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

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Problem to Be Addressed, Hypothesis and Objectives

The Puget Sound region, in the forearc of the North American plate above the Cascadia subduction zone, is simultaneously home to several million people and vital infrastructure including ports and military bases, and to a dynamic and seismically active geologic setting (Figures 1 and 2). In the short historical record of the Puget Sound region, there have been only three earthquakes greater than magnitude 6.0. These events were deep, yet resulted in a total of 15 deaths, extensive property damage, and damage to infrastructure. Characterizing the complete seismic hazard in the Puget Lowland requires the study of the primary and secondary effects of paleoearthquakes because there have been no large, historic, shallow, crustal-fault events (or subduction-interface events). For example, a study by Johnson *et. al.* (2004) on the Utsalady Point fault indicates northwestern Whidbey Island primarily characterized seismic hazards associated with the Naval Air Station, the Seaplane Base, the town of Oak Harbor, and the Deception Pass bridge, which is Whidbey Island's only land connection to the mainland. The objective of this study is refine our understanding of seismic hazards that pose a threat to northern Whidbey Island by investigating the paleoseismic history of northeastern Whidbey Island and comparing the results to Johnson *et al.* (2004). My study will focus on two study areas in northeastern Whidbey Island, Crescent Harbor and Dugualla Bay (Figure 3).

Whidbey Island is crosscut by two main fault zones, the 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)(Figs. 2 and 3). 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.

In order to completely assess the seismic hazard of northern Whidbey Island, it is crucial to determine if the area was affected by the 900-930 AD Seattle Fault tsunami. If this tsunami did reach northern Whidbey Island, a tsunami from a similar rupture in the future could damage infrastructure, property and the economy. Once this study is complete, the information can be utilized by emergency management officials in Island County and by Emergency Operations officials at Naval Air Station (NAS) Whidbey, both of whom acknowledge that the hazards presented could have a devastating effect on the infrastructure and safety of the area (Island County, 2007).

<u>Previous Work</u>

Few studies exist on the crustal faults of the northern Puget Sound. Hayward *et.al.* (2006) worked on the Devils Mountain Fault, which trends east-west across the north end of Whidbey Island, north of the study area. The Utsalady Point fault trends east-west across Whidbey Island just to the south of (NAS) Whidbey and continues under Oak Harbor and across Saratoga Passage to Utsalady Point on Camano Island (Figure 3). It strikes obliquely across northern Whidbey Island, is northwest trending and has a minimum length of 28 km (Johnson *et. al.* 2001). Johnson *et al.* (2004) trenched this fault on the west side of Whidbey Island near Rocky Point and found evidence for two ruptures, one not tightly dated, between 1100 and 2200 14C years BP, and a younger one between 100 and 400 14C years BP.

Existing northern Puget Sound paleoseismicity studies also include the work of Kelsey *et al*. (2004), who studied the South Whidbey Island fault zone. The tsunami generated by the 900-930 AD rupture of the Seattle Fault is known to have affected Whidbey Island (Atwater and Moore 1992). Additional deposits from this event have been found throughout Puget Sound (Atwater and Moore, 1992; Sherrod, 2001; Bourgeois and Johnson, 2001; Arcos, 2012—includes summary map to date). Although these few previous studies of the region are high quality, there is a paucity of study locations in northern Puget Sound, so we cannot fully define the hazards that these crustal faults present.

<u>Plan to address the problem and test hypothesis</u>

To determine the earthquake history at Crescent Harbor and Dugualla Bay I will investigate the stratigraphy of both marshes to find evidence of seismicity at these sites. The evidence that would indicate earthquakes could include tsunami deposits, liquefaction or land-level change.

Tsunami: If present, tsunami deposits will consist of sand layers intercalated with marsh sediments. Tsunami deposits are often described as thin (typically less than 25 cm thick), sheet like, thickening into depressions, and fining landward (as summarized, e.g., in Arcos, 2012). Tsunami deposits found in Crescent Harbor marsh would likely consist of sand-sized grains, but not in Dugualla because there is not beach present. If found, macrofossil samples will be collected for radiocarbon analysis from directly above or below the sand layer to date the tsunami.

Liquefaction: If present liquefaction deposits will consist of sand dikes, sills and sand volcanoes in the marsh stratigraphy. Sand dikes and sills are typically complex systems of fluidized-sediment filling in cracks within the surrounding sediment. Dikes cut through layers and sills are parallel to layers. Sand volcanoes are a result of fluidized sand reaching the surface and tend to have a wedge shape. Martin and Bourgeois (2012) discuss differentiating liquefaction and tsunami sands, with specific examples from Puget Sound localities.

Land- level change: Co-seismic land-level change is either subsidence or uplift as the result of an earthquake. These changes will be represented in marsh stratigraphy by sharp and unusual facies changes, as a result of transitioning from one depositional setting to another in a very short amount of time. Sharp contacts of elevation-dependent facies are often used to indicate coseismic land-level change, of which mud-over-peat deposition from co-seismic subsidence is one of the easier to identify. Nelson *et. al.* (1996) outlined how gradual versus abrupt peat-mud contacts can provide information about the seismic history of a marsh. Marshes in seismically active areas tend to have sharp peat-mud contacts, whereas passive margins typically have gradual contacts. Arcos (2012) describes examples of sharp peat-over-mud contacts indicating uplift. If peat-mud contacts are found at either field site I will note their characteristics and collect samples for radiocarbon dating.

The stratigraphy of Crescent Harbor and Dugualla Bay marshes must be mapped and analyzed in order to establish the seismic record at both sites. To map the marsh stratigraphy I will examine gouge cores and also cut-bank exposures of the tidal channel at Crescent Harbor (Figure 4), and gouge cores only at Dugualla Bay (Fig. 5) because there are no accessible cutbanks due to water-level regulation. These studies will establish the stratigraphic units present, their thicknesses and locations, and the nature of contacts between units. In detailed analysis of tidal-channel exposures, I will look for sand dikes and sills indicating liquefaction. Both cores and cutbanks will be examined for evidence of tsunami deposits and land-level change. Hand-held GPS units will record the location of each sample and survey, while a total station will be used to collect very precise elevation measurements. A GPS base station will be set up at each site to continually collect precise GPS to relate the total station measurements to real-world positions and to establish accurate coordinates for each core and cutbank location. After collecting modern elevations of the facies that are present, I will make an estimate of land-level change based on the elevation differences between modern facies and facies that are recorded in the marsh stratigraphy.

Along with analyzing radiocarbon dates, lab work for this project will include grain size analysis of intertidal mud, sand, gravel and tsunami and/or liquefaction deposits (if found). Modern sediment samples of the facies present at both locations will act as proxies in comparing the various sediments. Grain size analysis will help distinguish similar layers from each other and will allow us to determine the source of units, as well as distinguishing tsunami deposits from liquefaction deposits (Martin and Bourgeois 2012). Analysis of mud will be performed at Central Washington University using a Mastersizer and the sand and gravel will be analyzed at the University of Washington using a CAMSIZER.

Finally, I will create a geographic information system (GIS) database using ArcGIS and the GPS and elevation data to compare units spatially. All units present at both field sites will be input as individual layers in order to map a three-dimensional model of the marsh. This will allow for reconstruction of marsh history and aid in making an estimate of any land-level change that may have occurred throughout the history of the marsh. Google Earth imagery, historical aerial photographs and historical maps of the study areas will be used to mitigate for human involvement and alteration of both marshes throughout the 20th century.

Anticipated Results and Benefits

Whether or not tsunami deposits from the 900-930 AD Seattle Fault rupture might be found in Crescent Harbor stratigraphy is an open question. The harbor is south facing, and open, which might allow the tsunami to inundate the area if the wave height is large enough to overtop the beach berm. However, the closest recorded evidence of the tsunami is at the Snohomish delta (Bourgeois and Johnson, 2001), 45 km away, which, combined with the complicated bathymetry west of Whidbey Island and barriers like Camano Island, makes it likely that the wave attenuated below the height of the beach berms by the time it reached northern Whidbey Island. Dugualla Bay is farther north and faces east so is even less likely than Crescent Harbor to have recorded the Seattle Fault tsunami there. Other sources of tsunamis in Puget Sound include the 1894 Commencement Bay delta failure and the 1949 Tacoma Narrows subaerial landslide (Gonzalez *et. al.* 2002).

Evidence of land-level change is plausible at Crescent Harbor. The Utsalady Point Fault runs almost directly through the Crescent Harbor field site, and Johnson *et al.* (2004) found evidence of two prehistoric earthquakes with 1.5 meters of vertical slip only 7 km west of Crescent Harbor. Dugualla Bay is less than 2 km south of the Devils Mountain Fault (Figure 2.) Earthquakes on either the Utsalady Point or Devils Mountain faults would produce strong shaking in my field areas, thus liquefaction is also expected.

Ultimately, this study will add to the rupture history and neotectonics of shallow, crustal faults in northern Puget Sound, of which little is currently known. The data will contribute to a hazard analysis by emergency management officials to either confirm their current procedures or potentially lead to revisions of those plans. Results could also refine the timing of the ruptures on the Utsalady Point Fault from Johnson *et al.*(2004).

Duration

July 2014- May 2016

Budget

Radiocarbon dating: Direct AMS, Bothell, WA

5 AMS dates @ $279.00/sample =	$1116.00
4 bulk sediment dates @ $229.00/sample =	$916.00
Food per diem: $50/day/per 3 people for 10 days =	$1500.00
Lodging: Lodging (2 rooms @ $59.00/ night for 9 nights) =	$1062.00
Stipend for Brian Ostrom:	$1000.00
Mileage for Brian Ostrom: $0.56 per mile, 150 miles one way from Eatonville WA to Oak Harbor, 4 times one way =	$336.00
Rental car for Dr. MacInnes and Frances Griswold: $24 per day+ $0.29 per mile, 187 miles one way from Ellensburg to Oak Harbor, 4 one way trips =	$457.00
Total:	**$6387.00**

Budget Justification

This project requires radiocarbon dating to establish the ages of stratigraphic units and contacts; 9 total samples are requested. AMS dates are preferred over bulk sediment dates because AMS provides a more accurate date; smaller samples are required, thus in situ organic material, such as seeds, can be used making the date more reliable. Bulk dates will be necessary for layers that do not contain in situ macro organic material (seeds, leaves, etc.).

Standard per diem rates are used to budget food for three people for the ten days of proposed field work. State standard mileage rates are used to reimburse Brian Ostrom for four one way trips from Eatonville, WA to Oak Harbor, WA. A rental car is required for Dr. MacInnes and field assistant Frances Griswold to transport field equipment from Ellensburg to Oak Harbor. Brian Ostrom is taking time off from his summer job to complete this fieldwork, resulting in a stipend to cover lost wages. Fieldwork will be complete from July 7th to 17th 2014.

Timeline

July 2014- Complete fieldwork and data collection

Fall 2014 through Spring 2015- Data analysis, process radiocarbon samples, analyze radiocarbon age results, begin developing GIS database

Spring 2015- Thesis proposal defense

July 1st 2015- Preliminary report due to Island County Department of Emergency Management

Summer 2015- Continue building GIS database, begin writing first draft of thesis

February 2016- First draft of thesis

May 2016- Thesis defense and submit thesis

Figures

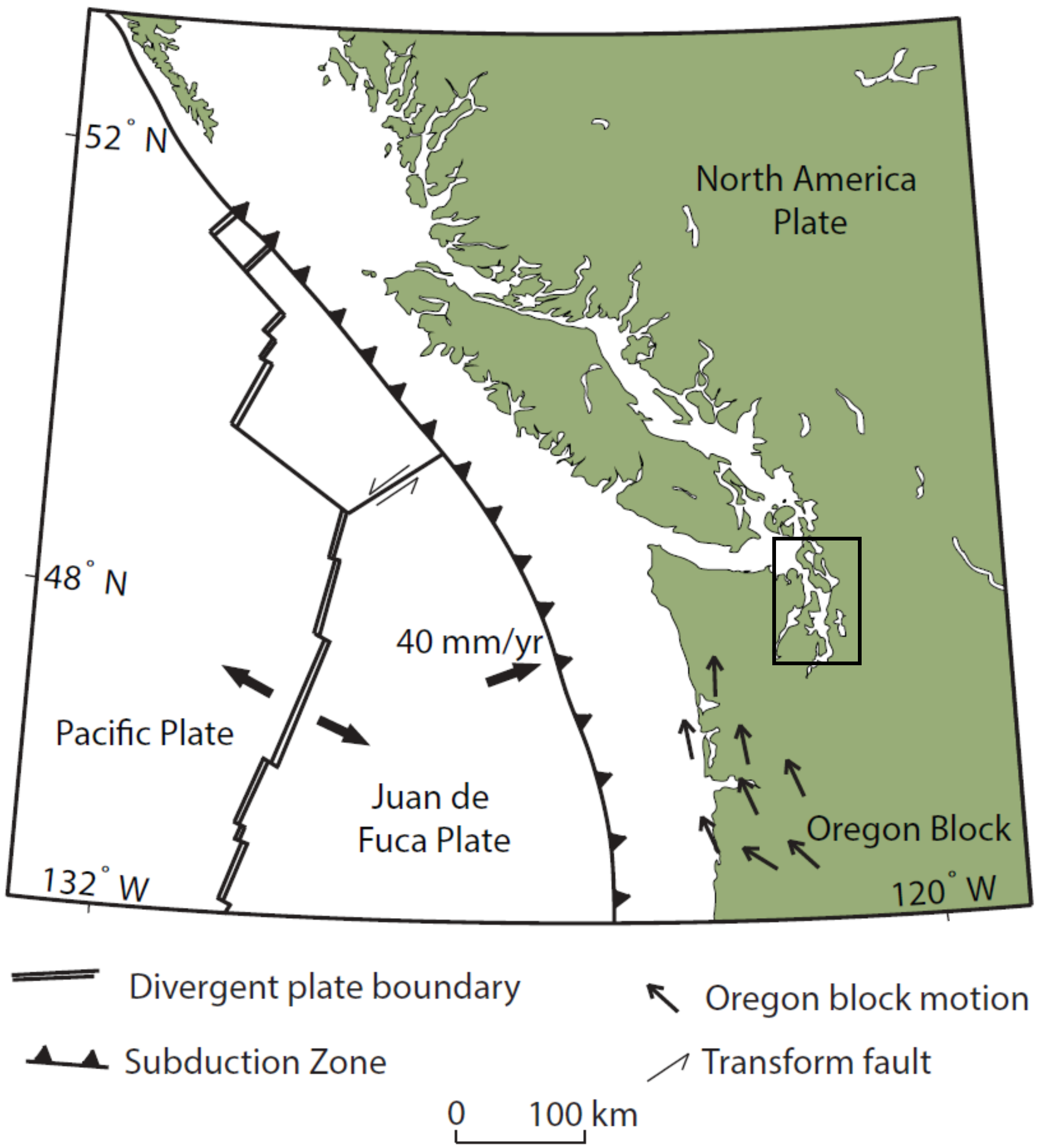

Figure 1. Regional tectonic setting showing the plate motions of the Pacific Plate and North American Plate along with the rotation of the Oregon block. The general study area is outlined in black. (after Hayward *et. al.* 2006)

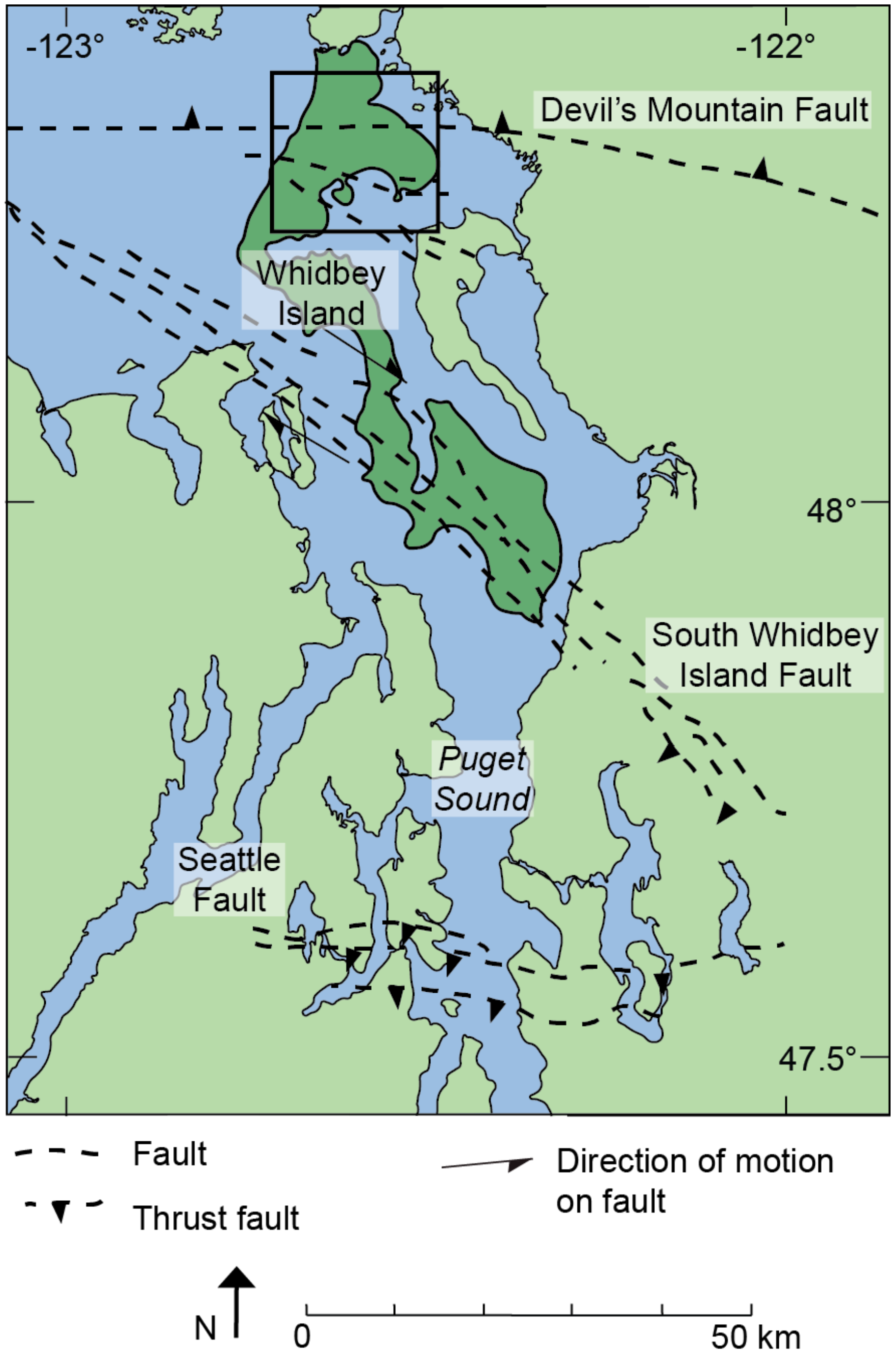

Figure 2: Fault map of the Puget Sound showing the location and orientation of the main fault zones in the region (after Arcos, 2012).

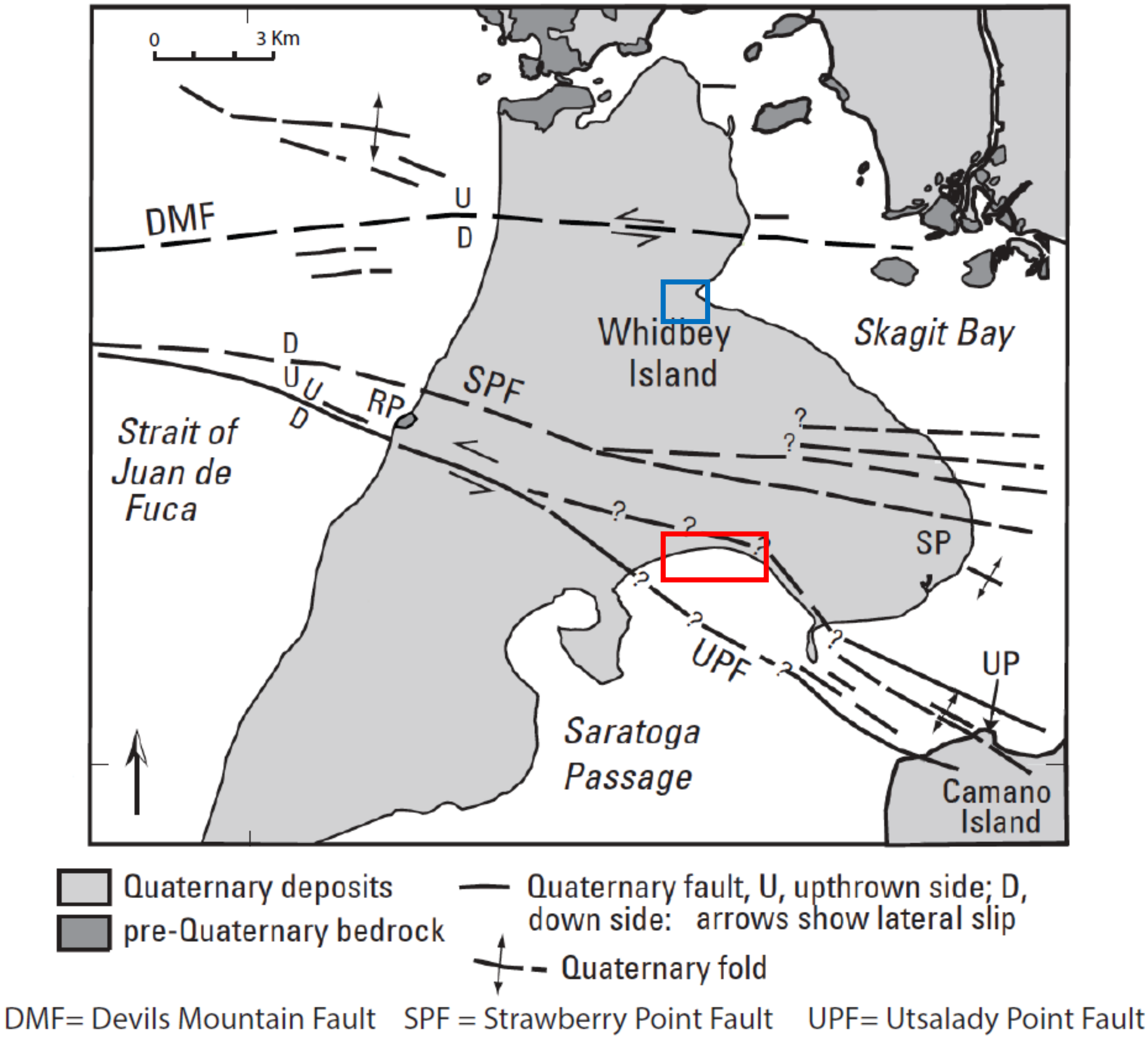

Figure 3. Fault map of northern Whidbey Island. Crescent Harbor study area is denoted by the red square, Dugualla Bay is denoted by the blue square (after Johnson *et al.*, 2004).

Figure 4. Google Earth image of Crescent Harbor showing the main tidal channel and the extent of the tidal influence (marked by dead tree line). Square feature in the middle is a water treatment facility.

Figure 5. Google Earth image of the Dugualla Bay field site. Mention the dike and the permanent freshwater (no longer tidal)

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