Mysterious mounds of southern Hood Canal:
dumpsites, landslide deposits, or glacial debris

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Non-technical summary

During a 2005 student cruise the University of Washington research vessel, *R/V Thomas G. Thompson*, discovered two large mounds in southern Hood Canal just west of Dewatto Bay. The mounds measured approximately 35-40 m in height and 350-450 m wide. Both mounds were located along the eastern side of Hood Canal and were within 1 nautical mile of each other. My project focused on trying to identify the origin of these mounds and their potential age. This was done using shipboard acoustic equipment to generate high resolution images of the mounds, and to gather information of their structure below the seafloor. A series of sediment samples were taken on and around the mounds to gather grain size information about the sediments that compose the mounds relative to their surroundings. Furthermore a sediment core was taken north of the mounds for possible dating of the mounds using radiometric techniques.

The findings show that the mounds extend 20-40 m below the seafloor. The high resolution images reveal that the mounds are almost teardrop shaped and are both oriented in a north south direction parallel to the shore. Analysis of the sediments on and surrounding the mounds show that the mounds are generally composed of coarser and more poorly sorted material than that of the surrounding area. Radiometric dating indicates that the age of the mounds is in excess of 10,000 years.

Acknowledgments

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Abstract

In 2005 two large seafloor mounds 30-40 m high and approximately 350 m in diameter were partially imaged in southern Hood Canal. Initial speculation as to their formation leaned toward dredge spoils. Growing interest in marine habitats in greater Puget Sound sparked renewed interest in the mounds and a study was undertaken to solve the mystery of their origin. On 23 March 2007 the mounds were surveyed using digitally-recorded 3.5 kHz profiler and 30 kHz swath bathymetry aboard the *R/V Thomas G. Thompson*. These surveys were followed by bottom grab sampling on and near the mounds. A box core was obtained 10 km north of the mounds to permit calculation of sediment accumulation rate. The swath imagery showed both mounds to be elliptical in plan view, oriented generally parallel to the axis of Hood Canal. Migration of the 3.5 kHz data showed conclusively that the mound structures extended up to 40 m below the seafloor. Surface sediments on the mounds consisted of coarse silty sand (mean size 2-0 ϕ), with abundant rounded pebbles and cobbles. Sediment near the mounds was much finer, mean size 8-9 ϕ. Accumulation rate determined from box core sediment using ^{210}Pb was about 0.31 cm y^{-1}. The geophysical and sediment data indicate that the mounds are at least 12,000 years old and consist of much coarser material than the surrounding seafloor. The shape and size of the mounds, including the subbottom portion, are consistent with an interpretation that they are glacial features – drumlins – created during the Vashon Stage glaciation of the Puget Lowland. A review of past geophysical data such as subbottom profiles taken in Hood Canal showed that there are likely more of these features present along the axis of Hood Canal south of Dabob Bay.

Introduction

In 2005, during a student research cruise aboard the *R/V Thomas G. Thompson,* two large mounds were discovered in southern Hood Canal with the ship's EM300 multi-beam system (Fig.1, Fig. 2). The southern mound measured approximately 35-40 m tall, 350m wide, and 450m long with the northern mound of similar size. If we were to assume that the southern mound was a perfect cone with a radius of 200 m, the estimated volume would be 1.7 million m^3. When the EM300 data was collected, the ship was traveling in excess of 10 kts. Removing the flow noise caused by traveling at such high speeds, resulted in images with degrade resolution. 3.5 kHz subbottom profiles were also made of the mounds (Fig.3). These profiles suggested that the mounds extended nearly 40 m below the seafloor. However, because the 3.5 kHz data was not recorded digitally, the data could not be migrated to determine if the subbottom signals were real reflections or the result of diffraction. Ultimately the shipboard science party almost unanimously declared the mounds to be dredge spoils. Since then, the origin of the mounds has remained unknown and a number of ideas have been suggested. These ideas include glacial features, dumped material from past disposal of dredging or land modification, and landslides.

The landscape of the Puget Lowland from the Strait of Juan de Fuca down to Olympia was carved out during the last glacial period when the Cordilleran ice sheet expanded southward from present day British Columbia (Booth et al. 2003, Porter and Swanson 1998, Goldstein 1994). Channel networks in the Puget Lowland are believed to have been carved out by subglacial water flow (Booth and Hallet 1993). Hood Canal "is filled with thick Quaternary deposits of unconsolidated and semi-consolidated glaciolacustrine, glacial-fluvial, and transgressive marine sediment deposited during multiple advance and retreat cycles…" (Haug 1998). The growth and retreat of glaciers over time can result in the creation of large geologic features. As glaciers progress, the leading edge of the glaciers can push material like a bulldozer and carry that material great distances. When the glaciers begin to retreat, the unconsolidated material that had been carried by the glacier is then left behind creating a ridge along the edge of where the glacier used to be. This feature is called a moraine. In some cases, glaciers can carry extremely large boulders which are then deposited when the glaciers melt. These "glacial erratics", as they are called, typically differ both in size and in rock type compared to the rocks of the surrounding area.

Another glacial related mechanism that can deposit mound-like formations is floating ice. Material can be picked up by ice as a result of scraping and freezing to debris beneath the ice, or material can be deposited on top of an ice sheet (Holmes and Creager 1974). In either case, the ice sheet can break away from a glacier and float away carrying the material. When the ice melts, the entrained debris separates from the ice sheet and settles to the bottom. It may be possible for material carried on top of an ice sheet to be deposited in a single large dumping event as the ice melts and potentially gives way under the weight of the material.

Glacial phenomena are not the only mechanisms for the transportation and deposition of large amounts of material. Removal of material for land modification and dredging of channels have taken place throughout human history. Within the Puget Sound area, one of the largest cases of land modification was the Denny Hill regrade of the late nineteenth and early twentieth centuries. The material from this regrade was ultimately dumped into Elliot Bay creating a large mound. During a survey of the Denny Hill regrade dump site, Loeffler et al. (1989) showed that there was a concentric distribution of grain sizes at the Denny Hill regrade dump site. The coarser materials (gravels and sands) settled at the center of the bank and the finer materials (silts and clays) were carried farther away by the resulting turbid plume before settling (Loeffler et al. 1989).

A third potential mechanism scheme for the formation of the mounds is landslide activity. Puget Sound is a geologically active region with numerous faults running through it. A number of these faults have been accompanied by submarine landslides due to earthquakes associated with the faults (Karlin et al. 2004). A landslide occurs when a section of a slope fails and material starts to slide down. When the material is displaced, it leaves behind a scarp and a rupture surface on the slope. The scarp, in particular, is one of the most noticeable landslide features. On the leading edge of landslide flows, material is compressed by the movement of the displaced mass and form compression ridges (Hampton et al. 1996). In many cases, the displaced mass is highly deformed as a result of the slide and rests close to the actual rupture surface. However, sometimes the displaced mass can maintain cohesion with relatively little deformation and rest beyond the rupture surface (Hampton et al. 1996). When the displaced mass from a slide does travel far enough, it can take on the appearance of a mound. Landslide features are not always visible. Slump blocks, landslide deposits, and failure surfaces can be buried by sediments following the slide or by later landslides (Hampton et al. 1996, Greene et al 2006).

This project seeks to test which of the processes mentioned earlier (glacial, spoil sites, or landslide) is likely to have been the origin of the mounds. A grain size analysis can be used to search for a concentric distribution of grain size where the coarsest materials are located at the center of the mounds with progressively finer grains located away from the center and beyond the mounds. This would suggest that the mounds are the result of material being dumped at their locations. The presence of compression ridges on the west side of the mounds and landslide scarps on the eastern side, will confirm the presence of a past landslide originating from the eastern side of Hood Canal.

Methods

To determine the possible origin of the mounds, the field work was broken up into multiple phases starting with a survey phase. The first survey involved the use of the shipboard Kongsberg-Simrad EM300 multibeam echo sounder. The EM300 uses a transducer array mounted to the bottom of the ship. This array transmits a fan of 135 individual beams of sound. Each beam is approximately 1 degree wide. The system can be used to map from 10-5000 m depth.

Three dimensional images of the mounds and surrounding areas were obtained using the EM300 system. Particular attention was given to imaging the area to the east of the mounds which was not covered in the TN 178 cruise. A series of survey lines were set up running parallel to the shoreline. Each survey line was spaced approximately 600 m apart in order to prevent gaps in the data (Fig 4). This is because the width of the swath that the system is able to scan is limited to three times the water depth beneath the ship. The ship’s speed was kept at 4-5 knots to reduce the distance traveled in between pings and obtain the highest image resolution possible.

In addition to the bathymetric survey, sub-bottom profiles were taken using the shipboard Knudsen 320M echo sounder. The system uses a TR-109 3.5 kHz transducer array. Depth soundings from the system are recorded both as printed hard copies, and digitally as seg-y and keb files. A total of four sub-bottom profiles were taken, two for each mound. These profiles consisted of an east to west transect of each mound, and a north to south transect of each mound (Fig. 4). The primary objectives of this survey were to search for any buried landslide features and to determine if and how far the mounds extended below the seafloor. An additional objective of the survey was to help finalize the coordinates for the grab sampling stations on and around the mounds.

Near bottom current measurements were taken using the ship's RDI Acoustic Doppler Current Profiler (ADCP) that has an operating frequency of 75 kHz. The ADCP can measure current speeds over depths from 8-1000 m. The system remained operating throughout the cruise and collected current speed data throughout Hood Canal from the Hood Canal sill to just north of the Great Bend. The focus of these measurements is to obtain information on the near bottom current speeds in Hood Canal in order to test the sediment carrying capacity of the sediments.

Following the survey phase of the field work, was the sampling phase. The sampling phase consisted of two separate sampling schemes. The main sampling scheme involved nine grab sampling stations on and around the mounds, using a Van Veen grab sampler. The bulk of the sampling stations were situated along two axes radiating from the summit of the southern mound. One axis radiated westward from the summit and the other radiated northward from the summit toward the northern mound (Table 1, Fig. 4). This configuration of sampling stations was selected in order to determine how grain sizes were spatially distributed around the mounds. Each grab sample was homogenized before being sub-sampled in order to obtain a representative sample of grain sizes. A total of two grabs were taken on top of the mounds at stations N and Z in order to ensure that the samples from the summits were representative of the material present on the mound summits. During the sampling at station N, large cobbles were recovered in the Van Veen, preventing the sampler from completely closing. As a result of the sampler's inability to completely close, some sediment was washed out before recovering the sampler. Grain size analyses were conducted on the grab samples back at the University of Washington.

The second type of sampling involved a 20x30 cm spade box core for ^{210}Pb accumulation rate analysis back at the University of Washington (Carpenter et al. 1985, Lavelle et al. 1986, and Nittrouer 1978). The core was taken at station A, located north of the mounds near central Hood Canal (Table 1). The location for this station was coordinated with several other student projects in order to economize on ship time. A sub-core was taken of the box core using a PVC pipe 60 cm long and 15 cm in diameter. Sub-samples were taken of the sub-core at 1 cm intervals for the first 15 centimeters starting from the surface layer, then 2 cm intervals for the rest of the core. The sub-samples were bagged and sealed to retain moisture for post cruise ^{210}Pb analysis. Upon retrieval of the box core, the presence of a worm hanging from the bottom of the core was noted. This may have an affect on the results of the ^{210}Pb analysis because it is unclear if the worm was actually present that deep in the sediments or if it was caught when the core closed during recovery. If it was indeed present in the sediment, then it maybe unlikely any accumulation rate data can be obtained due to bioturbation.

The digital 3.5 kHz data was given to Professor Tom Pratt at the University of Washington School of Oceanography so that a migration could be performed on the data. When dealing with acoustic data, the shape of a feature can be distort in the profiles obtained. In cases where the ship is over a flat surface, or over the peak of a submarine feature, the depth data obtained is accurate. However, in cases where a ship is over a slope, the depth reading obtained is actually shallower than in reality. This can result in false contours and shallower slopes showing up in the data. To remove the errors in the data, the seg-y files were ran through a computer program to migrate the data.

Data from the ADCP were taken back to the University of Washington. The portions of the data taken within Hood Canal were extracted then viewed using Matlab, and a profile of current speeds through the water column over time was generated. The Matlab processing and viewing of the data was done using a Matlab script provided by Professor Susan Hautala.

A granulometric analysis of the grab samples was conducted back at the Univeristy of Washingon. Samples of 6-12 grams were measured from each grab sample and mixed in a dispersing agent of 0.05% $NaPO_3$. The samples were then sonicated for 15 min to 1 hour before being wet sieved using a 64 μm sieve. The solutions containing the silt and clay fraction were then analyzed with a Micromeritics Sedigraph 5100 in order to obtain statistics on the grain sizes smaller than 64 μm within the samples. The sedigraph derives its statistics using Stoke's Law for spheres:

$$R=6\pi r\eta v$$

where R is the resistance in g cm/sec^2, r is the radius of the particles, η is the viscosity of the fluid (in this case, the fluid being 0.05% $NaPO_3$), and v is the velocity of the particles.

The coarser materials were dried in pre-weighed tin trays that were placed in an oven and dry sieved using nested sieves of 4, 3, 2, 1, 0, -1, -2, -2.5, and -3 Φ. After dry sieving, the separated grain sizes from each sample were weighed in order to determine the grain size makeup from each grab sample. Initial runs with the sedigraph showed that 6-12 grams of sediment to be insufficient because of very low quantities of silt and clay for reliable readings. To compensate, larger samples of 20-30 grams were measure from each grab and prepared using the methods mentioned previously. This proved sufficient for all but three grabs which still had such low amounts of silt and clay that they required at least two weeks of sitting before sufficient water had evaporated in order to have a high enough concentration of particles in suspension before performing a sedigraph analysis.

The ^{210}Pb analysis performed was modified from Nittrouer 1978. Between 20-30 grams of sediment were weighed in order to ensure at least 5 grams (dry weight) would be available. The samples were placed in an oven to dry. Their dry weight was recorded before the sample was ground with a mortar and pestle. Approximately 5 grams of sediment was taken to conduct the ^{210}Pb analysis. 1 ml of a ^{209}Po spike was added to each sample. The samples were heated to dryness in the presence of 15.8 N HNO_3 then with 6 N HCl (Nittrouer 1978 also included $HClO_4$). The residue was then rinsed into centrifuge tubes and brought to volume (approximately 40 ml), before being placed in a centrifuge. The ^{209}Po and ^{210}Pb were then extracted from the resulting solutions by soaking a silver disc in each solution. These discs were then placed in either an Ortec Octet Plus alpha spectrometer or an Ortec Octet PC alpha spectrometer. The accumulation rate was then calculated using a modified Advection/Diffusion Equation:

$$S = \lambda Z/\ln(A_o/A_z) - (Db/Z)*\ln(A_o/A_z)$$

Where S is the apparent accumulation rate. λ is equal to 0.693 divided by the half life of 210-Pb (22.3 years). Z is equal to the depth of the profile. A_o is the activity at the base of the surface mix layer. A_z is the activity at depth (above the supported value). Db is a mixing coefficient that is used if there is deep mixing present in the core. In this case, the assumption is being made that there was no deep mixing, therefore the Db term is equal to zero.

Results

The EM300 survey was successfully able to show the near shore bathymetry on the eastern side of the mounds which was not covered in by the TN178 cruise (Fig.2 and Fig.5). No landslide scarps or compression ridges were observed. In addition to the eastern side, the EM300 images also obtained parts of the western shoreline slopes of Hood Canal (Fig. 6). The closest near-shore feature to the west of the southern mound shown in the EM300 image is the Lilliwaup delta. The image also shows some displaced material from a landslide originating from the delta.

The images obtained did show a number of peculiar features from both mounds. The first features of interest involve the morphology of the mounds. Both mounds are clearly shown to be elongated features with steep northern slopes and shallower southern slopes (Fig. 5). Another feature of interest is that both mounds are lined up nearly parallel to the shore in a roughly north south orientation (Fig. 5). The images also show that the southern mound has a scarp-like formation where material might have once been.

The processed 3.5 kHz sub-bottom profiles show that the mounds extend below the seafloor. However, there are no indications of any buried landslide scarps or compression ridges. In the case of the northern mound, the formation appears to extend in excess of 20 m below the seafloor (Fig 7, 8). For the southern mound, the profiles indicate that the mound extends nearly 30-40 m below the seafloor (Fig. 9, 10). Furthermore, the profiles of the southern mound also give us a side view of the scarp-like feature on the summit (Fig. 10). Slopes of the north, south, east, and west faces were calculated from the 3.5 kHz profiles. These slopes are 20, 12, 18 and 21 degrees for the northern mound; and 22, 15, 23, and 27 for the southern mound.

The current profiles of Hood Canal showed near bottom currents of between 5-10 cm/s for most of southern Hood Canal and 10-15 cm/s near northern Hood Canal (Fig. 11). This would allow for suspended load transportation of sediments with a 0.1 mm mean grain diameter or less according to the Hjulstrom diagram from Sternberg, 1972 (Fig. 12).

The grain size analysis results were organized using a ternary plot and each grab sample was categorized into one of nine categories (Fig. 13). The sediments were classified using categories from Roberts (1979). All of the samples taken from the mounds (grabs N, N-2, O, Z, and Z-2) consisted of approximately 55-90% sand, 10-40% gravel, and 5-20% mud. Most of the grabs taken away of the mounds (grabs Q, V, W, X, and Y) consisted of 85-95% mud, 5-15% sand, and 0% gravel. Grab P appears to be an outlier. While grab P was taken away from the mounds, its sediment breakdown is similar to those of the mound grabs. All of the grabs taken away from the mounds, with the exception grab P, had a mean grain size of between 8-9 Φ; while the means for the samples taken from the mounds as well as grab P were considerably coarser and ranged from 2-0 Φ (Table 2).

Large cobbles were present in the grab samples taken from stations N and O. These cobbles ranged from approximately 2 cm to in excess of 10 cm in length (Fig.14). A number of these cobbles from station N were encrusted in manganese. Most of the cobbles taken from both N and O were smooth with well rounded edges.

The ^{210}Pb analysis did not show any indication of bioturbation throughout the length of the core. This indicates that the worm that was found in the bottom of the core was not present at depth in the sediments and was likely caught during the pullout of the box core. The activity plot shows that the profile follows the expected exponential decrease in activity with depth (Fig. 15). The activity in the core decreases from about 6.3 dpm/g near the surface of the profile, to approximately 0.2 dpm/g at around 34 cm depth. From these numbers the accumulation rate appears to be approximately 0.31 cm/yr. The activity values were corrected by using a supported activity value of 0.5 dpm/g that was derived from the profile.

Discussion

During the planning stages of this field project, a number of possible explanations as what the mounds were had to be considered. One of the earliest suggestions was that the mounds might be dumpsites for dredge spoils or land modification spoils. Given the large scale and environmental impact of such civic projects, permits and other documentation would have existed. After corresponding with Mason and Kitsap counties, the Washington State Department of Natural Resources, and the US Army Corps of Engineers, no records of any kind of dump site(s) in southern Hood Canal could be found. The Puget Sound Dredged Disposal Analysis (PSDDA) of June 1988 from the US Army Corps of Engineers has shown several existing and alternative disposal sites in

Puget Sound located at Tacoma, Seattle, and Everett; however, there are none Hood Canal.

Another possibility that surfaced early in the project planning was that the mounds could be large cohesive landslide blocks. There are a number of features that landslides have which can be searched for. These include scarps, failure surfaces, displaced mass, and compression ridges (Hampton et al. 1996). In some cases, the displaced mass can move beyond the rupture surface. The images obtained by the EM300 multibeam echo sounder clearly show both the mounds and the slope leading to the eastern shoreline of Hood Canal (Fig. 5). The shoreline slope is smooth and continuous without any indication of a rupture surface, or a scarp. To the west of the northern mound is a hint of a ridge. However, the lack of a rupture surface or scarp makes the landslide explanation highly unlikely.

While the EM300 data did not show any landslide features, it is possible that some features such as compression ridges, scarps, and rupture surfaces can be buried over time (Hampton et al. 1996, Greene et al. 2006). The east-west 3.5 kHz profiles of both mounds showed that the mounds do indeed extend below the seafloor by 20-40 m (Fig. 7 and Fig. 10). However, these profiles still did not show any indications of buried landslide features.

Based off of the profiles, the southern mound is now estimated to be 63 m tall, 400 m across, and 530 m long as opposed to the original estimate of 35x350x450 m based on the TN178 EM300 data. So if we were to assume that the southern mound had a radius of 233 m, the estimated volume would be 3.6 million m^3. This is roughly double that of the original 1.7 million m^3 estimate. Furthermore, the depth to which the mounds extend beneath the seafloor indicates that the features are potentially very old, perhaps dating back to the last glacial period. If so, this would completely preclude the possibility of civic dumping as the origin of the features.

The last possible origin for the mounds that came up in the project planning was glacial features such as moraines or other similar features. As mentioned previously, the 3.5 kHz subbottom profiles indicated that the mounds extended 20-40 m below the seafloor, thus indicating that the mounds are potentially glacial. Using the apparent accumulation rate derived from the ^{210}Pb analysis of the box core taken from station A, an approximate age of mounds of 12400 yrs was calculated using an apparent accumulation rate of 0.31 cm/yr and a depth of 40 m (Fig. 10). This age estimate is based off of the assumption that the accumulation rate has remained constant over time.

In addition to the 3.5 kHz subbottom profiles, the results of the granulometric analysis were also able to further distinguish the mounds from the surrounding seafloor. The grabs taken from the surroundings of the mounds (grabs Q, V, W, X, and Y) consisted of fine sediments of at least 80% mud with the remaining 20% or less being composed of sand and no gravel. In contrast both of the mounds (grabs N, N-2, O, Z, and Z-2) contained approximately 20% mud or less with the remainder being some combination of sand and gravel (Fig. 13). The ternary plot shows a large disparity between the two grab samples taken at station N. Grab N falls into the gravely-sand category while N-2 falls into the sandy-gravel category. This disparity is likely due to the large cobbles that were present in both grabs from station N (Fig. 14) which prevented the grab sampler from completely closing and causing partial washouts of the samples. The differences in the size composition of the sediments between the mounds and their surroundings are also reflected in the mean grain sizes where the mounds have an average size of 2-0 Φ which is substantially coarser than the off mound grabs which have a mean size between 9-8Φ (Table 2).

The results of the granulometric analysis suggest that the mean grain size of the sediments surrounding the mounds is roughly between 9-8 Φ. This translates to a particle diameter as small as 2 μm. This is in conflict with the ADCP profile that shows near bottom current velocities to be roughly 5-10 cm/s (Fig. 11). According to the Hjulstrom diagram (Fig. 12), average current velocities of 10 cm/s will allow for suspended load transport of sediments with and average diameter of 0.1 mm or less. Light transmission levels from a CTD cast taken near the mounds shows a nepheloid layer below 100 m depth where the light transmission decreases from a max of 84% above 100 m to 77% at the bottom. It is possible that the unexpectedly fine grain sizes from the off mound grabs is the result of river deposits and landslides from the nearby Lilliwaup delta (Fig. 6).

Another peculiarity is station P which was located to the north west of the southern mound (Fig. 4). Even though station P is not located on the mound or directly on the base of the mound, its sediment size characteristics are very similar to those of the mounds instead of the other off mound grabs (Table 2, Fig. 13). This could indicate landslides or slumps have taken place on the western face of the southern mound and deposited some of the material from the mound at the location of station P. In general, slopes composed of marine sediments become unstable at inclines in excess of 17.5^{o} (Lee, 1986). In the case of the southern mound, it is likely that the strength of the slopes is more robust than in the case of normal marine sediments. However, given that the slope of the western face of the mound is estimated to be near 27° it is possible that the slope is or has been on the border of being unstable.

Ultimately, these mounds appear to be isolated piles of coarse and poorly sorted debris, also known as diamicts. Over time, they have been partially covered by post glacial sediments. These types of formations can be created by a number of mechanisms such as ice rafting in which an iceberg breaks from the calving margin of a glacier. The iceberg carries debris which is then dumped when the iceberg melts (Powell, 1984). Also subglacial mechanisms such as subglacial outwash may leave behind diamicts. As the welt water from under a glacier is forced out of the glacial margin under pressure from the weight of the ice, material can then be carried from under the glacier by the outwash stream from a point source at the glacial margin (Hart 1994, and Lonne 1995).

Even though there are a wide variety of glacial formations to choose from, the mounds do have a number of features that tend to point to one particular type of glacial formation called a drumlin. The EM300 images of the mounds show that both features are elongated with steep stoss-sides and shallow lee-sides (Fig. 5). The northern mound showed a slope approximately 20 degrees on the northern face and a slope of 12 degrees on the southern slope. Likewise, the southern mound showed a slope of 22 degrees on its northern face and 15 degrees on its southern face. These features are characteristic of "classical drumlins" (Hart 1997, and Knight 1997).

Drumlin formations in the Puget Lowland are not uncommon. In fact the Puget Lowland contains a drumlin field 170 km long and 100 km wide (Fig. 16). Analysis of the 3.5 kHz subbottom profiles from previous cruises into Hood Canal has revealed the presence of numerous mound shaped features. However, many of these features either do not, or just barely break the seafloor surface (Fig. 17). Based on three 3.5 kHz tracks from past cruises, there are at least 11 possible features located to the north and south of the mounds within Hood Canal (Fig. 18).

Future studies focused on the internal structure and makeup of the mounds would be necessary to better classify them. The Van Veen grab sampler is limited to obtaining surface sediments. Furthermore, subbottom profiles of the mounds' interiors were not possible because of limitations of the 3.5 kHz subbottom profiler.

Conclusions

3.5 kHz sub-bottom profiles of the Hood Canal mounds have shown that the mounds extend 20 m or more below the seafloor. This indicates that the mounds are likely quite old, perhaps dating back to the last glacial period. Images taken using an EM300 multibeam system showed that the mounds are elongated features with steeper northern slopes compared to their southern slopes. The apparent age of the mounds along with their peculiar morphology indicate that the mounds may be drumlins that were formed as a result of the Cordilleran ice sheet during the last glacial period.

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Sternberg, R. W. 1972. Predicting Initial Motion and Bedload Transport of Sediment Particles in the Shallow Marine Environment 61-82. *In* D. J. P. Swift, D. B. Duane, and O. H. Pilkey [eds.], Shelf Sediment Transport Process and Pattern

Table 1. Coordinates of all samples taken from the mounds and surrounding areas. Station A is the box core that was taken north of the mounds near central Hood Canal. The remainder are grab sample stations located on or around the mounds. Note that stations Z and N have repeat grabs at the same location as indicated by the number 2.

Station	Latitude	Longitude
A	47-32.79	123-00.49
Y	47-27.39	123-04.98
Z	47-27.45	123-04.67
Z-2	47-27.35	123-04.7833
X	47-27.2147	123-04.9224
W	47-27.1143	123-05.0259
V	47-26.9982	123-05.1982
N	47-26.8697	123-05.3202
N-2	47-26.8707	123-05.3204
O	47-26.9226	123-05.4218
P	47-26.9780	123-05.5208
Q	47-27.0399	123-05.6227

Table 2. Grab samples and their respective mean grain sizes.

Station	Mean Φ
P	0.58
N	0.50
N-2	-0.55
Z	1.50
Z-2	2.05
O	2.33
X	8.65
V	8.78
Y	8.43
Q	8.88
W	8.80

Figures

Fig. 1: A chart showing the general location of the mounds in Hood Canal. The inset shows the location of the mounds in relation to Puget Sound as a whole.

Fig. 2: The EM300 image taken in 2005 from the *R/V Thomas G. Thompson* during the TN178 cruise.

Fig. 3: A 3.5 kHz profile of the southern mound taken from the TN178 cruise showing possible signals from real subbottom reflections or diffractions.

Fig. 4: The tracks for the EM300 and 3.5 kHz surveys as well as locations for the grab samples in relation to the mounds.

Fig. 5: The image taken from the EM300 survey of the mounds and surrounding area. Note that there is a 6 to 1 vertical exaggeration. This image has not been edited to remove bad pings and high frequency nadir noise along the survey tracks.

Fig. 6: The EM300 data with contour lines superimposed showing the nearby Lilliwaup delta (circled), and possible landslide from the delta (boxed). The contours highlighted in light blue represent the actual shoreline. This image has not been edited to remove bad pings and high frequency nadir noise along the survey tracks.

Fig. 7: The 3.5 kHz east to west subbottom profile of the northern mound. Panel (A) shows the migrated data. Subbottom reflectors from the mound are circled. Panel (B) shows the un-migrated data.

Fig. 8: The 3.5 kHz north to south subbottom profile of the northern mound. Panel (A) shows the migrated data. Subbottom reflectors from the mound are circled. Panel (B) shows the un-migrated data.

Fig. 9: The 3.5 kHz north to south subbottom profile of the southern mound. Panel (A) shows the migrated data. Subbottom reflectors from the mound are circled. Panel (B) shows the un-migrated data.

Fig. 10: The 3.5 kHz east to west subbottom profile of the southern mound. Panel (A) shows the migrated data. Subbottom reflectors from the mound are circled. Panel (B) shows the un-migrated data.

Fig. 11: A profile of current speeds taken with the ship's ADCP during the time spent in Hood Canal.

Fig. 12: A Hjulstrom diagram showing the relationship between flow velocity, grain size, and state of sediment movement. Taken from Sternberg (1972).

Fig. 13: A ternary plot showing sediment composition of the grab samples using the sediment classification from Roberts (1979).

Fig. 14: Photographs of cobbles recovered from the grab samples. Panel (A) shows cobbles from the first grab at station N. The black color on the cobble in the upper right is a manganese layer. Panel (B) shows cobbles from the second grab at station N. Panel (C) shows cobbles taken from station O. Refer to Fig. 4 and Table 1 for locations of the grab stations.

Fig. 15: An activity plot from the ^{210}Pb accumulation rate analysis of the box core taken from station A near central Hood Canal.

Fig. 16: A chart showing the locations and orientations of other known drumlins in the Puget Lowland. Taken from Goldstein (1994)

Fig. 17: A 3.5 kHz subbottom profile from a previous *R/V Thomas G. Thompson* cruise showing other buried or partially buried mounds in Hood Canal.

Fig. 18: A chart of Hood Canal showing the locations of other buried or partially buried mounds. The locations are based on only 3 subbottom profile tracks and are not intended to show the location of all the possible mounds in Hood Canal.

Figure 1

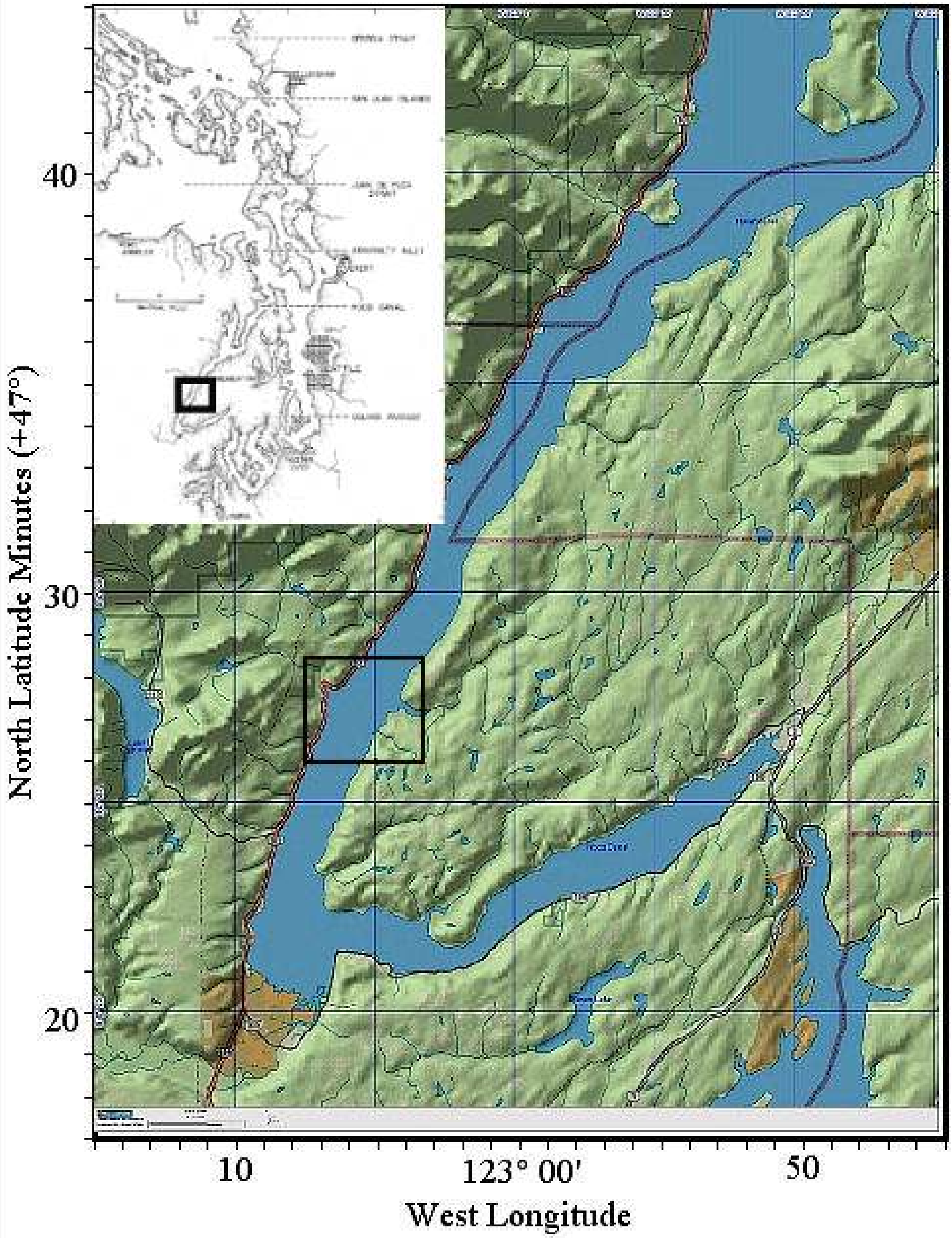
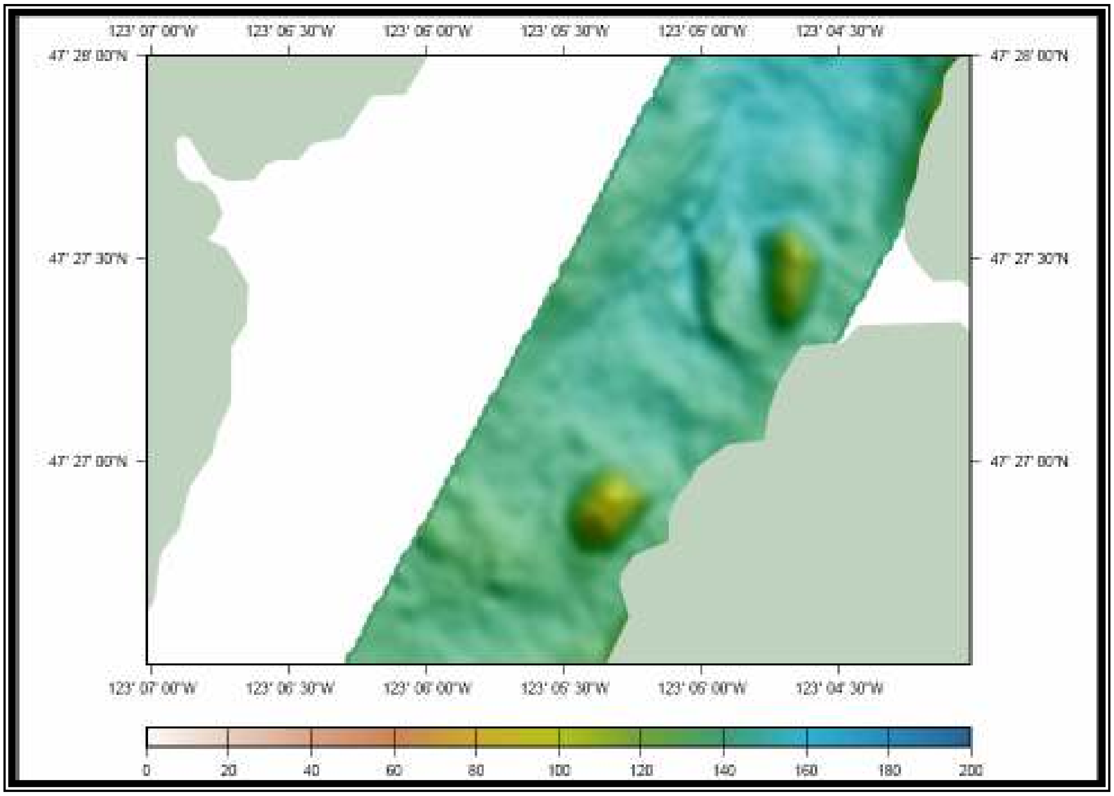

40
30
20
North Latitude Minutes (+47°)
10
123° 00′
50
West Longitude

Figure 2



123° 07' 00"W
123° 06' 30"W
123° 06' 00"W
123° 05' 30"W
123° 05' 00"W
123° 04' 30"W
47° 28' 00"N
47° 27' 30"N
47° 27' 00"N
0
20
40
60
80
100
120
140
160
180
200

Figure 3

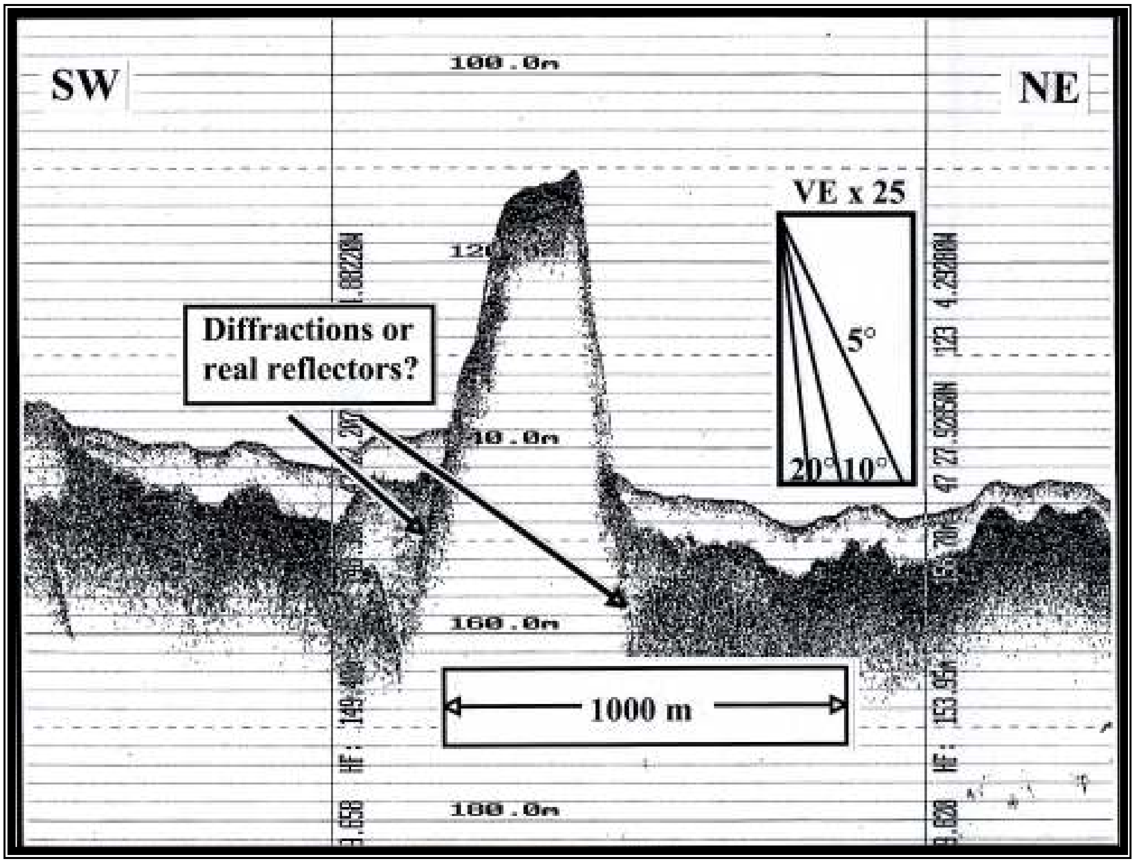

Diffractions or real reflectors?

Figure 4

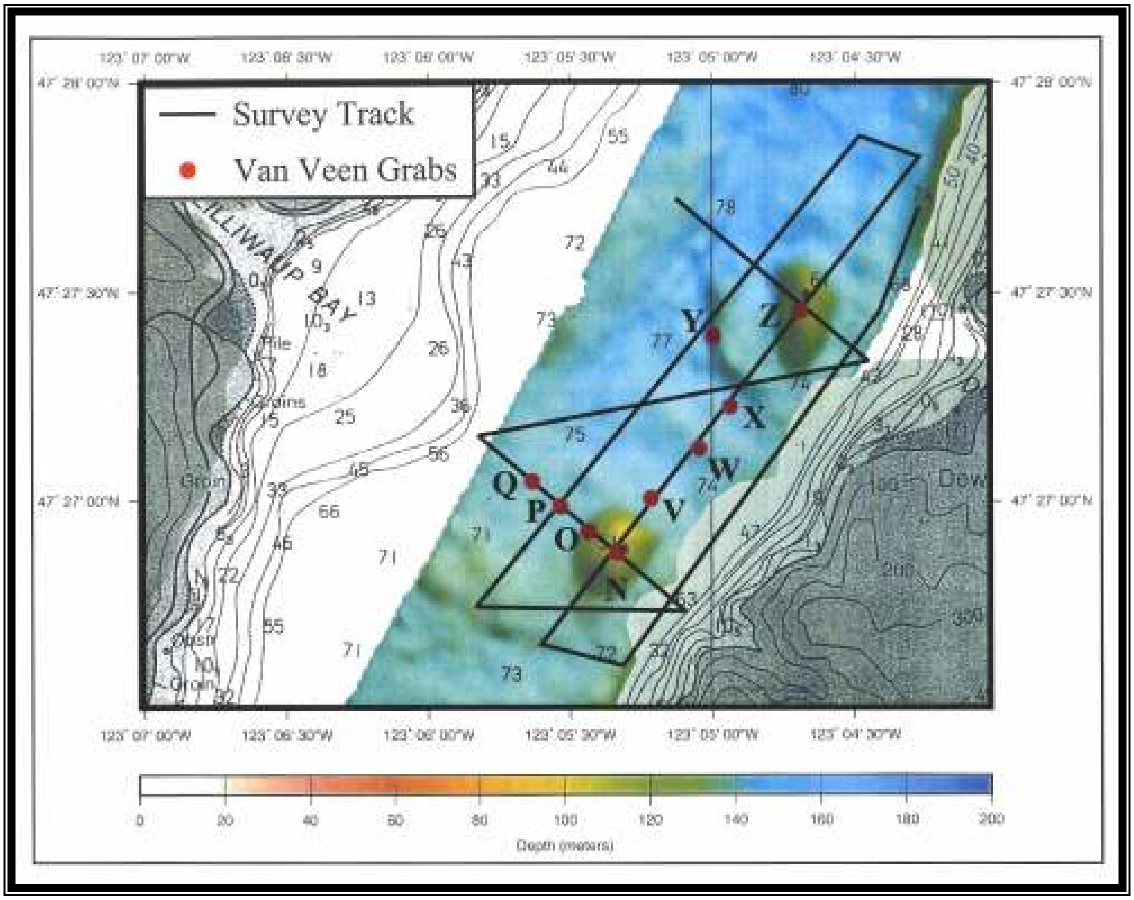

Survey Track
Van Veen Grabs
LILLIWAUP BAY
Q
P
O
N
V
W
X
Y
Z
123° 07' 00"W
123° 06' 30"W
123° 06' 00"W
123° 05' 30"W
123° 05' 00"W
123° 04' 30"W
47° 28' 00"N
47° 27' 30"N
47° 27' 00"N
0
20
40
60
80
100
120
140
160
180
200
Depth (meters)

Figure 5

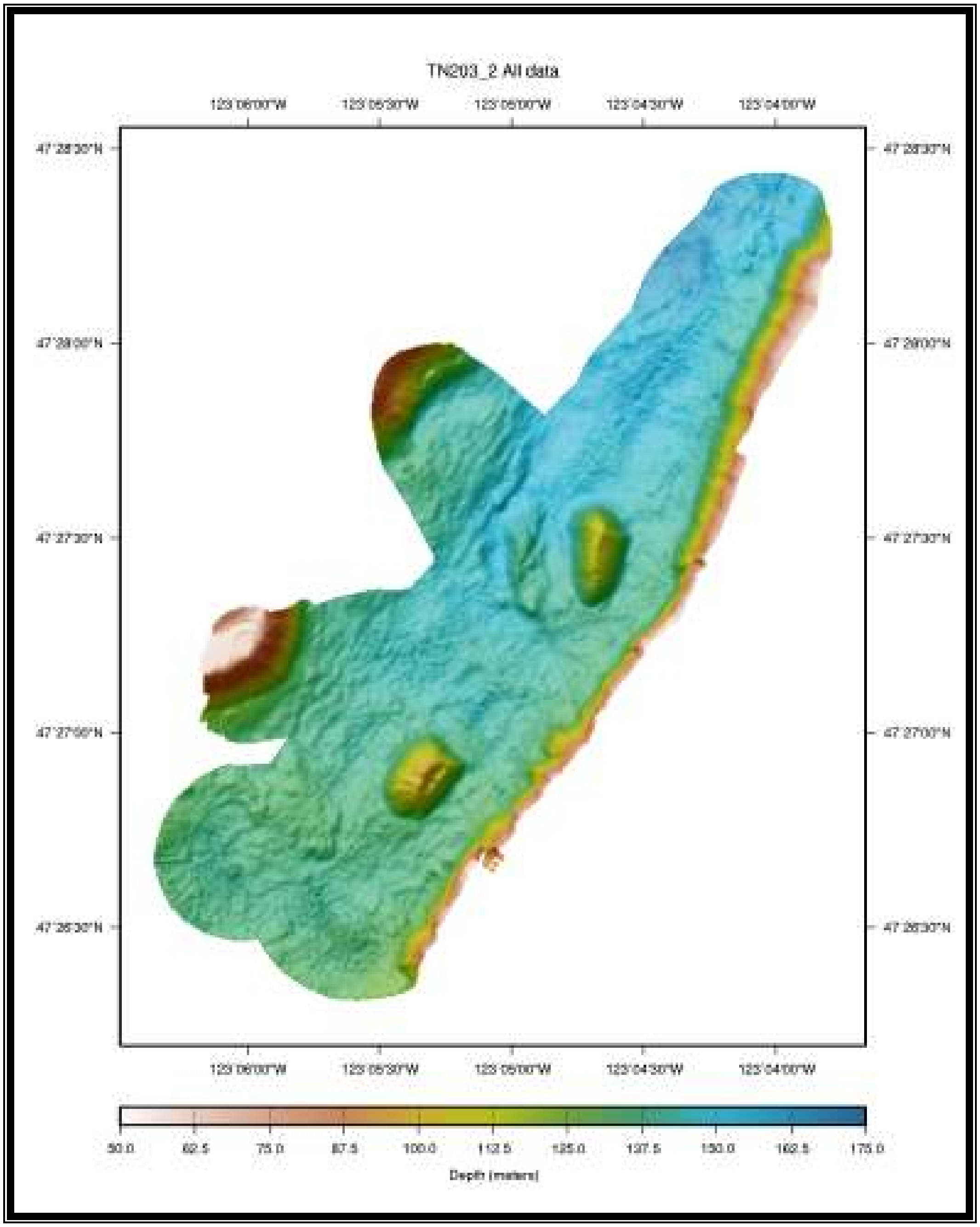

TN203_2 All data
123°06'00"W
123°05'30"W
123°05'00"W
123°04'30"W
123°04'00"W
47°28'30"N
47°28'00"N
47°27'30"N
47°27'00"N
47°26'30"N
50.0
62.5
75.0
87.5
100.0
112.5
125.0
137.5
150.0
162.5
175.0
Depth (meters)

Figure 6

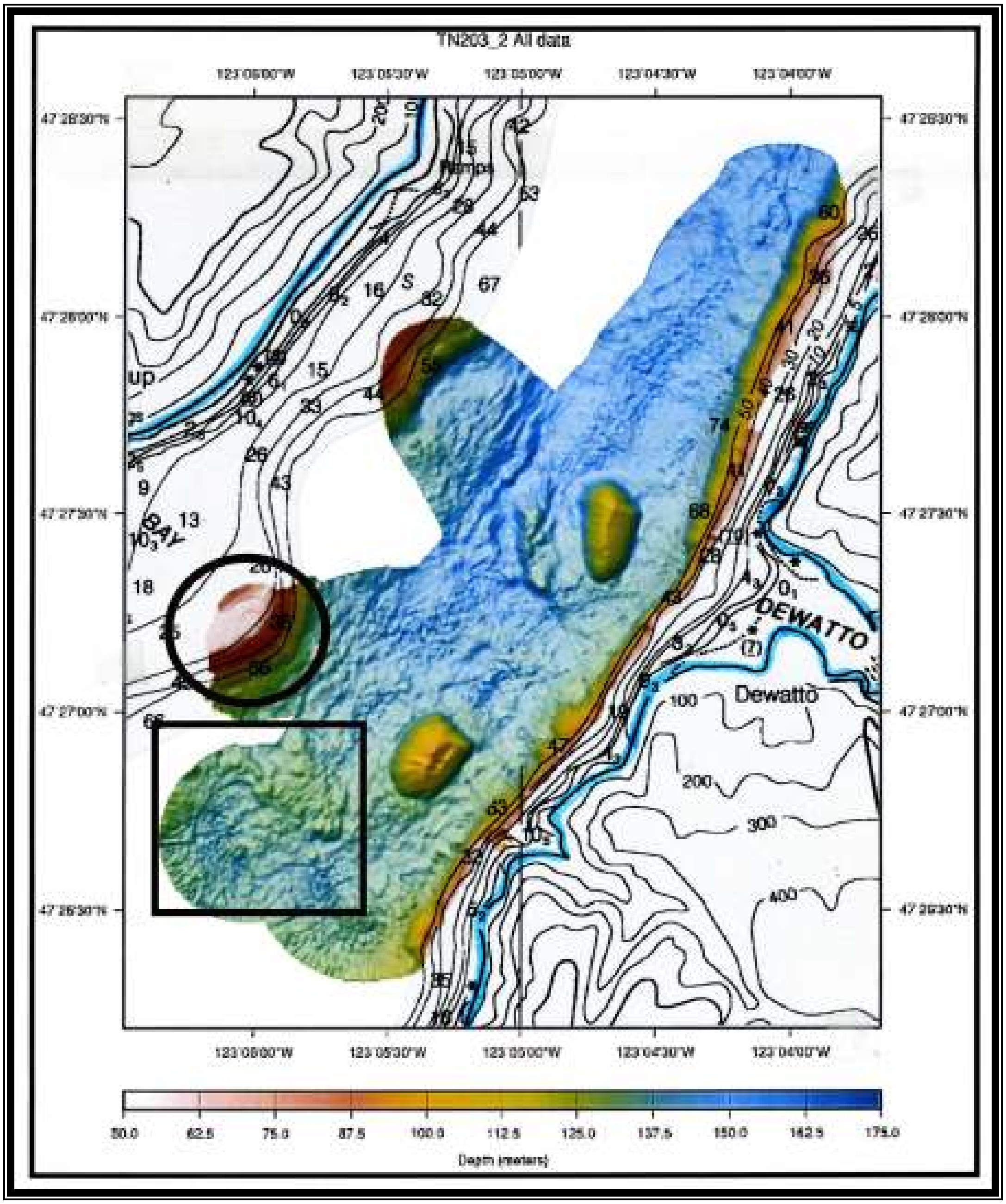
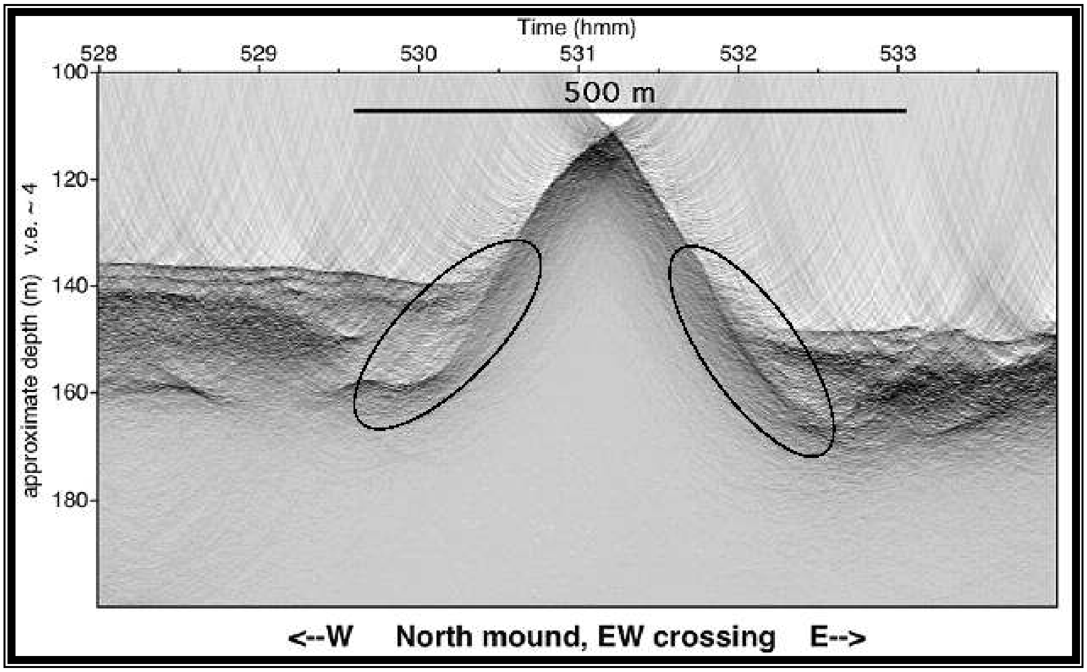

TN203_2 All data
123°06'00"W
123°05'30"W
123°05'00"W
123°04'30"W
123°04'00"W
47°28'30"N
47°28'00"N
47°27'30"N
47°27'00"N
47°26'30"N
BAY
DEWATTO
Dewatto
100
200
300
400
50.0
62.5
75.0
87.5
100.0
112.5
125.0
137.5
150.0
162.5
175.0
Depth (meters)

Figure 7

A)


Time (hmm)
528
529
530
531
532
533
100
120
140
160
180
approximate depth (m) v.e. ~ 4
500 m
<--W North mound, EW crossing E-->

B)

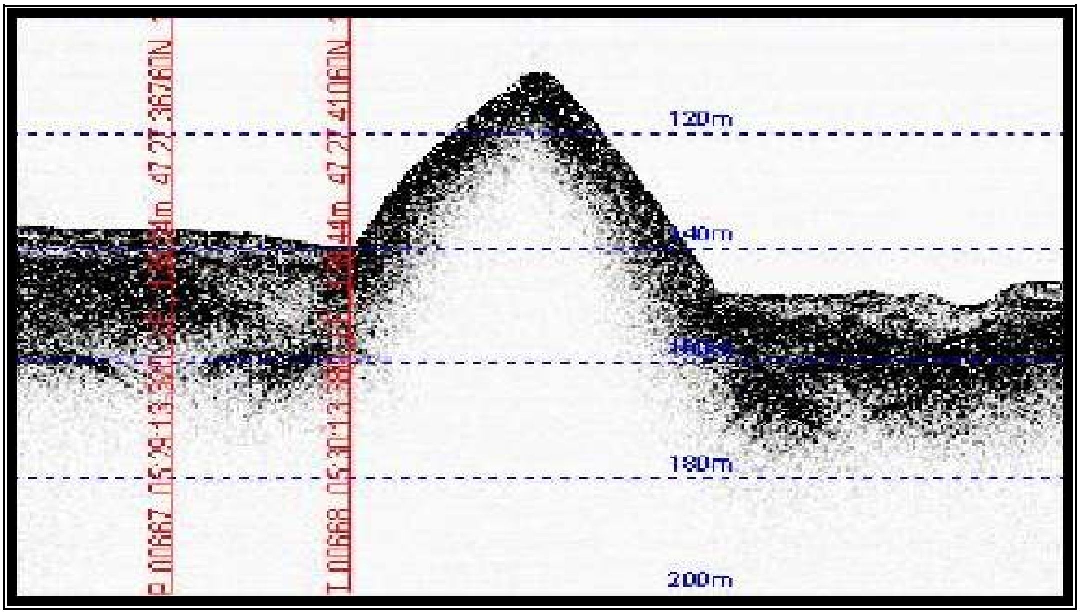
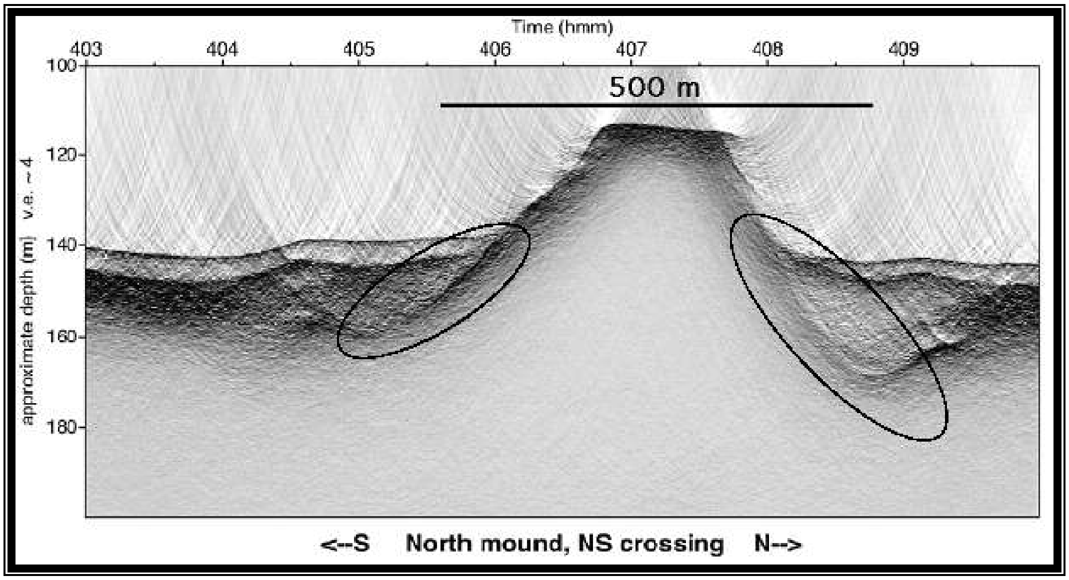

47 27.3876N
47 27.4106N
120m
140m
160m
180m
200m

Figure 8

A)


Time (hmm)
403
404
405
406
407
408
409
500 m
approximate depth (m) v.e. ~4
100
120
140
160
180
<--S North mound, NS crossing N-->

B)

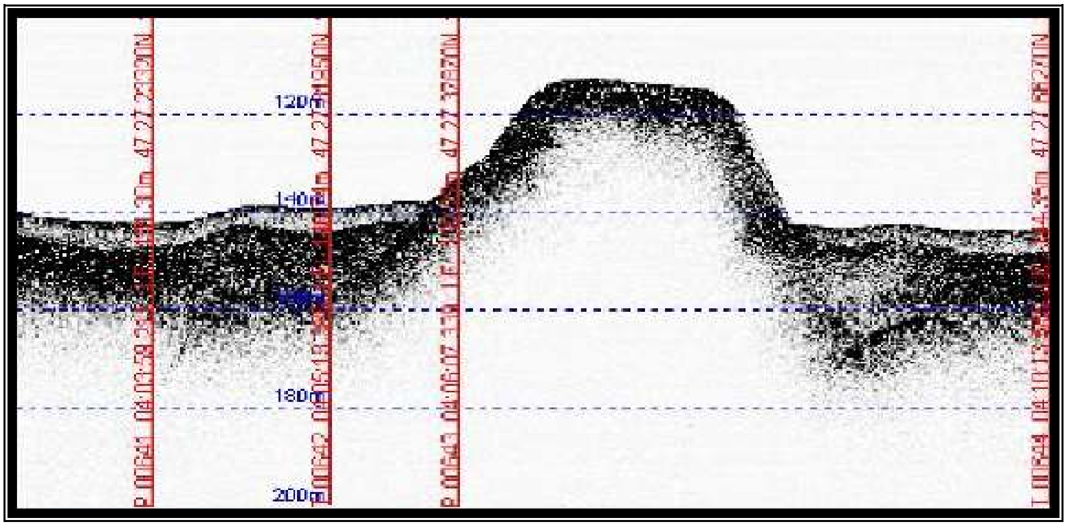

120m
140m
180m
200m

Figure 9

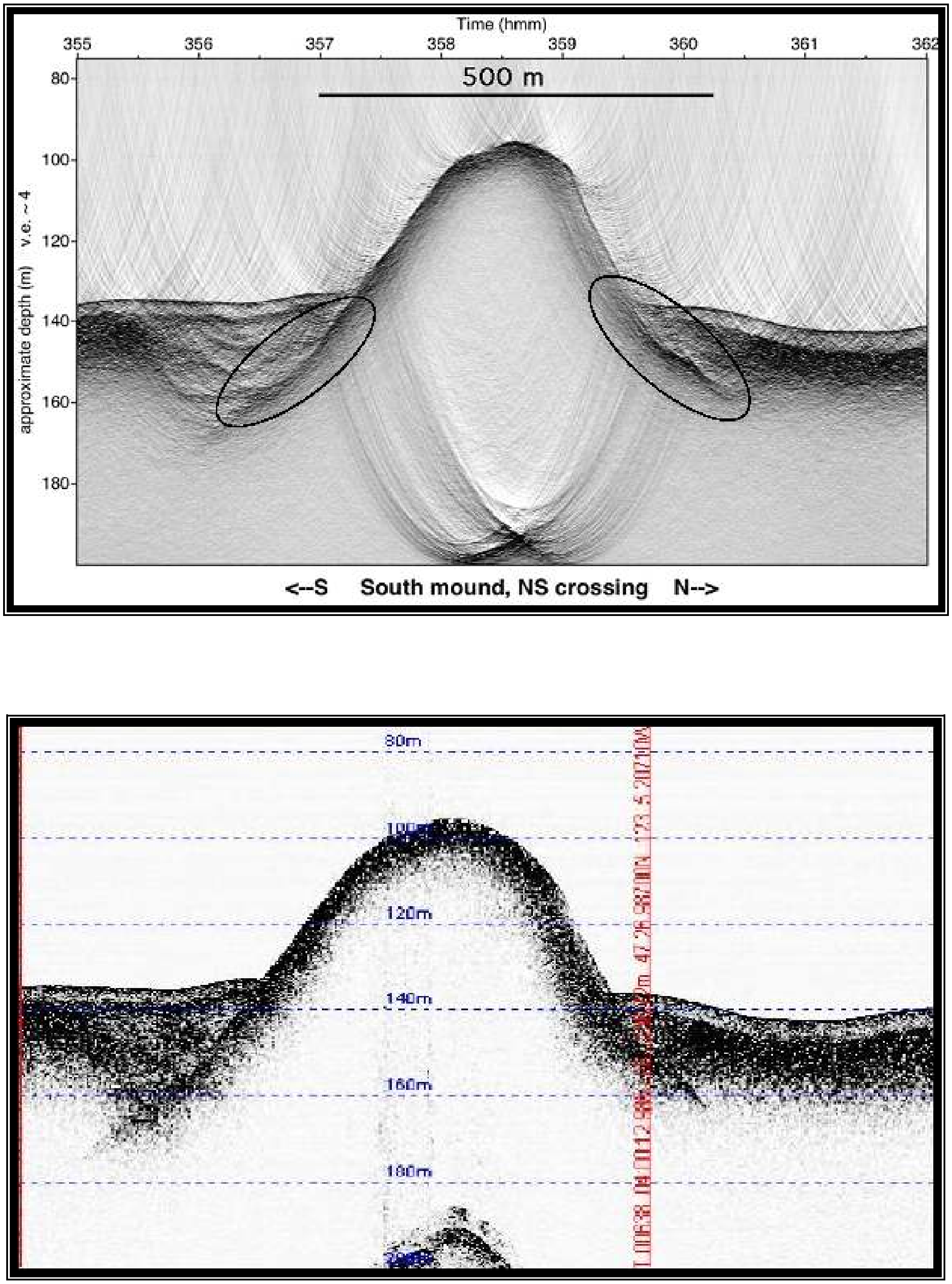
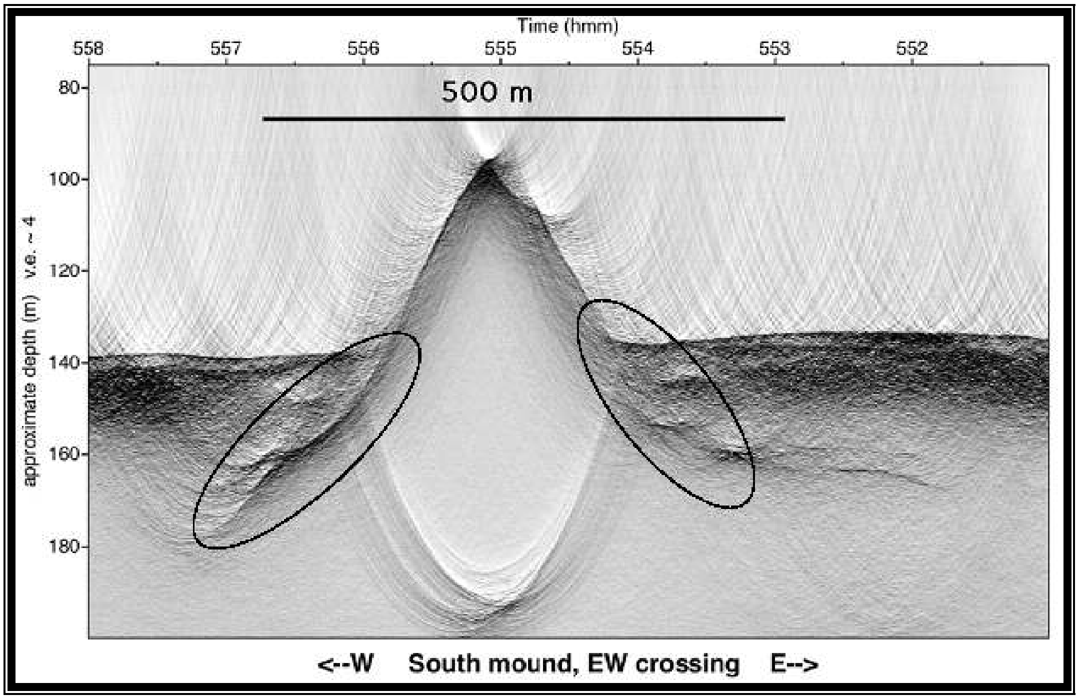

A)
Time (hmm)
355
356
357
358
359
360
361
362
500 m
80
100
120
140
160
180
approximate depth (m) v.e. ~4
<--S South mound, NS crossing N-->
B)
80m
100m
120m
140m
160m
180m
200m

Figure 10

A)


Time (hmm)
558
557
556
555
554
553
552
500 m
approximate depth (m) v.e. ~ 4
80
100
120
140
160
180
<--W South mound, EW crossing E-->

B)

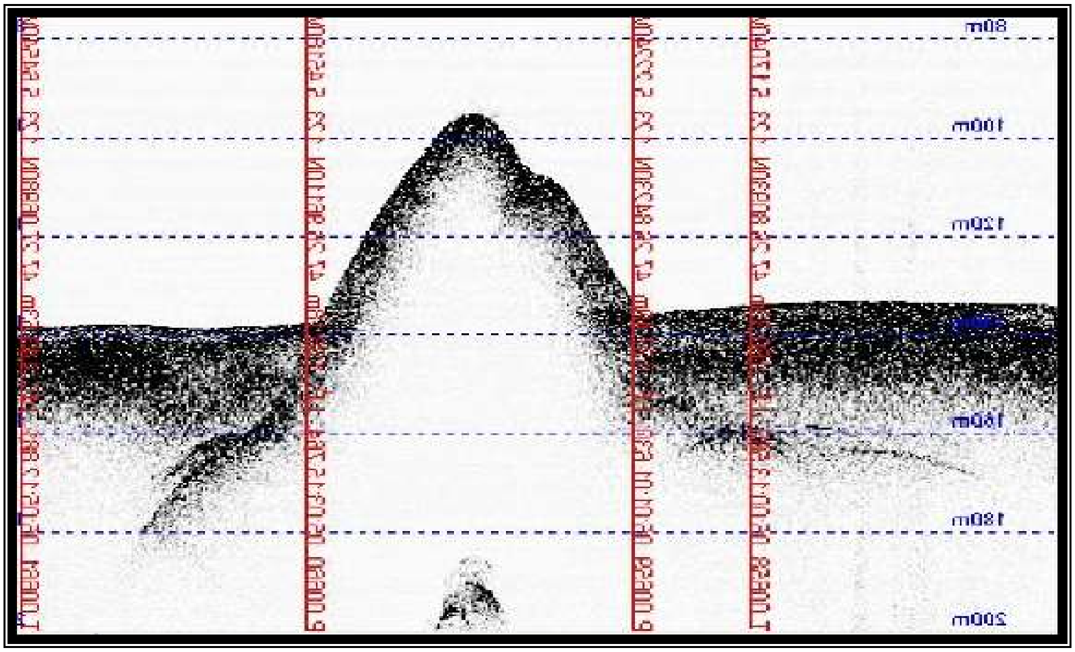
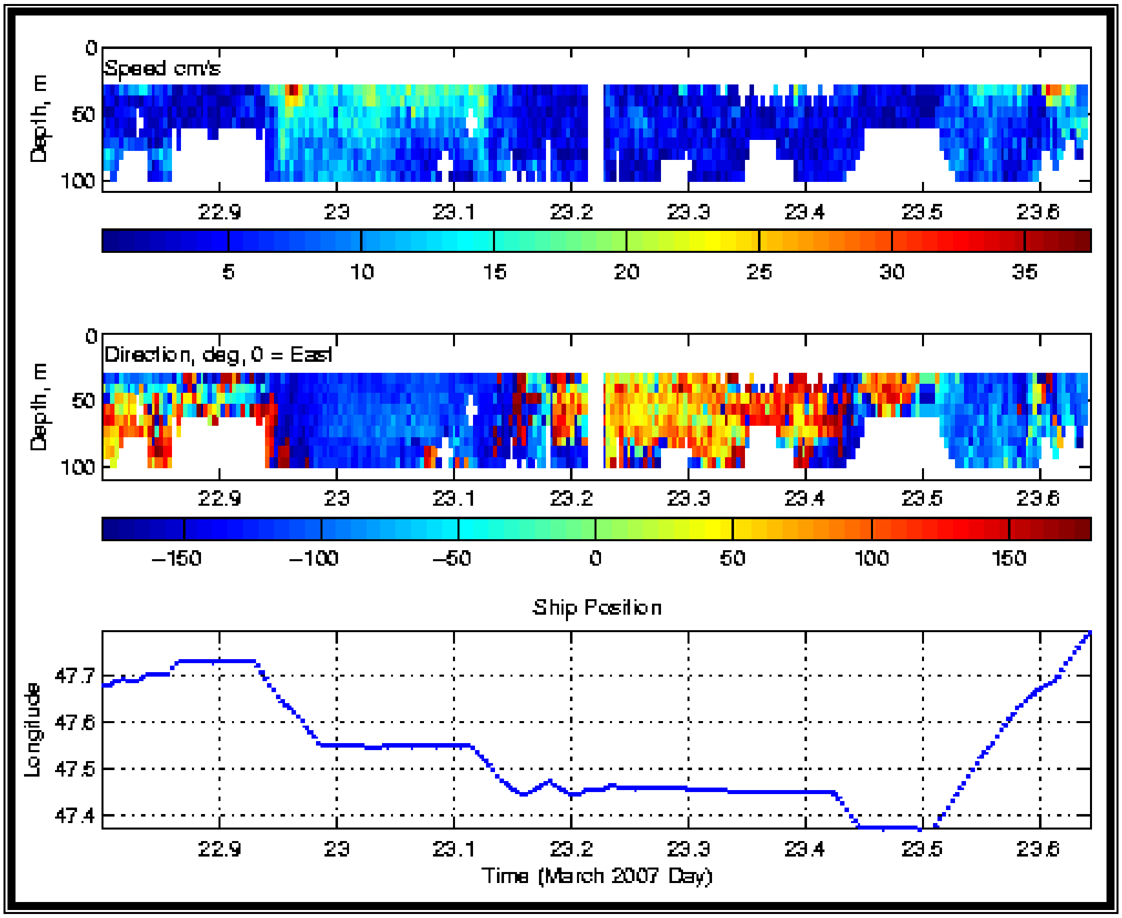
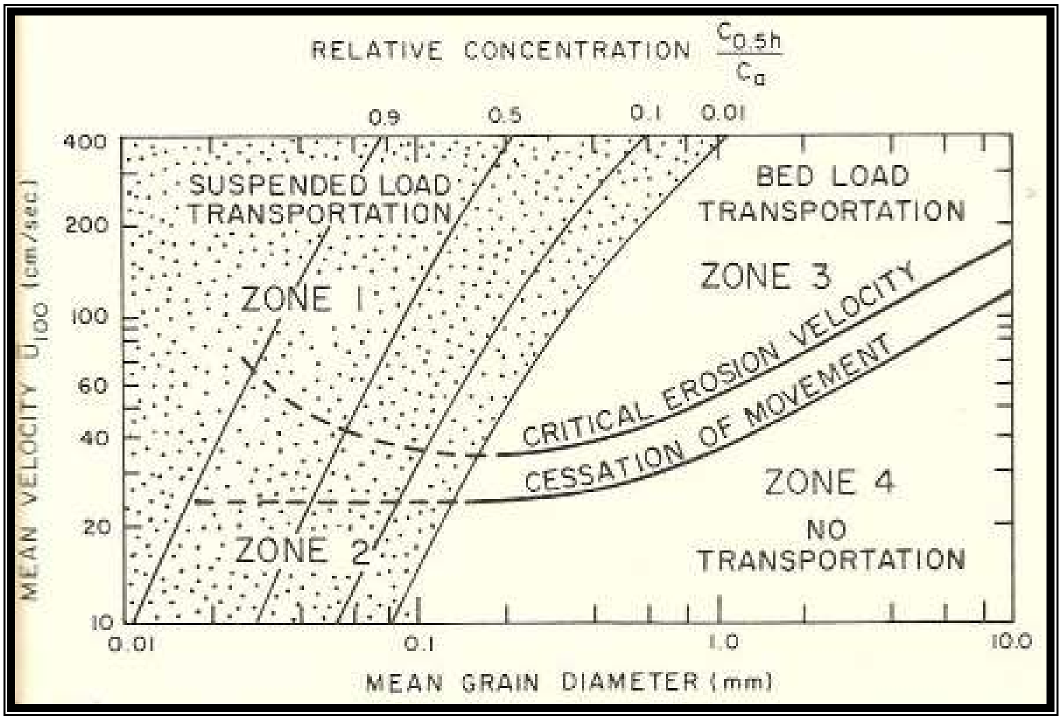

80m
100m
120m
160m
180m
200m

Figure 11



Speed cm/s
Depth, m
0
50
100
22.9
23
23.1
23.2
23.3
23.4
23.5
23.6
5
10
15
20
25
30
35
Direction, deg, 0 = East
Depth, m
0
50
100
22.9
23
23.1
23.2
23.3
23.4
23.5
23.6
−150
−100
−50
0
50
100
150
Ship Position
Longitude
47.7
47.6
47.5
47.4
22.9
23
23.1
23.2
23.3
23.4
23.5
23.6
Time (March 2007 Day)

Figure 12



RELATIVE CONCENTRATION $\frac{C_{0.5h}}{C_a}$
0.9
0.5
0.1
0.01
SUSPENDED LOAD TRANSPORTATION
ZONE 1
ZONE 2
BED LOAD TRANSPORTATION
ZONE 3
CRITICAL EROSION VELOCITY
CESSATION OF MOVEMENT
ZONE 4
NO TRANSPORTATION
MEAN VELOCITY U_{100} (cm/sec)
400
200
100
60
40
20
10
0.01
0.1
1.0
10.0
MEAN GRAIN DIAMETER (mm)

Figure 13

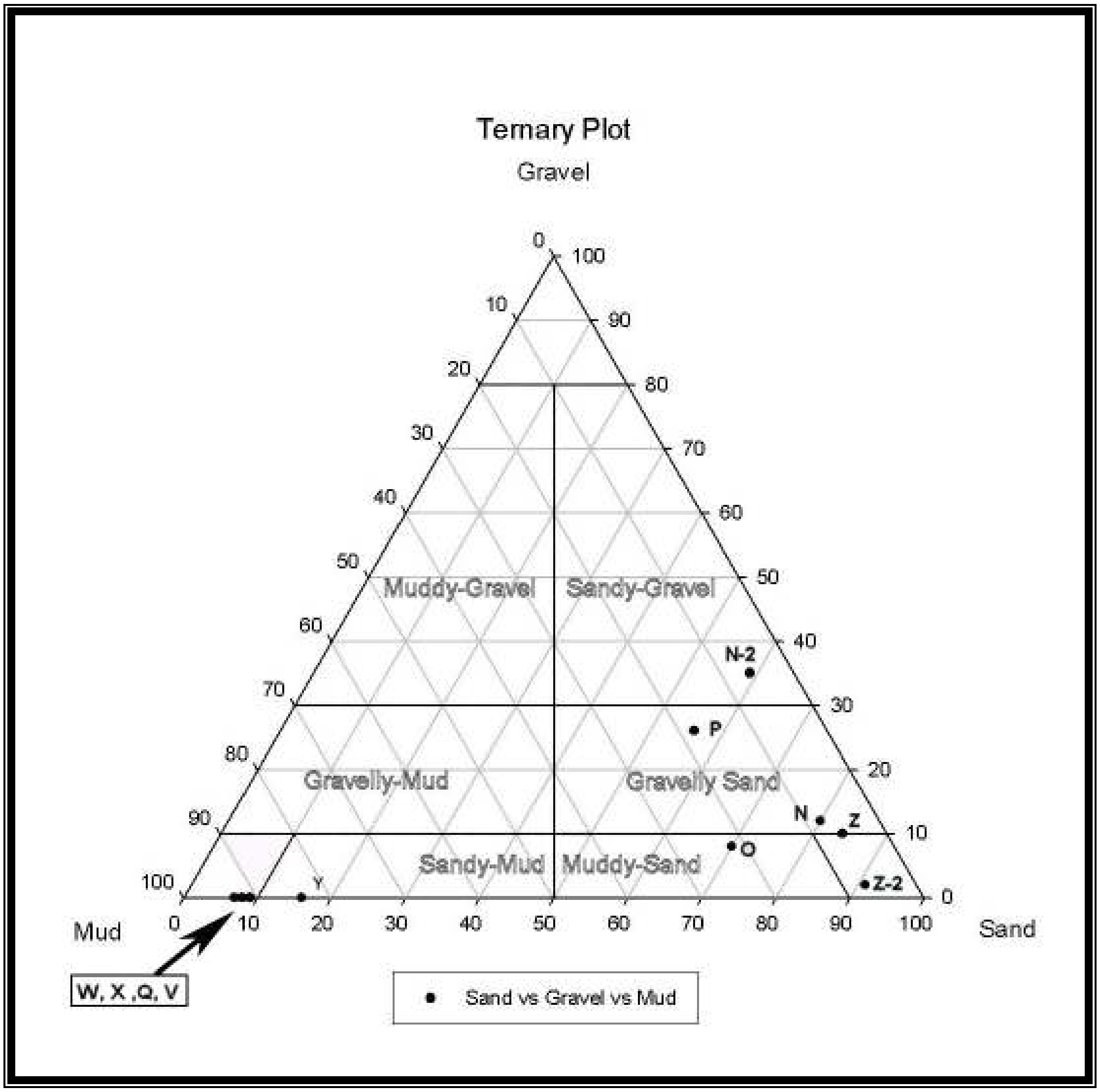

Ternary Plot
Gravel
Mud
Sand
0
10
20
30
40
50
60
70
80
90
100
Muddy-Gravel
Sandy-Gravel
Gravelly-Mud
Gravelly Sand
Sandy-Mud
Muddy-Sand
N-2
P
N
Z
O
Z-2
Y
W, X ,Q, V
Sand vs Gravel vs Mud

Figure 14

A)

B)

C)

Figure 15

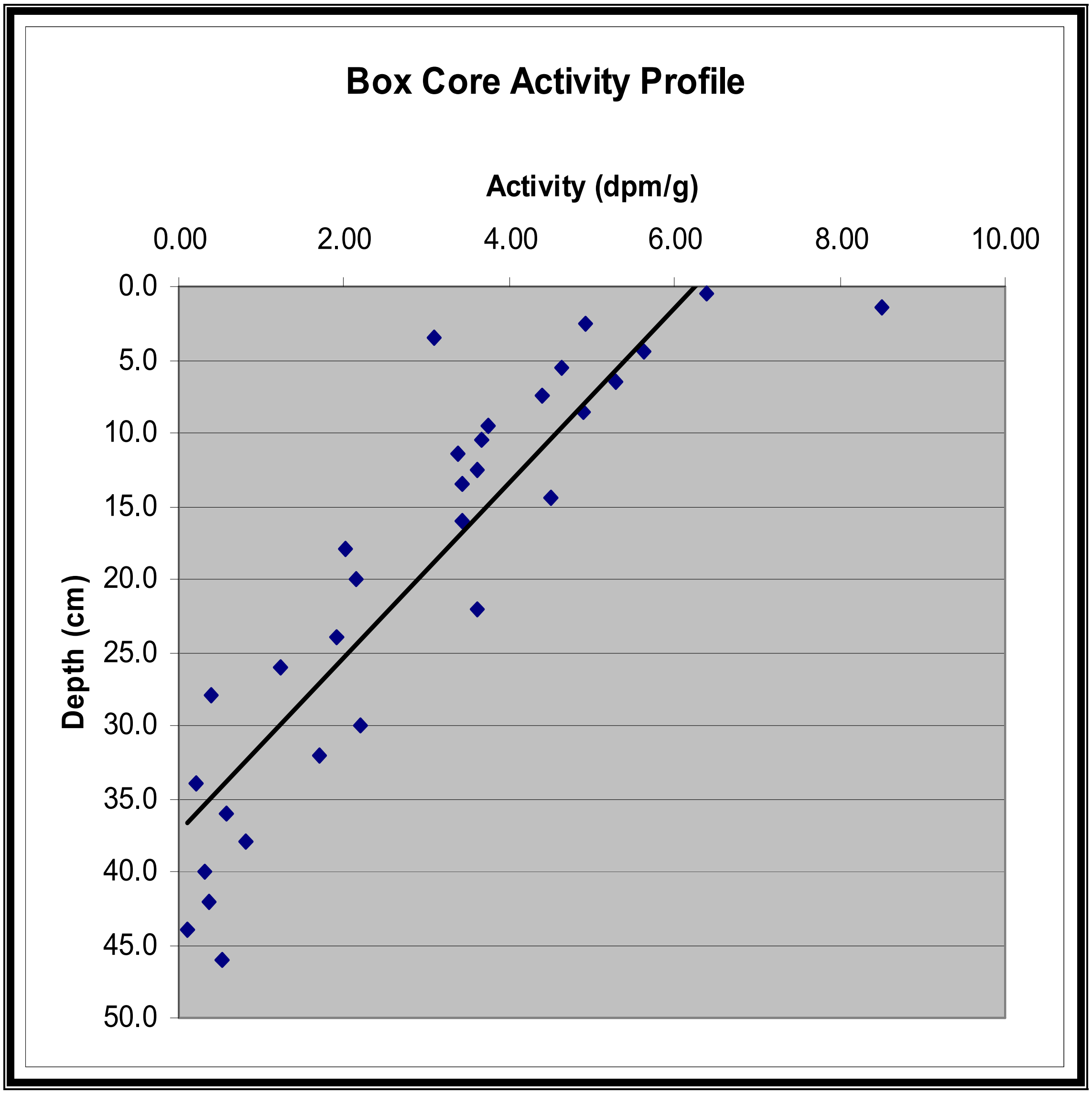

Box Core Activity Profile
Activity (dpm/g)
0.00
2.00
4.00
6.00
8.00
10.00
Depth (cm)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0

Figure 16

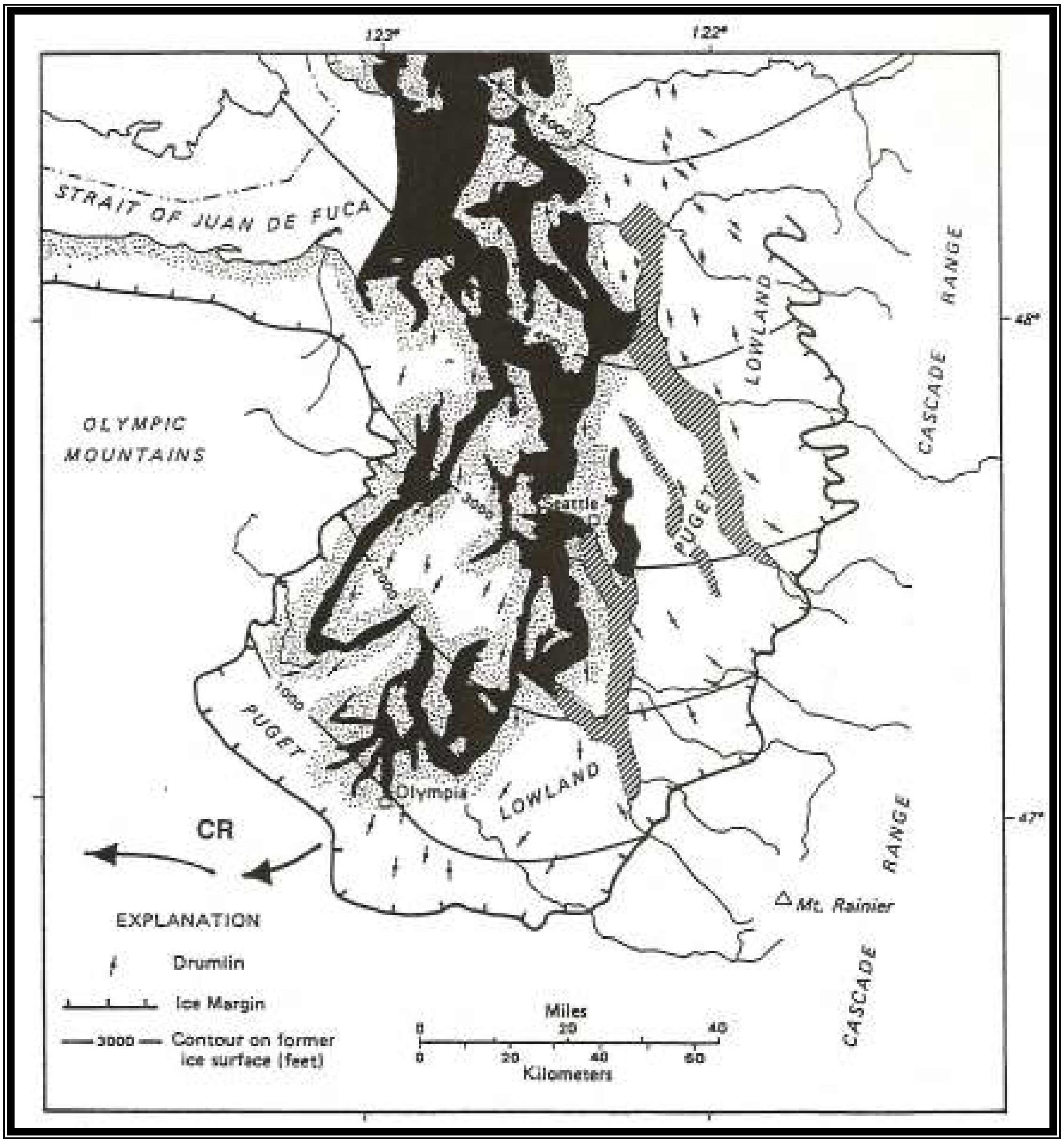

123°
122°
48°
47°
STRAIT OF JUAN DE FUCA
OLYMPIC MOUNTAINS
PUGET LOWLAND
PUGET LOWLAND
CASCADE RANGE
CASCADE RANGE
5000
3000
2000
1000
Seattle
Olympia
Mt. Rainier
CR
EXPLANATION
Drumlin
Ice Margin
3000 Contour on former ice surface (feet)
Miles
0 20 40
0 20 40 60
Kilometers

Figure 17

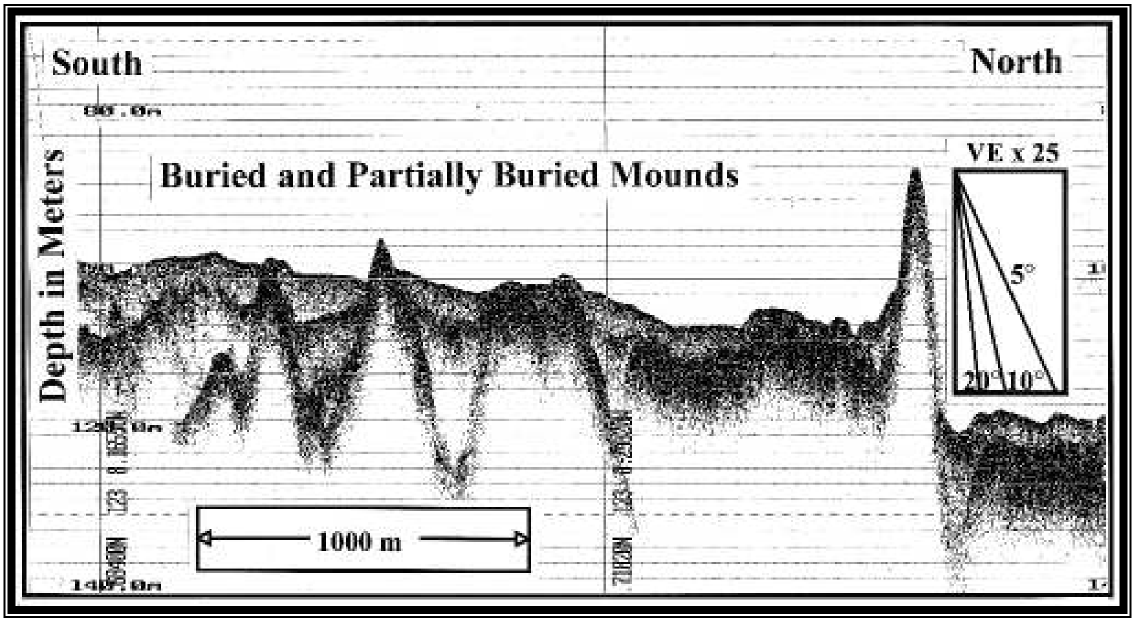
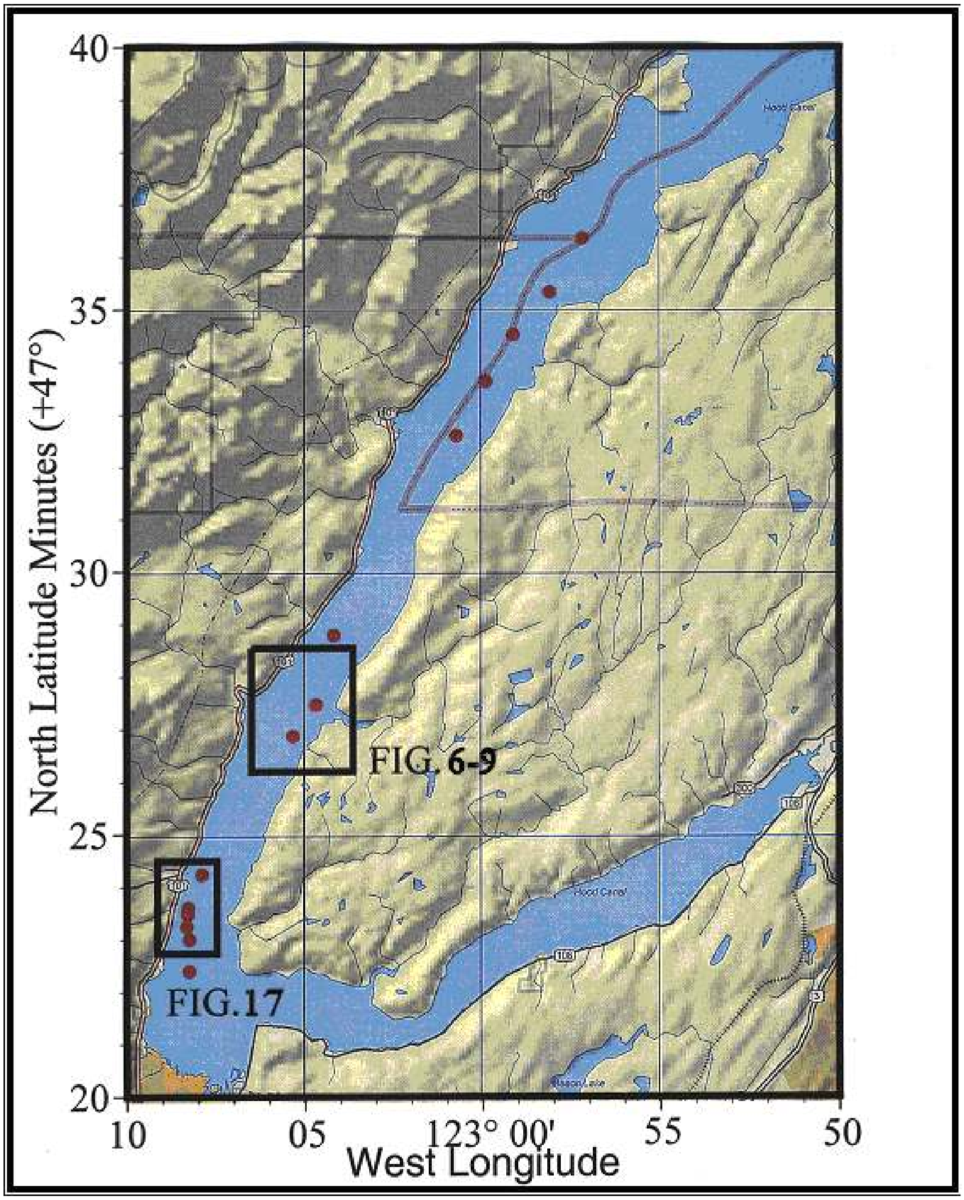

South
North
80.0m
Buried and Partially Buried Mounds
VE x 25
5°
20°
10°
Depth in Meters
120.0m
1000 m
140.0m

Figure 18


40
35
30
25
20
North Latitude Minutes (+47°)
10
05
123° 00'
55
50
West Longitude
FIG. 6-9
FIG.17
Hood Canal
Hood Canal
101
106
300
Mason Lake