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J. Vaughn Barrie, Philip R. Hill, Kim W. Conway, Kashka Iwanowska and Kim Picard

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See table of contents

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Article abstract

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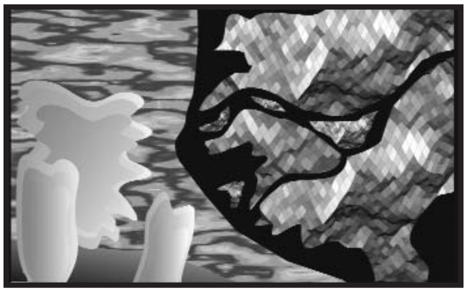
SERIES



Environmental Marine Geoscience 4: Georgia Basin: Seabed Features and Marine Geohazards

J. Vaughn Barrie, Philip R. Hill, Kim W. Conway, Kashka Iwanowska and Kim Picard
Geological Survey of Canada, Institute of Ocean Sciences, PO Box 6000, Sidney, British Columbia V8L 4B2 vbarrie@nrcan.gc.ca

SUMMARY

A multibeam bathymetric swath-mapping program of the Strait of Georgia has provided a 5-m resolution map of the seabed. Numerous geological features of the basin, some of which are considered geohazards, are clearly defined. During the Olympia interglacial period most of the basin was filled with sediment and then subsequently excavated during the Fraser Glaciation, except for a group of isolated banks; the southern basin was partially filled by the prograding Fraser River Delta during the Holocene. Marine geohazards that exist in this seismically active region include, slope stability features, active faults, gas pockmarks, and large migrating sedimentary bedforms. Other features, such as sponge reefs, have developed because of the glacial history and dynamic oceanography of the basin and provide unique and critical habitats to marine species.

SOMMAIRE

Un programme de levé par balayage bathymétrique a faisceaux multiples dans le détroit de Georgie a permis la production d'une carte du fond marin d'une résolution de 5 m. De nombreux éléments géologiques du bassin y sont clairement définis, dont certains constituent des géorisques clairement définis. Durant la période interglaciaire d'Olympia, la plus grande partie du bassin a été rempli de sédiments, lesquels ont par la suite été excavés durant la glaciation de Fraser, sauf un groupe de bancs isolés; la partie sud du bassin a été partiellement remplie par progradation du delta de la rivière Fraser à l'Holocène. Les géorisques marins de cette région d'activité sismique comprennent certains éléments de stabilité des talus, des failles actives, des cratères d'échappement de gaz, et de grands éléments topographiques sédimentaires migrants. D'autres éléments, comme des récifs de spongiaires se sont développés à cause de l'histoire glaciaire et de la dynamique océanographique du bassin, constituent un habitat essentiel pour des espèces marines.

INTRODUCTION

The spectacular landscape of the Georgia Basin surrounds a bountiful inland sea that encompasses three areas: Puget Sound, the Strait of Georgia and the Juan de Fuca Strait and connecting straits (Fig. 1). The basin is surrounded by the largest coastal population and development growth in the country and lies within the most seismically active zone in Canada (Rogers, 1998). The Fraser River Delta, located in the southern Strait of Georgia (Fig. 2), is of particular concern (Groulx and Mustard, 2004) because it is the site of a significant population, ferry terminals, port facilities, airport, a major fishery, and a critical electrical transmission and communication cable corridor to Vancouver Island. Furthermore, the rate of development in the basin continues to increase. Recent geophysical surveys have delineated active faults within the basin (Barrie and Hill, 2004), yet the response of the basin to a major earthquake remains largely unknown. The submarine and coastal parts of this basin are thus subject to both large development pressures and natural geologic hazards.

To help safeguard the population, protect existing and future development, and effectively manage the resources and future use of the basin, the Geological Survey of Canada initiated a multi-year mapping program in 1999. The primary dataset consists of contiguous multibeam swath bathymetric coverage of the central and southern Strait of Georgia, eastern Juan de Fuca Strait and the inter-island waterways that separate the two straits. The specific objectives of the program are to map the distribution of different seafloor types; predict sub-seabed geotechnical conditions through an understanding of Quaternary processes; determine the seafloor expression of earthquakes (neotectonics); and establish the geologic controls on geohazards such as slope instability and tsunamis.

One result of the mapping program is the first complete visualization of the morphology of the marine basin, equivalent to that provided by high resolution topographic maps on land. Numerous previously unidentified features of the seafloor have been revealed and new insights into the Quaternary history and active processes have been obtained. The objective of this investigation is to highlight the initial findings of the program in the Georgia Basin and display, for the first time, the multibeam image of the basin.

SETTING

The modern Georgia Basin, in part, overlaps two older sedimentary basins; a Late Cretaceous foreland basin preserved as the Nanaimo Group (Mustard, 1994; Mustard and Rouse, 1994; England and Bustin, 1998) and an early Tertiary non-marine basin dominated by the sedimentary rocks of the Chuckanut Formation (Johnson, 1984; Mustard and Rouse, 1994). The basin lies between southern British Columbia, Vancouver Island and Washington State (Fig. 1). Subsidence began in the Late Cretaceous (90 million years ago) and the tectonic regime, over the last 40 million years, has been dominated by subduction of the Juan de Fuca Plate. The North American Plate is presently overriding the oceanic Juan de Fuca Plate at a rate of about 45 mm/yr (Riddihough and Hyndman, 1991). The basin consists of a series of structural depressions, over-deepened by Tertiary erosion and Quaternary glaciation, and partially infilled by glacial and post-glacial sediment.

The Strait of Georgia is approximately 220 km long in a northwest-southeast direction between Vancouver Island and the mainland; the overall width varies from 25 to 55 km. The average depth of the Strait of Georgia is 155 m and the deepest point is 420 m (Thomson, 1981). Large areas of the strait reach depths of between 100 to 250 m, although several shallow banks exist down the axis of the basin. The strait connects with the open sea in the south, first through the Gulf Islands and San Juan Islands, and then through the Juan de Fuca Strait (Fig. 1). Bottom topography in the Gulf/San Juan Islands area is complex but mostly shallower than 100 m, except for a few narrow, deep channels. In the north, the Strait of Georgia connects to the open shelf of Queen Charlotte Sound through four narrow channels having sill depths of 90 m or less.

Three types of earthquakes occur and have distinct source regions within the basin (Rogers, 1998): continental crust earthquakes, deep earthquakes within the subducting oceanic plate, and very large earthquakes on the boundary between the continental and subducting oceanic plates. Crustal earthquakes are the most common and result from a compressive stress parallel to the continental margin, oriented north-northwest (Rogers, 1998). Both the largest historic earthquake in southwestern British Columbia, on central Vancouver Island in 1946 (M = 7.3), and the large prehistoric Seattle earthquake (M = 7+) were crustal earthquakes. Higher magnitude subcrustal earthquakes are caused by a tensional stress regime within the subducting plate in a depth range of 45 to 65 km (Rogers, 1998), the February 2001 Nisqually earthquake (M =6.8) in Washington State being a recent example. The largest and least frequent earthquakes, subduction earthquakes, have occurred at intervals of several centuries with the most recent one in 1700 (Satake et al., 1996).

Glaciation affected the Pacific margin of Canada many times, although extensive evidence has been found for only the youngest glacial episode over much of the area (Barrie and Conway, 2002). The Fraser Glaciation began approximately 25,000 – 30,000 years ago (Clague, 1977, 1981) and during the early stages thick, well-sorted sand deposits (Quadra Sand) were deposited in front of, and possibly along the margins of, glaciers moving down the Strait of Georgia as distal outwash aprons (Clague, 1976, 1977, 1994). Ice moving south from the Coast Mountains of the Canadian Cordillera and Vancouver Island progressively coalesced, over-rode and eroded these deposits. Ice flowing southeastward along the axis of the Strait of Georgia joined ice coming out of the Fraser Valley and then divided into two tongues, one following Juan de Fuca Strait toward the ocean and the other going southward into Puget

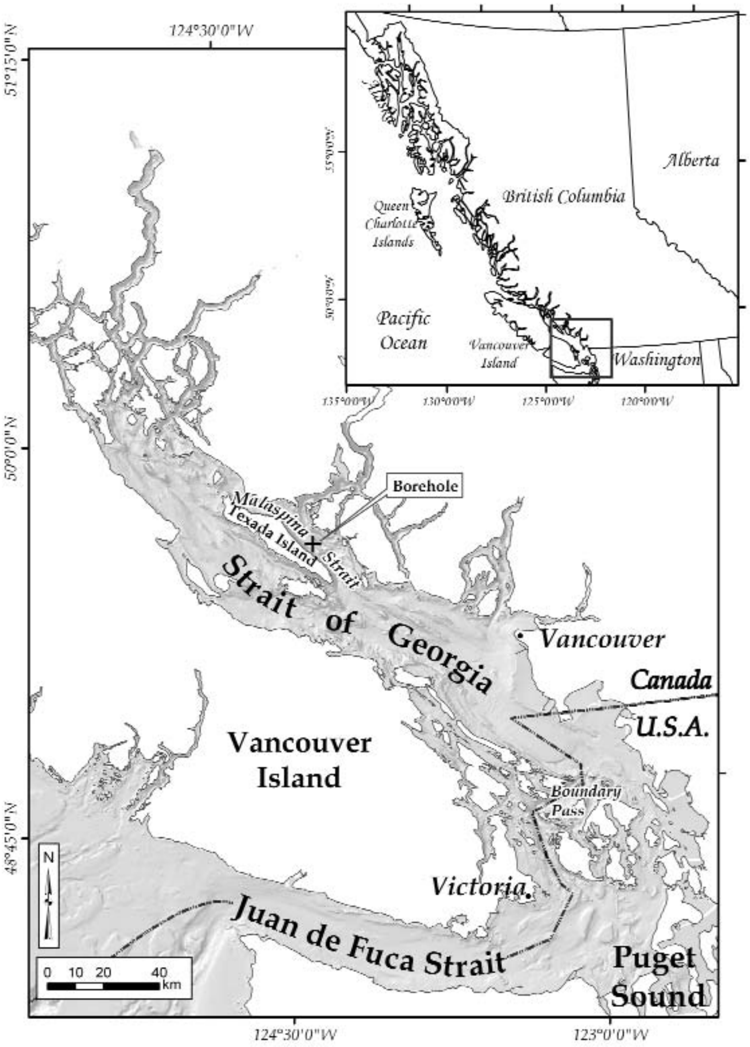


Figure 1. Georgia Basin.

Sound. This large glacier reached the south end of the Puget Lowland and the western Juan de Fuca Strait at its maximum extent (Waitt and Thorson, 1983; Hewitt and Mosher, 2001; Mosher and Johnson, 2001), at about 14,000 C^{14} BP (Porter and Swanson, 1998) and it deposited an ice-contact diamicton of variable thickness throughout most of the basin. Most of the Strait of Georgia was ice-free by 11,300 C^{14} BP (Barrie and Conway, 2002); deglaciation was very rapid with regional downwasting and widespread stagnation (Guilbault et al., 2003). This resulted in a stratigraphy comprising thick (30 - 60 m) diamicton (till), overlain by a unit of ice-proximal glaciomarine sediments and a thin, discontinuous ice-distal glaciomarine unit (Barrie and Conway, 2002). Within the southern Strait of Georgia, sedimentation from the Fraser River dominates the surficial geology where Holocene sediment thicknesses vary from zero on Pleistocene ridges to greater than 300 m (Mosher and Hamilton, 1998). Present day sedimentation rates vary from 10 cm/year near the river mouth, to less than 3 cm/year in the distal parts of the prodelta (Hart et al., 1998).

Modern circulation in the Strait of Georgia is characteristic of a partially mixed estuary having moderately strong tidal currents (2.6-3.4 m tidal range), seasonally varying stratification and late summer and late winter deep-water density intrusions (LeBlond, 1983; Crean and Ages, 1971; Thomson, 1994; Masson, 2002). The Fraser River runoff reaches a maximum of 10,000 m^3/s during the spring freshet and a minimum of around 1,000 m^3/s in late winter. The Fraser River accounts for about 73% of the mean annual freshwater discharge of 158 x 10^9 m^3 into the Strait of Georgia (Johannessen et al., 2003). This freshwater influx then forces estuarine circulation in the southern strait, which is characterized by a net outflow of low salinity water toward Juan de Fuca Strait in the upper layer (<50 m depth), and a net northward inflow of high salinity water in the lower part of the water column that reaches the Strait of Georgia in late summer (Mosher and Thomson, 2002).

METHODS

During several field programs from 2000 to 2004 (Fig. 2), about 5000 km^2 of multibeam swath bathymetry coverage was obtained over the central and southern Strait of Georgia. The objective of this mapping project was to collect contiguous full seafloor coverage of the strait. The surveys were carried out from the *CCGS R.B. Young, CCGS Vector*, and *Revisor* by the Canadian Hydrographic Service, in cooperation with the Geological Survey of Canada, using a hull-mounted Kongsberg-Simrad EM1002 system for the deeper regions of the basin (> 50 m water depth) and a hull-mounted Kongsberg-Simrad EM3000 system for the shallow parts of the basin (< 50 m water depth). The tracks were positioned so as to insonify 100% of the seafloor with a 100% overlap. Positioning was by broadcast differential GPS and the multibeam data were corrected for sound speed variations in the stratified water column using frequent sound speed casts. The data were edited for spurious bathymetric and navigational points and subsequently processed using CARIS software. The gridded data were exported as ASCII files and imported into ArcInfo software for processing and image production.

The multibeam swath images formed the interpretive framework for delineation of geological features including potential hazards. Based on this interpretation, several areas were highlighted for further investigation. In November 2000, aboard the *CCGS John P. Tully*, and again in December 2001, aboard *CCGS Vector*, surveys were undertaken using Huntec DTS high-resolution sub-bottom profiler, 10 cubic inch airgun and Simrad MS992 sidescan sonar (Mosher and Simpkin, 1999). In addition, piston cores were collected from the central and southern Strait of Georgia during the 2000 program. The cores were split in the laboratory, photographed and sampled for textural analyses, radiocarbon dating, as well as foraminiferal, pollen and diatom analyses. The results of the foraminiferal, pollen and diatom analyses are presented in Guilbault et al. (2003).

OBSERVATIONS

Geological Features

Bedrock

Deposition of the Fraser River sediment is not ubiquitous in the central and southern Strait of Georgia. As a result, part of the basin has limited or no sedimentation. For example, on the western

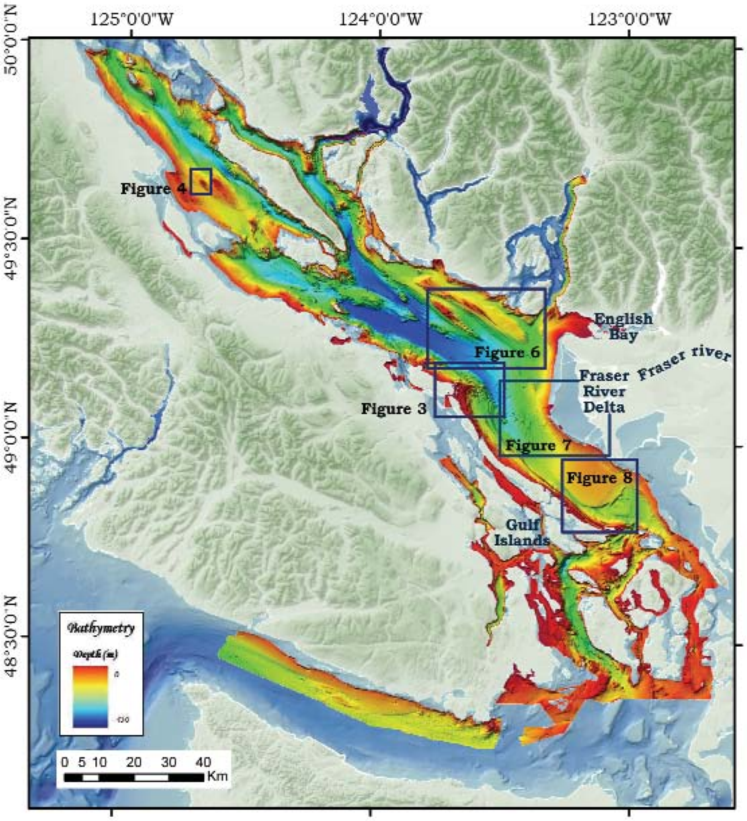


Figure 2. Multibeam image and digital topography for the Georgia Basin showing the location of Figures 3, 4, 6, 7, and 8.

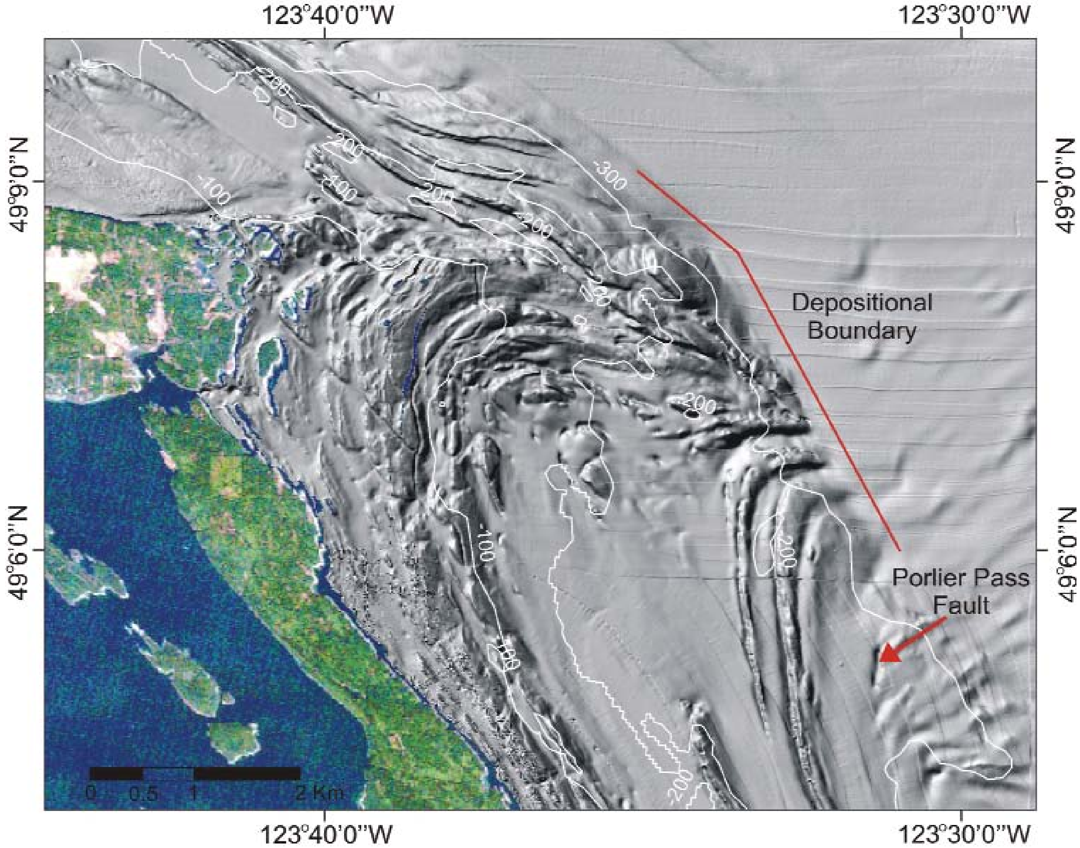


Figure 3. Multibeam image of a bedrock fold on the eastern side of the Strait of Georgia. Notice the location of Porlier Pass Fault and the depositional boundary between Holocene sediments and Nanaimo Group bedrock.

side of the basin into Boundary Pass and opposite the delta, bedrock is well exposed (Fig. 2). The basin is moderately deformed along a series of mainly northwest trending faults and folds (Fig. 3) having northeast to east dipping beds (Mustard, 1994). Figure 3 is an example of a northwest trending fold that occurs at the northern extension of a rock ridge that runs parallel to the eastern side of the strait adjacent to the Gulf Islands (Fig. 2).

Basin Banks

Clague (1977) suggested that Georgia Basin would have filled with sediment during the nonglacial to glacial transition at the beginning of the Fraser Glaciation. Ice moving south from the Coast Mountains of the Canadian Cordillera and Vancouver Island coalesced and eroded these deposits. However, as with the coastal Quadra Sand deposits (Clague, 1976, 1977, 1994), not all of these pre-glacial deposits were eroded and removed by the Cordilleran ice. Thick Quaternary sediment, occurring in several banks and shoals within the basin, represents remnants of these pre-glacial sediments (Figs. 4 and 5). The major banks of the central Strait of Georgia (Fig. 1) basin are made up of greater than 80 m of highly stratified sediment composed of well-sorted very fine silt (Fig. 5). The stratified muds contain very few marine and non-marine macro or microfossils suggesting rapid deposition in a brackish or marginal marine environment. A borehole drilled into this sediment facies in Malaspina Strait (Fig. 1) returned dates from wood debris of 41,260 to 43,020 C^{14} BP (Table 1), dating to the late stages of the Olympia interglacial and the early stage of the Quadra Sand (Clague, 1989). The banks tend to have steep north to northwest faces that have slopes in excess of 25°, where the flat lying strata are exposed (Figs. 4 and 5). Generally, these units are overlain, conformably, by an ice-contact diamicton.

Glacial Flutes

On the central banks of the strait, linear ridges are apparent. These constructional fluted tills formed by the action of the glaciers moving down the Strait of Georgia, particularly where bedrock or Pleistocene highs, such as Halibut Bank (Fig. 6), formed obstructions to the flow. The orientation of the ice movement (100-110 °) down the axis of the strait is clearly evident from the flutes (Fig. 6).

Sponge Reefs

Siliceous sponges form reefs on Fraser Ridge (Fig. 7), an isolated bank just off the Fraser Delta (Conway et al., 2004a), and in two areas of McCall and Halibut Bank (Figs. 2 and 6; Conway et al., 2004b). The Fraser Ridge complex has formed in an area where sedimentation rates adjacent to the reef site are greater than 2 cm/year (Conway et al., 2004a). The Fraser Ridge reefs consist of roughly circular inter-connected mounds up to 14 m in height and 200 m in diameter, found in water depths of 150 to 190 m and restricted to the top and flanks of an isolated promontory in the midst of the rapidly expanding Holocene prodelta (Fig. 7). Two species of hexactinosidan sponges, *Aphrocallistes vastus* and *Heterochone calyx*, build a framework of densely packed sponge skeletons while several other species of hexactinellida and demosponges are accessory fauna.

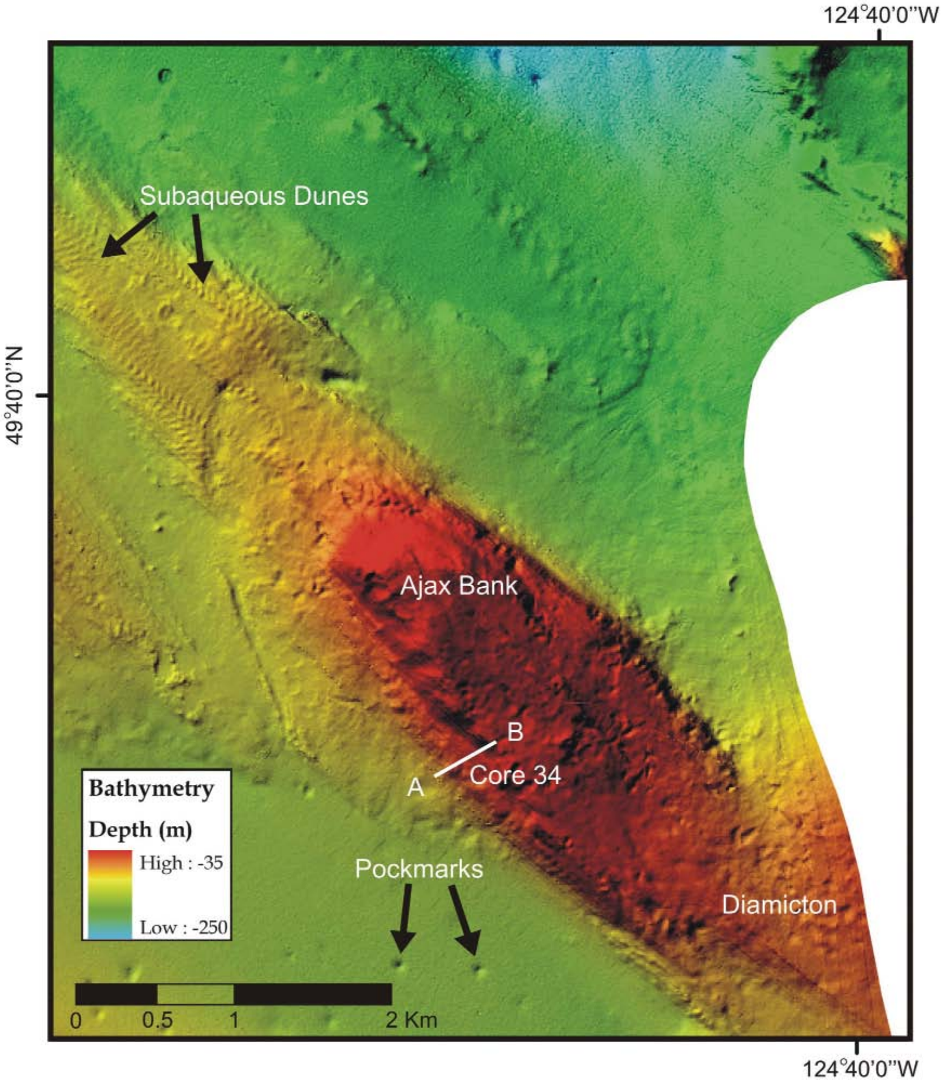


Figure 4. Multibeam image of Ajax Bank in the central Strait of Georgia (Fig. 2) that consists of thick stratified pre-glacial sediments (Fig. 5) covered with ice contact diamicton. Notice the randomly spaced pockmarks off the bank in fine-grained sediments.

The McCall and Halibut Bank reefs occur in a submarine valley formed between banks and on the northern fluted flank of Halibut Bank, in water depths from 120 to 210 m (Fig. 6). The reefs are up to 14 m in height, are bedform-like in shape and aspect ratio (Fig. 6), and have a wavelength of between 30 and 100 m. Morphologic differences in the frame-building species are interpreted as responses to the extremely different environmental conditions of the sediment starved northern BC shelf (Conway et al., 1991, 2001; Krautter et al., 2001) versus the turbid delta habitats of the Fraser Ridge (Conway et al., 2004a). The reefs of Halibut and McCall Bank are similar to the northern BC reef complexes, and like the Fraser Ridge reefs, are composed of only the two species (Conway et al., 2004b).

Foreslope Hills

The central basin of south-central Strait of Georgia, an area of >60 km^2, has a ridge and swale morphology, which has been identified as the Foreslope Hills (Mathews and Shepard, 1962; Terzaghi, 1962; Hamilton and Wigen, 1987; Hart, 1993). Mosher and Thomson (2002) recently interpreted these 20 m high, >5 km long ridges (Fig. 7) as sedimentary bedforms, similar to many deep-water sediment waves. To generate these waves there is a requirement for the initial seabed surface to have some regular rugosity (Mosher and Thomson, 2002). The initial rugosity upon which the Foreslope Hills developed may be related to en echelon thrust faulting of the Cretaceous to Holocene sediments in the northwest quadrant of the Foreslope Hills, which created the seabed structure that is part of the Porlier Pass Fault (Fig. 3, Barrie and Hill, 2004).

Geohazards

Pockmarks

Pockmarks or seafloor craters, reaching tens of metres wide and several metres deep, are typically found in groups (Hovland and Judd, 1988) and are formed by the removal of sediment as fluid (commonly gas) escapes into the water column. On the western slope of the Norwegian Trench, elongated depressions associated with pockmarks have been related to faulting within soft, silty, unconsolidated clay sediments (Hovland, 1983). Aligned pockmarks within the Ibiza Channel, in the western Mediterranean, have formed by the escape of gases and associated waters through faults from a hydrothermal field beneath the surficial sediments (Acosta et al., 2001). Shallow submarine slides in the Eivissa Channel of the western Mediterranean Sea are associated with pockmark swarms (Lastras et al., 2004). Similarly, the linear pockmark chains identified by Barrie and Hill (2004) off the Fraser River Delta foreslope (Fig. 6) have been associated with crustal faulting. Other areas of pockmarks that

Table 1: Radiocarbon dates obtained from a borehole in Malaspina Strait (Fig. 1) in the central Strait of Georgia.

Lab #	Core	Water Depth (m)	Sample Depth (m)	Dated Specimen	Radiocarbon Date (yr BP)
62770	A4	12	22.9	Wood Fragment	43,020±900
62770	A4	12	22.9	Wood Fragment	41,260±730

Radiocarbon analysis undertaken at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory.

show definite orientation occur in the central and northern strait and could also indicate faults.

A field of up to 200 pockmarks has been discovered on the seabed of English Bay, at the entrance to Vancouver Harbour (Hill, 2003). These pockmarks are located in water depths from 18 to 65 m, range in diameter from 15 to 100 m and are 5 to 15 m deep. Mainly circular in plan, the pockmarks are in places aligned along linear traces and coalesce to form more irregular, near-linear trenches similar to the pockmarks along the Fraser Delta Fault (Fig. 6). Some pockmarks are located in designated shipping lanes for vessels approaching the Vancouver Port and others coincide with designated anchorages for large vessels waiting outside the port (Hill, 2003).

Active Faults

Multibeam bathymetric data collected in the Strait of Georgia have revealed two areas of seabed disturbance, interpreted to be faults (Barrie and Hill, 2004). The easterly fault zone (Fraser Delta Fault) is defined by a pockmark chain that extends along strike from a known, southwesterly dipping fault having a throw of over 50 m (Fig. 6). The pockmarks occur in a region of high sedimentation, located in the Fraser River prodelta. The western strait fault zone (Porlier Pass Fault, Fig. 3) occurs within a fold of the Cretaceous Nanaimo Group, where a series of thrust faults displace Cretaceous to Holocene sediments by up to 40 m with over 2 km of along-strike-surface expression. These faults are considered to be active based on Holocene stratigraphic displacement in an area of significant sedimentation (Barrie and Hill, 2004).

Delta Foreslope Features

The Sand Heads submarine channel system, located at the mouth of the main channel of the Fraser River (Fig. 7), is an area of high sediment discharge, which commonly induces liquefaction and slope failure at the canyon heads (Kostaschuk et al., 1992; Hart et al., 1992). Four tributary canyons that have steep failure scarps and gullied walls show signs of recent mass-wasting (Carle, 2003). The freshest looking tributary canyon appears to have captured an older channel (directly east and

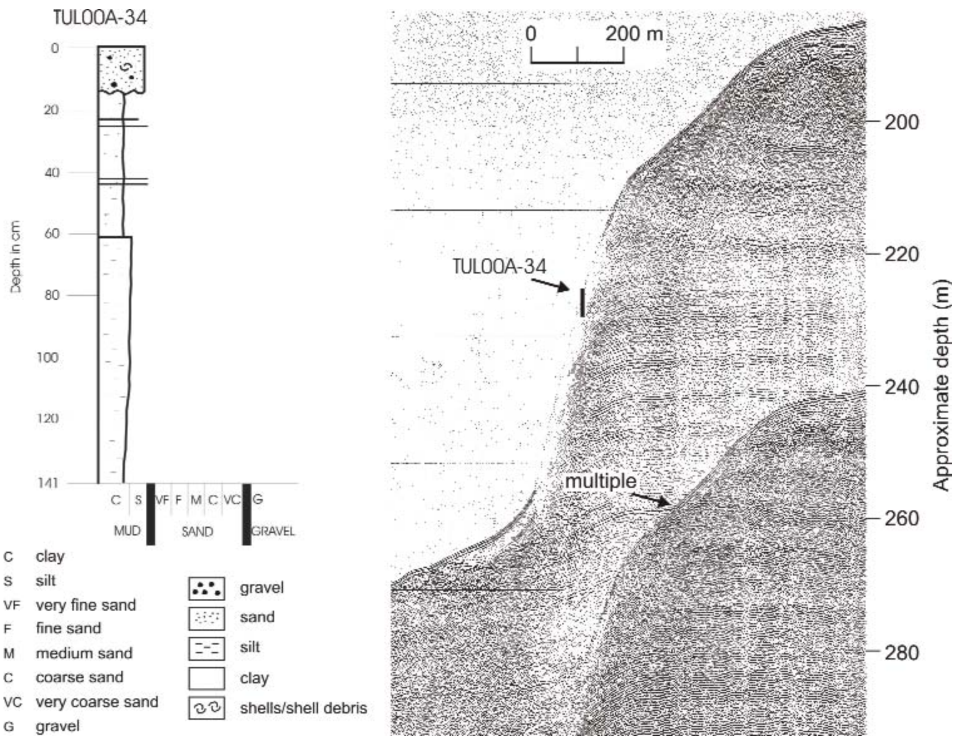


Figure 5. Huntec DTS sub-bottom profile of the western side of Ajax Bank (Figs. 1 and 4) showing the thick flat lying stratified sediments to the base of the bank. The illustrated Core (TULOOA-34) is taken from the mid slope of the bank.

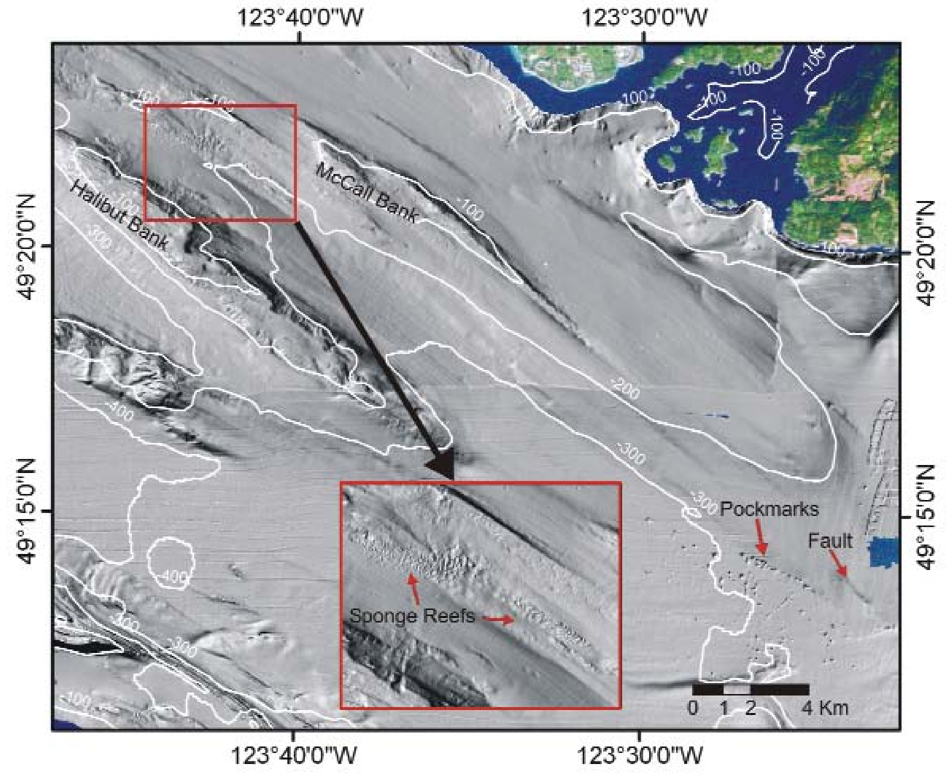


Figure 6. Multibeam imagery of Halibut and McCall Banks illustrating glacial fluting, small sponge reefs (see inset) and the Fraser Delta Fault with adjacent linear chain of pockmarks.

northeast of the feature labelled Submarine Channel in Figure 7). The tributary canyons converge on the delta slope to form a single channel of 100 to 380 m width, 18 to 60 m depth and 6 km length (Hart et al., 1992; Kostaschuk et al., 1992; Christian et al., 1998), with coarse-grained sediment at the base of the channel (Fig. 7).

Just to the south of the Sand Heads submarine channel is an area of sub-parallel ridges documented by Terzaghi (1962), Hart et al. (1992) and Christian et al. (1998). The morphology results from either shallow rotational sliding (Hart et al., 1992) or creep deformation (Christian et al., 1997). The ridges are crescentric and have their convex face downslope. They are 2 to 3 m high, have a wavelength between 60 and 100 m and are discontinuous in the along-slope direction. Two smaller channels and several smaller subdued gullies cross the slide complex, and accentuate the junctions between the crescentric ridges (Carle, 2003).

South of these ridges is Roberts Bank Channel, Canoe Passage Channel and the Roberts Bank Failure Complex (Hart and Barrie, 1995), is an area of partially exposed relict distributary channels and channel failures (Fig. 7). The channels of the Roberts Bank Failure Complex were active as early as 3,570 C^{14} BP up to about 100 years ago (Barrie, 2000). Since then, this part of the delta has been eroded by strong tidal currents, which has been enhanced by a limited sediment supply, in part, caused by human development (Hart et al., 1998; Barrie and Currie, 2000).

Sedimentary Bedforms

Three areas of central and southern Strait of Georgia have fields of active large-scale bedforms, 1) southern Roberts Bank, 2) southern Strait of Georgia, and 3) Boundary Pass (Figs. 7, 8 and 9). Within the Roberts Bank Failure Complex (Fig. 7) is a large subaqueous dune field; dunes have wavelengths of 10 to 100 m and heights of 0.5 to 5 m (Kostaschuk et al., 1995; Currie and Mosher, 1996). The dune field presumably results from flood-tide, current erosion of delta sediments (Hart et al., 1995; Barrie and Currie, 2000). The dunes may have been generated at this location because of the slight morphological bulge of the Roberts Bank

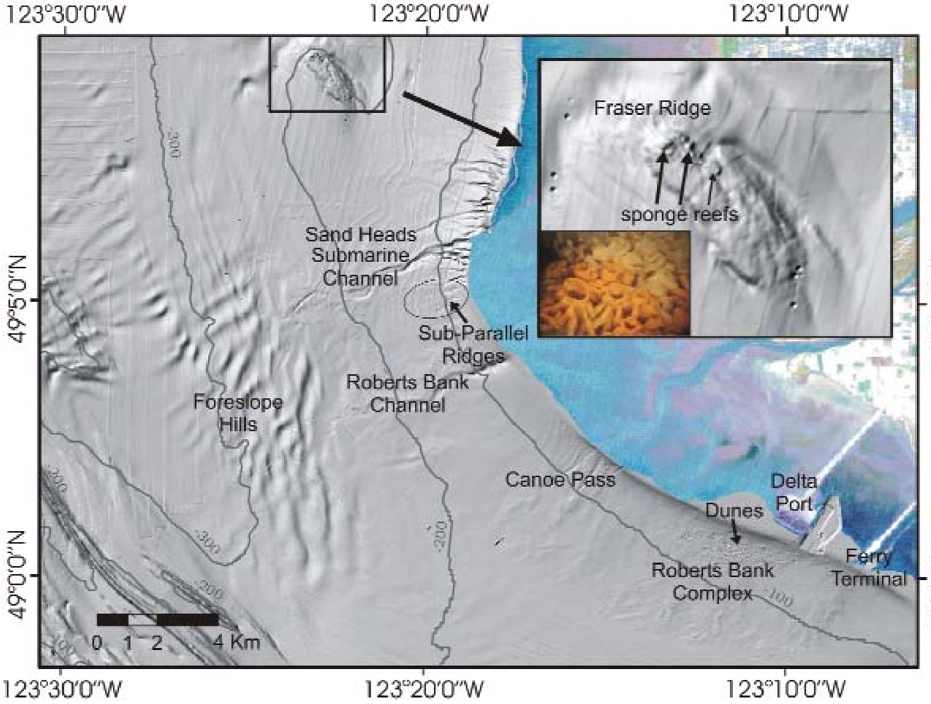


Figure 7. Multibeam imagery of the Fraser River Delta foreslope illustrating several seabed features and geohazards (see text). An inset of Fraser Ridge shows the sponge reefs that occur on the northeast flank.

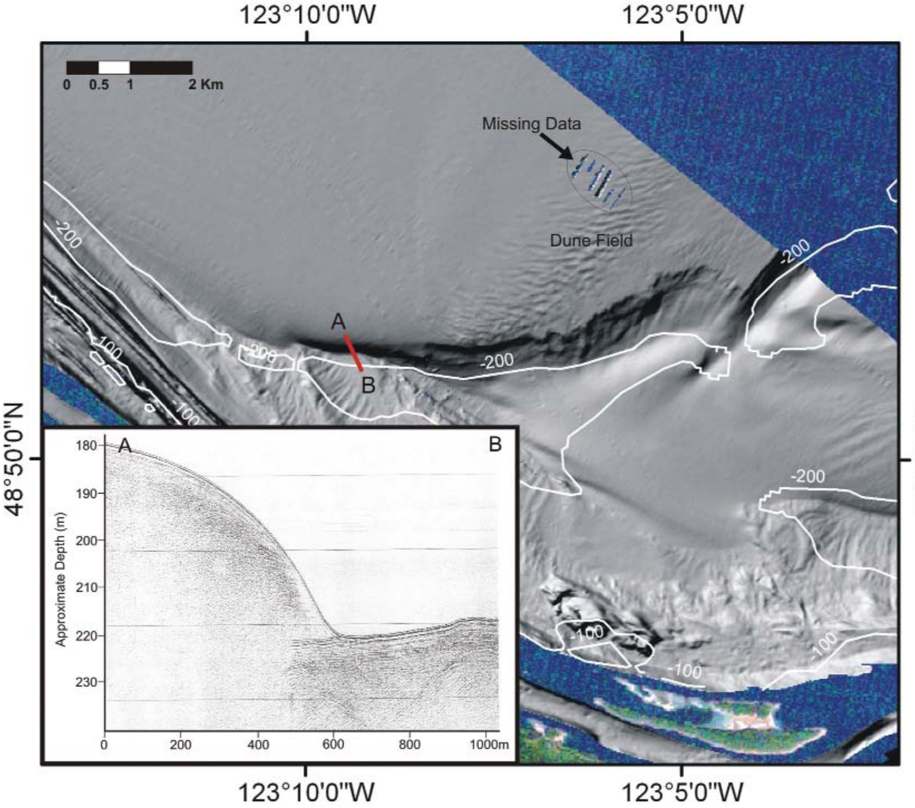


Figure 8. Multibeam image of the southern Strait of Georgia where active delta sedimentation ends and the seafloor becomes erosional. Also evident on the image is a field of subaqueous dunes, just above the depositional boundary. Inset is a north south Huntec DTS sub-bottom profile illustrating the erosional truncation of Holocene sediments.

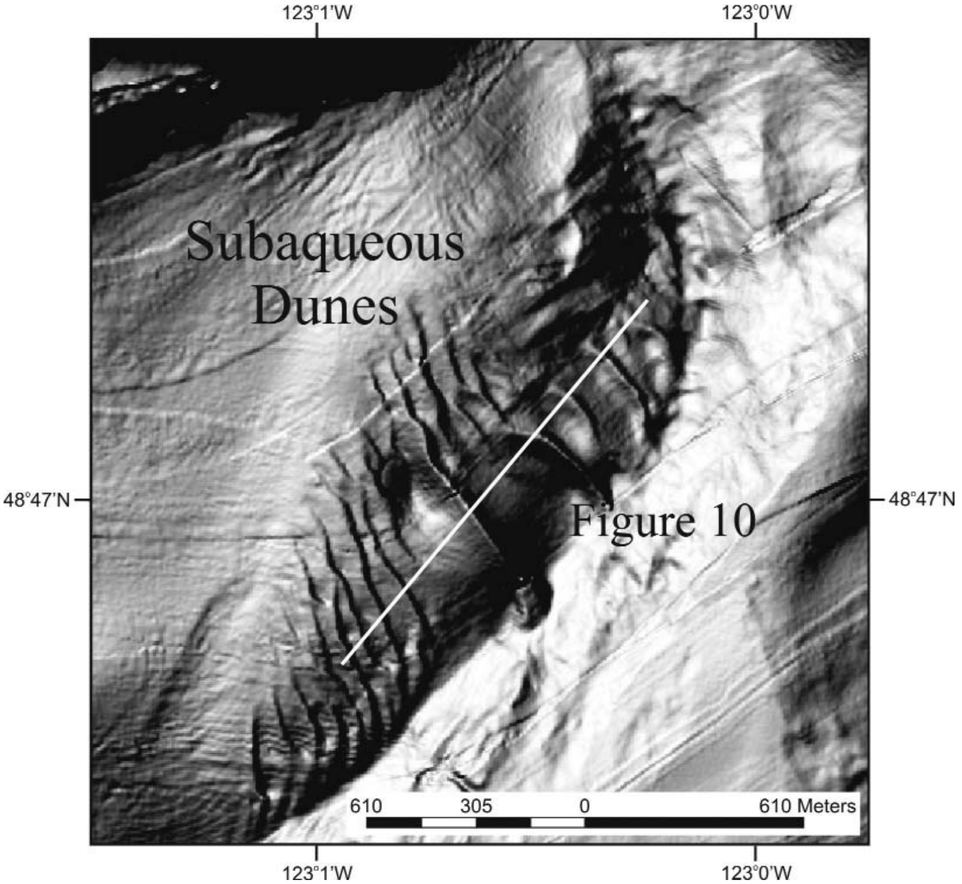


Figure 9. Multibeam imagery of a series of very large subaqueous dunes located in Boundary Pass (Fig. 1).

Failure Complex, which induces a local acceleration of the tidal current (Carle, 2003).

The southern Strait of Georgia dune field consists of large subaqueous, symmetrical dunes that have wavelengths of 150 to 300 m and wave heights of 2 to 3 m covering an area of 7 km^2 (Fig. 8). This field lies just above a depositional boundary and the direction of movement is sub-parallel to the erosional scarp (Fig. 8).

In Boundary Pass, along the US-Canada border (Fig. 1), there is a series of nearly symmetrical, very large subaqueous dunes that have wavelengths between 100 and 300 m, covering an area of 2.5 km^2 in 170 to 210 m of water (Figs. 9 and 10); they consist of well-sorted coarse-grained sand and gravel. These features are hydrodynamically formed, of an unknown age, and rank amongst the largest ever observed globally. Similar submarine sand dunes have been identified in the eastern Juan de Fuca Strait (Mosher and Thomson, 2000). The largest of these dunes measures 28 m in height and 760 m in ridge crest length (Figs. 9 and 10). The dunes are classified as linear, slightly asymmetrical, stoss-erosional, lee-depositional, two dimensional, very large dunes (classification nomenclature of Ashley,1990). Net transport is in a northerly (flood) direction (Fig. 10).

Two current meters were installed, 10 km to the southwest of the dune field by Fisheries and Oceans Canada, for a two year period, at 110 and 125 m water depth. Maximum current velocities of 1.94 m/s occurred in a northeast (flood) direction with the highest recorded ebb velocities of 1.29 m/s. A second mooring put in by ASL Environmental Services for less than 2 months just northeast of the Fisheries and Oceans mooring measured velocities up to 2.23 m/s within the water column (ASL Environmental Services, 2001). Current velocities over the dunes would be expected to be much higher than those recorded by these two moorings

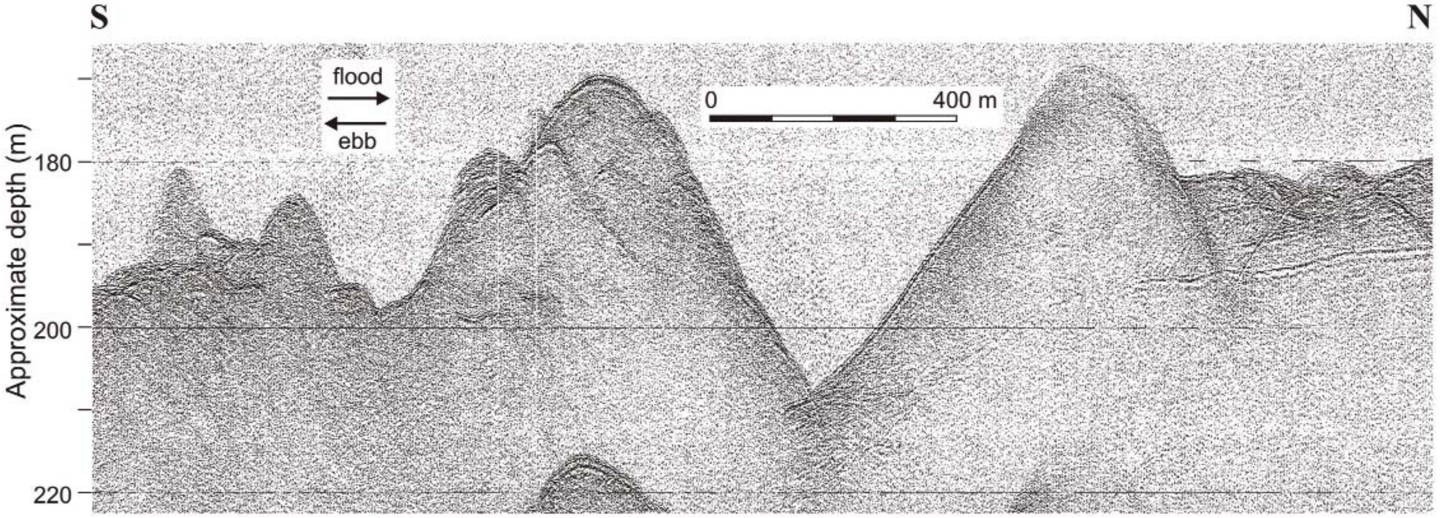


Figure 10. Huntec DTS sub-bottom profile through the subaqueous dune field in Boundary Pass. Notice the northward lee face of the very large dunes suggesting northward migration and the smaller dunes that occur on, and between, the larger dunes.

because of topographic constriction of the flow to the east, and because the mooring sites were off to one side of the main channel axis. The water column is primarily well mixed, suggesting the near-bottom velocities could be expected to approach the maximum velocities measured (R. Thomson, personal communication, 2002). Using the currents observed from the two moorings and the mean sediment grain size (0.5 to 1.0 mm) as inputs into the Ashley (1990) classification of large-scale subaqueous bedforms, it is clear that these dunes are mobile. It is likely that deep flood tides and estuarine circulation during summer construct the dunes. The original multibeam survey of the Boundary Pass dunes was undertaken in November 2001; a repeat survey undertaken in October 2003 suggests that the dunes are moving to the north. The question of dune age, mobility, and stability remains unanswered, but is of critical engineering importance for placement of submarine pipelines and cables.

Sediment Distribution Pattern

Pharo and Barnes (1976) originally described the surficial sediment distribution pattern for the Fraser River Delta, and later, it was described by Barrie and Currie (2000) using a far more detailed sediment sampling grid. Generally, the sediments grade from fine grained sands in the delta front, the wave-influenced part of the delta at the seaward limit of the tidal flat, to silt on the delta slope to clay on the prodelta (Fig. 11). On southern Roberts Bank, this sediment distribution pattern changes from a dominant sandy delta plain that continues and coarsens well out onto the delta slope, but becomes finer grained at the base of the slope (Fig. 11). The mean grain size of the sediment of the delta front and slope is coarser than the present sediment load carried by the Fraser River (Barrie and Currie, 2000), and there is no evidence for present day sedimentation (Hart et al., 1998). This change in sediment pattern over the Roberts Bank Failure Complex is attributed, in part, to restriction of the river channels by jetties, construction of three causeways across the intertidal delta and dredging of the river over the past century (Hart et al., 1998; Barrie and Currie, 2000; Barrie, 2000).

Deposition from the Fraser River plume controls the surficial sediment distribution pattern from the central Strait of Georgia, just south of Texada Island (Fig. 1), to just past the US-Canada border in the south (Fig. 11). North of this area, the surficial sediment distribution pattern is dominated by local sediment inputs and sediment reworking by wave and tidal energy in the shallower waters (Fig. 11). In particular, the shallow coastal plain along eastern Vancouver Island consists largely of low-gradient broad sand and gravel beaches, derived mainly through erosion of abundant unconsolidated sediment underlying the lowland (Clague and Bornhold, 1980). The coastal plain is exposed to the dominant southeasterly storm direction, resulting in northerly transport of sandy sediments. In the deeper troughs of northern Strait of Georgia, the sediments are primarily silty clay (Fig. 11).

Post-glacial deposition is dominated by river output and modern oceanographic conditions. However, fine-grained deposition is not ubiquitous within the southern Strait of Georgia and in several areas, such as Fraser Ridge (Fig. 7), close to the main channel of the river, no deposition has taken place recently. Two boundaries between contrasting types of thick Holocene deposits are observed on multibeam imagery (Figs. 3 and 8). One of these boundaries is west of the delta, just east of folded Nanaimo Group bedrock (Fig. 3). Another boundary is south of the delta, off Point Roberts, where a sharp contrast in deposition extends across most of the southern Strait (Fig. 8). This boundary is defined by a ragged, erosional escarpment, where the slope varies from 3 to 4° to greater than 12°. The sub-bottom profile (Fig. 8) illustrates the truncated Holocene beds along the steep slope and the eroded glacial to early post-glacial sediments at the base of the slope.

SYNTHESIS

The contiguous coverage of multibeam swath bathymetry in the central and southern Strait of Georgia, in combination with seismic reflection profiling, provides data necessary to interpret development of the basin morphology. Even though the seafloor of this region of the basin is dominated by discharge from the Fraser River, features from its geological past are evident.

Cretaceous to Tertiary bedrock is exposed along the entire western side of the basin and into the Gulf Islands and Boundary Pass (Figs. 2 and 3). Interglacial and preglacial sediments form the banks along the centre of the strait. Generally, these sediments are discontinuous and exist as eroded remnants that have steep slopes. The flat lying strata suggest that the entire basin was infilled about 40,000 years C^{14} BP, prior to the last glaciation. As ice moved down the strait, it scoured out most of these sediments and subsequently laid down an extensive diamicton. The rem-

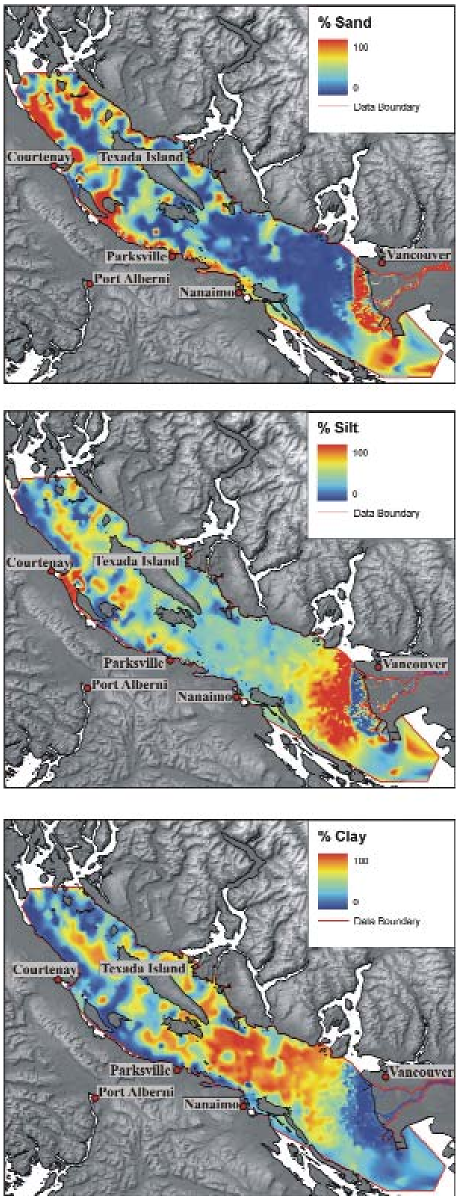


Figure 11. Surficial sediment distribution (% sand, silt and clay) on the seafloor of the Strait of Georgia, based on over 4,400 grab samples.

nant Pleistocene highs under the flowing ice allowed for the formation of glacial flutes over many parts of the basin (Fig. 6). Ice-contact diamictons from the Fraser Glaciation are exposed over much of the central and northern strait, evident by the rough bouldery surface (Fig. 4).

Preglacial banks, mantled with diamicton provided the requisite habitat for the formation of sponge reefs (Conway et al., 2004b). Sponge reefs have been identified on Fraser Ridge (Conway et al., 2004a), the swale between McCall and Halibut banks, and on the northern slope of Halibut Bank (Fig. 6). The Georgia Basin reefs have formed on glacial highs or on glacial flutes, where the raised surfaces of boulders and cobbles provide a hard substrate for benthic epifaunal organisms to colonize. Hexactinosan sponges, in particular, use this hard substrate to settle and initiate growth. As the currents deflect and accelerate over and around the elevated ridge, there is greater possibility of increased access to nutrients.

The absence of some geological features also provide insight into development chronology. Single channel high-resolution geophysical data (Barrie and Conway, 2002) and foraminifera data from cores (Guilbault et al., 2003) suggest that deglaciation was rapid with in place downwasting and stagnation of the ice at nearly the same time over most of the Strait of Georgia. The multibeam data support this interpretation. Whereas features of glacial advance are abundant (diamictons, flutes), features typical of glacial retreat, such as retreat moraines and iceberg scouring, are clearly not present.

Holocene deposition, primarily from the Fraser River, dominates most of the seafloor in the deeper parts of the southern basin. The sediments are rich in organic matter and the prodelta sediments are known to have extensive interstitial gas (Hart and Hamilton, 1993). This gas may give rise to the discontinuous regions of pockmarks within the southern basin. However, the linear chains of pockmarks off the northern delta, which are associated with an active fault (Fig. 6), could also result from thermogenic gas accumulations that exist within Tertiary sediments of Georgia Basin (Mustard, 1994; England and Bustin, 1998). The linear pockmark chains, particularly where faults occur, may present a potential zone of migration to the surface.

In areas away from the dominant Holocene deposition, strong tidal currents amplified by estuarine flow are capable of moving large volumes of coarse grained sediment and eroding the underlying seabed. Depositional pattern changes, such as found in the southern strait (Fig. 8), may have resulted from current pattern changes related to the rapid progradation of the Fraser River Delta into the southern strait during the Holocene. Anthropogenic effects may account for more recent changes in sediment distribution patterns and erosion on Roberts Bank.

The new, complete imagery of the seafloor makes potential hazards more apparent. For example, the very large subaqueous dunes of Boundary Pass appear to be migratory and occur in an area of seabed cables and a proposed gas pipeline. Understanding the migration rates and patterns of these dunes is critical. Active faults and unconsolidated sediments on steep slopes, in a region of significant shallow seismicity (Cassidy et al., 2000), could generate tsunamis. These potential hazards, therefore, require further investigation, considering the large and growing population and infrastructure of Georgia Basin, including the urban areas of the Greater Vancouver Regional District and those of eastern Vancouver Island.

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