, with ~10-20% sand
		Mud with at least 50% sand, produces a .5in ribbon. Organics throughout including wood fragments, some gravels to 1.2cm,
19	166	sand is fine to caorse
	at 169	>90% sand
	at 175	>90% sand
		~50% sand in brown mud, abundant organics
10	185	
	195	

	El_29 Depth P1	
45	0	Top soil
11	45	Transition from soil to clay
3	56	Soupey, unconsolidated mud with >80% coarse sand and gravels
2.5	59	Grey mud with <5% sand
5	61.5	Mud with ~50% sand, sand is medium to coarse, sub angular and concentrated into veins/pockets
2.5	66.5	Mud with ~20-30% sand
	at 69	Concentration of sand >80%
34	69	Grey mud with ~50% sand, some gravels throughout to 1cm, sand contains quartz and is fine to coarse
	at 74	Concentration of sand >80%
	at 90	Concentration of sand >80%
	103	End push 1
	P2	
8	103	Smooth brownmud <5% sand, large gravel 2cm
8	111	Smooth mud with no sand, large gravels
3	119	Sand >50% in grey mud, large gravel at base
11	122	Grey mud with ~30% sand
12	133	>50% sand in mud, sand is fine to coarse, poorly sorted gravels throughout (about 15-20% total comp) to 1cm
	at 140	Concentration of of fine sand and organics seen throughout
11.5	145	Mud with ~50% sand, large gravels to 2.5cm with ~80% sand around gravels
8.5	156.5	~80% sand in mud, sand is fine to coarse, sub rounded
3	165	Soupey mud with ~80% coarse sand and gravels
8	168	Soupey mud with large gravels and sand >60%

4	176	90% sand and gravels in mud, poorly sorted gravels to .5cm
3	180	Smooth brown mud, <20% sand
3	183	Soupey, unconsolidated with ~80% sand
4	186	Unconsolidated soupey return, brown mud with some coarse sand and small gravels
8	190	Mud with ~30-50% sand and gravels, grey brown color, gravels are subrounded
	198	End Push 2

El_30
Depth
0

P1

40 Grey mud with ~30% coarse sand,
mottled colors of brown and grey

49 >80% sand in mud, fine to coarse,
one large gravel 2.6cm in size

53 Grey mud with <30% sand

56.5 90% sand, coarse, in mud, gravel at
base 1cm

58 Mud, grey with 40-50% sand and
gravels to 1cm, sand is medium
coarse and subrounded

77 50-70% sand in mud

84 Soupey mud with ~20% sand,
contains gravels

89 ~50% mud and ~50% sand, with
coarse gravels to 1cm

at 97 Sand is concentrated here

103 End push 1

P2

103 Sandy brown mud, sand ~50-70%

117 Soupey mud, with ~50% sand,
gravels to .5cm

133 End Push 2

Refusal

El_31

Depth

P1

0

P1

Top soil

55

Grey mud with <10% (~5%) sand,
some mica sands seen throughout

at 80

sand in small layer

at 89

small amount of sand and gravels
present in concentration

104

End push 1

P2

whole push: Mud, dark grey with
ares of concentrated sand and
occasional gravels, mud contains

104

<10% sand

111

Sand >80%

117

Sand >80%

126-127

Sand >80%

133

Sand >80%

149

Organic rich section - brown
Below 150, <5% sand and produces a
1.5cm ribbon

150

1.5cm ribbon

195

Sand >80%

Soupey return at bottom -

197

unconsolidated mud

203

End push 2

	El_32 Depth	
#VALUE!	P1	Top soil, bottom 10cm are a gradual transition from top soil to clay rich
		Grey mud with ~10% organics,
		basically no sand <5% mud has grit,
54	50	2+ in ribbon
	104	End push 1
	P2	
9	104	Grey clay rich mud with <10% sand
7	113	Sand ~20% in grey mud
0	120	Concentration of sand ~50%
		<10% sand, clay mud with organics
24	120	~20%
20	144	Compact grey mud with <5% sand
2	164	Soupey brown mud
10	166	Compacted grey mud with <5% sand
		>50% sand in grey mud, sand is fine to coarse, with quartz and mica composition
16	176	
13	192	Same as above with ~40% sand
	205	End push 2

	El_33	
	Depth	
	P1	
54	0	Top soil, organic rich
30	54	A horizon, well developed soil
		Grey mud with <5% sand, some large organics throughout, produces a 2in ribbon
20	84	
	104	
	P2	
17	104	Grey mud with <5% sand
1	121	Sand concentrated, ~50%, sand is fine
2	122	~50% sand fine, gravel at base to 1cm
12	124	<5% sand in mud, same as above
1	136	Area of fine sand and gravel s
5	137	<5% sand in mud
10	142	Mud with ~30% sand, fine to medium, sub angular
5	152	Dark brown mud with <5% sand
20	157	Dark brown silty clay with 10-20% sand, produces a 1.5in ribbon
6	177	Dark mud with ~20% sand
2	183	Large gravel, well rounded
8	185	Dark grey >70% sand in mud
7	193	Dark brown mud with <20% sand, mooth slightly gritty to touch
	200	End push 2
		end of barrel is soupey, unconsolidated wet sand

Appendix 2: Vibracore Descriptions

	VCS1_N	Location: Ship Harbor, Anacortes	Date core collected:	Compaction:	Date core analyzed:	Starting length: 10ft	322.975	
					9/9/2018	IF:	180.975	
						OF:	55.753	
			Compaction factor:	0.468606627		Si	125.222	
						Pi	267.222	
						Du (excpeted)	123.825	
						Du (actual)	142	
						Difference:	18.175	
Thickness (cm)	Corrected depth for compaction (cm)	Depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape/Rounding	Gradeing	Boundary to lower horizon	Notes
105.7	0.0	0.0	Brown	Peat	Coarse, plant structures not identified		gradual	100% peat, produces turbulent water when squeezed
82.2	105.7	32.0	grey brown	Clay				Peat on side of core, decreases downsection, mostly high organics clay
27.2	187.9	88.0	black, white, grey	Clay	Fine, smooth		wavy	Clay mud with abundant organics
2.2	215.1	106.5	Black, white, grey	Sandy clay		sand is well sorted	unclear	Band of sand, mostly sand
11.7	217.3	108.0	Grey, black	Sand pockets within mud		well sorted		pockets of sand contained in mud
27.9	229.0	116.0	grey brown	Clay		well sorted	diagonal	Clay mud, no sand
10.3	256.9	135.0	Brown grey	Clay, organics				Partially clay tapering off, organic at base of core, large organic at base = appears to be a cattail reed root.
	267.2	142.0						

VCS2_N			Location: Ship Harbor, Anacortes	Date core collected:	Compaction:	Date core analyzed:	Starting length: 13ft	409.5
			At S12			9/17/2018	IF:	160.528
							OF:	59.69
				Compaction factor:	0.288241986		Si	100.838
							Pi	349.838
							Du (actual)	249
							Du (expected)	235.712
							Difference:	13.288
Section Thickness (cm)	Corrected depth for compaction (cm)	Depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape/Rounding	Gradeing	Boundary to lower horizon	Notes
106.4	0.0	0.0	5YR 2.5/1, 10YR 2/2	Organic - peat			gradual, over 8cm	Peat with 100% organics
42.5	106.4	60.0	4/10Y with lighter color mottled throughout, with mottling decreasing dowsection	Clay, organics present throughout			Gradual end of mottled coloring	Large organic from 69-71cm
6.4	148.9	93.0	4/10Y	Clay, organics present throughout, <5% sand			gradual	
11.6	155.3	98.0	4/10Y	Clay with <5% sand, ~30% organics throughout			gradual	Large organics present
48.3	166.9	107.0	4/10Y	Clay with <5% sand			Gradual	
15.5	215.2	144.5	4/10Y	Clay with 10-20% organics			Gradual	at 144.5cm, large organic fragment

23.8	230.7	156.5	4/10Y, 2.5/N	Clay , sand, organics, clay coatings on shells, large shell fragments throughout, sand is sorted well into its own areas with shells		Well sorted	gradual, with pockets of sand extending downwards and into lower section	South marked section of core contains a half a muscel shell, herbaceous organics from 167-171cm
25.8	254.5	175.0	4/10Y	Clay, clear organic at 183cm			Gradual	No sand
9.0	280.3	195.0	3/10Y	Clay with ~20-30% sand, large gravel between 198-201cm.			Gradual, cut off by large wood	
8.4	289.3	202.0	3/N	Sand, fine to lower coarse	Sub angular to subrounded		Gradual	Shell fragments throughout, shells appear stratified
22.5	297.7	208.5	4/10Y	Sandy mud and gravels	Subrounded	Sorted	abrupt change in gravel content	Gravels present are concentrated between 112-116, sand and mud are well sorted in areas
29.6	320.2	226.0	2.5/N	Coarse gravesl and shelss mised with sand and mud, Large gravel at base is 4cm in diameter	Subrounded	Normally graded		235-238 More mud, 235-237 Shell debris present
349.8	349.8	249.0						

		Location: Ship Harbor, Anacortes	Date core collected:		Compaction:	Date core analyzed:	Starting length: 13ft:	405.385	405.385
							IF:	159.385	139.385
				Compaction factor:	0.09781054		OF:	132.715	132.715
					0.024461804		Si	26.67	6.67
							Pi	272.67	272.67
							Du (actual)	246	
							Du (expected)	236.855	
							Difference:	9.145	
Corrected for material removed (cm)	Depth, corrected for compaction (cm)	Depth (cm)	Color	Mottling?	Texture, grain sizes, % present, other important features	Shape/Roun ding	Gradeing	Boundary to lower horizon	Notes
0.0	20.0	-20	Material removed in field						
20.0	0.0	0	10YR 2/2, 10YR 3/2, 10YR 3/1	Varying colors of brown from 30-40cm	Peat			gradual over 78- 83	100% peat
102.1	82.1	80	4/10Y		clay				10% organics, herbaceous throughout
118.5	98.5	96	4/10Y to 4/5GY	Mottled, transtion to darker	clay		normal - greater sand % at base	Gradual with "pockets" of sand extending from below	
134.9	114.9	112	4/10Y to 4/5GY	Mottled similar to above	clay with some sand which is well sorted	subangular to subrounded		Gradual, whole section is a transition	Organics 10%
145.1	125.1	122	2.5/5GY, 3/10Y	mottled color	sand	subangular to subrounded		Gradual	5-10% organics

158.5	138.5	135	2.5/5GY, 3/10Y	mottled color	sand, clay, organics	subangular to subrounded		Gradual	Greater % clay in section, organics 30%
169.7	149.7	146	3/10Y, 4/10Y	mottled color	sand >80% medium to coarse, Gravels 20%	subangular to subrounded	normal	Gradual, large shell at base	Some gravels are imbricated at 164cm, section is poorly sorted
197.4	177.4	173	3/10Y, 3/N	clay and sand vary in color	Sand 80%, fine to coarse, well sorted	subangular to subrounded	sorted	Gradual	Large shells, broken down @172-176 and 181-182
210.7	190.7	186	3/N, 2.5/10Y		Fine to coarse sand, and coarse gravels to 2cm	subangular to subrounded	reverse	Abrupt, wavy	Coarser gravels at top of coarse sand mixed in, 190-192 is 100% sgravels, clast supported
225.6	205.6	200.5	4/10Y, 3/10Y	mottled color	Clay, smooth, with ~5% gravels			Gradual	10% organics, less mottled towards bottom
258.9	238.9	233	3/n, 4/10Y		Sandy, fine upper to coarse	subangular to subrounded	Normally graded, with mud at top and coarser materials at base	end	At 237cm shell fragment, and some gravels at base to 4cm
272.2	252.2	246							

		PM18_VCS4	Compaction:	Date core collected:	Compaction:	Date core analyzed:		Root subtract	
						Starting length: 13ft	408.45	408.45	
						IF:	247.65	223.52	
			Compaction factor:	0.266849		OF:	156.21	156.21	
						Si	91.44	67.31	
						Pi	252.24	252.24	
						Du (calculated)	148.59		
						Du (actual)	160.8		
						Difference:	12.21		
Thickness (cm)	Corrected Top Depth for removal of roots and compaction (cm)	Corrected depth for compaction (cm)	Depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape/Rounding	Grade in g	Boundary to lower horizon	Notes
24.1	0.0	24.1	-24.1		Modern root structures, removed prior to coring			gradual	clear root structures still present, partial catail root at 37cm depth
39.2	24.1	0.0	0.0	10YR 2/2	H4-H5 humification peat			gradual	From 33-43 slightly darker brown color
47.9	63.4	39.2	16.8	10YR 3/1	H5-H6 peat			gradual	Transition zone from peat to clay
6.6	111.3	87.1	54.6	10YR 3/2 and 2.5Y 3/2	Clay rich mud with 50% organics			gradual	With above layer together form a transition zone from peat to mud/clay
13.2	117.8	93.7	59.8	2.5Y 4/2	similar to above but decreasing organic % downsection, mud is very smooth			abrupt, but same material extends upwards along edge	Ranges from black to dark brown, vey distinct avrupt

2.3	131.0	106.9	70.2	7.5YR 2.5/3	100% organics, wood fragments, H4 peat?			abrupt	Minor organics throughout 5-10%
10.6	133.3	109.2	72.0	4/10Y	clay rich mud, <2% sand, minor grit to touch of mud, few rounded micas visible	rounded		x	Few organics throughout
11.4	143.9	119.8	80.4	4/10Y and 3/10Y, mottled	Clay rich mud, no sand except visual mica grains			gradual	Occasional
5.3	155.3	131.2	89.4	4/10Y and 3/10Y	mud, clay rich with 40% organics			gradual but clear	mottling disappears
24.6	160.7	136.5	93.6	4/10Y and 3/10Y	Clay rich mud few micas seen	rounded	poorly sorted	gradual	More mica grains seen at bottom of section
27.9	185.2	161.1	113.0	3/10Y	Clay rich mud, occasional mica, 5-10% organics throughout			gradual	gradual
4.1	213.1	189.0	135.0	3/10Y	50% organics, more sand (unclear %, perhaps 30-40%, some clay rich mud fine to coarse			gradual	subrounded
15.2	217.2	193.0	138.2	3/10Y	clay rich mud, 10-20% gravels throughout, 10-20% sand, well sorted into "pockets"			abrupt	some organics at bottom along edges of core barrel
13.4	232.4	208.2	150.2	3/N	Large gravels 50-60%, 40% sand, coarse, sand contains quartz and micas	subangular to subrounded		end	
245.8	245.8	221.7	160.8						

		VCS5_N	Location: Ship Harbor, Anacortes	Date core collected:	Compaction:	Date core analyzed:	Total length: 10ft	309.1375	309.1375
							IF:	84.1375	53.6575
				Compaction factor:	0.141704575		OF:	46.99	46.99
					0.025434154		Si	37.1475	6.6675
							Pi	262.1475	262.1475
							Du (expected)	220.6625	
							Du (actual)	225	
							Difference:	4.3375	
Thickness (cm)	Corrected top depth for roots removed and compaction (cm)	Corrected depth for compaction (cm)	Depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape Rounding	Gradeing	Boundary to lower horizon	Notes
30.5	0.0	30.5	-30.5						
26.6	30.5	0.0	0.0	10YR 2/1 (bottom), 10YR 2/2 (top)	Peat - H4 hum			color and roots change	more identifiable plan materials
16.2	57.1	26.6	25.8	5YR 2.5/1, 5YR 2.5/2	Peat H5 hum			change in visible roots	few roots present
31.6	73.3	42.8	41.6	10YR 2/2, 10YR 2/1	Peat H5 hum			gradual	Peat
3.9	104.9	74.4	72.4	10YR 3/2	5% fine sand in clay with organics 50+%			gradual	Gradual transition from peat to clay-rich mud
2.3	108.8	78.3	76.2	5Y 4/2	50% fine sand in clay rich mud	subrounded		abrupt	
2.7	111.0	80.6	78.4	5Y 4/2	<5% fine sand in clay rich mud			seperated	
1.0	113.7	83.2	81.0	5Y 4/2	50% fine sand in mud/clay			seperated by charcoal	

7.2	114.7	84.3	82.0	4/10Y	Sand >80%, fine to medium, contains quartz and micas, some mud 15-20%	subrounded to rounded		clear bur wavy	Top is horizontally oriented, charcoal is close to 30% organics
8.2	121.9	91.4	89.0	Clay: 4/10Y, upper 3/N	25% sand with 25% clay mixed with 50% organics, which are brown/dark brown			clear and abrupt	micas seen throughout, organics are fibrous and appear as wood and pinecones
2.5	130.1	99.6	97.0	3/10Y	good amount of visible mica sands, with 50% sand in mud, 40-50% organics			gradual	lots of organics, very small 40-50%
3.5	132.6	102.1	99.4	3/10Y	Some mottled color, Mostly clay rich mud with ~5% gritty fine sand when rubbed between fingers			clear	Some visible mica grains
2.8	136.1	105.6	102.8	3/10Y	Large sand section - smaller along edges, 50% sand contains micas and quarts with 50% mud				amorphous organics present throughout
5.2	138.8	108.4	105.5	3/10Y	Similar to 99.4-102.8, few mica sand grains throughout, mostly mud which is clay rich with some sand, organics 20% and fibrous			abrupt- curved	Pocke of sand from 109-109.6

7.0	144.1	113.6	110.6	3/10Y	Clay-rich mud with fine sand 5-10%			abrupt	20% organics visible, fibrous and running up and down core
4.7	151.0	120.6	117.4	4/10Y	50% sand, clay and mud 20%, 30% organics			abrupt	very large branch within section, appears to be oriented vertical towards the east
8.8	155.8	125.3	122.0	3/10Y, dark brown	clay-rich mud 60%, visible sand 10%, organics 30%	subrounded		clear and abrupt	
0.4	164.6	134.1	130.6	2.5/5GY	Sand up tot 20%, thin sline of organics, dark brown and make up 2/3 of barrel			abrupt, curved	orgnaics appear fiverous
5.1	165.0	134.5	131.0	3/10Y	Mud similar to 122-130.6, some sand		normal	becomes 100% sand	Sand % increasess downsection, organics 30% throughout
7.8	170.1	139.6	136.0	2.5/5GY	Mix of sand, 70%, and gravels 10-20%. Mud 10%. Larger gravels from 137-141	subroudned to rounded		gradual	some organics seen througout, especially around gravels
3.5	177.9	147.4	143.6	4/10Y	lower % sand, 60%, but similar to above and below, higher clay rich mud 20%, with some gravels	subrounded		gradual	organics are small and fibrous

9.2	181.4	150.9	147.0	3/N	Sand 60%, mud 10%, and gravels 30%	subangular to subrounded	sort of normal with larger gravels at base	slanted but abrupt and curved	Bottom section is slanted in barrel, sand contains quartz, micas, fibrous, light brown organics
6.8	190.6	160.1	156.0	4/10Y	Clay-rich mud 60-70%, sand 20% and organics 10-20%	rounded		abrupt, wavy, change in grain size, some intermixing with lower level	Whole section slanted in barrel to east.
43.5	197.4	166.9	162.6	3/N	Gravels and coarse sand 90%, mud 10%	subangular to rounded	poorly sorted	end	Mixed sand and gravels, clast supported, large gravel 3.5cm in size at base
20.5	240.9	210.4	205.0	Last section was lost during core recovery - assumed to be similar to above, gravelly					
261.4	261.4	230.9	225.0						

VCS6tN				Date core collected:	Compaction:	Date core analyzed:	Total length: 10ft	311.645	311.645
North marked half							IF:	106.045	60.325
		Compaction factor:	0.24838692				OF:	38.1	38.1
			0.081248058				Si	67.945	22.225
							Pi	273.545	273.545
							Du (excpeted)	198.755	
							Du (actual)	205.6	205.6
							Difference:	6.845	
Thickness (cm)	Corrected depth for compaction and root removal (cm)	Corrected depth for compaction (cm)	Core referenced depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape/Rounding	Gradeing	Boundary to lower horizon	Notes
45.7	0.0	45.7	-45.7						
19.6	45.7	0.0	0.0	5YR 2.5/1, black	Peat, H4 humification, releases very muddy water, past like residue			abrupt	Roots and other features identifiable
17.5	65.3	19.6	13.0	10YR 3/1, Very dark grey	Peat, H5-H6 humification, little muddy water, mostly amorphous peat between fingers, past-like			abrupt	
0.6	82.8	37.1	29.2	2.5Y 2.5/1	Thin dark line			abrupt	potentially a fire? Very dark, slanted in core barrel
0.6	83.5	37.7	29.8	Same as 13-29.2				abrupt	

42.8	84.1	38.4	30.4	10YR 2/2, very dark brown	Peat, H6 humification, closer to H7 at base			gradual	amorphous plant material, well composed, stringy roots visible
11.9	126.9	81.2	70.0	4/10Y, 10YR 4/1 at top	Transition from peat to mud	54.71		abrupt	organic content decreases from >80% to ~20% at bottom
4.3	138.8	93.1	81.0	4/10Y	~90% organics, appears to be a cattail root				Huge root, root came out with S. half, cut to place back
16.9	143.1	97.4	85.0	4/10Y (spots), 4/10GY, mottled color	clay rich mud, <5% fine sand, few micas seen throughout, ~20% organics throughout				mottled color throughout
16.7	160.0	114.3	100.6	4/10Y (spots), 4/10GY	Clay with <5% fine sand, ~20% organics throughout			clear	mottling decreases downsection
5.4	176.7	130.9	116.0	4/10GY	Clay with ~50% organic fragments			gradual	Organics appear fibrous and concentrated into area, decreasing organics towards bottom to ~40%

23.8	182.1	136.4	121.0	4/10Y, color lightens downsection	Clay with <5% sand, few micas seen throughout, 10-20% organics			gradual	Many organic "blobs" at top extending from a mostly organic section at top and decreasing in visible organics downsection
1.1	205.9	160.1	143.0		Pocket of sand fills 1/3 of core barre			abrupt	sand is dark and appears isolated in section fo barrel
7.6	206.9	161.2	144.0	4/10Y	Continuation of above				
6.9	214.5	168.8	151.0	4/10Y	Clay with an increasing sand % downsection	subangular	normal	gradual	sand appears mixxed mica, quartz, feldspars
1.7	221.4	175.7	157.4	3/10Y	Sand ~50-90% fine to upper medium. 20-50% organics within section. One visible gravel .6cm diameter @157.6.	subangular to subrounde d		abrupt	159-162cm is very soupey/unconsolidated and full of organics

10.8	223.2	177.4	159.0		1/3 of barrel is filled with clay lob, appears to come up from below in barrel, or sand is squished downwards - very wavy contact. Sand appears lobed at base along contact			Contact is abrupt but not horizontally well defined/isolated, and is very wavy	
9.9	234.0	188.3	169.0	4/10Y	Clay-rich mud with <2% sand - some grit to touch			abrupt	few organics throughout, warped towards core barrel edges
0.6	243.9	198.2	178.2	dark brown	Line of organics, fibrous ~60% in clay			abrupt	
5.0	244.6	198.8	178.8	4/10Y	Section of mud, similar to above with "pockets" of sand			gradual	
24.0	249.5	203.8	183.4	4/10Y	Clay with very little sand, very little grit to touch, 10% organics which are fibrous			end	Clay is very smooth and dries light grey, large lack/dark brown organic at 200.4cm
	273.5	227.8	205.6						

VCEI1		Location: Eliza Island	Date core collected:	Compaction:	Date core analyzed:	Orig Length: 10ft	315.56	
						IF:	78.89	
						OF:	38.42	
						Si	40.47	
			Compaction factor:	0.146027279		Pi	277.14	
						Du (excpcted)	225.91	
						Du (actual)	236.67	
						Difference:	10.76	
Thickness (cm)	Corrected depth for compaction (cm)	Depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape/Roun ding	Gradeing	Boundary to lower horizon	Notes
25.4	0.0	0	10YR 2/2, very dark brown	Peat, H3-H4 hummification			clear, wavy	lear roots, easily identifiable, releases muddy water when squeezed, some roots are thick to .5cm diameter
8.0	25.4	17	10YR 2/2	Peat, H5 hum, more broken down			Unclear, graudal	Fibrous peat with few identifiable roots
32.8	33.4	24	10YR 2/2, 10YR 2/1	H6-H7 hummification			Clear, wavy, clear color and texture change	Few identifiable roots, half of beap escapes between fingers when squeezed
6.2	66.2	52.6	10YR 3/1	Peat, H9 hummification, past produced with 1 identifiable root			Abrupt, wavy	
17.2	72.4	58	3/10Y - base, 4/10Y- mottling spots	Clay 80%, sand 5%, some grit to touch, fibrous organics 15%	Rounded		Mottling ends	Some gravels throughout section @67cm, concentration of motteling in color decreases downsection
11.5	89.6	73	3/10Y	Clay 60%, sand 20% fine to medium size, micas seen visually, organics 20%, occasional gravels	Rounded	Normally graded	Color and texture clearly change	Gravels at base of seccion

7.8	101.0	83	4/10Y	decreas in sand to 5-10%, increase of clay to 80%, organics 10+%			Clear texture change	No gravels seen on surface, organics concentrated at base
16.3	108.8	89.8	3/10Y	Clay 75%, sand 15% and fine, organics 10%		Well sorted, sand concentrate into pockets	clear, curved	Few small .4cm gravels - quartz sand concentrated from 90-93, appears <u>dispursed in pockets</u>
4.6	125.1	104	10YR 3/1, color extends down to form mottled color. Mottling decreases downsection below	Sand <5%, fine in organic rich mud, which is pasty. Sand is not visible		Normal, less sand downsection	gradual	Appears very smooth, very littl grit to
12.6	129.7	108	3/N	Organic rich mud, with <2% fine sand			end top	Large organic, looks like a well-preserved stick or root, organics present, small, throughout section
34.6	142.3	119	3/N	Clay and silt rich mud, with <2% sand, with occasional coarse sand seen			abrupt, gravel along contact	Samll oranics throughout <.4cm
11.8	176.9	149.2	2.5Y 2.5/1	Mud 40%, sand 60%, medium to coarse, organics 10%	Subrounded to rounded		gradual but clear, decreases in sand amount downsection	Sticky, sand appears white to black, gravels throughout to 1cm
17.8	188.7	159.5	3/N	Coarse sand 30%, mud 60%, gravels 5-10%, organics 5%	Subrounded	Sand is concentrated more in one section	gradual increas in sand % downsection	Gravels throughout to 1cm
14.9	206.5	175	4/N	Sand 80%, fine to coarse, gravels 10%, organics 10%	Subangular to subrounded	Normal	Unclear if boundary, grain size abruptly changes	Sand contains quartz

13.8	221.4	188	3/N	Sand 90%, fine to coarse, mud 10%	Subrounded to rounded	Poorly sorted sand	More organics below	Almost 100% sand, contains organics and lots of quartz, few gravels seen
41.9	235.1	200	2.5Y 3/1	Sand 80%, fine to coarse, mud 10% and organics 10+%			end	More root structures appear to hold unit together - very difficult to split without disturbing materials
	277.1	236.6						

210 Below 201 the area was disturbed during the splitting process
236.67 last 10.5in lost in field - 26.67cm

	VCEI2_N	Location : Eliza Island	Date core collected:	Compaction (cm):	Date core analyzed:		Orig length: 8ft	248.21
							IF:	59.21
			Compaction factor:	0.122998325			OF:	32.703
							Si	26.507
							Pi	215.507
							Du (expected)	184.63
							Du (actual)	189
							Difference:	4.37
Thickness (cm)	Corrected depth for compaction (cm)	Depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape/Rounding	Gradeing	Boundary to lower horizon	Notes
17.86	0.00	0	7.5YR 3/1, 7.5YR 2.5/1	Peat			Gradual	>95% organic top soil
38.86	17.86	13	10YR 2.5/1, 10YR 2/2	Peat, visible roots in tact			gradual	from 37-49 darker color
2.25	56.72	47.6	10YR 2.5/1	Peat			Abrupt, roots extend downwards	Dark top soil - O horizon
1.12	58.96	49.6	4/5GY	Clay			Gradual	No motteling in color - flat color
12.80	60.08	50.6	3/10Y, 5Y 3/1	Clay, occasional gravel/coarse sand to .3cm			Gradual	Large orgnaic in South core from 50-55cm, small gravel @60.8cm
11.68	72.89	62	2.5/10Y (dark areas between .6- 1.4cm in diameter), 2.5/N - motteling in color	Clay			Abrupt	Scattered organics throughout
8.98	84.57	72.4	2.5Y 3/1	Clay			abrupt, clear	Scattered dark organics (small) throughout
1.80	93.55	80.4	2.5Y 3/2	Clay, <5% sand containing micas (visually)			abrupt, clear	Fine mica sands, lighter color to clay than above and below

25.83	95.35	82	2.5Y 3/1	clay-rich mud, with small % sand - micas visually seen			Gradual	Large dark are from 82-86.5, dark organics seen throughout
10.11	121.18	105	2.5Y 3/1, 2.5Y 2.5/1, mottled color starts lighter and gradual at top, and increases in mottling down section to create a solid color of lower section	Clay rich mud, with sand <5% increasing downsection		Normal graded	Gradual	Sand <5%, organics seen throughout
11.23	131.28	114	2.5/10Y	Clay rich mud, with 5-10% sand - micas			Clear but gradual	
13.48	142.51	124	3/N	Sand >80%, with some clay rich mud	Subrounded	normally graded, with sand coarsening at bottom	Gradual	
7.41	155.99	136	3/N	Sand decreases in %, with clay and mud % increasing (20%?)	Subrounded		abrupt but some mixing	
10.56	163.40	142.6	3/N, 2.5Y 3/2	Coarse sand and some organics, sand to .3cm	Subrounded and subangular		Gradual	>90% organic fragments, mixed with coarse sand and fine gravels, trash layer
6.06	173.96	152	2.5Y 2.5/1, 2.5/N	Clay with 10% coarse sand and gravels to 1.5cm, gravels at base		Normal	Clear but gradual	Abundant small organics throughout
15.27	180.02	157.4	3/10Y	Clay with gravels to .8cm	Angular to subangular		Clear and abrupt	Some very large clasts burried - unsure how large

3.37	195.29	171	2.5/10Y	Mud, clay rich, with <5% sand and gravels, fine sand felt to touch but not visually seen			clear	
8.98	198.66	174	5/10GY	Mud with gravels, 1.5cm at least for largest gravel present			clear	Very large gravels @181
	207.65	182	2.5/10Y	Mud, <5% sand			end	Same as 171-174, super smooth mud, dark in color
	215.51	189						

VCEI3_N		Location: Eliza Island	Date core collected:	Compaction:	Date core analyzed:	Orig Length: 10ft	312.156	
					9/30/2018	IF:	91.756	
			Compaction factor:	0.1237138		OF:	60.64	
						Si	31.116	
						Pi	251.516	
						Du (excpeted)	213.044	
						Du (actual)	220.4	
						Difference:	7.356	
Thickness (cm)	Corrected depth for compaction (cm)	Depth (cm)	Color	Texture, grain sizes, % present, other important features	Shape/Rounding	Gradeing	Boundary to lower horizon	Notes
20.71	0.00	0	7.5YR 2.5/2, 7.5YR 3/3	Organic, O horizon			Gradual	Abundant roots, organics
5.62	20.71	15	10YR 3/2	Gravles to 1.5cm	Rounded	Normal	Gradual but clear	Gravels are normally graded with >50% organics
6.74	26.32	20	3/10B (Grey 2)	40% organics, with mud and coarse sand and gravels to 1cm	subrounded		Clear color change	Appears to be smaller gravels
10.68	33.07	26	4/N	20% organics and gravels, gravels to 2cm				Larger clasts than above and below
5.06	43.74	35.5	4/10Y	Gravels, generally small, but large gravel in southern half				
20.23	48.80	40	3/10Y	Abundant gravels >80%	subrounded			49cm gravels are imbricated, gravels appear white
6.74	69.02	58	3/N	Gravels and sand, sand is coarse	Subrouded to rounded		Abrupt	Coarse sand and gravels, biggest gravels at base

9.66	75.77	64	3/10Y	Mud 90%, sand <10%, few gravels <1cm	rounded			Gravels appear around edges, shell fragments seen @65 and @69cm
4.94	85.43	72.6	3/N	Mud with some sand				Same as above, except color
5.62	90.38	77	2.5/10Y	Mud >80% with coarse sand throughout <10%, 10% organics				Organics speard throughout - black and brown, about 10%
7.87	95.99	82	2.5/10Y	Same as above with more sand along edges and more organics				
2.47	103.86	89	3/10Y	Mud with some gravels to 1 cm, large pocket of sand makes up 1/3 of core barrel				Large organic "blob" next to sand pocket
2.92	106.33	91.2	2.5/10Y	Same as 89-91cm, but different color				
2.02	109.25	93.8	Mottled color, 2.5/N and 3/10Y	Large sand pocket in middle of core 2cm vertical in barrel, within clay-rich mud				
7.19	111.28	95.6	Mottled color, 2.5/N and 3/10Y	Clay-rich mud, with sand at 67.4cm				Mud
2.25	118.47	102	3/10Y and 10YR 2/1	Large cobble 2cm by 3cm. Some other small gravels seen too				
4.49	120.72	104	3/10Y	Clay-rich mud, with 10% coarse sand	subrounded			Some organics present at bottom

12.36	125.21	108	3/10Y	Clay-rich mud 80%, gravel to 1cm, 10% and coarse sand 10%	Subrounded to rounded	well sorted, sand and gravels are concentrated into areas	Graudal but clear	Some organics throughout, sand concentrated between 115-118.5
2.92	137.57	119	2.5/10Y	Mud, very smooth >90%			abrupt	Black organics seen throughout
15.06	140.49	121.6	3/10Y, 2.5/10Y	Mud matrix 50%, gravels to 2cm at top and base 30%, coarse sand 20-30%		poorly sorted	clear, wavy	Organics throughout, large @128.6-130.6, sand in large pocket at top
1.69	155.55	135	2.5/10Y	Less consolidated mud with 50% sand				Appears "smushed" between upper and lower sections
9.55	157.24	136.5	3/N	Sand 70%, mud 30% and minor gravels	Subangular to subrounded	well sorted, sand and gravels are concentrated into areas	clear but slanted and wavy	142-143.5 large pocket of white coarse sand, roots and organics present
2.81	166.79	145	5Y 2.5/1	Mud >80%, sand 20% in matrix	Subrounded	poorly sorted (well mixed)	abrupt	less consolidated "Mud"
4.61	169.60	147.5	5Y 2.5/1	Sand 50%+ in mud, some small gravels 5-10%	Subrounded	homogeneous	Graudal but clear	Similar to 136.5-145 section
4.49	174.20	151.6	2.5/N	Clast supported >80% gravels, with some mud and coarse sands. Gravels range in size up to 2cm	Subrounded to rounded		clear and abrupt	

11.69	178.70	155.6	2.5/N, 2.5/10Y	Mixed gravels and sand 70% with mud 30%. Gravels to 2cm in size.	Subangular to subrounded	Normally graded	clear change in sand size makes the boundary clear	Large gravels throughout, but sand is graded, gravels are matrix supported
6.74	190.39	166	3/N	Coarse sand and fine gravels are 90% of matrix, with 10% mud mixed in	Subangular to subrounded	poorly sorted	abrupt	Mostly coarse sand. Disturbed section when splitting core, most came out in the southern half when split
6.29	197.13	172	3/N, 3/10Y	Large rock fragments, bladed, appear to be serpentinite 50%, fine to medium sand 25%, mud 25%	Subangular to rounded	clast supported in sections	abrupt and slanted	Mica sands seen, rock fragments appear imbricated
6.07	203.42	177.6	4/N	Coarse sand, medium to coarse 95%, some minor clay/mud	subrounded	homogenous	abrupt, wavy, slanted	Minor amount of organics seen
42.03	209.49	183	5/5G and 5/10GY	Clay >90% with 10% fine grained sand	subrounded	well sorted	end	Some organics throughout, Sand in "pockets" or lines throughout. Large sand pocket present. Sands are white with micas seen
	251.52	220.4						

Appendix 3 Smear Slide Images
VCS2, reference depths: 80-90cm

VCS6, reference depths: 178-185cm

VCEI2, reference depths: 82-92cm

VCEI3, reference depths: 80-90cm

Equations used to calculate PSV curves adapted from Butler (1992)

EXPECTED MAGNETIC FIELD DIRECTION

The problem here is to derive expressions that allow determination of the magnetic field direction expected at an observing site (λ_s, ϕ_s) due to a geocentric dipole with pole position (λ_p, ϕ_p) . We also derive expressions for the confidence limits on the expected direction that result from circular confidence limits (usually A_{95}) on the pole. The geometry of the problem is illustrated in Figure A.5.

Figure A.5 Geometry used to determine the expected magnetic field direction from a magnetic pole. The magnetic pole is at $P(\lambda_p, \phi_p)$ with circular confidence limit A_{95} ; the site location is at $S(\lambda_s, \phi_s)$; N is the geographic north pole; p is the magnetic colatitude of the site; p_s is the geographic colatitude of the site; p_p is the geographic colatitude of the magnetic pole; $\Delta\phi$ is the longitudinal difference between the magnetic pole and the site; D_x is the expected magnetic field declination at the site with confidence limit $= \Delta D_x$.

A spherical triangle SPN is constructed with N at the geographic pole, P at the magnetic pole (λ_p, ϕ_p) , and S at the site (λ_s, ϕ_s) . Having gone through a similar problem before, we realize that the declination of the expected magnetic field direction, D_x , at site (λ_s, ϕ_s) is the angle at apex S .

The first step in the derivation is to determine the angular distance, p , from (λ_p, ϕ_p) to (λ_s, ϕ_s) . Apply the law of sines to triangle SPN in Figure A.5 to get

$$\cos p = \cos p_p \cos p_s + \sin p_p \sin p_s \cos \Delta\phi \quad (\text{A.53})$$

Now substitute

$$p_p = \frac{\pi}{2} - \lambda_p, \quad p_s = \frac{\pi}{2} - \lambda_s, \quad \text{and} \quad \Delta\phi = \phi_p - \phi_s$$

into Equation (A.53) and use

$$\cos\left(\frac{\pi}{2} - \lambda_p\right) = \sin \lambda_p \quad \text{and} \quad \sin\left(\frac{\pi}{2} - \lambda_p\right) = \cos \lambda_p$$

to find

$$\cos p = \sin \lambda_p \sin \lambda_s + \cos \lambda_p \cos \lambda_s \cos(\phi_p - \phi_s) \quad (\text{A.54})$$

from which you can determine p .

The expected inclination, I_x , can be determined from p by using the dipole equation (Equation (A.10)):

$$I_x = \tan^{-1}(2 \cot p) \quad (\text{A.55})$$

The confidence limit on I_x is defined as ΔI_x and can be determined from the equation that we derived to get dp from ΔI ($= \alpha_{95}$ in Equation (A.52)) and substituting A_{95} for dp :

$$A_{95} = 2\Delta I_x \left(\frac{1}{1 + 3 \cos^2 I_x} \right) \quad (\text{A.56})$$

which rearranges to give

$$\Delta I_x = \frac{A_{95}}{2} (1 + 3 \cos^2 I_x) = A_{95} \left(\frac{2}{1 + 3 \cos^2 p} \right) \quad (\text{A.57})$$

To determine the expected declination, D_x , we can use Equation (A.28) derived above:

$$\sin \lambda_p = \sin \lambda_s \cos p + \cos \lambda_s \sin p \cos D \quad (\text{A.28})$$

and rearrange to solve for D_x :

$$\cos D_x = \frac{\sin \lambda_p - \sin \lambda_s \cos p}{\cos \lambda_s \sin p} \quad (\text{A.58})$$

from which D_x can be determined.

The confidence limit on D_x is ΔD_x , which can be derived by applying the Law of Sines to the spherical triangle STP (Figure A.5):

$$\frac{\sin A_{95}}{\sin \Delta D_x} = \frac{\sin p}{\sin T} \quad (\text{A.59})$$

Now note that $T = \pi / 2$ (thus $\sin T = 1$) and rearrange to give

$$\Delta D_x = \sin^{-1} \left(\frac{\sin A_{95}}{\sin p} \right) \quad (\text{A.60})$$

If you actually go through some calculations of ΔI_x and ΔD_x , you will find that these confidence limits change with I_x (and p) in a systematic fashion. For small p (steep inclination), $\Delta D_x > \Delta I_x$; $\Delta I_x \approx \Delta D_x$ at about $p = 60^\circ$ ($I_x \approx 50^\circ$); for $60^\circ < p \leq 90^\circ$ ($I_x < 50^\circ$), $\Delta I_x > \Delta D_x$.

This determination of the confidence limits ΔI_x and ΔD_x produces a confidence *oval* (not circle) about I_x, D_x . ΔI_x is the semi-axis of the confidence oval in the vertical plane through I_x, D_x . But the other semi-axis of the confidence oval is not ΔD_x . Remember that ΔD_x is the projection of the direction space confidence limit onto the periphery of the equal-area projection (Figure A.4a). The required dimension of the confidence limit about I_x, D_x can be determined from Equation (A.44) by substituting the desired angular distance c (Figure A.4a) for α_{95} . This leads to

$$c = \sin^{-1}(\cos I_x \sin \Delta D_x) \quad (\text{A.61})$$

Equations for AMS parameter calculations:

n1 relates to $K_{\max}$, n2 relates to K_{int} and n3 relates to $K_{\min}$

$$L = K_{\max}/K_{\text{int}}$$

$$F = K_{\text{int}}/K_{\min}$$

$$P = K_{\max}/K_{\min}$$

$$P_j = \exp\{\sqrt{2((n_1-n)^2+(n_2-n_0)^2+(n_3-n)^2)}\}$$

$$T = (2n_2-n_1-n_3)/(n_1-n_3)$$

$$U = (2K_{\text{int}} - K_{\max} - K_{\min}) / (K_{\max} - K_{\min})$$

$$Q = (K_{\max} - K_{\text{int}}) / (K_{\max} + K_{\text{int}}) - K_{\min}$$

$$E = (K_{\text{int}})^2/(K_{\max} * K_{\min})$$