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Abstract

An investigation into evidence of deposits of rapidly moving landslides that may have triggered displacement waves during the post glacial period in Howe Sound, British Columbia, was initiated by the Geological Survey of Canada (GSC) in collaboration with researchers from the Department of Earth Sciences, Simon Fraser University. It consisted of two initiatives: investigation of the present stability of the western slope of Mount Gardner on the west side of Bowen Island and of post glacial sedimentation and rates of sedimentation in Howe Sound. Investigation of sedimentation rates sought to determine

the age of the run-out deposits along the sea floor of Collingwood Channel (west of Bowen Island) and to determine the duration of time that rock slide deposits would remain visible to swath multibeam bathymetry (SMB) before they were buried by subsequent sedimentation.

A study combining structural geological mapping with geomorphic analysis of the subaerial and submarine portions of Collingwood Channel was carried out below Mount Gardner. More than 800 structural measurements at over 400 outcrops were made. A LiDAR digital elevation model) and orthophotos of Bowen Island were studied along with a digital elevation model of the sea bottom generated from MSB data. The investigation found that deep-seated gravitational deformation appears to have occurred along parts of the western slope of Mt. Gardner (MG) due to its geological structure and topographic factors. Evidence of ongoing deep-seated deformation was not found. Over all, a likelihood of major failure was not found.

As a part of the marine geology investigation, three piston cores were collect from the bottom of Collingwood Channel below MG to sample contrasting local depositional environments. Two piston cores were also collected at the same latitude west of Lions Bay in the widest part of HS. One sampled a submarine fan and the other the sea bottom protected from submarine fan sedimentation. Seismic reflection surveys were carried out in the Collingwood Channel and Lion's Bay and a remotely operated vehicle (ROV) traversed the sea bottom in both areas and the traverses were recorded by a high definition television system. The seismic reflection profiles determined initial relief of run-out deposits on the sea floor.

The cores collected from shallowest depths in Collingwood Channel (62 to 84.5 m) were entirely deposited during deglaciation. They yielded uncalibrated ^{14}C ages of ca. 13.1 to 12.5 years before present (yBP). No Holocene sediments were present.
In the Lions Bay area, one of the widest reaches of Howe Sound, a 7 m core taken from a depth of 136 m intersected mud containing scattered plant fragments and invertebrate shells. Carbon-14 ages ranged from 8450 to 5700 yBP with the lowest 4 m of the core yielding statistically indistinguishable ages ca. 8450 yBP. Virtually no sediment post-dating 5700 ^{14}C yBP was intersected. This indicates that very rapid sedimentation occurred up to the middle Holocene with virtually none after that. This is consistent with enhanced erosion and sediment transport as a result of the paraglacial effect following deglaciation.

The other core from Lions Bay core was taken at a depth of 139 m from the submarine fan below debris-flow-prone Lone Tree Creek. The core site is flanked to the north and south by entrenched submarine channels presumably cut by sediment-gravity flows. The core contains sediments at least as old as the oldest ^{14}C dated sample ca. 4250 y BP. The core displays extensively bioturbated sediments containing wood fragments as well as angular clasts of dark Gambier Group volcanic rock which underlies much of the Lone Tree Creek basin. Intertidal invertebrate tests are present in the sediments. The most striking feature of the core is the inversion of stratigraphy with: a wood fragment with a ^{14}C age of ca. 3740 y BP lies 500 cm below a bivalve shell dated at ca. 4250 y BP. This is attributed to the high energy environment expected for a submarine fan where older sediment can be reworked by sediment gravity flows crossing the fan. Only the upper 80 cm of the core was deposited during approximately the last 4000 years. The small amount of sedimentation over the latter half of the Holocene also reflects the waning of the paraglacial effect over this period.

The low sedimentation rates over the latter half of the Holocene in Howe Sound make it unlikely that the deposits of any large and rapidly moving rock slide, large enough to generate a destructive displacement wave over the approximately the past 5000 years, would escape detection by the SMB imaging that was carried out in 2007.

Introduction

Displacement waves caused by rapid landslides entering fiords rapidly are well documented natural hazards. For example, in January, 2007, a seismically triggered landslide created a displacement wave that killed 10 people and severely damaged fish farm installations in Fiordo Aisén, Chile (Sepúlveda et al., 2010). In Norway, historic records since 1500 C.E. indicate that landslide displacement waves have killed hundreds of people and repeatedly destroyed towns (Blikra et al., 2005). Archaeological investigations suggest that a fiord tsunami occurred in Knight Inlet in the 16th Century and destroyed the First Nations village of Kwalate (Bornhold et al., 2007).

Study of swath multibeam bathymetry (SMB) imagery generated in 2007 revealed what was interpreted as possible submarine rockslide run-out deposits on the sea floor of Collingwood Channel which separates Bowen and Keats islands. These deposits lie immediately adjacent to the western shore of Bowen Island. This caused immediate concern with regard to the potential for future landslide activity in this area that could cause displacement waves. Such waves could potentially impact nearby communities and marine traffic. At the time, little was known about the rates and patterns of sedimentation in Howe Sound. An initial working hypothesis was that the deposits in Collingwood Channel were recent due to their visibility in SMB imagery. This raised the question of how long such deposits might remain visible before they were buried by subsequent sedimentation. Because no other similar deposits were recognized by Jackson et al. (2008), the logical question that we asked was “could it be that fast moving landslides have entered Howe Sound in the past but their deposits are buried by sediment and are not visible to SMB”?

This report describes the results of the preliminary stratigraphic exploration of parts of the sea floor of the lower part of Howe Sound, British Columbia (Fig. 1) in an effort to document past rates and patterns of sedimentation in Howe Sound as they bear on the visibility of terrestrial landslides that may have entered the fiord and reached the sea floor.

It also summarizes the results of an investigation of slope stability along the west side of Bowen Island that was undertaken by one of the authors (van Zeyl) as a part of his

Masters of Science research at Simon Fraser University. This investigation bears on the origin of the run-out deposits on the adjacent sea floor and the likelihood of a rapidly moving landslide from this source in the future.

Setting

Howe Sound is one of the southernmost fiords on the mainland coast of British Columbia (Fig. 1). It joins the Strait of Georgia, an element of the inland Salish Sea, immediately north of the City of Vancouver.

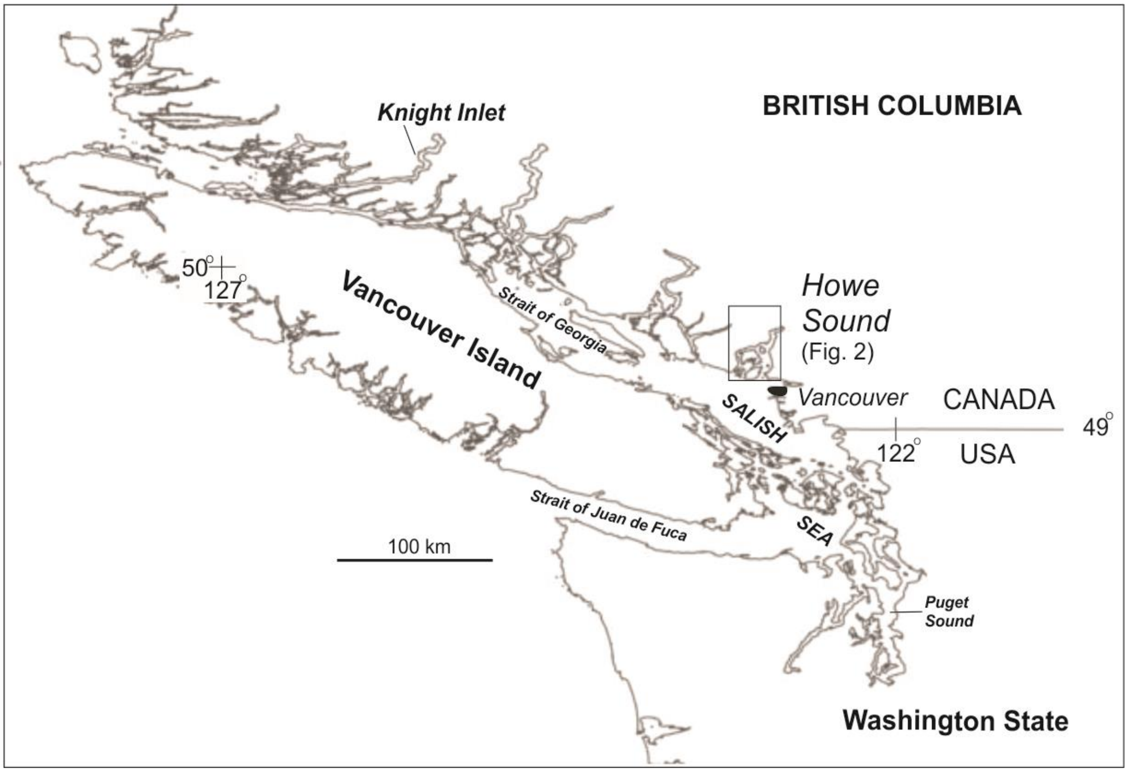

Figure 1. Howe Sound region

It measures 38 km along its long (north-south) axis and has an average width of 6 km. Typical water depths within Howe Sound are in the 200-250 m range. It contains numerous islands (Fig. 2). Gambier and Bowen islands are the largest (areas are 69 and 50 km^2, respectively). Howe Sound and surrounding parts of the rugged and glacially sculpted Coast Mountains are underlain by the Jurassic to Eocene crystalline rocks of the Coast Plutonic complex (Woodsworth et al., 1991, p. 515) and coeval volcanic assemblages and roof pendants of the Gambier Group and the pre-Jurassic Bowen Island Group (Roddick and Woodsworth, 1979). Mountain peaks rise 2000 m above sea level within 3 km of the shore. Immediate relief is commonly in the 1000 to 1500 m range. Landslide and debris flow activity is common around Howe Sound (Blais-Stevens and Septer, 2008).

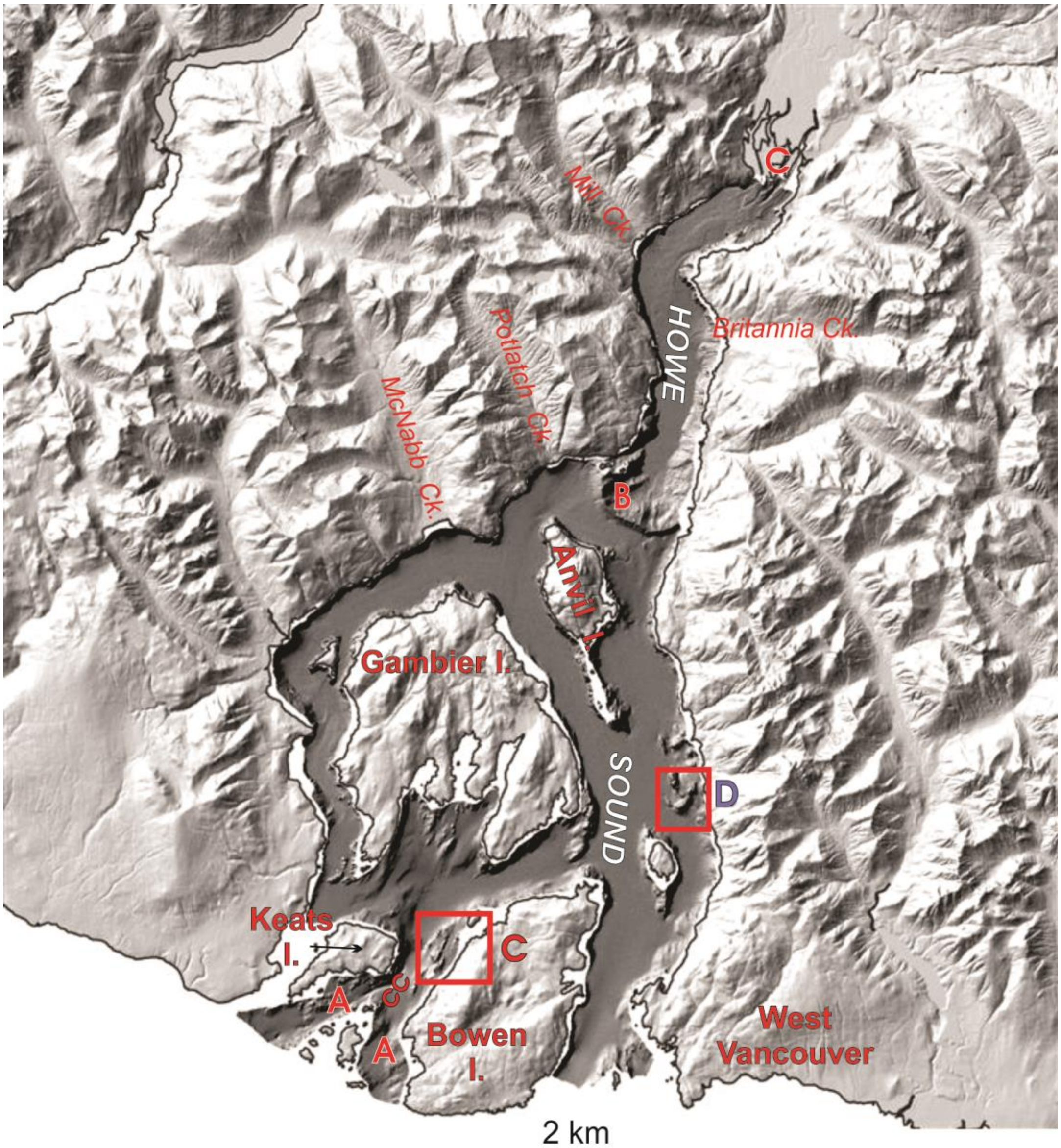

Figure 2. Digital elevation model of terrain around Howe Sound and the sea floor: A- outer sill of ice stagnation glacial sediments; B- glacial still-stand or readvance moraine which creates the inner sill that divides Howe Sound into upper and lower basins; C- precipitous west slope of Mt. Gardner on Bowen Island which produced one or more small rock slides or debris that entered Collingwood Channel (cc) and is undergoing creep. Cores 42-44 were collected from the adjacent sea floor; D- Lions Bay area: location of cores 40 and 40.

The Howe Sound area was inundated by the Cordilleran Ice Sheet during the Fraser Glaciation (marine oxygen isotope stage 2) which climaxed in the Salish Sea area between 16 950 and 16 750 calibrated ^{14}C years before present. The ice sheet retreated north from the south end of Puget Sound by rapid calving. The calving margin reached the San Juan Islands, in the area of the international boundary by 15.8 ka ago (Porter, 2011). Three radiocarbon ages document deglaciation of Bowen Island by as early as ca. 15,000 calibrated radiocarbon years ago (Fairbanks et al., 2005). These are presented in Table 1. The sampling site was revisited in 2010*. Its location was determine by GPS to be 49 23.651 N, 123 21.846 W (WGS 84).

Table 1. Ice free radiocarbon ages for Bowen Island, Bolton Road site 49° 23.651' N, 123° 21.846' W (NAD 84), elevation ~72 m a.s.l.

Radiocarbon age Y BP *Calibrated 14C Y BP*	Laboratory reference	Material	Comments
12 700±220 *14761±321*	Beta 16164	Steller's sea lion limb bone	dated in 1986
13 020±90 *15166±141*	Beta 79 860 CAMS 18423	Steller's sea lion limb bone	redated from same material as Beta 16164 in 1995
12 400±160 *14299± 274*	GSC-3681	Bivalve *Nuclana* sp.	Stratigraphically coeval with sea lion material

*The site was relocated with the help of the original collector, Mr. Stan Bolton. Elevation was determined above the high tide line by use of an altimeter with a resolution of 1 metre.

Previous work

Exclusive of the marine navigation charts and routine depth soundings, physical oceanographic studies of Howe Sound and other fiords along the British Columbia coasts began in the 1950s. These studies dealt with salinity, oxygen and density profiles, circulation patterns and seasonal changes in all of these oceanographic parameters. Pickard (1961) was the most comprehensive of these early studies of BC fiords and the first to note the presence of an inner sill (moraine) within Howe Sound (east-west at latitude of Porteau Cove) that divides it into two sub-basins.

Mathews et al. (1966) presented a comprehensive synthesis of the bathymetry, physical oceanography and geologic history of Howe Sound. Bathymetry was determined using hydrographic soundings plus 330 km of echo sounding tracks: the best technology for resolving submarine topography available to them at that time. They subdivided the submarine topography of Howe Sound into four bathymetric provinces:

1) Steep, rocky shore zone: this includes submarine extensions of fiord walls and the margins of islands.
2) Sills rising off the floor of the Sound: these include outer and inner sills which they interpreted to be submarine morainal features deposited during the latter stages of the (last) Fraser Glaciation (Fig. 2, A and B respectively). The depths of the outer sill is in the 60 m range whereas the crest of the inner sill is as little as 20 m depth.
3) Lower basin: the basin between the outer sill and inner sill. Maximum depth is in the 250 m range.

4) Upper basin: the basin between the inner sill and the delta of Squamish River at the northern limit of Howe Sound.

Syvitski and Macdonald (1982) investigated sedimentation patterns in Howe Sound based upon the mineralogy of grab samples taken from the bottom of the fiord. They recognized four contemporary natural sources including:

1) land-derived sediment from the Squamish River at the head of Howe Sound;
2) suspended sediment originating from surface waters influenced by discharges from the Fraser River 28 km to the south (annual discharge an order of magnitude larger than the Squamish River);
3) reworked Pleistocene lag deposits found on some shore platforms and sills throughout the sound;
4) sediment gravity flows entering the sound from adjacent uplands.

They also recognized that sedimentation patterns are highly influenced by tidal current patterns: shallow sills and shore platforms are areas of low to zero deposition due to tidal current winnowing whereas the deeper basins between the sills are not subject to reworking by strong bottom currents and are sediment traps.

Known mass wasting events and prehistoric features in Howe Sound

Rock slides, rock falls, debris flows and other landslide phenomena in the uplands around Howe Sound have caused damage to infrastructure and injury and death to humans since records began in the early 1900s (Blais-Stevens and Septer, 2008). There are records of failures along the shoreline but these were not associated with displacement waves. Among them are the failure of a sand and gravel delta at Woodfibre in 1955 (Terzaghi, 1956; Prior et al., 1982; Prior and Bornhold, 1984) which has become a textbook example of subaqueous sediment failure in coarse sand and gravel (Syvitski et al., 1987, p. 200). Slumps, debris flows, debris slides and turbidity currents have occurred in submarine sediments throughout Howe Sound (Prior and Bornhold, 1984; Jackson et al., 2008), notably at Britannia Creek, Mill Creek and the Squamish River delta. These events were conditioned by the physiography of Howe Sound: the glacially steepened submarine walls of this fiord have prevented or restricted the formation of fan deltas at the mouths of mountain torrents: debris flows and fluvial sediments discharged from these torrents have traveled to the base of the steep submarine walls where they have built submarine fans along the base of them. The submarine fans prograde onto the relatively flat, muddy floor of Howe Sound (Fig. 3). Lobate depressions with ridged rims were described and interpreted by Jackson et al. (2008) as products of the subaqueous run-out of bouldery debris flows or small rock slides that have recently traversed these submarine fans.

This Study

Jackson et al. (2008) reported submarine rock slumps or rockslides located in Thornbrough Channel near McNab Creek and along Ramilles Channel off the margins of Gambier and Anvil Islands based upon their interpretation of SMB imagery. However, what was interpreted as possible rock slide run-out deposits identified on the sea floor along the western shore of Bowen Island were of the most concern with respect to the possibility of future failures that could trigger displacement waves. The added concern was due to evidence of ongoing slope deformation along the adjacent slope. The submarine deposits consist of two lobate deposits with areas of approximately 0.057 and 0.035 km^2. The deposits could not be completely imaged to the base of the fiord wall due to ship safety limitations in working close to shore. The imaged parts of these deposits extend northwest from at least 72 m to at most 80 m depth for an inclination of 1.2-1.8° Investigation of the age of these deposits, and the likelihood of further failures here and whether or not sedimentation has hidden deposits of rock slides elsewhere in Howe Sound are the subjects of the present report.

This study consisted of terrestrial and marine components. The western slopes of Bowen Island were traversed to determine the nature of extant slope deformation. A detailed study of the structural geology was carried out along with a stability analysis (van Zeyl, 2009). The results will be summarized subsequently. The eastern coast of Keats Island immediately across Collingwood Channel was traversed to look for evidence of prehistoric run-up of displacement waves.

The marine geology component consisted of seismic reflection profiling to determine the sea floor stratigraphy in the area of the sediments. Piston cores were obtained so that actual sediments could provide control for the seismic reflection profiles including organic material that could be radiocarbon dated. A remotely operated vehicle traversed the sea floor along parts of the seismic reflection profile so that the sediments could be directly imaged by high resolution video.

Another objective of the marine component of the study was determine the general rate of sedimentation in lower Howe Sound (between A and B in Figure 2) in order to determine how rapidly rock slide deposits might become buried beneath sediments so as to not be identifiable by SMB. Lower Howe Sound receives suspended sediment primarily from the Squamish River, especially during spring freshet (Hickin, 1989). Locally, steep mountain streams that enter the fiord are sources of both suspended and coarse sediments including bouldery debris flows. The Lion's Bay area was chosen as an area to determine rates of sea floor sedimentation over extended periods of the Holocene. It lies in a broader area of lower Howe Sound and it is not subject to the strong currents that characterize Collingwood Channel. Seismic reflection profiles and piston cores from the bottom were obtained from the Lion's Bay area.

Terrestrial investigation of Bowen and Keats islands

Foot traverses were carried out along the western slopes of Bowen Island along Collingwood Channel. Although heavily forested, slopes above the submarine deposits showed evidence of past and present slope movement including successive en echelon scarps and fissures. Some of latter are currently enlarging as indicated by tilted or partly ripped-apart living trees (Figs. 3 and 4). This suggested to two of the authors (Hermanns and Jackson) that a rock slide into Howe Sound from this area was a possibility that merited further study, and the suspected hazard was reported to Bowen Island municipal authorities.

Figure 3. Tree being torn apart by spreading in hillside beneath its roots.

Figure 4. Open cracks in slopes above Collingwood channel

The eastern shore of Keats Island was traversed to look for evidence of past displacement waves. Pits were dug in flat-lying areas above the highest tide levels to search for anomalous sand or gravel deposits and isolated boulders that are suggestive of run-up by a displacement wave. No such evidence was found.

Slope Stability investigation

Geologic and structural mapping of the west slope of Mt. Gardner, the source of the run-out deposits, was conducted as part of a Master of Science thesis (van Zeyl, 2009) at Simon Fraser University http://summit.sfu.ca/item/9447. The work consisted of extensive use of LiDAR data generously supplied by the Bowen Island Municipality and mapping the structural geology of the west slope of Mt. Gardner at a scale of about 1:8000. A summary of the findings are provided below.

All of Mount Gardner except the northern and southern tips is underlain by the Lower to Middle Jurassic Bowen Island Group (Friedman et al., 1990), a succession of greenstone and hornfels whose protoliths include stratified siliclastic rocks, tuff and intermediate and felsic lavas (Figs. 5 and 6a). Despite greenschist-facies metamorphism, primary structures and large-scale stratification are well preserved within this succession. In contrast to the tight to isoclinal east-west trending folding described for these rocks elsewhere on Bowen Island, rocks on the east and west slopes of Mount Gardner generally display moderate dips to the northwest with the exception of a notable flexure on the southern part of the west slope where a gently plunging west-southwest trending synform is observed. LiDAR data and fieldwork revealed that counterscarps (Fig. 5) and other features indicative of past slope deformation are common throughout the west slope of Mount Gardner. These features took the form of either local or large-scale deformation features, as described below.

Local areas of shallow, sliding-related, creep-like deformation found throughout the west slope of Mount Gardner were indicated by the presence of counterscarps situated upslope of local steep areas where bedding-parallel fault zones were exposed in bluffs. The run-out deposits were likely related to one or more small rock slides originating from local areas of instability like those described above, although it cannot be ruled out that these deposits were produced by bouldery debris flows. Local instabilities, such as the ones associated with the run-out deposits, are expected to have limited potential to generate displacement waves in this setting, although additional analysis would be required to estimate possible wave heights. Such failures, however, would surely pose hazards to structures located within the run-out path.

A major area of deep-seated creep-like deformation was identified on the west slope of Mount Gardner between Eddy Creek and Donaghy Brook (Fig. 5). The deformation zone is concentrated between 300 and 700 m elevation, with counterscarps at higher elevations and cliffs at lower elevations. The lower boundary of the zone of deep-seated deformation is marked by a set of cliffs above a large, partially-forested talus deposit extending to sea level. Structural measurements, when interpreted against the detailed image of cliffs and counterscarps provided by the LiDAR digital elevation model, revealed that the deformation zone is associated with an open synform whose lower limb daylights in the cliffs near the base of the slope (Fig. 6a and b). Throughout this feature,

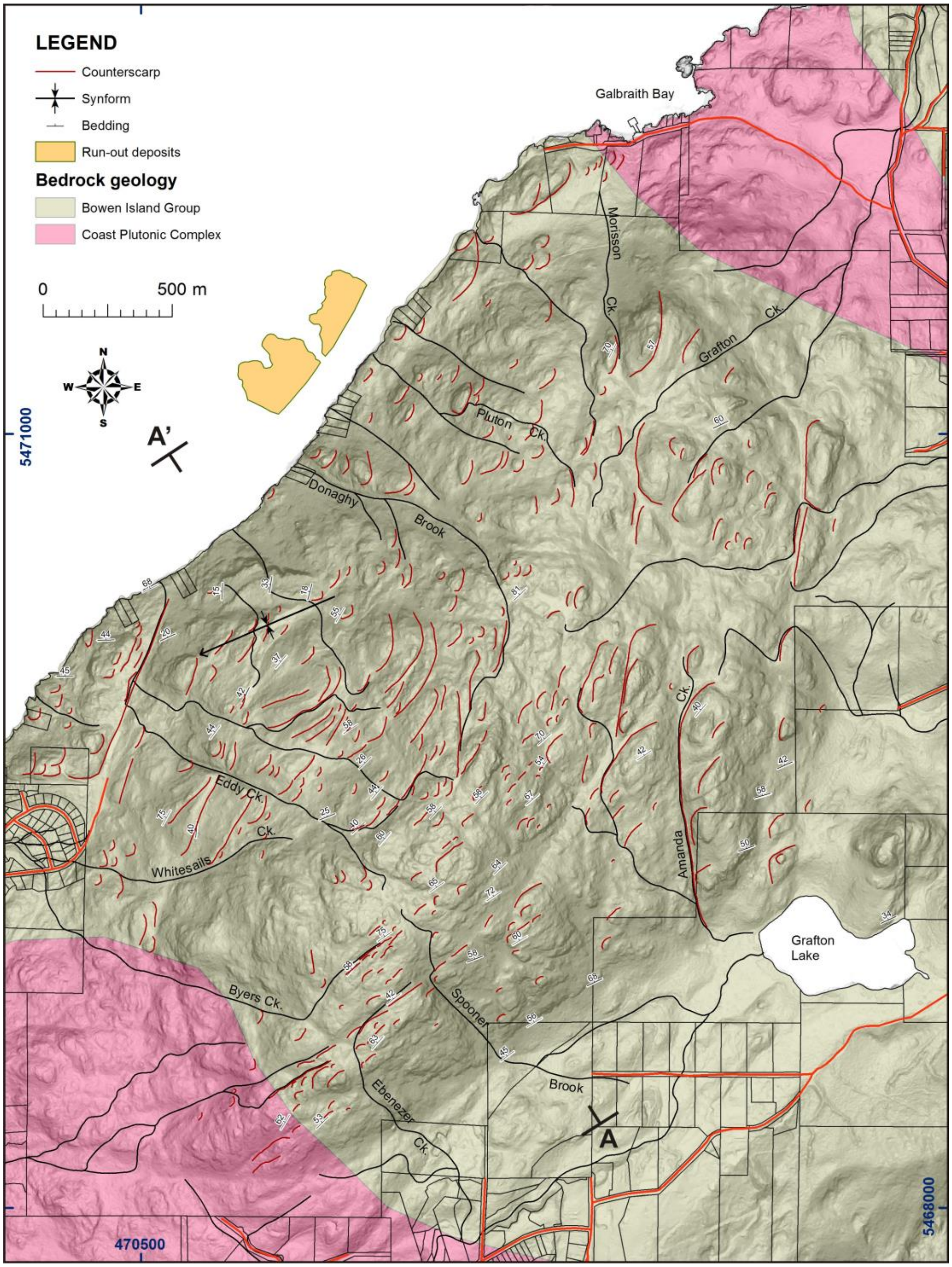

Figure 5. Bedrock and structural geology, tensional slope features in relation to run-out deposits along the western slope of Bowen Island. A-A' indicates location of the cross-section in Figure 6.

fault zones were found along weak stratigraphic horizons such as layers of highly fractured tuff and siliclastic rocks. These fault zones are likely tectonic in origin, associated with flexural slip folding during formation of the synform, and subsequent post-glacial gravitational reactivation seems likely given the morphological and structural evidence. This type of instability is referred to in the literature as a 'sagging slope' (Hutchinson, 1988) or 'sackung' (Agliardi et al. 2001). A very small number of these features have evolved historically into large catastrophic landslides. Many slope instability features like this have been described throughout the Coast Mountains (e.g., Bovis, 1982), and others likely exist in Howe Sound. Although no clear evidence of active large-scale movement could be found within this feature, it remains unclear whether it is presently deforming at a very slow rate. Long-term monitoring would be needed to confirm the state of activity of this feature. To date, no such monitoring has been carried out.

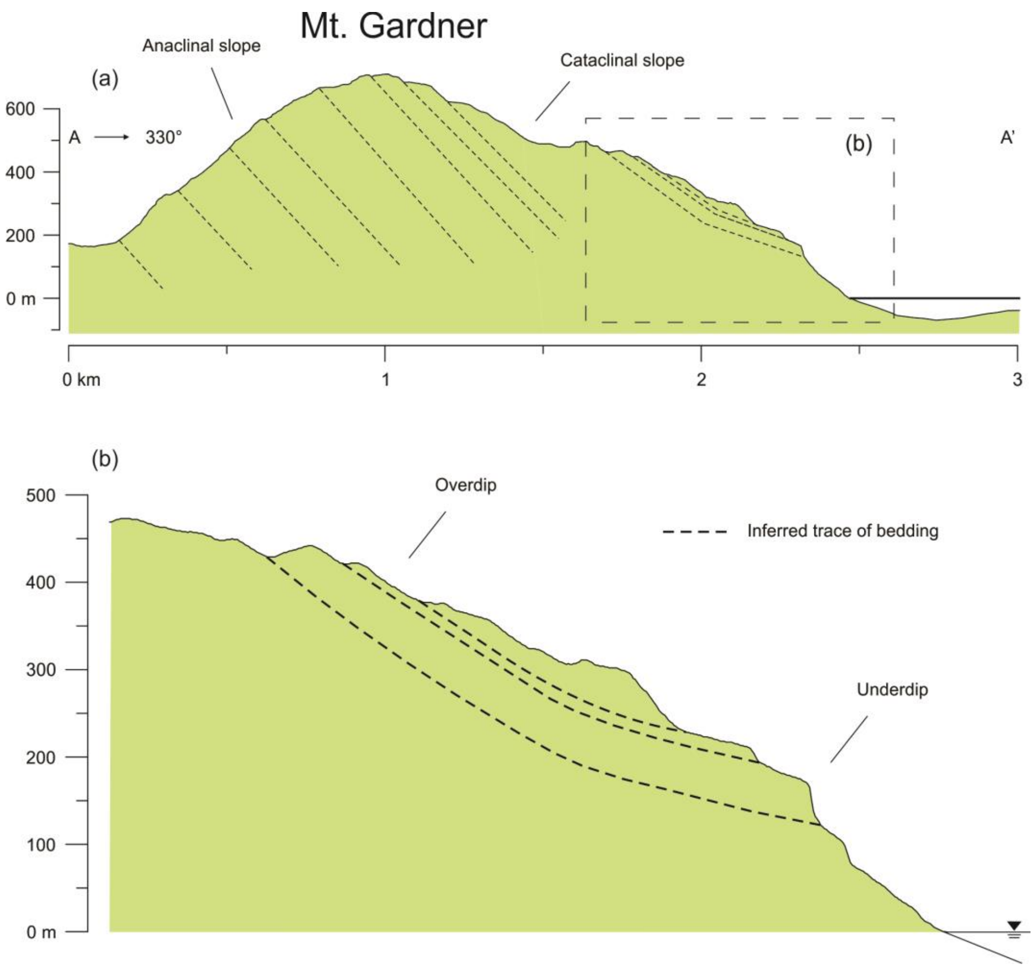

Figure 6. (a) Northwest to southeast cross section A-A' across Mt. Gardner(see Figure 5). (b) Cross section showing details of the synform underlying the deformed slope on the west flank of Mount Gardner. Dashed lines show bedding orientation inferred from surface exposures.

Investigation of Bowen Island offshore

A marine geology investigation was carried out in October, 2007 from the research ship CCGS John P. Tully. A succession of seismic reflection profiles (Fig. 7) were run generally parallel to the coast with one as normal to the coast as the research ship could

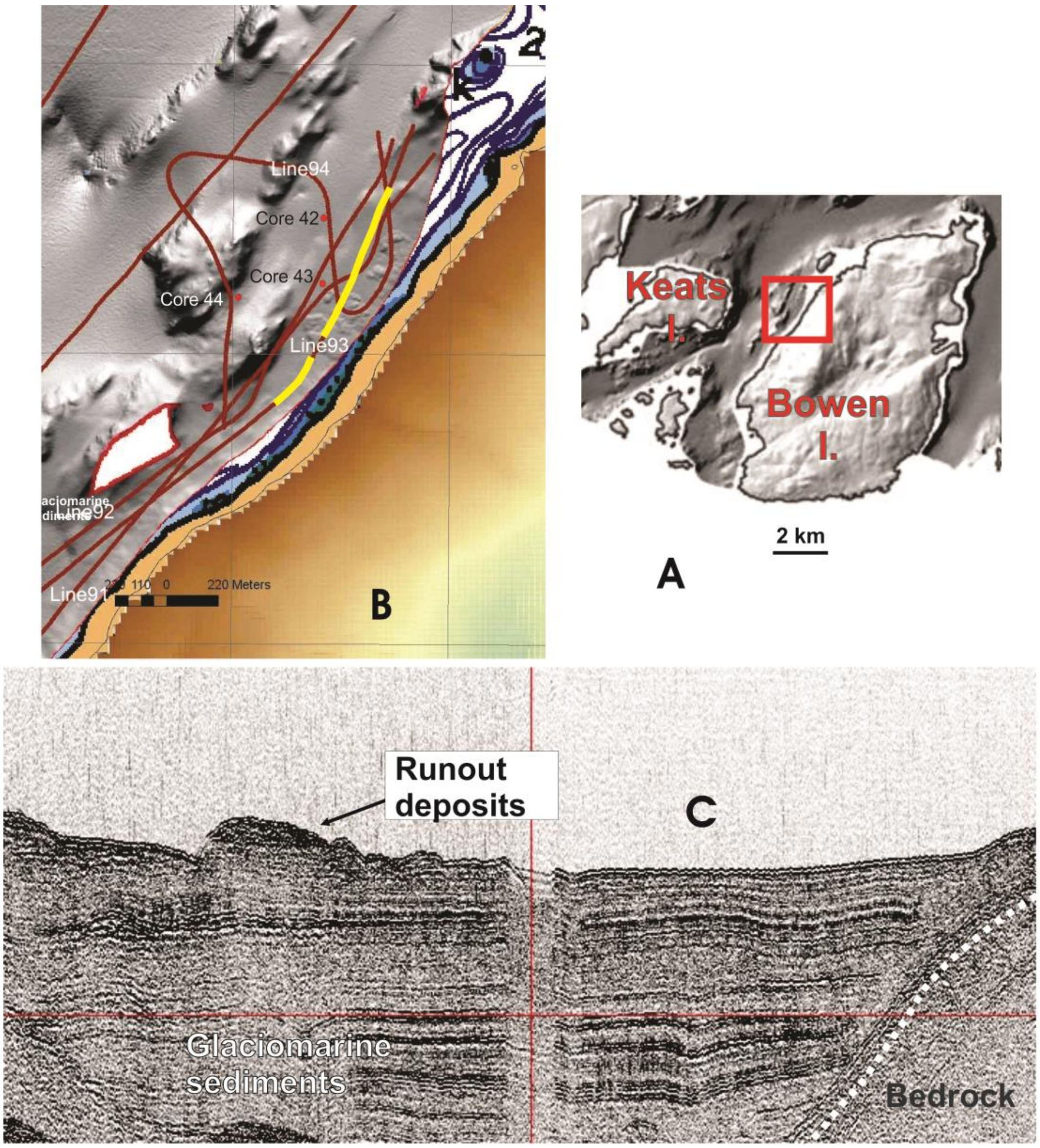

Figure 7. (A) Red rectangle defines west side of Mt. Gardner and sea floor area investigated. (B) Location of seismic reflection section 93 (highlighted in yellow). (C) Seismic reflection profile line 93 portraying the stratigraphy of the rock slide or debris flow runout deposits and underlying glaciomarine sediments. The runout deposits have a maximum local relief of ~1 m above the adjacent sea floor.

safely maneuver. The deposits were close enough to the shoreline that the major body of the deposits could not be profiled safely. However, seismic line 93 (Fig. 7) shows the general seismic stratigraphy. Figure 8 shows a detailed SMB image of the deposits and the location of three piston cores taken for sedimentological and geochronological control of sediments overlying the deposits. In addition, the sea floor was traversed by a

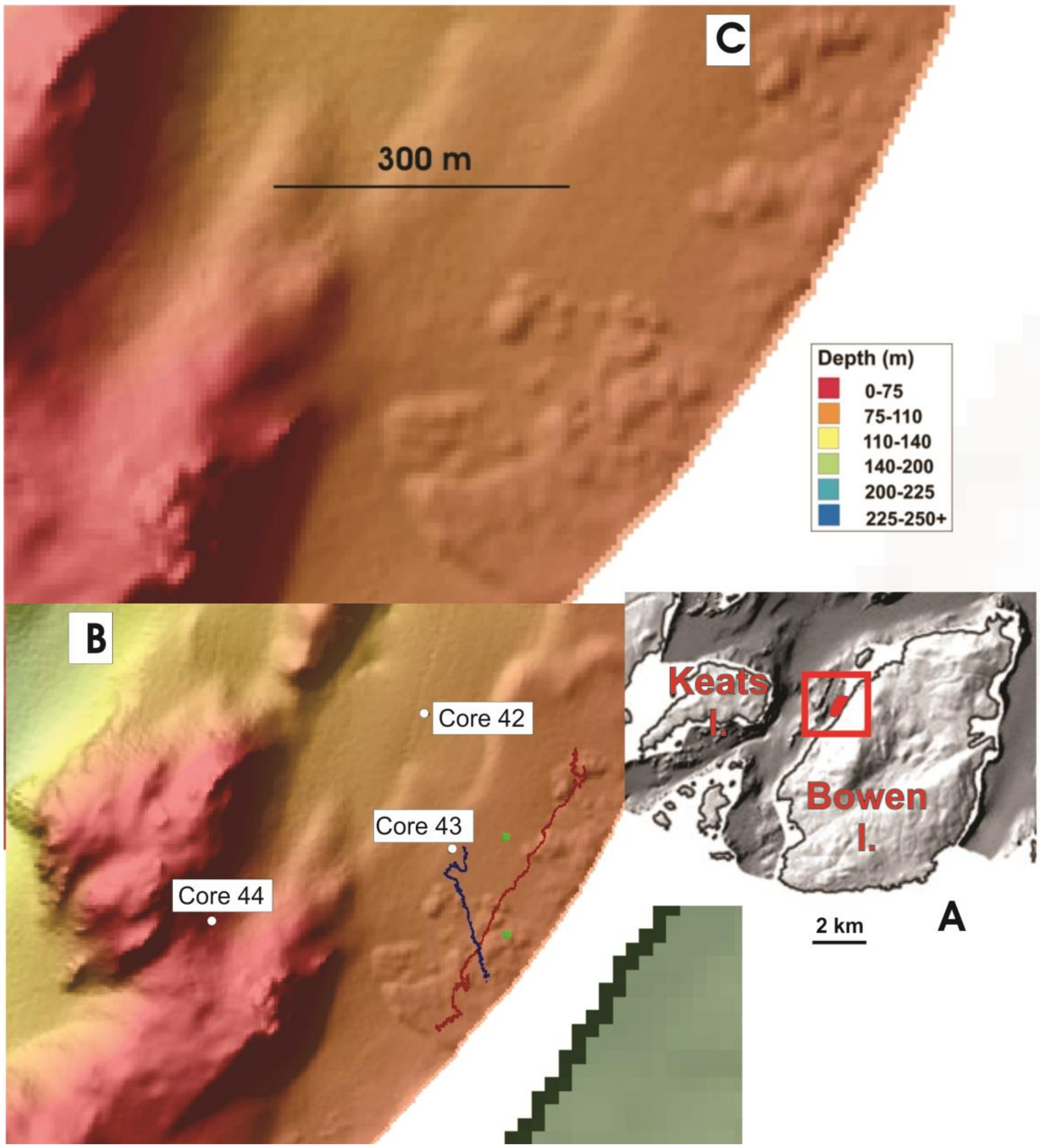

Figure 8. (A) Red rectangle defines west side of Mt. Gardner and sea floor area investigated. Red area within the rectangle shows the area of runout deposits. (B) Swath multibeam bathymetry (SMB) imagery showing the location of piston cores and ROV traverses (red and blue lines) in and around the runout deposits. (C) Detailed view of SMB imagery of runout deposits.

remotely operated vehicle (ROV) equipped with high definition video cameras. This application was not successful because the fine silt on the bottom was easily stirred up by the thrusters on the ROV which totally obscured bottom features.

Investigation of Lions Bay offshore

The origin of submerged hills immediately offshore of Lions Bay was investigated in order to determine if they were protuberances of bedrock projecting through sedimentary fill or slide material from the bowl-like concavity in the mountains above Lions Bay (Fig. 9). Results of a seismic reflection survey indicated that these submerged hills are *in situ* bedrock protuberances. In addition, ROV traverses of the bottom were carried out and two piston sediment cores were taken. The location of core 41 lies at a depth of 136 m along the west side of one of the submerged hills. We chose this site because we thought that this area would be protected from sedimentation originating from streams entering Howe Sound along Lions Bay. We anticipated that a core from this site would provide measurements of rates of deposition of suspended sediment, most of which originated from the Squamish River. The site of core 40 was taken from the submarine fan of Lone Tree Creek. This core was taken in order to investigate the nature and frequency of sedimentation from local steep mountain streams along the margin of Howe Sound.

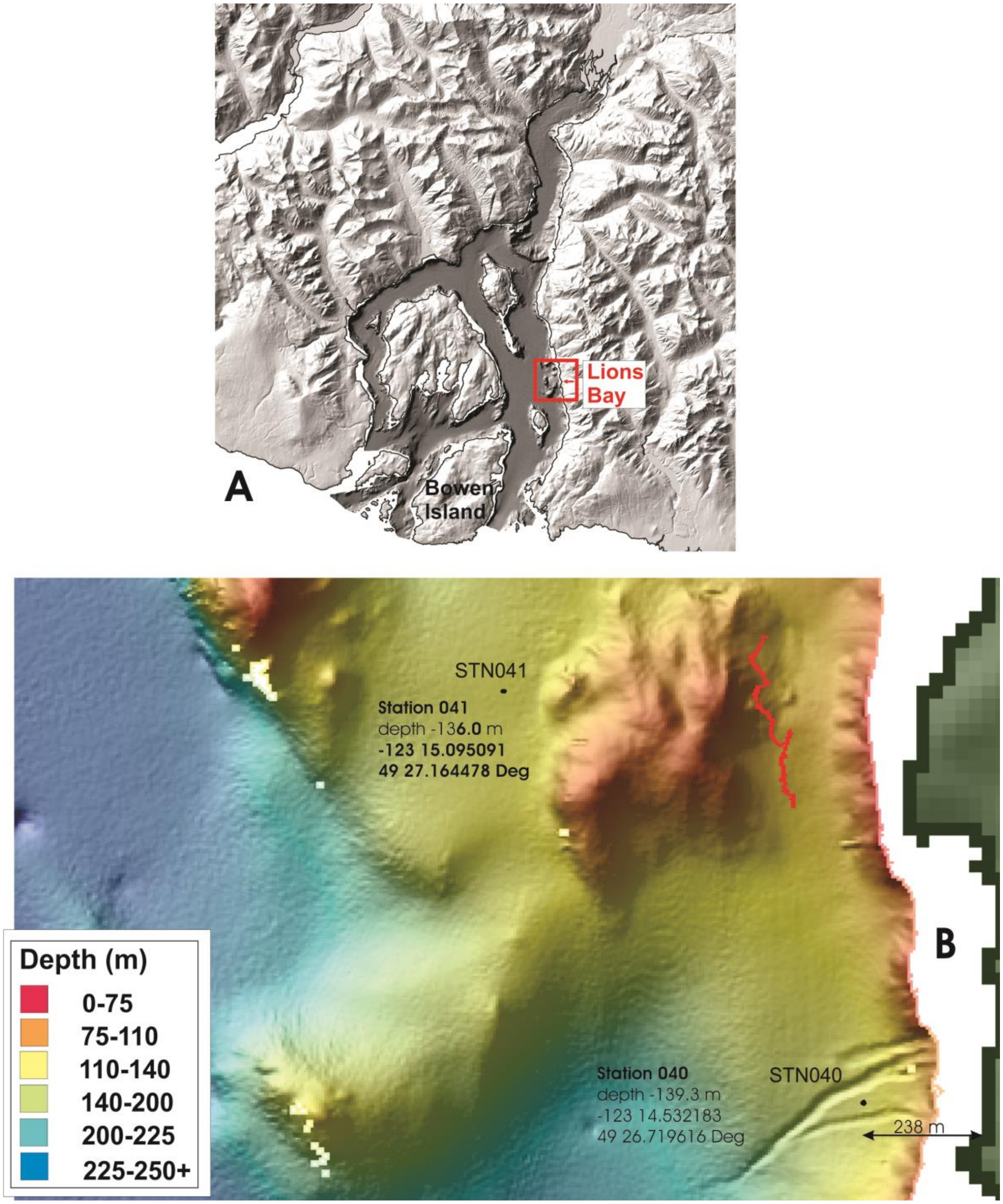

Figure 9. (A) Location of Lions Bay. (B) Swath multibeam bathymetry imagery of the sea floor beneath Lions Bay. Locations of piston cores and a ROV traverse (red line) are shown.

Investigation of sediment cores

Sedimentology and stratigraphy of sediment intersected by the piston cores was investigated in order to determine sedimentation rates and investigate sedimentary environments. Cores were obtained using a standard Benthos corer. These ranged from about 2 to 9 m in length (10 ft. barrels were used). Each core was cut into 1.5 m sections at sea. They were placed into refrigerated storage in the lab prior to being subsequently split lengthwise. Half was preserved as an archive. The other half was used for sampling. The sampled split was photographed and described. Textural samples were taken every 30 to 60 cm depending upon homogeneity. The weight percent content of sand, silt and clay components were determined by the sedimentology lab of the Geological Survey of Canada, Ottawa. Shells from mollusks, gastropods, brachiopods, and crustaceans were recovered from cores. Identification and interpretation of ecological environments were made by Renée Hetherington. Radiocarbon dating of selected samples by the AMS method was carried out at the University of California, Irvine and Beta Analytic, Miami Florida. For the purposes of this paper, the radiocarbon ages determined on shell and wood are reported as radiocarbon years before present (Y BP). Other organic material recovered included fish bone and wood fragments. Where clasts larger than sand size (>2 mm) were present, they were sampled to determine lithology (provenance). This was thought to be particularly significant in distinguishing between glaciomarine and poorly sorted non-glacial sediment-gravity-flow deposits from adjacent subaerial slopes.

Bowen Island cores

Core 42 (Fig. 10) is from the north-westernmost of the three core sites with respect to Bowen Island and is the longest in length. It was taken from a sea floor depth of 92.9 m. It predominantly intersects a sequence of sandy marine mud with dropstones. Holocene sediments only occur in the upper 30 cm of core. This part of the section lacks dropstones and postdates a radiocarbon age of 9485±15 Y BP (UCIAMS 54069) determined on a fragment of wood. The contact is shown in Figure 11.

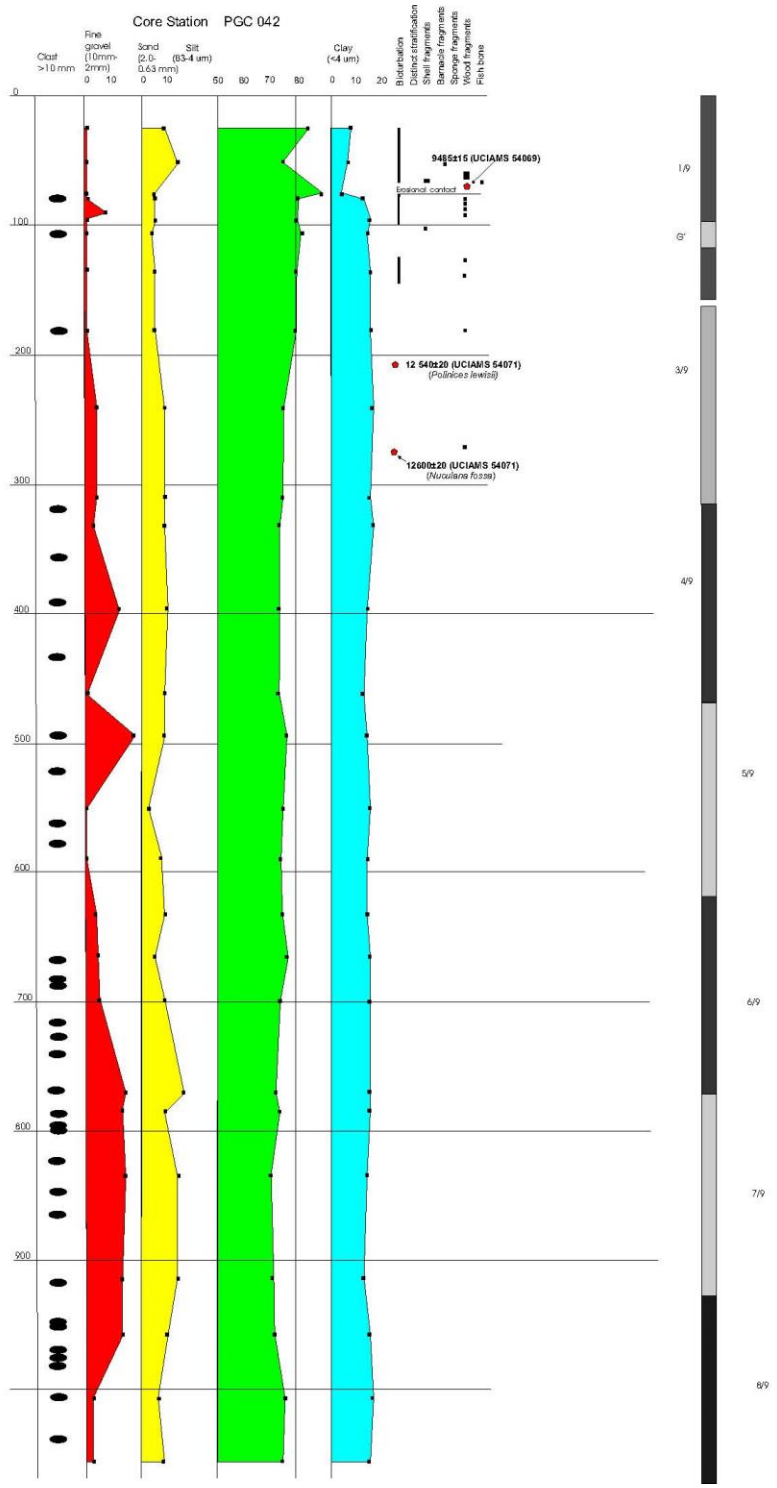

Figure 10. Granulometry and sedimentological features of core 42 sediments.

Figure 11. Dark grey organic-rich Holocene mud overlying lighter grey, relatively sterile and massive late glacial mud in core 42 (contact coincident with base of volcanic dropstone). An erosional break with a sandy lag separates the two. A radiocarbon age of 9485±15 Y BP (UCIAMS 54069) was determined on a fragment of wood along the contact.

The underlying marine mud contains evidence of stratification and bioturbation only over its upper 1 m. Below 1 m, it is grey mud with scattered dropstones. Figure 11 shows an example section of the core in which the massive nature of the mud and a clast of vesicular andesite or basaltic andesite (visual identification) are clearly visible. Volcanic clasts From the Garibaldi volcanics make up much of the dropstones in the sediment core and suggest that active calving of the Howe Sound glacier in the area of Squamish where volcanic rocks would underlie the glacier and contribute debris to the glacier's surface from surrounding volcanic uplands and peaks.

Core 43 (Fig. 12) is about half the length of core 42. It was taken at a sea floor depth of 84.5 m. It is the closest core to the runout deposits. The upper 40 percent of the sediments intersected has radiocarbon dating control spanning about 600 radiocarbon years from *ca.* 13.1 to 12.5 kY BP. No Holocene sediments are present. Dropstones are present to the top of the sediments intersected by the core indicating distal glaciomarine conditions throughout. As with the sediments intersected by core 44 (see below), it appears that there was little or no accumulation of sediment during the Holocene. The predominance of silt and clay in the fine sediment fraction, presence of bioturbation and some stratification, and scattered dropstones suggests that deposition was dominated by suspended sediment from the water column with periodic deposition of coarser ice-rafted sediment from perhaps centuries before 13.1 kY until the Holocene, when sediment accumulation ended. The rate of sedimentation based on the dated interval was between 1 and 2 cm/year. The coeval interval intersected by core 42 lacks stratification or bioturbation features. Samples below 250 cm were not analyzed due to laboratory oversight. However, the lack of larger dropstones may indicate a period of enhanced rainout of iceberg-rafted coarse sediment between ~13.1 and 12.5 kY BP.

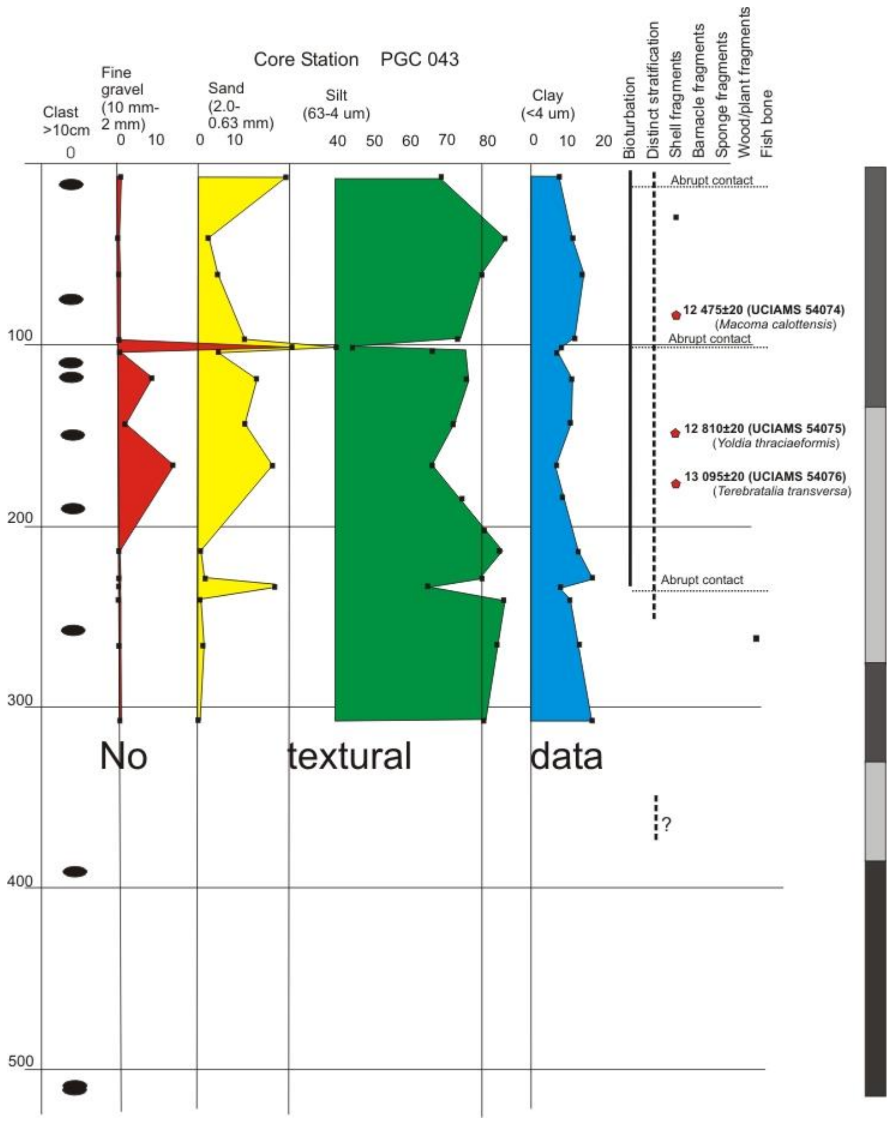

Figure 12. Granulometry and sedimentological features of core 43

The sea floor at the site of Core 44 (Fig. 13) is 62 m below sea level. The site is situated in a valley between two submerged north-south trending bedrock ridges (Fig. 8). The highest point along the eastern of the two ridges is emergent during low tide. The two ridges funnel north-south tidal currents and almost certainly increase their local

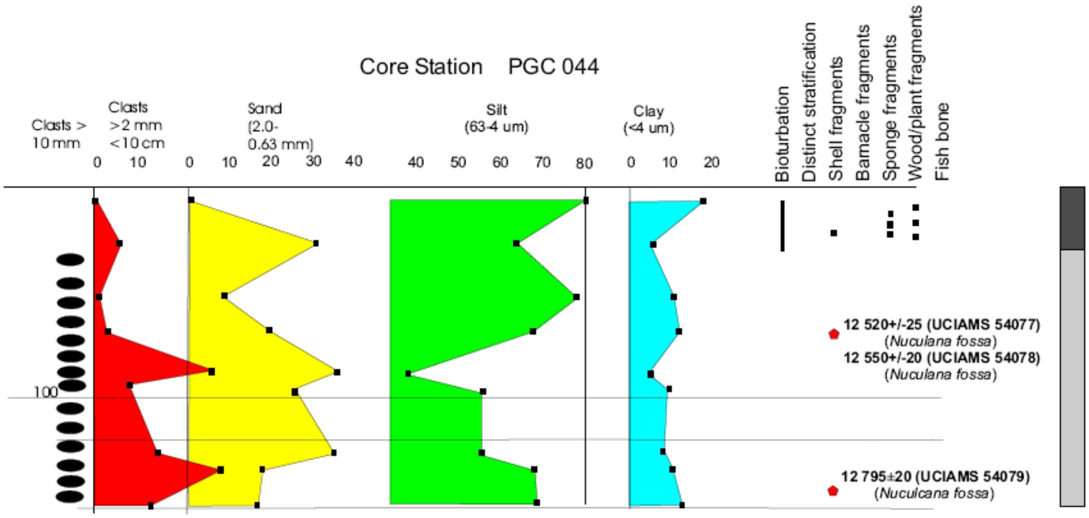

Figure 13. Summary of sedimentology and granulometry of sediments intersected by core 44

velocities. The core is only 177 cm in length but the sediments intersected span a slightly shorter period than core 43. The upper 30 cm of sediments is heavily bioturbated and contains dropstones as well as glass sponge fragments, shell fragments, and fragments of conifer needles. This zone appears to be a bioturbated mixture of Holocene and late glacial sediments. The lower 147 cm is a mixture of massive mud and sand and fine gravel. The succession is interpreted as a mixture of fines deposited from the water column, iceberg-rainout of coarse sand and gravel, and resedimentation due to sediment gravity flow from adjacent submarine ridges. Reworking by strong currents caused by constriction of tidal flow between the adjacent bedrock ridges is also likely. Radiocarbon ages between 12.8 and 12.5 kY BP span the lower 90 cm of the sediments. At first glance, this would indicate a rate of sedimentation of perhaps 0.5 cm/year. However, as noted above, it is not clear how much sediment was scoured by bottom currents at this constricted site. Consequently, estimation of sedimentation rates from the sediments intersected by this core is likely unreliable. The extensive number of dropstones in excess of 10 mm is similar to core 43 and indicates that the 12.8-12.5 kY BP interval was a period of active iceberg sedimentation in lower Howe Sound. Clasts >2 mm are predominantly Garibaldi volcanics: vesicular basaltic andesite or andesite, dacite, and rhyolite (visual identification).

Lions Bay cores

Core 41 intersected slightly over 700 cm grey, bioturbated and massive silty mud (Fig. 14). Bioturbation gives the core a mottled appearance. Fine sand makes up less than 3 weight percent of the sediment. The mud contains scattered plant material, fecal pellets and shell fragments. In rare cases, intact bivalve remains were found. Grains only marginally larger than 2 mm were found in two of the textural samples in the lower 200 cm of the core. These made up less than 0.1 weight percent of the sample. The texture of this core contrasts sharply with the glaciomarine sediments of cores 42-44. The lack of

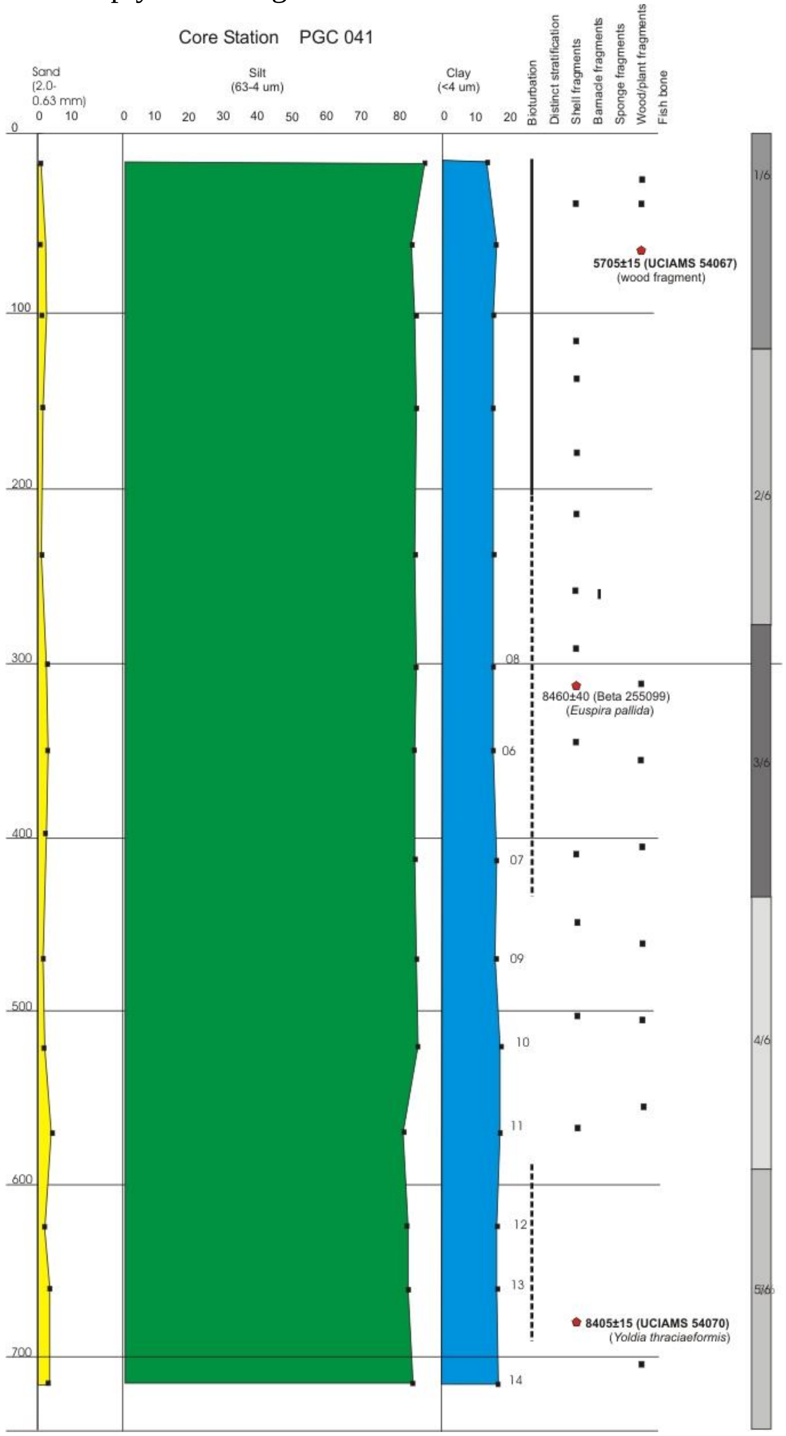

Figure 14. Granulometry and sedimentological features of sediments intersected by core 41, Lions Bay area.

dropstones documents termination of rainout of ice-rafted material by the time of deposition of the sediment at the base of this core. However, radiocarbon ages determined on bivalves over the lower part of this core do not agree with slow and progressive sedimentation. Statistically indivisible ages of 8405±15 Y BP (UCIAMS 54070) and 8460±40 Y BP (Beta 255099) are separated by about 350 cm of sediment. Dismissing the possibility of sedimentation rates orders of magnitude faster than the late glacial rates estimated for cores 42-44, it appears that part of the section is repeated in this core. This may be the result of submarine landsliding that has resedimented part or all of the material in the core, extremely disruptive bioturbation or the nearby formation of a gas escape structure (Barrie et al., 2005). With respect to landsliding, no failure planes or diapiric structures were noted in the bioturbated sections of the sediments intersected by this core. Gas escape structures are formed by the eruption of methane gas, water and sediment. Crater- like gas escape structures are common features on the floor of Howe Sound (Fig. 15) and can be ten metres in diameter or more (Jackson et al., 2008). They have presumably formed throughout the Holocene where organic-rich sediments were buried. Coring and radiocarbon-dating of sediments at more sites will be required to determine whether such disruption of stratigraphy has been common or exceptional in similar environments of the Howe Sound sea floor during the Holocene.

The uppermost radiocarbon age of 5705±15 Y BP (UCIAMS 54067) underlies the upper 70 cm of the sediments within the core. The quotient of this length divided by 5700 years is ~ 0.1 mm/year. This assumes that the bivalves submitted for radiocarbon analysis were *in situ* and not out of sequence due do landsliding or bioturbation.

Core 40 (Fig. 16) was taken from the sea floor at a depth of 139 m. Its site is situated on the submarine fan below the fan delta of Lone Tree Creek. The Lone Tree Creek basin has the same physiographic characteristics as adjacent debris-flow-prone basins (Jackson et al. 1985) although there has been no historically recorded debris flow activity (Blais-Stevens and Septer, 2008). The core site is flanked to the north and south by entrenched submarine channels presumably cut by sediment-gravity flows which were the submarine continuation of debris flows from Lone Tree Creek or failures of its fan delta. The core contains sediments at as old or younger than the oldest radiocarbon dated sample (4250±40 Y BP (Beta 255100)). The sediment core is extensively bioturbated and contains fragments of wood as well as angular clasts of dark Gambier Group volcanic rock (which underlies much of the Lone Tree Creek basin) and barnacle fragments including barnacles attached to angular Gambier Group clasts. The bivalve *Protothaca staminea* (Conrad, 1837) on which Beta 255100 was determined has a depth range of intertidal to -10 m. Its presence at 140 m below the surface further documents the transport of organic and inorganic sediment from sea level to the submarine fan. This core also intersects inverted stratigraphy: a radiocarbon age of 3740±15 Y BP (UCIAMS 54066) determined on a wood fragment lies 525 cm below the bivalve dated at 4250±40 Y BP (Beta 255100). This is not surprising due to the high energy environment of a submarine fan below a steep, high relief submarine and subaerial fiord margin. Two possibilities could explain the inversion of stratigraphy in this submarine fan environment:

1. A submarine slump could have transported and deposited older deposits, from higher on the submarine fan on to the core site.

2. A turbulent, fast moving sediment gravity flow may have ripped the *P. staminea* shell from the wall of an adjacent channel and deposited it to the surface of the fan.

The zone of massive sediment between -450 and -550 cm may have been created as a result of either process. There is insufficient evidence to accept or reject either hypothesis.

There is an erosional contact 20 cm above the upper radiocarbon-dated horizon in the core dated at 4250±40 Y BP. The contact zone contains scattered angular stones up to several cm in length. There is no radiocarbon dating control on the overlying 80 cm of sediment. Although there is no historical documentation of debris flow activity on Lone Tree Creek, its submarine fan has experienced several depositional events during the latter half of the Holocene.

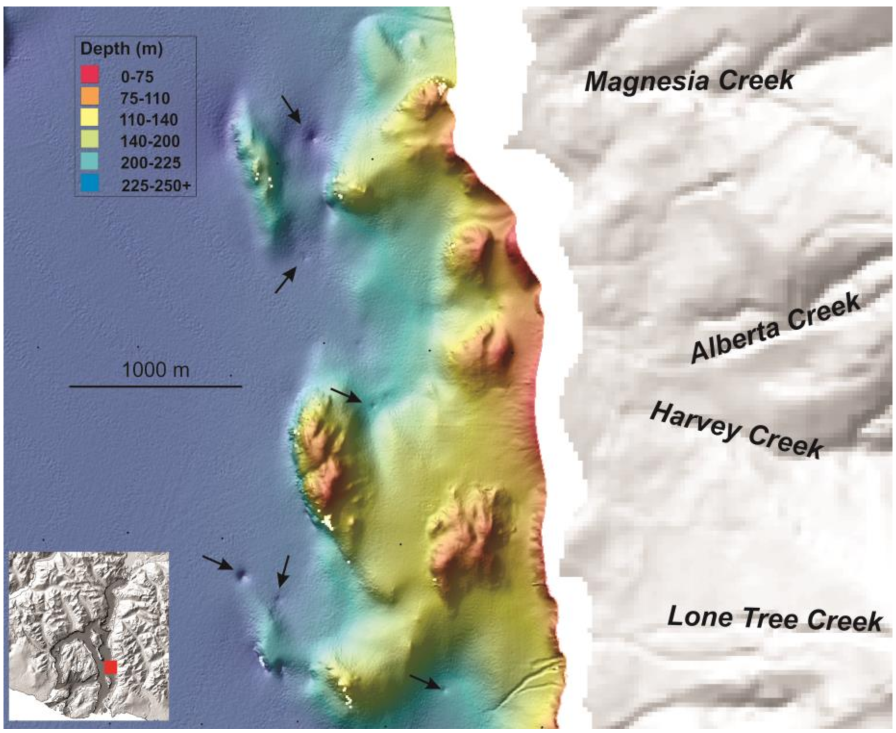

Figure 15. Swath multibeam bathymetry image of the floor of Howe Sound and digital elevation model of the adjacent terrain. Arrows show the location of crater-like gas escape structures.

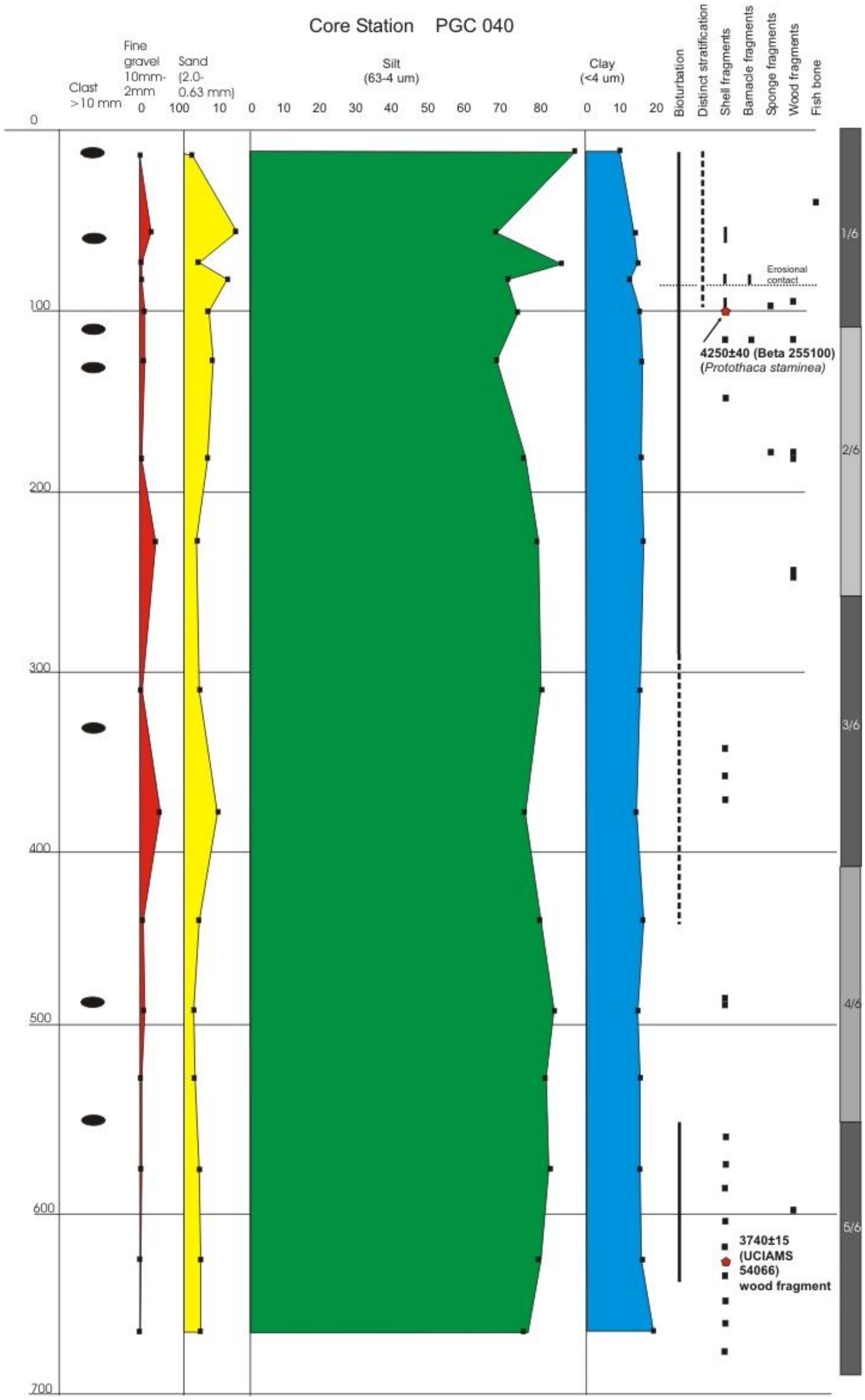

Figure 16. Granulometry and sedimentological features of sediment core 40.

Discussion

Although only 5 sediment cores have been taken from the floor of lower Howe Sound, the following preliminary observations can be made:

1. Glacial marine sedimentation ceased by ca. 9400 radiocarbon years before present based upon the dating of the cessation of the deposition of dropstones and sterile silt and clay in core 42. This apparently indicates the cessation of glacier margin calving and iceberg production at the head of the Howe Sound (the location of the closest retreating glacier margin).

2. The contemporary non-uniform rates of sedimentation in Howe Sound (Syvitski and MacDonald, 1982) characterized the entire Holocene: Holocene sedimentation rates have apparently been almost zero in Collingwood Channel between Bowen and Keats islands (cores 42-44). Although accurate estimation of sedimentation from level to level within cores 40 and 41 is not possible due to inversion of some ages, the overall range of ages suggests that sedimentation was in the order of more than a metre per thousand years until the mid-Holocene (ca. 5000 years BP) in the wide and deep basin of lower Howe Sound (core 41) and within the submarine fan below the mouth of Lone Tree Creek. Likely causes of inversion of the radiocarbon ages include disturbance by bioturbation, methane eruptions (Fig. 16), or localized sliding of the bottom.

3. The records of cores 40 and 41 indicate that sedimentation rates dropped dramatically in the areas of these core sites since the mid-Holocene.

With respect to point 3 above, the mid-Holocene reduction in sedimentation to core sites 40 and 41 is expected based upon documented geomorphic changes across the recently deglaciated Canadian Cordillera during the Holocene. Erosion and transport of sediment relict from recent glaciation is most intense early in the post glacial period and progressively approaches new rates adjusted to non-glacial conditions. This is referred to as the ‘paraglacial effect’ (Church and Ryder, 1972). This has been documented on alluvial fans and river systems throughout glaciated areas of the North American Cordillera (Jackson et al., 1982; Ritter and Ten Brink, 1986; Church and Slaymaker 1989), and recently deglaciated mountains elsewhere (Iturrizaga, 2008).

In the case of core site 41 (separated from the influx of fiord-margin torrents by submarine topography), sediment accumulating on the sea floor was entirely derived from the water column. Presently, the flux of suspended sediment to the area of core site 41 is dominated by suspended sediment discharged from the Fraser River that is transported north via currents in the Strait of Georgia (Syvitski and MacDonald, 1982). However, it cannot be assumed that suspended sediment from the Squamish River, which discharges into north end of Howe Sound, did not reach the site of core 41 earlier in the Holocene. Brooks (1994) found that the Squamish River and its tributaries incised through glacial fill to bedrock thousands of years before the present so that present rates of sediment transport to Howe Sound by the Squamish River is small compared to sediment transport rates earlier in the Holocene. Whether sediments at site 41 were derived from enhanced suspended sediment discharge from the Squamish River, Fraser River or both during early half of the Holocene, the rate of sedimentation was greater during the early half of the Holocene compared to its latter half and is consistent with the paraglacial effect.

Likewise, although the record is much shorter in sediment core 40, Lone Tree Creek (and likely other mountain torrents around Howe Sound) experienced a similar pattern of initial intense erosion and sediment transport during the early half of the Holocene with rates decreasing as relict glacial deposits dwindled later in the Holocene.

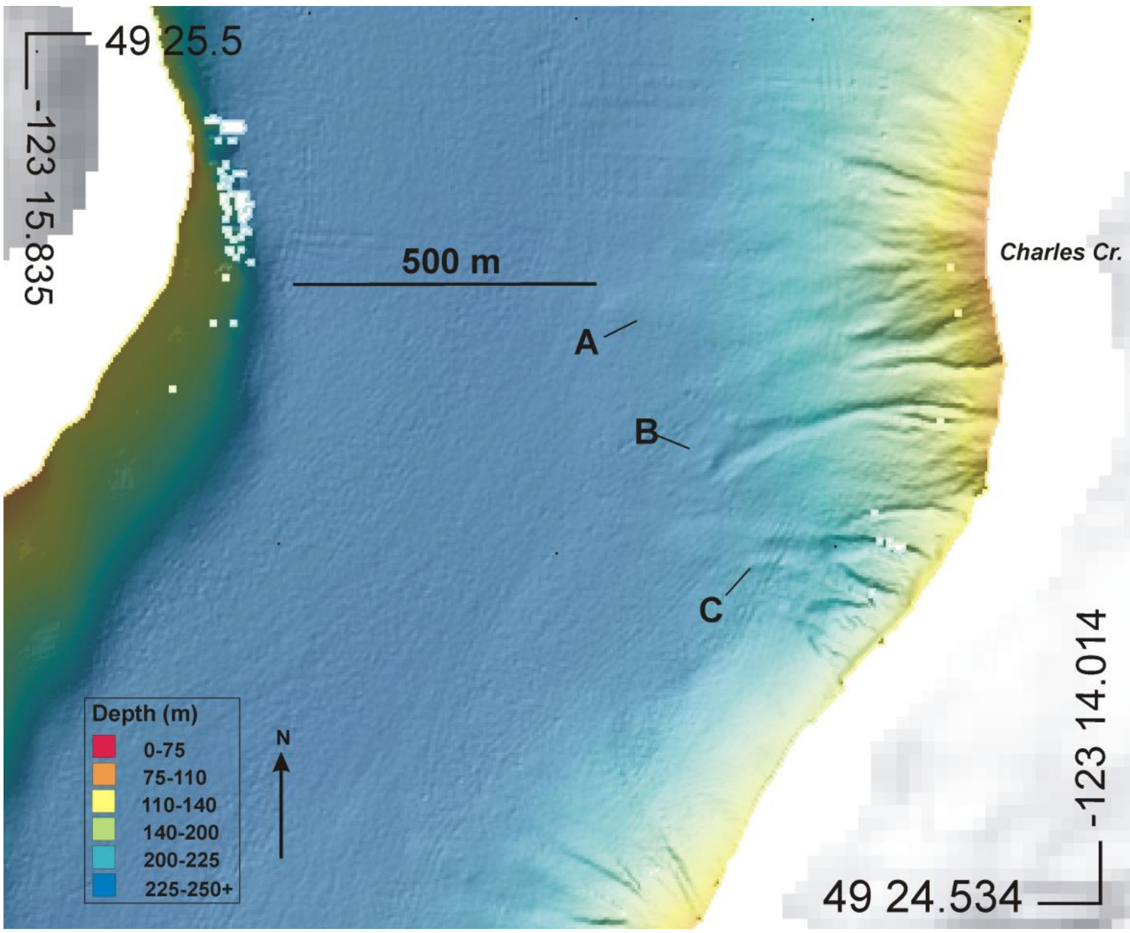

Figure 17. Swath multibeam bathymetry image from Jackson et al. (2008) showing features postulated to be levees created by debris flows that traversed and foundered in soft marine mud. Such features have relief of 1 m.

The most recent mass flows to have traversed the submarine fans along the eastern margin of Howe Sound display elongated enclosed depressions (Fig. 17). These apparently were created by the foundering of the flows into soft marine mud on the floor of Howe Sound with attendant diapiric disturbance along their margins. Jackson et al.

(2008) did not have any indication as to the age of these features beyond a Holocene age. Based on the sedimentation rates determined from the upper portion of core 41, these features could be as young as historic to a few thousands of years old.

Conclusions

Holocene sedimentation ranges from almost negligible in Collingwood Channel to many metres in the Lions Bay area. However, where it occurred, most of the sedimentation predated the latter half of the Holocene. This was apparently due to the paraglacial effect on sediment delivery to Howe Sound. Consequently, rock slide run-out deposits with relief of more than a metre would likely be visible to SMB if they were deposited during the latter half of the Holocene (a period of about 5000 years). The lack of such features in lower Howe Sound suggests that large rapidly moving rock slides capable of generating displacement waves have not occurred during this time period.

The deep-seated slope deformation identified on the west slope of Mount Gardner is an example of a type of slope movement commonly known as a sackung or sagging slope. Hundreds of these features exist throughout the British Columbia Coast Mountains, and others likely exist elsewhere in the Howe Sound area. Historically, only a very small number of these features have evolved into catastrophic landslides. Monitoring would be required to establish whether the feature on Mount Gardner shows signs of activity or if it is stable.

The run-out deposits on the seafloor beneath Mount Gardner were likely related to one or more small rock slides or debris flows originating from local areas of instability. No evidence of a significant displacement wave on Keats Island across Collingwood Channel was found during fieldwork. More analysis would be required to determine the possible size of impulse wave that could have been generated from small rockslides or debris flows like the ones on the sea floor along the west slope of Bowen Island. It is expected that such slides would have limited potential to generate destructive waves in this setting.

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