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Hazard Identification and Coastal Stratigraphy in Crescent Harbor, Northeast Whidbey Island, Washington

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HAZARD IDENTIFICATION AND COASTAL STRATIGRAPHY IN CRESCENT HARBOR, NORTHEAST WHIDBEY ISLAND, WASHINGTON

A Thesis
Presented to
The Graduate Faculty
Central Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Geological Sciences

by
Brian Alan Ostrom
May 2016

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

We hereby approve the thesis of

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Dean of Graduate Studies

ABSTRACT

HAZARD IDENTIFICATION AND COASTAL STRATIGRAPHY IN CRESCENT HARBOR, NORTHEAST WHIDBEY ISLAND, WASHINGTON

Brian Alan Ostrom

May 2016

Crescent Harbor marsh, on northeastern Whidbey Island, records evidence of co-seismic land-level change 1825 to 1925 cal. yrs. BP. The lithostratigraphy and diatom microfossil assemblages reveal a marsh peat abruptly overlain by intertidal mud, indicating rapid subsidence. Analysis of the modern-day position of depositional facies indicates subsidence from a high marsh to a tidal-flat environment representing an estimated 1.7 m elevation change. The timing of subsidence fits within the dates of a rupture found on the nearby Utsalady Point fault between 1,100 and 2,200 years BP (Johnson et al. 2004). Likely, the stratigraphy at Crescent Harbor records the same event and refines the age of rupture to ~2,000 yrs BP. Crescent Harbor stratigraphy supports evidence that the Utsalady Point fault is an active feature in northern Puget Sound and poses a seismic hazard to northern Whidbey Island. In addition to the paleo-seismic interpretation, stratigraphy also indicates that tidal exchange in the marsh was restricted or non-existent for the last 1,000 years BP, up until AD 2009 when the barrier was intentionally breached and the majority of the marsh became intertidal.

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I would like to thank my advisor, Dr. Breanyn MacInnes, for her leadership and assistance throughout the duration of my master’s degree. She provided an amazing balance of approachability and respect, while still providing authority andleadership that I think is rare to find in an advisor. This made the experience truly enjoyable and one that I will always remember. Last, but certainly not least, I would like to thank my family and friends for their amazing support over the course of my education.

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CHAPTER I

INTRODUCTION

The Puget Sound region, in the forearc of the North American plate above the Cascadia subduction zone, simultaneously is home to several million people and vital infrastructure including ports and military bases, and is a dynamic and seismically active geologic setting. The east-west trending, shallow crustal faults that cross-cut Puget Sound (Fig. 1) are an acknowledged hazard. Whidbey Island, in northern Puget Sound, is intersected by two main fault zones, the Darrington-Devils Mountain and the South Whidbey Island fault zones, along with the smaller Utsalady Point and Strawberry Point faults (Hayward et al. 2006; Kelsey et al. 2004; Johnson et al. 2004) (Fig. 1). Any of these faults could pose a significant hazard to the residents and infrastructure of Whidbey Island, including shaking caused by an earthquake, and associated land-level change, liquefaction, and tsunamis. However, characterizing the complete seismic hazard in the Puget Lowland requires study of the primary and secondary effects of paleo-earthquakes because there have been no large, historic, shallow ruptures. In the short historical record of the Puget Sound region, there have been only three earthquakes greater than magnitude 6.0. These were deep ruptures with relatively minor shaking, yet resulted in a total of 15 deaths, extensive property damage, and damage to infrastructure (Stover and Coffman 1993; Nisqually Earthquake Clearinghouse Report 2001).

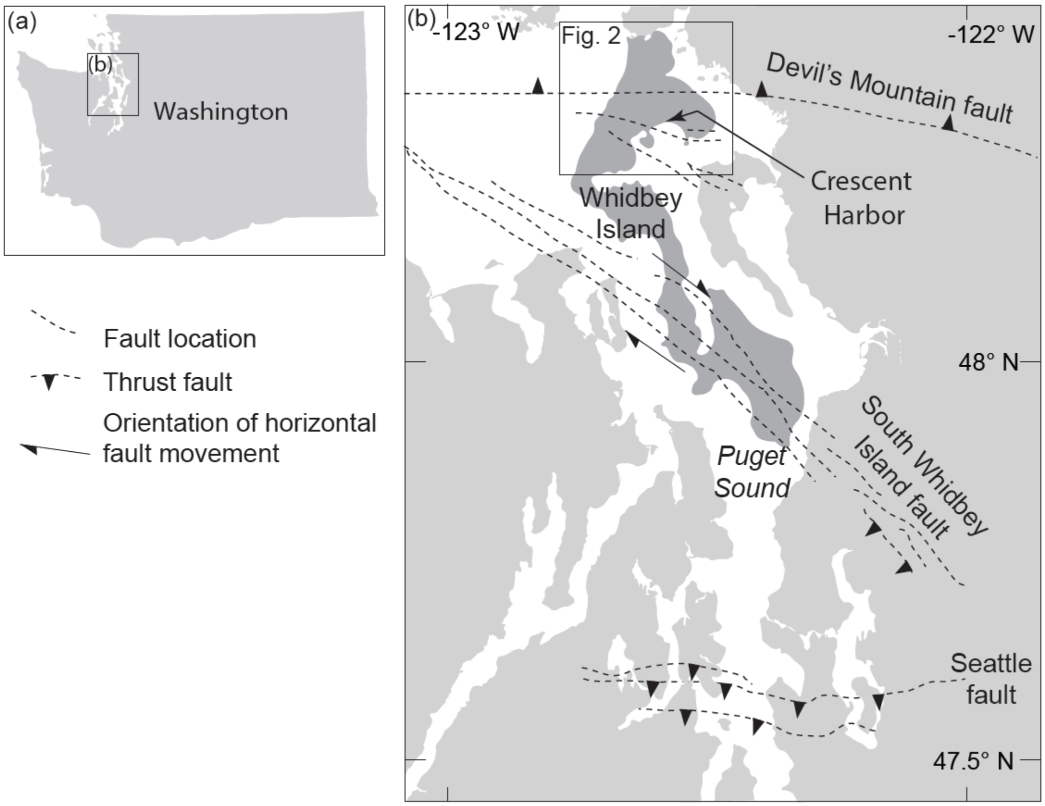


Fig. 1 Northern Puget Sound fault map, (a) Index map of Washington State with the central and northern Puget Sound region outlined in the black box. (b) The location of the Darrington-Devils Mountain, South Whidbey Island and Seattle faults. Whidbey Island is a darker shade of grey. Box outlines northern Whidbey Island, the extent of Figure 2. The Crescent Harbor field area is indicated by the arrow.

A reliable method of extending the seismic record to include paleo-earthquakes is using coastal marsh stratigraphy to identify and date abrupt (co-seismic) land-level changes. This method was first applied after the 1964 Alaska earthquake when subsidence was recorded in marsh sediments (Overshine et al. 1976) and has since been used in many paleoseismology studies throughout Puget Sound (e.g., Sherrod et al. 2000; Sherrod 2001; Bourgeois and Johnson 2001; Arcos 2012). Lithofacies and microfossils are valuable in identifying depositional environments because they have specific elevations at which they form and are deposited throughout the tidal zone, primarily based on tidal inundation. Marshes are ideal for the use of lithofacies and microfossils to identify depositional environments because they are very sensitive to elevation changes and have good preservation. Nelson et al. (1996) outlined how gradual versus abrupt peat-mud contacts can provide information about the seismic history of a marsh, specifying that sharp contacts likely represent active tectonics while gradual contacts are more typical of non-tectonic processes such as compaction subsidence or slow sea-level rise.

In this study we focus on a marsh at Crescent Harbor, located on the east coast of northern Whidbey Island, adjacent to the town of Oak Harbor and the Naval Air Station (NAS) Whidbey Seaplane Base (Fig. 2). This site sits within hundreds of meters laterally of the Utsalady Point fault, which is known to have produced at least two surface ruptures to the west of Crescent Harbor in the last 2,000 years (Johnson et al. 2004). We use the stratigraphy of Crescent Harbor marsh to determine if and how the area was affected by these two or other paleo-earthquakes, in addition to determining the general history of the marsh.

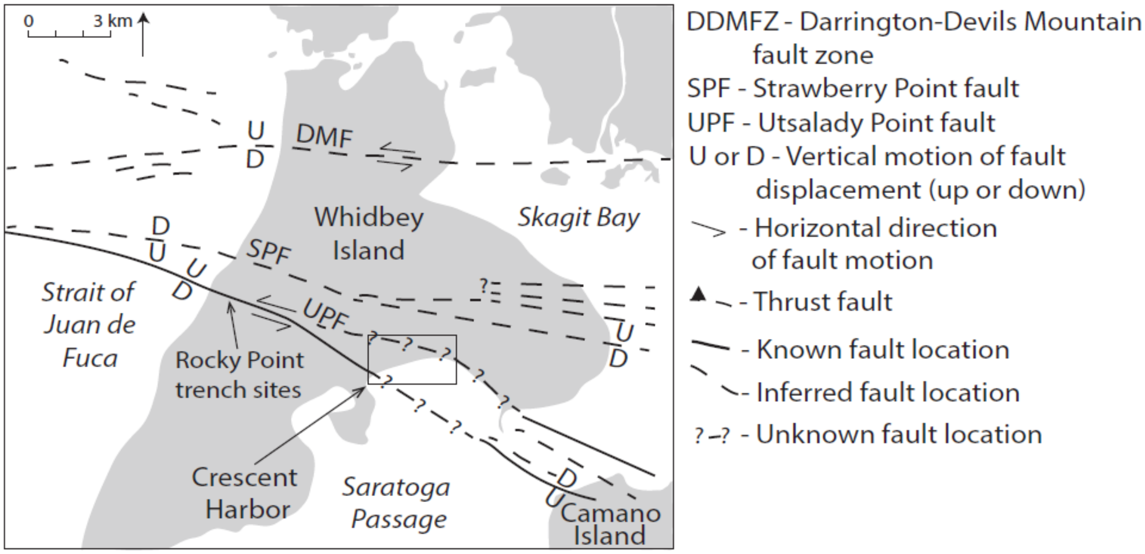


Fig. 2 Northern Whidbey Island fault map showing main faults, their orientations and sense displacement. Note the bifurcated segments of the Utsalady Point fault and uncertain location of those segments. The up-down sense of the Utsalady Point fault changes somewhere between western Whidbey Island and Camano Island. Crescent Harbor is outlined by the small box near the center of the figure (Johnson et al. 2001; Johnson et al. 2004).

CHAPTER II

LITERATURE REVIEW

Tectonic Setting and Paleo-Events

Little previous work has been devoted specifically to characterizing faults in the vicinity of northern Whidbey Island. Although these few previous studies (summarized below) are high quality, the paucity of studies along these faults cannot fully define the hazards that these features present. The northern Whidbey Island studies primarily focus on three main faults; the Darrington-Devils Mountain fault zone (DDMFZ) and Utsalady Point, and Strawberry Point faults that all trend east-west across the island (Fig. 2). The DDMFZ, north of the field area, is the largest and extends >125 km east-west across northern Puget Sound from Victoria, British Columbia southeast to Darrington, Washington (Personius et al. 2014). Hayward et al. (2006) used seismic reflection profiles to characterize DDMFZ and presented evidence to suggest that the Utsalady Point fault and DDMFZ were once part of the same feature and have since divided into separate faults. Trenching investigations by Personius et al. (2014) ~30 km east of Crescent Harbor found evidence for an earthquake on the DDMFZ about 2,000 cal. yrs. BP. The Strawberry Point fault has been proposed to make landfall from the Strait of Juan de Fuca about one kilometer north of Rocky Point on the west side of Whidbey Island (Johnson et al. 2001) (Fig. 2). This fault bifurcates on the east side of Whidbey and becomes a broad fault zone made up of four strands, each with apparent south-side-down offset. There is currently no evidence that this fault has been active since ~80 to 130 ka, based on a lack of deformation in sediments younger than the Whidbey Formation (last interglacial) near Strawberry Point on Whidbey Island (Johnson et al. 2001).

The Utsalady Point fault extends from the Strait of Juan de Fuca and traces just to the south of NAS Whidbey, under Oak Harbor, and across Saratoga Passage to Utsalady Point on Camano Island (Fig. 2). This fault was first recognized in seismic reflection profiles by Johnson et al. (2001) and has been trenched on the west side of Whidbey Island near Rocky Point by Johnson et al. (2004) who found evidence for two ruptures, one between 1,100 and 2,200 cal. yrs. BP and a younger one between 100 and 400 cal. yrs. BP. The Utsalady Point fault is characterized by near-vertical fault dip and a reversal of offset along strike; the fault possibly splays just west of Crescent Harbor (Fig. 2 in Johnson et al. 2001). West of this possible splay, the sense of motion is oblique left-lateral with south side down, based on offshore seismic reflection profiles. From the splay towards Camano Island (and past Crescent Harbor), one trace runs north of Crescent Harbor and one just to the south (Fig. 2), although the exact positions are uncertain due to a lack of a surface trace. The two strands of the fault appear on Camano Island near Utsalady Point, at which point the south strand displays south-side-up faulting, a reversal from the west end of the fault. The vertical orientation of the northern strand at Utsalady Point is unknown (Johnson et al. 2001).

There is evidence that northern Puget Sound has been affected by non-Cascadia tsunamis as recently as 1,800 years BP. Williams and Hutchinson (2000) show evidence for two potential tsunami deposits at Swantown marsh on the west side of northern Whidbey, both dated as ~1800 to 2100 years BP, which they proposed were produced by faulting in the eastern Strait of Juan de Fuca because the dates did not correlate with known plate-boundary earthquakes (Atwater and Hemphill-Haley 1997). Their work was before published local fault studies in the eastern Strait of Juan de Fuca. Since then, Johnson et al. (2004) reported a rupture on the Utsalady Point fault that overlaps in age with the tsunami deposit reported by Williams and Hutchinson (2000).

Glaciation and Holocene Sea Level Change

In order to discuss the development of coastal stratigraphy, it is necessary to establish the source of sediment and morphology of the area. The last glacial advance, the Fraser glaciation, reached its maximum at about 15,000 yrs BP (Booth 1994; Porter and Swanson 1998) and the Puget Lobe of this glaciation had retreated to Whidbey Island by about 14,000 yrs BP (Mosher and Hewitt 2004) leaving behind reshaped pre-existing surfaces with locally thick layers of glacial till and outwash. The effects of these processes have buried and/or erased older surficial fault markers, leaving only (at most) the last 15,000 years of fault motion visible in the landscape.

Isostatic rebound in northern Puget Sound following glacial retreat started about 13,500 yrs BP and was quite rapid (Dethier et al.1995). Mathews et al. (1970) conclude that the majority of isostatic rebound at Victoria BC had occurred prior to 10 ka. Other studies from northern Puget Sound indicate that the rate of sea-level rise exceeded rebound prior to 7 ka near southern Whidbey Island and the Fraser Lowland (Thorson 1980; Clague 1983), indicating rebound had already slowed at this point. Relative sea-level fall due to high rates of isostatic rebound would have been a factor in northern Puget Sound sea-level for only 3,000 to 6,000 years following glacial retreat (Fig. 3).

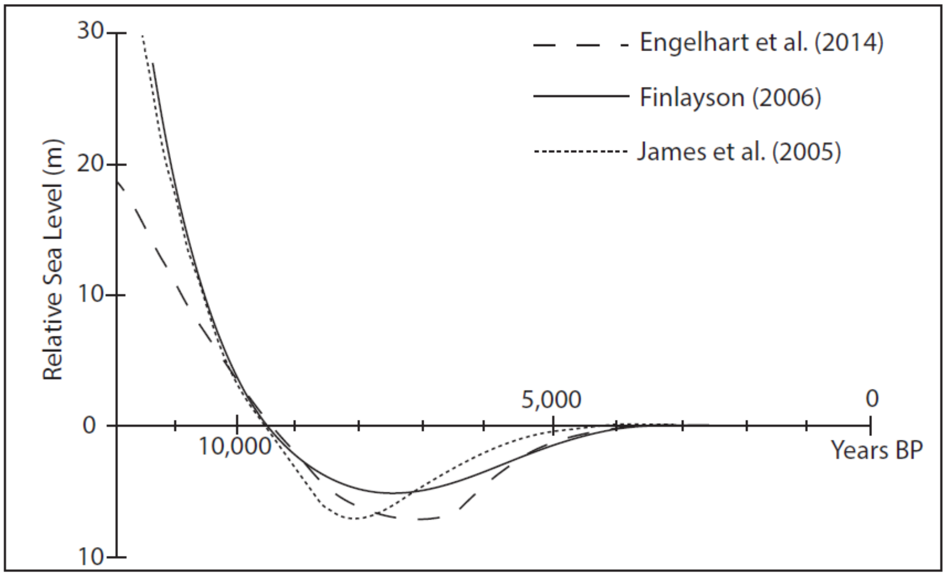


Fig. 3 Combined sea-level curve using data from three studies of north Puget Sound sea-level (Engelhart et al. 2014; James et al. 2005; Finlayson 2006).

Rising sea level is predicted to have stabilized to near present levels in northern Puget Sound by ~5,000 years ago (Fig. 3; Engelhart et al. 2014, James et al. 2005 respectively), allowing for coastal marshes, spits, and beaches to form where they are today. Even with some disparities, all studies indicate that Puget Sound sea level has risen less than a meter in the last 1,000 years (Engelhart et al. 2014, James et al. 2005) and that by about 5,000 years BP northern Puget Sound sea level was within 2 to 3 meters of present values (Beale 1990; Finlayson 2006)(Fig. 3).

Stratigraphic Markers of Tectonics

The natural stratigraphy of a marsh prograding due to sedimentation, with sea level stable or rising more slowly than sediment accumulation rate, is a sequence from subtidal-intertidal mud transitioning upward into peat and potentially into dryland soil.

Gradual contacts separate the facies as the marsh slowly builds up out of the intertidal zone (Nelson et al. 1996). This sequence could be reversed if transgression occurs, with sea level rising faster than deposition, but there would still be gradational contacts separating those units (Fletcher et al. 1993a; Kelley et al. 1995; Gardner and Porter 2001). In the rare case that the shoreline is stable due to equilibrium between sea-level rise and sediment supply, stratigraphic sections would show one uniform facies with no contacts (Allen 1990).

A sharp contact of mud over peat is generally recognized as a marker for co-seismic subsidence (Atwater 1987; Bourgeois and Johnson 2001; Graehl et al. 2015) and peat over mud for uplift (Shennan et al. 2009; Arcos 2012). These contacts will be represented in marsh stratigraphy by sharp changes in the type of sediment deposited, as a result of instantaneous transition from one depositional environment to another. For example, peat forms at or above high tide; thus the surface would have to drop rapidly into the lower intertidal zone to allow a mud devoid of plant material to form above the peat.

Microfossils such as diatoms can be used to reconstruct the environmental history of tidal marshes and are commonly used in paleoseismology studies globally (Atwater et al. 2004; Shimazaki et al. 2011; Dura et al. 2015) and throughout Puget Sound (Sherrod et al. 2000; Sherrod 2001; Kelsey et al. 2004; Williams et al. 2005). Diatoms are particularly useful in paleoenvironmental reconstructions because their sensitivity to differences in tidal inundation, substrate and salinity enables their assemblages to be unambiguous indicators of elevation within a tidal marsh (Shennan et al. 1999; Dura et al. 2016). Previous studies in Puget Sound show that modern diatom species are distributed along major environmental gradients and can be separated into subenvironments (e.g., freshwater marsh, high marsh, low marsh, and tidal flat; Sherrod 1999; 2001). The relation between diatom assemblages and modern subenvironments can be applied to fossil diatom assemblages present in cores and/or outcrops in order to reconstruct paleoenvironmental changes and to estimate the amount of land-level change across sharp stratigraphic contacts (Hemphill-Haley 1995a).

Recent Marsh History

Crescent Harbor marsh was diked and drained in the early 1900’s to allow for attempts at agriculture; fence posts can still be found throughout the marsh. The Navy bought the property in early 1940s as a location for a sea plane base, and still controls the property today. During construction of the sea plane base, the SW corner of the marsh was used as a barge landing to offload equipment and supplies, as well as a dumping area for dredge material. The city of Oak Harbor built a waste-water treatment plant in the marsh in the early 1960s, which is still in use today. The area remained a freshwater wetland until the mid to late 1990s when the tide gate that had kept saltwater out of the marsh was modified to allow saltwater inflow to the marsh. In 2009, the barrier was completely breached, and saltwater now has access to the entire marsh, with daily tides (Mickelson et al. 2009). Appendix A illustrates human-induced changes to the marsh through the last ~60 years.

The topographic sheet of Crescent Harbor published by the U.S. Coast and Geodetic Survey in 1888 does not show an inlet or mouth that would indicate that the marsh was open to Crescent Harbor. The map indicates a salt marsh, and not that it is submerged. Historical accounts indicate that the marsh was mostly wet prior to diking and draining in the early 1900's. Aerial photography from August of 1977 shows that the marsh has water in the drainage channels but no standing water is observed.

CHAPTER III

METHODS

Field Data Collection

Stratigraphic data was collected at a total of 118 locations including 18 pits, 39 channel bank exposures and 61 push cores (Appendix B). We divide the field area up into two general areas that are referred to throughout the rest of the paper: the *back marsh* is the area north of the inflow pipe that delivers water to the treatment plant, and the seaward half or *front marsh* is the area southeast of this pipe (Appendix B “Marsh area”). The west and southwest part of the marsh was either physically inaccessible, due to the saturated nature of the substrate, or was composed of dredging material deposited in the 1940s during construction of the Sea Plane Base.

Field data collected in this study included detailed descriptions of marsh stratigraphy at geo-referenced excavations, cores, and cutbank outcrops, and samples for radiocarbon, grain size, and microfossil analysis. Our preferred method for describing the stratigraphy of Crescent Harbor marsh was analysis of the tidal-channel cutbank in the SE quadrant of the field area (Appendix A). This work allowed for accurate identification and measurement of stratigraphic layers and their spatial distribution. However, the limited extent of the tidal channel required our primary stratigraphic method to be coring with a push core or auger. Although trenching was not an option due the high water table, shallow pits were dug on and adjacent to the modern berm. The primary goal of our core-transect grid was to map spatial variations in stratigraphy (Appendix B).

We recorded precise elevations and positions of all cores and outcrops using a total station and corrected for a global reference frame with GPS base stations. We also measured a transect of the modern beach and berm to record elevations of vegetation and sediment changes, as well as the height of the modern beach ridge/berm and the position of driftwood. All measurements were set relative to Mean Lower Low Water (MLLW), the sea-level datum for Washington State.

Monoliths were taken directly from the tidal channel bank in the front marsh and were extracted using plastic trays which were centered on the contacts that were of interest. Three monoliths were taken two from the lower mud contact (061S and 147) and one from the upper mud contact (061L) and there stratigraphic position was recorded. The samples were then wrapped and refrigerated until analysis.

Sample Analysis

Samples for accelerator mass spectrometer (AMS) radiocarbon age dating were taken at stratigraphic horizons marking changes in lithology. As outlined by Kemp et al. (2013), these samples were selected for macroscopic organic material that could represent surficial deposition, such as seeds, leaves, or shallow rhizomes. Some units did not contain sufficient macro-organic material so were dated as bulk sediment. Radiocarbon dates were calibrated in OxCal version 4.2 (Reimer et al. 2013).

The grain sizes of major stratigraphic units were analyzed for use in comparing and defining marsh facies. These samples included mud, sand, and gravel deposits. We analyzed the grain size of mud-sized sediment samples using a *Mastersizer* laser particle analyzer and the sands and gravels using a *CAMSIZER*, a high-speed photo analyzer.

We subsampled the stratigraphy of monoliths 147, 061S, and 061L at one-centimeter intervals above and below major changes in stratigraphy for microfossil analysis. Methods for preparing the samples and identifying the microfossils follow Dura et al. (2015). When possible, >400 diatom valves were counted with each species expressed as a percentage of total diatom valves counted. Only species that exceeded 5% of total valves were used for paleoenvironmental interpretations. Diatom species were classified into three marsh subenvironments—freshwater/high marsh, low marsh, and tidal flat—following previous studies in Puget Sound and the Pacific Northwest (Atwater and Hemphill-Haley 1997; Hemphill-Haley 1995b; Sherrod 1999; Sherrod et al. 2000; Sherrod 2001; Witter et al. 2009). Samples were also scanned for the abundance of chrysophyte cysts (freshwater golden algae) to help distinguish freshwater from tidal environments (Dura et al. 2015).

Facies Depositional Environments and Land-Level Reconstructions

We separated the stratigraphy of Crescent Harbor marsh into facies, or stratigraphic units, each having distinct characteristics and forming in a specific depositional environment. Our facies were separated using lithologic composition, relative organic matter content, grain size, and color as defining characteristics. The main factor used to define facies was sediment type, whether organic or mineral in composition, followed by the percent of organic matter if present. Initial identification of facies was done in the field, based on visual and physical characteristics, such as texture, color, grain size and sediment type.

Land-level change was estimated using methods similar to those of Hemphill-Haley (1995b), which use diatoms to determine subenvironments and then calculate the elevation difference between those subenvironments. The elevation difference is the estimate for co-seismic land-level change for that specific field area. This method can only be used if there are sharp stratigraphic contacts separating elevation-dependent facies. Other studies in the northwest have used similar methods for paleoenvironmental reconstruction and estimates of land-level change (Atwater and Hemphill-Haley 1997; Hemphill-Haley 1995a; Sherrod 1999; Sherrod et al. 2000; Sherrod 2001; Witter et al. 2009). The nearest modern diatom transect is from central Puget Sound (Sherrod et al. 2000) which provides an acceptable analog to the diatoms of Crescent Harbor.

CHAPTER IV

RESULTS

Lithostratigraphy and Lithofacies

Crescent Harbor marsh shows evidence of a varied yet somewhat predictable stratigraphy throughout the marsh (Fig. 4) with some lithofacies more persistent than others.

Sandy gravel: The basal unit throughout much of Crescent Harbor marsh is sandy gravel (Fig. 5a), with grain size ranging from coarse sand to small cobbles, ranging from sand dominated to gravel dominated. The sediment is poorly to very poorly sorted and of mixed lithology; the grains are well-rounded. Subtle layering within the gravel exposed in the cutbank at the front marsh slopes seaward. The layering appears to be due to differences in sorting and grain size of the unit. Sorting values from modern beach samples range from 1.6 to 2.3 (poorly to very poorly sorted). *Sandy gravel* taken from the marsh stratigraphy has a sorting value of 2.9 (very poorly sorted).

Gravelly sand with silt: The basal deposit in excavations from the back marsh (Fig. 5a) is subangular to subrounded, moderately sorted sand with gravel and silt-sized particles mixed in. The sediment is mostly medium- to coarse-grained sand with gravel ranging from pebbles up to 3 cm in diameter. Powdery silt is visible on the sand and gravel when observed with a hand lens. Even though silt is present, this unit is better sorted than the *sandy gravel,* with sorting values ranging from 0.78 to 0.85 (moderately sorted).

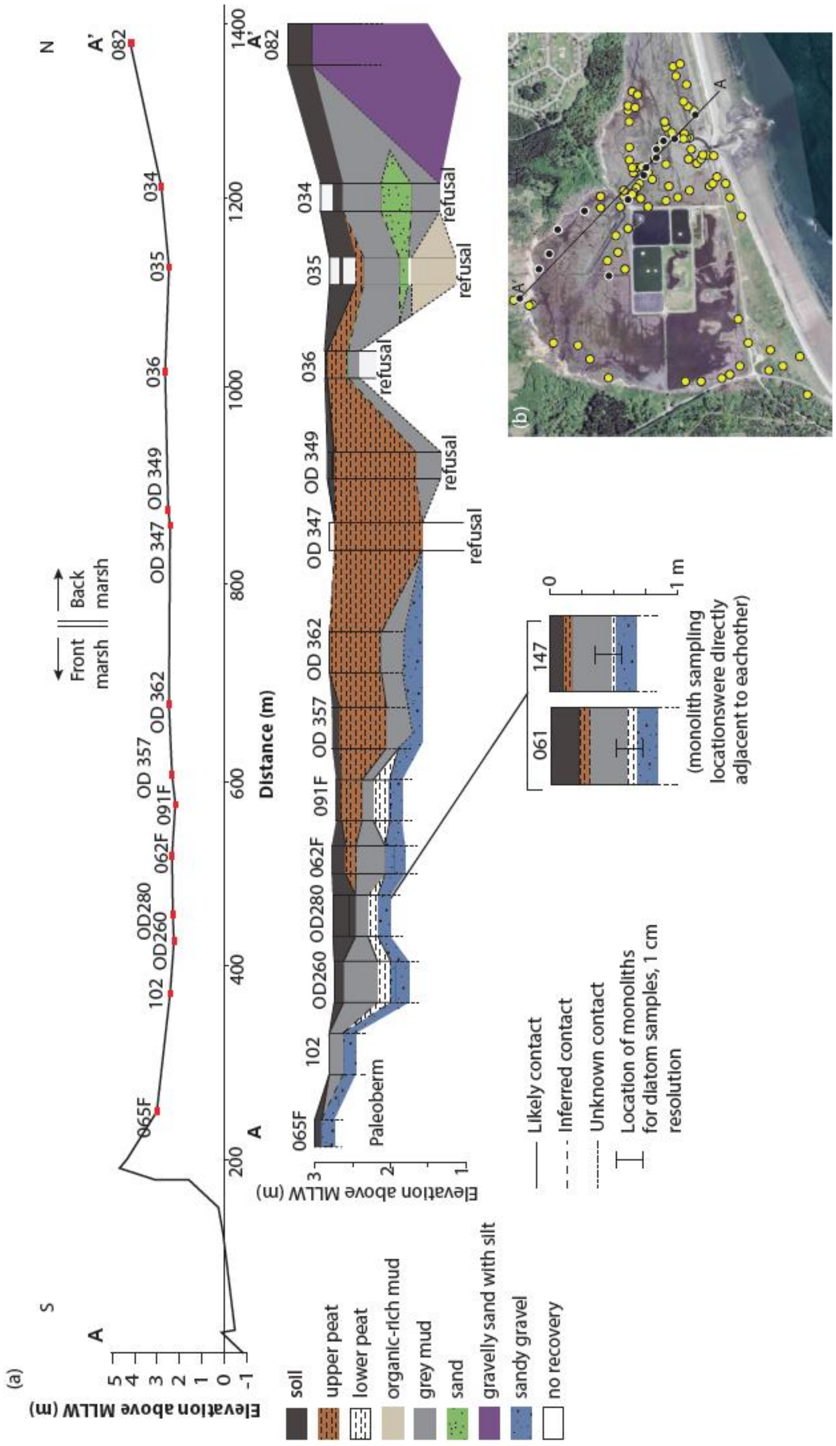


Fig. 4 (a) Marsh transect and cross-section across Crescent Harbor marsh from SE to NW using core and tide channel exposures. Elevations from total station measurements. Monolith sample location analyzed for microfossils are indicated. (b) Map showing the corresponding A-A' line for the transect. Black dots represent the location of cores and tide channel exposures used to create the cross-section.

Gray mud: Gray compact mud is present in the marsh stratigraphy at most locations (Fig. 5b). The grain size is mostly silt with some clay and has a negligible amount of detrital plant material and small wood fragments.

Peat: There are two stratigraphic units of brownish orange peat composed of *in situ* and detrital fibrous plant material, roots, and minor amounts of wood fragments. The *lower peat* is present locally in the front marsh between *sandy gravel* and the *gray mud* (Fig. 5c). The *upper peat* is present above the *gray mud* at many locations in the front marsh and is common in the back marsh (Fig. 5d). Woody debris is present in the *upper peat*, just above the mud-peat contact. The fragments are >2 cm in diameter and tens of centimeters long. The wood does not appear to be in growth position.

Organic-rich mud: Grayish-brown mud rich in detrital plant material and clay-sized organics is distinctive from the *gray mud* and *peat* facies and can be considered an intermediate between the two. It has significantly more organic material (unidentifiable plant leaves and stems) than the *gray mud*, but not enough plant matter to be considered a peat. The percentage of organic material in Crescent Harbor today increased from lower to higher parts of the intertidal zone. While not identified in many sample locations, the organic-rich mud facies is present in both back and front marshes (Fig. 5e).

Soil: Dark brown to black soil is present mainly in the upper 40 cm in many locations throughout the marsh (Fig. 5f). This soil has significant amounts of decomposed plant matter in it, including roots and stalks of *Typha latifolia*. It is more decomposed, less fibrous, darker and less orange than the peat facies.

Sand lenses: Sand lenses are present at almost every depth in ~20% of cores/excavations throughout the marsh. The sand is mostly medium grained and poorly to moderately sorted and the lenses are commonly mixed with the units above or below it, such as mud or peat. Lenses range in thickness, with 1 to 2 cm being the most typical, and extend horizontally typically 1 to 3 meters.

Microfossils

Monolith 147:

Diatom assemblages in four samples from the *lower peat* are composed of a mix of freshwater marsh (e.g., *Pinnularia microstauron, Pinnularia viridis, Staurosira construens*), high marsh (e.g., *Cosmioneis pusilla*), and low marsh (e.g., *Diploneis interrupta*, *Nitzschia recta*) species (Fig. 6; Relative abundances of each species can be found in Appendix C). *Lower peat* samples also contain abundant freshwater chrysophyte cysts. In contrast, two samples from the overlying *gray mud* are dominated by tidal-flat diatoms (e.g., *Achnanthes brevipes, Caloneis westii, Paralia sulcata, Trachyneis aspera, Scolioneis tumida*) with minor abundances of low marsh diatoms (e.g., *Surirella brebissonii*).

Monolith 061S:

Two samples from the *lower peat* contain abundant freshwater diatoms (e.g., *Aulacoseira* sp., *Pinnularia microstauron*, *Pinnularia viridis*) and chrysophyte cysts with minor abundances of a variety of low marsh (e.g., *Diploneis notabilis*) and tidal flat (e.g., *Caloneis westii*, *Gyrosigma exigua, Paralia sulcata*) diatoms (Fig. 6; Relative abundances of each species can be found in Appendix C). In contrast, four samples from the overlying *gray mud* are dominated by tidal flat diatoms (e.g., *Achnanthes brevipes*, *Auliscus* sp., *Cocconeis clandestina*, *Diploneis notabilis*, *Gyrosigma eximium*, *Paralia sulcata*, *Trachyneis aspera*) with minor abundances of low marsh diatoms (e.g., *Nitzschia linearis*).

Monolith 061L:

Three samples from the *gray mud* facies contain tidal flat diatoms (e.g., *Caloneis westii, Gyrosigma eximium, Melosira nummuloides, Nitzschia levidensis, Scolioneis tumida*) and low marsh diatoms (e.g., *Nitzschia* sp.). In contrast, three samples from the overlying *upper peat* are dominated by freshwater diatoms (e.g., *Aulacoseria* sp., *Eunotia pectinales*, *Gomphonema subclavatum*, *Pinnularia microstauron*, *Pinnularia viridis*) and chrysophyte cysts (Relative abundances of each species can be found in Appendix C).

Chronostratigraphy

Radiocarbon dates from the study area show that deposition began before ~4,500 years ago and has continued until the present. A bulk sediment date taken from a plant-rich mud at 280 cm collected in the back marsh returned an age of 4293 to 4446 cal. yrs BP (Table 1). This is the oldest and deepest sample we collected and it provides a minimum age for the marsh; we were unable to retrieve samples from the deepest part of the back marsh. We expect initiation of the marsh to be slightly older, on the order of 4,500-5,000 years BP, based on when sea-level stabilized near today’s elevation in the region (Fig. 3).

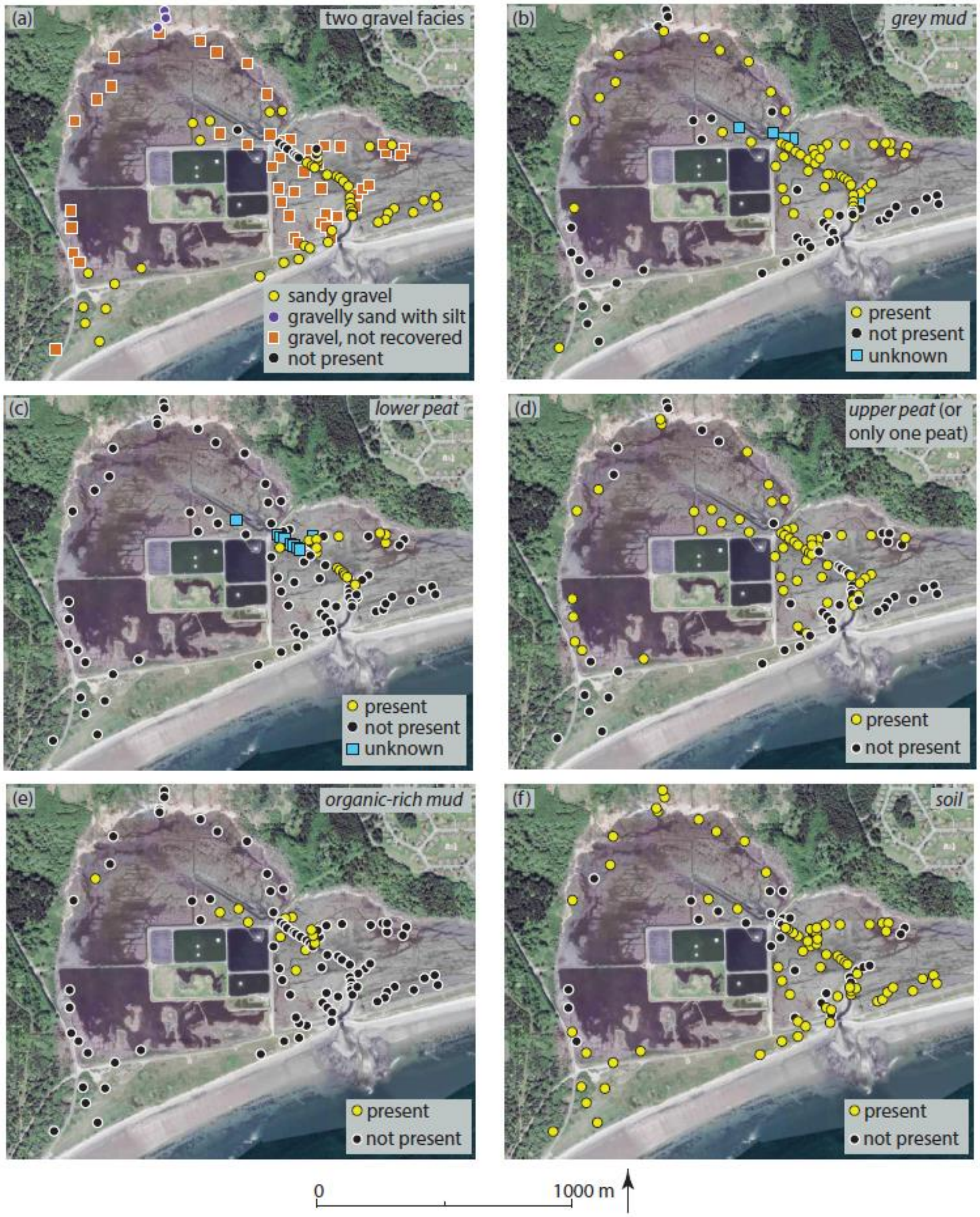


Fig. 5 Facies maps showing the presence and extent of the major facies identified in cores, pits and cutbanks in Crescent Harbor including: (a) two gravel facies, (b) *grey mud*, (c) *lower peat*, (d) *upper peat*, (e) *organic-rich mud* and (f) *soil*. The SW corner of the marsh was been affected by dredging in the 1940's. Sand lenses are not shown, but can be found in Appendix 2.

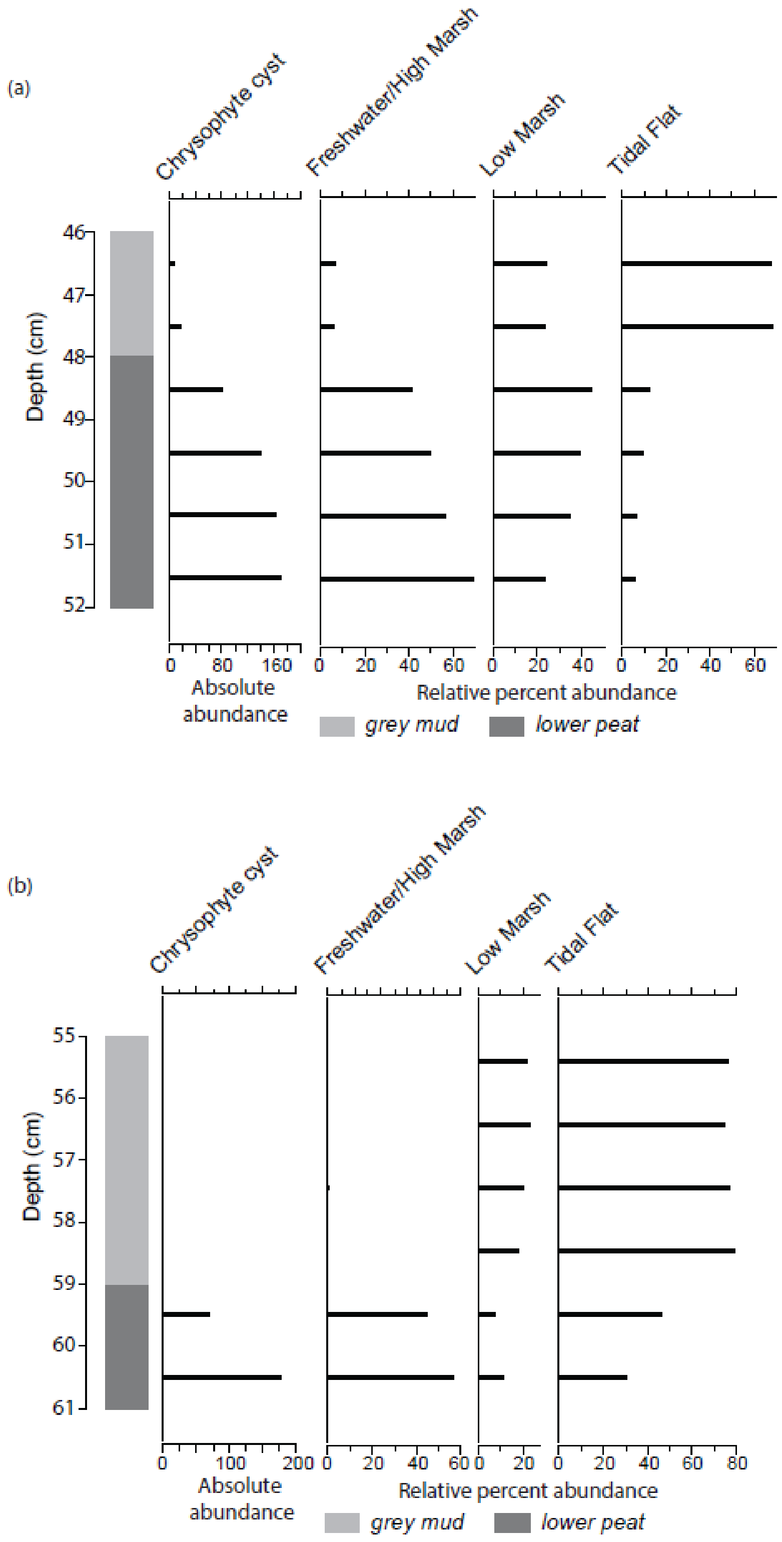


Fig. 6 Diatom relative abundance plots of diatoms from two monolith samples taken from the tide channel bank in the front marsh. (a) monolith 061S and (b) monolith 147.

Two radiocarbon samples help establish the chronostratigraphy of the middle and back marsh areas (Table 1) and show that it has been depositing mud for a significant amount of time. Two bulk mud samples, one from the northwest corner of the marsh at 228 cm and the other from the center of the marsh at 190 cm, returned dates of 3557 to 3644 cal yrs BP and 2489 to 2719 cal yrs BP, respectively. These dates in the *gray mud* facies show that the marsh was open to tidal influence throughout these time periods and also suggests that the marsh has been prograding through its history.

Table 1 Radiocarbon dates from Crescent Harbor marsh with ages, material dated and comments about the relevancy of each date. Dates were calibrated using OxCal version 4.2 (Reimer et al. 2013)

Lab number	Radiocarbon age (14C yr BP)	Calibrated age	Material dated	Dating method	Comments
D-AMS 008469	1023 ± 24	915 – 1006 BP	*Rumex crispus* seeds	AMS	Upper peat/Grey mud contact; Time period D
D-AMS 008468	1914 ± 25	1816 – 1926 BP	*Rumex crispus* seeds	AMS	Lower peat/Grey mud contact; Event 1
D-AMS 008471	1984 ± 26	1883 – 1992 BP	*Rumex crispus* seeds	AMS	Lower peat/ Sandy gravel contact; Time period A
D-AMS 008466	2047 ± 27	1930 – 2069 BP	Mud	Bulk	Taken directly above Lower peat
D-AMS 007024	2487 ± 22	2489 – 2719 BP	Plant rich mud	Bulk	190 cm depth, center of the marsh
D-AMS 007025	3349 ± 23	3557 – 3644 BP	Plant rich mud	Bulk	228 cm depth, NW edge of the marsh
D-AMS 007023	3944 ± 26	4293 – 4446 BP	Plant rich mud	Bulk	Oldest and deepest date in the marsh

Three dates help define the timing of *lower peat* deposition (Table 1; Fig. 7). A date using *Rumex crispus* seeds from the contact between the *sandy gravel* and *lower peat* calibrates to 1886 to 1992 cal. yrs. BP while a bulk mud date from above the *lower peat* and *gray mud* contact returns 1930 to 2069 cal. yrs. BP.

The final date, from the bottom of the *upper peat* at approximately 30 cm depth, indicates the approximate time period by when the site was no longer open to tidal influence in the front marsh. This dated to 915 to 1006 cal. yrs. BP using *Rumex crispus* seeds (Table 1) and shows the onset of deposition of the *upper peat* near the cutbank in the front marsh.

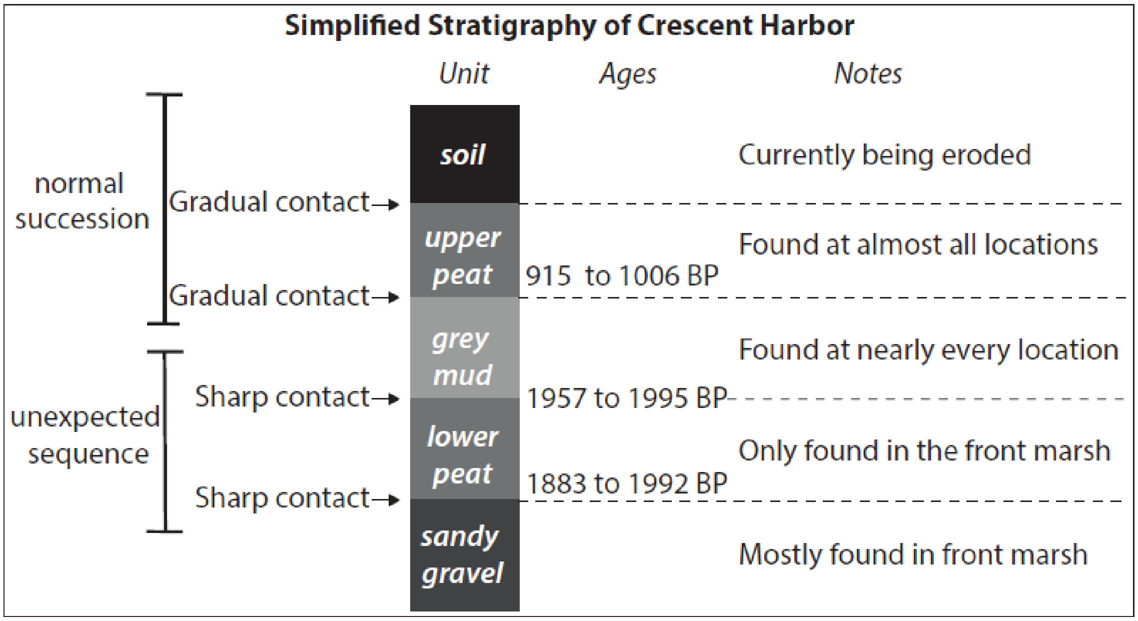


Fig. 7 Simplified stratigraphy of Crescent Harbor marsh showing contacts, units, dates and notes. We consider a normal succession to be what is expected if the marsh is accreting under conditions including: stable sea level, a sediment accumulation rate higher than sea-level rise, or the rate of sea-level rise is higher than the rate of sediment accumulation. An “unexpected sequence” occurs where facies that are not directly adjacent in map view are stratigraphically adjacent.

Environmental Interpretation of Lithofacies

A summary of facies, characteristics and interpretations can be found in Table 2.

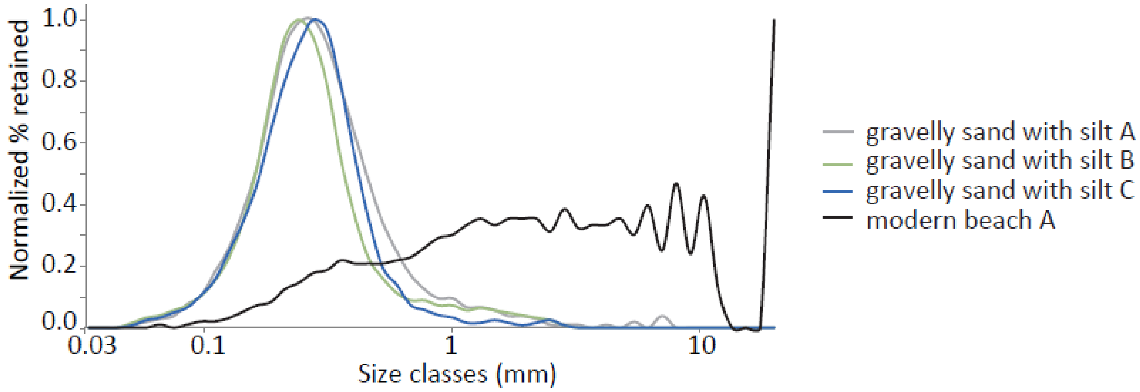
Sandy gravel: Paleo-beach. We interpret the gravel unit to be sediment deposited on a paleo-beach because of similarities with gravel found on the modern beach at Crescent Harbor, including grain size, rounding and sorting (Fig. 8a). When compared to modern beach samples, the *sandy gravel* has a similar range of grain sizes although it is not a perfect comparison. They both range from medium to coarse sand up through cobbles. Sphericity values for six samples of modern beach gravel ranged in sphericity from 0.79 to 0.86. The *sandy gravel* facies had a similar sphericity value of 0.84. The lack of fine material in this gravel facies is likely the result of the wave reworking of beach material over the last several thousand years based on the age of Crescent Harbor and similar features within Puget Sound.

The source of material to Crescent Harbor beach is the erosion and reworking of the coastal exposures of glaciomarine drift to the east of the marsh (Dragovich et al. 2005). The direction of longshore drift at Crescent Harbor is from the southeast and is a result of prevailing winds from the south, leading to sediment transport from east to west across the beach at Crescent Harbor (Johannesson 1992).

Table 2 Lithostratigraphic facies with characteristics and environmental interpretations.

Facies	Characteristics	Environmental interpretation
Soil	Brown to black; decomposed, modern surface	Freshwater; not saturated
Upper peat	Orange-brown; detrital fibrous plant material. Includes some woody material	Freshwater/high marsh
Lower peat	Orange-brown; detrital fibrous plant material	Brackish-fresh high marsh
Grey mud	Grey, silt and clay; little to no organics	Intertidal
Organic-rich mud	Brown-grey; mud dominated but contains organics	Upper intertidal
Sandy gravel	Coarse sand to cobbles, poorly sorted, mixed lithology	Paleo-beach
Gravelly sand w/silt	Medium to coarse sand, moderately sorted	Glacial outwash
Sand lenses	Medium sand, moderately sorted, typically 1-2 cm thickness	Liquefaction or tidal channel deposits

(a) Comparison of gravelly sand with silt facies vs modern beach



(b) Comparison of sandy gravel facies vs modern beach

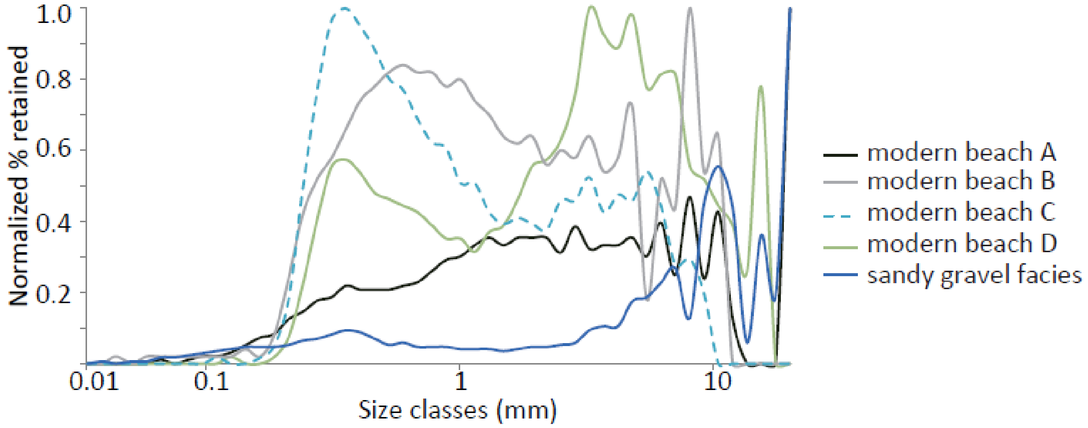


Fig. 8 Gravel grain size comparison, (a) Comparison of modern beach sand taken from the beach at Crescent Harbor to the gravelly sand with silt that was taken from the northernmost excavations. (b) Comparison of modern beach gravel taken from the beach at Crescent Harbor and a *sandy gravel* sample from the cutbank of the tide channel in the front marsh. Additional *sandy gravel* samples are not shown because they unrecoverable from cores. Sampling depths and locations can be found in Appendix 1.

Gravelly sand with silt: Glacial outwash. We interpret the basal unit at the back marsh of Crescent Harbor as glacial outwash based on the presence of silty sediment (Fig. 8b), the moderately sorted nature of the deposit, and the local geology. The underlying geology of the Crescent Harbor region is composed of the Deming Sand and Eversion

Glaciomarine Drift, deposited during the final retreat of the Frasier Glaciation (Easterbrook 1969). This glacial sediment is the pre-existing surface that the Holocene marsh sediments were deposited on after sea-level rise was at or near today's position.

Gray mud: *Intertidal.* We interpret the *gray mud* to be the result of lower intertidal deposition due to a lack of plant matter or sand and the dominance of tidal- flat diatom species in fossil assemblages. Lower intertidal to subtidal sediment typically has a low organic content as few plants can survive highly saline conditions and submergence (Peterson and Darienzo 1991; Fletcher et al. 1993b). Sand is generally not found in this zone if the area is a protected lagoon setting because of the lack of energy to transport sand-sized sediment. While there is not a modern example of mud deposition at Crescent Harbor, nearby embayments such as Dugualla Bay on Whidbey Island (Fig. 9), Triangle Cove on Camano Island, or Miller Bay on the Kitsap Peninsula provide good examples. Three samples of *gray mud* from Crescent Harbor were compared to two samples of intertidal mud from Dugualla Bay, one modern and one sample from about 300 cm depth. All five of these samples are very similar in grain-size distribution, indicating that modern Dugualla Bay may be a good analog for Crescent Harbor in the past. Tidal-flat diatoms (e.g., *Achnanthes brevipes, Auliscus* sp., *Caloneis westii, Cocconeis clandestina, Diploneis notabilis, Gyrosigma eximium*, *Paralia sulcata, Trachyneis aspera*, *Scolioneis tumida*) dominate the *gray mud* facies in monoliths 147 and 061S, supporting a lower intertidal interpretation.

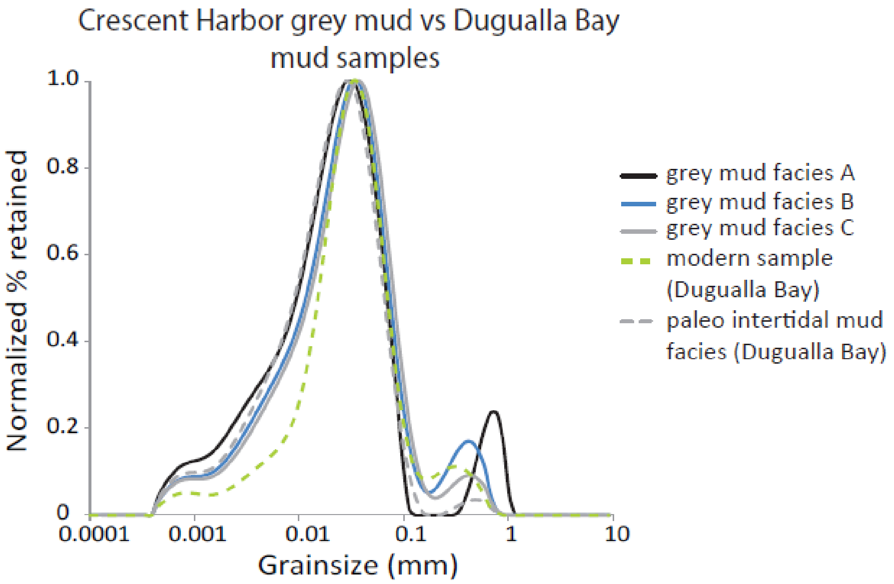


Fig. 9 Mud grain sizecomparison of samples at Crescent Harbor and Dugualla Bay. sample A is from about 315 cm depth, sample B is from the cutbank of the tidal channel and sample C is from about 270 cm depth. The modern sample from Dugualla Bay is from the tidal flat just offshore from the modern shoreline. The paleo intertidal mud sample from Dugualla Bay is from about 300 cm depth in the open grassy area behind the current beach ridge.

Organic-rich mud: *Upper intertidal.* We interpret the organic-rich mud to be deposited on a muddy, low (upper intertidal) marsh that was vegetated with salt-tolerant plants. Likely species include *Salicornia virginica* and *Distichlis spicata*. The presence of such vegetation would likely rule out a lower intertidal location.

Lower peat: *Brackish-fresh high marsh.* We interpret the *lower peat* to be a high-marsh facies, an area only submerged under highest high tide or storm conditions. Diatom samples from the *lower peat* indicate a high marsh depositional environment (Fig. 6). The high-diversity assemblages are dominated by freshwater (e.g., *Aulacoseira* sp., *Pinnularia microstauron*, *Pinnularia viridis*) and high marsh (e.g., *Cosmioneis pusilla*) species, but also contain low abundances of low marsh (e.g., *Diploneis* *interrupta*) and tidal flat (e.g., Paralia sulcata) species which were likely carried onto the higher parts of the marsh by the highest tides or storms (Hemphill-Haley 1995a; Sherrod 1999). The high abundance of freshwater chrysophyte cysts in *lower peat* samples supports a freshwater to fresh-brackish environment.

Upper peat: Freshwater/high marsh. The *upper peat* facies, which includes some woody material, likely represents a marsh with some amount of shrubs rather than a purely grass marsh, and suggests a significant intolerance to saltwater and an area that was not or rarely inundated. This interpretation is based on the content of the unit being inconsistent with plants present in the intertidal zone, which mostly comprise *Salicornia virginica* and other halophytes, and the dominance of freshwater and high-marsh microfossils. This means the peat is more likely a deposit of grassy wetland and shrubby upland than only the salt tolerant species found today in the intertidal zone. Woody material was found within this unit and may be driftwood as opposed to in-place growth.

Soil: We interpret the *soil* at the surface of Crescent Harbor marsh to be the result of deposition during the ~100 years when the marsh was diked and drained, which allowed the formerly active peat to drain and become more decomposed. Plants that occupied the marsh prior to breaching of the barrier included *Juncus effusus* and *Typha latifolia* along with common grasses. This would be considered a residual histosol as it has formed in place from existing organic material (NRCS 1999).

Sand lenses: *Liquefaction or surface channel deposits.* We interpret isolated sand deposits throughout all facies to be deposits either from liquefaction associated with earthquakes or from small tidal channels. Tidal-channel deposits would be a marker for the surface of the marsh at the time the sand was deposited, whereas liquefaction/injection could occur at various depths throughout the stratigraphy, including eruption at the surface. Liquefaction processes could explain why sand lenses are present at inconsistent depths throughout the marsh stratigraphy. Liquefaction deposits tend to contain a variety of sedimentary structures, which can vary laterally over meters both in outcrop and map view (Martin and Bourgeois 2012). An important feature of liquefaction is feeder dikes, which transport fluidized sediment. While we found no feeder dikes associated with these layers to verify a possible liquefaction origin (as in Obermeier and Pond 1996), the majority of our data comes from cores, which do not have the spatial context for identification of feeder dikes.

CHAPTER V

DISCUSSION

Environmental History

A cross-section through the marsh using actual core and outcrop data, as well as accurate spatial data (Fig. 4) was used to make interpretations of the environmental history (Fig. 10). We break our reconstruction of the environmental history of the marsh (Fig. 10) into time periods that include processes occurring over hundreds to thousands of years. The term *event* is reserved for processes that occur over minutes to months.

Time period A: Formation of a spit

The basal gravel that underlies the marsh is the result of the pre-existing glacial deposits. The paleo and modern berms are likely the result of spit growth from east to west over thousands of years. Deposition of sands and gravels associated with the spit/beach in the field area likely commenced with sea-level stabilization ~5,000 years ago (Finlayson 2006).

By at least 4,500 years BP, when sea-level was on the order of ~1 m lower than today (Fig. 3), a spit had built across much of Crescent Harbor providing a protected lagoonal area behind the spit, evidenced by buried intertidal mud and organic-rich mud in the backmarsh. Some of the cores in the back of the marsh never hit gravel, indicating the back marsh is likely deep and deposition has likely occurred there for a longer time than other areas, supported by radiocarbon dates taken from deep in the back marsh.

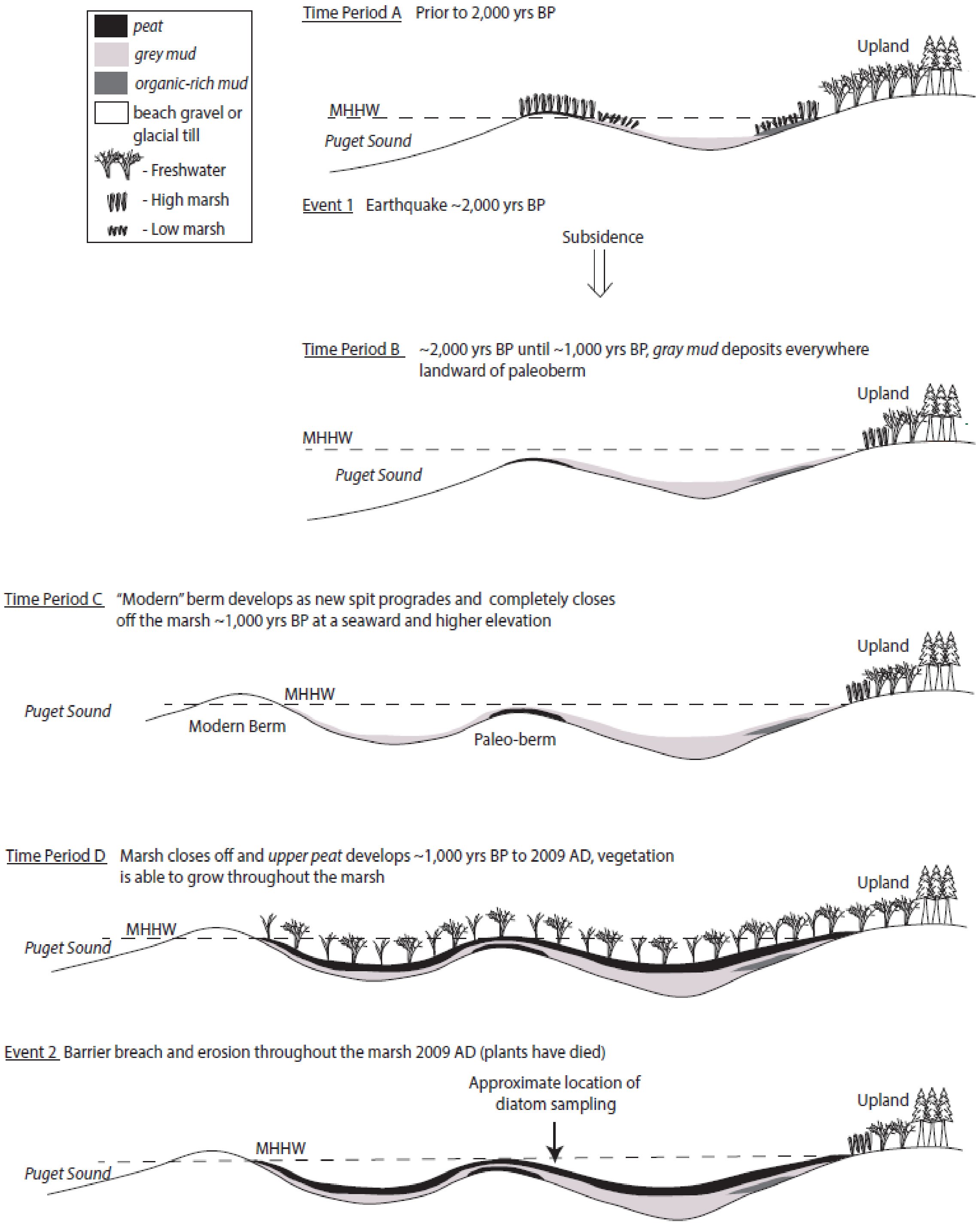


Fig. 10 Environmental history cartoon of Crescent Harbor marsh from before 2,000 yrs BP (top) to present (bottom). Note that the underlying stratigraphy is interpreted to be gravel and/or glacial sediment. Not to scale.

In time period A the spit was closer to land, resulting in a smaller marsh area than today. At least one buried paleo-berm is present, as shown in Fig. 4. As the marsh evolved, the *lower peat* was deposited on the landward side of the paleo-berm, while intertidal mud continued to be deposited in the backmarsh. The peat was spatially restricted and would have appeared as an isolated zone of vegetation.

Event 1: Co-seismic subsidence ~2,000 *BP*

At *1825-1925 cal yr BP* an abrupt change in marsh lithology is recorded by a transition from *lower peat* (high marsh) to *gray mud* (tidal flat) in the front marsh. This transition is interpreted to be the result of coseismic subsidence, due to the sharp contact between the peat and intertidal mud and the elevation difference between their depositional environments (Fig. 10). This abrupt transition is found everywhere the *lower peat* and *gray mud* are found. In the back marsh, deposition prior to 2,000 years ago was already intertidal to subtidal, thus subsidence resulted in no apparent change in stratigraphic units.

Time Period B: Mud deposition throughout the marsh and development of modern berm after ~2,000 yrs BP

After coseismic subsidence lowered the marsh, intertidal sediment was deposited throughout the marsh, including on top of the paleoberm (Fig. 10). Lowering caused progradation or lateral migration of a new spit with a modern position ~1.5 m higher and ~200 m seaward of the older, lower spit and a lagoonal setting throughout most of the marsh. Throughout this time, deposition in the back marsh remained intertidal, with more than a meter of *gray mud* being deposited in some locations (Fig. 10; Appendix B), indicating the area was continuously exposed to tides. The marsh would have been similar to the size and shape it has today.

Time period C: Spit closing ~ 1000 cal yrs BP

We interpret the change from *gray mud* to *upper peat* as a result of the broad tide flat of the previous time period being closed off from tidal exchange as the spit built completely across the field area (Fig. 10). Freshwater conditions allowed the *upper peat* to develop throughout the marsh, as this facies is found virtually everywhere (Fig. 5d). The berm could have built across the marsh slowly leading to a transgressive contact or it could have closed rapidly with a uniform date across the *gray mud- upper peat* contact. It is difficult to determine which is the case at Crescent Harbor without more extensive diatom samples and radiocarbon dates from the *gray mud – upper peat* contact.

Time period D: Marsh accretion and soil development, ~1000 cal yrs BP to AD 2009

This time period is characterized by natural accretion of salt marsh peat and a transition from a peat into a modern soil (Fig. 10), as supported by a gradational contact between the upper *peat* and *soil*. Diking and draining the marsh, and attempts at agriculture at the onset of the 20th century likely played a role in the development of the soil cap.

Event 2: Breach of spit in 2009

The final event in the history of the marsh is the engineered breach of the spit (Fig. 10). This resulted in dramatic changes to the marsh including daily submergence of vegetation that we suggest had established over the preceding ~1,000 years, leading to the loss of much of that vegetation. There has also been an increase in erosion of the modern marsh surface as high energy tides flow in and out the marsh. This erosion has widened the tide channel in the front marsh area over the last 7 years.

Estimates of Amount of Vertical Land Level Change

On the basis of abrupt shifts in the diatom composition of the *lower peat* and the overlying *gray mud*, we can estimate the amount of coseismic subsidence across the contact to be ~1.7 m. Diatom analysis indicates that the *lower peat* facies is a result of a high marsh environment and the *gray mud* is the result of a tidal flat environment (Fig. 6; sampling location on Fig. 4). The minimum elevation difference between the depositional environment of the *lower peat* (>3.5 m above MLLW) and the *gray mud* (<1.8 m above MLLW) is ~1.7 m. This estimate is based off the lowest elevation that peat could form in the marsh (3.5m above MLLW; MHHW for Crescent Harbor) and the highest elevation mud devoid of organic matter could form (1.8m above MLLW; measured lowest vegetation elevation). These two parameters have been defined by Hemphill-Haley (1995a). The actual subsidence could be larger than these values because the *upper peat* could have formed higher than our elevation estimate for the high marsh environment and the *gray mud* could have formed below our value for the tidal flat environment.

Assuming that the conditions which influence berm development have not changed much in the last 2,000 years, the elevation difference between the modern berm and the buried paleo-berm, an amount of ~1.5 m, corroborates the ~1.7 m diatom estimate of coseismic subsidence.

Alternative Explanations for Marsh Stratigraphy

The two other possible explanations for the mud-over-peat stratigraphy can both be ruled out in Crescent Harbor. First, intertidal deposition above supratidal could exist if sea level were to rise faster than sediment accumulation and marsh growth rates, and would result in mud eventually being deposited over peat (Fletcher et al. 1993a; Kelley et al. 1995; Gardner and Porter 2001). This scenario cannot be the case at Crescent Harbor because sea level has not risen significantly in the last 5,000 yrs and the contact is not gradual.

The second possibility is that if there were no tidal inlet through the spit into Crescent Harbor allowing for a freshwater marsh (and the marsh surface was below MHHW), the spit could have been breached, suddenly allowing tidal exchange and resulting in abrupt facies change. Negligible sea-level rise about 2,000 years ago would likely not be enough to cause a berm failure.

Diatom data from the *gray mud- upper peat* contact indicate that there is an abrupt transition from tidal flat diatoms to freshwater/high marsh diatoms (Appendix C). It is our interpretation that this transition is the result of the berm closing off ~1,000 yrs BP and not the result of a younger land-level change event in the marsh. As the berm prograded across the marsh it would likely have resulting in variations in the abruptness of contacts and the diatom assemblages found at those contacts. While an earthquake could produce uplift in the marsh resulting in an abrupt transition from tidal flat to high marsh, we do not have sufficient evidence to support this possibility. The *gray mud-upper peat* contact is represented by a sharp contact in some locations and a gradual contact in others. The diatom samples were taken in a location with a sharp contact, and without a sample from another area of the marsh we cannot confidently characterize this contact through the entire field area.

Tectonics of the Utsalady Point and Strawberry Point Faults

The known sources for subsidence at Crescent Harbor marsh could be from earthquakes on the Strawberry Point fault (SPF) or the two traces of Utsalady Point fault (UPF) on either side of Crescent Harbor (Fig. 11), however, both the SPF and northern trace of the UPF can be ruled out as unlikely. The SPF lies 2 km to the north of Crescent Harbor; Johnson et al. (2001) report south-side down displacement, which would produce subsidence at Crescent Harbor during an earthquake (Fig. 11).

While no trenching studies have been done on the SPF to identify potential Holocene ruptures, we expect that if the SPF had produced significant vertical offset 2,000 years ago, this offset should be readily observable on the surface and in offshore investigations like those of Johnson et al. (2001). On the west side of Whidbey Island, the sole strand of the UPF shows south-side-down subsidence (Fig. 2), however, it splays just west of Crescent Harbor (Johnson et al. 2001). From this split east to Camano Island there is a reversal to north-side-down displacement on both of the segments of the fault, meaning Crescent Harbor would be on the up side of the northern strand, allowing us to rule it out as a likely candidate.

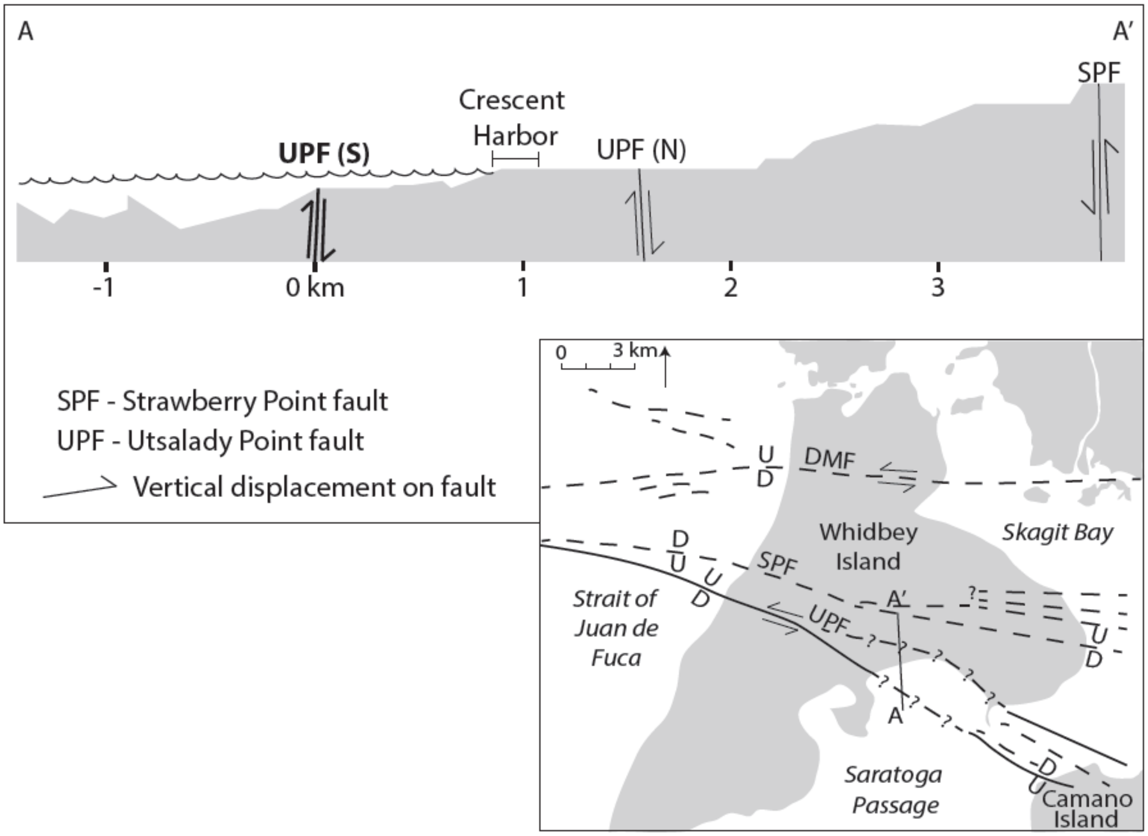


Fig. 11 Interpretation of the mechanics of the Utsalady Point fault and Strawberry Point fault in causing the observed stratigraphy at Crescent Harbor marsh. Only a rupture on the south splay of the **UPF** or the SPF could cause the subsidence observed. However, the SPF is not known to have ruptured in the Holocene and it is likely too far away to have produced 1-2 m subsidence in Crescent Harbor.

Therefore, the most likely fault responsible for the subsidence at Crescent Harbor is the southern trace of the UPF. We correlate the earthquake that produced subsidence in Crescent Harbor to the second earthquake of Johnson et al. (2004) at Rocky Point on the west side of Whidbey. Our date of ~2,000 years BP for the earthquake fits within their date of 1,100-2,200 BP and our estimate of ~1.7 m extends their estimate of 1 to 2 meters of vertical offset across Whidbey Island.

Implications of Results

This study adds to the understanding of the faults and seismic setting of northern Puget Sound. Personius et al. (2014) suggests that there may be a clustering of events around 2,000 years ago in northern Puget Sound, that include the Darrington-Devils Mountain, Utsalady Point and Seattle faults, similar to the proposed clustering of events in the Puget Sound around 1,000 years ago (Sherrod and Gomberg 2014). Our date for the Utsalady Point fault rupture provides additional support for this interpretation.

Our dating and correlation of land-level change to an Utsalady Point fault rupture that extends to western Whidbey Island allows us to suggest that this event may have caused a tsunami. Williams and Hutchinson (2000) reported two tsunami deposits of unknown origin at Swantown marsh, just south of where the UPF enters Puget Sound on western Whidbey Island, dated to 1810 – 2060 and 1830 – 2120 yrs BP. The rupture of the UPF with up to 2 m of land-level change at Rocky Point (Johnson et al. 2004) could be the source of one of the tsunami deposits, although modeling is required to calculate if a tsunami from this earthquake would be large enough to inundate Swantown.

We did not find direct evidence for the younger 100 – 400 cal. yrs. BP earthquake on the Utsalady Point fault reported by Johnson et al. (2004) in Crescent Harbor. If true, the lack of land-level change indicates that offset from this earthquake did not extend as far east on the fault to affect Crescent Harbor. This could mean that this earthquake had a smaller magnitude than the older earthquake, as it may have been a shorter rupture.

Evidence of the 100-400 cal. yr BP earthquake should be within the extensive *upper peat* or *soil* facies. No clear boundaries or markers are found within the *upper peat* to suggest land-level change. We did not date the onset of soil formation in the front marsh, but we considered it related to diking and draining of the marsh ~100 years ago. Potentially, this transition could have instead been caused by uplift of the marsh by the northern strand of the Utsalady Point fault.

Although many isolated sand lenses exist throughout the marsh stratigraphy (Appendix B), no sand layer could be correlated between cores, making them all unlikely candidates for tsunami deposits (Martin and Bourgeois 2012). A possible source of sand lenses includes liquefaction deposits produced by the shaking during an earthquake (Bourgeois and Johnson 2001; Martin and Bourgeois 2012). Liquefaction is a common feature in Puget Sound marshes, including the Snohomish delta (Bourgeois and Johnson 2001) in northern Puget Sound, and the Skykomish delta, Lynch Cove, and Issaquah Creek (Martin and Bourgeois 2012) in southern Puget Sound, and in the Fraser delta (Claque et al. 1997) in British Columbia.

CHAPTER VI

CONCLUSIONS

Crescent Harbor marsh on northern Whidbey Island contains evidence for cosesimic land-level change about 2,000 years ago based on an abrupt peat-to-mud contact found in the marsh and changes in microfossil assemblages associated with that abrupt contact. Using estimates of elevations of diatom depositional environments of a high marsh prior to the earthquake to tidal flat after, we calculate a minimum estimate of ~1.7 m of vertical deformation. The earthquake source is most likely the southern trace of the Utsalady Point fault. This research only found clear evidence for one rupture on the Utsalady Point fault, although evidence for a more recent rupture exists on the western side of Whidbey Island.

About 1,000 years ago the Crescent Harbor spit closed off the marsh from tidal exchange, but has since been breached to restore the "natural salt marsh habitat". It is our conclusion that a freshwater, closed-off marsh was the natural state, and breaching the berm created an environment that had not been present for ~1,000 years.

This research supports that of others in establishing seismic hazards in northern Puget Sound. While extensive work has been done in Puget Sound with regards to paleoseismology, most involve the 900 AD Seattle fault rupture and resulting tsunami, and little has been in northern Puget Sound. Future work should include trenching studies to establish the rupture history of the Strawberry Point fault and tsunami modeling of past ruptures on Utsalady Point to determine how or if a tsunami may affect Whidbey Island. Potential liquefaction deposits at Crescent Harbor could be identified and dated to determine if the marsh experienced shaking from the 100 – 400 BP event reported by

Johnson et al. (2004). Finally, trenching the Utsalady Point fault on Camano Island could refine estimates of the 2,000 yr. BP rupture length to better refine estimates of the earthquake's magnitude.

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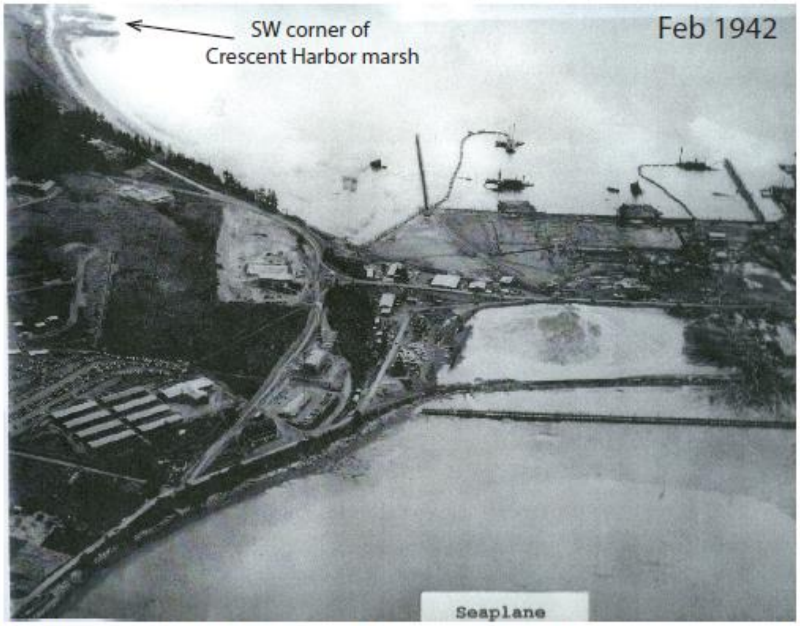
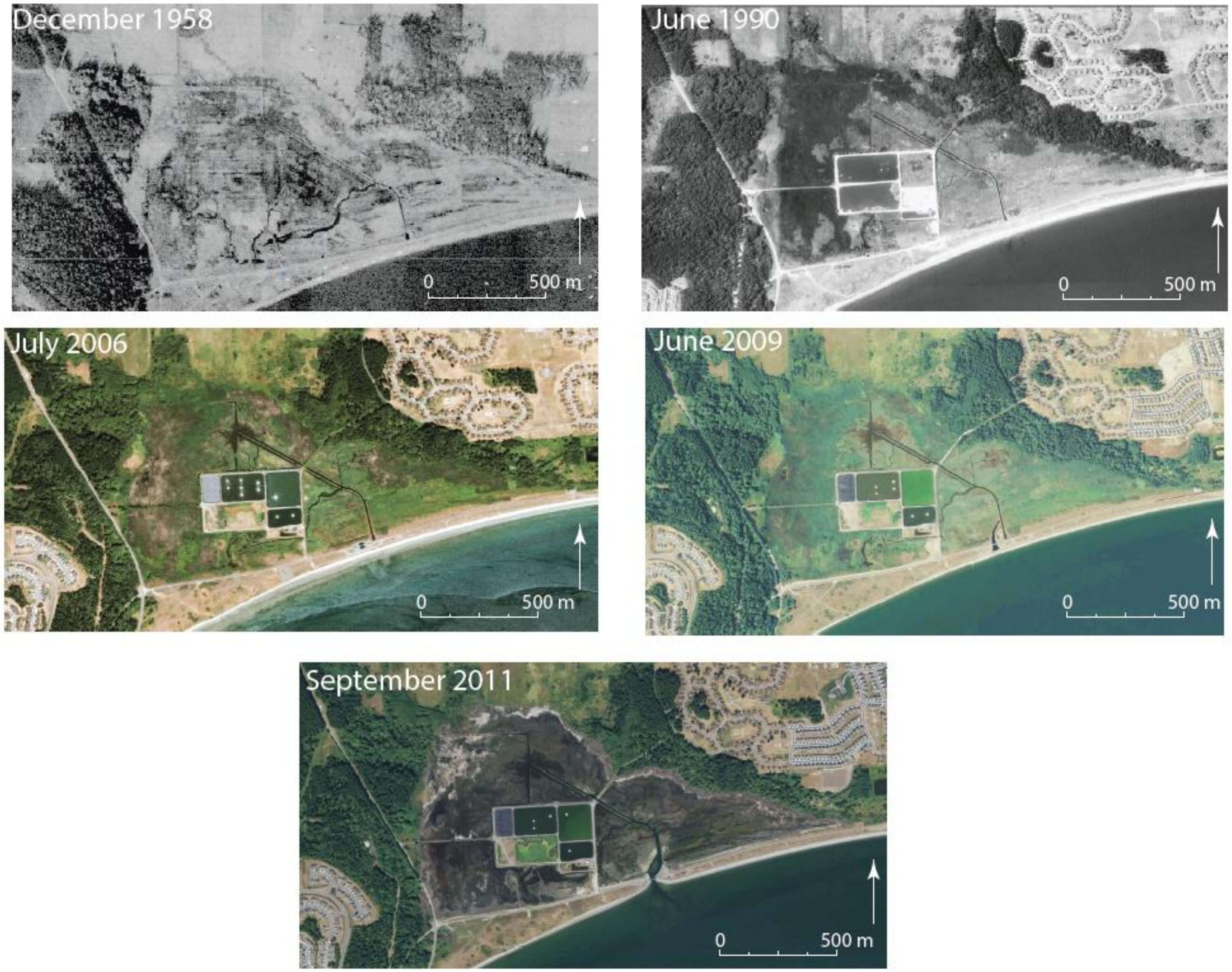
Appendix A Historic and modern air photos of Crescent Harbor marsh showing historical progression of marsh characteristics and uses. 1958 image is from the US Navy, all others are from Google Earth. 1941 and 1942 Images are courtesy of Island County.

Photograph taken from the top of the bluff on the eastern side of Crescent Harbor looking back toward the west. Image courtesy of Island County.

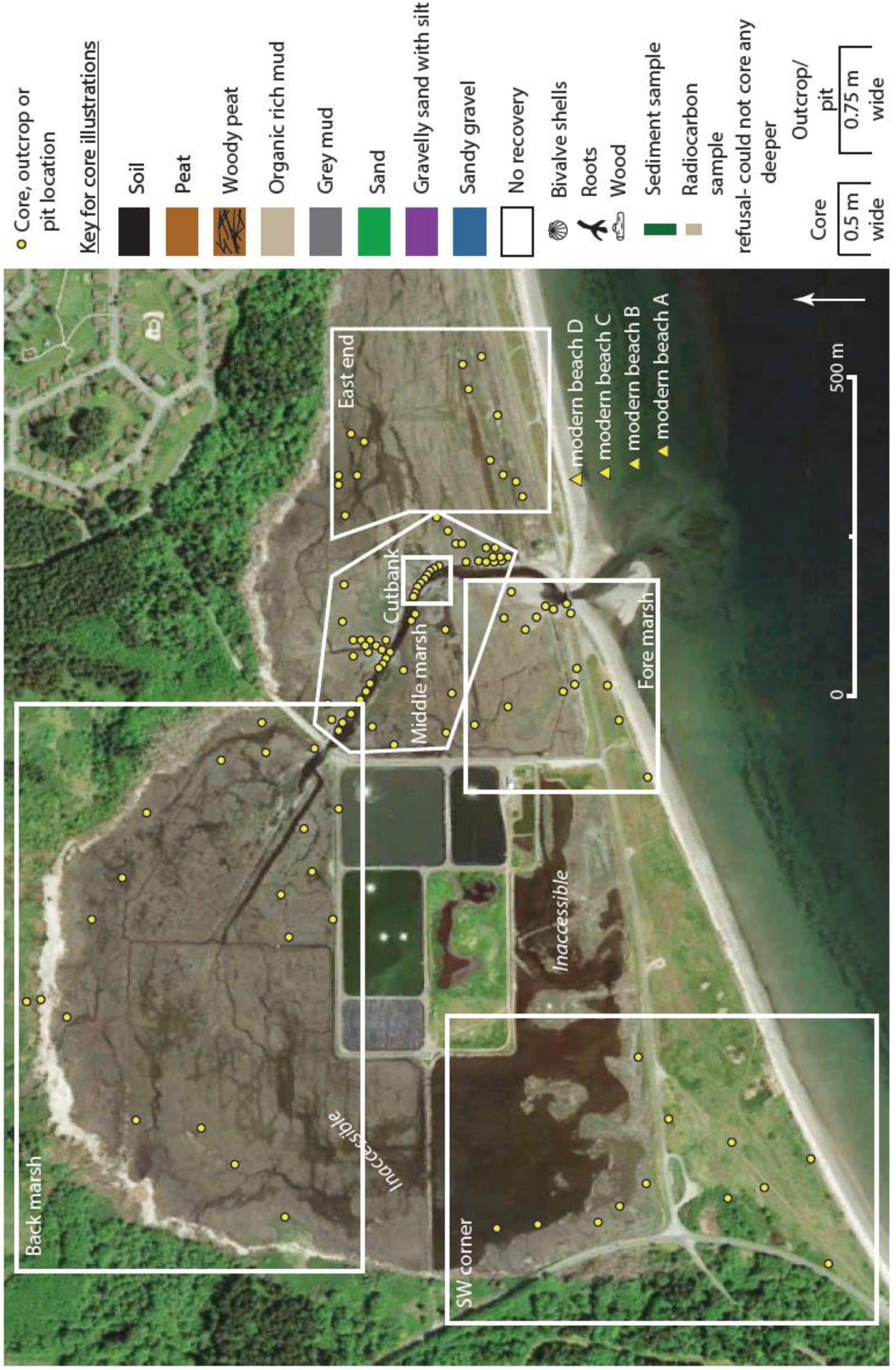


Aerial photograph taken from west of Crescent Harbor looking back toward the east. Notice the construction of the Sea Plane base in the middle of the image and the apparent barge landing area in the upper left, which corresponds to the SW corner of the marsh. Image courtesy of Island County.

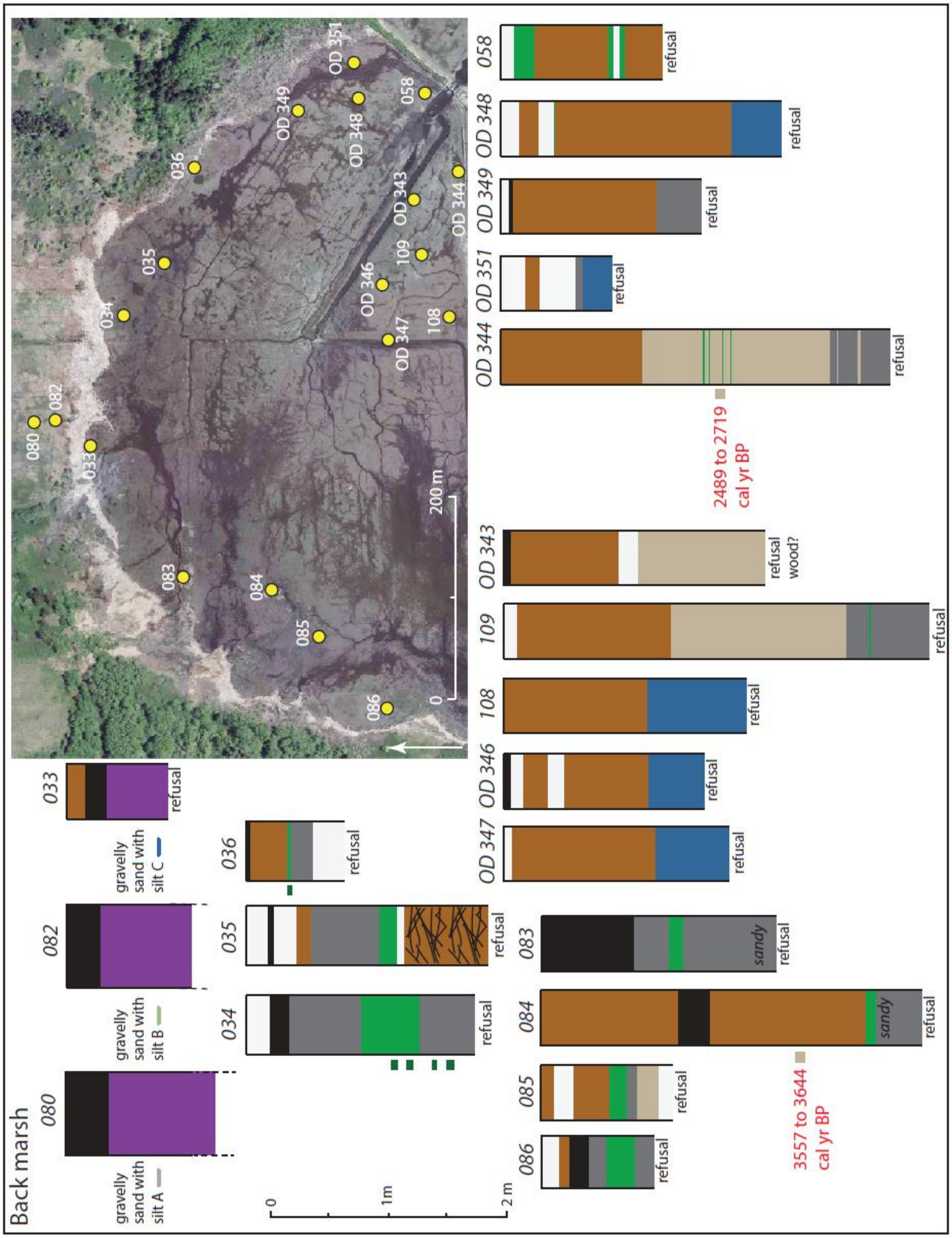


Images of Crescent Harbor marsh showing human induced changes over the last ~60 years. Notice the addition of the waste water treatment plant after 1958 and the breaching of the dike after June 2009. December 1958 image is courtesey of the US Navy. The other four are from GoogleEarth.

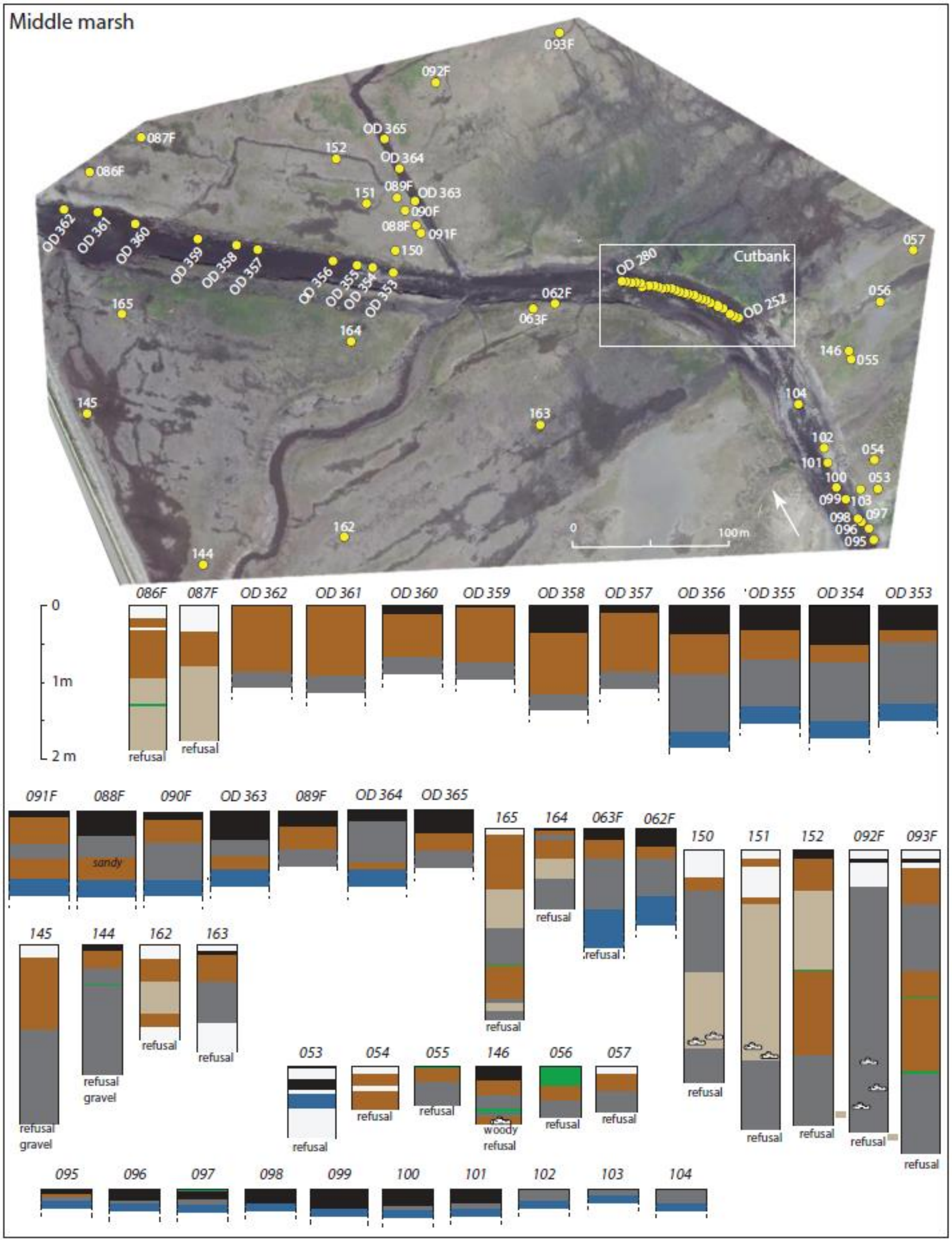
Appendix B Core and outcrop illustrations with map showing the different areas that we divided the marsh into in order to present the core and outcrop data. These areas include: Back marsh, SW corner, Fore marsh, Middle marsh, Cutbank and East end all of which are attached and broken down in more detail.



Map with all core, outcrop and pit locations. White boxes denote sub-locations of the following core illustrations. The key is for the core illustrations that correspond to each area location within the marsh. Modern beach samples correspond to Fig. 8b in the text.



Back marsh
080
082
033
gravelly sand with silt A
gravelly sand with silt B
gravelly sand with silt C
refusal
034
035
036
0
1m
2 m
086
085
084
083
sandy
3557 to 3644 cal yr BP
OD 347
OD 346
108
109
OD 343
wood?
2489 to 2719 cal yr BP
OD 344
OD 351
OD 349
OD 348
058
0
200 m
OD 349
OD 348
OD 351
OD 343
OD 344
OD 346
OD 347


Middle marsh
093F
092F
087F
086F
152
OD 365
OD 364
151
089F
OD 363
090F
088F
091F
150
OD 362
OD 361
OD 360
OD 359
OD 358
OD 357
OD 356
OD 355
OD 354
OD 353
165
164
062F
063F
OD 280
Cutbank
OD 252
057
056
146
055
104
145
163
102
101
054
100
053
099
103
097
098
096
095
162
144
0
100m
0
1m
2 m
086F
087F
OD 362
OD 361
OD 360
OD 359
OD 358
OD 357
OD 356
OD 355
OD 354
OD 353
refusal
refusal
091F
088F
090F
OD 363
089F
OD 364
OD 365
sandy
165
164
063F
062F
150
151
152
092F
093F
refusal
refusal
refusal
145
144
162
163
refusal
refusal
refusal
gravel
refusal
gravel
053
054
055
146
056
057
refusal
refusal
refusal
woody
refusal
refusal
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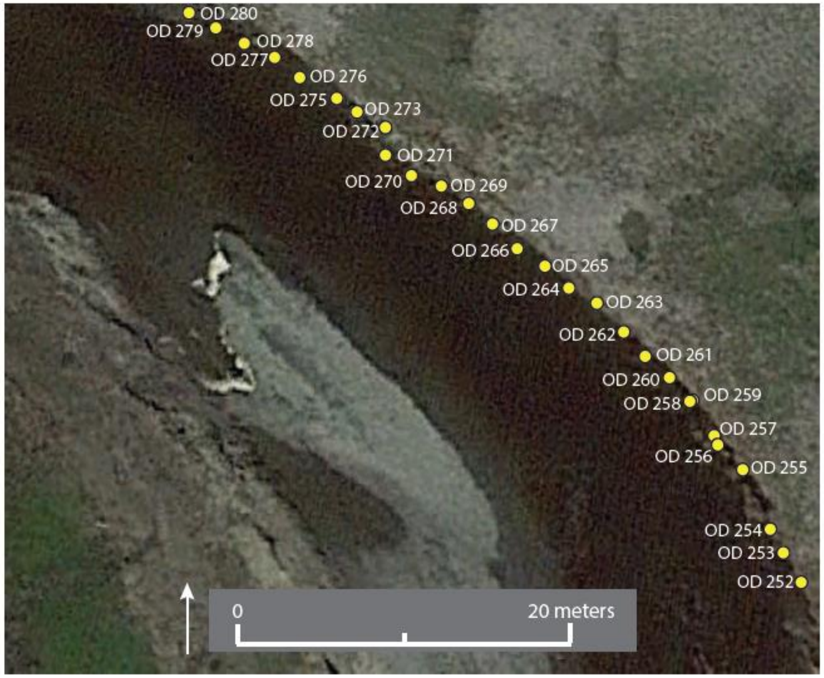
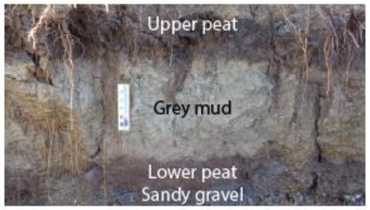
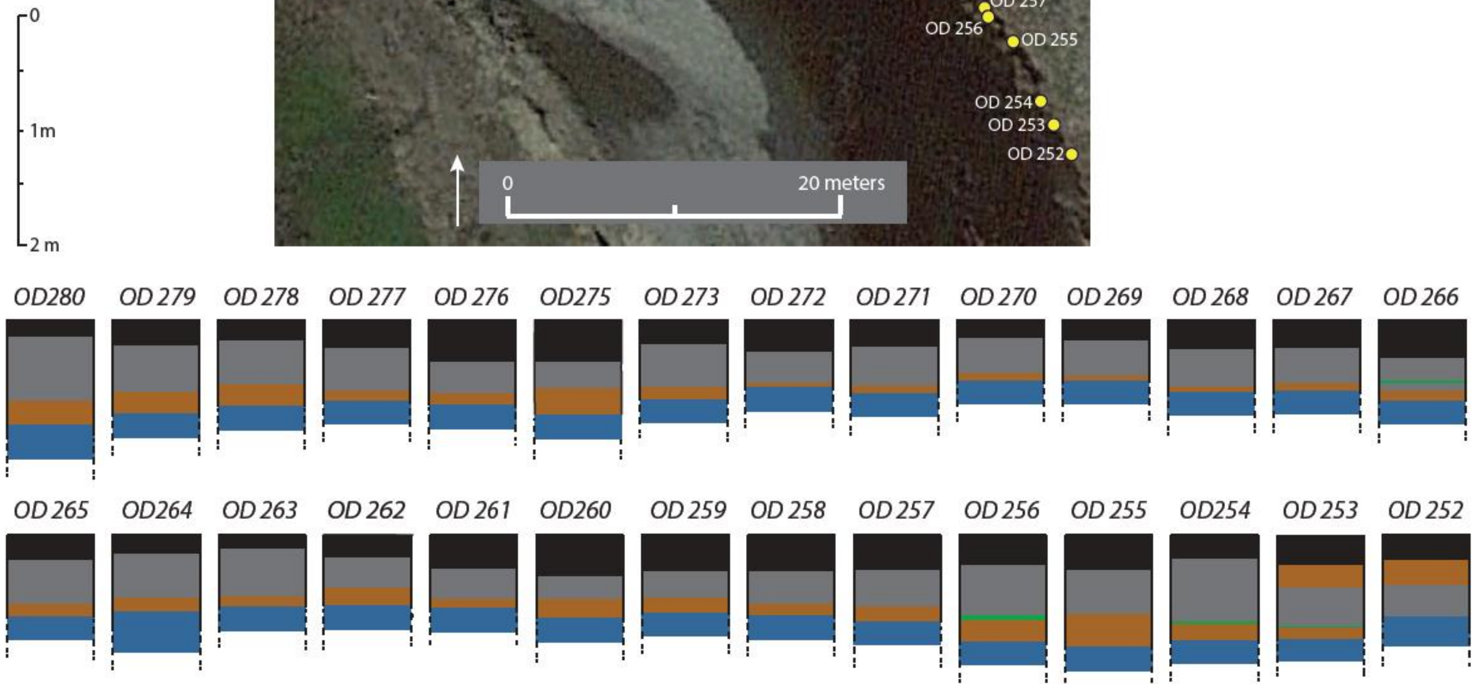
refusal
refusal
refusal
refusal
095
096
097
098
099
100
101
102
103
104

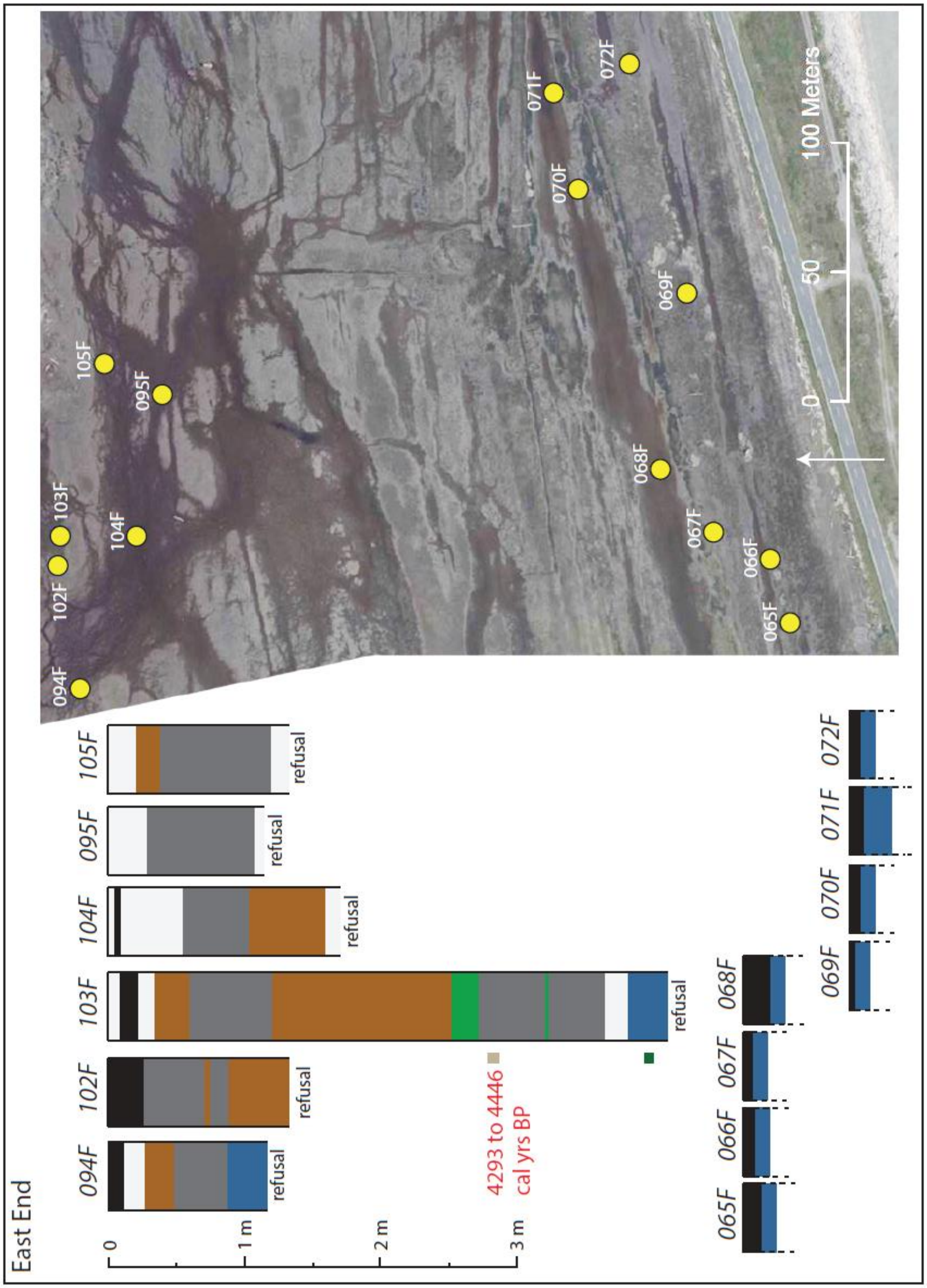
Cutbank

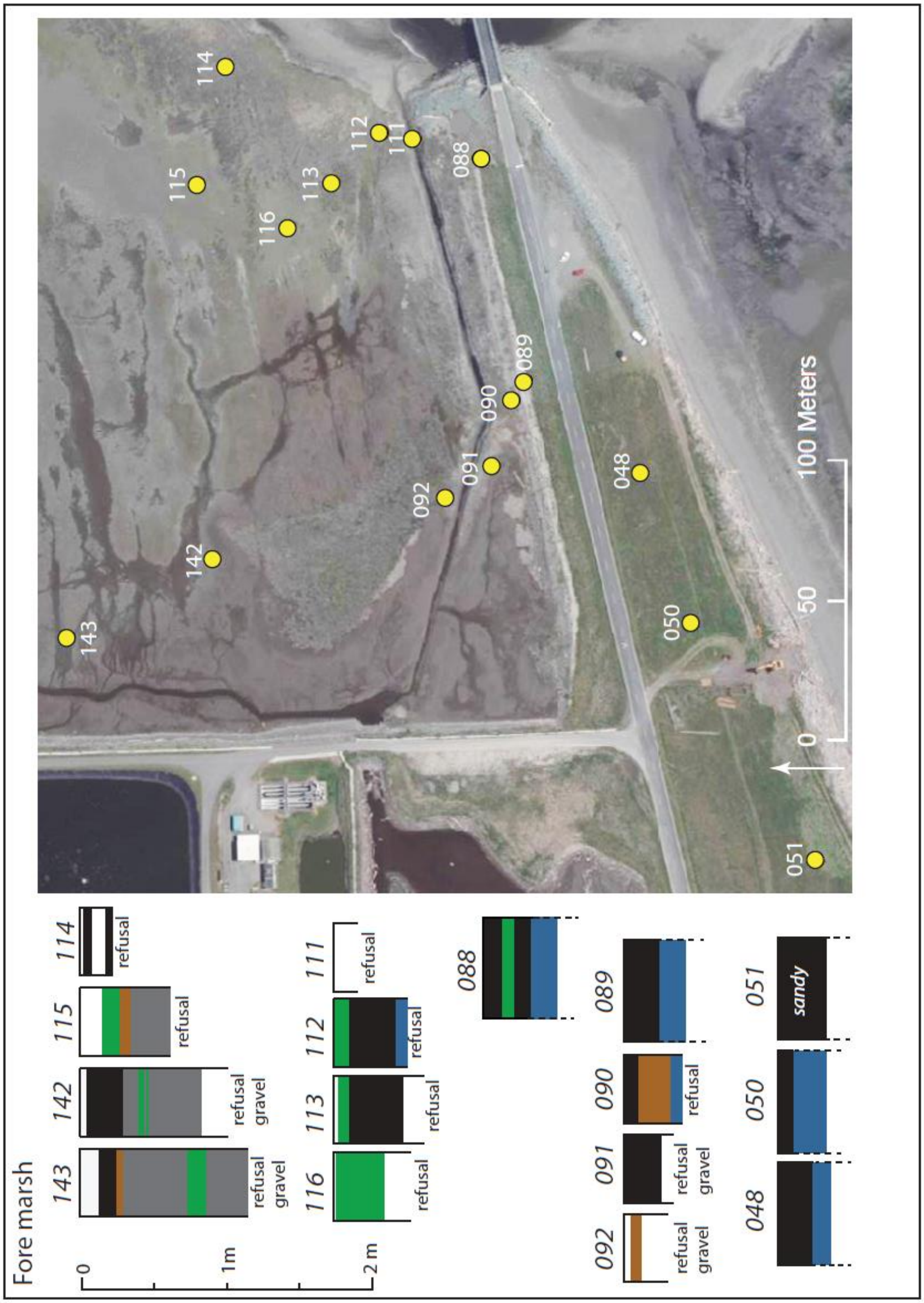


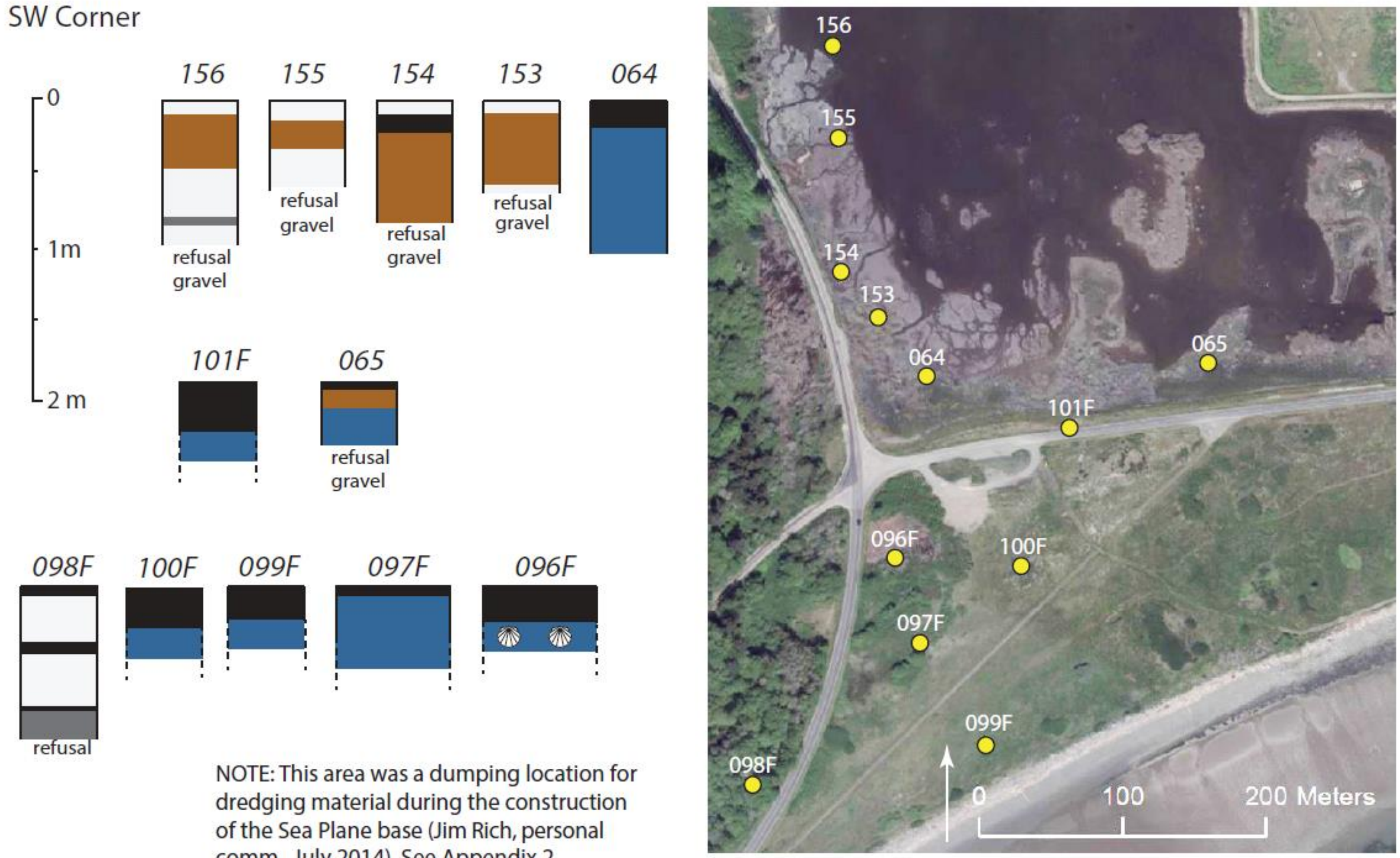


Annotated photograph of the stratigraphy found in the cutbank of the tide channel.



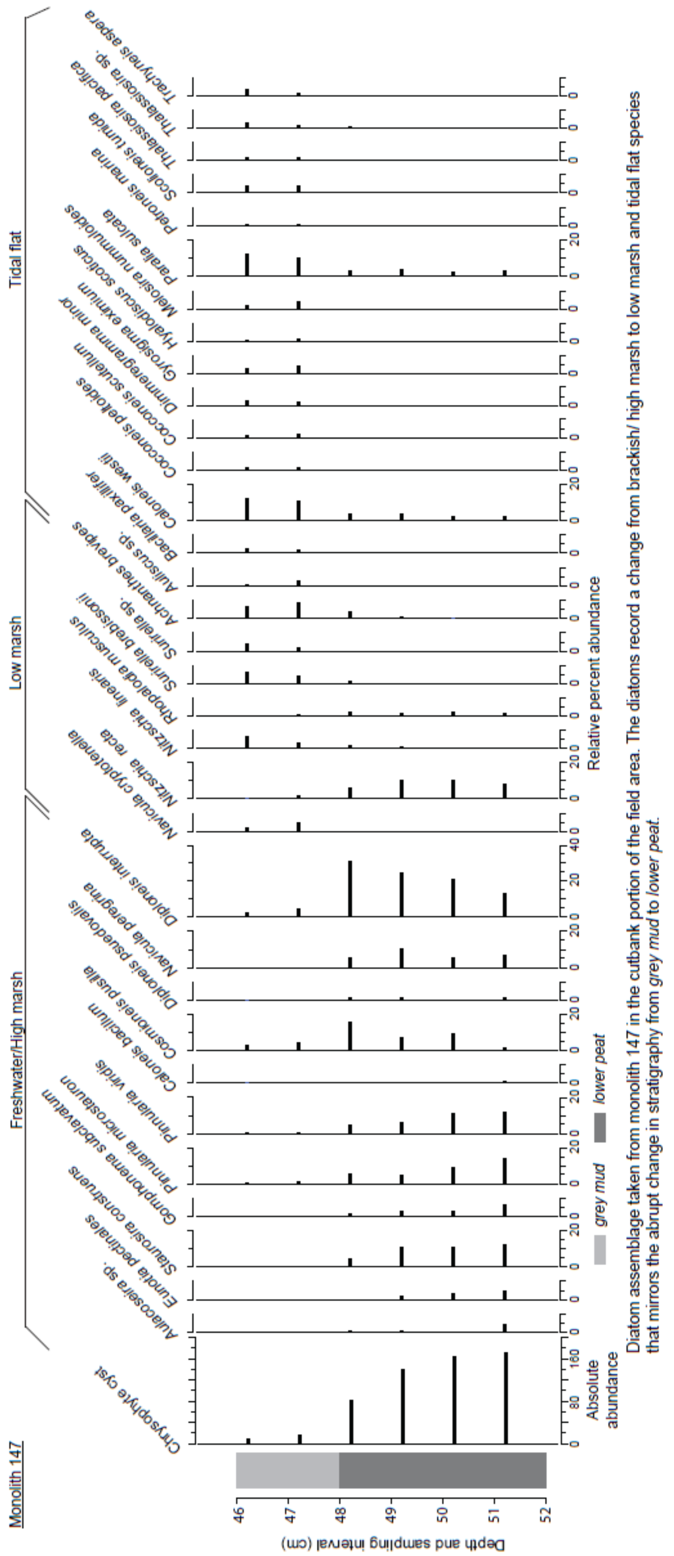

East End
0
1 m
2 m
3 m
094F
102F
103F
104F
095F
105F
refusal
refusal
refusal
refusal
refusal
refusal
4293 to 4446 cal yrs BP
065F
066F
067F
068F
069F
070F
071F
072F
094F
102F
103F
104F
095F
105F
065F
066F
067F
068F
069F
070F
071F
072F
0
50
100 Meters


Fore marsh
0
1m
2 m
143
refusal
gravel
142
refusal
gravel
115
refusal
114
refusal
116
refusal
113
refusal
112
refusal
111
refusal
088
092
refusal
gravel
091
refusal
gravel
090
refusal
089
048
050
051
sandy
114
115
113
116
112
111
088
089
090
091
092
142
143
048
050
051
0
50
100 Meters

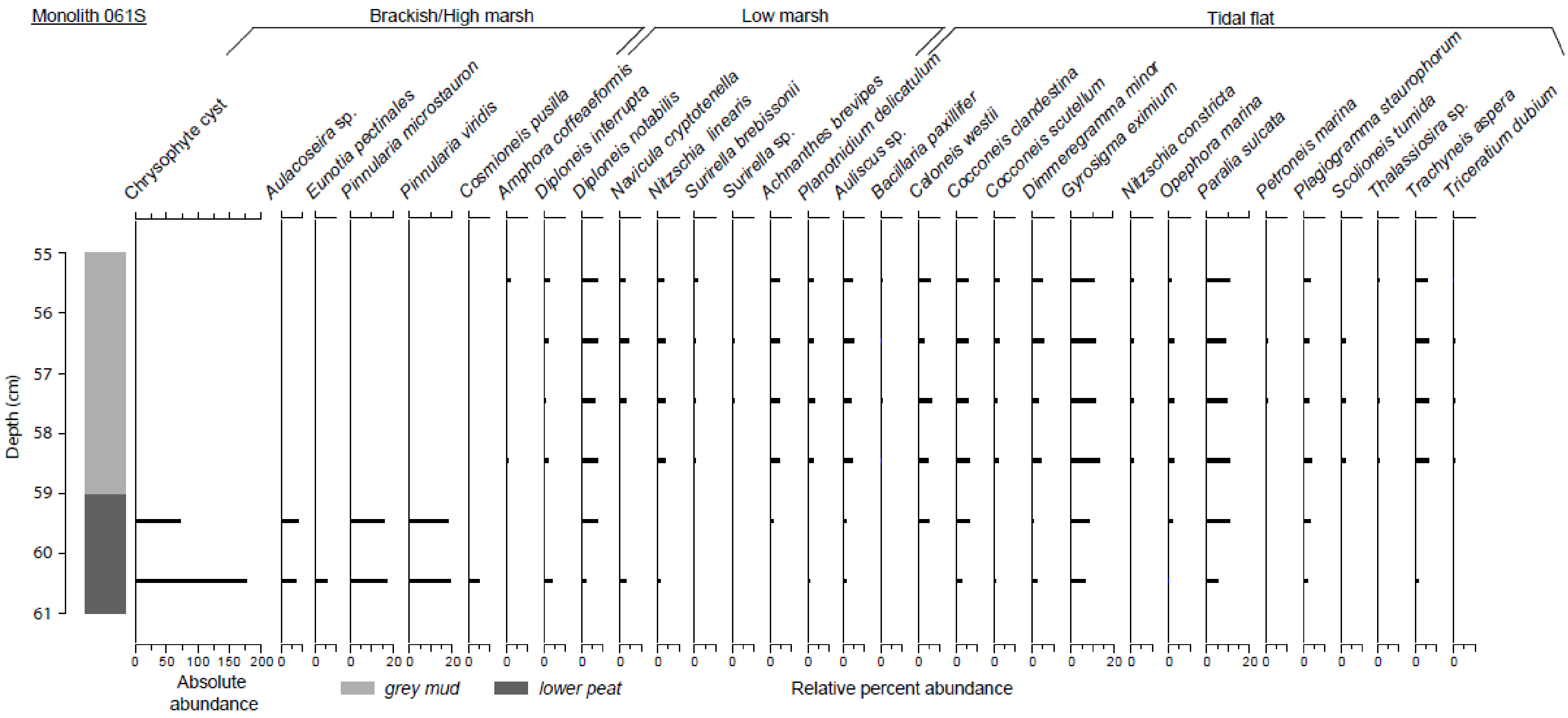


NOTE: This area was a dumping location for dredging material during the construction of the Sea Plane base (Jim Rich, personal comm., July 2014). See Appendix 2.

Appendix C Relative abundance diatom plots of all species from Crescent Harbor marsh for monliths 061S, 061L and 147.

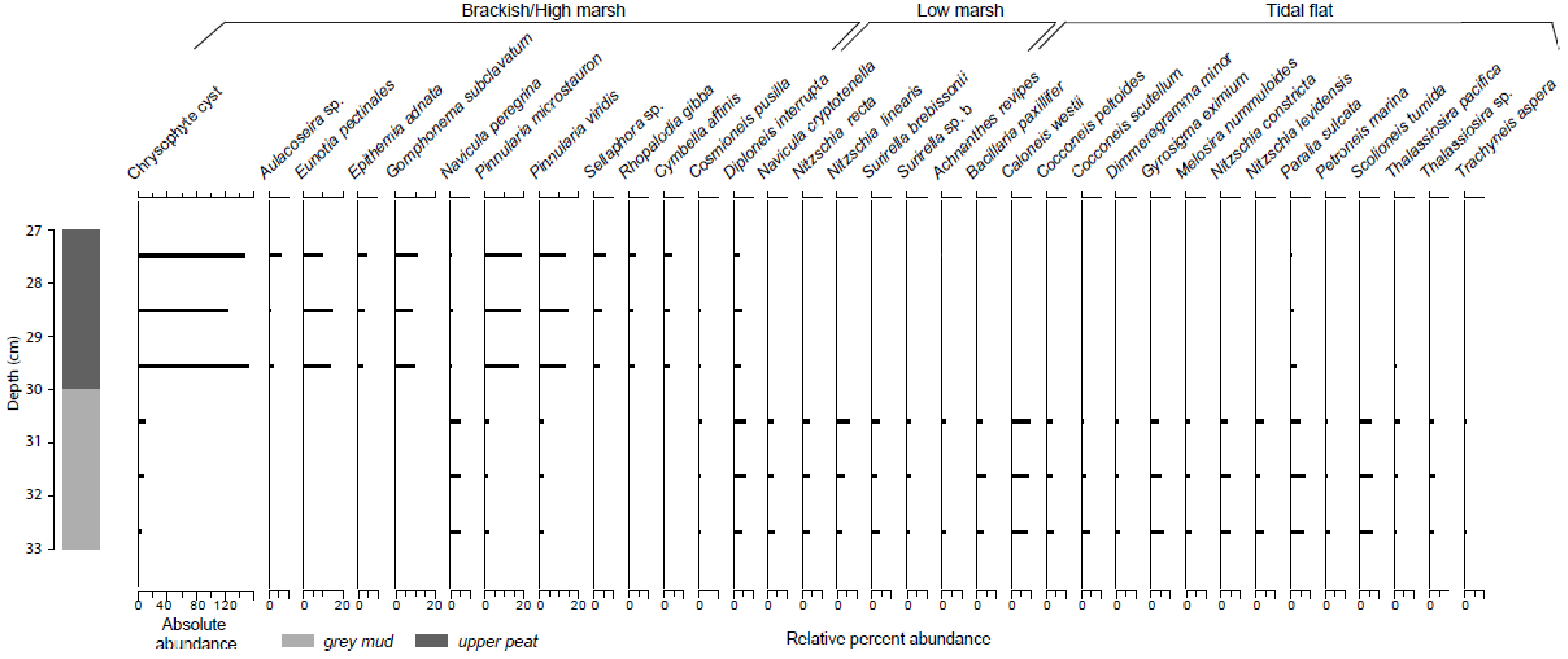


Diatom assemblage taken from monolith 147 in the cutbank portion of the field area. The diatoms record a change from brackish/ high marsh to low marsh and tidal flat species that mirrors the abrupt change in stratigraphy from *grey mud* to *lower peat.*



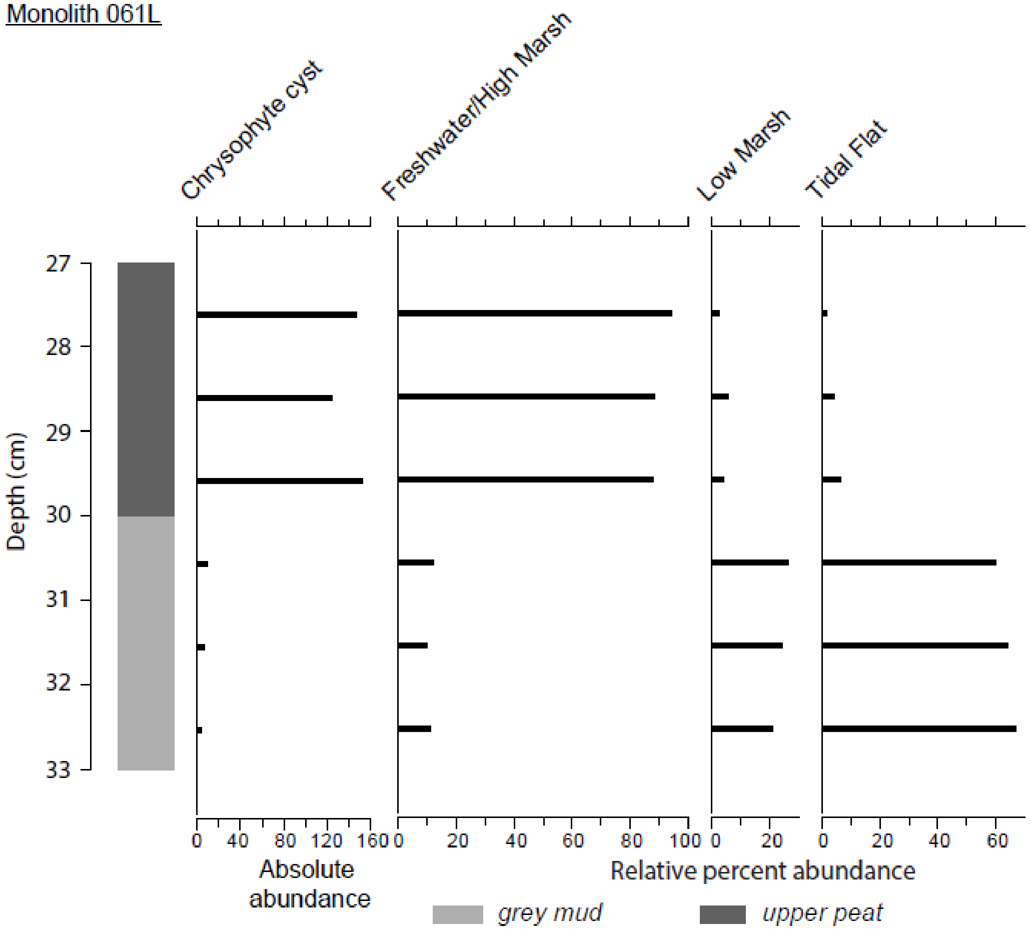
Diatom assemblage taken from monolith 061S in the cutbank portion of the field area. The diatoms record a change from brackish/high marsh to low marsh and tidal flat species that mirrors the abrupt change in stratigraphy from *lower peat* to *grey mud*.

Monolith 061L



Diatom assemblage taken from monolith 061L in the cutbank portion of the field area. The diatoms record a change from low marsh and tidal flat species to brackish/high marsh that mirrors the abrupt change in stratigraphy from *grey mud* to *upper peat*.

Monolith 061L



Diatom subenvironments from monolith 061L. Note abrupt shifts in diatom assemblages between the *grey mud* facies and the *upper peat* facies. Chrysophyte cysts are measured in absolute abundance, all others are relative percent abundance.