

# **Elwha Delta Morphology and Grain-size Distribution**

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Marine Sedimentary Processes Apprenticeship  
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## **Abstract**

New sediment is being released from the Elwha River dam reservoirs into the Strait of Juan de Fuca for the first time in 100 years, but it is unknown where this sediment will settle and how it will affect the geological environment. In this study, we examined the overall profile of the Elwha River delta and how it is influenced by the new sedimentation. Beach surveys, fathometer transects, and grain-size analyses were combined to evaluate the entire delta front. Grain-size and delta slopes were not found to be correlated in this study. The foreshore of the delta had the steepest slope and was comprised of sandy substrate. The low-tide terrace consisted of large cobbles and had a near horizontal slope. Offshore, the substrate varied widely but no relationship was found between substrate composition and slope. Profiles of the subaqueous delta revealed much longer topsets to the east of the river mouth, suggesting eastward littoral transport. Furthermore, three submarine ancient spits to the east of the delta demonstrate this historical transport pattern. One reason the substrate morphology of the Elwha delta does not look predicted is because the Elwha has been starved of sediment for the past century. Data from this study established a platform for further studies and hints at a future relationship that could be discovered.

## **1. Introduction**

River deltas are formed from many dynamic geologic and oceanic processes. Some of the factors influencing delta formation include climate, local geology, and relief for the river gradient. Sediment dispersal and resedimentation at river deltas relies on existing geomorphology, shear stresses on the delta seabed, and overall rate of supply to

the delta (Orton and Reading, 1993). In the Salish Sea, Washington, there has been little modern input of sediment, so most sediment within the region results from glacial outwash that has been reworked from shallow banks and redistributed (Hewitt and Mosher, 2001). In 2001, Hewitt and Mosher characterized the mixed substrate composition within the Strait of Juan de Fuca due to the Fraser glaciation. Substrate composition itself has been studied with the Strait, but little research has been conducted on how grain-size influences river deltas that are subject to oceanic processes. However, grain-size does in fact impact multiple processes. Grain-size influences the gradient of the delta plain, mixing as the sediment discharges into the relief, type of shoreline at the river mouth, and how deformation and resedimentation occurs on the delta front (Orton and Reading, 1993).

The morphology of the Elwha delta is indicative of former glaciations. The shoreline has changed over 100 m in elevation over the course of the most recent Fraser glaciation (Mosher et al., 2004). While the long time-scale formation of the Elwha delta is relatively well understood, changes occurring now are more complicated. The Elwha River restoration provides a unique opportunity to observe these processes in action and understand sedimentation dynamics that occur over a comparatively smaller timescale. The removal of the Elwha and Glines Canyon dams will release previously trapped sediment into the Strait of Juan de Fuca after a century of limited sediment supply. This study will look at the overall profile of the delta front and how it is influenced by new sedimentation from the Elwha River. New sediment is known to be important for biological habitats and reversing ongoing beach erosion, but it is unknown how the new sediment will settle and how the delta structure will be modified, if at all. Here we focus

on the delta as a whole, using beach surveys, fathometer transects, physical sediment samples, and digital grain-size analyses (Cobble Cam). The combination of these data sets is used to provide insights on how substrate composition affects the morphology of the beach and subaqueous delta.

## **2. Regional Setting**

The Elwha River watershed lies on the Olympic Peninsula on the south shore of the Strait of Juan de Fuca, Washington. Present day coastal morphology is a product of sedimentary, volcanic, and glacial processes. During past glaciations, large glacial deposits left poorly sorted alluvium, silts and clays, which can be seen in the eroding bluffs on the coasts in the region (Warrick et al., 2011). At its terminal position, the Juan de Fuca lobe of the Fraser glaciation, reached the shelf edge at  $14,460 \pm 200$  years before present (BP). During this time, the continental crust was isostatically loaded by ice and depressed. Along the Olympic Peninsula, the high-stand maximum was estimated to be +50 m at  $12,500 \pm 60$  years BP (Mosher and Hewitt, 2004). Isostatic rebound and eustatic sea-level rise occurred simultaneously but isostatic crust rebound occurred at a faster rate, causing isostatic sea level to appear lower (Mosher and Hewitt, 2004). Marine transgression took place between 10,300-7,500 years BP until present day sea level was reached around  $5,470 \pm 115$  years BP (Mosher et al., 2004).

Over the past century, bluffs have been the main sediment source to the Strait of Juan de Fuca. Once returned to a natural state, the mountainous basin created by the Olympics will deposit sediments onto the Elwha subaerial delta, which is approximately  $0.35 \text{ km}^2$  and is a large alluvial flood plain with sediment gathered into channeled sand bars (Warrick et al., 2011).

The river flows north from the Olympic Mountain range into the Strait and has a mean annual discharge of  $43 \text{ m}^3 \text{ s}^{-1}$ . The Elwha River has been dammed by the Elwha Dam since 1910, 8 km upriver of the mouth, and by the Glines Canyon Dam since 1927, 21.6 kilometers upriver (Duda et al., 2011). Lake Mills and Lake Aldwell were reservoirs created by the dams, which trapped over  $26 \times 10^6 \text{ m}^3$  of sediment ([www.nps.gov/olym/](http://www.nps.gov/olym/)). Sediment composition of these reservoirs is 85% and 95% fine sands and silt in Lake Mills and Lake Aldwell, respectively (Duda et al., 2011). Removal of these dams is the largest dam removal project in the United States and is expected to reverse downstream river and coastal erosion, which have caused coarsening of the seabed. Deconstruction of the Glines Canyon Dam will be completed in July 2013, and the Elwha Dam removal was completed in May 2012.

The removal of the dams will result in a dramatic increase of sediment supply to the river mouth where it will be subject to oceanic processes (Warrick et al., 2011). Because the Strait of Juan de Fuca is a narrow channel, it is protected from most open ocean wave energy, but in the winter months, oceanic water can flow all the way to Port Angeles (Cannon, 1978). Wind, currents, and tides play a large and widely varying role in sediment transport. Waves in the Strait are a combination of swell coming from the Pacific Ocean and local wind-generated waves. Since the fetch across the Strait of Juan de Fuca is only 70 km, wind-generated waves are not fully developed and have higher frequencies than swell, ranging from 4-8 seconds (Warrick et al., 2011b). Average wave height at the mouth of the river is 1-2 m and waves propagate along the shoreline from the northwest (Warrick et al., 2009). This creates an oblique angle of approach to the beach, causing littoral transport that is most dramatic east of the river mouth. Currents

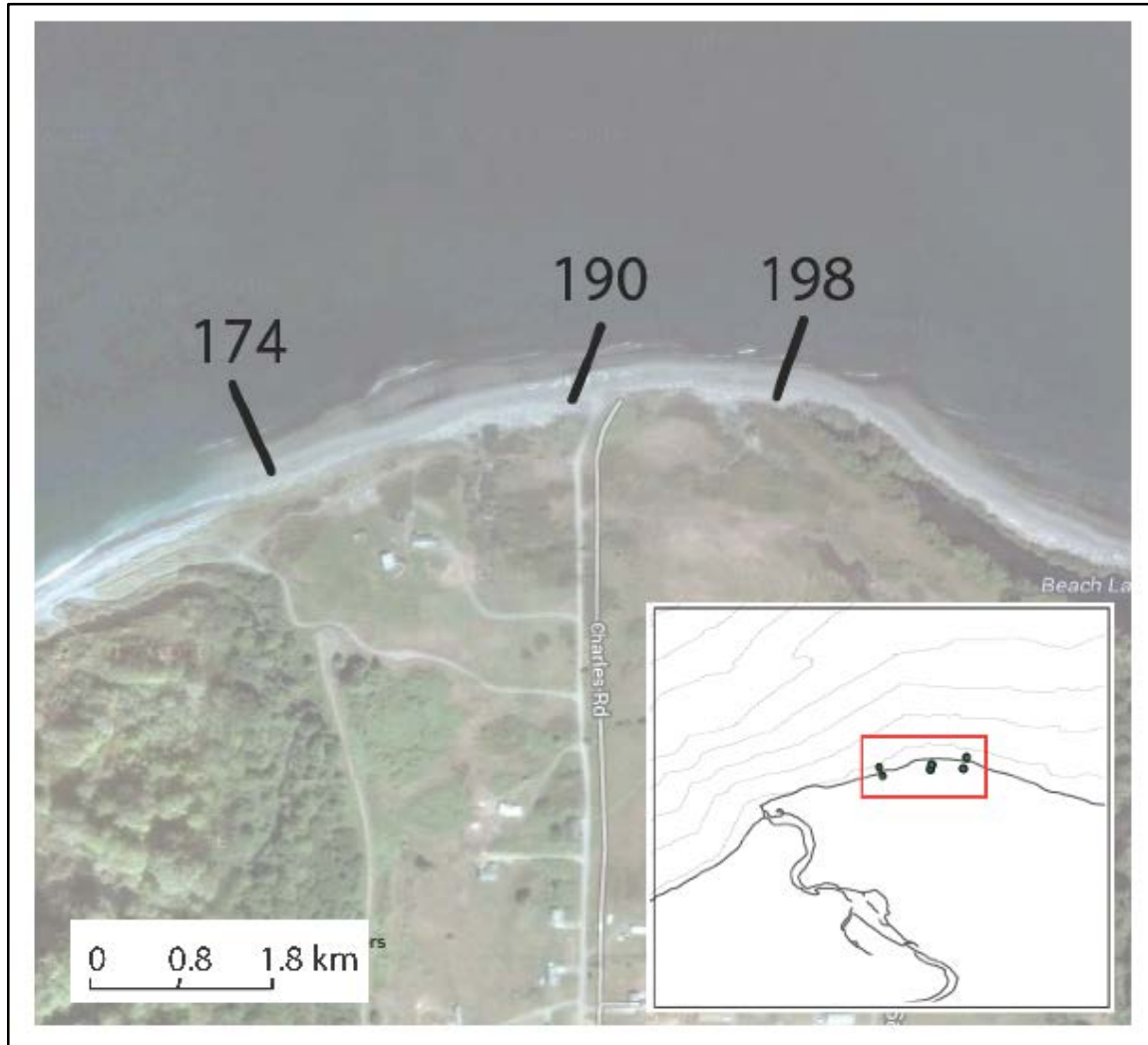
formed by wave processes in the channel drive most of the eastward longshore sediment transport (Warrick et al., 2011b). Sediment has been measured to move up to 100 meters a day in winter conditions (Warrick et al., 2009). Most variation in flow direction is due to seasonal wind processes (Cannon, 1978).

The geomorphologic, wave, current, and weathering processes have all contributed to the current substrate composition of the beaches surrounding the delta. On the east beach, a woody backberm drops onto a sandy foreshore. The beach then forms a large cobble terrace along the low-tide water line. Grain-size ranges from 1-256 mm (Warrick et al., 2009). Most of this sediment is reworked glacial deposit from the last glaciation (Mosher and Hewitt, 2004). With the removal of the dams, a larger mass of sediment transport is expected to drastically modify the coastline and reverse the ongoing erosion that has endured the last century. Sediment deposition is expected to become increasingly fine-grained with increased river discharge in the future (Warrick et al., 2009). In general, grain-size distribution along the submarine Elwha Delta will be supplemented by previous studies as it examines the overall profile and change that has occurred post-dam removal.

### **3. Methods**

#### *3.1 Topographic and Bathymetric Profiles*

Data collection for this project was primarily conducted on the *R/V Clifford A. Barnes* April 12-16, 2013. On shore, cross-shore beach profiles were recorded using a Lasermark LMH self-leveling rotary laser with a Stadia Rod. Three designated transects, Line 174, Line 190 and Line 198, were visited on three consecutive days (Fig. 3.1).



**Figure 3.1.** Beach transects on the east beach of the Elwha Delta. Proximity to the Elwha River is shown in the subplot for reference.

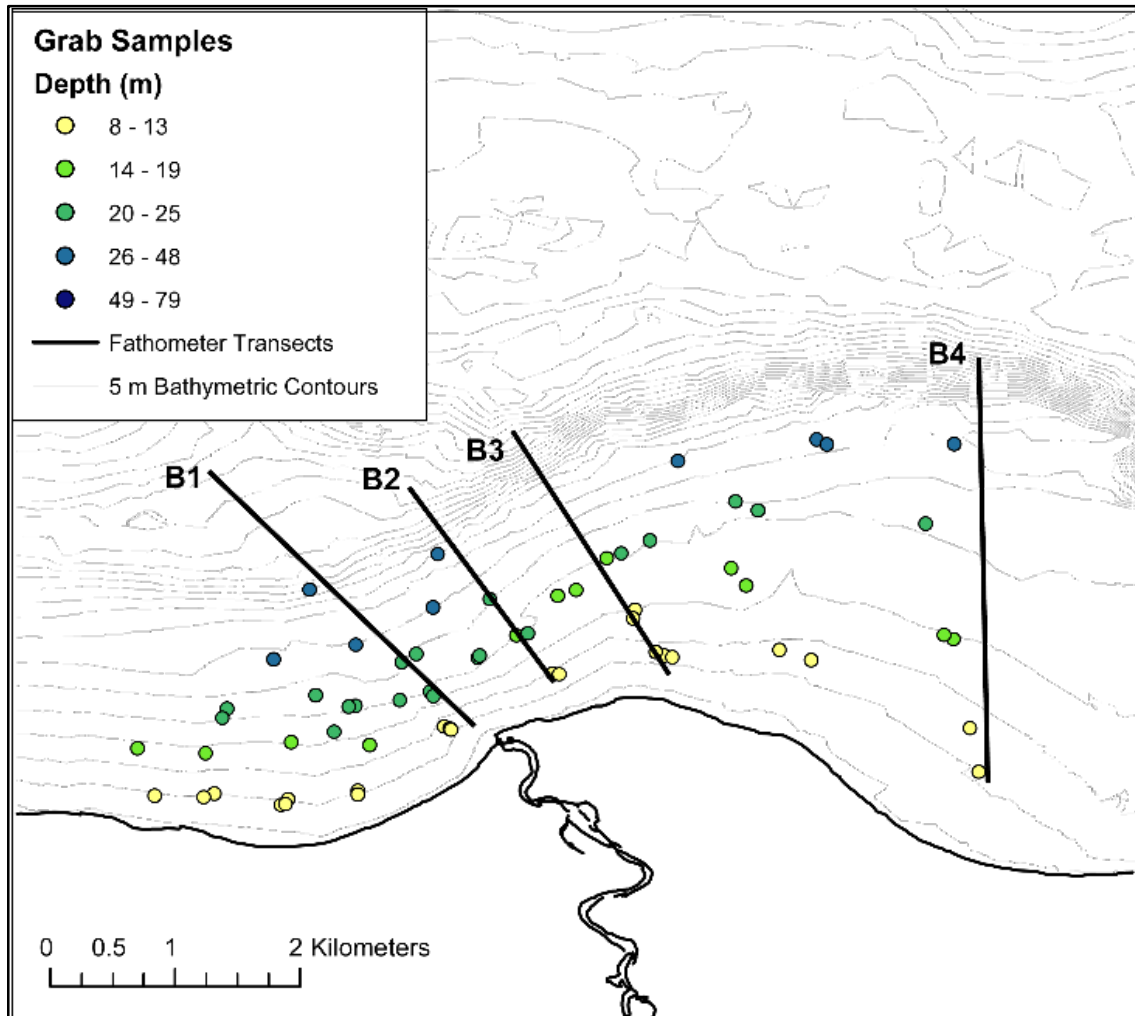
Elevation was measured in increments of 1 m on the berm and foreshore and 3-5 m on the terrace.

Off shore, four separate cross-shore transects were conducted aboard the *R/V Barnes* to attain fathometer depth data in the study area (Fig 3.2). Fathometer data was transmitted using a Knudson 3260 and 320BR, configured at 12 KHz operating at 2KW. This was used as ground-truth for topographic data that was obtained from the Elwha River Spatial Data Server (<http://deptweb.wvu.edu/huxley/huxweb/elwha/>). Fathometer data was processed using Matlab and adjusted to MLLW according to tide data captured at the Neah Bay Buoy, NOAA station 46087 ([www.ndbc.noaa.gov](http://www.ndbc.noaa.gov)). GIS models of the delta bathymetry were analyzed for comparison.

### *3.2 Sediment Samples*

Along the beach transects, digital photographs were taken at the same increments as the elevation measurements using a 12.1 megapixel resolution Canon Powershot camera. The camera was held parallel to the beach and camera height from the beach varied with sediment size. Larger grained sediment was photographed from a farther distance. A fifteen centimeter scale was placed in each photo as reference. Woody and biological debris was removed from the photo frame to prevent misrepresentation in the data. Photos were then analyzed with a Cobble Cam script, using an autocorrelation analysis, which can be reviewed in detail in Warrick et al., 2009.

Additional samples were taken by hand on the foreshore east of the river mouth along the three designated beach transects. Three physical samples were taken on each transect line where smaller grained regions of the beach was observed. One sample was



**Figure 3.2.** Map of the study area showing depth and location of grab sample stations as well as transect line location and relative distances offshore.

specifically taken at MLLW on line 174 to analyze mud composition. Smaller grained samples were collected to supplement Cobble Cam data and verify correct grain-size distributions for finer grains.

Furthermore, 47 grab samples were taken around the submarine delta using a Shipek grab sampler (Fig. 3.2). Physical sediment samples were wet sieved through a  $4\Phi$  sieve to separate mud from the coarser grains. Homogenous samples were subsampled prior to wet sieving. The mud fraction was then run through a pipette analysis and the remaining coarse sediment was dry sieved in a Ro-Tap (UW, 1998; Folk and Ward, 1957). GRADISTAT used Folk and Ward statistics for pipette analysis and grain-size was then categorized using the Wentworth scale (Blott, 2001).

### *3.3 Video Imagery*

Underwater video surveys using the SideWinder Color Underwater Video Camera, on loan from the USGS, were collected during the *R/V Barnes* cruise near the Elwha River mouth at the grab sample sites. Drifting occurred and location was recorded by GPS waypoints to ensure spatial accuracy. Two lasers were attached to the camera 11 cm apart, along with a 13 cm ruler for reference on the seabed. The camera was manually lowered overboard to within 0.5 m of the seafloor and footage was recorded with a Sony digital recorder. Snap-shot images were collected from the live footage as verification of substrate composition.

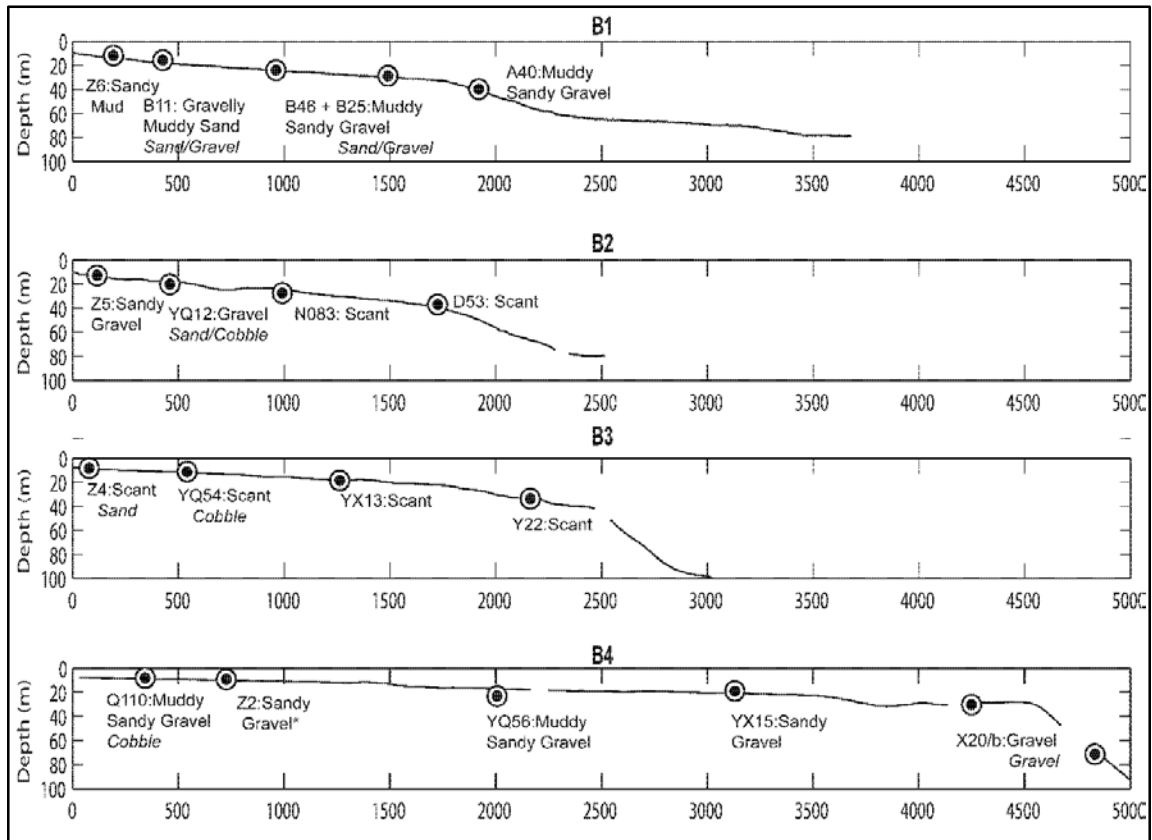
## 4. Results

### 4.1 Bathymetry and topography

Four offshore transects were measured seaward from the Elwha River delta: lines B1, B2, B3, B4 (Fig. 4.1). B1 had a topset that extended 1750 m offshore and ranged from 10.0-32.8 m deep. The foreset began at 1750 m offshore at 32.8 m and dropped to 60.9 m, 2300 m offshore. The bottomset proceeded from 78.2 m depth. Transects B2, B3, B4 all had similar depths but topset distances offshore varied by 2700 m as seen in Table 4.1. A spatial overview of the transects and their depths is shown in Figure 4.2.

Beach profiles were measured in three transects: lines 174, 190, and 198 (Fig. 4.3). Elevations above MLLW ranged from 0 to 4 m. On average the berm was 3.5 m high, followed by a foreshore 15 m wide and 1-3.5 m in elevation. The cobble low-tide terrace followed the foreshore, and spanned from the edge of the foreshore to the water's edge at MLLW on the April survey dates. The low tide terrace elevation decreased from 1.5 m to 0 m above MLLW. At a distance of 77 m along the transects, runnels cut across the beach from water runoff and lowered beach surface elevations 0.195 m below MLLW.

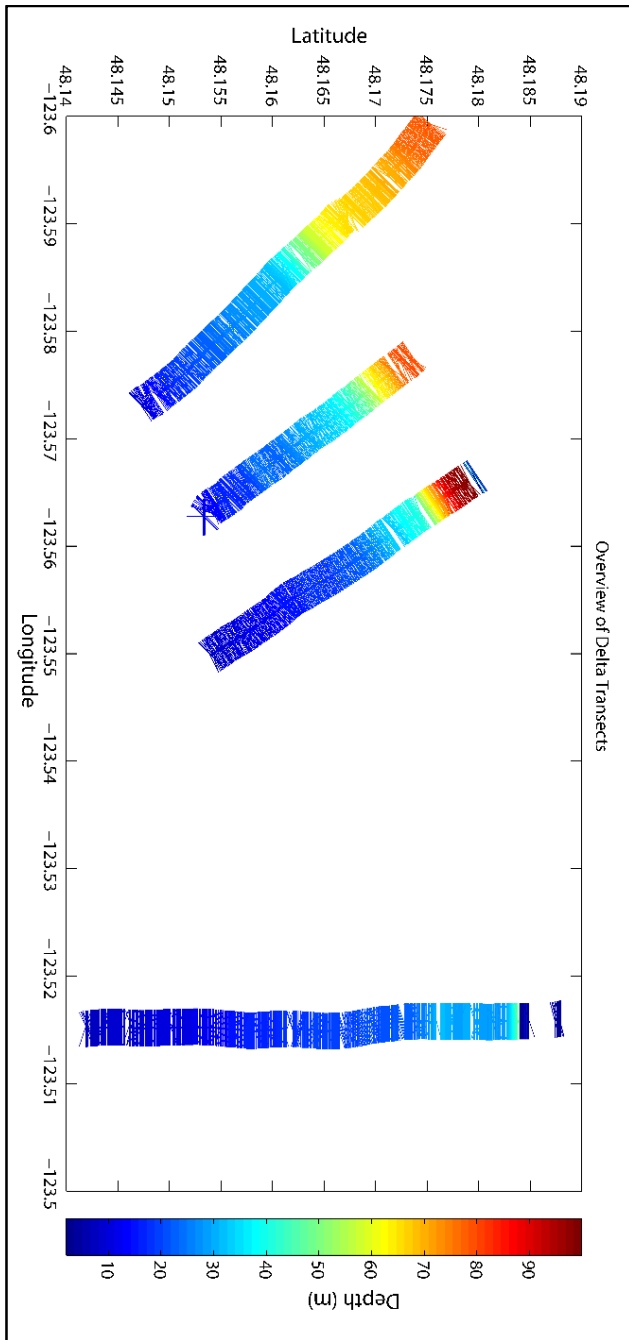
Beach slopes for all three of the transects were fairly similar (Table 4.2). The foreshore showed the steepest decrease in elevation. Then, the profile showed a prominent transition to a flatter sloped low-tide terrace that extended until the runnel zone. Just prior to MLLW, near the runnel hollows, beach slope steepened and descended until MLLW.



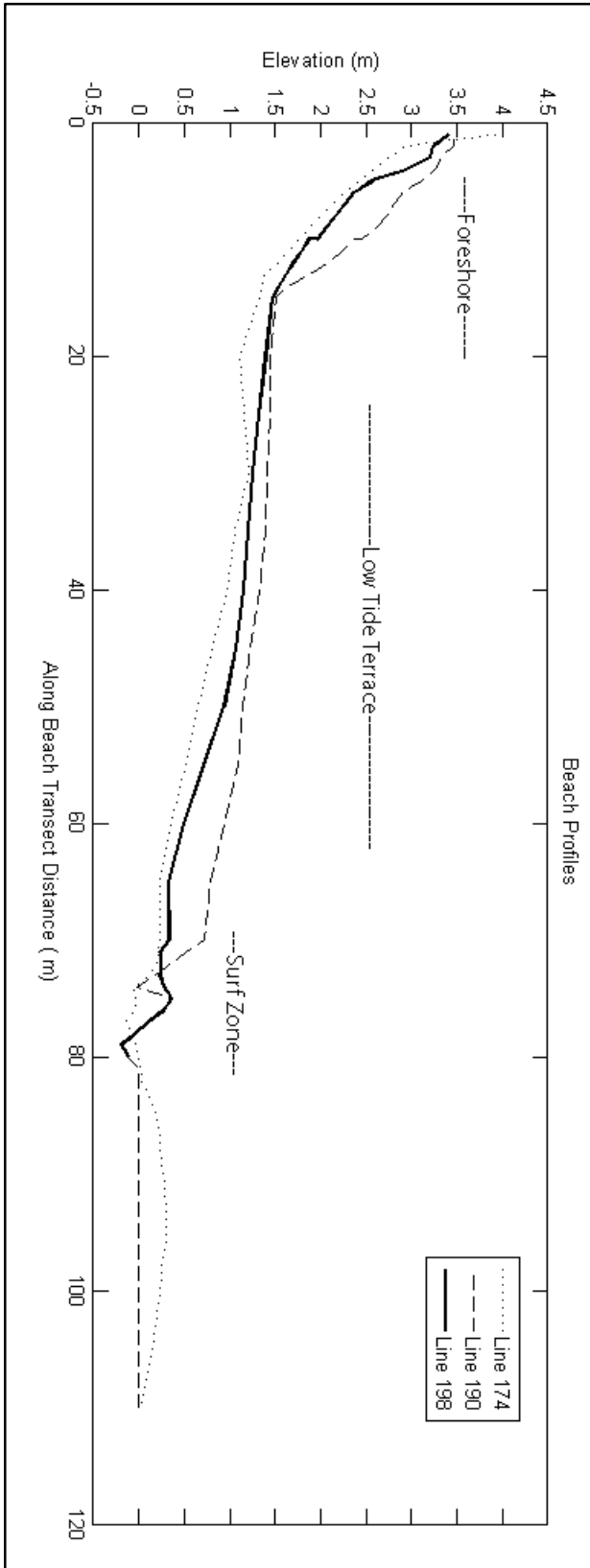
**Figure 4.1.** Delta Transect Profiles. Transect profiles show grab samples sites (dots) with a summary of substrate composition beneath. Video classifications are shown in italics.

**Table 4.1.** Distances offshore, depth, and slopes for the different portions of the submarine Elwha Delta.

Table 4.1 Delta Profile Features									
	TOPSET			FORESET			BOTTOMSET		
Transect	Dist. (m)	Depth (m)	Slope	Dist. (m)	Depth (m)	Slope	Dist. (m)	Depth (m)	Slope
B1	0-1750	10.0-32.8	-0.0131	1750-2300	32.8-60.9	-0.0444/ -0.0132	2300+	60.9-78.2	-0.0080
B2	0-1600	10.5-36.2	-0.0173	1600-2350	36.2-78.0	-0.0619	2350+	78.0-80.1	-0.0082
B3	0-2500	7.7-41.8	-0.0134	2500-2900	41.8-95.4	-0.1119	2900+	95.4-98.0	-0.0277
B4	0-4500	7.5-28.2	-0.0047	4500-5000	28.2-93.2	-0.1338	5000+	93.2-98.8	-0.0619



**Figure 4.2.** Overview of the offshore transects showing location and depth below sea level (m).



**Figure 4.3.** Beach Profiles. Elevation profiles of Lines 174, 190, and 198 with relative foreshore, low-tide terrace, and surf zones.

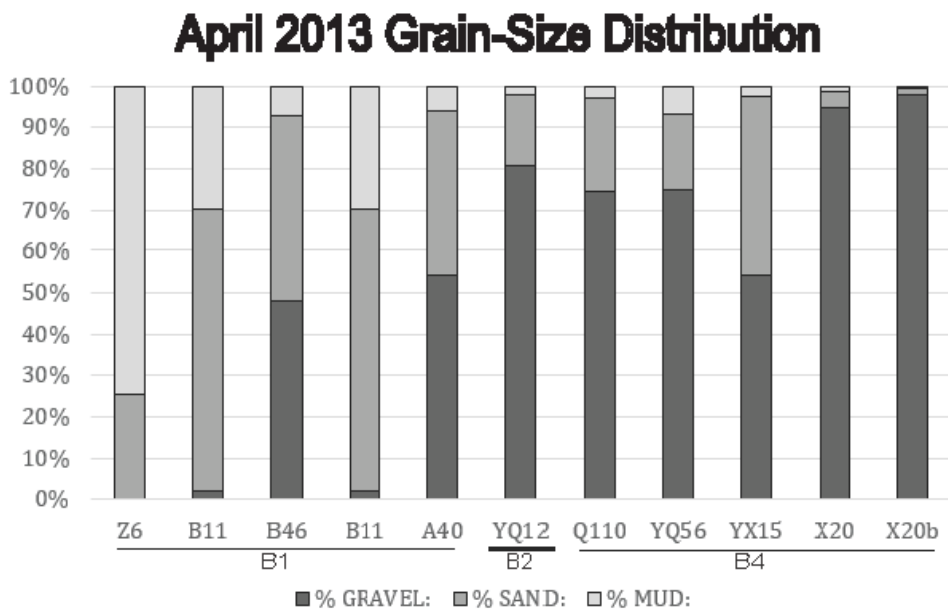
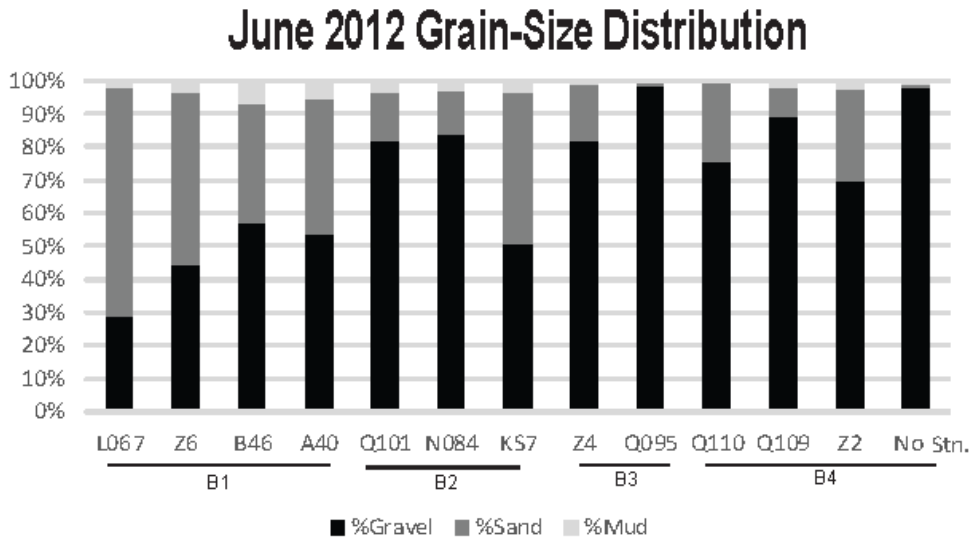
**Table 4.2.** Beach profile slopes for distinct beach zones.

	Foreshore	Low Tide Terrace	Runnel Zone
L174	-0.2196	-0.0197	-0.0058
L190	-0.1504	-0.0144	-0.0649
L198	-0.1382	-0.0203	-0.268

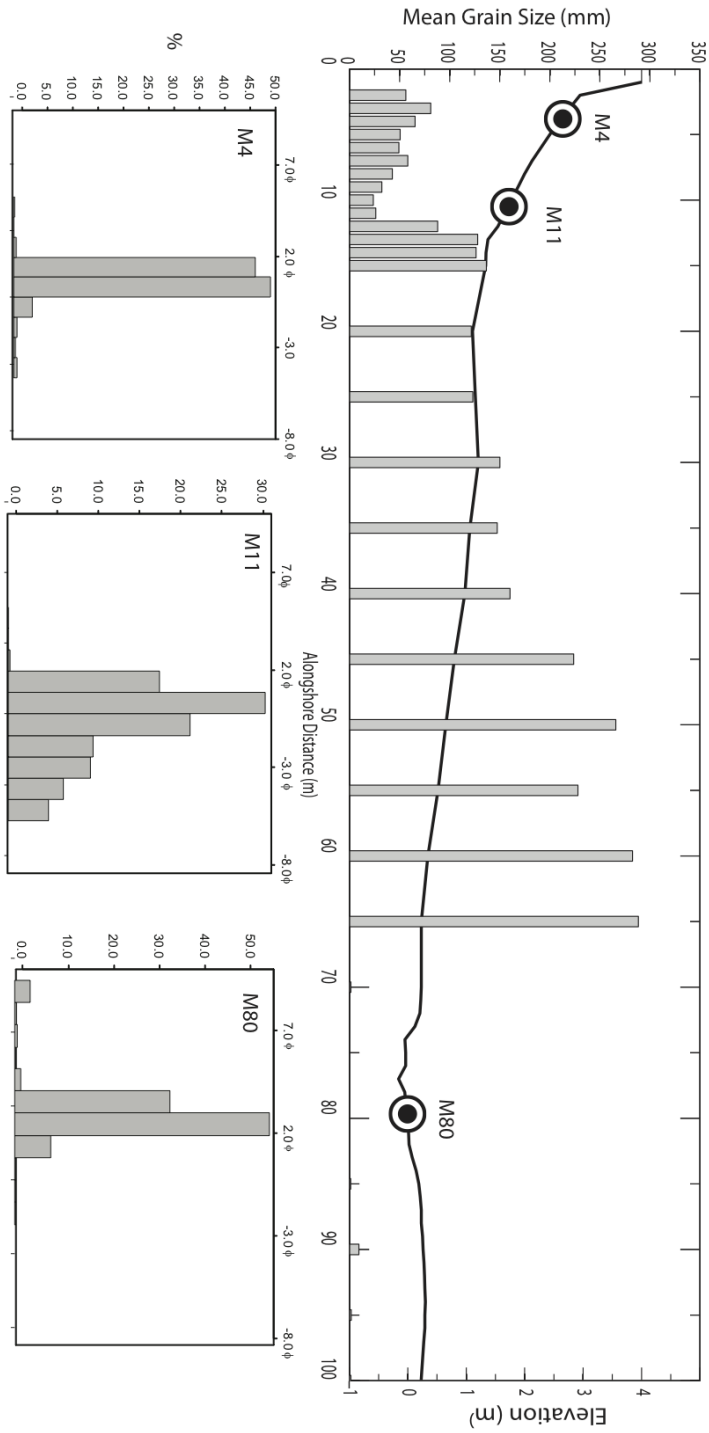
## *4.2 Sediment samples*

Of the 19 grab samples that were taken along the offshore transects in April 2013, 7 were scant and therefore unrepresentative of the local substrate. For further information, data from July 2012 was included in the analyses. Grab sample analyses of sites along the transects revealed a principal mix of sandy gravel, with spatial variation of higher mud percentages west of the river mouth or higher gravel percentages to the east (Fig. 4.1). Gravel, sand, and mud percentages are shown for each grab sample on a transect line taken April 2013 (Fig. 4.4). Sample analyses from April 2013 showed slightly higher mud composition than the analysis from July 2012, especially at sites in close proximity to the river mouth (Fig. 4.4). Both dataset analyses exhibited sandier samples to the west of the river mouth in Freshwater Bay and grain-size became increasingly coarser to the east of the delta.

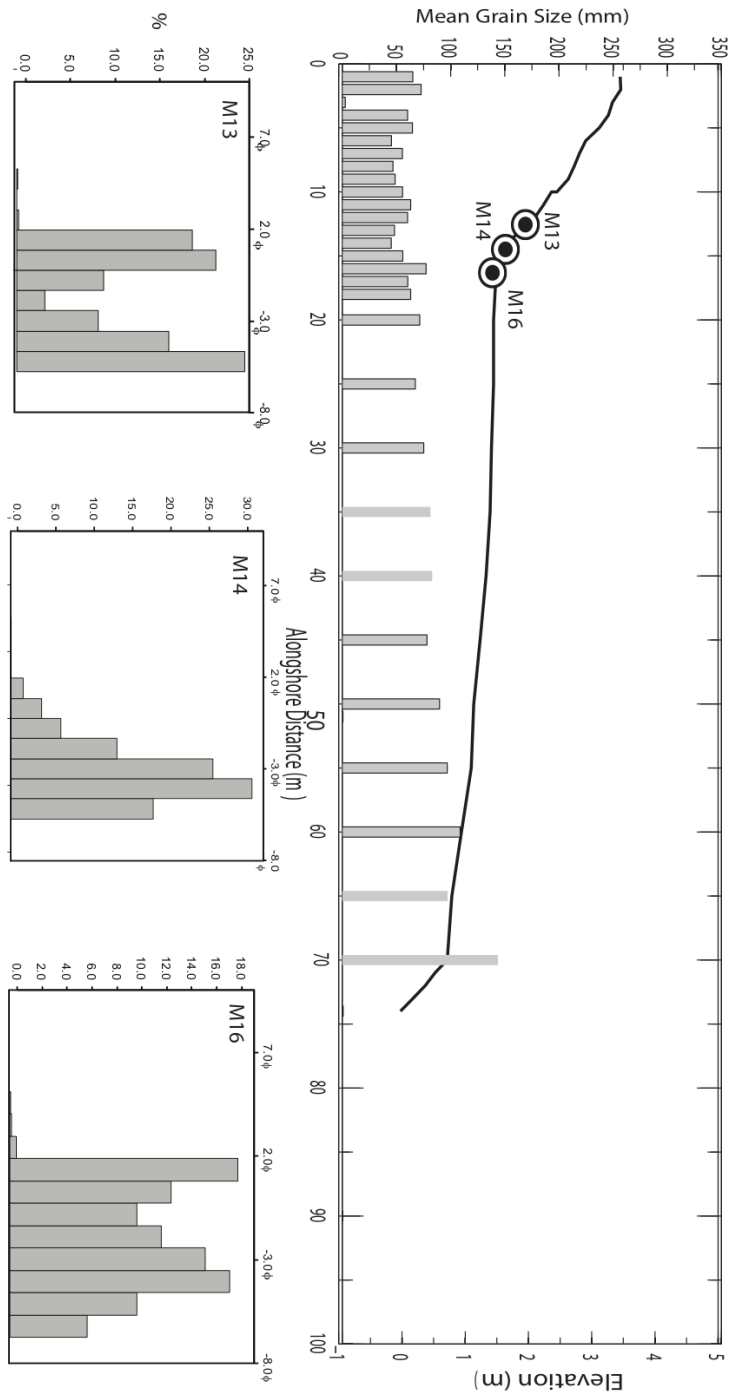
Mean grain-size estimates for the beach transects were calculated using grain-size images with Cobblecam. Lines 174, 190, and 198 had some spatial variability and profiles changed to a minor extent daily. Overall, results show a coarsening of grain-sizes descending from the berm to MLLW (Fig 4.5, 4.6, 4.7). Average grain-size along the foreshore ranged from 25 to 125 mm. Along the low-tide terrace, average grain-size coarsened from 75 to 300 mm across the shoreline. Physical samples on the beach only represent smaller grains because larger cobbles were excluded from the samples. Line 174 had higher sand composition and the only mud found of the three transects, which was found at meter 80 (Fig. 4.5). Line 190 had the coarsest samples with the highest percent of gravel (Fig 4.6). Line 198 showed a similar, less dramatic trend of the grain-sizes analyzed on Line 174, with substrate coarsening along the transect, extending from



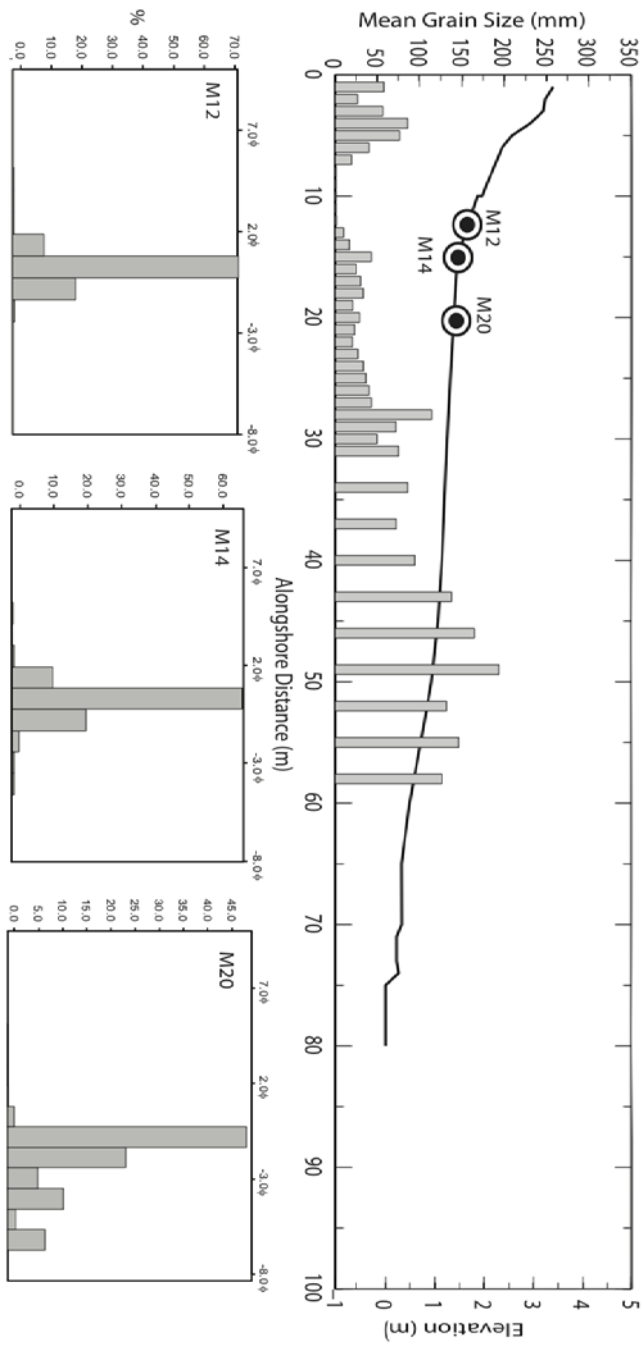
**Figure 4.4.** Grain-size distributions (gravel, sand and mud percentages) along offshore transects.



**Figure 4.5.** Line 174 beach profile and mean grain-size along the cross-shore transect. Physical samples are depicted by dots with histograms showing phi size and percent weight class



**Figure 4.6.** Line 190 beach profile and mean grain-size along the cross-shore transect. Physical samples are depicted by dots with histograms showing phi size and percent weight class.



**Figure 4.7.** Line 198 beach profile and mean grain-size along the cross shore transect. Physical samples are depicted by dots with histograms showing phi size and percent weight class.

10 m seaward (Fig. 4.7). Since only sporadic samples were taken on the beach at varying locations, they do not represent the overall transect compositions, but rather complement the digital grain-size analysis for finer grained samples.

### *4.3 Video Images*

Twelve still shots were taken at offshore study sites to depict seafloor composition and five of these fell on the transect lines (Fig. 4.1). Sand, gravel, and mixed composition were distinguished in the frames. Cobbles were observed in the video footage where Shipek grab samples were scant. In conjunction with the grain-size analysis, the video allowed us to show that coarser samples were found more numerous east of the delta and sandier samples were collected to the west.

## **5. Discussion**

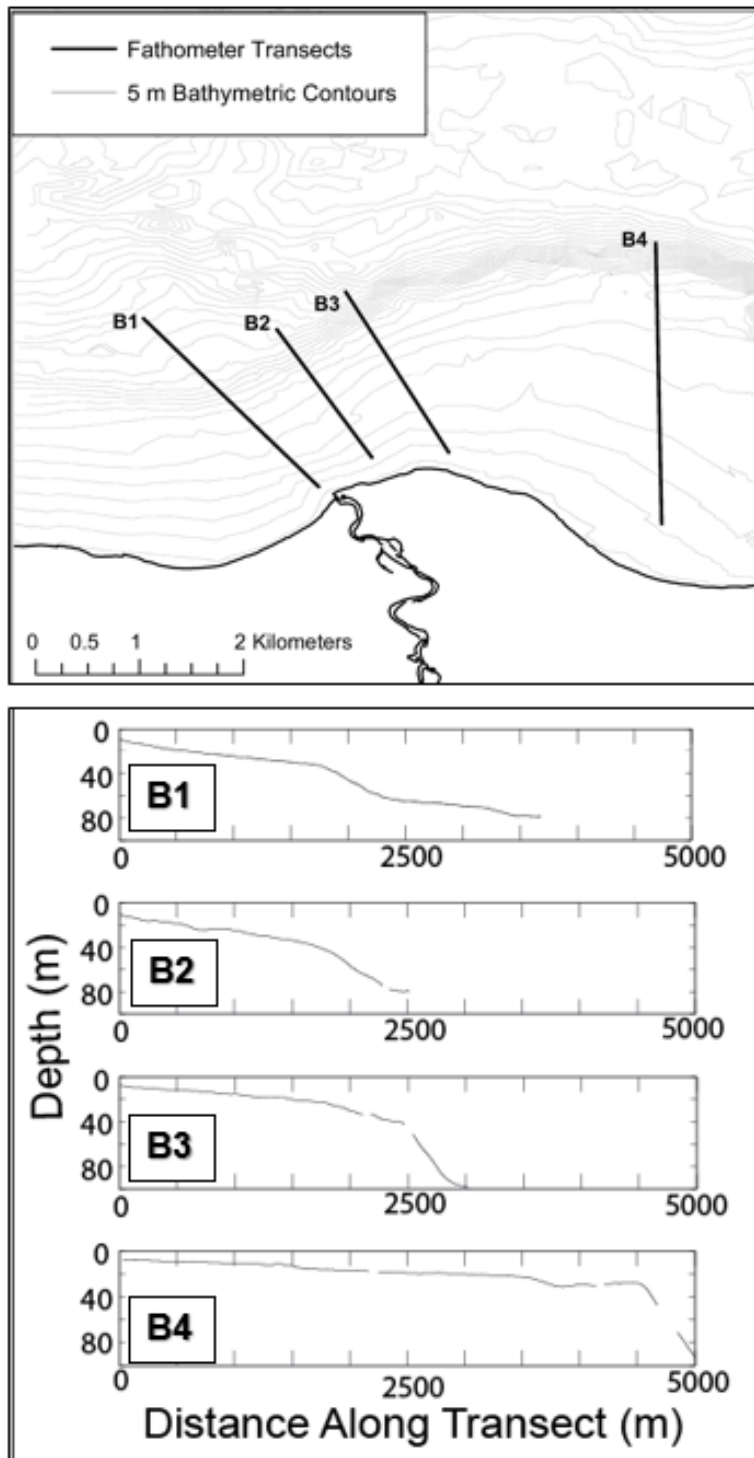
### *5.1 Elwha Delta Formation*

Sediment deposition patterns on the submarine delta provide insight to how the delta formed. Just offshore of the subaerial Elwha Delta, three drowned spits lie to the east, as a result of the sea-level history over the last ~10,000 years. These spits are thought to have formed during marine transgression, not regression, because they do not appear to have endured any long exposure on land (Mosher et al., 2004). The former spits occur at -6, -8, and -25 m depth in Figure 5.1 (Mosher et al., 2004). The proximity of the ancient spits 3-5 kilometers offshore and their eastward direction provide significant evidence as to where historical Elwha delta shorelines previously existed. This evidence

is supported by the findings of submarine delta topset distances offshore within this paper (Fig. 5.1). The topset extends farther offshore on the east side of the submarine delta, meaning more sediment has accumulated there.

The Fraser glaciation left the Pacific Northwest seafloor with a layer of ice contact, glacial-marine sediment, and post-glacial sediments (Hewitt and Mosher, 2001). Most of the sediment within the Strait is likely reworked post-glacial sediment that has been removed and redistributed from glacial outwash banks (Hewitt et al., 2001). Along the submarine study transects, much of the seabed was sand mixed with coarser gravel and cobbles. This is likely glacial marine sediment described in Hewitt and Mosher (2001). Hewitt and Mosher (2001) specifically found organic-rich sandy mud with shell fragments dating 10,000-13,000 years old, north of the Elwha River. Mixed substrate composition found in this study are in accord with the historical sediments. The organic rich detritus most likely was delivered to the seafloor from the Elwha River. Overall, sediment supply to the Strait of Juan de Fuca has been limited since the start of the Anthropocene and the damming of the Elwha River. At present a lag layer of glacial sediment is observed, but there is potential for riverine basin sediment to drape over in the upcoming future, even though this is not yet seen.

The formation of the Elwha River Delta provides an excellent case study of how sea-level rise will affect the local region and other similar regions globally. While sea level rise is predicted to affect geographic regions differently, it is estimated to rise between 0.8 to 2 m by 2100 (Zecca et al., 2012; Pfeffer et al., 2008). As eustatic sea level

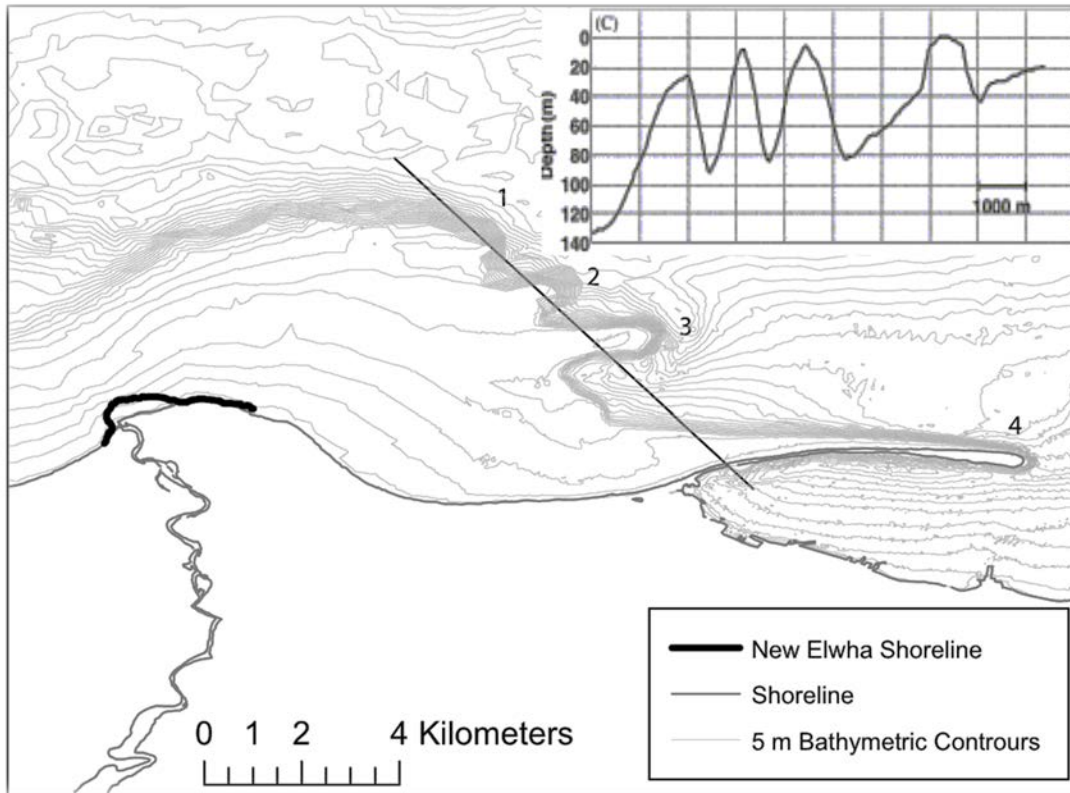


**Figure 5.1.** Spatial overview of the subaqueous transects (top). Depth profiles for all four transects with depth and distance along transect in meters (bottom).

continues to rise we may see the pattern of submerged spits continue as the subaerial delta marches landward and eventually is consumed by water once again on the Elwha flood plain.

## *5.2 Currents and circulation in the Strait of Juan de Fuca*

Ediz Hook and the three abandoned spits east of the delta are evidence of the littoral transport driven by alongshore currents along the southern coast of the Strait of Juan de Fuca. Comparing the delta transect profiles, it is apparent that more sediment has accumulated on the eastern side of the delta, a result of the wave-generated transport cell (Fig. 5.2). Even though sediment is predominantly transported to the east along the shoreline, farther offshore, currents can be driven by tides and winds, sometimes in opposite directions of sediment along the beach. In the main channel of the Strait, extending west of the Victoria-Green point sill, a slender layer of surficial glacial marine sediment suggests strong and deep bottom currents that thinned surface material during deglaciation (Hewitt and Mosher, 2001). In the near future, the increased sediment supplied to the delta, post dam removal, will most likely continue to be transported predominantly to the east in the surf zone current. However, as sea level continues to rise and the surf zone is moved landward, we may see the historical Elwha delta sediments



**Figure 5.2.** 5 m contour bathymetry map of the Elwha Delta. Depth profile shown of the historical spits, 1 corresponds to the deepest offshore spit (farthest left). Modified from Mosher et al., 2004 and Andy Ritchie, National Park Service, 2013.

reworked by deeper currents and redistributed. Eventually, all sediment could be removed from the subaqueous spit formation and begin to resemble the seafloor Hewitt and Mosher found in the main channel of the Strait (Hewitt and Mosher, 2001).

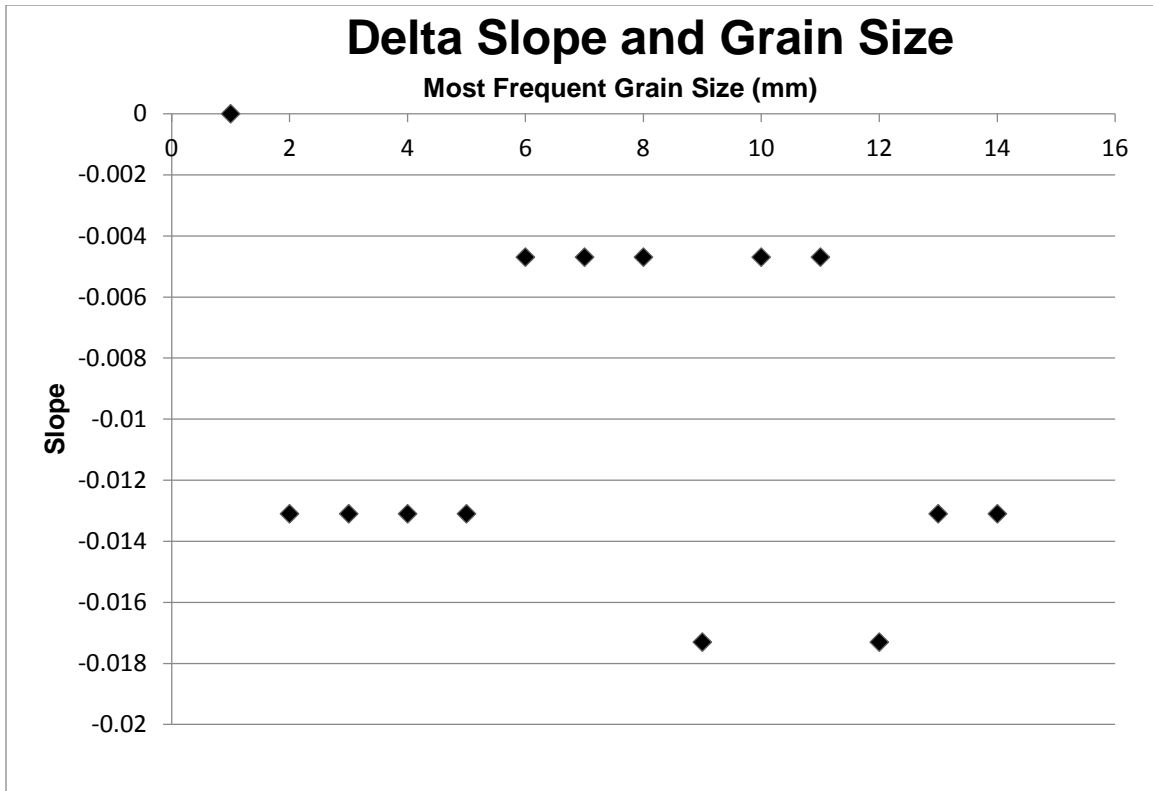
### *5.3 Relationships between delta morphology and grain-size*

The relationship between grain-size and beach slopes does not appear to be linear for the Elwha delta. Typically sediment delivered to river deltas fines farther away from the river mouth (Davis, 1978). In the April 2013 cruise, higher percentages of finer grained material were instead observed on the beach, and close to the river mouth, specifically to the west along transect B1. This fine-grain sediment is known to be recently deposited and originated from the Elwha River post-dam removal. In areas where new mud flats were observed along the end of line 174, the beach slope was almost zero. Elsewhere on the beach, the dissipative cobble terrace occupied most of the beach surface area where we would expect to see a steeper slope. When wave energy percolates into gravelly substrate on the beach, backwash is minimal which supports a steeper beach slope (Orton, 1993), but is not observed at the Elwha. Because the Elwha has been starved of sediment for many decades, the cobbles may have been exposed from continuous erosion during that period, while finer sediment was transported away. Since smaller grained sediment is easier to transport, sand may have moved up the beach onto the foreshore in the wave swash where there are steeper slopes.

The offshore transect profiles show foreset slopes that increase towards the east of the river. Finer grained substrate was found more frequently to the west of the river

mouth and larger cobbles and gravel were found to the east, which is opposite of what is expected. Grain-size and delta slope were not found to be correlated in this study (Fig. 5.3). Analysis of the most frequent grain-size found at different samples stations along the submarine transects showed five of the larger grained modes at a slope of -0.0047, which is fairly planar. Four of the finer grained modes were analyzed from the delta where the slope was steeper at -0.013. This does not necessarily mean that the fine-grained sediment is associated with this steeper slope; rather a new accumulation has blanketed coarser sediments since dam removal. While the data from this study is not sufficient evidence to establish a clear relationship between grain-size and delta morphology slopes on the Elwha Delta, it does hint at a future relationship that could be better developed and discovered, especially with the supply of new sediment post-dam removal.

In the future, studies on the evolution of beach morphology and grain-size distribution could be linked to a similar morphology of the submarine delta. If recent finer-grained sediment settles in front of the river mouth, delta topset length is predicted to extend farther offshore and maintain a flat slope. Currently, change is very minimal and fine-grained sediment input from the river has not had a substantial impact on the overall delta morphology.



**Figure 5.3.** Delta slope and grain-size mode in millimeters for the particular grab sample site. There does not appear to be any linear relationship. The Elwha delta is comprised of very mixed substrates.

## **6. Conclusion**

In summary, the Elwha delta morphology is indicative of former sea-level rise due to the Fraser glaciation. Because the three subaqueous spits all resemble Ediz Hook, it appears that sediment has always been deposited and transported to the east in this part of the Strait of Juan de Fuca. While the present subaqueous delta did not reveal any relationship between grain-size and slope, it did show a longer topset to the east, meaning more sediment accumulation there, and supporting the historical evidence of eastward transport. On shore, beach profiles and grain-size analyses revealed an unexpected relationship, where sediment was coarser on flatter beach slopes. However, the beach currently appears to be changing in a predicted manner, as a result of the dam removals over short-time scales. Where sediment is being added, the beach profiles flatten. As the system aims for equilibrium the Elwha delta may experience aggradation. Furthermore, as sea-level rise pushes the shoreline landward, new sediment deposits resulting from the dam removals will be exposed to oceanic processes and erosion may occur once again.

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