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Coastal and Hydraulics Laboratory

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Framework Geology of Cape Shoalwater and Northwest Willapa Bay, Washington

Assessing Potential Geologic Impacts on Recent Shoreline Change

Heidi M. Wadman, Jesse E. McNinch, and Jarrell Smith

September 2020

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Final report

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Abstract

The shoreline along Cape Shoalwater and northwest Willapa Bay has experienced the highest rates of erosion along the entire Pacific Coast of the United States, due in part to rapid northward migration of the navigation channel. Recently, channel migration and shoreline erosion in this region have slowed, but the cause of this relative stabilization, and thus the longevity of these new patterns, is unknown. Given the complex neotectonics and geologic framework of the southern coast of Washington, it is possible that underlying, erosion-resistant geologic units have become exposed along the channel and/or in the nearshore, and are acting to reduce or halt channel migration and/or shoreline erosion. Conversely, the apparent reduction may be due to subtle, short-term changes in regional hydrodynamics and/or sediment transport, and thus future rates of channel migration and/or shoreline erosion might increase back to historical rates. The purpose of this special report is to detail the geologic and neotectonic framework of the northern Willapa Bay region, and determine how the underlying framework geology might be impacting channel stability and adjacent shoreline erosion rates. Suggested research questions to quantify potential geologic control are also presented, including the potential benefits of the research to the district.

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Preface

This study was conducted for the US Army Corps of Engineers, Seattle District, under Funding Account Code 4372013; AMSCO Code 086000. The technical monitor was Mr. David J. Mallinson.

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The authors acknowledge the assistance of Mr. Steven Spencer, former Environmental Resources Director for the Shoalwater Bay Tribe; Mr. David Cottrell, North Willapa Harbor Grange; and Dr. George Kaminsky, University of Washington, for their gracious assistance both in the field and during later discussions of this research.

The Commander of ERDC was COL Teresa A. Schlosser, and the Director was Dr. David W. Pittman.

1 Introduction

1.1 Background

The Willapa Bay region is an evolving regional spit and inlet system that is part of the larger Columbia River littoral system and is located in a complex, tectonically active area on the west coast of Washington State (Figure 1a-c). Extensive tidal flats and barriers have accreted and eroded over the last ~150 yr[1,2], especially near the outer region of the entrance into Willapa Bay (Figure 1b, c). In particular, shoreline change rates have dramatically changed since ~1900 along the northern entrance into Willapa Bay, including along Cape Shoalwater and the Tokeland Peninsula. Cape Shoalwater has switched from an aggrading shoreline to a retreating one, and long-term erosion rates are estimated to be in excess of 30 m yr^{-1}, making it the most rapid and sustained erosion site on the Pacific Coast of the United States (e.g., Kaminsky et al. 1998; Kaminsky et al. 2010). This erosion has been augmented, and potentially driven by, the northern migration of the primary navigation channel in Willapa Bay. In 1986, Terich and Levenseller (1986) summarized multiple joint research efforts between the US Army Corps of Engineers (USACE) and the University of Washington. Overall, they found that the northward migration of the navigation channel brought large winter waves closer to the shoreline, greatly increasing local erosion (Terich and Levenseller 1986, and references therein). Despite multiple studies, no short- or long-term engineering strategy was identified that would result in a stabilized shoreline and a navigable channel, at a feasible cost. This continuous shoreline retreat has resulted in the loss of multiple private homes as well as territorial land belonging to the Shoalwater Indian Tribe, including traditional shellfish harvesting grounds. Further erosion threatens (1) State Highway 105, a critical tsunami evacuation route, (2) additional private homes, (3) Shoalwater Indian tribal lands, (4) parts of the Willapa Bay Wildlife Refuge, and (5) a cranberry industry with a farm gate value

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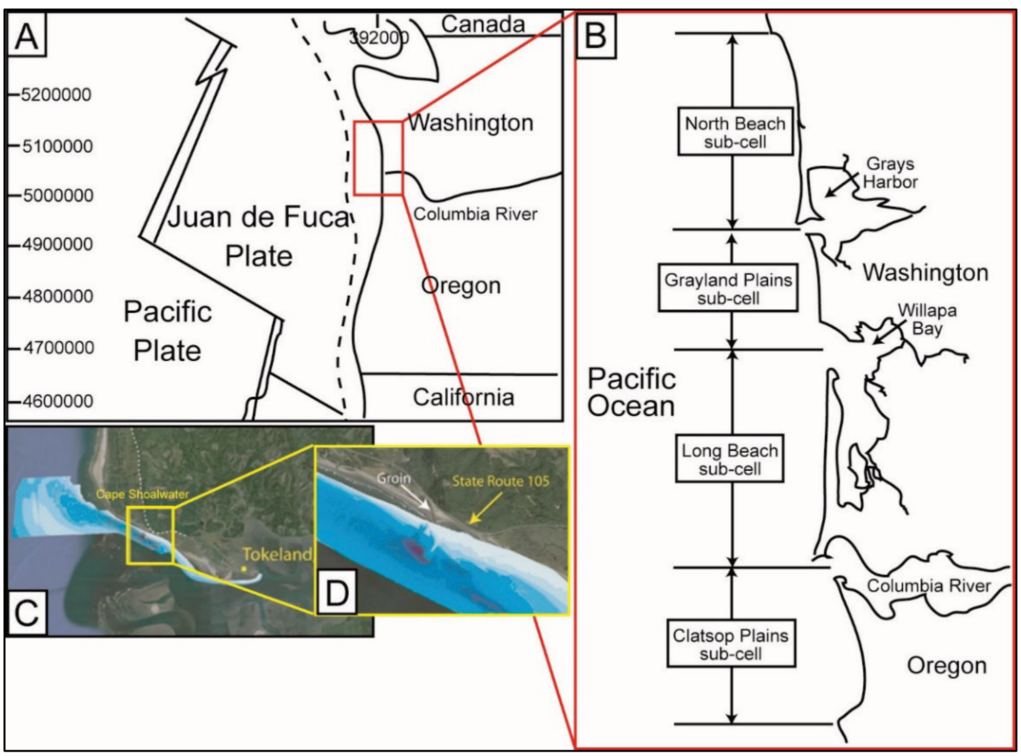
[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

(for the entire Pacific Grays Harbor Region) of approximately $8 million in 2013 (http://www.chinookobserver.com/20130528/ocean-spray-growers-independent-growers-and-the-current-surplus-of-cranberries). State Highway 105 acts as a dike between Willapa Bay and the nearby cranberry bogs. If coastal erosion were to breach the road, the cranberry bogs would be at risk of not just flooding but of also washing into Willapa Bay, threatening the health of the extensive Bay oyster fishery that currently represents ~15% of the entire US oyster industry.

Figure 1. Location of the Willapa Bay system. (A) Regional tectonics impacting coastal Washington State. Dashed line indicates general region of subduction zone (modified from Peterson et al. 2000). (B) Location of Willapa Bay in the greater Columbia River littoral cell (modified from Peterson et al. 2010). (C) Bathymetry of the Willapa Bay entrance channel, Cape Shoalwater, and Tokeland Peninsula. (D) Close up of Cape Shoalwater where a groin was installed adjacent to St Highway 105 to prevent erosion due to channel migration. Bathymetry on panels C and D provided by the USACE Seattle District.



1.2 Additional background information

To understand the potential impact of framework geology on the observed, short-term changes in shoreline change rates at Cape Shoalwater, the coastline must be considered in the context of the larger region.

1.2.1 Regional littoral cell

Cape Shoalwater, Willapa Bay, and the greater Columbia River littoral cell have been the subject of extensive research over the last 20+ years. Willapa Bay lies within the Grayland Plains Sub-Cell of the Columbia River littoral cell (Figure 1d) and, over the Holocene, has largely functioned as a small sediment sink (e.g., Gelfenbaum et al. 1999; Gelfenbaum and Kaminsky 2010). Regional shorelines have experienced severe shoreline retreat caused by sudden 1–2 m drops in land elevation along the coast associated with large subduction-zone earthquakes that occur approximately every 500 yr (e.g., Gelfenbaum and Kaminsky 1999; Peterson et al. 2010). More recently, the sediment supply delivered to the littoral cell from the Columbia River has been reduced due to (1) the construction of dams within the river itself; (2) dredging of sediment from the channel and subsequent placement offshore, out of the littoral cell; and (3) the construction of jetties which altered sediment exchange across ebb-tidal deltas and adjacent coastlines (e.g., Sherwood et al. 1990; Gelfenbaum et al. 1999; Gelfenbaum and Kaminsky 2010; Kaminsky et al. 2010). It is unclear if this reduction in supply, however, is sufficient to completely explain the increase in sediment erosion (e.g., Terich and Levenseller 1986) and thus if an increase in sediment supply would be sufficient to counteract it. Other potential impacts on shoreline stability include changes in storm tracks and frequency during El Niño events (e.g., Kaminsky et al. 1998; Ruggierio et al. 1998; Ruggierio et al. 2005), as well as by variable tectonic activity (explained further in Section 2.4, below). In addition to the above research, extensive modeling and observational efforts have been undertaken to further understand the relationships between the regional hydrodynamics, geology, and shoreline stability (e.g., Hedgpeth and Obrebski 1981; Seabergh et al. 2002; Morang et al. 2007), all of which elucidate the complexity of shoreline processes in this area.

1.2.2 Channel stability

The location of the channel thalweg has recently stabilized, and short-term erosion rates have reduced along Cape Shoalwater. Whether or not these represent permanent changes in channel and shoreline migration rates, and what might be causing the observed changes, is currently unknown. This leaves the USACE Seattle District (NWS) with few feasible options for protecting the region, and further research is critical for understanding the underlying geologic processes that may be influencing shoreline change rates along the Cape shoreline, as well as understanding how those processes might have changed in the last few years.

1.2.3 Tidal flat study

In addition to the aforementioned research, the Office of Naval Research (ONR) identified the Bear River tidal flats in southern Willapa Bay as a focus site for its ongoing meso- to macrotidal flat research program (ONR Tidal Flats). As part of this effort, extensive research on linkages between hydrodynamics, sediment dynamics, and morphology change of the Bear River tidal flats was conducted between 2008 and 2011 (e.g., Nittrouer et al. 2013). Specific topics addressed include sediment properties such as variations in deposition rates and sediment characteristics (Barry et al. 2013; Boldt et al. 2013; Hill et al. 2013; Law et al. 2013; Nittrouer et al. 2013; Wheatcroft et al. 2013; Wiberg et al. 2013), patterns of suspended sediment transport (Hill et al. 2013; Nowacki and Ogston 2013), and both local and regional hydrodynamics (Mariotti and Fagherazzi 2013; Nowacki and Ogston 2013). Although this research does not directly address the Cape Shoalwater region of Willapa Bay, the lessons learned about seasonal variations in sediment characteristics and erodibility of the Bear River tidal flats should be considered when addressing the erosion susceptibility of the Cape Shoalwater tidal flats.

1.2.4 Potential navigation channel changes

In 1998, the Washington State Department of Transportation, with the support of the USACE NWS, installed a groin near the Willapa Bay north entrance channel and bar (Figure 1c) in an effort to stabilize the shoreline in the face of northerly channel migration. Post-completion, significant scour occurred north of the groin, resulting in sloughing of the shoreface and an increase in coastal erosion (Figure 1c). To help address the above observations, the NWS has addressed the erosion problem both with modeling efforts and with shoreline engineering projects. In 2000, the NWS requested that the US Army Engineer Research and Development Center (ERDC) explore the feasibility of abandoning the northern primary entrance channel in favor of the central or southern channels. Kraus et al. (2000) and Smith and Ebersol (2000) used numerical modeling to explore the feasibility and shoreline impacts of both dredging and maintaining a channel in the spit that extends northward from the Long Beach Peninsula, as well as whether either of the other two natural channels into Willapa Bay would be easier or more economical to maintain. Model results indicated that although it was feasible to dredge a channel through the actively accreting and migrating spit, the local hydrodynamics would actively work to fill the new cut post-dredging, making the maintenance costs unrealistic. In addition, the model results suggested that the middle or southern channels would be just as expensive, or more so, to deepen and maintain as the northern channel. Ultimately, the northern channel was identified as the most feasible channel to continue to maintain, without an intentional breach through the spit, despite the risk to the adjacent shoreline.

1.2.5 Recent channel stabilization

More recently, repeated bathymetric surveys by NWS indicate that over the last several years, migration of the channel thalweg has temporarily slowed, and anecdotal observations suggests that the associated shoreline erosion has also been reduced. After the completion of the ERDC research referenced above, and in collaboration with the ERDC, the US Geological Survey, and the University of Washington's Department of Ecology, NWS examined the shoreline erosion along Tokeland Peninsula and Cape Shoalwater with a Flood and Coastal Storm Damage Water Resources Development Study (e.g., NWS 2007; Michalsen et al. 2010). During this effort, it was noted that if no action were taken, the relocation of the coastal community component of the Shoalwater Reservation would be unavoidable. Relocation of the tribe was estimated to cost in the millions of dollars, not including the spiritual and cultural loss of traditional tribal lands. Several options were considered to mitigate coastal erosion along Cape Shoalwater including a sea dike, extensive revetment along the shoreline, and extensive dune restoration (with and without extended flood berms). In large part due to the seeming *stabilization* of the channel thalweg, it was determined that the dune restoration option (without a flood berm) would provide the best balance between cost and potential shoreline protection. Since the construction of the dune in 2011 using sediment dredged from the entrance channel, extensive back-barrier sediment has filled in via natural processes, resulting in restored shellfish habitat as well as extensive nesting grounds for several species of endangered birds (Figure 2a). Winter storms have eroded the dune face (Figure 2b), though it is not known if the sediment eroded is being preserved in the shoreface or instead lost to the entrance channel, and thus likely transported out of the local littoral cell.

Figure 2. (A) View of the tidal flats between the Tokeland Peninsula and the USACE-NWS-installed dune field. (B) Example of dune scarping during the winter of 2016–2017.

1.3 Objective

Although migration of the navigation channel seems to have stalled, possibly explaining the anecdotal reduction in shoreline erosion, coastal erosion has not stopped at Cape Shoalwater, and it is possible that erosion could intensify again in the near future. Without knowing what influence, if any, the geology of the shoreface might be having on channel migration, it is difficult for NWS to effectively plan future engineering efforts to further protect the shoreline. Accordingly, in Fiscal Year (FY) 16 and FY17, NWS requested support from the Dredging Operations and Technical Support program to allow ERDC to explore if the framework geology of the shoreface might be impacting channel migration and/or shoreline erosion in the form of alongshore variations in sediment volume and erodibility. This special report details the geologic and tectonic framework of Cape Shoalwater and northern Willapa Bay and explores the way geology might be influencing bathymetric change and shoreline stability. It outlines several related research questions, methods by which they can be addressed, and the potential benefit to NWS.

1.4 Approach

To address the complexity of the issues facing NWS in managing this region, an extensive literature review of the regional and local geology and tectonics of the Cape Shoalwater region was conducted. Multiple site visits funded by DOTS provided opportunities to observe the real-time erosion and explore unpublished data resources not available via traditional channels. Based on these efforts, research options moving forward are provided.

2 Approach

To address the ways in which framework geology might be impacting the shoreline and coastal erosion observed in the Cape Shoalwater region, the geologic nature and history of the region was first researched. Site visits allowed for observation of which geologic units were previously observed in well logs in the region, as well as which are exposed adjacent to the shoreface in the present day. The geologic history of the area and the in-person observations were then considered in the framework of the modern, ongoing processes observed most recently during recent ERDC and university research studies. Research questions that could be addressed both via field and numerical modeling efforts were able to be suggested. Results from one or more of these proposed studies would ultimately enable NWS to better predict and manage future coastal erosion in this region.

2.1 Pleistocene sequence

The Quaternary sediments of the Cape Shoalwater region overlie an extensive Pleistocene sequence comprised of partially indurated fluvial, estuarine, intertidal, and subtidal deposits. These more erosion resistant deposits form a distinctive topographic terrace along the Cape Shoalwater shoreline. In 1983, Clifton provided a detailed comparison between modern coastal deposits and the Pleistocene deposits to distinguish different depositional environments, and thus units, in the Pleistocene formation. Briefly, Clifton (1983) identified five major units in the Pleistocene formation, and mapped their relative position near Ramsey Point, Willapa Bay (Figure 3a-b). The oldest sequence (~190kya), Unit I, is a dominantly intertidal sequence of laminated, bluish fine sand and mud, overlain by a thick, bioturbated bluish mud. An erosional contact separates Unit I from the overlying, subtidal Unit II, composed primarily of muddy and/or cross-bedded sand. Throughout Unit I and II, small runoff channels were noted. These small features (e.g., 10s of centimeters to meters in extent) lack classic tidal or fluvial stratigraphy (e.g., interbedded sands, muds, and/or gravels), and Clifton (1983) postulated that these were potentially formed by ephemeral tidal flows or upland runoff (see Figure 4a-b for an example).

Unit III is comprised of well-defined, though spatially variable, extensive channel deposits composed primarily of mud with abundant wood. These channels cut into both Units I and II and are also noted between the laminated sediments and the bioturbated mud within Unit I. Note that in these three units, gravel deposits are thin and discontinuous, if present at all. Overlying Unit III are the younger (~100kya) sediments of Unit IV, a laterally continuous, shallowing-upward, stillstand substrate of large-scale sand and mud strata, plus additional layers of cross-bedded gravels, sands, and mud exemplified in the exposure shown in Figure 4c-e. Unit IV is distinctive in that it preserves spatially variable, thick lags of disarticulated shells, pebbles, wood fragments, and abundant shells including *Ostrea lurida* in growth position. Finally, Unit V is comprised predominantly of estuarine-to-fluvial channel fill, dominated by laminated mud and silty-fine sand with little or no bioturbation, which cuts through all the other units. The Unit V channel axes, where exposed at Ramsey's Point, often contain abundant logs and large wood fragments oriented parallel to the channel axis, with thick, discontinuous sequences of pebbles and/or coarse sand.

Figure 3. (A) General geography of Willapa Bay. (B) Stratigraphy of Pleistocene units as exposed along Ramsey Point, Willapa Bay (modified from Clifton [1983]).

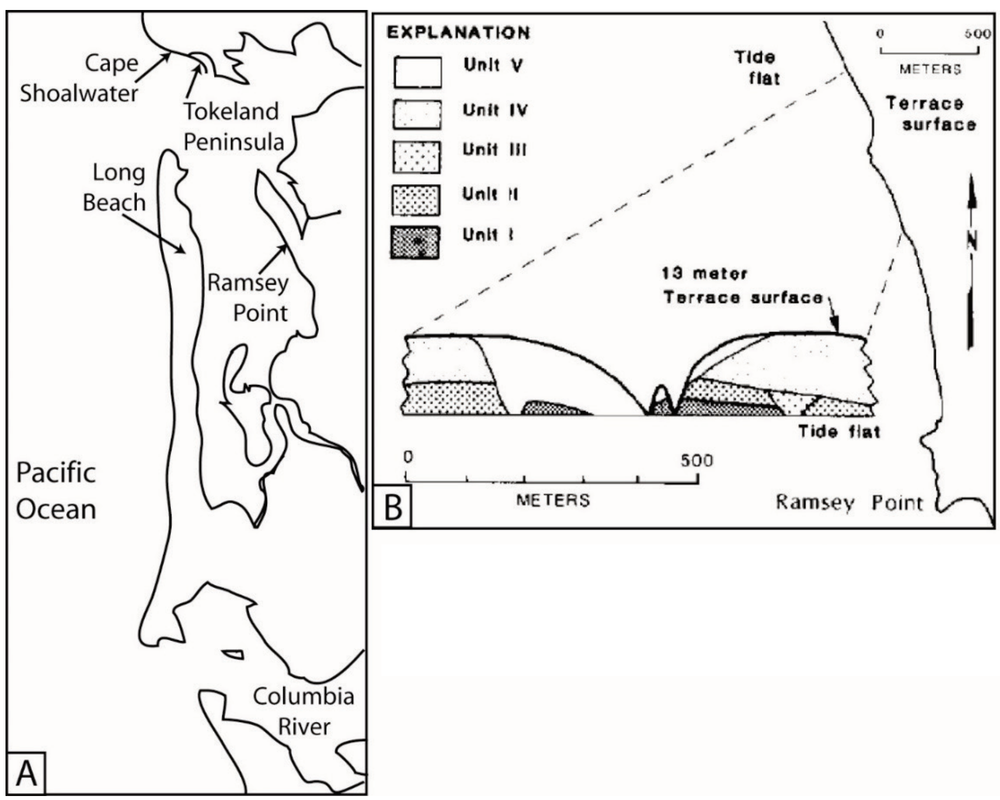
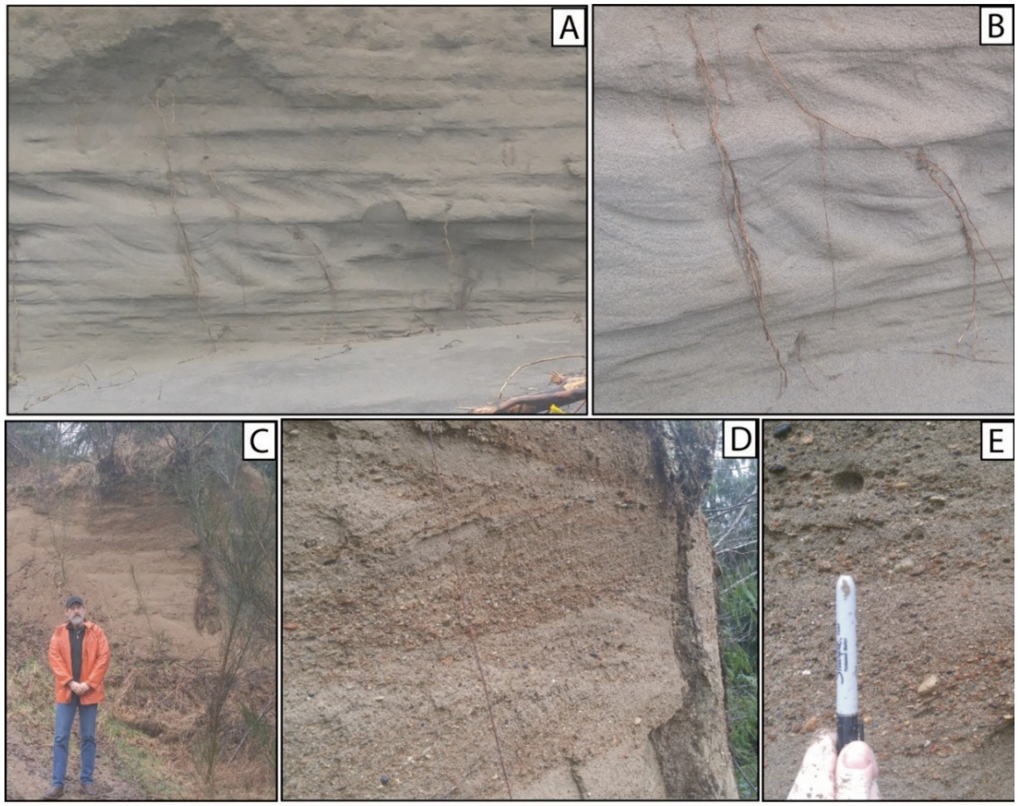


Figure 4. Geology of the Pleistocene sequence comprising the terraces inland of Cape Shoalwater. (A) Run-off channels exposed in Unit I or II along the shore line of Cape Shoalwater. (B) Close up of run-off channels. (C) Exposed upper Pleistocene sequence (likely Unit IV) in the terrace inland of Cape Shoalwater. (D) Example of cross bedding preserved in Unit IV. (E) Close up of part of a pebble-gravel lag preserved in Unit IV.



2.2 Local well logs

Discerning the extent of the Pleistocene sequence potentially exposed in the shoreface along Cape Shoalwater is challenging without an extensive geophysical mapping effort. However, a general sense of the sequence's extent can be derived via existing core logs from numerous wells drilled for both municipal and domestic use near Cape Shoalwater since the 1970s. The Shoalwater Indian Tribe sought to have the water quality of the primary regional aquifer quantified in the early 2000s. As part of this effort, borehole logs of 21 water wells were compiled by Lane and Ebbert (2001), along with extensive water quality testing. Note that some of these wells were drilled for the aquifer studies; others predated the effort, occasionally by decades. In addition to these wells, borehole logs for 19 additional wells that were not included in the Lane and Ebbert (2001) study, were provided to EDRC by the Shoalwater Tribe[1]. All of these well logs included location data of the well locations, but identifying the exact locations of these wells (named as WWR_# in Figure 5) proved challenging as the logs noted, at most, a township, range, and section. Some of the wells had a quadrant identified, or a description of the property, others did not. Thus, the locations as plotted in Figure 5 might be in error. Despite the location uncertainty, the well logs still provide an insight into the general stratigraphy of the region, and they are included in this interpretation.

Figure 5. Location of wells used in this study. WW_# indicates an unpublished well at the time this report was written. Red wells indicate the presence of the Upper Member of the Pleistocene sequence; blue wells indicate the presences of only the Lower Member of the sequence. Outcropping bedrock along the North River is noted by the white arrow. (A) All wells used in this study. (B) Close up of wells from the upper region of the Tokeland Peninsula. (C) Close up of wells from the lower region of the Tokeland Peninsula.

Unfortunately, none of the well logs noted the surface elevation of the well relative to a common datum, limiting their use in constructing vertically

[1] Steven Spencer. Personal communication. Environmental Resources Director for the Shoalwater Bay Tribe. February, 2017.

referenced fence diagrams, which are used to represent stratigraphy in three dimensions. Despite this limitation, the data still yield insight into the relative distribution of the potentially erosion resistant, partially indurated Pleistocene sequence in this region. To aid interpretation, the upper Units IV and V of the Pleistocene sequence have been grouped in this report as the “Upper Member.” Overall, this includes indurated, massively bedded sands and sandy clays, cross-bedded gravels, sands, and mud, and extensive lag deposits (up to 3–5 ft thick) of pebbles to gravel, with abundant shell and wood, plus laminated channel deposits. Well logs that contained this geology are noted by red circles in Figure 5. Units I, II, and III have been grouped into the “Lower Member” and include white to blue-gray laminated sands and mud, blue-ish bioturbated mud, and minor muddy channel sequences. Lag deposits are minor to absent in this sequence, and wells with this sequence are plotted as blue circles on Figure 5. If a well log indicated both Upper and Lower members, it was plotted as a red circle on Figure 5. In addition, note that, of the forty wells mapped in this effort, at least five were previously drilled in regions of the Cape that have subsequently been lost to shoreline erosion (Figure 5). Those logs are still relevant, however, as they provide insight as to the type of sediment potentially exposed in regions of the shoreface.

From Figure 5, it is clear that the most of the wells near the terrace and along the coastal edge of Cape Shoalwater contain at least some of the Upper Member of Pleistocene units. With few exceptions, overall these data suggest that the indurated Upper Member is still present along some sections of the Cape Shoalwater shoreline and potentially acting to slow coastal erosion, and thus shoreline retreat, in this region, as some researchers have suggested (e.g., Gelfenbaum and Kaminsky 1999; Morton et al. 2007; Morang et al. 2007). Wells with only the lower sequence preserved are located primarily in the lower Tokeland Peninsula, as well as in some Cape Shoalwater wells, which have been lost to erosion since installation. This overall variability is supported both by the spatial variability in the Pleistocene sequences mapped by Clifton (1983), and anecdotally by the recollections of Ray Williams, one of the primary well drillers in this region during the mid-to-late 1900s. In particular, the distribution of the sequences suggests that the eastern end of Tokeland Peninsula might be comprised of less erosion-resistant sediment than the rest of the region, highlighting the importance of mapping these different geologic units in a comprehensive and quantitative manner to identify the most erosion-susceptible substrates near the shoreline.

2.3 Basement geology

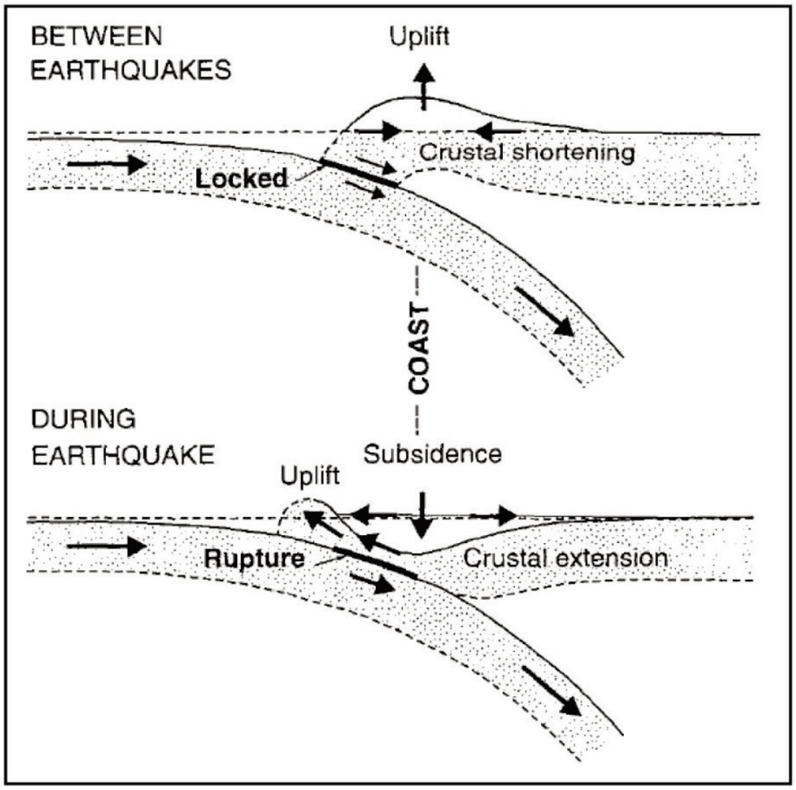
Given the possibility that the Pleistocene sequences have been partially or completely eroded in some regions, it is worth examining the potential that basement rock might be cropping out in the nearshore, impacting local erosion rates. The basement rock in this region is the Crescent Formation, a lower- to mid-Eocene sequence of basalt flows and basaltic breccias (Huntting et al. 1961; Beikman et al. 1967). This formation is overlain by the Eocene-Oligocene marine sedimentary rocks of the Lincoln Creek Formation, which are predominantly composed of tuffaceous siltstone and fine-grained sandstone (Beikman et al. 1967). Note that the closest subaerial exposure of the Lincoln Creek Formation to Cape Shoalwater is upstream on the North River, which is located approximately 8 miles west of Tokeland (Washington State Department of Natural Resources, Division of Geology and Earth Resources 2010) (Figure 5). Above this formation an extensive erosional gap exists, as overlying units are either Tertiary sedimentary rocks, the Pleistocene sequence previously described, or Quaternary sediments (e.g., Beikman et al. 1967; Washington State Department of Natural Resources, Division of Geology and Earth Resources 2010). This erosional and/or non-depositional hiatus between the lower rocks and the overlying Pleistocene or Quaternary sediments is likely due to both fluctuating sea levels that eroded the sedimentary sequences and regional tectonic uplift (Clifton 1983). These processes are further described in Section 2.4, following. The possibility that outcrops of basement rock are being exposed in the channel, thereby resulting in the apparent recent stabilization, cannot be discounted due to (1) uncertainty in the elevation (and thus potential exposure) of basement rock near or within the main channel or along the shoreline; (2) the overall variability in thickness and extent of the overlying Pleistocene sequence; and (3) the significant erosional hiatus noted by Clifton (1983) between the Pleistocene sequence and the underlying basement rock. If the migration of the channel has eroded the overlying Pleistocene sequence completely, the result would be that the position of the channel thalweg would be stabilized by exposed basement rock outcropping along the channel edge, thereby resulting in the observed reduction in migration rates and possibly explaining the reduction in the rate of retreat of the adjacent shoreline.

2.4 Neo-tectonics

Superimposed on the complex hydrodynamics and variable geology is the impact of neo-tectonics on the framework geology. Washington State lies inland of the subducting Juan de Fuca Plate (Figure 1a). Overall, at least six major subduction-related earthquakes have impacted this region over the last 7000 years, resulting in regional subsidence (Atwater 1987). Willapa Bay has been one of the primary research sites for quantifying both regional and local tectonic uplift and subsidence in this region, including the last great Cascadian earthquake of 1700 (estimated magnitude of 8.7–9.2), which resulted in the devastating “Orphan Tsunami” along the coast of Japan (Atwater et al. 1995; Atwater et al. 2011). Geologic evidence for these past tectonic events includes buried fluvial or forest sediment overlain immediately by marsh sediment or peat, with sharp bottom contacts indicating rapid submergence and erosion, and gradual upward contacts indicating slower shoaling and formation of a new marsh (Atwater et al. 1995; Peterson et al. 2000; Atwater et al. 2011).

Localized submergence of a continental shelf during a subduction earthquake occurs when, during the earthquake itself, there is co-seismic stress release caused by the strain on the continental plate and uplift due to the subducting plate (e.g., Nelson et al. 1996; Nelson et al. 2006; Simms et al. 2017) (Figure 6). As a result, although the entire region experiences overall uplift in response to the regional subduction event, there is localized subsidence during the event. In addition, subsidence can also occur between major earthquakes as partial strain release. In nearby Grays Harbor, several events with subsidence on the order of 2 ± 0.5 m have been mapped (e.g., Atwater et al. 1995; Peterson et al. 2000). Although similar events have likely occurred at Willapa Bay, the overall subsidence is supposed to have been of a smaller magnitude at Willapa Bay than Grays Harbor, as Grays Harbor is located closer to the most recent subduction event (Atwater et al. 1995). As a result, Willapa Bay has likely experienced tectonically created increases in accommodation space that have allowed it to act as a sediment sink for the Columbia River littoral cell, as postulated by Gelfenbaum et al. (1999) and Gelfenbaum and Kaminsky (2010) in preceding Section 1.2.

Figure 6. Simplified earthquake cycle showing local subsidence during a subducting earthquake. From Peterson et al. (2000).



2.5 Influence of modern processes

The decrease in beach aggradation, and thus the subsequent increase in coastal erosion noted in Willapa Bay (specifically along Cape Shoalwater), might thus be related not just to a reduction in sediment supply by the construction of jetties at the Columbia River and Grays Harbor, but also to the previous tectonically created accommodation space being filled, ultimately resulting in sediment bypassing. Finally, although not the focus of this review, interactions between the modern morphology and the local hydrodynamics may explain much or all of the observed variation in channel migration rates and/or shoreline change rates. For example, the highly dynamic sandbar and shoal morphology at the mouth of the bay likely influences the position of the main channel, which in turn impacts where along the shoreline the channel exerts hydrodynamic stress (e.g., Terich and Levenseller 1986). The morphology and growth of Long Beach is also quite variable and may greatly influence short-term sediment availability to the region, further influencing the relative stability of Cape Shoalwater and Tokeland Peninsula.

3 Conclusions and Proposed Research Questions

Ultimately, it is uncertain from existing data just how thick or variable the Quaternary and Pleistocene sequences are in the shoreface of this region, and thus it is unclear if the indurated Pleistocene units are acting to resist erosion along the channel thalweg or the Cape Shoalwater shoreface and shoreline. The specific resistance to erosion of these Pleistocene sediments has not been quantified. In addition, it is unclear at what elevation either the Crescent Formation or the Lincoln Creek formation basement rocks underlie the Quaternary and Pleistocene sequences, and thus the possibility that one or both of these geologic units are outcropping along the channel edge and/or in the shoreface should be considered. The composition and/or potential erosion resistance of the rock or sediment currently comprising the channel edge and/or shoreface needs to be quantified in order to determine (1) if channel migration and/or shoreline erosion can be expected to continue at historical rates and (2) what engineering solutions could work to mitigate ongoing and expected future erosion.

3.1 Primary research questions

In an effort to examine the overarching question of whether erosion-resistant outcrops may be significantly influencing erosion rates at Cape Shoalwater and the Tokeland Peninsula, the following questions should be addressed:

1. Are Pleistocene or older basement rock units exposed in the shoreface and are they influencing erosion rates?
2. If the shoreface is comprised of the sedimentary Pleistocene deposits or Quaternary sediments, do those geologic units vary spatially? Are there significant variations in erosion resistance between the Quaternary sediments and the Lower Member Pleistocene or Upper Member Pleistocene units? Do these variable erosion rates, coupled with a geologic map of the shoreface, nearshore, and channel edge, explain the recent changes in channel migration rate and coastal erosion?
3. How variable is the volume of transport-relevant sand along the shoreface? Is there the same amount of sand available to feed the beach from the shoreface and nearshore along the entire study area? Is there a spatial relationship between sand volume and adjacent shoreline stability?

Benefit to NWS. Quantifying the impact of framework geology, if any, on observed channel migration and shoreline erosion rates will allow NWS to better assess the success of potential future mitigation strategies. For example, if basement rock is exposed in the migration channel, stabilizing it, then NWS no longer needs to consider mitigation strategies that include channel stabilization, as the channel will be naturally stabilized by the location of the basement rock. In contrast, if the channel is instead actively eroding the more resistant Pleistocene units, as postulated by Morang et al. (2000), the observed reduction in migration is likely only temporary. In this case, by quantifying the spatial extent and volume of the resistant sediment using chirp sub-bottom imagery, and the erodibility of the resistant sediment layer using the SEDflume, ERDC could provide NWS an estimated time frame over which channel migration will be slowed by the erosion-resistant sediment.

3.2 Additional research

It is possible that the geologic study outlined above will not identify an obvious geologic control along the channel edge or in the shoreface. In that case, the variations in the northern migration rate of the channel, as well as the processes resulting in the rapid and variable erosion along Cape Shoalwater and the Tokeland Peninsula, are likely purely driven by complex interactions between the modern morphology, sediment supply, and hydrodynamics. In that case, the following research topics should be addressed:

1. Changes in Sediment Supply: Gelfenbaum et al. (1999) have suggested that changes in regional sediment patterns caused by the construction of the jetties at the Columbia River mouth and the entrance to Grays Harbor might have reduced the amount of sediment being transported to Willapa Bay and, specifically, Cape Shoalwater. A lack of observed significant variation in shoreface geology might suggest that there has been a change in local sediment transport, suggesting an updated sediment transport observational and numerical modeling effort might be useful in the future.
2. Regional geomorphology: The highly dynamic sandbar morphology at the mouth of the bay may be influencing the hydrodynamics such that the degree of erosion stress acting on the channel boundary and/or the adjacent coastline may vary as the size and orientation of the sandbar changes due to fluctuations in sediment supply, storm frequency, or

other factors. A targeted observational and modeling effort could address the relationships between morphology change at the inlet, local and regional hydrodynamics, and associated channel and shoreline stability.

Benefit to NWS. A targeted observational and numerical modeling effort could be focused on the hydrodynamics and sediment transport resulting in the observed morphology change. The study could delineate the process or processes with the most significant impact on channel migration and/or shoreline erosion, allowing NWS to plan future mitigation efforts with those processes in mind.

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14. ABSTRACT
The shoreline along Cape Shoalwater and northwest Willapa Bay has experienced the highest rates of erosion along the entire Pacific Coast of the United States, due in part to rapid northward migration of the navigation channel. Recently, channel migration and shoreline erosion in this region have slowed, but the cause of this relative stabilization, and thus the longevity of these new patterns, is unknown. Given the complex neotectonics and geologic framework of the southern coast of Washington, it is possible that underlying, erosion-resistant geologic units have become exposed along the channel and/or in the nearshore, and are acting to reduce or halt channel migration and/or shoreline erosion. Conversely, the apparent reduction may be due to subtle, short-term changes in regional hydrodynamics and/or sediment transport, and thus future rates of channel migration and/or shoreline erosion might increase back to historical rates. The purpose of this special report is to detail the geologic and neotectonic framework of the northern Willapa Bay region, and determine how the underlying framework geology might be impacting channel stability and adjacent shoreline erosion rates. Suggested research questions to quantify potential geologic control are also presented, including the potential benefits of the research to the district.

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