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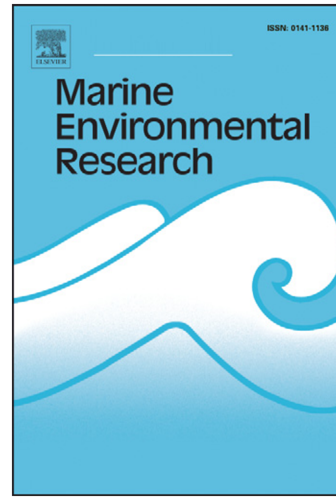

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Sedimentary Processes and Sediment Dispersal in the southern Strait of Georgia, BC, Canada

Philip R. Hill[1*], Kim Conway[1], D. Gwyn Lintern[1], Samuel Meulé[1,2], Kim Picard[1], and J. Vaughn Barrie[1]

[1]Natural Resources Canada, Geological Survey of Canada, Box 6000, Sidney, B.C., V8L 4B2

[2]Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, Unité Mixte de Recherche 6635 CNRS/Université Aix-Marseille, Europôle de l'Arbois, BP 80, 13545 Aix-en-Provence Cedex 04, France.

*Corresponding author. Tel.: +1 250 363 6617; fax: +1 250 363 8836.

E-mail address: phill@nrcan.gc.ca (P. Hill).

Abstract

This paper presents a review of sediment dispersal processes in the Strait of Georgia, based on marine geological studies. Sediment from the Fraser River is dispersed around the Strait through a variety of transport pathways. Most sand and coarser silt fractions settle out and are deposited within a few hundred metres of the channel mouths. Both channelled and non-channelled gravity flows probably transport sediment down-slope and onto the basin floor. Asymmetric tidal currents force a predominantly northward sediment drift, resulting in a reworked slope off Roberts Bank and a finer-grained depositional slope off Sturgeon Bank. Far-field sediment accumulation is controlled by local morphology and sediment dynamics. Multibeam mapping and seismic profiling reveal that some parts of the basin floor are characterized by bottom sediment reworking and erosion. Given the complexities of sediment dispersal and seafloor reworking, generalizations about sediment dispersal paths and sedimentation rates are difficult. Future understanding will be advanced by the cabled observatory, VENUS, which will enable near real-time monitoring of key processes.

Keywords:

Marine geology

Sediments

Coastal waters

Sediment dispersal processes

Sediment transport pathways

Sediment sinks

Multibeam mapping

Seabed morphology

1. Introduction

Stewardship of the coastal ocean requires an understanding of how sediment particles and their associated contaminants are dispersed in the marine environment. Particles of all grain sizes are naturally discharged into the ocean by rivers and through erosion of the coast and seabed, while human activities such as sewage disposal, dredging, dredge waste disposal and aquaculture introduce particles at various point sources. Regardless of their origin, particles are moved and dispersed within the ocean through natural processes such as gravity, surface waves and currents. In the Strait of Georgia, the semi-enclosed nature of the basin, the mix of natural and anthropogenic sources and the complexity of sediment dispersal processes present a challenge to ocean managers to understand the fate of discharged particles. The Strait is bordered by three major metropolitan areas, Greater Vancouver, Victoria and Nanaimo (Fig. 1) and numerous smaller population centres, which sanction varying levels of sewage treatment. It is a major transportation corridor, hosts significant fish and marine mammal populations, provides unique habitat such as sponge reefs and has huge cultural, aesthetic and recreational value to the people of the region.

The objective of this paper is to provide a synthesis of present understanding of sediment dispersion pathways in the Strait of Georgia, based on previously published work and the results of recent studies. We take a marine geologic approach, identifying key sedimentary processes and seabed evidence for depositional environment. No distinction is made here between inorganic and organic particles.

2. Setting

The Strait of Georgia (Fig. 1) is the modern manifestation of the Georgia Basin, a tectonic forearc basin located on the Cascadia convergent margin. The basin was formed by crustal folds related to subduction of the Juan de Fuca oceanic plate beneath continental North America. The same folding contributes to the high-relief, mountainous terrain of the Coast Range. During the Pleistocene era, glacial ice extended over most of the basin resulting in erosion of the basin floor giving maximum water depths in excess of 400 m. The resulting topography is one of deep, N-S oriented and flat-floored basins separated by shallow ridges. Bedrock and glacial deposits outcrop on the ridges, forming a hard substrate that favours the growth of deep water corals and sponge reefs (Conway et al., 2007). The glaciation also formed the deep coastal fjords that characterize the British Columbia coast.

This geological setting provides for a relatively restricted marine basin, separated from the Pacific Ocean by narrow and, at places, shallow straits. The basin is protected from Pacific Ocean swell waves, so that the wave regime is relatively benign and largely fetch-limited. The maximum recorded significant wave height from the few measurements recorded in the basin is 3.4 m but heights of 1 m or more occur less than 4% of the time (Hill and Davidson, 2002). The restricted nature of the basin, however, makes tidal exchange quite vigorous, particularly in the narrow entrances to the Strait, where tidal current speeds can exceed 2 m s^{-1} (Barrie et al., 2005). At the Fraser Delta, the tide has a range of 3 to 5 m and is characterized by strong semi-diurnal and diurnal tides that create inequalities between successive tides (Thomson, 1994).

3. Methods

This review is based on three principal techniques: acoustical mapping of the seabed and underlying sediments, grab and core sampling, and water column measurements. Acoustical mapping of the seabed has been a staple of Geological Survey of Canada research for the last 30 years. Traditional techniques include high resolution seismic and sidescan sonar surveying. The more recent development of multibeam sonar surveying has greatly advanced studies of the seabed and, for the first time, provided full bottom coverage and comprehensive high resolution bathymetric imaging of the Strait of Georgia seafloor below 5 m water depth (Barrie et al., 2005). These acoustic data provide an overview of the nature of the seafloor and can be used to identify areas of net accumulation vs. non-deposition or erosion.

Grab and core samples are used to confirm these interpretations and characterize bottom sediments. A comprehensive set of grab samples in the Strait of Georgia has been analyzed for sediment grain size (Barrie and Currie, 2000). Core samples are used to determine the age of sediments immediately underlying the seafloor. In areas of non-deposition or erosion, seafloor sediments may consist of older glacial or glaciomarine deposits whose age can be determined from radiocarbon dating or biostratigraphic techniques (Guibault et al., 2003). In areas of sediment accumulation, the rate of sediment accumulation can be determined from radiocarbon dating and/or ^{210}Pb dating (Johannessen et al. 2003; Picard et al., 2006).

Sediments are advected through the water column either in suspension or along the bottom through bedload transport. In both cases, current meters that provide time series of current speeds and direction can be used to estimate sediment flux and pathways. Suspended sediment flux can be estimated by combining current speeds with suspended concentrations. The latter are measured directly by sampling volumes of water with Niskin bottles or indirectly using a range of optical and acoustical techniques. Most of the data presented in this paper are derived from acoustic Doppler current meters which measure current speeds and acoustic backscatter at numerous levels in the water column. Making assumptions about acoustic attenuation with depth, we can estimate sediment concentration from the acoustic backscatter and vertical CTD profile. Because this method requires exhaustive calibration and correction for grain size, absolute values are difficult to obtain and the data presented here should be considered semi-quantitative. Bedload transport is even more difficult to quantify without extraordinary effort, so the understanding of sediment transport in the Strait of Georgia remains at a qualitative level.

4. Sources of Sediment

In global terms, river sediment loads and yields show a log-linear relationship with basin area and the maximum elevation of the river basin (Milliman and Syvitski, 1992), so that forearc basins like the Strait of Georgia tend to be efficiently supplied with sediment. The Fraser River, with a mean annual fresh water discharge of 1.15 x 10^{11} m^3 and mean annual sediment discharge between 1 and 3 x 10^{10} kg is the dominant source of sediment to the basin (Johannessen et al., 2003). Smaller rivers such as the Campbell and Squamish Rivers contribute approximately 20% of the total. However, much of the discharge from smaller rivers on the continental side of the basin is trapped in fjord basins and does not reach the Strait.

Sediment discharge from the Fraser River has been impacted by the construction of jetties, transportation causeways and training walls to maintain river position. River mouth sedimentation has therefore been anthropogenically altered (Barrie and Currie, 2000). The river bed has been and is being dredged to allow commercial freighter traffic access to port facilities upriver through the Main Channel. The bedload of the Fraser River is redistributed by these dredging operations and disrupts the "natural" delivery of these sediments to the delta slope (Hill, in press).

5. Sediment Dispersal Processes

5.1 Estuarine Circulation and the Sediment Plume

Sediment dispersal in the Strait of Georgia is greatly influenced by the dynamic processes that occur at the mouth of the Fraser River. The outer parts of the distributary channels of the Fraser are strongly influenced by the buoyancy of the outflowing river and the semi-diurnal tide, setting up a classic estuarine circulation with saline water intruding up to 18 km upstream when the river discharge is at its minimum (Ages and Woollard, 1976). The distance of saline intrusion and the position of the estuarine salt wedge at any given time depend on the river flow and the tidal elevation at the mouth of the river.

During peak discharge in late May/early June, the salt wedge is pushed out beyond the channel mouth at low tide (Kostaschuk et al, 1995).

Under most river flow conditions, significant outflow from Main Channel is maintained in a buoyant surface layer, forming a surface plume in the Strait. Satellite and aerial imagery and ADCP backscatter data indicate that significant inertial flows occur from all minor channels and tidal creeks on the falling tide (Meulé, 2005). The resultant surface plume displays as a complex pattern of turbidity comprising many fronts and eddies (Fig. 2). The plume structure is continuously modified by the changing tidal and wind-driven surface currents. The majority of satellite images indicate that the plume tends to extend southward over the southern end of the Strait (Johannessen et al., 2005). However, because these optical images correspond to particular weather conditions, i.e. days with little cloud cover, there may be some bias in this interpretation. Wind data from Vancouver International Airport (Environment Canada) indicate that for all months, easterly winds are most frequent. Current data from off Roberts Bank indicate a strong asymmetry of tidal currents resulting in a predominant northward drift along the delta slope (Fig. 3; Meule, 2005). Some northward advection of the plume very likely occurs under conditions not captured by the satellite images.

Sediment in the plume behaves non-conservatively because of its settling property. Coarser grains and flocs with higher settling velocities settle first while finer grains remain in suspension for longer periods of time. ADCP backscatter measurements made off Roberts Bank indicate that a large proportion of the suspended sediment flowing out of Canoe Passage at ebb tide settles 40-50 m to the seabed within two hours, indicating a settling rate of 1.5 to 35 mm s^{-1} (Fig. 4; Meulé, 2005). This is consistent with Stokes settling velocities for fine sand but may be augmented by convective settling (McCool and Parsons, 2004). Thirty-five percent of the sediment load of the river consists of sand (Thomas and Bendell-Young, 1999). At other river mouths, flocculation of finer grain sizes has been documented as an important process favouring rapid deposition (Hill et al., 2000; Fox et al., 2004; Milligan et al., 2007). Typical floc settling rates are in the order of 1 mm s^{-1}, an order of magnitude slower than calculated above. Nevertheless, flocculation is very likely an important process for reducing the concentration of fine-grained sediment in the surface plume.

Rapid settling of fine sand translates into rapid rates of accumulation close to the river mouth. This is confirmed by repeat multibeam surveys that indicate accumulation rates greater than 1 m yr^{-1} between 1994 and 2006 at the top of the delta slope. These rates decrease exponentially downslope, consistent with models of suspension settling controlled primarily by grain size (Syvitski et al., 1998).

5.2 Gravity Flows

Recent repeat multibeam bathymetric surveys have shown that up-slope migrating sediment waves are present on the slope off the Main Channel river mouth (Hill, in press). Such features are known from environments where turbidity currents are active (Normark et al., 2002) and raise the possibility that gravity flows may occur on the non-channeled portion of the delta front. For such events to occur, suspended sediment concentrations must be sufficiently high (typically several g L^{-1} in sea water) to generate hyperpycnal (excess density) conditions at the river mouth. In an earlier analysis, Mulder and Syvitski (1995) calculated that suspended sediment concentrations in the Fraser River were unlikely to be high enough to generate hyperpycnal conditions through direct river discharge. However, recent research has shown that, in cases such as the Amazon and Eel Rivers, gravity flows have been observed despite the river borne suspended sediment concentrations being sub-critical (Kineke et al., 1996; Ogston et al., 2000). There is now recognition that gravity flows in near-bottom layers can be supported by velocity shear resulting from currents and waves (Wright and Friedrichs, 2006; Friedrichs and Scully, 2007).

No direct observations of hyperpycnal conditions have been made on the Fraser, but the most likely time for the conditions to exist would be in June when the snowmelt peak occurs and river flow peaks. At these times, the estuarine salt wedge is pushed out of the channel and is located over the delta slope (Kostaschuk et al, 1995; Orton et al., 2000). During these conditions, sediment is eroded from the bed of the distributary channel and transported to the edge of the delta slope. As in other salt wedge estuaries, a turbidity maximum concentrating near bed suspended sediment through advective convergence is present and near-bed suspended sediment concentrations have been observed to increase to levels approaching 1 g L^{-1} (P.M. Orton, 2007, personal communication). This high river stage does not typically coincide with high wave conditions, but strong tidal currents associated with spring tides may provide the velocity shear to support hyperpycnal conditions.

Down slope gravity flows can also be generated from entrainment of submarine slides. The multibeam records indicate that sediment accumulates rapidly at the mouth of the river, with accumulation exceeding 1 m yr^{-1} at the top of the slope (Hill, in press). Such high rates of accumulation create unstable conditions at the top of the slope and slope failures are known to occur on an inter-annual time scale (McKenna and Luternauer, 1987; McKenna et al., 1992). These slope failures probably initiate by liquefaction and are transformed into turbidity currents as they flow down the steep slope. The current accelerates and entrains more sediment from the base of the flow (Pratson et al., 2000), thus eroding a channel into the slope. Evidence for this process can be seen in the incised submarine channel present on the slope at the mouth of the Main Channel (Fig. 5).

The submarine channel consists of several tributary channels, which converge at mid-slope to form a single feature. Repeat multibeam surveys indicate that several of the tributary channels have been the location of small erosional events between 2001 and 2006. In the amphitheatre-like canyon heads of the southern tributary, several metres of sediment have been lost between surveys, indicating failure events (Hill, in press.). Other erosion events were noted in the southern tributary channels themselves. These may also have been slope failure events, although erosion by turbidity currents cannot be ruled out. In contrast, the northern tributary channel has been largely infilled by a set of backstepping depositional wedges. These have been interpreted as the deposits of “stalled” turbidity currents, possibly triggered by dredge disposal (Hill, in press.).

In common with other submarine channel and canyon systems (Paull et al., 2006), there is evidence that some turbidity currents transport sediment the length of the channel system, while others do not. Those that do, transport sand to the base of slope where the ambient sediment, deposited from suspension fall-out, is mud. The coarser grain size shows as high acoustic backscatter in multibeam data, delineating a broad fan-shaped area of sandier sediments (Fig. 6). High backscatter areas are also found on the leveed margins of the channel, indicating that the turbidity currents sometimes spill over the channel margin, depositing sand.

5.3 Tidally-driven sediment transport

The delta slope is swept by strong asymmetric tidal currents (Fig. 3). On Roberts Bank, flood tidal currents are stronger, with mean velocities exceeding 1.2 m s^{-1}, and directed along slope toward the north while ebb currents rarely exceed 0.5 m s^{-1} and are directed southward (Meulé, 2005). Peak currents are sufficient to cause resuspension of fine sand off the seabed under both flood and ebb flows (Figs. 4, 7), but because the flood current maintains higher bed shear velocities in excess of the critical threshold for erosion for longer periods, net sediment transport is directed northward with the flood current. Current speeds generally decrease downslope, but bed shear velocities exceed critical values to depths as great as 90 m (Kostaschuk et al., 1995).

As a result of this high energy sediment transport, the seabed off Roberts Bank is characterized by subaqueous dunes (Carle and Hill, in press.; Fig. 8). A variety of forms are found, both 2-D and 3-D, with heights ranging from 0.3 to 2.6 m and wavelengths from 26 to 55 m. The distinct asymmetry of the bedforms, with steeper faces towards the northwest, confirms net sediment transport in the flood direction. The only exception is a small area at the southern end of Roberts Bank, in the lee of the peninsula of Point Roberts, where ebb-oriented bedforms are found. A particular form of irregularly spaced subaqueous dune showing a variety of planforms from sinuous to chevron, heights up to 3.5 m and apparent wavelengths ranging from 25 to 180 m is present on the slope in water depths less than 60 m (Fig. 8). This form of dune is thought to be characteristic of high rates of sediment transport that effectively make it impossible for the dune to fully form (Carle and Hill, in press).

North of Sand Heads, the delta slope off Sturgeon Bank has a distinctly different character. No bedforms are observed. Rather, the morphology of the slope is smooth, indicating a less energetic environment where bed re-suspension is rare

5.5 Wind and Wave Action

On open shelves, storm wave energy is often the dominant driver of sediment transport (Amos and Judge, 1991). In more restricted shelf basins such as the Strait of Georgia, wave energy is greatly limited by the available fetch. The limited wave regime of the Strait restricts the influence of waves to water depths of 20 m or less for typical storm wave conditions (Hill and Davidson, 2002). Nevertheless, the orbital and linear motions induced by surface gravity waves and wind-driven currents respectively can locally accelerate or decelerate tidal currents. Such interactions make sediment transport processes complex in shallow water. On high tides, waves penetrate onto the tidal flats where they are strongly dissipated by bottom friction, whereas at low tide, the waves tend to break on the upper delta slope (Meulé, 2005).

Multibeam imagery provides some evidence for wave erosion on the upper slope in the form of outcropping beds (Fig. 8; Carle and Hill, in press.). Sediment transport modeling suggests that the unidirectional component of flow (i.e. alongslope tidal currents) determines the predominant direction of sediment transport; however, for certain bathymetric configurations and under certain directions of incident waves, an offshore component of transport may be expected.

5.6 Far-Field Sediment Dispersal

Due to the above processes, most of the coarser fractions (sand and silt) are deposited relatively close to the delta front. However, some fine sediment does escape the river mouth and is deposited in topographic basins hundreds of kilometres away from the river mouth (Johannessen et al., 2003; Picard et al., 2006). The processes involved in this long range dispersal have not been studied in detail. In particular, it is not clear how effective the surface plume would be in dispersing sediment long distances. Because flocculation close to the river mouth reduces the suspended sediment concentration of the distal plume, aggregation rates of the remaining sediment are low and the sediment can stay in suspension for long distances. However, given the strength of tidal currents on the delta slope and elsewhere in the Strait, it is likely that sediment is regularly being resuspended and bottom sediments being reworked throughout the basin. Evidence for this is presented in the next section.

6. Sediment Sinks

The principal sediment sinks in the Strait of Georgia can be identified from analysis of the seabed morphology and seismic reflection profiles. When glacial ice retreated from the area between 10,000 and 8,000 years before present (BP), the seafloor would have been characterized by steep-sided troughs and ridges. This high seafloor relief was gradually reduced by preferential accumulation of post-glacial sediment in the basins. These depocentres include the main basin of the southern Strait as well as the deep bathymetric troughs between McCall and Halibut Banks (Fig. 9). Basins such as Ballenas Basin, have captured more than 25 m of postglacial mud (Picard et al., 2006), as have Howe Sound, English Bay and channels as far north as Malaspina Strait (Fig. 1). Sediment has not generally accumulated on ridges or basin margins (Fig. 9).

The predominant control on far-field deposition is the local current regime. Sediment is trapped in basins where bottom currents are minimal and fine particle settling can occur. Many basin margins are swept clean of sediment because ambient currents tend to accelerate across and around the obstacles formed by topographic ridges and slopes. In these marginal settings and in restricted channels between islands, the sedimentation patterns can be quite complex (Fig. 9) and local sedimentation rates are quite variable. Where sediment accumulation does occur, the currents may winnow the sediments, leaving them coarser-grained, typically sandier. Where erosion or non-deposition occurs, the seabed is often characterized by a gravel lag deposit, consisting of coarser clasts derived from the eroded sediments, often glacial deposits with a significant coarse-grained fraction.

Multibeam backscatter and grab sample data (Barrie et al., 2005) indicate that in some areas of earlier sediment accumulation, seafloor currents have eroded and winnowed sediments. Once such area is the broad zone from the Fraser Swell to the approaches to Boundary Passage (Fig. 9). Smooth, muddy substrates where sediment is accumulating are normally associated with low backscatter intensity. However, much of the Fraser Swell is characterized by intermediate to high backscatter intensities indicating either coarser (current-winnowed) surficial deposits (e.g. sand) and/or a rougher seabed due to erosional or non-depositional conditions (Fig. 9 inset). Another sign of seabed reworking is the presence of bedforms in some areas on the Fraser Swell. This evidence all suggests that the surface of the Fraser Swell is being winnowed by the modern-day current regime. At the southern edge of the swell, seismic data indicate the truncation of beds at the seabed, a direct indication of active current erosion. South of this depositional boundary, very limited recent deposition occurs (Barrie et al., 2005).

The depositional history of the southern Strait of Georgia is thus complex, the area having experienced a change from predominantly low energy conditions favouring sediment accumulation to higher energy conditions favouring winnowing and reworking of the older sediments.

Seafloor areas north of the Fraser Swell do not show this erosion of previously deposited sediment and thick recent mud accumulations are apparent on seismic data (Barrie et al., 2005). However, even in these areas, where morphologic and seismic data provide a first order indication of modern-day sediment accumulation, seismic data are not reliable for estimating modern sedimentation rates because of uncertainties related to geologic history and interpretation (Picard et al., 2006). Better estimates are obtained by using radioisotope profiles from cores (Johannessen et al., 2005; this volume). Sedimentation rates as measured at box core stations for the southern Strait exceed 3 cm yr^{-1} proximal to the Fraser River, and to between 2 and 3 cm yr^{-1} measured at stations to the south (with one exception, station GVRD-07, Johannessen et al., this volume). In the northern Strait of Georgia, the sedimentation rate is everywhere <1 cm yr^{-1}.

Multibeam images of the central part of the southern Strait of Georgia reveal the presence of some large (20-m-high, >5-km-long ridges) sedimentary ridges and swales in 230–350 m water depth that are informally named the Foreslope Hills (Fig. 9). These features, have been examined by numerous authors who have attributed various origins to them, including submarine slide, mud diapirs, in situ rotational failures, and creep deformation (Mathews and Shepard, 1962; Terzaghi, 1962; Shepard, 1967; Tiffin et al., 1971; Luternauer and Finn, 1983; Hamilton and Wigen, 1987; Hart, 1993). However, Mosher and Thomson (2002) make a convincing case, based on detailed seismic analysis, that the Foreslope Hills are sediment waves that have accumulated over the last few thousand years at most. The waves are thought to be formed by lee waves (Flood, 1988) generated in the density gradient formed by strong flood tides or severe biannual density intrusions (Mosher and Thomson, 2002).

7. Implications for Management and Future Studies

7.1 Interpretations of Sediment Data in Complex Environments

This paper has concentrated on natural sediment transport processes. In ocean management, the concern is often with the pathways for dispersal and/or concentration of anthropogenically introduced particles and associated contaminants. In the Strait of Georgia, these include sandy material introduced by dredge waste disposal and finer particulates from sewage outlets, storm water and drain runoff (Fig. 1; Burd et al., this volume).

The above review illustrates that the pathway between source and sink can be a complex one for sediment particles in the Strait of Georgia. There are a near infinite number of possible pathways depending on particle size and density, how particles first enter the system, whether in near-surface suspension or near-bottom gravity flow, on the opportunities for reworking by waves, tidal currents and gravity, and on the dynamics of the final site of deposition. Basin-wide generalizations about particle fluxes and accumulation rates based on short term measurements at individual sites are therefore risky without a solid understanding of the regional and local dynamics. This is well illustrated by the example of sediment accumulating in the southern part of the Strait (Fig. 9). To arrive at this location from the Fraser River, sediment particles have likely been transported in a complex pattern around the Strait. Most were probably delivered into the surface plume, then advected around the basin depending on the cumulative effects of wind driven and tidal currents over a minimum of several days before being deposited. Some particles may have been delivered to the deep basin by turbidity currents and subsequently moved to a new location by currents generated by density intrusion or tides. Either pathway may have included intermediate steps of temporary deposition and resuspension by bottom currents. Point measurements of accumulation rates in the southern Strait indicate relatively high rates of sediment accumulation (Johannessen et al 2003; Burd et al, this volume). Yet, mapping of bottom sediment cover using multibeam and seismic data shows that there are local areas of no deposition and complex patterns of accumulation (Fig. 9). If a core had been dropped a few 10's of metres away from the sample sites, a completely different result may have been obtained.

Given the complexity of pathways and processes, horizontal sediment fluxes could probably be modelled successfully. However, vertical fluxes and net accumulation are highly influenced by the local and temporally variable fluid dynamics. Geological evidence in the form of sediment accumulation maps derived from multibeam sonar and seismic data provide a qualitative but important guide to these dynamics. Past attempts to map sediment accumulation from seismic interpretations (Mathews and Murray, 1965; Tiffin, 1969; Mosher and Hamilton, 1998) have suffered from issues of generalizing from discontinuous data as well as from inaccuracies introduced by age assumptions in seismic interpretation (Picard et al. 2006). However, the full bottom coverage and high spatial resolution provided by multibeam bathymetry and backscatter maps provides much greater confidence in the identification of depositional vs. non-deposition areas.

Combined with seismic interpretation and radiocarbon dating of cores, they can be used to semi-quantitatively estimate accumulation rates and place station data into the local and regional context necessary for interpretation of vertical flux and accumulation rate data.

7.2 Present and Future Monitoring Efforts

Repeated multibeam surveys have proven useful for quantifying accumulation rates, measuring sediment transport in bedforms and identifying erosional events in tributary canyon heads of the Fraser River delta (Hill, in press). In the case of dredge waste, disposal sites can be monitored using a combination of bathymetry and backscatter. At the mouth of the Fraser River delta, annual mapping has revealed the deposits associated with dredge material disposal and provided insight into the sediment dynamics of dredge disposal (Hill, in press).

Sediment dispersal pathways continue to be a focus of research in the Strait of Georgia, driven by ocean management concerns related to its proximity, and therefore importance, to a large population. Of particular relevance to sedimentation and erosion patterns in the Fraser swell area is the occurrence of deep water renewal events during which turbulently mixed waters of Boundary Passage and Haro Strait spill over into the deep Strait of Georgia causing bottom resuspension (Masson, 2002). In order to understand these deep water events more fully, benthic landers including instruments for measuring particle sizes and transport velocities will be deployed for extended periods of time.

Ship based and mooring programs have revealed vital information about some of the processes in the Strait. However, the trigger mechanisms and fundamental drivers of these processes remain poorly understood. The requirement for future research is for a method by which multiple processes can be measured at all time scales. The Victoria Experimental Network Under the Sea (VENUS) is placing a fibre optic scientific network in the southern portion of the Strait of Georgia. At the time of writing, a trunk cable carrying DC power and fibre optic data transmission capability has been installed in a looped configuration within the southern part of the Strait (Fig. 10). The objective is to provide long term, continuous and high frequency measurements of key ocean processes with data delivery to the scientist's and manager's laboratories in near real time through the Internet. The VENUS observatory includes platforms (or other sockets) to connect instruments on a transect from the river mouth (40 m depth) down the delta front to two deep observatory nodes at 170 and 300 m respectively. At all connection points, interface packages will enable interested scientists to plug in their own specialized instruments for measurements of processes in real time, and over all time scales. Data will be accessible in near real-time from the project web site (www.venus.uvic.ca).

The two deep nodes (170 and 300 m; Fig. 10 A) and the shallowest (40 m) connection points will have, as a start, instruments for measuring currents, tides, and sediment concentrations. A heavily instrumented 'lander' (Figure 10C) at the northwest corner of Roberts Bank will collect data about environmental and sediment conditions at the interface between river and ocean. This lander will contain instruments that measure bedform migrations, near bed sediment transport and water column oceanographic conditions. For the deep nodes, instrumentation includes zooplankton acoustic profilers (ZAP) to measure the concentration of backscattering targets in the water column. Though untested, the ZAP profilers will likely give a return signal for suspended sediment and should provide images of the Fraser River plume and other suspension events. Finally, a major installation on the Fraser Delta will measure pressures in the sediment (Fig. 10B), and the forcing mechanisms which affect them, in an ongoing endeavour to understand the conditions leading to slope instability, failure and downslope transport.

Combined with frequent resurveys of the river mouth area by multibeam sonar, VENUS data will shed new light on how sediments are transferred from the delta to the rest of the basin. VENUS represents a quantum leap in collecting data in the Strait of Georgia. It is expected that new insight will be gained into the mechanisms and time variability of sediment transport and in situ bed conditions.

8. Conclusions

The sedimentary dispersal processes operating in the southern Strait of Georgia are complex and linked to the fluvial and deltaic processes associated with the Fraser River, which is the primary source of sediment. Near field dispersal of sediment is strongly influenced by the strong tidal currents present on the east side of the basin, but gravity flows originating as wave- or tidal current-supported density flows or from submarine slides transport sediment into deep water. Far-field dispersion of the fine fraction of Fraser River sediment is by wind and tidal current advection of the surface sediment plume and redistribution of previously deposited material. While tranquil settling of particles into deeper basins is typical of the northern Strait, local current conditions make the southern Strait more complex. Future studies of the southern Strait will be enhanced by the seabed cabled observatory, VENUS, that will allow long term, continuous monitoring of sediment fluxes.

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FIGURE CAPTIONS

Figure 1 Physiographic and bathymetric map of the Strait of Georgia showing location of largest sewage outfalls and dredge disposal sites. The map merges a shaded relief image of the land physiography (lighter grey tones) with a shaded relief image of the multibeam-derived bathymetry of the Strait of Georgia (darker grey tones). Blank areas between represent unsurveyed areas.

Figure 2 Landsat image (July 30, 2000) of Fraser Delta and turbid surface plume showing numerous entry points and inertial jet structure of the river flow as it enters the strait.

Figure 3 24-hr record of current flow on the Fraser Delta slope (located by star on Figure 1) obtained from a hull-mounted ADCP. The black line shows tide height over the time period. Note strong flood currents during the rising tide and weaker, though still significant, ebb current. This tidal asymmetry leads to net sediment drift northward with the flood tide.

Figure 4 Consecutive backscatter profiles along an onshore-offshore transect in the region shown by star in Figure 1, collected from a hull-mounted ADCP during ebb tide. High backscatter values represent high suspended sediment concentrations.

Figure 5 A) Shaded relief multibeam image showing the extensive submarine channelling on the delta slope seaward of the mouth of Main Channel. B) 3-D rendering of the boxed area in A.

Figure 6 Multibeam backscatter image of the submarine channel system off Main Channel. Bright areas represent higher backscatter intensity. In this case, the broad fan-shaped area at the base of the slope shows up as higher intensity, indicating coarser grained sediments that have been deposited by turbidity currents travelling down the submarine channel.

Figure 7 Consecutive backscatter profiles along an onshore-offshore transect in the region shown by star in Figure 1, collected from a hull-mounted ADCP during flood tide. High backscatter values represent high suspended sediment concentrations. The profile locations are the same as in Figure 4.

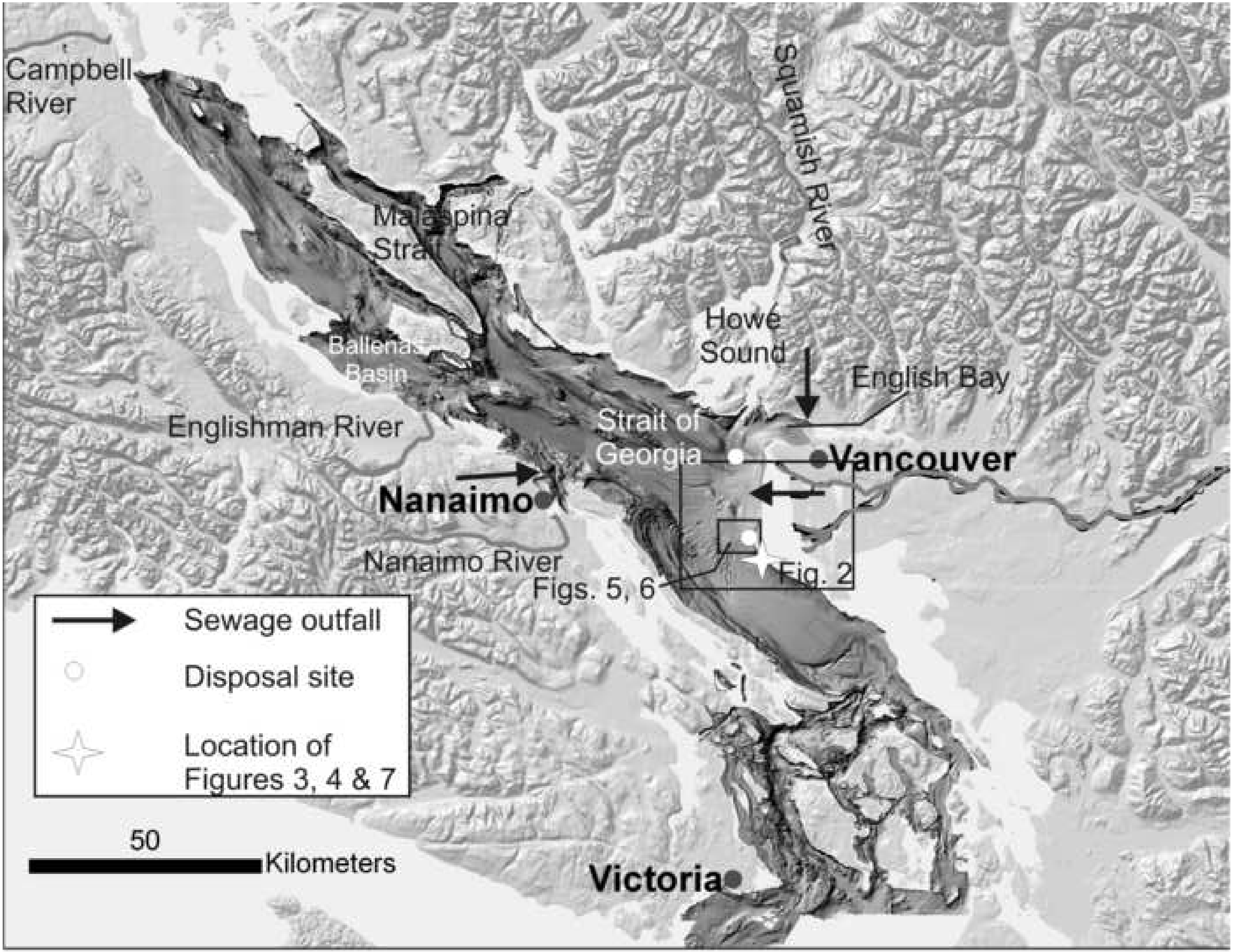
Figure 8 Subaqueous dunes on the delta slope off Roberts Bank. The dunes can be classified into four geometric types shown in the inset boxes. A) large 3-D high-relief dunes; B) large 3-D low-relief dunes; C) large, sinuous-crested 2-D dunes; D) large, straight-crested 2-D dunes. Different dune geometries form as a function of current speed, grain size and sediment supply. A fifth type of dune, termed isolated dunes are found on the upper slope and are thought to be under-developed dunes formed at high current speeds.

Figure 9 Multibeam backscatter intensity map of the Strait of Georgia. Blue indicates areas of low backscatter intensity corresponding to the presence of fine-grained sediments, usually an indication of sediment accumulation. Red colors indicate stronger backscatter intensity, typically related to the presence of coarser sediments or hard bottoms. Anthropogenic deposits refer to ocean disposal areas. The map can be used as an indicator of sediment accumulation vs. non-deposition. Note that in the northern strait, most deep-water areas accumulate sediment, while some ridges and basin margins are non-depositional. The pattern is more complex in the southern strait where previously deposited fine sediments are being winnowed and eroded, leaving areas of higher backscatter intensity.

Figure 10. Schematic illustration of Strait of Georgia VENUS installation. The cable connects two nodes (A) to a shore station transmitting DC power and data. Instruments can be plugged into the nodes. In the case of the Fraser delta deployments, an extension cable and Science Instrument Interface Module (SIIM) module is required. The SLIP array (B) consists of four seismic piezometers for measuring in situ pore pressures and seismic activity. The

SEDI lander (C) is instrumented with devices to measure sediment fluxes and near bed sediment transport.

Figure 1



Campbell River
Malaspina Strait
Squamish River
Howe Sound
English Bay
Ballenas Basin
Englishman River
Strait of Georgia
Vancouver
Nanaimo
Nanaimo River
Figs. 5, 6
Fig. 2
Sewage outfall
Disposal site
Location of Figures 3, 4 & 7
50
Kilometers
Victoria

Figure 2

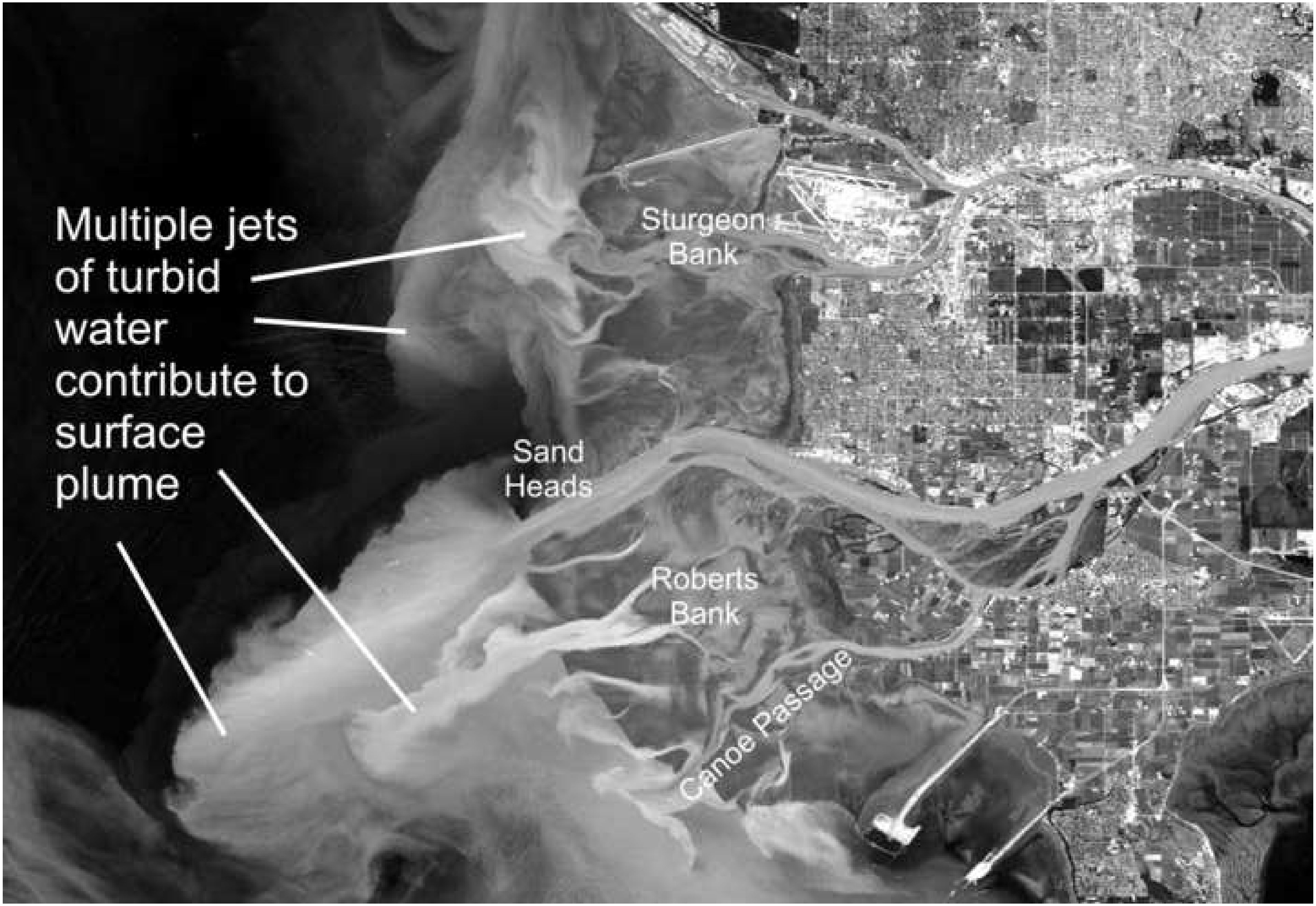
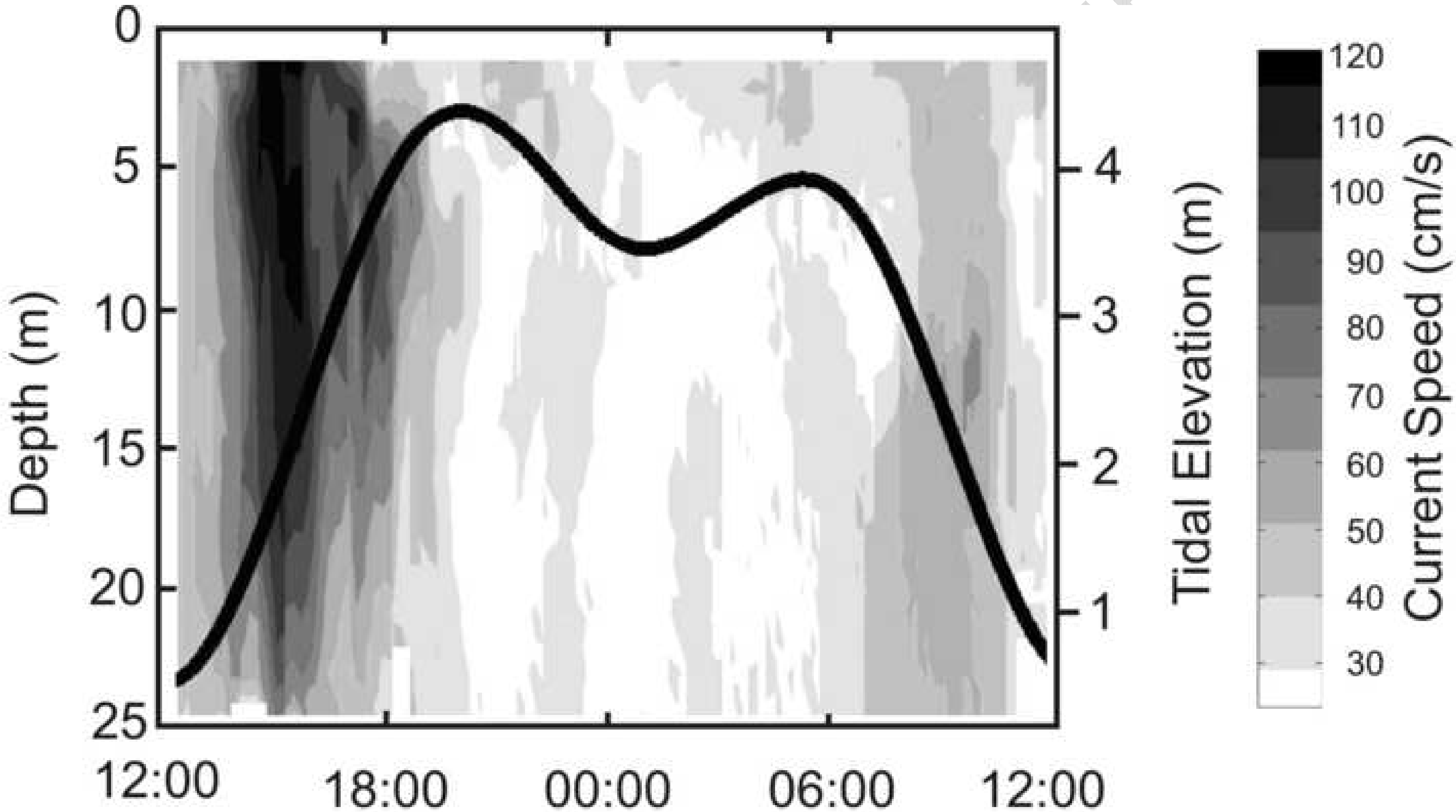

Multiple jets of turbid water contribute to surface plume
Sturgeon Bank
Sand Heads
Roberts Bank
Canoe Passage

Figure 3



0
5
10
15
20
25
Depth (m)
12:00
18:00
00:00
06:00
12:00
4
3
2
1
Tidal Elevation (m)
120
110
100
90
80
70
60
50
40
30
Current Speed (cm/s)

Figure 4

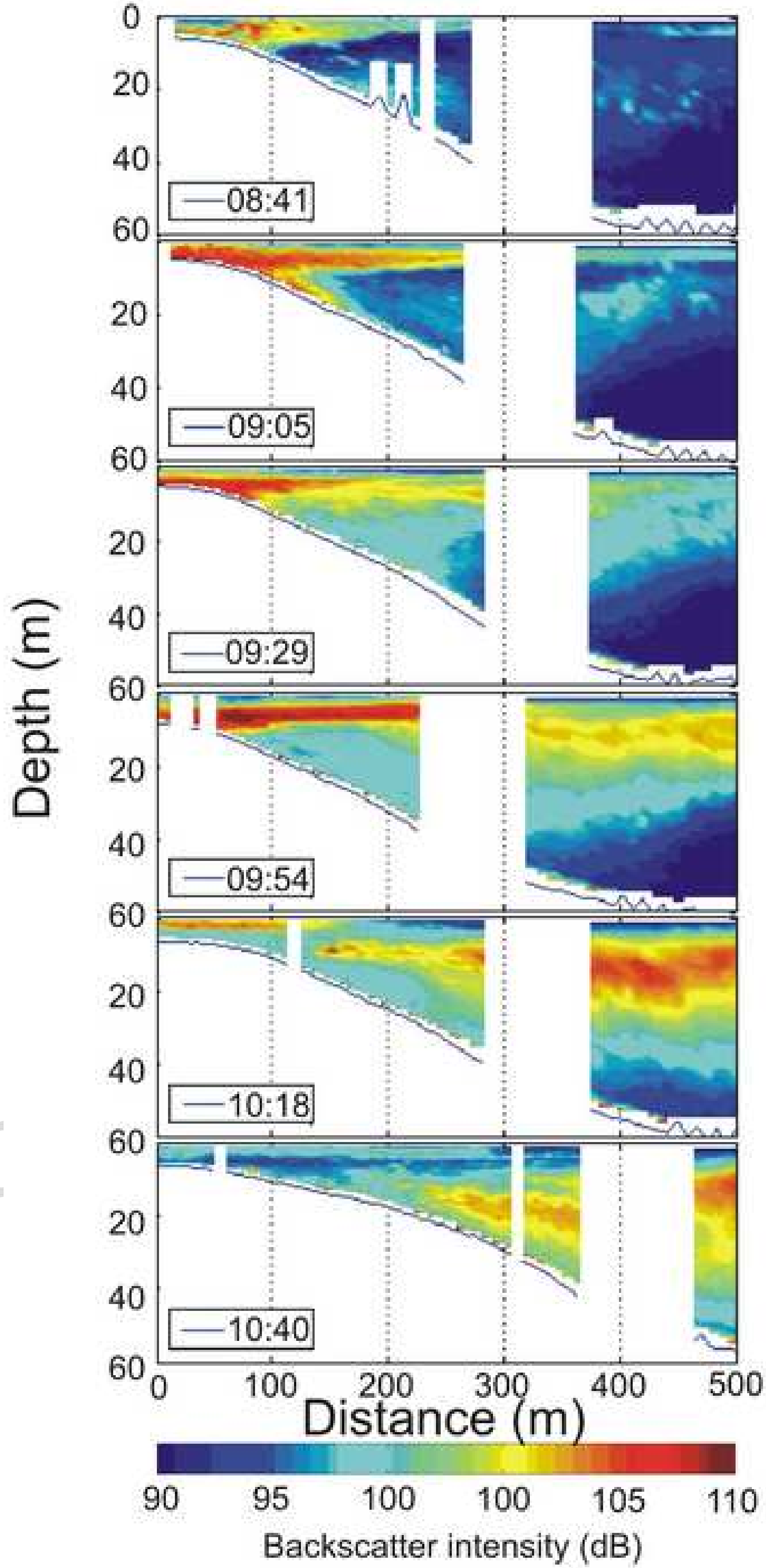

Depth (m)
0
20
40
60
08:41
09:05
09:29
09:54
10:18
10:40
0
100
200
300
400
500
Distance (m)
90
95
100
100
105
110
Backscatter intensity (dB)

Figure 5

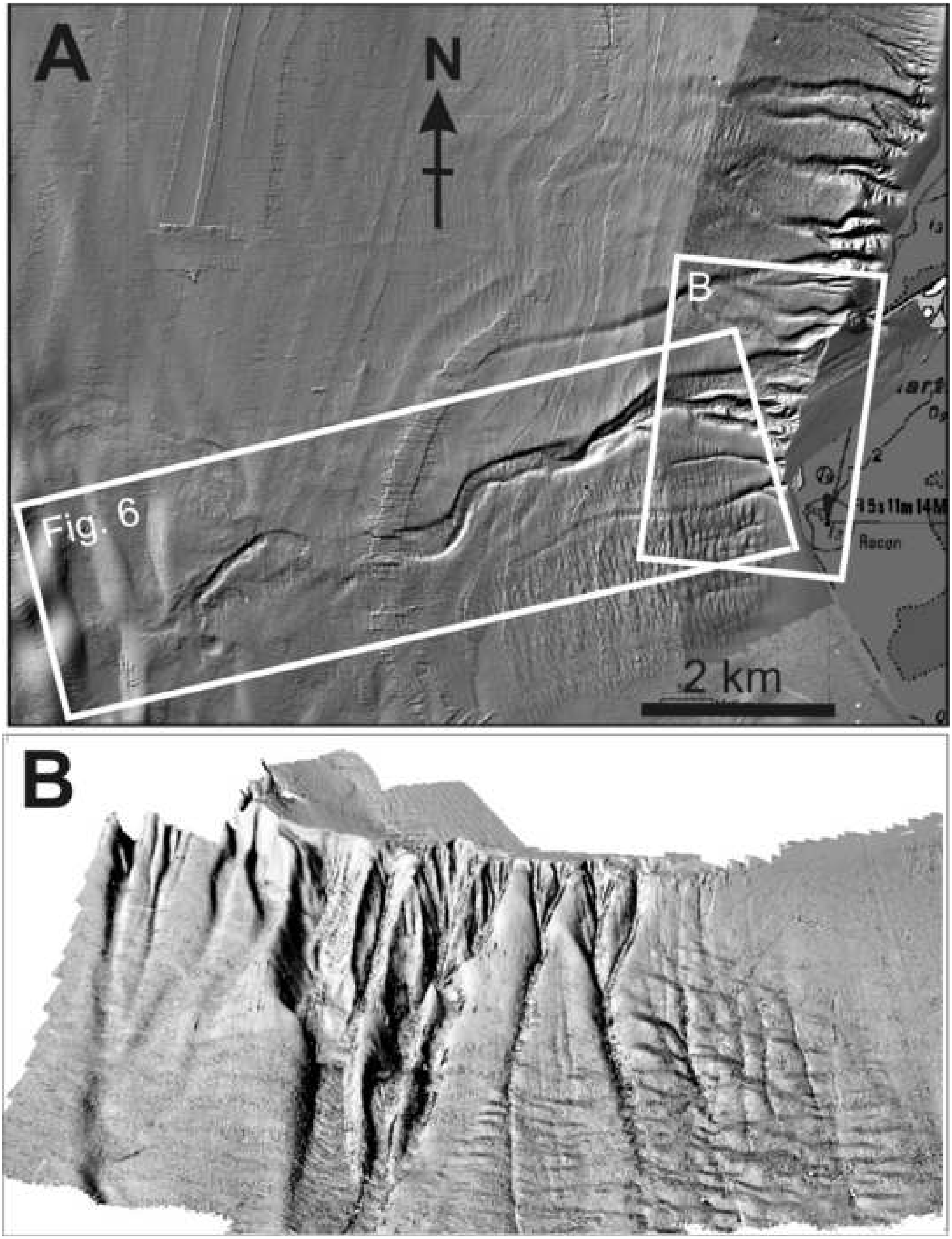


Figure 6

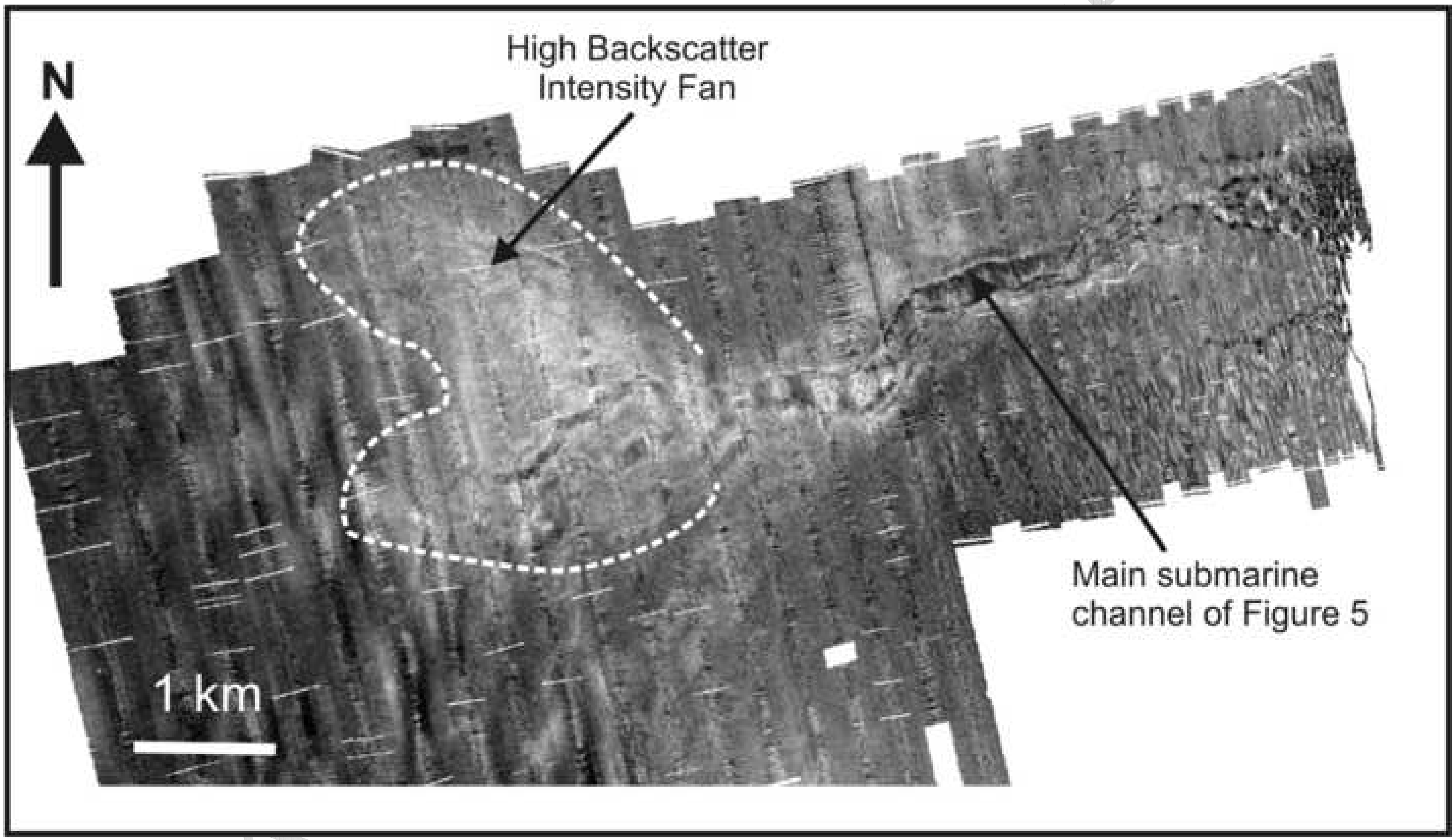
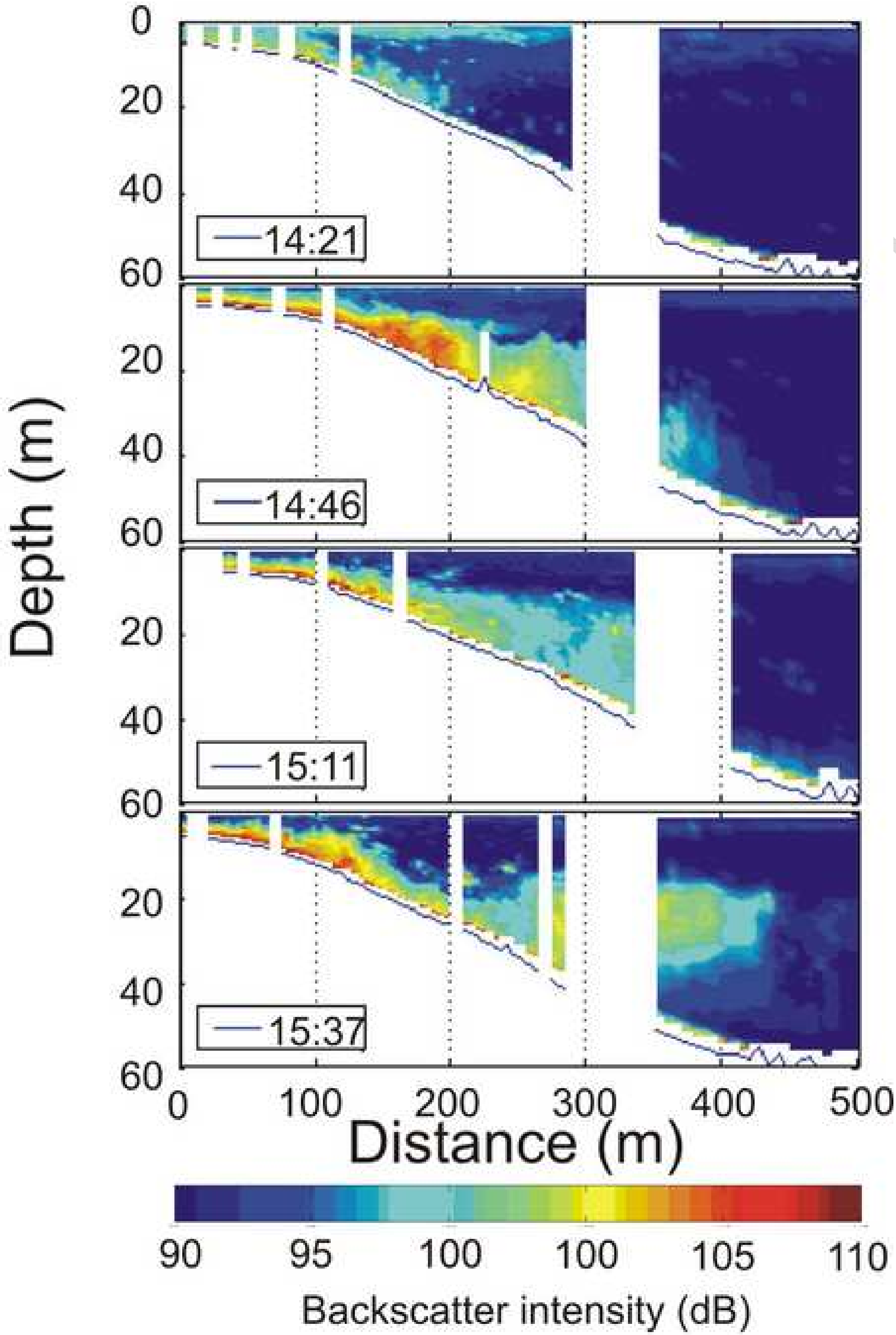

N
High Backscatter
Intensity Fan
Main submarine
channel of Figure 5
1 km

Figure 7



Depth (m)
0
20
40
60
14:21
14:46
15:11
15:37
0
100
200
300
400
500
Distance (m)
90
95
100
100
105
110
Backscatter intensity (dB)

Figure 8

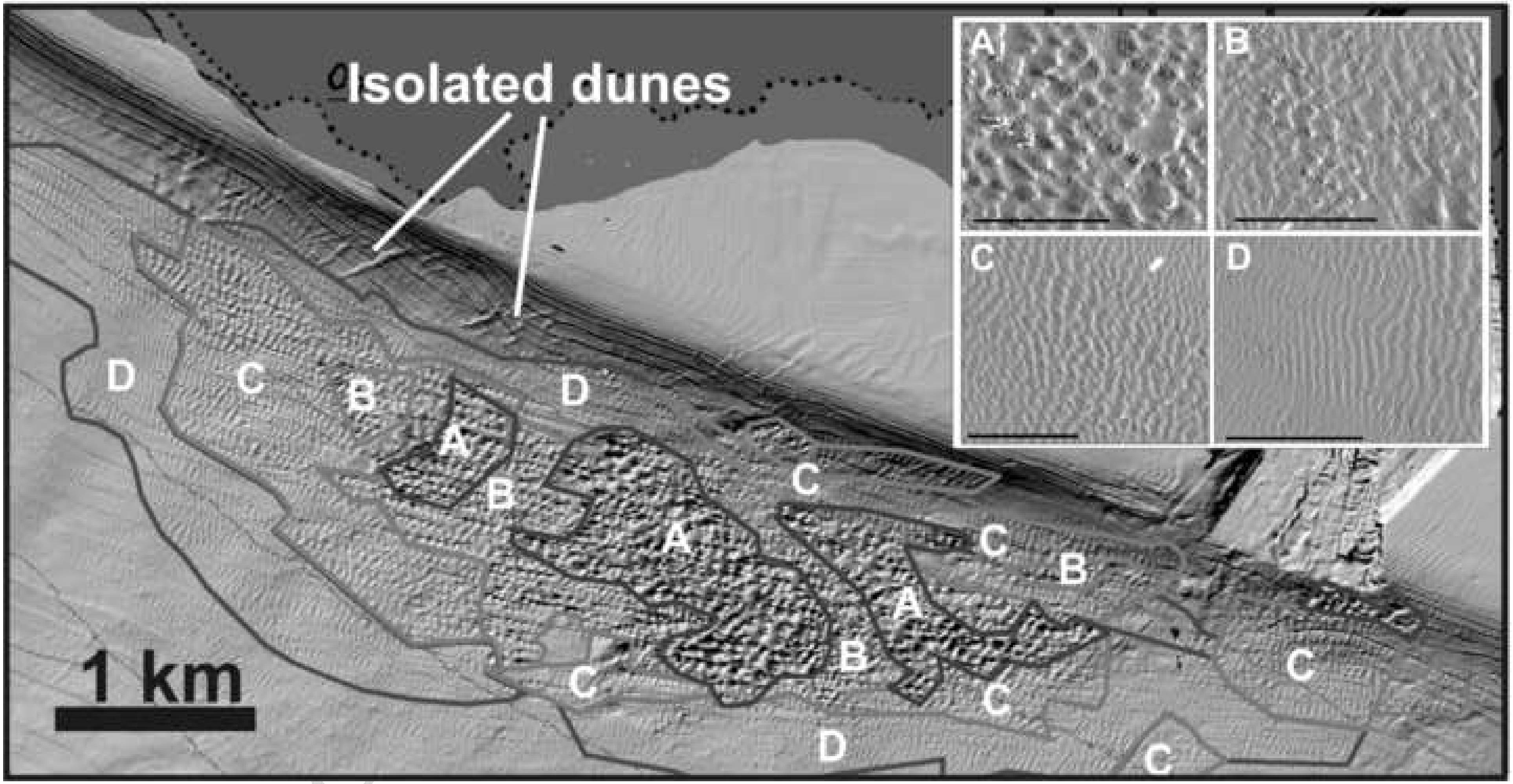


Figure 9

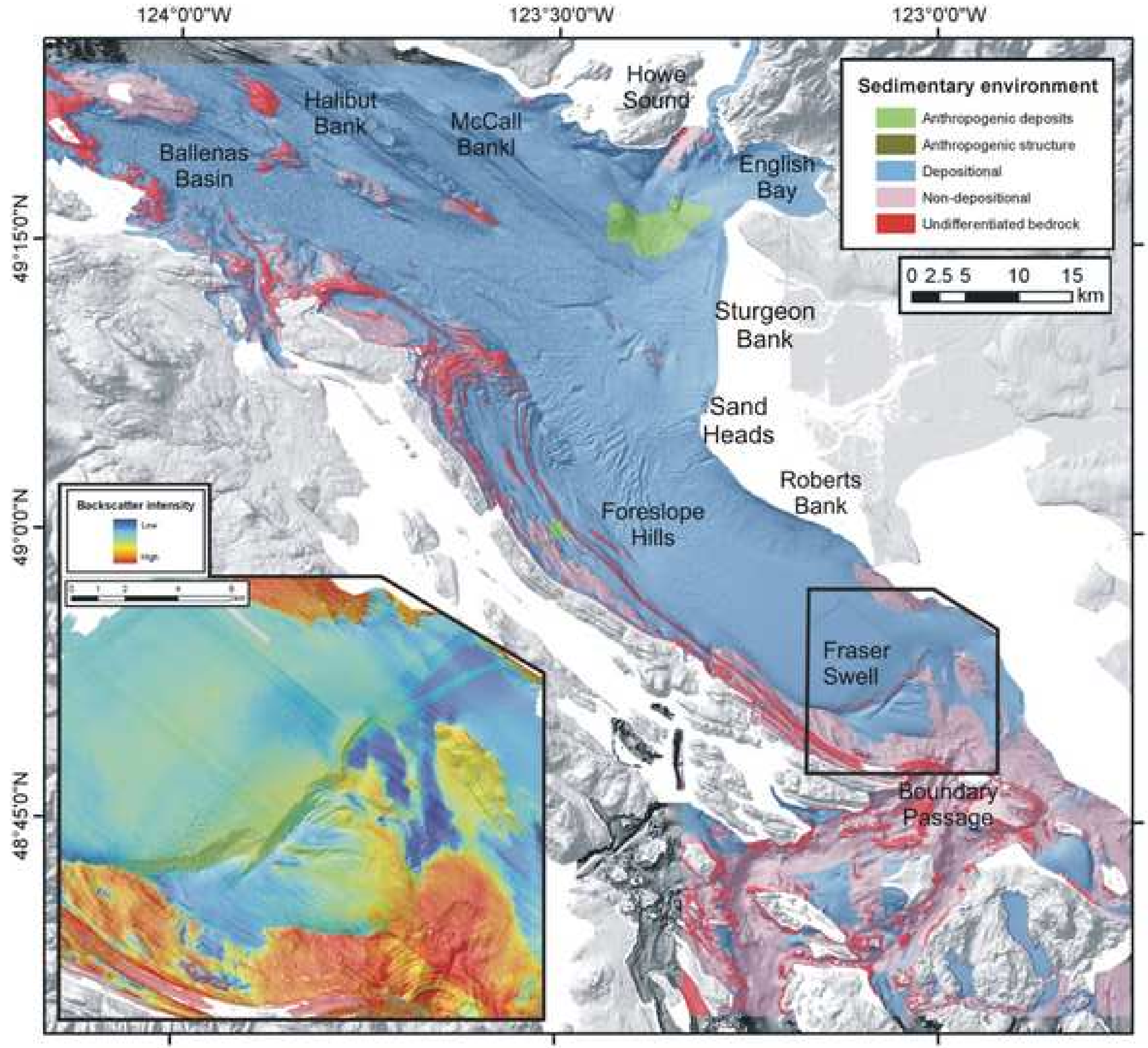
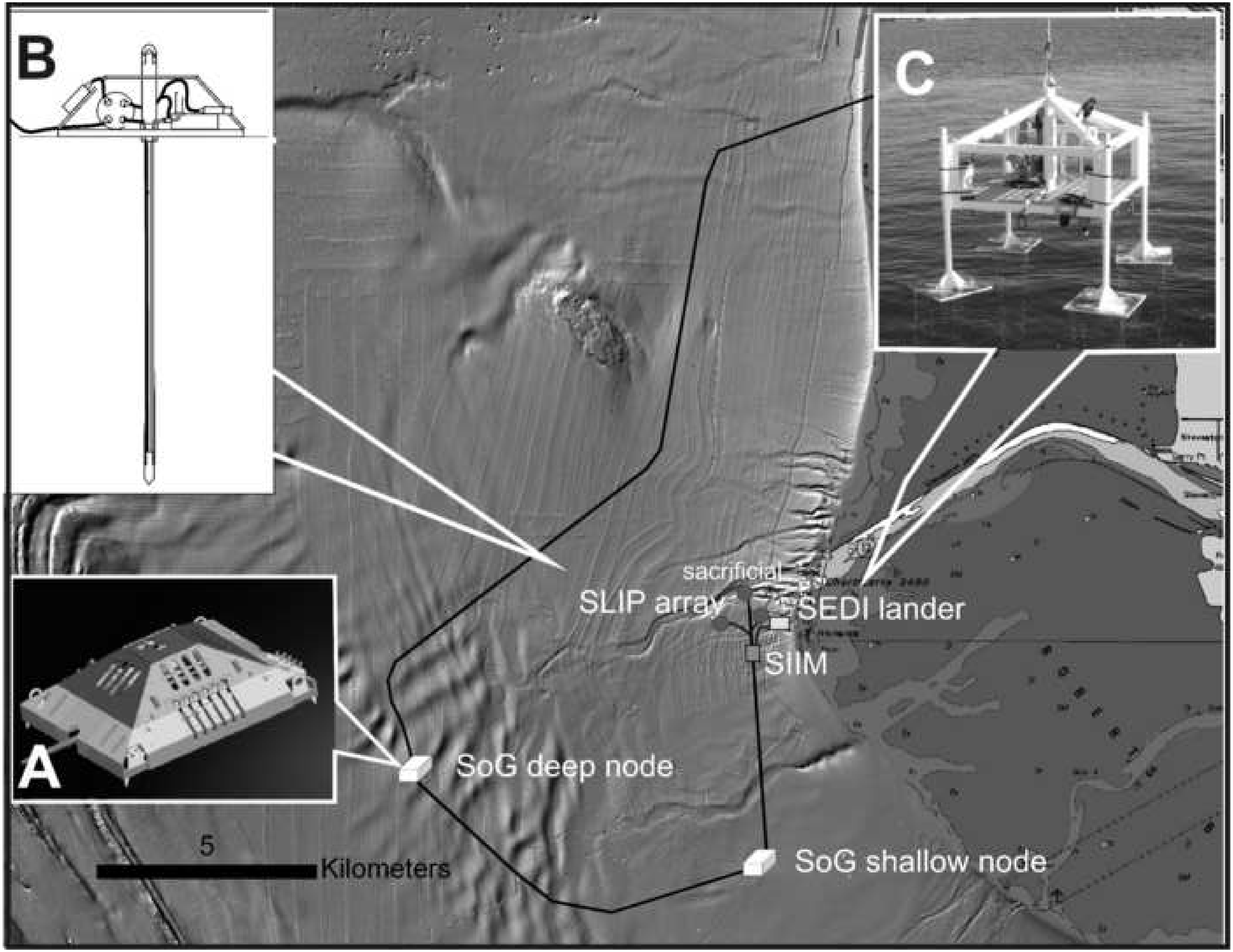

124°0'0"W
123°30'0"W
123°0'0"W
49°15'0"N
49°0'0"N
48°45'0"N
Howe Sound
Halibut Bank
McCall Bankl
Ballenas Basin
English Bay
Sturgeon Bank
Sand Heads
Roberts Bank
Foreslope Hills
Fraser Swell
Boundary Passage
Sedimentary environment
Anthropogenic deposits
Anthropogenic structure
Depositional
Non-depositional
Undifferentiated bedrock
0 2.5 5 10 15
km
Backscatter intensity

Figure 10


B
C
sacrificial
SLIP array
SEDI lander
SIIM
A
SoG deep node
5
Kilometers
SoG shallow node