Names: ESS 315
Lab # 2 Tsunami Hazards in Puget Sound

Tsunami Hazards: A tsunami is a wave train, or series of waves, generated in a body of water by an impulsive disturbance that vertically displaces the water column from its equilibrium condition. Earthquakes, landslides, volcanic eruptions, explosions, and the impact of meteorites, can generate tsunamis. In the case of earth-quake generated tsunamis, the water column is disturbed by the uplift or subsidence of the sea floor. The water above the deformed area is displaced from its equilibrium position. Waves are produced as the displaced water mass, which acts under the influence of gravity, attempts to regain its equilibrium. Large vertical movements of the earth's crust can occur at tectonic plate boundaries. Subduction zone earthquakes tend to be the most effective in generating tsunamis. The catastrophically deadly Indian Ocean tsunami of Dec. 26, 2004 was created by a large (M 9.0) subduction zone earthquake on the interface between the India and Burma plates.

Submarine landslides, which often accompany large earthquakes, as well as collapses of volcanic edifices, can also disturb the overlying water column as sediment and rock slump downslope and are redistributed across the sea floor. Tsunamis generated from submarine landslides tend to dissipate quickly and rarely affect coastlines distant from the source area, unlike the Pacific-wide tsunamis caused by subduction zone earthquakes.

Tsunamis are unlike wind-generated waves, in that they are characterized as **shallow-water waves, with long periods and wavelengths.** The wind-generated swells one observes rhythmically rolling in at an ocean beach may have a period of about 10 seconds and a wave length of 150 m. Conversely, a **tsunami** can attain wave lengths that **exceed 100 km and periods greater than one hour.** Because tsunamis have long wavelengths, they behave like shallow-water waves (i.e., the ratio between the water depth and wavelength becomes very small). Shallow water wave velocities equal the square root of the product of the acceleration of gravity (9.8 m/s^2) and water depth:

$$v = \sqrt{g * d_w}$$

Calculate the velocity of a tsunami wave generated off the northern coast of Chile as it travels across the Pacific Ocean. The Pacific Ocean has a typical water depth about 4000 m.

What would the travel time be for such a wave to reach the Hawaiian Islands? (use a world map to estimate the distance of travel between the two locations).

What would be the travel time for such a wave to reach Japan?

The rate at which a wave loses energy is inversely related to its wavelength. **What does this relationship tell you about energy loss of tsunami waves versus wind-generated waves over great transoceanic distances?**

Tsunami Hazards along the Cascadia Subduction Zone

Tsunamis in the Puget Sound can be generated by movement on local, crustal faults, by subaqueous landslides into Puget Sound, or by deformation along the Cascadia Subduction Zone. R.C. Bucknam (1989), based on field evidence, proposed that the fault running from Bainbridge Island to Seattle had moved suddenly in the recent past (Fig. 2-1). At the very southern tip of Bainbridge Island, a wave-cut platform was uplifted 7 meters (~27 feet) above the present intertidal zone (See Photo 2-1). The timing of this faulting event is inferred to be ~1100 years ago based on ^{14}C dating of organic matter associated with uplifted tidal marshes lying to the south of the fault.

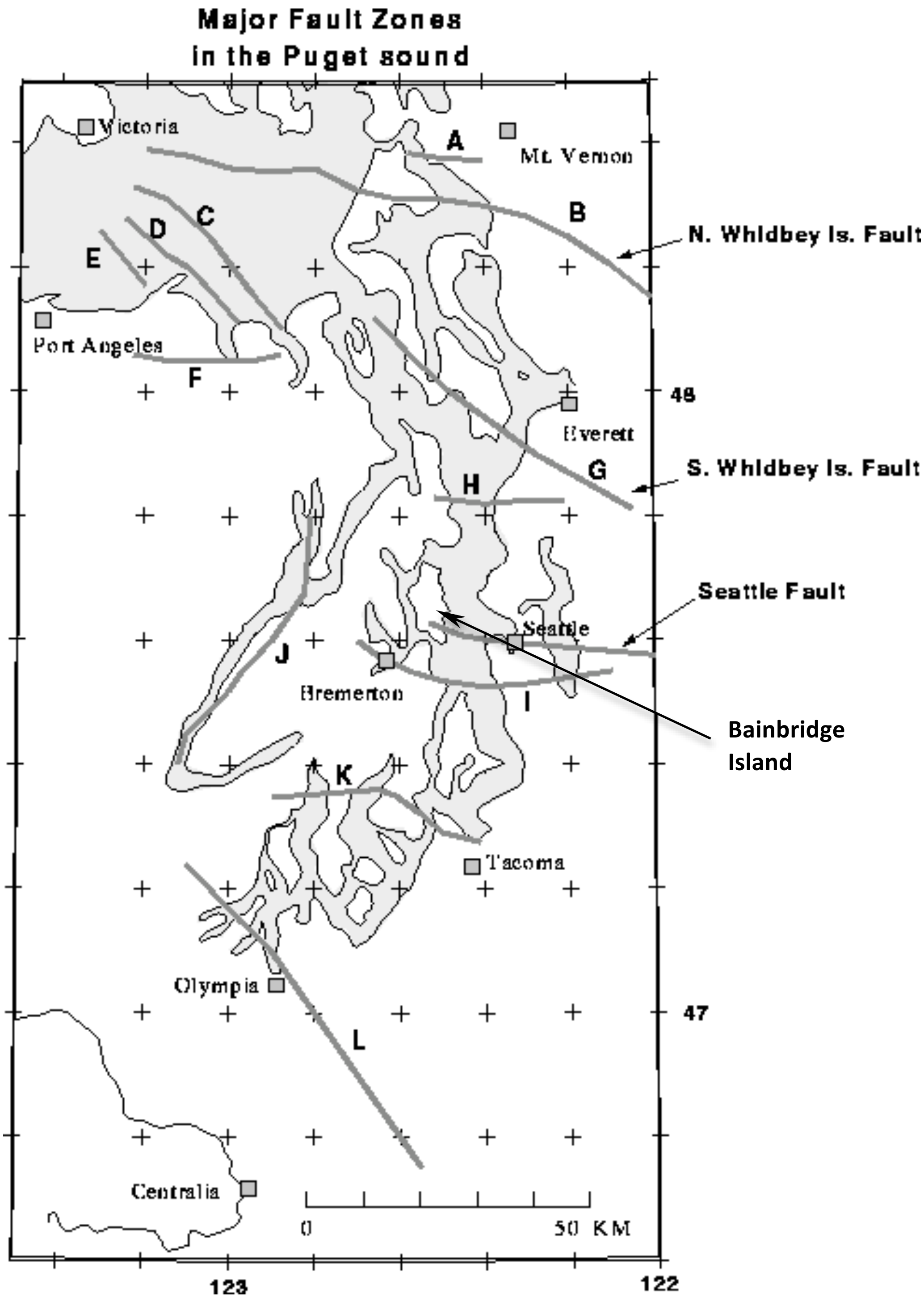


Figure 2-1: Index map of Puget Sound region with Seattle fault zone shown.

The map in Fig. 2-1 shows the spatial relationship of the Seattle fault zone and the Puget Sound region. A tsunami wave will tend to have the greatest impact on a shoreline that is perpendicular to the incoming wave because it sustains less energy-draining refraction. Shallow marine embayments along such shorelines are the most susceptible to tsunami inundation. We have provided a copy of a map (Fig. 2-2) that shows which areas were submerged by a tsunami following the 1883 eruption of Krakatau.

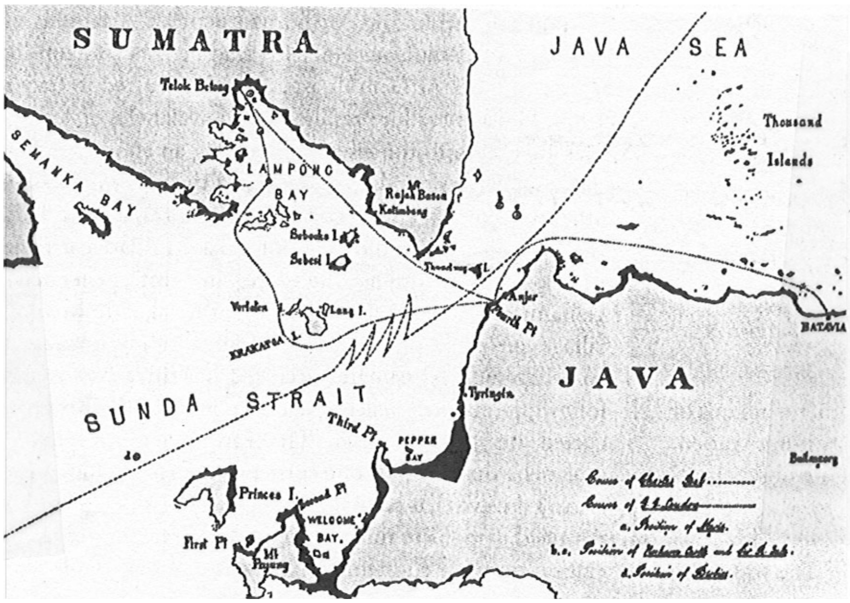


Fig.2-2: Tsunami inundation of the Krakatau coastline.

Based on the information shown in Fig. 2-2, and the spatial relationship between the coastline of the Puget Sound and the Seattle-Bainbridge Fault, use a colored pencil to indicate on Figure 2-1 which portion(s) of the coastline would likely be inundated by a tsunami wave generated along the S-B Fault.

How would topography along the coastline control the area of wave inundation? (e.g., compare the coastline at Elliot Bay to a place like Perkins Lane)

Andrew L. Moore, a former graduate student in the Department of Geological Studies at UW and now a professor at Kent State University, used a similar approach to predict where he might find a tsunami deposit related to the offset along the S-B Fault ~1100 years ago. Based on his projected travel path of such a tsunami wave, he concluded that Cultus Bay, Whidbey Island would be an ideal location where tsunami deposits might be preserved from this faulting event (Fig. 2-1; USGS Maxwellton WA 7.5 minute quadrangle map).

What factors would make Cultus Bay, Whidbey Island a likely location to find tsunami deposits preserved from the S-B faulting event? List at least two.

Many studies have shown that tsunamis can leave a distinct sediment record preserved along coastal margins that were inundated by the wave. Studies of recent tsunamis indicate that marine sand can be picked up by the incoming wave and transported hundreds of meters inland where the sand mantles pre-existing topography. Moore (1994) has listed several conditions that should be met in order to infer a tsunami origin for a sand sheet in the Puget Sound:

1. The sand should show evidence of a marine or estuarine environment.

2. Because the tsunami wave carries the sand at high shear stresses over the shoreline and loses those stresses rapidly, the sand should show evidence of rapid deposition from suspension. **Think about the sediment characteristics of rapid deposition of sand. Would it be a stratified (layered) unit? Would it be a massive unit? Why?**

   How would the grain size tend to change from the base of the sand sheet to its top?

3. Because tsunamis are rare events in Pacific Northwest, the sand sheet should be unique or nearly unique within coastal marsh stratigraphic sections. **How would you discriminate a tsunami sand sheet from storm-induced sandy deposits?**

4. **Depostion of the sand should correlate with a known or inferred source of the wave.** How would you correlate a sand sheet found within a coastal marsh stratigraphic section in Cultus Bay with offset of the S-B Fault?

Tsunami Deposits in Cultus Bay, Whidbey Island

Now we will further examine the geologic evidence that Moore (1994) used to conclude that a tsunami deposited a 5-15 cm thick sand sheet over a coastal lowland in the northern Puget Sound. The source of this tsunami is likely the S-B Fault and not the result of a subduction zone earthquake along the Olympic Coast. To search for the tsunami deposit, Moore collected data from 150 2-cm cores and 210 m of exposed stratigraphy in a drainage ditch from the Cultus Bay marsh (Fig 2-3).

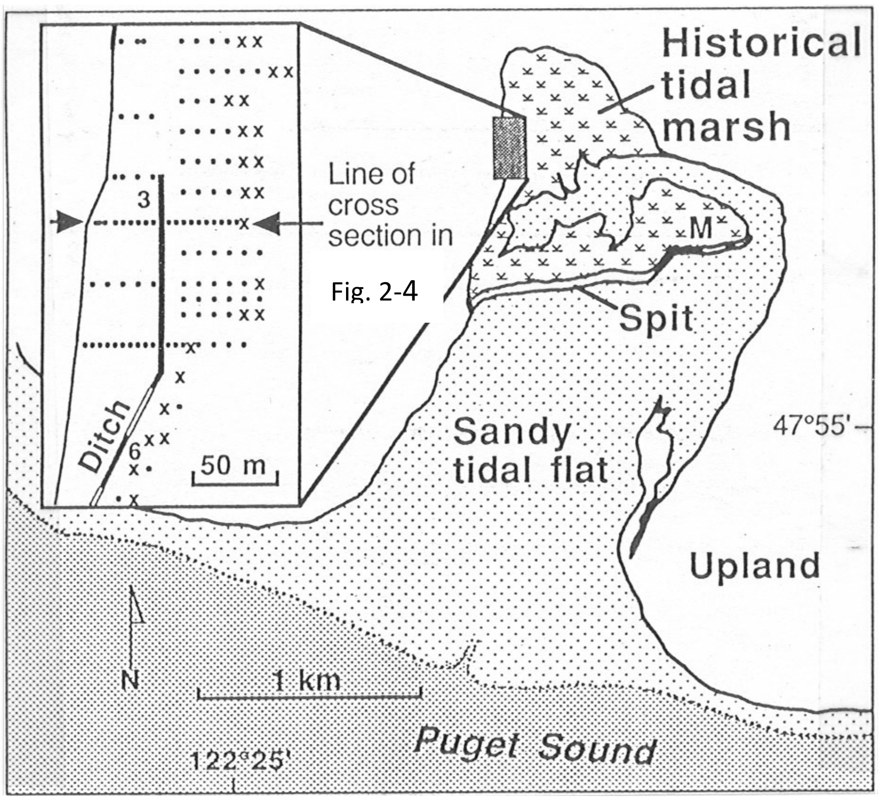


Figure 2-3: Study area in Cultus Bay. Data from sediment cores and drainage ditch collected in shaded region on index map.

An East-West cross-section through the western side of the tidal marsh (Fig. 2-4) shows the relationship of the sand-sheet to the pre-existing topography as well as existing radiocarbon ages (± error in years) from the stratigraphic section.

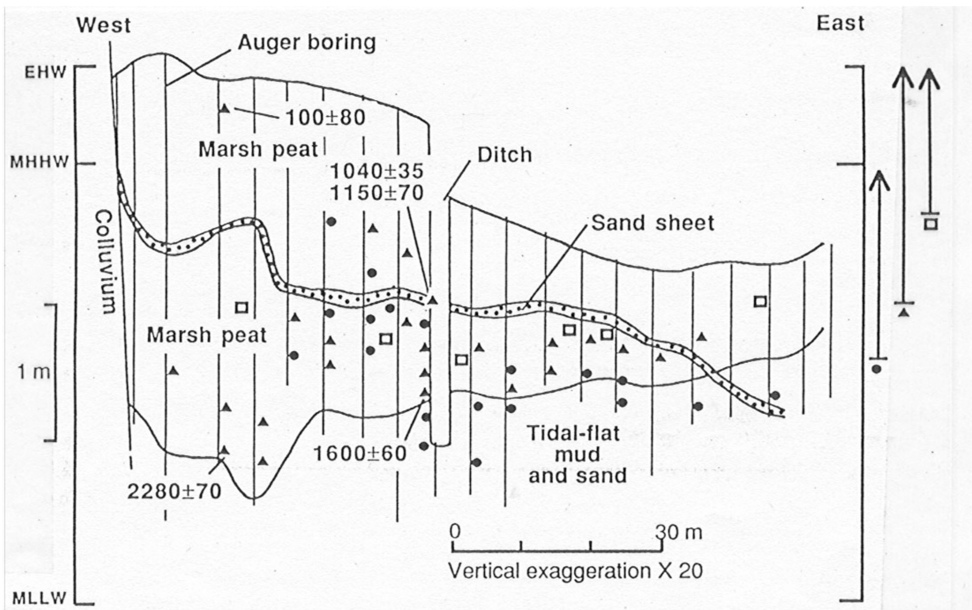


Figure 2-4: Cross-section along line of auger borings. Location of cross section shown on Fig. 2-2 (labeled as "Figure 4").

Based on the above cross section data what can you infer about the pre-existing topography?

Based on the radiocarbon ages shown on cross section, what can you infer about the age of the sand sheet?

How many sandy units do you see deposited in this stratigraphic section?

Why is this information important to the inference that the sand sheet was deposited by a tsunami rather than a winter storm event?

We have provided an infrared satellite image of the Cultus Bay area (Photo 2-2)? **Do you see any potential source for the sediment that comprises the sand sheet?**

Where do you think that the sediment was ultimately derived?

The sand unit contains marine diatoms (examples of marine diatoms are shown on Photo 2-3). **What is the significance of the marine diatoms to Moore's working hypothesis of this sand sheet being a tsunami deposit?**

Refer to the Maxwelton 7.5 minute quadrangle map (you have a copy attached to the back of this handout, Appendix 1) and Photo 2-2. Please locate and draw a box around the study area on your copy of the map (Page 15). What is another potential source for the sand found in the sand sheet?

Refer to Fig. 2-5. This figure shows the distribution of grain size across the study area in millimeters. The contour interval is 0.025 mm. Based on the grain size distribution data,

what can you infer about the direction that the tsunami wave moving relative to the study area? Draw the flow direction on Figure 2-5 below.

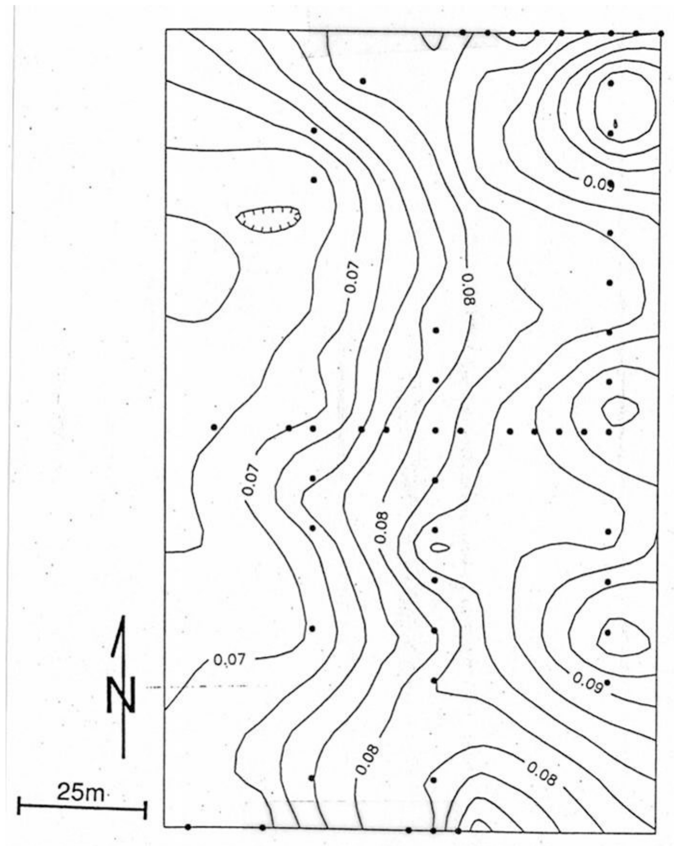


Figure 2-5: Distribution of mean grain size (in mm.) across the study area.

Now, indicate the path of movement of the tsunami wave as it enters Cultus Bay and onto the historical tidal marsh, using arrows drawn with a colored pencil on your copy of the map (Page 15).

Depth and Time/Depth-Averaged Velocity of the Tsunami in Cultus Bay

The depth and time/depth-averaged velocity of tsunamis leaving sand deposits can be estimated using a simple advection model for well-suspended particles. Moore (1994) assumes that the transporting flow of a single tsunami wave can be considered turbulent, uniform and unidirectional. Once suspended, sediment grains would fall back to the bed at their settling velocity (w_s) while being transported laterally at the average velocity of the flow (<U>) (See Fig. 2-6). Division of the sediment grain's initial height in the flow (y) by the settling velocity yields time in transport (t), which can also be determined by dividing the horizontal distance traveled (1) by the average flow velocity.

$$\frac{y}{w_s} = t = \frac{1}{< U >}$$

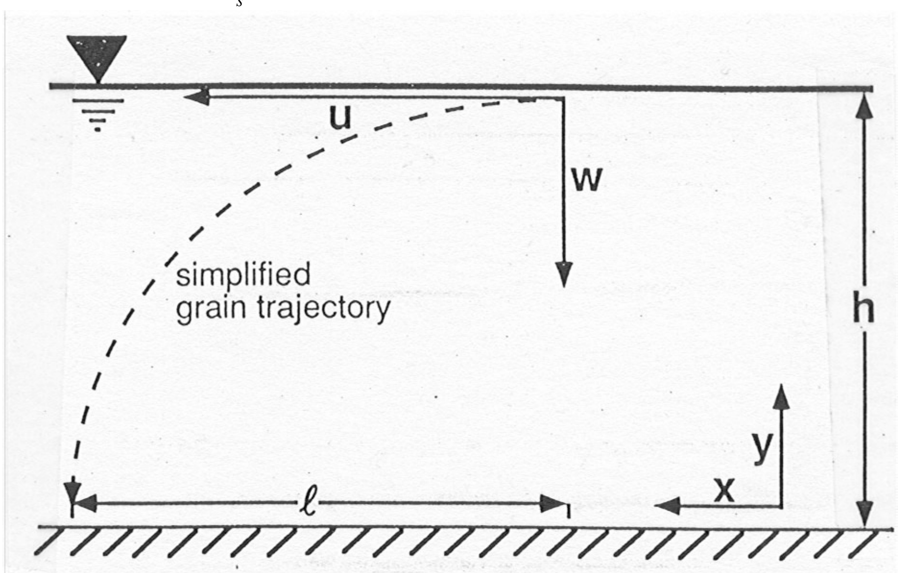


Fig. 2-6 Settling trajectory for suspended grains in uniform, unidirectional flow.

The above equations show that the product of two measurable quantities, the settling velocity of a given particle and the particle's horizontal position in the deposit, yields the product of two desired quantities, flow velocity and the particle's initial height above the bed.

$$w_s 1 = < U > y$$

Initial particle height will vary for suspended grains in the flow, attaining a maximum value of the flow depth (h). If the supply of new particles to the flow is cut off (i.e., in this case the transition from tidal flat muds to tidal marsh peats) grain size variation at any point will be produced solely by changes in the settling velocity and the initial particle height.

Look at Photo 2-4. What does the graded bedding in the sand unit tell you about the relationship between settling velocity and the grain size of a sediment clast?

Because coarser particles have a faster settling velocity for a given density, they will fall faster through the flow than finer particles; thus, you can infer at a given point along the sand bed, the coarsest particles had the greatest initial height above the bed (Fig. 2-7).

$$w_{sMAX} l = \langle U \rangle h$$

where w_{sMAX} is the settling velocity on the bed for a given distance l .

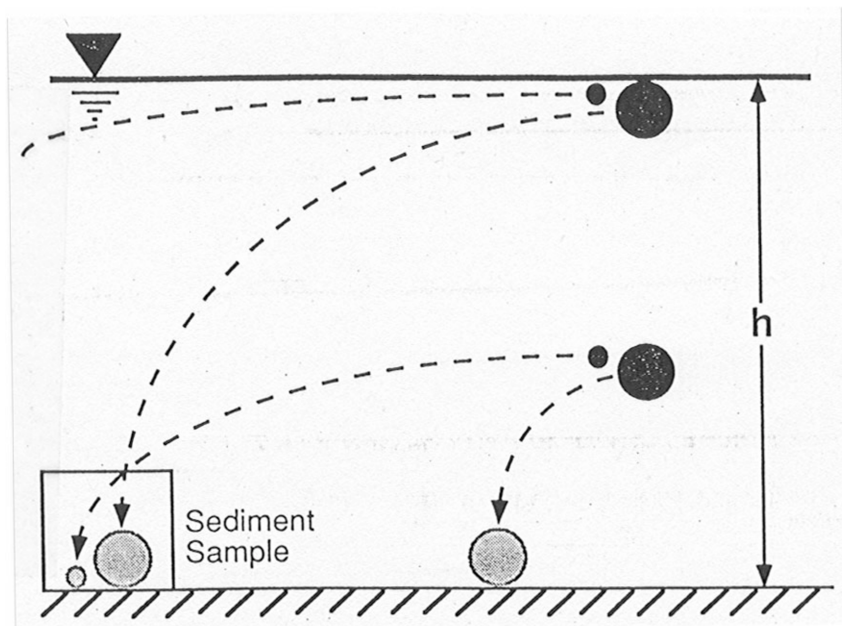


Figure 2-7: Trajectory of sediment falling through a unidirectional flow. For any given sediment sample, the largest grains have fallen the greatest vertical distance.

Moore (1994) felt that the largest grain sizes were difficult to accurately characterize in the sand deposit so he used a set of sieves to measure the coarsest 10% (D_{90}) of the grains. (See Fig. 2-8).

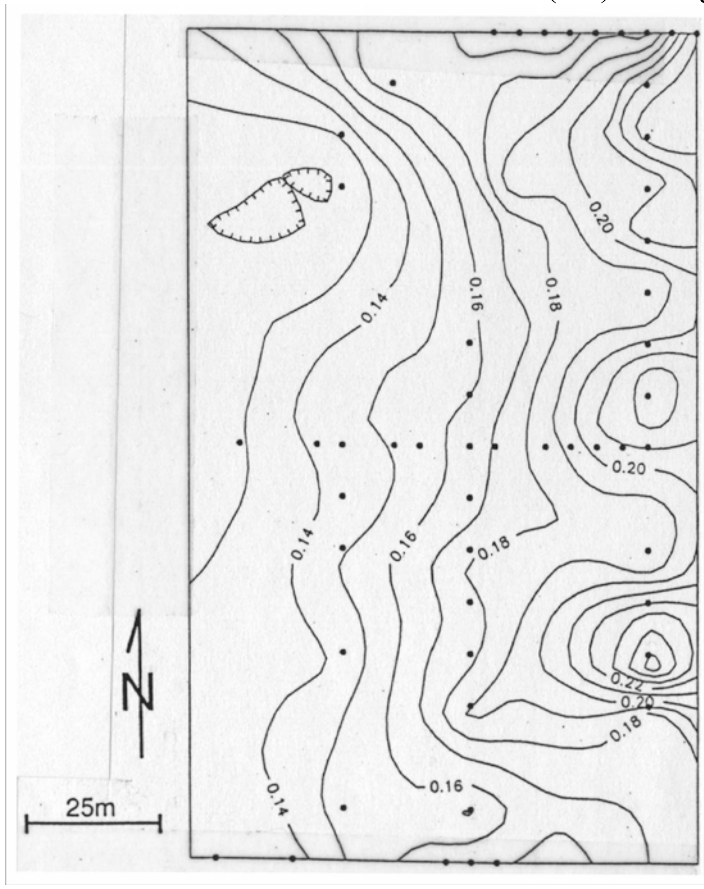


Fig. 2-8: Distribution of D_{90} across the study area (in mm). Contour interval is 0.5 mm.

Based on the above data, was Moore (1994) correct to infer that the tsunami wave was unidirectional? (Hint: Look at the contour line pattern).

Moore (1994) converted the grain size data to grain settling velocity. The product of settling velocity and characteristic length is a constant, *k*. Consequently, a plot of l versus $(w_{smax})^{-1}$ should show a linear trend, with the slope of the trend equal to *k.* The best-fit line for these data yields constants of 1.77 for all of the data and 1.31 for a single east-west transect. Remember that we earlier defined that the settling velocity-characteristic length product equals flow-depth velocity product. The constants derived for settling velocity-characteristic length (1.77 and 1.33) can be assigned to the depth-velocity constants. Fig. 2-9 shows a log-log plot of the two depth-velocity constants. Moore used these to constrain the permissible depth-velocity combinations for the surge washing through Cultus Bay. Also plotted in this graph are the depth-velocity combinations at Everett, Washington for a modeled tsunami generated by a M_w=8.5 earthquake directly outside the Strait of Juna de Fuca along the Cascadia Subduction Zone.

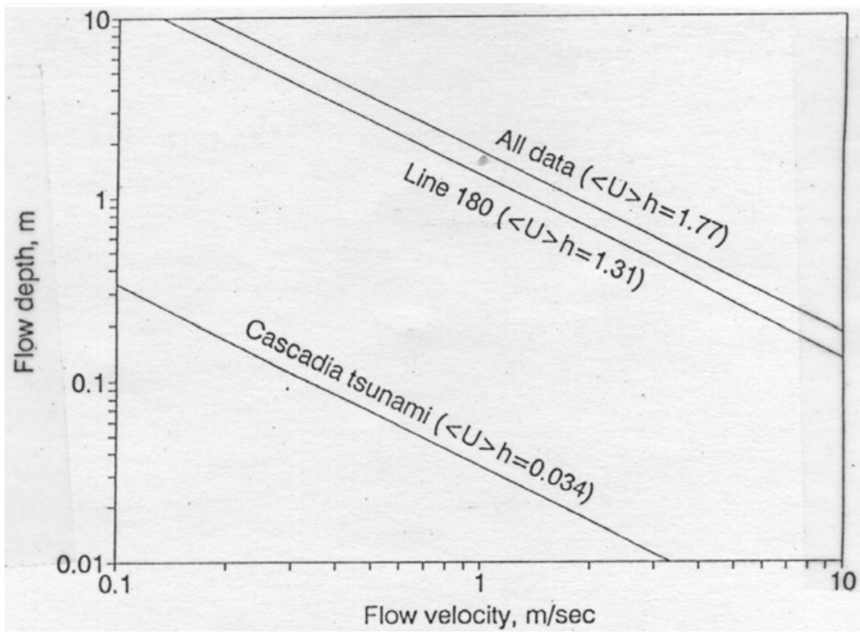


Figure 2-9: Permissible flow depth/velocity products for all the data and a single east-west transect within the study area. Permissible flow depth/velocity products for a hypothetical tsunami generated at the Cascadia Subduction Zone is also shown.

Based on the above data, did Moore (1994) have reasonable grounds to rule out the Cascadia Subduction Zone as potential source of this tsunami sand sheet? Provide reasonable evidence to support your answer.

Figure 2-10 shows permissible flow depth/ velocity products from Figure 2-9 plotted over a bedform stability diagram for 0.10-0.14 mm diameter sand grains. This information can be used to constrain the velocity and flow depth of the wave into the tidal marsh of Cultus Bay.

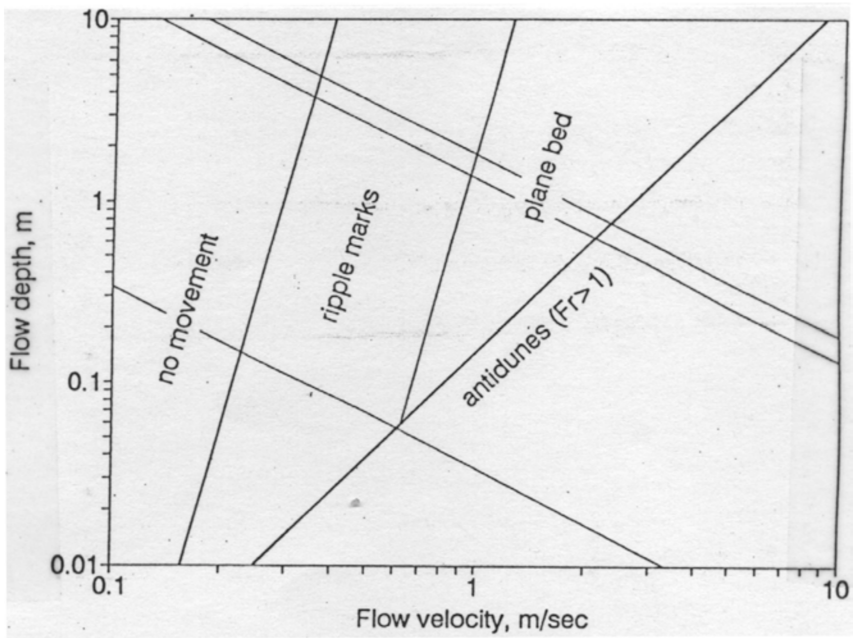


Figure 2-10: Permissible flow depth/ velocity products from Figure 2-9 plotted over a bedform stability diagram for 0.10-0.14 mm diameter sand grains.

Look at the photo of the sand sheet again (Photo 2-4). In what bedform field does the sand unit lie?

What constraints can you place on the height (in meters) of the tsunami wave as it surged into the tidal marsh region of the study area?

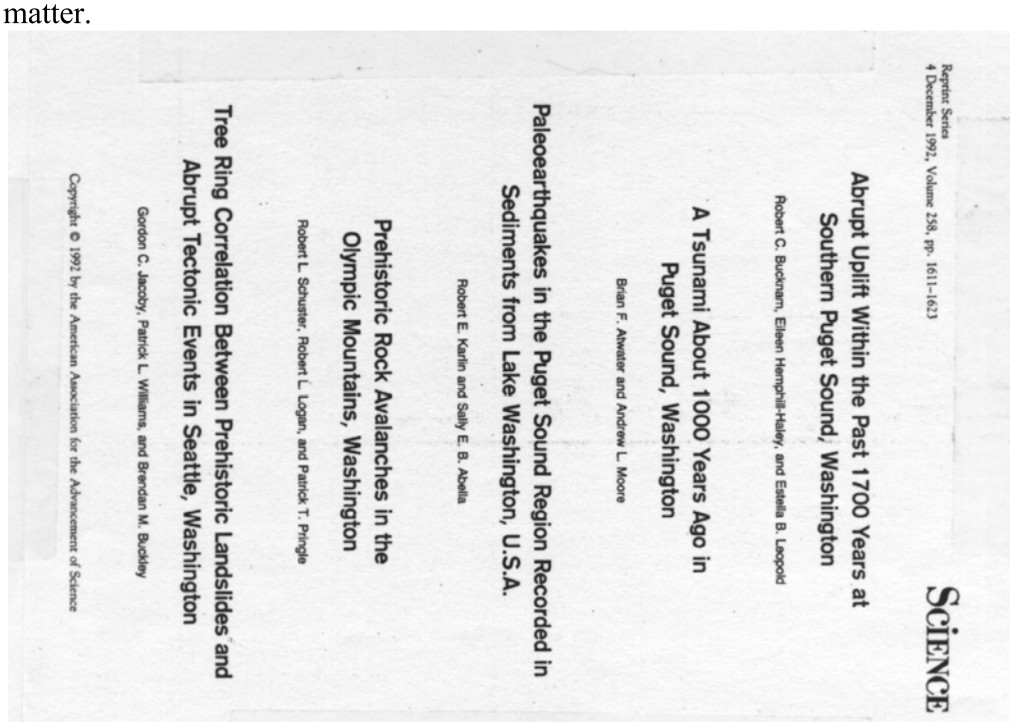
What constraints can you place on the velocity of the tsunami wave as it surged into the tidal marsh region of the study area?

Are these values maximum or minimum estimates for this tsunami wave? (Hint: think about the grain-size distribution Moore (1994) used for his data set).

It is important to note that the above tsunami wave constraints of Moore (1994) are based on modeled calculations and have not been empirically validated. The velocity and height of the wave would be controlled by local bathymetry as the wave entered Cultus Bay. We have several copies of an 1892 coastal survey map of this region. Look at the most recent USGS 7.5 minute topography map. What natural features have changed or have been modified in the last 100 years?

The community of Sandy Hook is situated near the southeast mouth of Cultus Bay. If Moore's (1994) modeled wave height estimates are correct, which areas of the Sandy Hook community would be most susceptible to inundation by a tsunami wave generated at the S-B Fault? Use a colored pencil to draw (use the map copy provided with this lab) the potential run up height of a tsunami wave near the Sandy Hook location in Cultus Bay based on Moore's (1994) modeled estimates.

Much of the information provided in this laboratory is taken from the M.S. thesis of Andrew L Moore (1994) in the department of Geological Sciences, University of Washington. Several research articles presented in the journal *Science,* provide important background material to this subject matter.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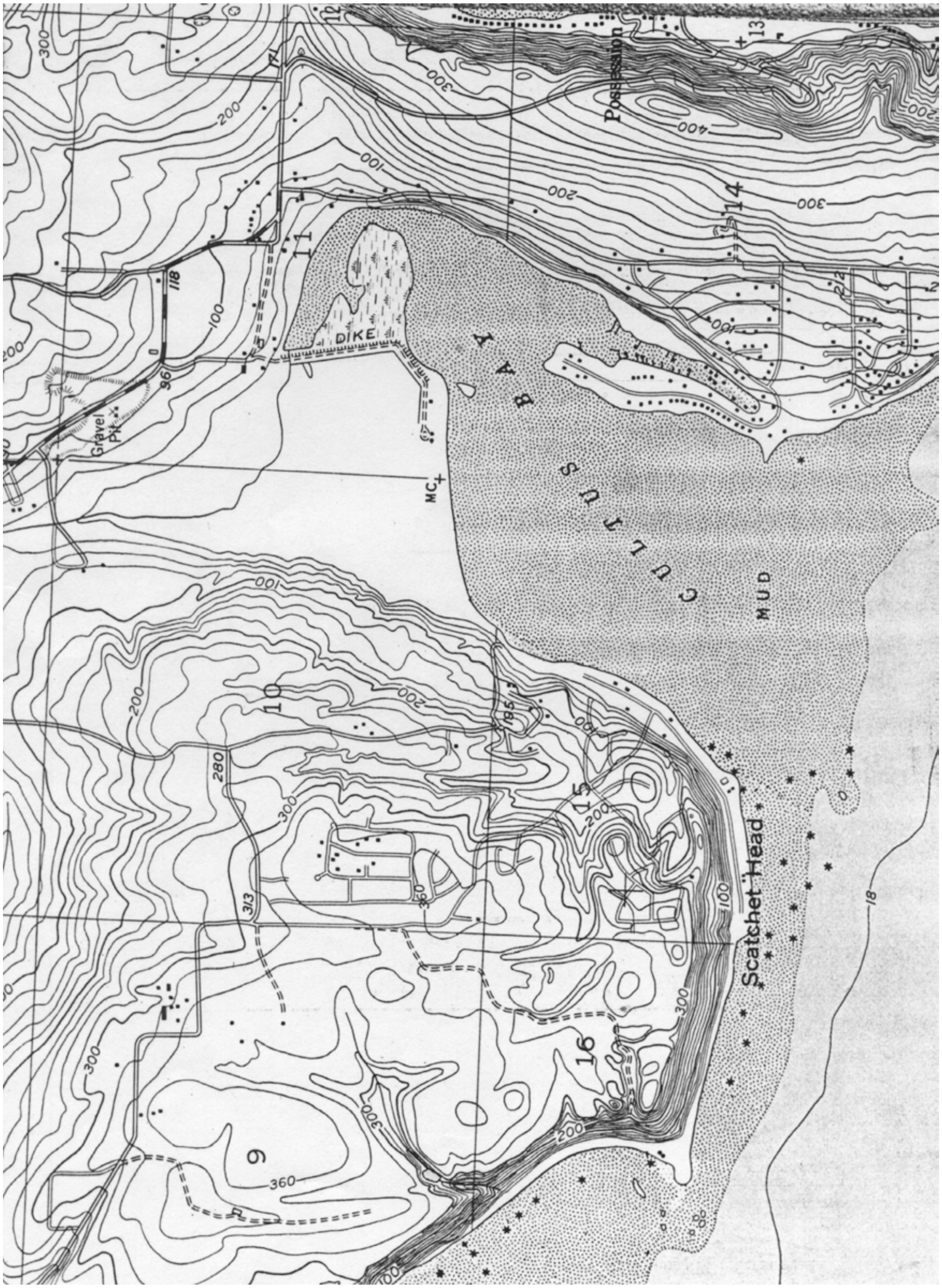

Appendix 1: A portion of the Maxwelton WA 7.5 minute quadrangle map.