

Linking surficial geomorphology with vertical structure in high and low energy marine environments

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Abstract

Puget Sound is a complex system of high energy river inputs to lower energy large basins with direct connection to the open ocean through the Straits of Juan de Fuca. Using a high resolution bathymetric surface derived from multibeam sonar synchronized with low frequency sub-bottom acoustic profiles, the depth of acoustic penetration is correlated with a focal calculation of seafloor roughness. Observable differences in the sub-bottom data indicate an association between higher energy systems, such as the Elwha River, with harder sediments and lower ranges of depth recorded with acoustic profiles, with lower energy systems, such as South Possession Sound, indicating softer sediments and higher ranges of depth. Seafloor roughness at these high and low energy sites are nearly identical, indicating that the surficial layer masks the vertical structure of the seafloor.

Introduction

Puget Sound is a unique and ever-changing estuary located in the State of Washington. Due to the high activity that occurs both on land and in the estuary, seafloor geomorphology is constantly being modified. Some of these larger modifications occurred as a result of oscillating glaciation periods that covered and shaped the sound, as well as parts of Washington State. The most recent retreat of the Cordilleran ice sheet has helped contribute to the geomorphology of the sea floor through the addition of features such as moraines, otherwise known as sills, and scarps.

In addition to having been shaped through glaciation, Puget Sound has also been formed through the active subduction of the Pacific Plate beneath the North American Plate, on which the Sound resides. As an active convergent boundary, deformation is expected through processes such as faulting (Liberty, 2006). Earthquakes are also an anticipated result of subduction and the Pacific Northwest has a history of producing large magnitude earthquakes in addition to the numerous small earthquakes that occur in the region. These earthquakes, depending on magnitude and/or location, may create significant consequences such as, inducing landslides and localized tsunamis within the Sound (Karlin, 2004).

As these large scale processes are important factors for making the Puget Sound what it is today, several smaller processes are currently shaping the Sound. Submarine geomorphology is affected by high and low energy systems. Rivers and other fast moving bodies of water are high energy systems, while areas less directly influenced are low energy systems. Some areas within Puget Sound that would be considered as a high energy system include the Elwha River due to the large fluvial input and the Strait of Juan de Fuca because of the interface between the Pacific Ocean and the rest of Puget Sound. The area where the Elwha River empties into the Strait of Juan de Fuca is a high energy system as a result of those two active systems interacting with one

another. An example of a low energy system is South Possession Sound, as it is located at the end of a relatively wider channel within Puget Sound. South Possession Sound is also protected by Whidbey Island from the tides and currents running from the Strait of Juan de Fuca through Admiralty Inlet.

Multibeam sonar is one way to collect data to create surficial bathymetric maps of these high and low energy study sites. The resulting bathymetric surfaces portray geomorphic features, such as bedforms. Bedforms may be seen at the mouth of the Elwha River due to the large outflow of sandy sediments that were released at a high rate over a short period of time (Gelfenbaum, 2015). The lower energy South Possession site would be expected to have minimal surficial geomorphic features expressed as the influx of material is less over a longer period of time.

A low energy system may not have many surficial features expressed, however more information about the vertical stratigraphy may be gained. Sub-bottom profiles, otherwise known as chirp data, is a single beam sonar that records the vertical stratigraphy of the seafloor at 3.5 kHz. These different stratigraphic units are determined when the acoustic impedance changes, indicating a unit boundary. The depth of penetration would be greater in a low energy system than a high energy system because of softer sediments, such as mud or silt, having a lower acoustic impedance and being predominantly deposited within a low energy system. Hard sediments, such as sand or glacial till, would have a higher acoustic impedance and be predominantly deposited within high energy systems.

Some studies using multibeam sonar and sub-bottom profiles were completed as case studies for understanding submarine geomorphological features in areas of predominately high latitude in complex systems. Many of these studies focus primarily on areas that have undergone

or are currently undergoing glaciation cycles (Hodson, 2014; O'Brien, 2015; Cauchon-Voyer, 2008). Multibeam derived bathymetric surfaces are used because they provide the ability to map larger areas in a shorter amount of time, therefore increasing our ability to investigate the seafloor. However, the link between the surface expression and the vertical stratigraphy are not uniform over all of space, especially where high and low energy systems are present.

Determining a link between the derived surfaces and vertical structure of two opposing environments may allow for multibeam data to provide insights previously unknown of the seafloor sub-surface.

Methods

Data Acquisition

Multibeam sonar soundings and 3.5 kHz sub-bottom chirp profile were collected during a seafloor mapping cruise aboard the R/V Thomas G. Thompson using synchronized multibeam sonar (Simrad, EM302, Kongsberg SIS) and Knudsen 3260 “chirp” sub-bottom profiler from November 13-15, 2015 (cruise number TN333). The surveyed study areas included South Possession Sound, Admiralty Inlet, and the area near the Elwha River in the Strait of Juan de Fuca, Puget Sound, Washington, USA (Figure 1). The two main study sites to be used in this investigation contained three parallel transect lines of comparable length, the first being from a high energy coastal zone, Elwha River, and the other as a low energy inland water setting, South Possession.

The multibeam sonar soundings and 3.5 kHz sub-bottom chirp profiles were collected in order to create bathymetric surfaces and surveys of the stratigraphy of the seafloor. To attain

sound velocity profiles for corrections in post-processing, CTD casts were collected at the beginning of a new survey and alternate with XBT casts, as needed during the survey. Survey lines for both the chirp and multibeam sonar data were recorded in single straight lines, with turn data incremented as separate survey lines.

Post-Processing and Analysis

Data from the multibeam sonar was post-processed in Caris HIPS and SIPS 9.0. Base surfaces were created using the Combined Uncertainty and Bathymetric Estimator (CUBE) algorithm at 10 meter resolution. These surfaces were used to identify surficial expression of geomorphic features correlating to high or low energy systems. 10 meter resolution CUBE base surfaces were created for each line, as the only area that would be compared in further analysis was along the track line in the center of the surface. Additionally, a single bathymetric surface containing the lines chosen for analysis was used to create a study area base surface (Figure 2 & 3). The bathymetric surfaces of individual lines was then exported to ESRI ArcGIS (ver. 10.1) as bathymetric attributed grid (bag) files.

The post-processing software SonarWiz was used to clip and remove survey turn data from the chirp data. A Matlab script was used to realign depth offsets created during acquisition. Knudsen Post Survey software was used to view and differentiate between various stratigraphic layers, determine the range of penetration, and the type of seafloor based on impedance (Figures 5, 7, 9, 11, 13, 15). Range of impedance is determined by calculating the approximate distance between the first hard return (occurring at the seafloor surface) and the last hard return (occurring at depth, if at all). In addition, the clipped lines were imported as shapefiles to ArcGIS. In ArcGIS, elevation profiles were created along the transect lines (Figure 4, 6, 8, 10, 12, 14) and spatial focal functions were used to determine seafloor roughness. Seafloor

roughness is a spatial metric, which represents the ratio between the two dimensional planar area and the three dimensional surface area over a common spatial extent. In this study, the value of roughness is calculated over a 30 meter square extent and assigned to the focal 10 meter core.

Results

The transect lines from the Elwha River study area (Table 1) contained larger ranges of seafloor roughness than the South Possession Sound study area (Table 2). The Elwha River also contained higher averages, but lower standard deviations in seafloor roughness. South Possession Sound had the largest minimum, while the Elwha River site had the largest maximum values for seafloor roughness. The range of impedance observed at the Elwha River site (Table 3) was 90-95% present within the 0 meter range for each line analyzed. In contrast at the South Possession Sound site (Table 4), the range of impedance varied across all depths recorded, with the largest observed occurring at depths of 6-10 meters.

Discussion

Initial analysis of the chirp data displayed evidence that the transect lines at the Elwha River site contained harder sediments, which is determined from the contrast of the dark first return, that is the seafloor, and the lack of further sub-bottom reflectors being displayed. One interference of this dark seafloor reflector occurs from the exposure of bedform features that is present in all lines at the Elwha River site. To determine how deep the chirp data was extending within each transect line, a visual percentage of depth ranges per line was recorded. In the instances where chirp data displayed more than the seafloor surface reflector, depth ranges of

five meter intervals was used to record percentages of the approximated line that contained chirp data that extended to that depths within each interval. As there were no instances of chirp data extending to a depth greater than 20 meters at either study area, the last interval is 15-20 meters. In comparison to the Elwha River site, South Possession Sound had chirp data that extended to a variety of depths. South Possession Sound Line 2 (Figure 5) is an example of how the range in varied from 0 to 20 meters throughout the line (Table 4). The lengths of 0 meter depth recordings occur at a small alluvial fan, as indicated by the shape, hard sediment contrast, and the presence of only the surface reflector. This alluvial fan is a noticeable contrast to the surrounding segments along the line where the depth reaches up to 20 meters. Directly comparing the contrast of the surface returns in the South Possession Sound and Elwha River transect lines, it was determined that the Elwha River site had harder sediments than at South Possession Sound.

The chirp data shared similar cross sections as those created from the multibeam bathymetric surfaces created in Caris, however more defined changes were not observable in the chirp cross sections. General trends were shared between the two data sources, however features such as the bedforms observed at the Elwha River site, were not recorded in their entirety within the chirp data. As such, the cross sections from the multibeam bathymetric surfaces were relied on for determining seafloor roughness. The cross sections of elevation indicate that transect lines at the Elwha River site cover a rougher surface, as seen through the larger ranged elevation changes along the line. The exposure of the hard surface, rough bedform features from the higher energy Elwha River site allow for these larger elevation ranges to occur within a relatively short distance interval along the transect line. In contrast the South Possession Sound site contained no evidence for features, such as the bedforms observed at the Elwha River site.

Smaller ranged elevation changes are observable in sections of the South Possession Sound cross sections. These small scale changes are most likely noise as a result of bad pings from the multibeam system, which would most likely disappear through more vigorous cleaning of the multibeam data.

Focal statistics of these cross sections helped quantify seafloor roughness at each study site. The analysis was confined to a 30 meter extent assigned to a 10 meter resolution, which prevented the large bedform features from being detected at the smaller extent. So while the highest observed maximum occurs at the Elwha River site due to the bedform features, the results at this extent did not properly represent the observed geomorphic features. At South Possession Sound, the standard deviation of the data is higher due to the sections of noise that occur along each line.

Conclusion

The survey lines of the high energy environment of the Elwha study area exhibit higher ranges of roughness when compared to the low energy environment of the South Possession Sound. While the results of the seafloor roughness calculated may not be statistically significant for defining a solid difference between the two sites, the observed range of depths indicates the harder sediments at the Elwha River site contain a higher impedance than those observed at South Possession Sound. This study suggests that surficial morphology masks vertical structure of both high and low energy systems, illustrating the need for synchronized surveys of both multibeam and sub-bottom sonars in order to receive a more complete picture of what the seafloor contains.

References

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Tables

Line	Min	Max	Mean	Std Dev	Range
2	-4.35	7.95	-0.02	0.50	12.30
3	-5.03	4.36	-0.02	0.38	9.39
7	-4.37	3.84	-0.01	0.49	8.21

Table 1. Statistics for seafloor roughness along each survey line in Elwha study area. All values are in meters.

Line	Min	Max	Mean	Std Dev	Range
2	-3.22	4.88	-0.10	0.55	8.10
4	-7.38	4.87	-0.10	0.78	12.25
6	-3.79	3.90	0.06	0.95	7.66

Table 2. Statistics for seafloor roughness along each survey line in South Possession Sound. All values are in meters.

Line	0m	1-5m	6-10m	11-15m	16-20m
2	90%	0%	10%	0%	0%
3	95%	5%	0%	0%	0%
7	95%	0%	0%	0%	5%

Table 3. Range of impedance observed between surface and last return in meter ranges at the Elwha study area.

Line	0m	1-5m	6-10m	11-15m	16-20m
2	17%	33%	17%	0%	33%
4	33%	33%	33%	0%	0%
6	0%	0%	50%	25%	0%

Table 4. Range of impedance observed between surface and last return in meter ranges at the South Possession Sound study area.

Figures

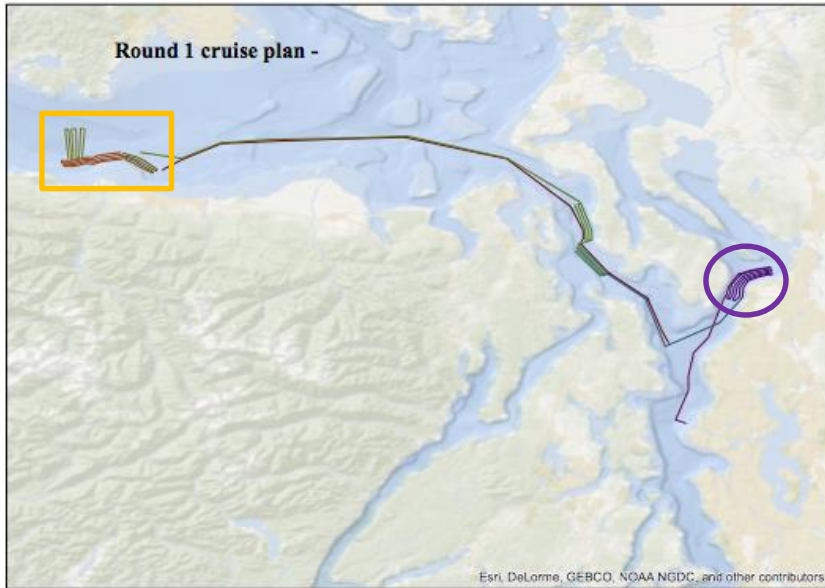


Figure 1. Study sites completed on 2015 Seamap Hydrographic Survey Cruise. South Possession is highlighted with a purple circle and the Elwha site is highlighted with an orange rectangle.

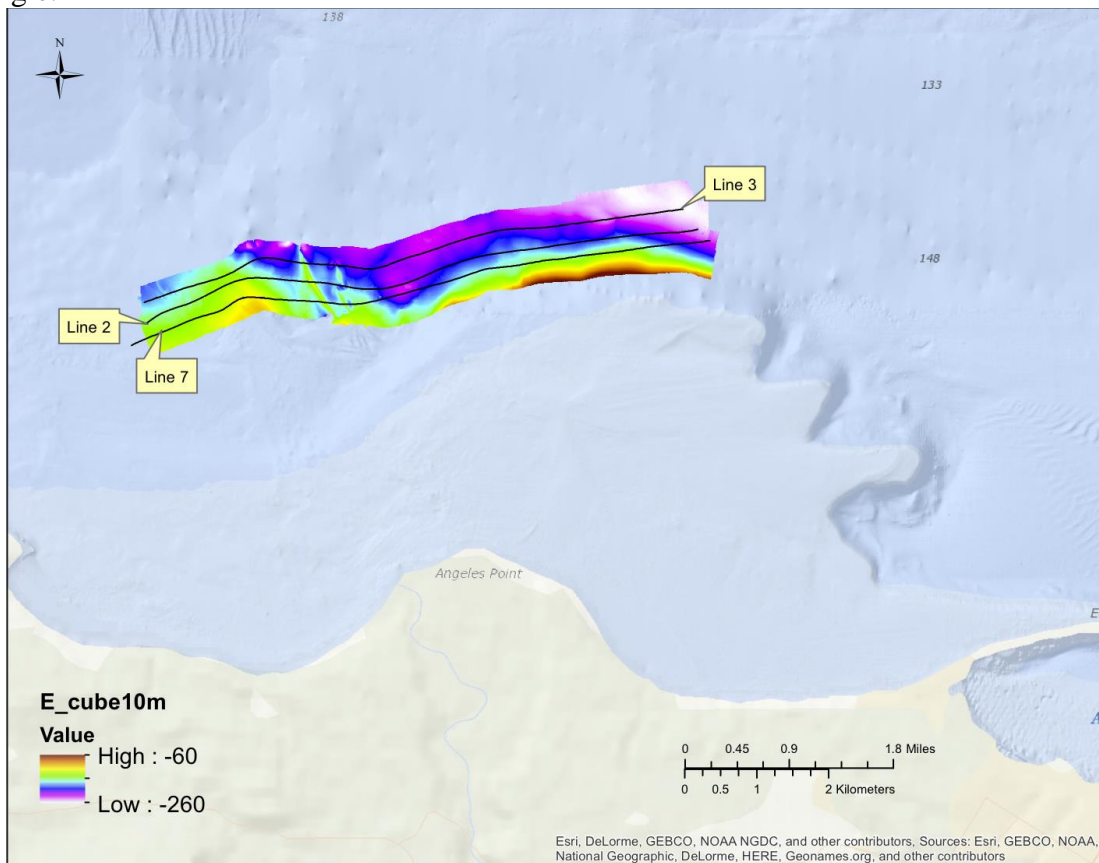


Figure 2. Elwha River study site with the three lines used for analysis.

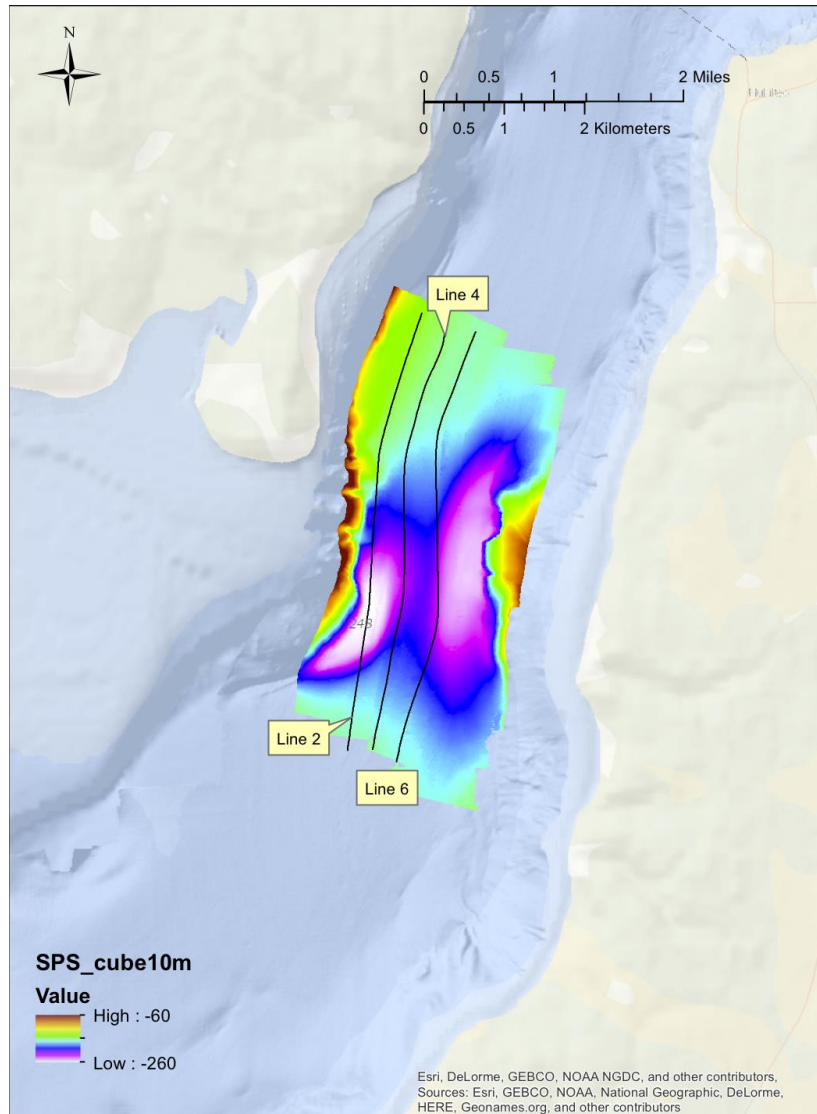


Figure 3. South Possession Sound study site with the three lines used for analysis.

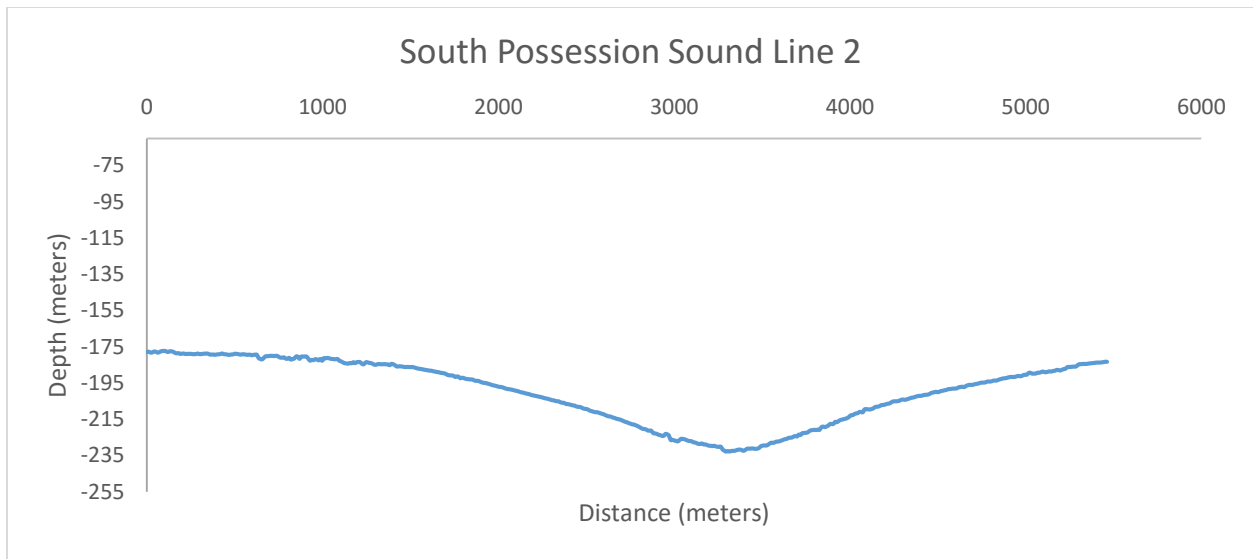


Figure 4. Elevation profile, in meters, of Line 2 from the multibeam bathymetric surface created in CARIS, at the South Possession Sound study area.

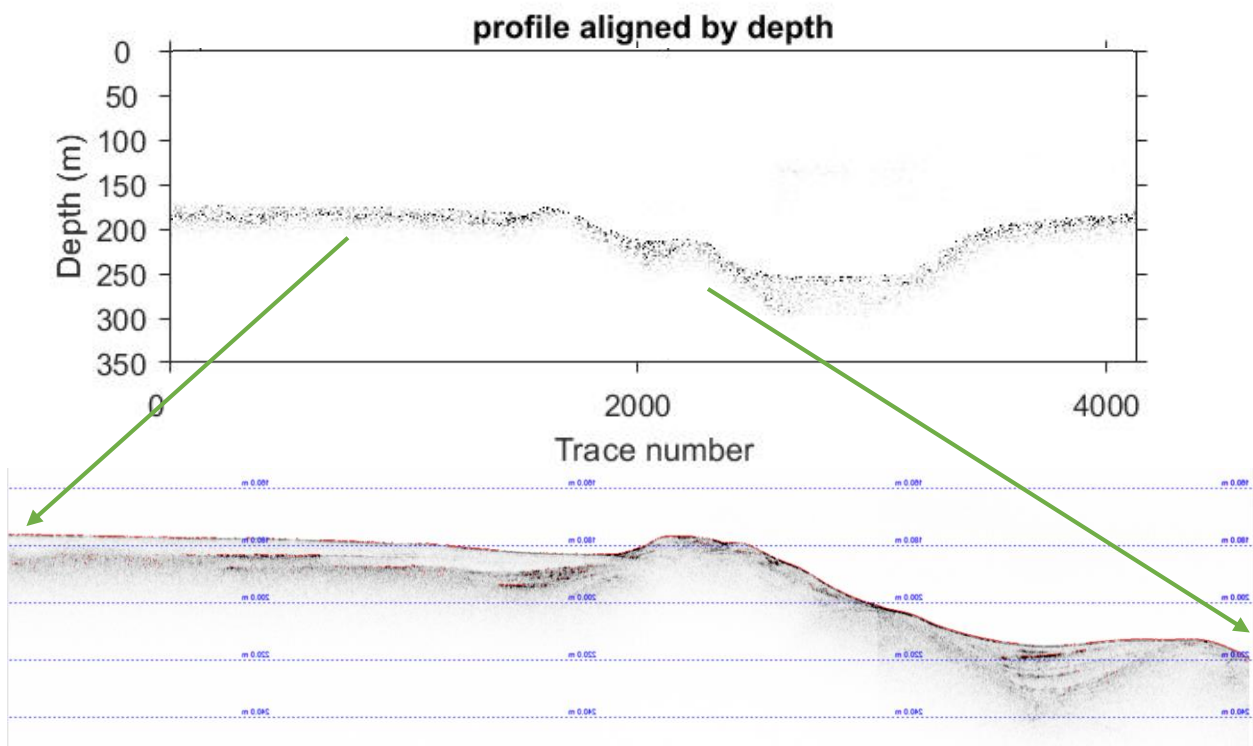


Figure 5. Elevation profile, in meters, of Line 2 at the South Possession Sound study area, created in Matlab to realign depth offsets within the chirp data. The callout below the full profile, is a section of the chirp line displayed in Knudsen Post-Survey to better display the vertical structure.

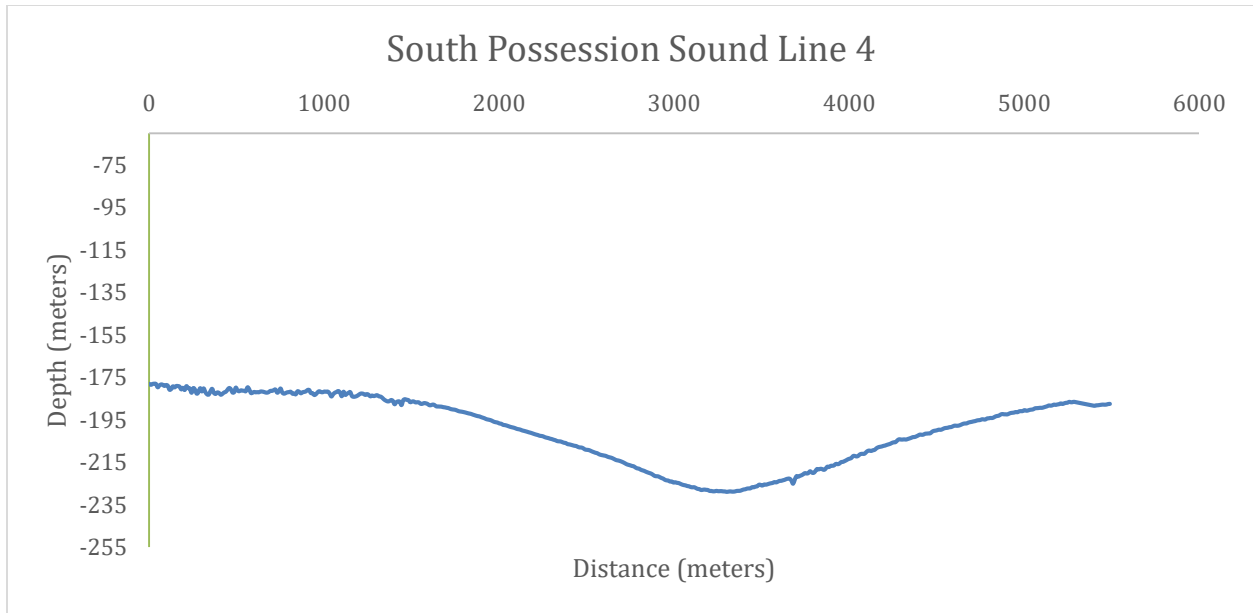


Figure 6. Elevation profile, in meters, of Line 4 from the multibeam bathymetric surface created in CARIS, at the South Possession Sound study area.

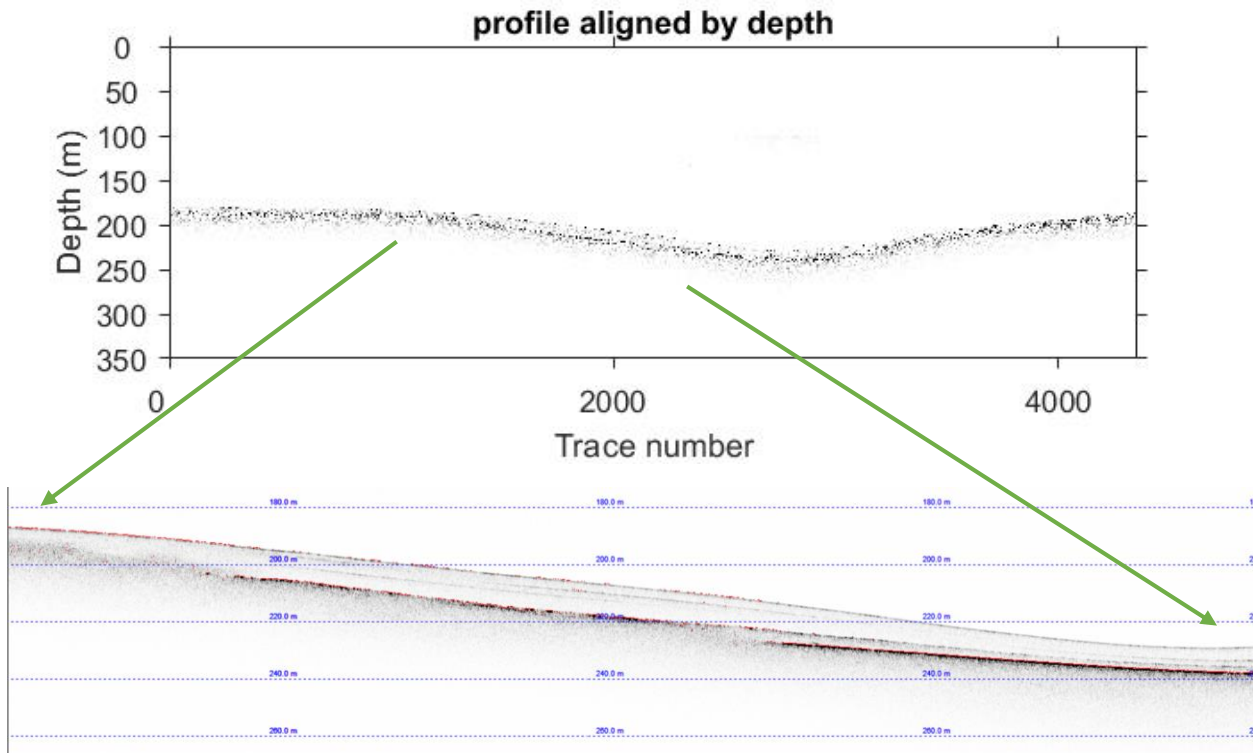


Figure 7. Elevation profile, in meters, of Line 4 at the South Possession Sound study area, created in Matlab to realign depth offsets within the chirp data. The callout below the full profile, is a section of the chirp line displayed in Knudsen Post-Survey to better display the vertical structure.

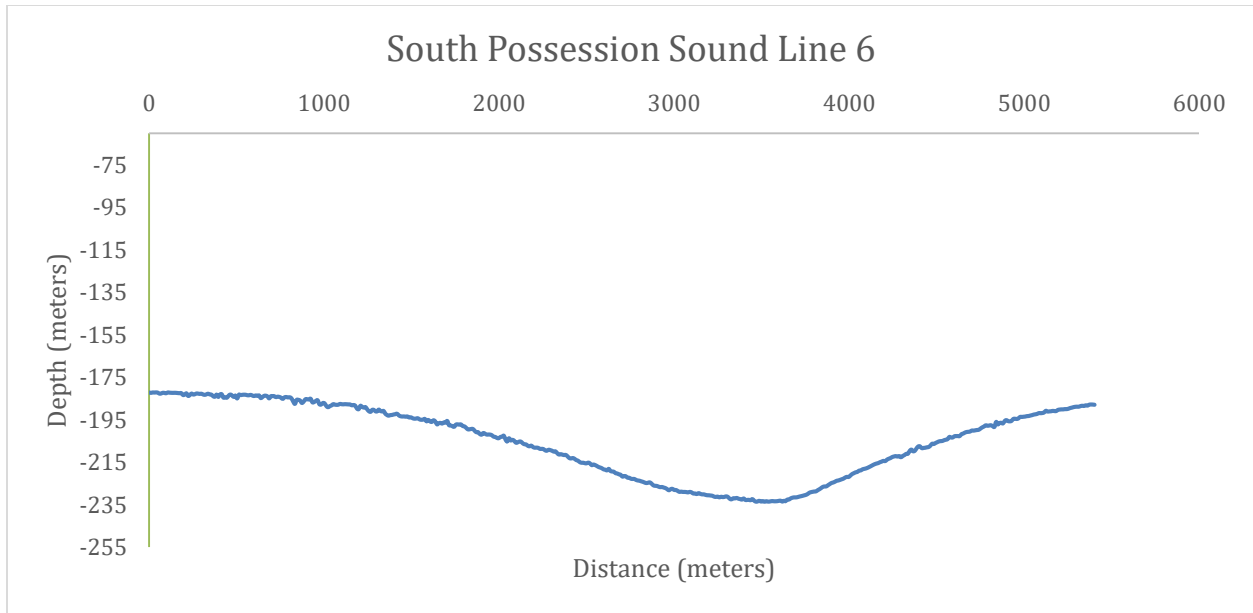


Figure 8. Elevation profile, in meters, of Line 6 from the multibeam bathymetric surface created in CARIS, at the South Possession Sound study area.

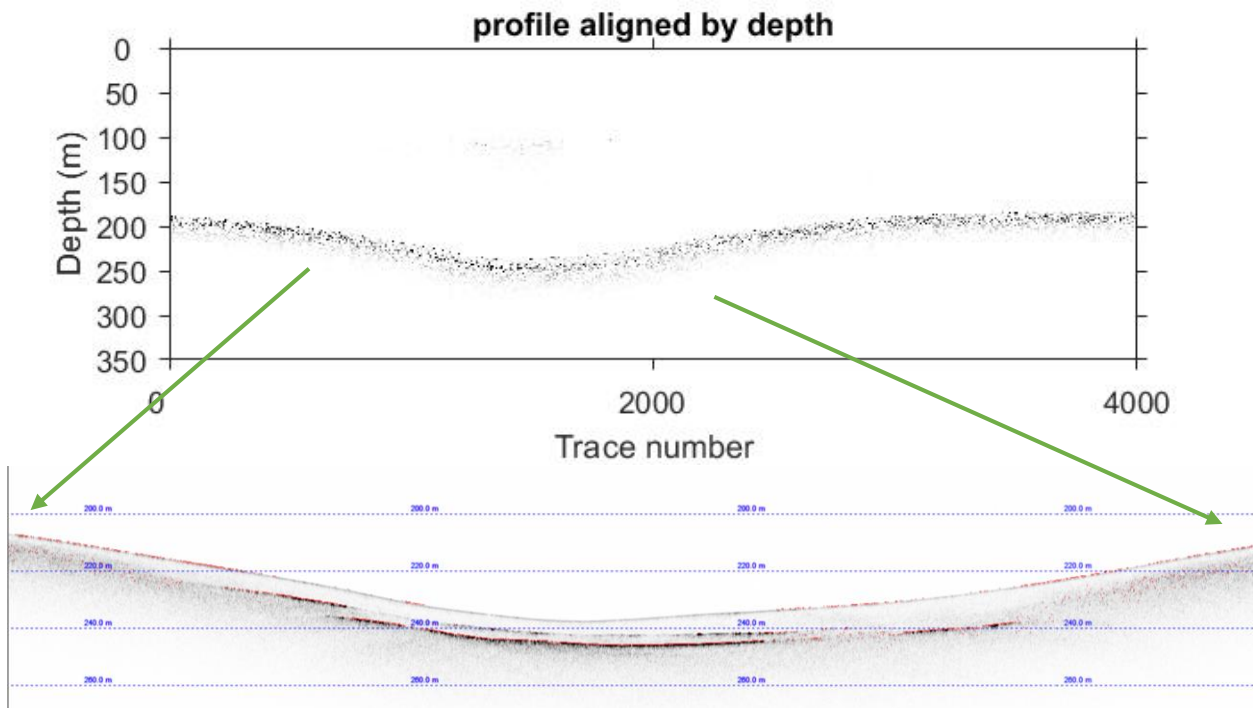


Figure 9. Elevation profile, in meters, of Line 6 at the South Possession Sound study area, created in Matlab to realign depth offsets within the chirp data. The callout below the full profile, is a section of the chirp line displayed in Knudsen Post-Survey to better display the vertical structure.

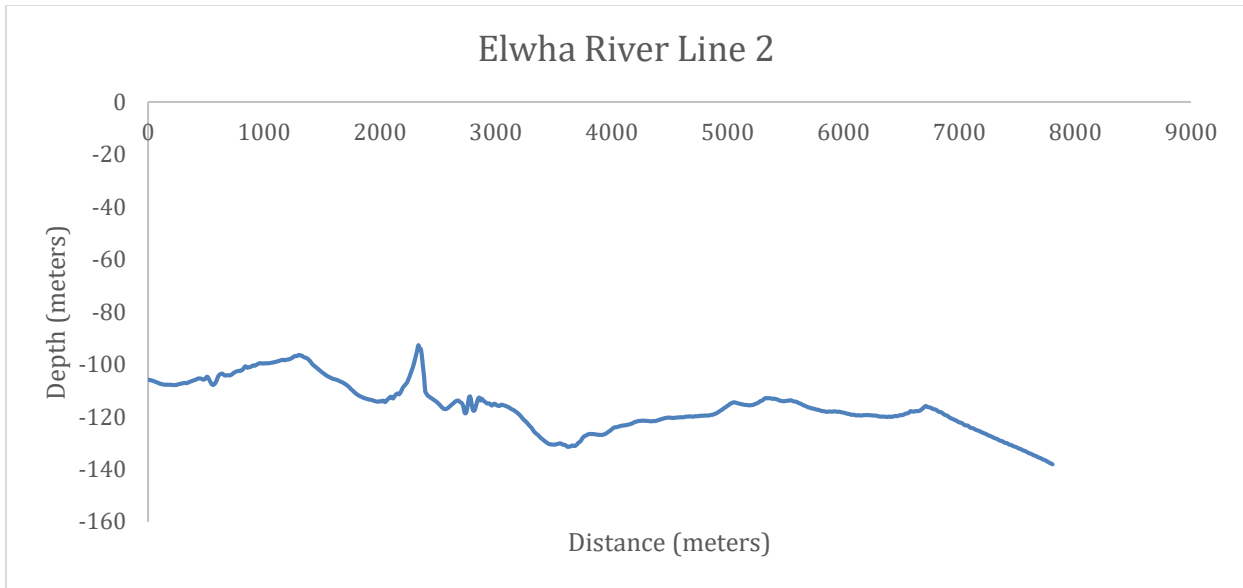


Figure 10. Elevation profile, in meters, of Line 2 from the multibeam bathymetric surface created in CARIS, at the Elwha River study area.

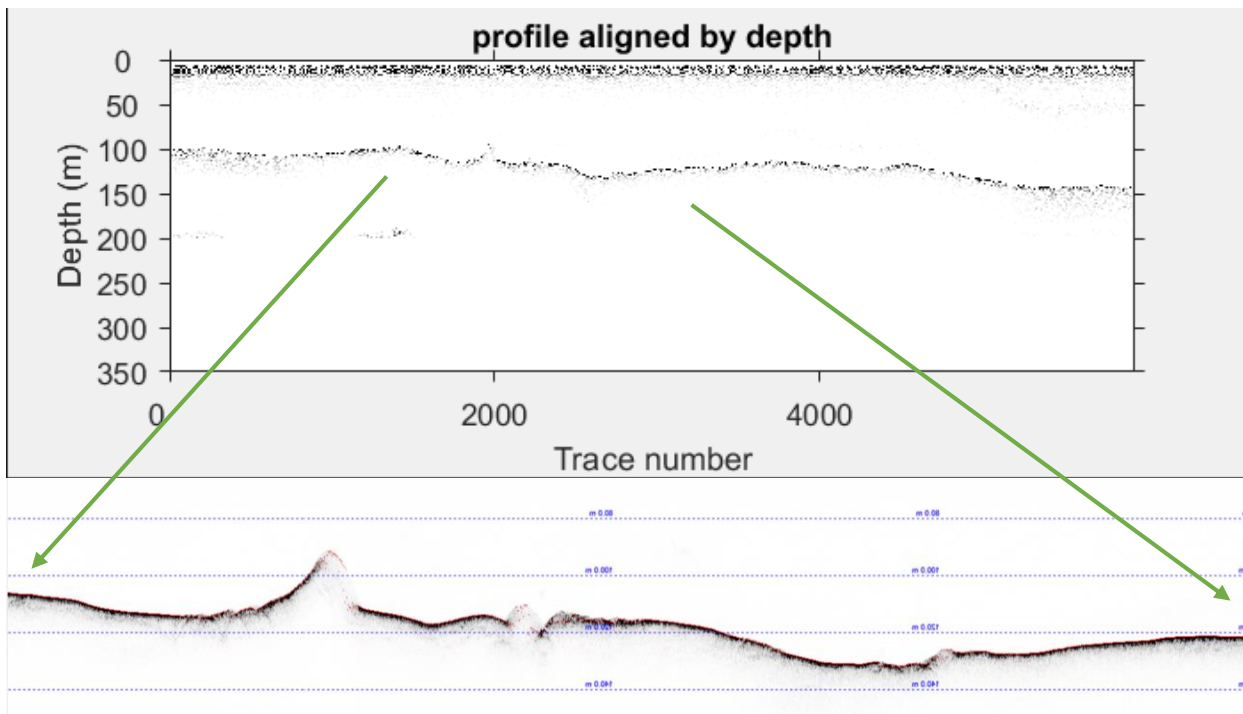


Figure 11. Elevation profile, in meters, of Line 2 at the Elwha River study area, created in Matlab to realign depth offsets within the chirp data. The callout below the full profile, is a section of the chirp line displayed in Knudsen Post-Survey to better display the vertical structure.

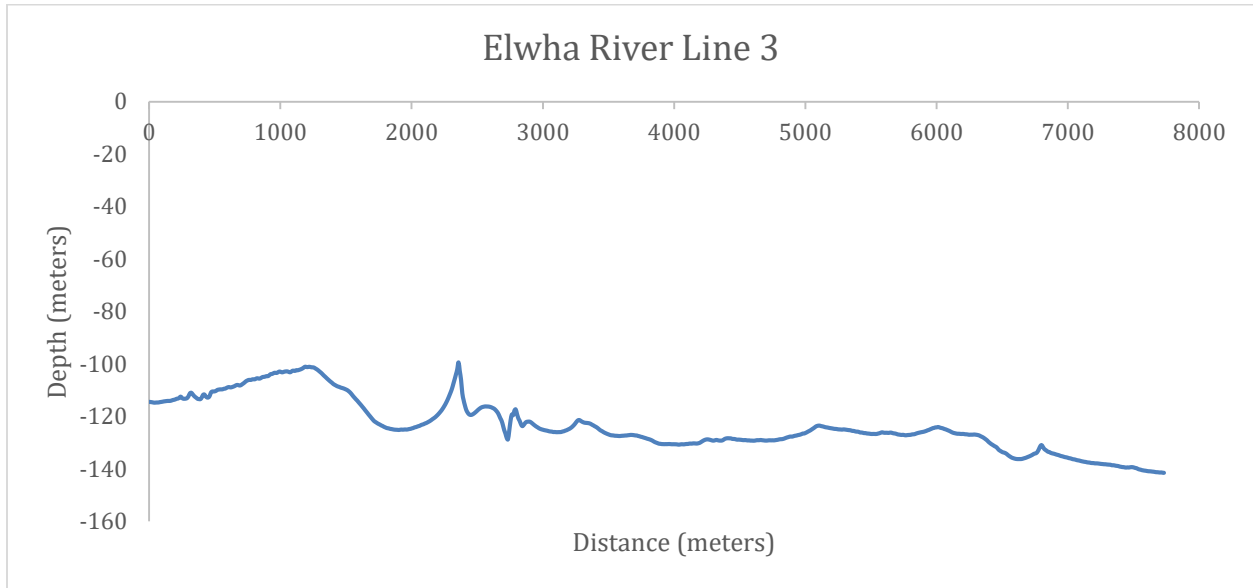


Figure 12. Elevation profile, in meters, of Line 3 from the multibeam bathymetric surface created in CARIS, at the Elwha River study area.

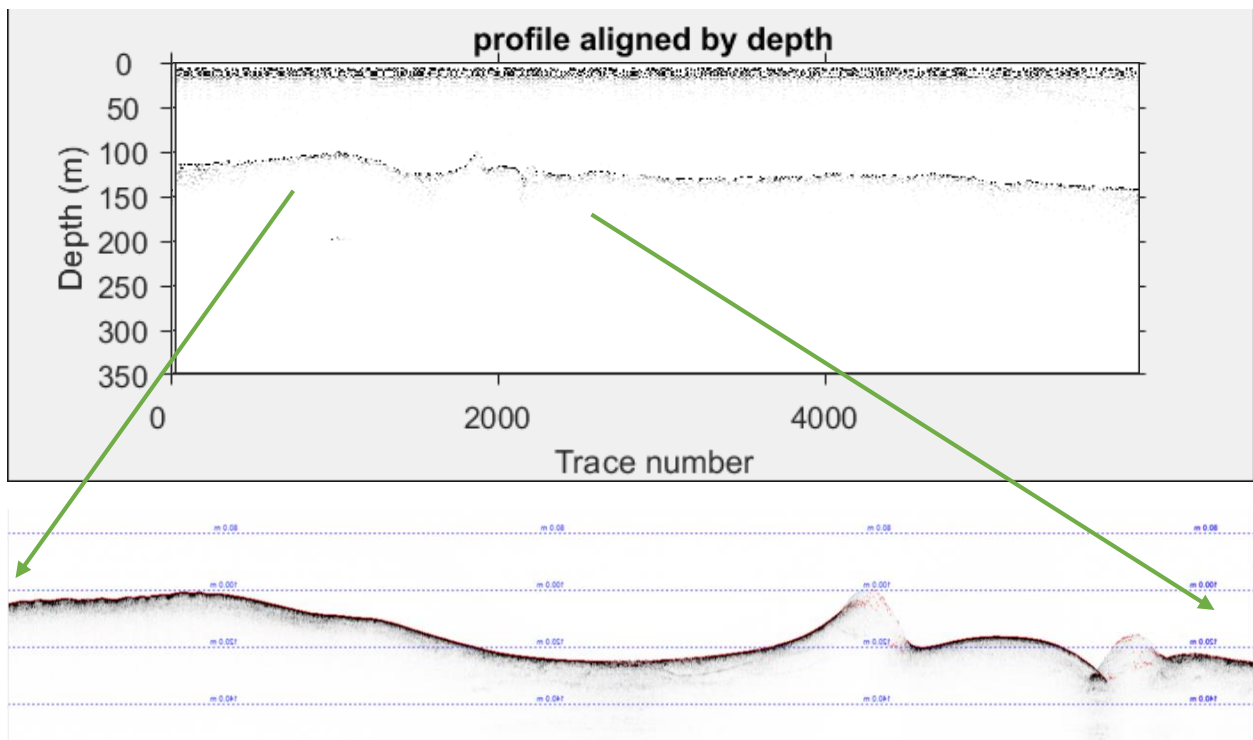


Figure 13. Elevation profile, in meters, of Line 3 at the Elwha River study area, created in Matlab to realign depth offsets within the chirp data. The callout below the full profile, is a section of the chirp line displayed in Knudsen Post-Survey to better display the vertical structure.

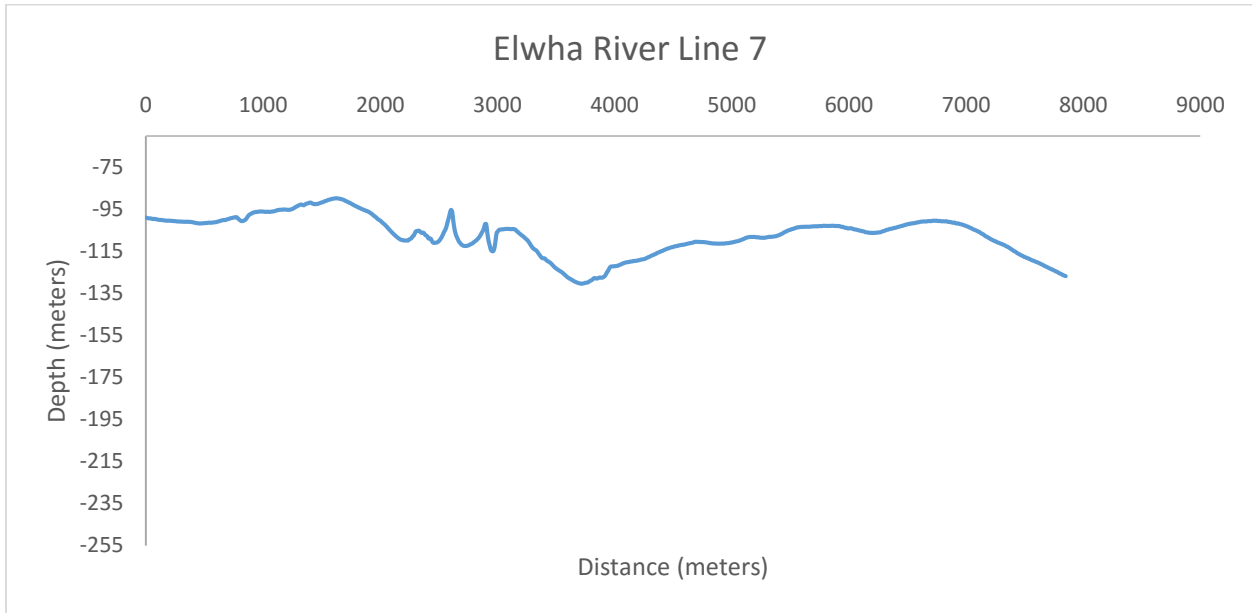


Figure 14. Elevation profile, in meters, of Line 7 from the multibeam bathymetric surface created in CARIS, at the Elwha River study area.

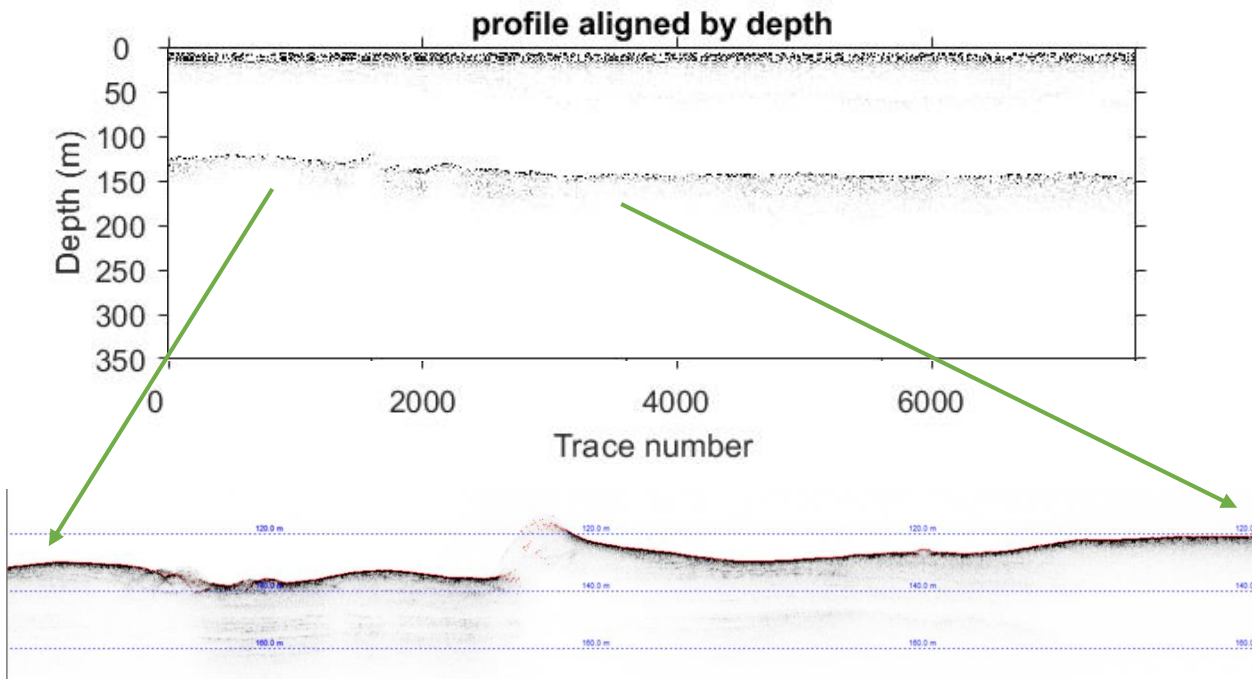


Figure 15. Elevation profile, in meters, of Line 7 at the Elwha River study area, created in Matlab to realign depth offsets within the chirp data. The callout below the full profile, is a section of the chirp line displayed in Knudsen Post-Survey to better display the vertical structure.