

**Characterizations of landslides in the Puget  
Sound and Lake Washington**

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**Abstract**

Lake Washington and the Puget Sound are home to many conditions that allow for the generation of landslides. In this paper, I used high-resolution multibeam, seismic reflection, and chirp data to characterize three landslides: one in Juanita Bay, one near Denny Park, and one south of the Mukilteo Ferry landing. I determined that the two types of landslides, those that originated as a failure of a river delta and those that began with a more general hillslope failure both originated subaqueously. The main difference between the two varieties of slide was the runout of the slide, the distance between the headwall and the eventual location of the failed material. The landslide examined that originated as a result of a delta failure, the Juanita Bay slide, had a runout over twice as long, 1.2 km, as the average runout of the landslides generated by hillslope failure, 500m. If this trend holds true, runout could become a way to determine the original conditions of landslide generation.

## **Introduction**

Landslides are a dominant process in the transport of sediments; in the marine environment, they play a part in the transport of sediments from shallow or even subaerial regions to the deep, (Jaeger et al, 1998). They are also hugely destructive events. By themselves, they can damage local infrastructure or take lives (Zhang S. and Zhang L., 2014), but they can also serve as a catalyst for other destructive events. With sufficient power, submarine landslides can trigger tsunamis, which represent a major hazard in coastal regions (Bornhold et al, 2010; Dufrense et al, 2017).

Landslides can also be triggered by seismic activity, (Lee et al, 2006; Migeon et al, 2011; Karlin et al, 2002). Slope failure is more likely to occur when disturbed by an earthquake; so studying past landslides through subbottom sediment records can be a way to track past earthquakes (Gardner et al, 2001).

In the Puget Sound region, while earthquakes can trigger landslides, (Karlin et al, 2002) more commonly they are the result of triggers such as storms or increased rainfall, (Gonzalez et al, 2002). The required condition shared by all of these triggers is a buildup of sediment, usually from a creek or river, which builds up the incident wall until it becomes unstable, (Twichell et al, 2009). In the Puget Sound, Gonzalez (2002), conducted a comprehensive study of known and predicted landslide locations. Not all of the predicted landslides have been studied in detail. In particular, two Lake Washington slides with different incidences, near Denny Park and Juanita Bay, and an area near Mukilteo were identified as being at a high likelihood for unstudied landslides.

I then looked at the size and space characteristics of the three landslides in Lake Washington and the Puget Sound with the goal of determining the originating source of

the slide. I looked at the volume, runout, and predicted incidence of each slides. By examining these three distinguishing characteristics between slides, I hope to identify commonalities that may predict landslide origins in this environment in the future, and help predict future slides.

## **Methods**

Bathymetric mapping of the Lake Washington landslide areas was conducted by the R/V *Barnes* on January 18th 2018. Seismic and chirp mapping of this area was collected on February 27th 2017. The R/V *Thomas G Thompson* collected multibeam and chirp data for the Mukilteo slide on January 11th 2018. Complimentary multibeam data was obtained from the USGS website, from a survey published February 8th, 2018. This complimentary data covered the region near the Denny Park slide and some parts of the Juanita Bay slide to fill holes in the original data sets.

Multibeam data were processed using a combination of MB-System, and CARIS. Seismic data were processed with Seismic Unix. Chirp and Seismic data were loaded into IHS Kingdom for analysis. Once the data were processed, I calculated volume by estimating the depth of the slide debris from the sub-bottom data, and the horizontal extent of each slide from the bathymetric data. Incidence was determined using the Slope (Spatial Analyst) tool in ArcGIS. Finally, runout was estimated using a combination of the estimated incidence location and the furthest extent of the main body of the slide.

These procedures were followed for both Lake Washington sites, in Juanita Bay, and the slide near Denny Park. No subsurface data, (chirp or seismic reflection), was available for the Mukilteo slide, so volume was instead estimated by digitally modeling the slide using available multibeam data. Incidence and runout of the Mukilteo slide were estimated in the same way as the other slides.

## Results

The Juanita Bay landslide was estimated to have a volume of  $4.8 \times 10^5 \text{ m}^3$ , (Figures 1, 3 and 4). Runout was around 1.2 km, and the landslide originated subaqueously, (Figure 2). The landslide originated from a failure of part of the Juanita Creek's river delta, (Figure 2). The main body of the landslide appears to be a semi-coherent unit, with a semi-circular ring of looser sediment surrounding the primary unit.

The Denny Park landslide was estimated to have a volume of  $2.8 \times 10^6 \text{ m}^3$ , (Figures 5 and 7). The landslide originated subaqueously, with a runout of 400m, (Figure 6). The landslide is divided into two units. The main unit rises to almost 20m above the surrounding seafloor, and is a contiguous block of the local shelf that failed. The second unit only rises an average of 2m above the seafloor, and exists seaward of the primary unit.

The Mukilteo slope failure was estimated to have a volume of  $6.9 \times 10^5 \text{ m}^3$ , (Figure 8). Runout was around 600m, directly down the coastal shelf, (Figure 9). The slide originated on the shelf, and left a distinct impression on the shelf. The resulting depositional slump is a single continuous unit at the base of the shelf.

Alternate volumes for the Juanita Bay and Denny Park slides were calculated using the same methods as was used for the Mukilteo slide, only using the multibeam data. Using that method, the Juanita Bay slide had a volume of  $4.7 \times 10^5 \text{ m}^3$  and the Denny Park slide had a volume of  $2.9 \times 10^6 \text{ m}^3$ .

These results are compiled in Table 1, (Figure 10).

## Discussion

The Juanita Bay and Denny Park landslides serve as examples of landslides that originate from river delta failures and more general slope stability failures respectively. From my observations of these slides, I drew conclusions about the characteristics of slope stability failure and delta failure landslides more generally. I then confirmed my conclusions through observations of the Mukilteo slide.

The Juanita Bay landslide appears to be the result of a delta failure, while the Mukilteo and Denny Park slides are the result of a slope stability failure. My results seem to indicate that the volume of the slump is unrelated to the incidence. My example slope stability slide, the Denny Park slide, had a volume six times greater than the Juanita Bay slide, but the Mukilteo slide was only 40% larger, (Figure 10). The main difference between the two types of slides was in their runouts.

Runout was substantially longer for the delta failure landslide. This is probably a result of the lesser contrast in bathymetry, established from the multibeam bathymetric data. The delta slope, determined from the slope analysis, was gentler than the two direct slope failures, which is illustrated most clearly in Figure 2. The point delivery of sediment in a river delta allows a buildup farther from shore, which results in a single, relatively contained failure zone. This buildup, combined with the gentler slope, gives more room for the failed, accreted material to travel, which resulted in the longer runout observed.

Some of the data studied varied in quality and type. In particular, the lack of seismic or chirp data for the Mukilteo slide meant that the volume of the slide had to be estimated entirely from the *Thompson's* multibeam data. Other studies have used this

method to estimated landslide volume (Karlin et al, 2002); so valid conclusions can still be drawn from it. Additionally, I estimated the volume of the other two slides using the same method, getting a result differing by at most 4% from my original estimates, (Figure 10). Although this data discrepancy is something to keep in mind, I do not believe it substantially impacted the results.

## **Conclusion**

I determined the volume, runout, and incidence of three landslides in the Puget Sound and Lake Washington to determine commonalities, with the ultimate goal of being able to use those characteristics to make predictions about the origin of future landslides. By establishing the similarities between landslides of differing sources, I concluded that the primary difference between landslides of these types is the length of their runouts.

Landslides that resulted from delta failures had substantially longer runouts than those that were the result of hillslope failures. Based on these results, I would expect that the primary deposition of slope failure events would be relatively close to the coast, (with a short runout), but failures originating from a river delta would be substantially farther beyond the submarine protrusion of the delta.

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**Figures**

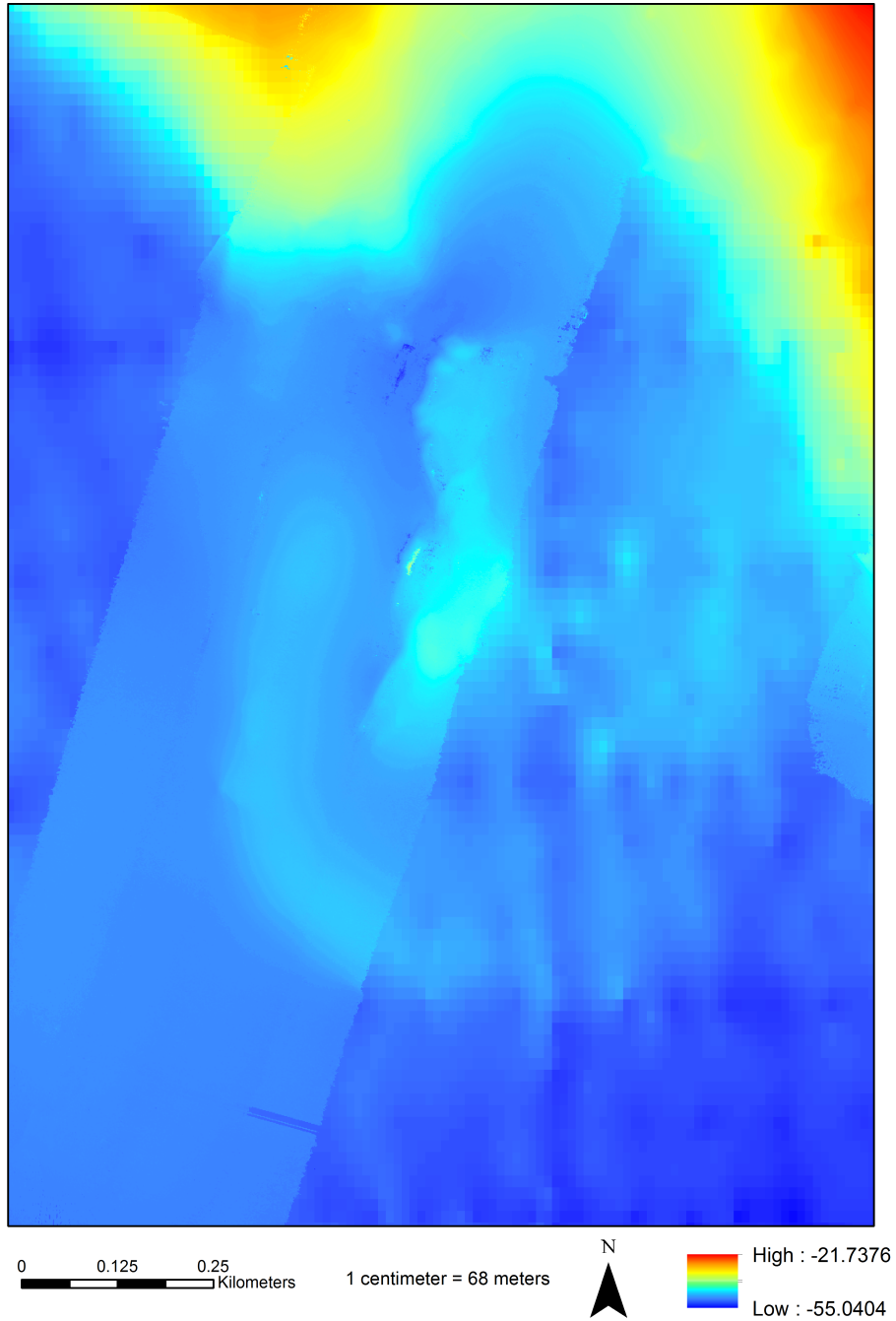


Figure 1. Bathymetric data for the Juanita Bay landslide

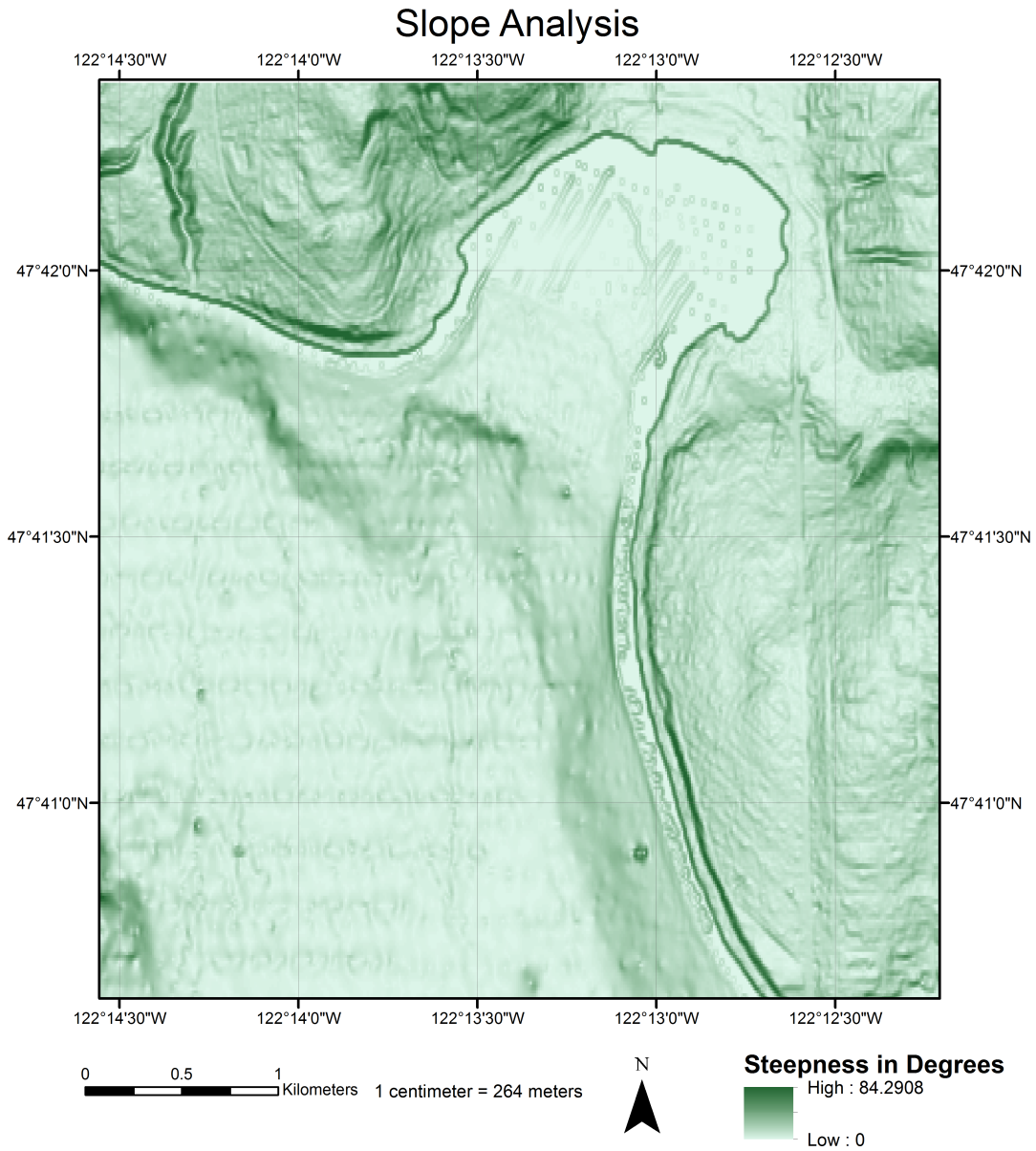


Figure 2. Slope Analysis of the Juanita Bay slide region

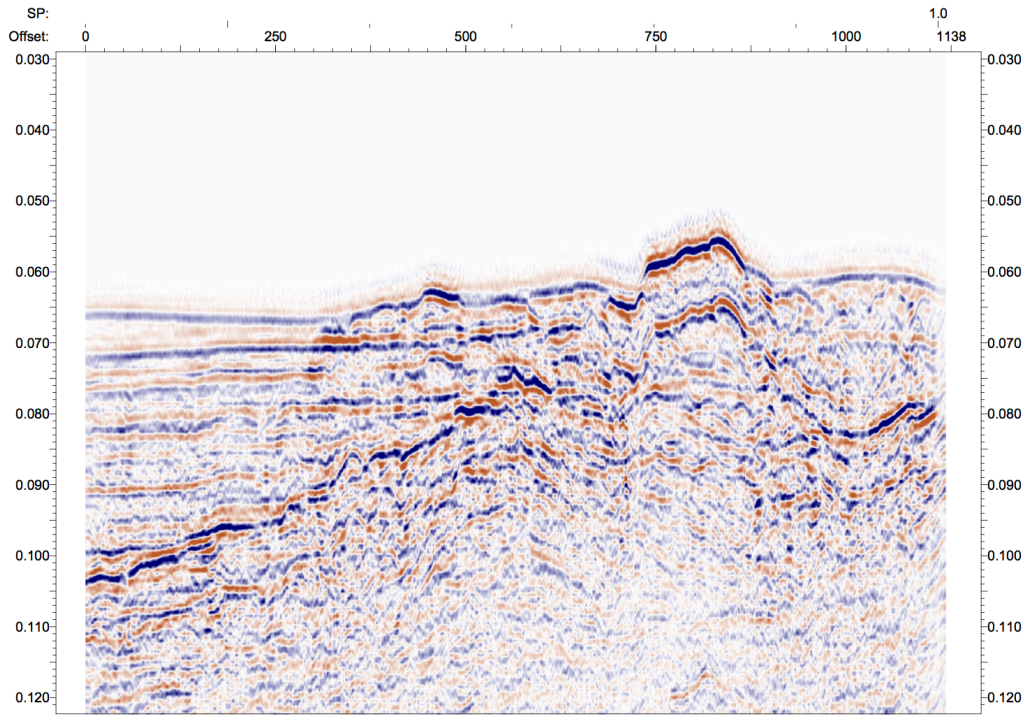


Figure 3. Seismic reflection data of the Juanita Bay Landslide

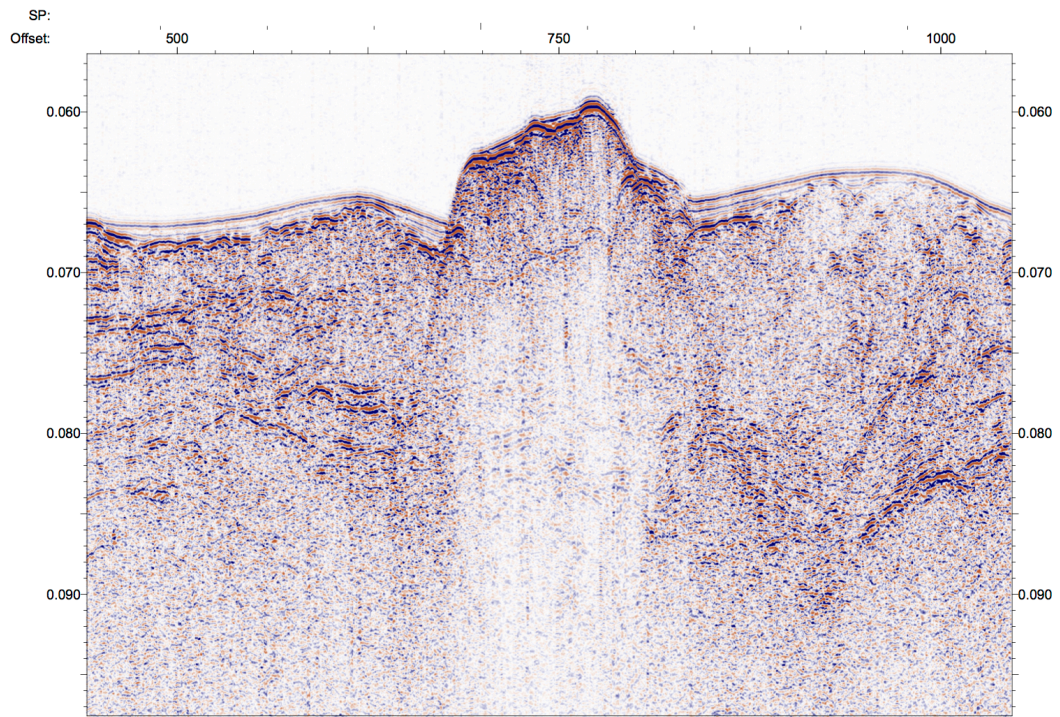


Figure 4. Chirp data of the Juanita Bay landslide

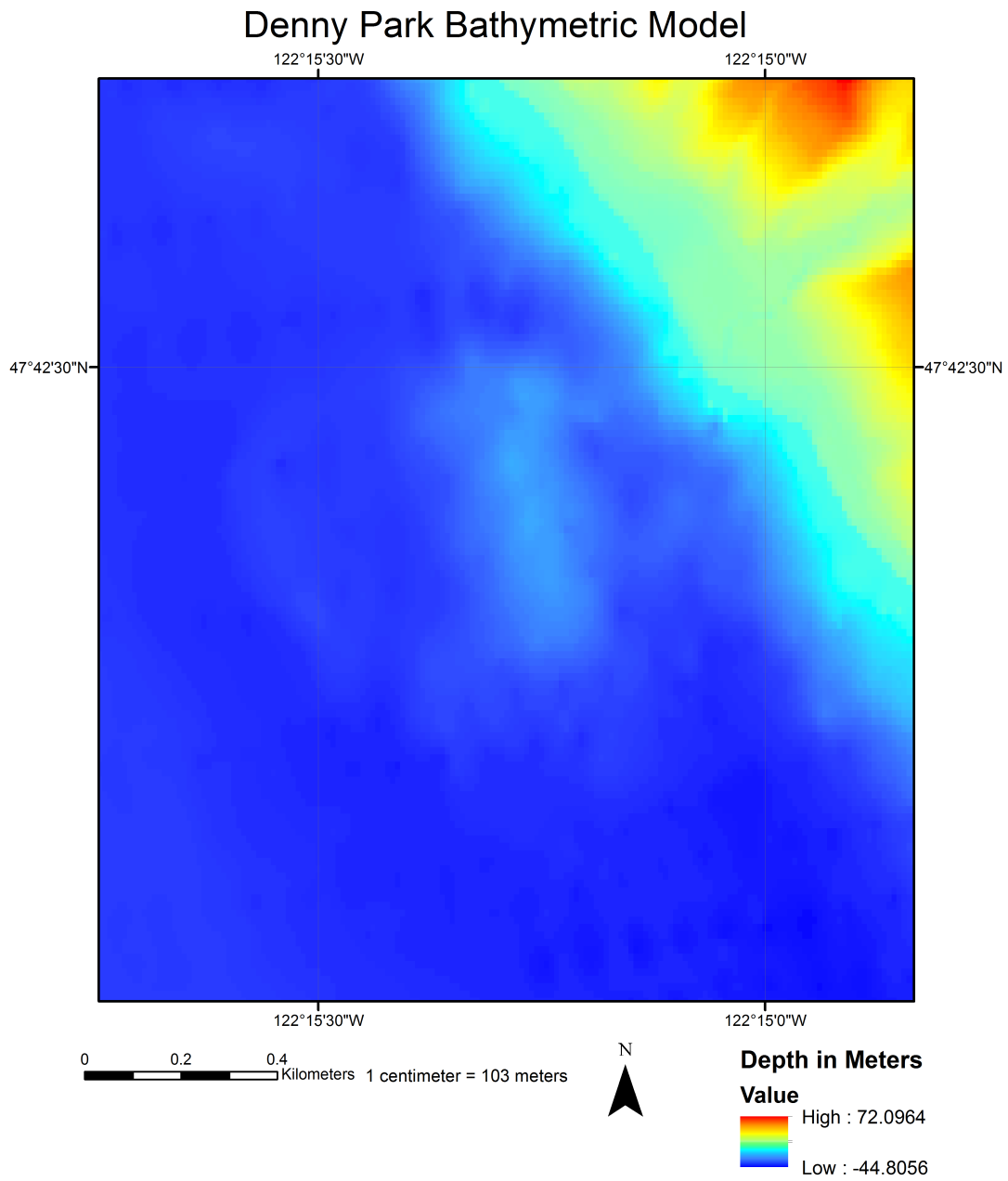


Figure 5. Bathymetric data of the Denny Park slide

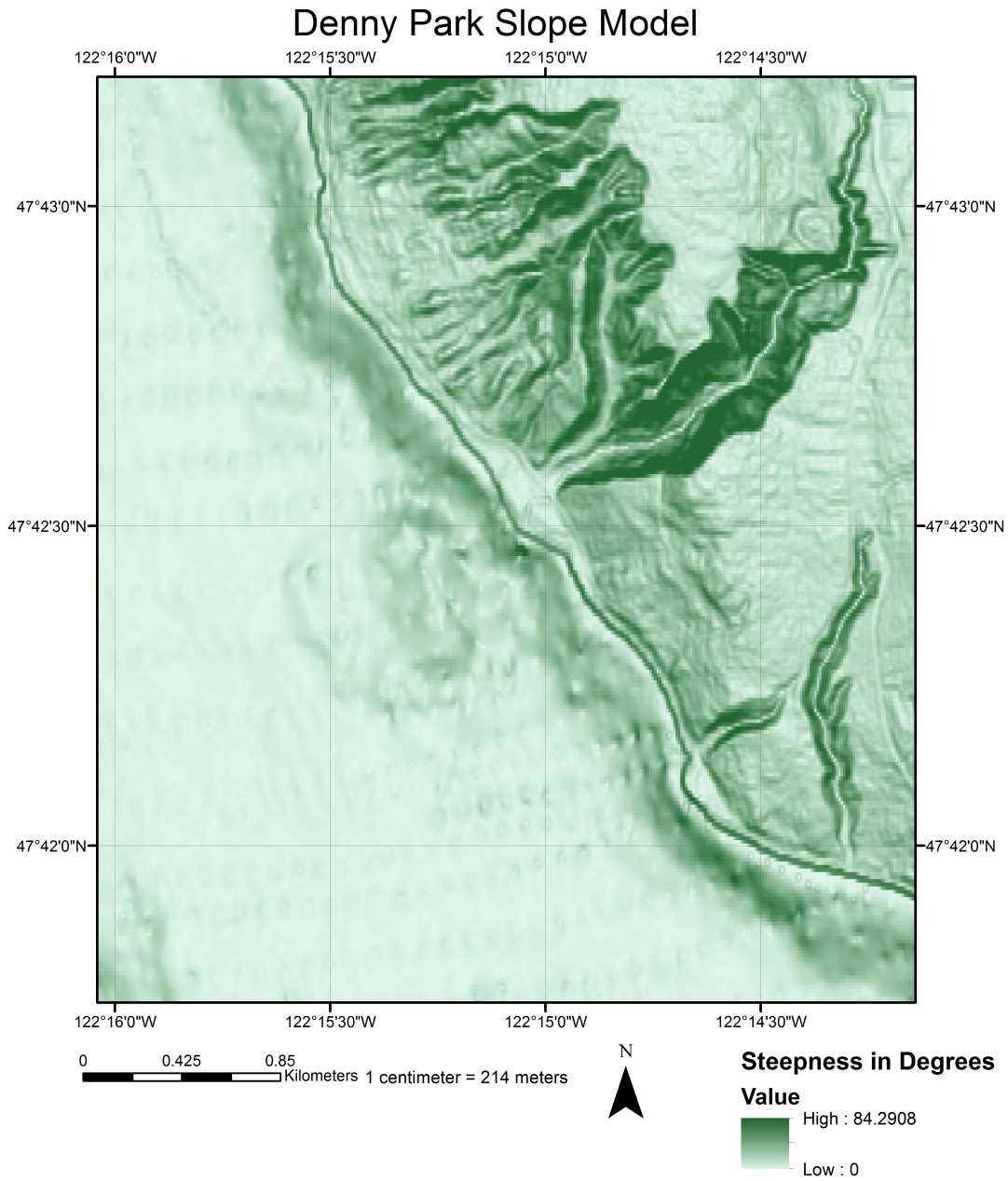


Figure 6. Slope analysis of the Denny Park Slide

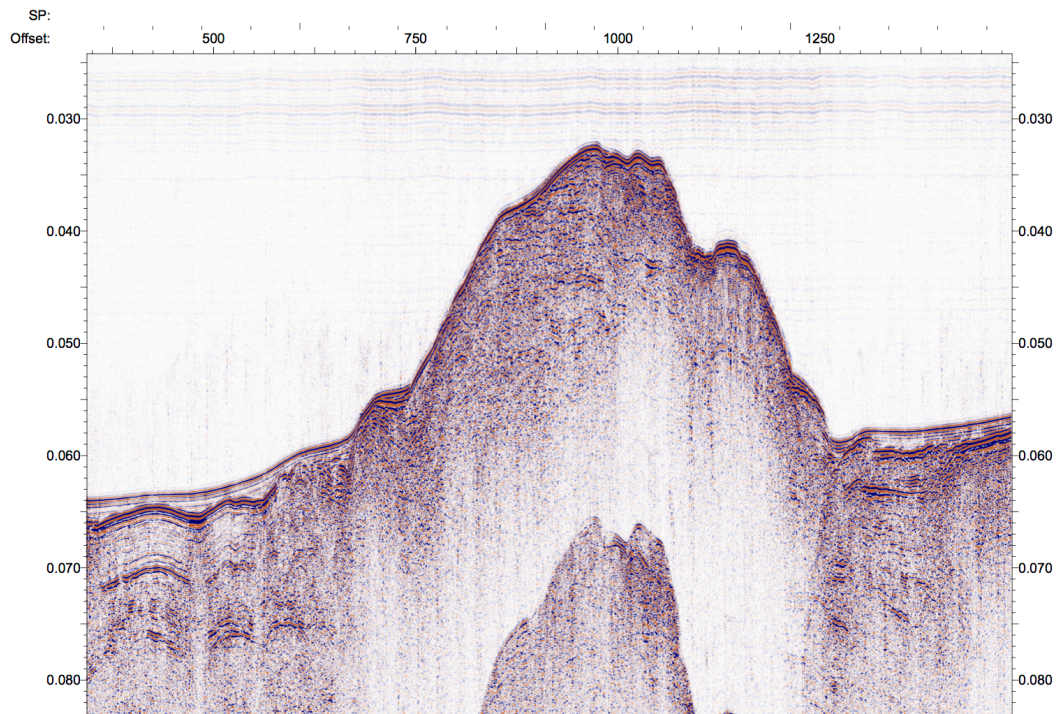


Figure 7. Chirp data for the Denny Park slide

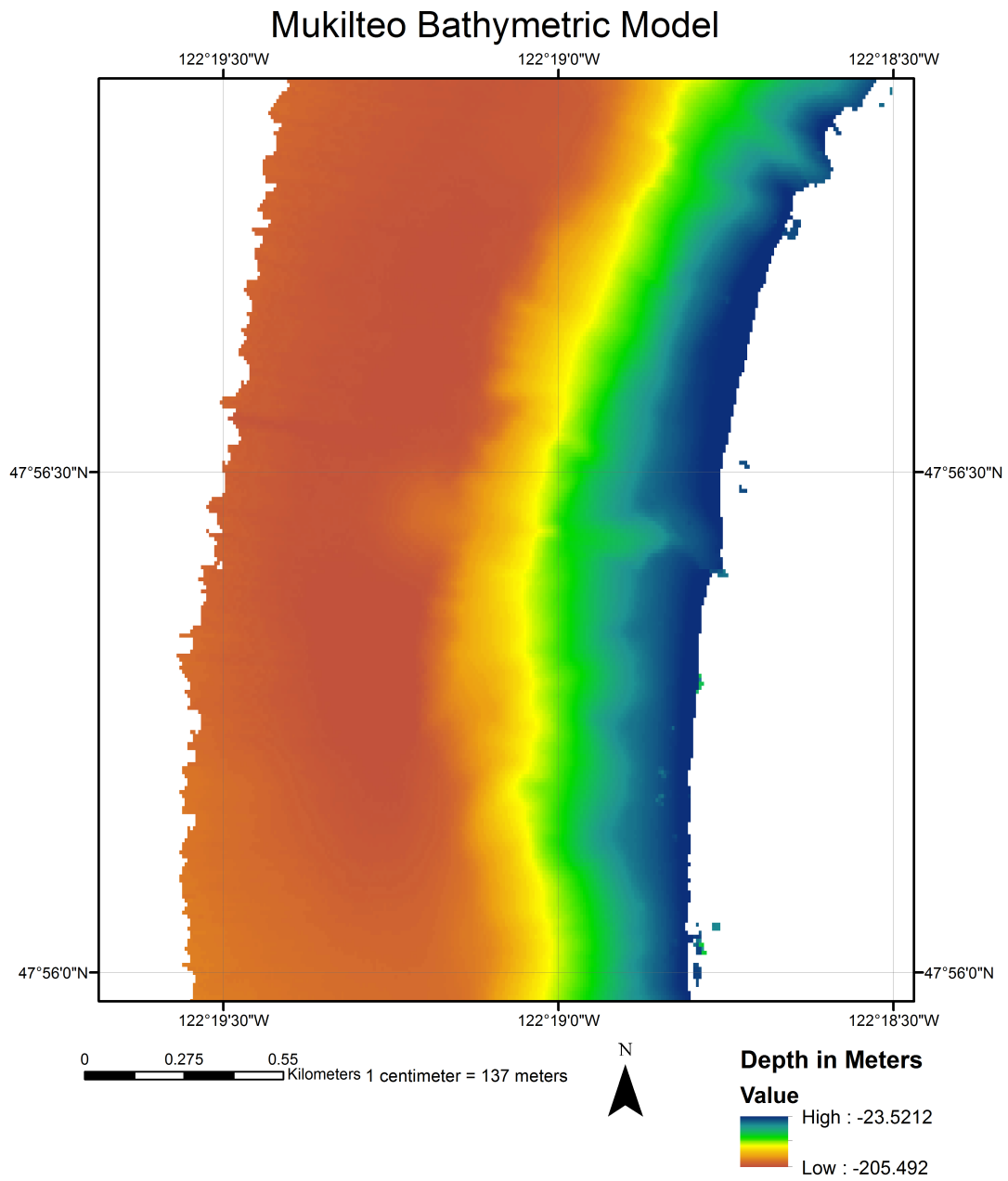


Figure 8. Bathymetric data of the Mukilteo Slide

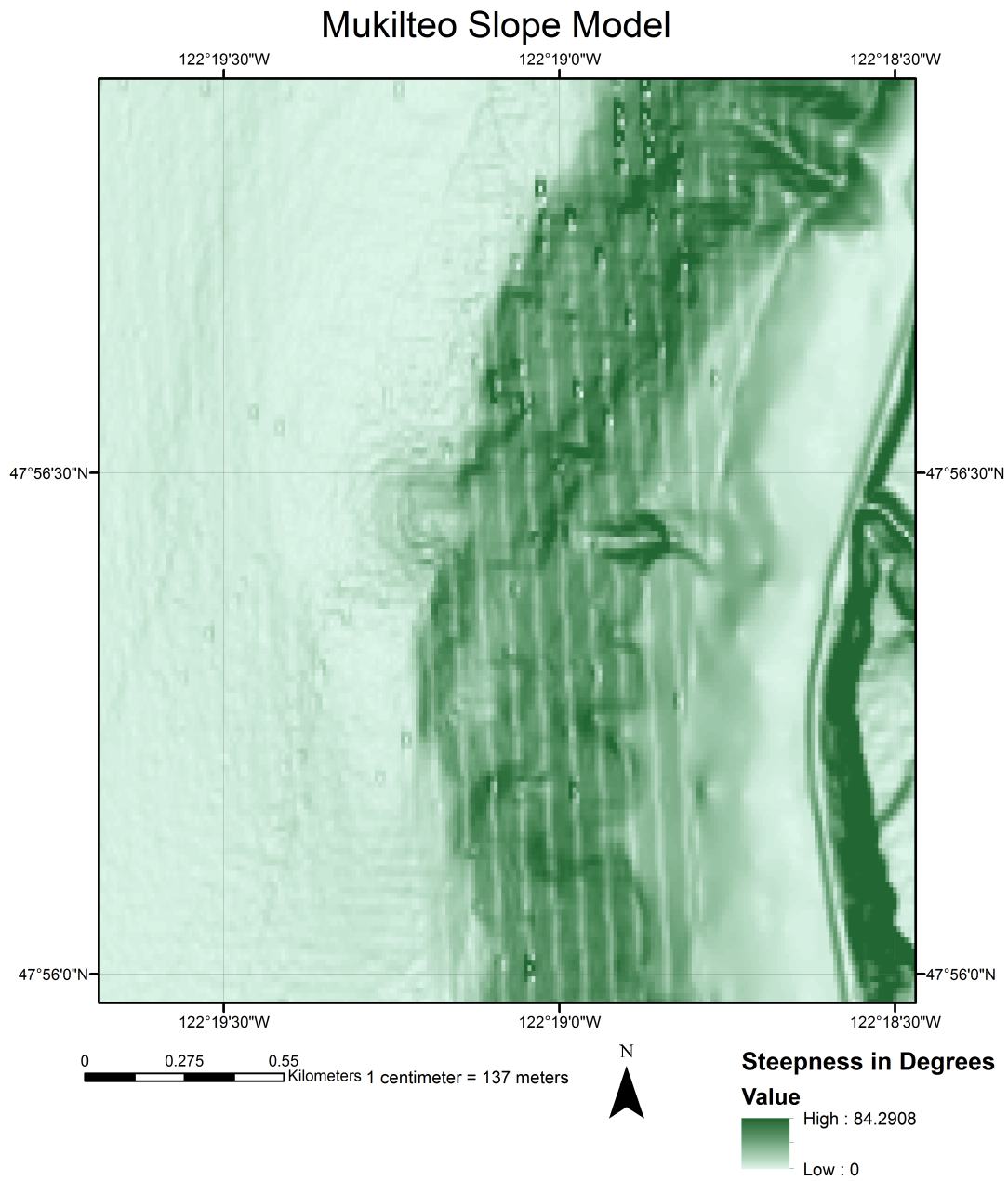


Figure 9. Slope analysis of the Mukilteo Slide

**Table 1** Slide Comparison

	<b>Slides</b>		
<b>Characteristic</b>	Juanita Bay	Denny Park	Mukilteo
Incidence Type	Delta Failure	Slope Stability Failure	Slope Stability Failure
Volume	$4.8 \cdot 10^5 \text{ m}^3$	$2.8 \cdot 10^6 \text{ m}^3$	$6.9 \cdot 10^5 \text{ m}^3$
Volume (alternate)	$4.7 \cdot 10^5 \text{ m}^3$	$2.9 \cdot 10^6 \text{ m}^3$	N/A
Runout	1.2 km	400 m	600m

Figure 10. A table comparing the main characteristics of each landslide.