EROSION, SUSPENDED SEDIMENT AND SEDIMENT TRANSPORT
BAY OF FUNDY

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Introduction

This paper is a review of the research on sediment transport and suspended sediments throughout the Bay of Fundy system. Sources of fine-grained material (silt and clay) are provided to the Bay from both natural and anthropogenic sources that include ocean dumping activities, river barrier construction, seabed fishing activities and natural erosion of the seabed and the adjacent land. Quantities of material and associated processes are compared and contrasted and assessed in relation to the potential contribution of fine-grained sediments from the development of a basalt quarry on Digby Neck.

Previous Research

Within the Bay of Fundy most of the research on seabed sediments, sediment transport and suspended sediment has been confined to the inner Bay with a historical emphasis on Minas Basin and Chignecto Bay. An early phase of the research was largely controlled by a need to understand the potential effects of erosion, sedimentation and suspended sediments associated with the construction of tidal barrages for proposed tidal power generation (Gordon and Dadswell, 1984). Increased sedimentation seaward of the Windsor Causeway and near the gypsum dock in Hantsport, together with the Petitcodiac River has further focused research on the inner Bay of Fundy.

In the outer Bay, a large project has been underway for over 6 years to investigate the fate of sandy and muddy dredge spoils regularly disposed to the seabed off Black Point derived from dredging activity in Saint John Harbour. This study is using a modern approach to the assessment of sediment transport associated with large scale dredge disposal and its effects on seabed habitat and in particular the lobster fishery. It also provides detailed information on the seabed and natural processes of the region.

Multibeam bathymetric systems are a new tool for seabed understanding that provides considerable insight into seabed processes of erosion, deposition and sediment transport (Courtney and Fader, 1994). Multibeam data were collected during three phases of study in the Bay of Fundy. The first collected information was off Margaretsville, in Minas Channel and in Scots Bay of the inner Bay of Fundy and these studies were intended to characterize dynamic bedforms that were discovered through earlier mapping of the surficial sediments (Fader et al., 1977) and to test and calibrate multibeam mapping systems. A second phase by the Geological Survey of Canada collected mutibeam bathymetry in Chignecto Bay in 1998 and was undertaken to investigate reported changes to sediment distributions and over-deepening of the seabed reported by the fishing community. A third phase conducted multibeam mapping over a number of issue related seabed features and processes in the outer Bay of Fundy: horse mussel bioherms, iceberg furrowed terrain, for sea level studies, archaeological discoveries and glacial ice dynamics. From all of these studies new insights have been gained into present conditions of erosion, sediment transport and deposition at the seabed and complex relationships with large sand waves that were not previously known. This knowledge could help explain some of the recent anecdotal observations on changes to water depth, concentrations of suspended sediments and sediment character within the Bay of Fundy system.

The Petitcodiac River, New Brunswick, is the largest river discharging into the upper Bay of Fundy. The hydrological and geological characteristics of the river were altered dramatically by the construction of a causeway between the City of Moncton and the Town of Riverview in 1968. The causeway has changed the hydrodynamics and accelerated the deposition of fine-grained sediment in the upper reaches of the estuary. Despite many studies over the last several decades, a fundamental lack of understanding of the basic dynamics of the system remained. In 2002 and 2003, the Science Branch of Fisheries and Oceans Canada, Maritimes Region, conducted 13 field surveys on the Petitcodiac River Estuary (Curran et al., 2004). The objectives of these surveys were: 1) to test instrumentation and develop sampling strategies for data collection; 2) to provide data in support of predictive modelling studies being conducted by consultants as part of an EIA; and 3) to provide data that would permit the conclusions of the EIA to be evaluated by Fisheries and Oceans Canada in a scientifically-defensible manner. Preliminary analysis indicates extremely high suspended sediment concentrations including the presence of fluid mud on the seabed and sediment deposition near the causeway that extends 34 km downstream out into the Bay of Fundy (Chignecto Bay).

As part of a project to determine underwater marine park boundaries, an ADCP (acoustic doppler current profiler) study was conducted in 2001 by the Ocean Mapping Group of the University of New Brunswick. They studied the M2 tidal circulation patterns at the mouth of the Musquash Estuary where it exchanges water, nutrients and sediments with the open Bay of Fundy. The aim of the experiment was to better define the seaward boundary of the proposed Musquash Marine Protected Area (MPA). Observations from this study show a large quantity of suspended sediment transferred from the estuary into the Bay of Fundy.

Recent observations of environmental characteristics of the Bay of Fundy indicate significant modern change (Percy et al., 1996). These include changing sediment grain size distributions on the mudflats, anecdotal observations from the fishing community of increasing water depths in some areas, and changing benthic communities. These concerns have led to a need to better understand the dynamics of the Bay of Fundy and a more detailed knowledge of seabed, sediment, suspended sediment, oceanographic and biological conditions. The recent observations of changing environmental conditions have highlighted the potential of increased dynamics and erosion of the seabed as a possible causative mechanism.

Suspended Sediment

The first comprehensive Bay of Fundy wide assessment of suspended sediment was conducted by Miller in 1966. Water samples were collected during both mid-flood and mid-ebb from 43 stations at the bottom, 1 metre from the bottom, 10 metres from the bottom and at the surface (Figure 1). Concentrations varied from 0.2 to 30.4 mg/l with an average value of 6.6 mg/l for the 263 samples collected in the study. Sediment concentrations for the entire water column throughout the tidal cycle greater than 8 mg/l occurred on the northeast side of the Bay near the New Brunswick coast. Concentrations of less than 4 mg/l were found on the south side of the Bay particularly near the entrance.

In comparing mid-flood with mid-ebb concentrations, Miller (1966) interpreted that high turbidity water during the ebb moves south and west toward the Gulf of Maine. He noted that high turbidity water enters the Bay from the southwest side of Saint John Harbour. The measurements from Miller (1966) are for mid ebb and mid flood conditions and concentrations of suspended sediments would be higher during maximum flow.

The distribution of turbidity during flood occurs with water moving in north and northwest directions. Highly turbid water occurs in a zone ten nautical miles wide along the northwest coast extending from the head of Chignecto Bay to Passamaquoddy Bay.

Miller also examined the suspended sediment and found sand, silt, clay, plankton and other organic debris. Silt and organic debris were the major components. Organic carbon was determined to comprise 0.3 to 2.65 % by weight of the suspended load. From X-ray diffraction analysis, illite, halloysite, kaolinite, quartz, feldspar and calcite were the constituents in decreasing abundance.

Miller characterized the suspended sediment system in the Bay of Fundy as an open system. He interpreted 4 components of the system: 1) an oscillating body of turbid water, 2) a seabed that exchanges sediment with the overlying water, 3) minor fresh turbid water input and, 4) minor turbid water release to the Gulf of Maine. He expressed the northwest nearshore zone as a mud facies in a state of short-term equilibrium with the overlying water. Seabed sampling at slack water revealed thin layers of fluid mud that appeared to have settled out on the seabed. As the tide begins to flow it is mobilized. The south side of Fundy is interpreted to be a winnowed Quaternary bottom of coarse sediment with a long term transfer of fine-grained material in the suspended load. He interpreted that this component eventually aggrades to the mud facies of the northwest side.

Figure 2 shows selected vertical turbidity profiles from the Bay of Fundy (Miller, 1966). Those from the upper bay show marked gradients but those from the lower Bay stations suggest that turbidity is well-travelled and homogenized throughout the water column. A great transfer of sediments with the water occurs on the tidal flats where mud is picked up by the flood tide and deposited during ebb (Pelletier and McMullen, 1972). Profile 4 (Figure 2) located off Digby Neck shows near bottom increased suspended sediment on the ebb tide indicating a source from the north east and not local erosion of the seabed. This study provided a bench mark on suspended sediment concentrations for the Bay.

Minas Basin

Suspended sediment was measured in Minas Basin by Pelletier and McMullen (1972) from 60 water samples. Concentrations of particulates varied from 72 to 2680 grams per cubic m. All but three samples had in excess of 90 grams per cubic m and more than half were between 100 and 200. The higher values came from samples collected at low tide near the sediment-water interface and the highest ones were collected after the tide had turned and was flooding across the exposed sediment surface. Most of the sediment was reported to consist of silt and clay sized particles but some was fine and even medium-grained sand.

Surface water at high tide contained 125 gm per cubic metre of sediment in suspension. This is a considerable amount of material as compared to the open ocean which contains on average 2 grams per cubic meter. Pelletier and McMullen (1972) interpreted that material brought into Minas Basin from the Bay of Fundy proper is the least important component of the sediment in Minas Basin system. The major contributor is the Avon, Salmon and Shubebacadie and other smaller rivers that dump into Minas Basin. In terms of sediment transport, they considered Minas Basin as almost a closed system which is filling up with fine-grained sediment.

Sediment Distributions and Geological History

Of prime importance to an understanding of sediment deposition, erosion and transport in the Bay of Fundy is the distribution of sediments at the seabed of the Bay and the geological and recent history. For example, large areas of the seabed of the outer Bay consist of gravel that occurs as a thin layer over till (Scotian Shelf Drift) that was deposited directly from glaciers which were grounded in the Bay (Figure 3). Some of these glacial surfaces were later modified by large icebergs that calved from the retreating glaciers. Little has happened to these gravels since they were deposited before 14 000 ybp. The only modification has been a winnowing of the surface by strong currents which later developed and removed remaining fine-grained sediments from between gravel clasts. These lag gravel surfaces are termed "relict", that is, they reflect deposition under differing conditions (very high energy) and have maintained these characteristics for thousands of years to the present. They are not necessarily in dynamic equilibrium with present conditions of erosion and deposition and must be understood as such.

Areas of the Bay of Fundy that are underlain by till, termed the Scotian Shelf Drift in the stratigraphic terminology for surficial sediments (King and Fader, 1986), occur in a broad zone at the entrance to the Bay seaward of a line between Sandy Cove, Digby Neck and Cape Spencer, New Brunswick (Fader et al., 1977 and surficial geological map 4011-G, Figure 3). These areas of till are non-depositional zones where fine-grained sediments are not deposited on the seabed. A few small areas of fine-grained sediment occur on the till surface and these are interpreted as glacially deposited muds. The till surfaces have been modified as a result of lowered sea levels, marine transgressions and regressions in water depths less that 60 m and the development of strong currents associated with the initiation of Fundy high tides. As a result, these sediments are not sources for fine-grained material to be eroded and transported throughout the Fundy system. If fine-grained silts and clays were dumped or deposited on these areas, only a minor component would remain trapped between gravel clasts and the bulk of the material would be transported to the northeast toward the head of the Bay.

Multibeam Bathymetry

Recently collected multibeam bathymetry and seismic reflection profiles across the till areas provide new insights into seabed morphology and processes. The multibeam bathymetry clearly shows that the seabed consists of a series of overlapping flute or horseshoe-shaped and transverse ridges formed in till (Figure 4). Iceberg furrows are common. These flutes and ridges indicate formation beneath a glacial ice stream and clearly suggest sub ice deposition. They are flow parallel features and indicate ice movement to the southwest. The multibeam imagery supports the earlier interpretation of Fader et al.,1977 for direct deposition of the areas of till by grounded glaciers. A dynamic understanding of ice movement was missing from the original interpretations, however.

In the inner Bay of Fundy to the northeast of the till seabed, that is northeast of a line from Sandy Cove to Cape Spencer, sediments, morphology, features and seabed processes are much different (Figure 5). In the 1977 study of Fader et al., the seabed was mapped as sand and gravel (Sambro Sand) with fields of large sand bedforms. The Sambro Sand is considered to be different in the inner Bay of Fundy than the adjacent Scotian Shelf. In the Bay it is considered to be formed both as a result of proximity to the low sea level stand but also from modern strong currents generated by the high tides of the Bay.

Unusual large areas of sub-sand mud were detected on the seismic profiles which in places cropped out at the seabed. These subsurface deposits were mapped on Map 4011G and considered to be Holocene muds deposited on the underlying till when the Bay of Fundy was much larger, deeper and at a time of minimal dynamics. These muds were later buried by two processes: proximity to the later low sea level stand which produced transgressions and regressions and the much later increased dynamics of the system from the development of the high tides. An extensive high-resolution seismic reflection and sidescan sonar survey conducted in 1998 provided insight into these interpretations and required a reinterpretation of the buried mud first considered to be the Holocene LaHave Clay.

The new information clearly shows that the buried mud in not the LaHave Clay but the glaciomarine Emerald Silt (Figure 6). This formation is much coarser than the clay and consists of silt, clay, sand and some gravel and was deposited by floating glaciers and glacial plumes from sub ice water but not directly by ice contact with the seabed. Cores of these sediments have been examined and consist of brick red thick clayey silt. They are ice recessional deposits and are widespread over the inner Bay of Fundy buried beneath sand and thin gravel lags. The Emerald silt is also interbedded with the till in the form of features termed till tongues and these represent former grounded ice positions. Through mapping of the feather edge of the till tongue positions, the source of the ice can be determined. The till tongues on the south side of the Bay clearly show the last ice was rooted on Nova Scotia and was drawn down into the Bay of Fundy. This supports the interpretation of the location and dynamics of the Scotian Ice Divide (Stea et al., 1998).

Through either low sea level stand associated marine transgressions or the onset of tidal dynamics, the inner Bay of Fundy seabed has been greatly modified and reflects more so the dynamics of present conditions in contrast to the relict tills in the outer Bay which have remained unchanged. Multibeam Bathymetry was collected off Margaretsville Nova Scotia in the inner Bay of Fundy over a field of large sandy bedforms (Figure 3). An interpretation of these bedforms and associated erosional moats has provided new insight into modern processes which are thought to contribute large amounts of glacial age mud to the water column. This represents a major new understanding of the sediment budget in the Bay of Fundy and has defined a previously unknown source of fine-grained sediment. It has implications to sediment transport, changes observed in the fishery, changes observed in the nature of the mud flats and their relationship to the semi-palmated sandpiper, and observations on seabed overdeepening.

The following is a discussion of an interpretation of the multibeam bathymetry and an assessment of the volumes of mud that have and are being eroded from the seabed in the inner Bay of Fundy.

Multibeam Bathymetry Interpretation

In 1994, the University of New Brunswick, conducted a multibeam bathymetric survey of areas of the inner Bay, from the Canadian Hydrographic Service vessel *FGC Creed.* Following the earlier research of Fader et al. (1977), they conducted surveys over previously identified areas of sandwaves (Figure 3). The images produced from the multibeam bathymetric data display water depth, shaded relief (Figure 7) and backscatter (Figure 8). The backscatter images are similar to sidescan sonar mosaics but with less resolution, approximately 2 m. They provide a remote method of assessing seabed sediment type. The shaded-relief images reveal the true morphology of the seabed with a resolution of 2 m horizontally and decimetres vertically. The images resemble aerial photographs of land areas.

The multibeam bathymetry off Margaretsville, Nova Scotia was collected over an area approximately 10 by 15 km covering 150 square km of seabed. It depicts areas of large, isolated, sandy, flow-transverse and flow parallel bedforms overlying thin lag gravels. Approximately 200 large singular sandwaves occur in this area. Subsequent surveys with high-resolution sidescan sonars and seismic reflection systems, together with cores and seabed samples, provide stratigraphic information for a three dimensional interpretation of lithology and seabed and subsurface processes. Other bedforms, such as sand ribbons, comet marks and megaflutes indicate net sediment transport to the northeast, toward the head of the Bay of Fundy.

An interpretation of the multibeam bathymetry and ground truth data collected on *CSS Hudson* Survey 95-030, provides considerable insight into geological conditions of erosion and deposition on the floor of the inner Bay off Margaretsville. The stratigraphy consists of thick glaciomarine mud (20 m thick), overlying till and bedrock. The glaciomarine mud is interbedded with tills deposited during the last Wisconsinan glaciation of the area, approximately 18 000 yBP. The glaciomarine sediments are overlain by a thin veneer of lag gravel. Across this delicate gravel veneer, sand is in transport in the form of sand ribbons, megaripples and sandwaves. The larger sandwaves (Figure 9), range in height from 4 to 12 m, are up 0.75 km in length, and occur in broad depressions.

As a result of their large size and orientation normal to current flow, the sandwaves increase water flow around them and locally induce erosion which is concentrated at their ends. This erosion cuts into the glaciomarine muds and forms depressions up to 10 m in depth (Figure 10 and 11). The large sandwaves become trapped in these local depressions and cannot migrate further across the seabed. A comparison of the 1994 and 1995 data indicates that their crest positions have not substantially moved during the time interval. However, on high-resolution sidescan sonograms, the ends of some of the bedforms can be seen migrating out of the scoured depressions (Figure 12), suggesting that both the sandwaves and the scoured depressions are enlarging. Erosion of these local depressions around the flow transverse sandwaves is a complex process, termed ballistic momentum flux, and one that results in local perturbation of bottom currents and a dissipation of energy through frictional effects.

The regional topography of the area is largely controlled by positive relief broad till features over Triassic/Jurrasic sandstone bedrock. Where exposed, the till surfaces appear as large triangular-shaped rises, likely formed by late glacial ice streams. Extensive deposits of glaciomarine sediment are thickest in broad depressions on the till surface.

The sandy bedforms are developed over thin lag gravel surfaces which overlie the thick glaciomarine sediments. The lag surfaces formed through erosion of the glaciomarine sediments in response to increased tidal currents in post-glacial time, as the Bay of Fundy approached resonance as well as at the time of lowered sea levels. In areas where the lag gravels are being eroded, the underlying glaciomarine mud is exhumed and this process provides fine-grained materials (suspended sediment) to the water column.

Seabed Erosion

Other areas of the seabed not directly associated with the sandwaves also appear to be eroding through the lag gravel and into the subsurface glaciomarine mud. Megaflute-like depressions appear to form locally (Figure 13) which coalesce into large areas of eroded seabed. These depressions also contain megaripples. Flutes are triangular-shaped erosional bedforms. They are deepest at their upstream apex end, and flare upward toward the seabed and outward toward the inner Bay of Fundy. The shape of these bedforms indicates erosion from currents moving from the southwest to the northeast, that is, up the Bay of Fundy, parallel with the axis of the Bay. Large quantities of fine-grained silt and clay are removed through the process of flute formation and the sand-sized particles appear to largely remain in the depressions where they are formed into megaripple fields, as a residual product of selective glaciomarine sediment erosion.

Based on an understanding of the processes of erosion of the seabed and knowledge of the materials, it is possible to assess the amount of fine-grained silt and clay that has been and is being contributed to the inner Bay of Fundy from erosion of the seabed. The average depth of erosion around individual bedforms and in the broad fluted areas is approximately 5 m, with some areas extend to 10 m deep. The area of seabed in the Margaretsville dunefield covered by either erosional moats around large sand waves or megaflutes is approximately 10 square km. This represents approximately 7 % of the seabed within the Margaretsville dunefield multibeamed area. Based on this coverage, approximately 5 million cubic m of sediment has been eroded in this area of the inner Bay. Because multibeam bathymetry has not been collected throughout the entire inner Bay of Fundy, in order to assess the total amount of erosion for the inner Bay, the area of large bedforms mapped on surficial geology map 4011G is used as a control. It indicates that approximately 6 times the area of the Margaretsville dunefield in the inner Bay of Fundy is covered with large sand waves. If we assume similar erosional processes associated with these additional areas of bedforms, then approximately 30 million cubic m of seabed erosion has occurred since erosion began.

The timing of the erosion has not been determined. Scott and Greenberg (1983) studied the tidal amplification in the Bay of Fundy and concluded that it did not occur at a uniform rate. The greatest rate of increase occurred between 7 000 and 4 000 ybp. They also determined that water depth on Georges Bank was the controlling factor on the Fundy tides. It is also not known when the erosion of the gravel seabed of the Bay was initiated. The large sand waves would first have to be formed to be followed by local scour around them which progressed to large areas of coalesced seabed erosion. If we assume a 4 000 year period of erosion then the seabed has contributed 7500 cubic m of mud to the water column per year. If erosion did not start until 90% of the tidal amplification was reached, then 12000 cubic m of material have been eroded per year. Although small on a yearly basis, the total volume of mud eroded from the seabed is a substantial contributor to the system. It is important to note that there is evidence that the sand waves are continuing to grow in size and that erosion of the seabed is also continuing to keep pace with bedform growth. The seabed of the inner Bay of Fundy remains as a modern contributor of fine-grained sediment from erosion of glacial age glaciomarine red mud.

This sediment budget assessment does not take into consideration erosion of glaciomarine sediments in Minas Channel or Chignecto Bay. Multibeam bathymetry and seismic reflection surveys of Minas Channel show that large areas of the seabed presently consist of bedrock and that erosion from strong currents has cut down through the overlying tills and glaciomarine sediments and overdeepened the seabed by over 50 m. Thick glaciomarine sediments occur on the flanks of the Minas Channel and appear to be presently eroding based on sharp well-defined sediment edges on the multibeam bathymetry. The volume of material eroded from Minas Channel is more difficult to calculate because of a lack of regional seismic control and difficulties in surveying in very strong currents. Based on the distribution of thick glaciomarine sediment on the flanks of Minas Channel and in Scots Bay, it is evident that Minas Channel has and likely is contributing large quantities of sediment to the Fundy system. These sediments have not been included in the above calculations.

The distribution of sediments and bedforms in the inner Bay of Fundy particularly in the areas of sandy bedforms indicates that fine-grained silt and clay are not accumulating at the seabed. Despite high concentrations of suspended material the currents generated by the high tides are too high to allow mud (silt and clay) deposition. These materials likely move to inner areas of Minas Basin and Chignecto Bay where they fall to the mudflats during slack water. Large deposits of mud at the Windsor causeway and the Petitcodiac River indicate major depositional sites and attest to shoreward movement of fine-grained sediments.

Bottom Fishing Impacts

Large areas of bottom fishing marks (trawl and scallop) can be seen on the sidescan sonar data preserved on gravel bottoms of the inner Bay of Fundy. Gravel seabeds are the dominant textural character of the inner Bay of Fundy seafloor. As previously discussed, the gravel seabeds are very fragile and thin and overlie both till and thick glaciomarine mud. It is possible that bottom fishing activity is also breaking through the thin and fragile lag gravel surfaces facilitating erosion of the underlying glacial age muds. This hypothesis remains to be fully assessed and the quantities of eroded sediments determined.

In report No. 166 of Fisheries and Oceans Canada a study was undertaken to review the fishery related disturbance in the Scotia-Fundy region by Maritime Testing Ltd (1991). They interpreted sidescan sonar profiles from the outer Bay of Fundy off Maces Bay, New Brunswick and from Scots Bay, inner Bay of Fundy. Areas of the seabed off Maces Bay were covered up to 5% overall with trawl marks and some areas were as high as 50%. The sediments in this area are muds (LaHave Clay) and would be easily resuspended by the trawling activity leaving behind the gear drag marks on the seabed. Scots Bay exhibited the largest area of trawling disturbance with some areas receiving over 50% seabed impact.

Sediment Transport Direction

At first glance the sandwaves in the inner Bay of Fundy appear to be symmetrical, suggesting equal current velocities during ebb and flood. Other bedforms (comet marks, sand ribbons, fan or sheet sand spill-overs) occur on the northeastern sides of many of the large sandwaves and suggest net sediment transport to the northeast, toward the inner Bay (Figure 14).

An interpretation of the new multibeam bathymetric and seismic reflection data suggests that the energy in the inner Fundy system may be increasing, possibly in response to tidal amplification as resonance is fine-tuned. If this is true, then some of the lithologic and depositional changes observed in the inner Fundy system could be attributed to natural variation as opposed to anthropogenic effects. On the other hand, the role of sediment supply from bottom fishing related erosion has not been quantified. In either case, the quantity and transport of fine-grained sediment to the inner Fundy area, and its eventual fate, is not fully understood. The dyking of the inner Fundy areas and continued damming and bridge construction present barriers to these fine-grained sediments, which would, in the absence of the dykes, normally be deposited in the marshes. An increase in mud content on the mud flats, which in Minas Basin are more like sand flats, could be the result of seabed erosion further out the Bay.

Early models of water circulation in the Bay of Fundy show the present of large gyres located in the inner Bay (Figure 15). Interpretation of the multibeam bathymetry clearly shows seabed features formed and controlled by bottom currents that are straight and parallel to the axis of the Bay. These include mussel bioherms and sand ribbons. Collectively they suggest that the tides merely reverse direction. Local gyres occur in the nearshore adjacent to rocky coastal protrusions into the Bay and the multibeam bathymetry often shows the location of sandwave fields in these local areas.

Chignecto Bay, Bay of Fundy

Multibeam bathymetry and backscatter data were also collected in Chignecto Bay, inner Bay of Fundy, between the provinces of Nova Scotia and New Brunswick (Figure16). A number of fisheries and geological changes have recently been observed in the inner Bay of Fundy that require an understanding of the processes operating there. The fishing community has reported major changes to the bathymetry of the bay (overdeepening) as well as changes in the distribution of sediment type at the seabed. These changes are considered to have affected the lobster and finfish fishery with declines in some species and enhancement of others. Additionally, changes to the sediment texture exposed on the mud flats of the inner bay, to an increase in mud content, have resulted in a threat to the survivability of the semi-palmated sandpiper population. These birds feed on *Corophium Volutator* on the mud flats during their migratory route toward South America.

The multibeam data reveal many features on the seabed that were previously unknown (Figure 16). The existing bathymetric charts did not accurately portray the morphology of the seabed, particularly the location and depth of a deep curvilinear channel in central Chignecto Bay off Cape Enrage. The maximum depth, 120 m, is approximately 40 m deeper that the older published hydrographic chart. Amos (1984) reported that 600,000 000 cubic m of sediment have been removed from this scoured channel since 1870. The multibeam data also indicates that the channel may be fault controlled. Bedrock linear structures are offset on either side of the channel, and a linear morphologic feature is well-expressed at the base of the channel. A slump deposit occurs along the north flank of the channel and it partially covers the fault controlled lineament in that area. Its surface is rough and hummocky with flute-like erosional scours on its surface suggesting recent erosion by strong currents.

In the inner area of Chignecto Bay, a narrow linear band of barchan dunes that degrade to smaller megaripples extends from the deep channel to the northeast. This narrow zone of bedforms suggests that currents are focused by the presence of the deep central channel and maintain their integrity beyond the deep channel to the northeast acting like a high energy water jet. Aerial photographs of the bay show the present of high concentrations of suspended sediment eminating from the deep scoured depression. Emanating from the asymmetry of these sand dunes it is clear that net transport of sand is up-bay to the northeast. In general the inner part of Chignecto Bay is flat featureless mud suggesting that it is a depositional zone.

Other features on the multibeam image (Figure 16) indicate erosion of the seafloor and the formation of linear depressions, flute-like scours and localized overdeepening. Some of these scour depressions suggest that the dominant currents are from the northeast to southwest during ebb, transporting suspended sediment toward the inner Bay of Fundy. Localized banks of sand dunes also occur on both sides of the bedrock promontory of Cape Enrage.

Petitcodiac River

Large-scale river barriers such as causeways can alter the physical, chemical, and biological conditions in tidal rivers, resulting in an alteration of the system's natural balance of erosion and deposition. Subsequently, the health of organisms that occupy and utilize the local habitat for survival may also be affected, such as in the Petitcodiac River (Wells, 1999). It is the largest river discharging into the upper Bay of Fundy (Richardson et al., 2002) and has been altered dramatically by the construction of a causeway, which changed the flow dynamics and accelerated the deposition of fine-grained sediment in the upper reaches of the river estuary (Bray et al., 1982; Galay, 1983). The following discussion is based on a major study of the environmental conditions within the Petitcodiac River, upper Bay of Fundy (Curran et al., 2004).

In 1968, the New Brunswick Department of Transportation constructed the Petitcodiac River Causeway between the City of Moncton and the Town of Riverview. It has radically changed the suspended sediment, water quality, and hydrodynamics within the Petitcodiac River Estuary. Prior to causeway construction, the saltwater intrusion associated with waters of the upper Bay of Fundy from Chignecto Bay extended upstream passed Moncton to near Salisbury (Schell, 1998). The intrusion formed brackish water that acted as a transition zone for sensitive fish species migrating between the upstream freshwater of the Petitcodiac River and the downstream saltwater of the upper Bay of Fundy (Locke et al., 2003). The saltwater intrusion provided important nursery habitat for several fish species. At present, the causeway acts as a barrier to the saltwater intrusion, despite the presence of five gates. A fishway designed to permit fish passage across the causeway also has been ineffective (Butler, 1969). Since the causeway's construction, elimination and reduction of several fish species within the Petitcodiac River have been observed (Locke et al., 2003).

In an attempt to re-establish fish passage and improve water quality, alteration or removal of the causeway has been proposed. This has resulted in an Environmental Impact Assessment (EIA) of 4 project options to restore fish passage in the Petitcodiac River System and an evaluation of the status quo. Despite many studies over the last several decades, a fundamental lack of understanding of the basic dynamics of the system remained (Schell, 1998; New Brunswick Department of Supply and Services, 2002). In 2002 and 2003, members of the Science Branch of Fisheries and Oceans Canada, Maritimes Region, conducted 13 field surveys on the Petitcodiac River Estuary. The objectives of these surveys were: 1) test instrumentation and develop sampling strategies for data collection in the unique conditions found within the Petitcodiac River System; 2) provide data in support of predictive modelling studies being conducted by the proponents as part of the EIA; and 3) provide data that would permit the conclusions of the EIA to be evaluated by Fisheries and Oceans Canada in a scientifically-defensible manner. The following is a summary of the most recent research.

Setting and Methods

The Petitcodiac River drains approximately 2300 km^2 of watershed located in southeast New Brunswick (Schell, 1998). It flows from its source in a northeast direction and east of Moncton shifts position approximately 90^o. It then flows in a south-southeast direction into Shepody Bay and Chignecto Bay of the upper Bay of Fundy. Above the causeway, the Petitcodiac River is joined by five tributaries: the Anagance River; Coverdale River; Little River; North River; and Pollet River. Below the causeway, the Memramcook River joins the Petitcodiac River at Hopewell Cape. The sampling effort (Curran et al., 2004) focused on the segment of the Petitcodiac River Estuary below the causeway, from the Gunningsville Bridge to Hopewell Cape.

From March 2002 to September 2003 data was collected during thirteen field surveys. Suspended sediment, water quality, and velocity data were collected during the thirteen field surveys and included velocity and acoustical backscatter profiles (ADCP), conductivity, temperature, and depth (CTD) profiles, optical backscatter (OBS) profiles, dissolved oxygen profiles (DO), discrete velocity (OTT), and discrete water samples. Subsamples were then analyzed for salinity (SAL), suspended particulate matter (SPM) concentrations, disaggregated inorganic grain sizes (DIGS), and dissolved nutrient concentrations (NUTS).

To illustrate some of the variation in measured values, for example, the following are measurements from March, 2002 extracted from Curran et al., 2003. "On March 27 th, the tidal bore passed at 1250 h, while causeway gates were not opened until 1710 h. As the flood tide progressed, salinity at 0.5 m depth increased from 1.6 to 6.8. At 1254 h following tidal bore passage, SPM at 0.5 m depth was 67.8 g 1^{-1}, which then decreased to 20.6 g l^{-1} at 1305 h. At 1312 h, the near surface SPM was 80.2 g l^{-1}, which was the highest concentration observed during the survey. The SPM then decreased to 16.6 g l^{-1} by 1354 h. The variable near surface SPM following tidal bore passage may reflect sediment heterogeneity due to turbulence associated with the tidal bore. At approximately 1500 h, two causeway gates were opened, which is reflected by the small increase in water level at this time. Following gate opening the near surface salinity decreased, ranging from 0.1 to 0.6, despite the saltwater intrusion associated with the flood tide. Prior to the causeway gate opening, SPM at 0.5 m depth ranged from 7.1 to 100.8 g l^{-1}. The highest SPM of 252.4 gl $^{-1}$ was observed following passage of a 0.25 m wave downstream, which was associated with freshwater discharged during gate opening. In contrast, only a slight increase in SPM, from 6.7 to 11.5 g l^{-1}, was observed following passage of the tidal bore at 1552 h." These values of SPM are very high.

River Velocity and Flow Dynamics

During gate opened surveys, the downstream ebb tide velocity was dominated by freshwater discharge from the causeway. During gate opened events the ebb velocity did not vary during the ebb tide, compared to the gradually increasing velocity observed when the causeway gates were closed. The maximum ebb velocity observed during gate opened surveys was up to an order-of-magnitude greater than the maximum ebb velocity observed during the gate closed events.

In general, opened causeway gates accelerated downstream flow during ebb tide and impeded the upstream flow during flood tide. It is believed that causeway gate openings also would accelerate flow in the downstream direction during slack tides.

Suspended Sediments

In the Petitcodiac River, high SPM (suspended particulate matter) concentrations were observed for most samples and the system is considered an extreme SPM environment. At Transect 101, the SPM concentration varied with causeway gate manipulation and the tide. Following gate opening there was an increase in SPM throughout the water column with passage of the freshwater wave downstream. This may in part be the result of bottom sediment resuspension, but also may result from the flushing of sediment that accumulates near the causeway gates. An increase in SPM at 0.5 m depth following gate opening was observed on October 9, 2002 with the surface SPM increasing to 252.4 g l^{-1}. Flushing of accumulated mud is part of the causeway gate management strategy.

In marine environments the deposition of fine-grained sediment occurs by gravitational settling of single grains or within flocs (Kranck and Milligan, 1991; Droppo and Ongley, 1994). The size-dependent removal of fine-grained sediment can be explained by assuming that suspensions consist of single discrete particles and flocs (Curran et al., 2002a). Single grain settling assuming Stokes' Law results in the progressive fining of the material in suspension through time, as larger grains deposit more quickly than smaller grains. Floc deposition results in the loss of all suspended material at a rate proportional to the floc settling velocity (Kranck and Milligan, 1991). The slight increase in the effective settling velocity of the larger single grains indicates that the relative proportion of single grain settling increases with increasing particle sizes. In suspension, floc formation scales with the square of concentration, while floc breakup only scales linearly with concentration (Dyer et al., 1996; Hill, 1998; Curran et al., 2002a. In the high sediment, low energy waters of the Petitcodiac River during slack tide, it is expected that large flocs should readily form. Unfortunately, the turbid conditions of the Petitcodiac River prevented direct measurement of floc size using in situ cameras.

It is believed that fluid mud may occur near the bottom of the river, with the thickness of the fluid mud layer increasing during slack low tide. Despite advancement in the understanding of fluid mud on the near bottom velocity field, several questions still remain including the affect of fluid mud on the overlying velocity, salinity, and temperature fields (Trowbridge and Kineke, 1994).

The source of sediment for most rivers characterized by fluid mud is the upstream watershed. The source of sediment in the Petitcodiac River is downstream from the

Upper Bay of Fundy (Chignecto Bay and areas beyond). Typically, the locus of fluid muds changes rapidly in space and time, as suspended sediment and river processes change (Wells, 1983). In the Petitcodiac River, the presence of fluid mud and a prograding wedge of bottom sediment downstream of the causeway are indicative of the dynamic nature of the river system. Despite the rapid in-fill of sediment that coincided with causeway construction in the upper reaches of the estuary (Bray et al., 1982; Galay, 1983), sediment continues to accumulate in the Petitcodiac River up to 34-km downstream of the causeway. This indicates that the sediment dynamics in the Petitcodiac River still have not reached equilibrium despite completion of the causeway more than 3 decades ago. Thus, potential impacts caused by the accumulation of sediment remain uncertain, and the downstream extent of the prograding sediment wedge remains unknown.

It is clear from the results of this study that causeway gate manipulation affects the Petitcodiac River hydrodynamics and suspended sediment properties up to 34 km from the causeway. Considering the sedimentary conditions of the river system still are not in equilibrium, the long-term effects of the causeway on the river system and Bay of Fundy sedimentation remain uncertain.

Conclusions Regarding Suspended Sediment Petitcodiac River System

The primary goal of the study (Curran et al., 2004) was to address a significant deficiency in information for the Petitcodiac River identified at the Petitcodiac River/Estuary Modelling Workshop held in March 2002. The data acquired during the study provide an overview of river processes under different causeway gate operations, tidal conditions, and seasons. Causeway gate manipulation affects the river velocity and flow direction up to 5 km from the causeway, while salinity and temperature effects were observed up to 34 km from the causeway. These may alter the flow conditions and magnitude of the saltwater intrusion on a daily basis. Elevated ammonia concentrations and low dissolved oxygen concentrations in the presence of extreme suspended sediment concentrations were also observed.

The high concentrations of sediment in the Petitcodiac River result in physical processes such as hindered settling and the formation of fluid mud near the seabed. The presence of a prograding sediment wedge further downstream indicates that the river system has not reached equilibrium even 36 years after the causeway was constructed. Although deposition of large amounts of sediment has been observed up to 34 km from the causeway, the distal extent of the prograding sediment wedge remains unknown. Indeed, the multibeam bathymetry from Chignecto Bay shows a thick sequence of muddy sediments in the inner part of the Bay unlike areas extending from Cape Enrage to the southwest where the seabed is rough and irregular and likely coarser. High concentrations of suspended sediment and the prograding depositional wedge are evidence for redistribution of large quantities of sediment in the system, one that however, is influenced by the tidal barrage on the Petitodiac River further to the northwest.

Disposal of Dredged Materials off Black Point, Bay of Fundy

In the Bay of Fundy adjacent to Black Point off Saint John, New Brunswick,ther e has been a large dredge spoil dumping project on the seabed since 1959. Annual dredging for the port of Saint John is required to remove sediments that are deposited during the spring runoff from the Saint John River. These sediments clog the dock areas and main shipping channels of the harbour. The quantities of these silty and sandy materials average 300 000 cubic m per year but have reached as much as 500 000 cubic metres per year. The Geological Survey of Canada and Environment Canada have been engaged in a cooperative assessment project of the dredge spoils since 1999 using a multidisciplinary mapping and sampling approach. It includes the collection of repetitive multibeam bathymetry, seismic reflection profiles, sidescan sonograms, photographs, seabed samples, biological samples, oceanographic measurements, in situ hydrodynamic and sediment transport measurements and environmental quality (Shaw et al., 2003). The purpose of the study is to determine the zone of influence, the magnitude and direction of dredge spoil dispersion, the distribution of heavy metals near the dumpsite, the biological impacts associated with the disposal, and recent changes in the disposal site. This knowledge will be used to plan long term use of this and other sites for future dredging and disposal projects.

The study has revealed that the dredge disposal process has placed a very large pile of sediment on the seabed that has decreased the water depth at the location from an original depth of 14 m to 4 m over a period of 1959 to 1983. The initial mound was greater than 500 m in diameter. By 1993 the mound was greater than 1 km across and by 2000 the mound had grown to over 1.5 km in size. Additionally, repetitive multibeam bathymetry surveys show that the surface of the dredge pile is continually changing. It is windowed in some areas and a previously unknown process, slumping, takes place on a regular basis with material migrating in a southerly direction across the deeper seabed of the Bay of Fundy to the south. These slumped sediments have moved a distance of 3 times greater than the size of the spoil pile, 3 km, spreading out across the seabed of the Bay. The slumps are up to 4.3 m in thickness.

The repetitive multibeam surveys clearly show changes to the disposal site and that some of the material is transported through erosion by strong currents. The adjacent seabed is dominantly sandy and the presence of sand waves and comet marks (scour around boulders) shows net natural transport to the south west. The dredge spoils are not in dynamic equilibrium with the energy of the system because of the fine-grained silt and clay content. Using bottom mounted cameras and current meters they found that the sand component was mobile from 48 to 60 % of the time during the tidal cycle. Tidal currents at peak ebb were westward at 60 - 70 cm/s and in the opposite direction during peak flood. They concluded that net transport at the dump site was to the south east. The maximum predicted depth averaged concentration of suspended sediment, spring tide, is over 100 mg /l trailing in easterly and westerly directions to between 10 and 20 mg/l. The predicted accumulation on the seabed during spring tide is 0.2 to 0.5 mm. Sedimentation rates for the region indicate that to the west of the dump site, rates vary between 1000 and 2000 cm per 1000 years. A measure of lead as a contaminant in the dredge spoils also confirms the net western transport direction.

Preliminary conclusions of the dredge spoil study indicate that the disposal site can be characterized as erosional with only 20% of the dumped materials remaining close to the original disposal location. Suspended load dominates over bedload. In situ measurements indicate that the site is very dynamic with currents reaching 60 cm/s with sand transport of 0.1 kg/m/s occurring during more than 50% of a tidal cycle.

Musquash Estuary

The Musquash Estuary is a macrotidal (6-8m tide range) bay lying ~ 20 km west of Saint John along the Bay of Fundy northwest coast. As part of an MPA (Marine Protected Area) designation, legal boundaries are required; an approach that is simple for terrestrial parks, but much more difficult for submerged areas. An ADCP (Acoustic Doppler Current Profiler) study was conducted by the Ocean Mapping Group at the University of New Brunswick (Hughes Clarke, 2003) to examine the M2 tidal circulation patterns at the mouth of the Musquash Estuary where it joins the open Bay of Fundy. Their findings are summarized here. The object of the experiment was to define the seaward boundary of the proposed Musquash Marine Protected Area (MPA).

Two boundaries had already been provisionally defined, an inner one limiting the penetration of scallop dragging rights and an outer one defining the seaward limit of the MPA. Both of these had initially been defined using lines between terrestrial landmarks, making no account of submerged topography, seabed sediments or oceanographic conditions. In addition, it had been recognised that, due to the large tidal prism, the majority of the volume of the estuary was replaced twice daily through the tides and thus a potential "outer buffer zone"might need to be defined to allow for this exchange.

Dense seabed topographic and surficial backscatter maps were created using a multibeam bathymetric mapping system. From these, the bathymetric framework and indicators of the likely surficial sediment distribution could be ascertained. The aim was to establish typical circulation patterns over an M2 tidal cycle. An unexpected observation was made during the last stages of the ebb when the data indicate that the water exiting the estuary actually moves to the east in the Bay of Fundy in a reverse direction to the main offshore ebb flow which is to the west. This direction was confirmed using aerial photography at low water spring tide that showed a clear plume of high suspended sediment exiting the estuary that was advected to the east. Suspended concentrations were not measured, but the photographs clearly confirmed that plumes of suspended sediment reach out into the Bay of Fundy making a contribution to the outer Bay in this area.

Summary of a Comparison of Natural and Anthropogenic Sediment Contributions to the Bay of Fundy

Based on an assessment of natural and anthropogenic processes that result in suspended sediment concentrations within the water column ofthe Bay of Fundy, it is evident that very large quantities of material and large areas of suspended sediment occur throughout the entire system. Populations of lobster and finfish are also found in some of these high suspended sediment areas, such as within Chignecto Bay of the inner Bay of Fundy.

An assessment of the erosion of seabed sediments by natural processes has indicated that a conservative measure of the volume of sediment contributed to the Bay of Fundy from areas of the inner bay seabed is approximately 7 500 cubic m of silt and clay/year assuming a 4 000 year time span of contribution. If the time frame is reduced, based on an initiation of an erosional threshold beginning when the tides reached 90 % of their present amplification, then the sediment contribution increases to 12 000 cubic m/ year. This amount does not take into consideration contributions from erosion in Minas Channel or Chignecto Bay, both areas with thick glaciomarine sediments at the seabed, regional unconformities on their surfaces and evidence of recent erosion. This amount could increase substantially the volume of sediment provided to the water column.

It also does not calculate the contribution from bottom fishing activities such as trawling and scallop raking across gravel lag surfaces that break through the thin gravel lags generating plumes of fine-grained sediment and exposing buried muds. These delicate lag surfaces once broken through will not self-repair and can allow and enhance additional erosion from strong currents. It took a global glaciation and related complex sea level change to form these delicate lag surfaces. The Bay of Fundy, particularly the inner area, is a unique offshore region in Atlantic Canada where large areas of thick glacial aged muds are vulnerable to erosion when their cover of thin gravel is broken by both anthropogenic and natural processes.

The large dredge disposal site on the north side of the Bay of Fundy approximately 75 km from Digby Neck is regularly used to dispose of over 300 000 cubic metres of sediment to the seabed each year, half of which is in the silt and clay size range (Shaw et al., 2003). Only 20 % of that material remains at the dump site and the remainder is transported to the east and west within the Bay of Fundy withsom e slumping to the south. The ultimate depositional fate of these materials has not been determined.

Studies of the Petitcodiac River system (Curran et al., 2004) and the adjoining Chignecto Bay indicate that suspended sediment concentrations in this area are at the extreme end of the scale. Large amounts of mud are released from the periodic opening of the control water gates and fluid mud exists in the system. A prograding wedge of fine grained sediment is accreting as far downstream as 34 km from the causeway. This indicates that the inner Chignecto Bay area contains large amounts of fine-grained sediment in transport and some is contributed to areas along the north shore of the upper Bay of Fundy.

The Musquash estuary contributes suspended sediment to the outer Bay of Fundy at the end of the ebb cycle and the direction of movement of the plume at times is to the east.

The sediments on the seabed of the outer Bay of Fundy including areas adjacent to Digby Neck are coarse, very old and stable. Fine-grained sediment introduced into this area would not be deposited on the seabed and would be transported and dispersed as suspended sediment to the northeast. Based on an understanding of the regional dynamics of the Bay of Fundy and patterns of sediment deposition, potential areas for deposition of fine-grained sediments are in Minas Basin, inner Chignecto Bay and areas to the east and northeast. Temporary deposition occurs along the south coast of New Brunswick in a narrow zone.

Based on an allowable permitted amount of 25 ppm of suspended sediment in discharged waters and the area of the quarry opened at any one time, the proposed quarry would generate only 2.45 cubic metres of dominantly silt sized sediment to the Bay of Fundy per year if the total amount of water was fully discharged. This is a minute quantity of material when compared with the natural erosion of the seabed, the contribution from rivers, run off from the surrounding land, dredge disposal and extreme concentrations of suspended sediments and the presence of fluid mud in the inner Bay of Fundy. It is the intention of the development plan to have 0 discharge as the water will be recycled and filtered through a series of settling ponds. The only release of material would be associated with settling pond failure or an excessive rain event.

If this material was released to the water column as suspended sediment off Digby Neck, none would be deposited on the local seabed. The seabed is dominantly a bedrock/gravel bottom with boulders and is swept clean of fine-grained sediments by the strong tidally generated currents. Suspended sediment would be advected toward the inner Bay and diluted as it moved from the source. The potential small quantities released from the quarry would be virtually undetectable from background suspended sediment.

Lobster Shelters

The seabed of the area where the marine terminal will be located off Whites Point consists of exposed bedrock at the seabed and thin coarse sand overlying bedrock occurs in adjacent deeper areas. Boulders are common across the area ranging to 5 m in diameter and lie on the bedrock as well as protrude through the thin overlying sand. Small pockets of coarse sand and gravel also occur on the bedrock. The bedrock surface is rough and irregular much like the morphology of the exposed bedrock along the shoreline of the south coast of the Bay of Fundy where bedrock forms the shore platform with a few pocket beaches.

The lobster shelters can be placed on both the bedrock and thin sand. As there is no sediment on the bedrock, once placed, the lobster shelters will not be buried through sediment transport, settling or alterations in sediment patterns. The current velocities of approximately 2.5 knots that have been reported on Canadian Hydrographic Chart 4118 adjacent to Digby Neck are not high enough to move the shelters. Once stability is attained after placement on the bedrock surface, they will not move by bottom currents. Some rocking and minor movement of the shelters may initially occur if they do not have a large area contact with the bedrock surface.

If positioned on the thin sand overlying bedrock, the lobster shelters will experience some limited settling into the substrate. This is not expected to be more than 10 cm. A lack of bedforms and scour moats in coarse sand around the large boulders in this region lends support to such an interpretation. The shelters will experience more initial stability on the sand then if placed on the rougher bedrock surface.

Figures

Figure 1. Map of the location of suspended sediment samples collected from the Bay of Fundy. Numbers are locations of turbidity profiles in Figure 2. From Miller, 1966.

Figure 2. Turbidity profiles of selected stations from the Bay of Fundy in Figure 1.

Figure 3. Surficial geology of the outer Bay of Fundy showing the dominance of till (Scotian Shelf Drift) at the seabed. From Fader et al., 1977.

Figure 4. Multibeam bathymetry of an area of the central outer Bay of Fundy between Saint John and Digby. The seabed shows an overlapping pattern of horseshoe – shaped ridges in till. These likely formed beneath a ground glacier (ice stream) during the latter stages of glaciation.

Figure 5. Surficial geology of the inner Bay of Fundy showing a seabed of sand and gravel overlying till and glaciomarine sediment. Sandwaves are mapped. The glaciomarine muds are mapped with they occur in the subsurface and are more widespread than shown.

Figure 6. A high resolution seismic reflection profile from the inner Bay of Fundy showing sand waves overlying thin gravel and thick glaciomarine sediments.

Figure 7. A multibeam bathymetric image from the Margaretsville dunefield inner Bay of Fundy. The seabed has many large sand bedforms which are very symmetrical in shape. Note the scour moats around many of the larger sand waves.

Figure 8. A backscatter image of the Margaretsville dunefield from multibeam bathymetry. Dark-toned areas are sand and light-toned areas represent gravel.

Figure 9. A high resolution seismic reflection profile of a large sandwave.

Figure 10. A sidescan sonogram of part of a large sandwave showing a local scoured depression surrounding it. Note the sand wave is confined to the scoured depression. Megaripples on the flank of the sandwave are normal to the crest.

Figure 11. A high-resolution seismic reflection profile across a large sand wave and its associated scoured depression.

Figure 12. A sidescan sonogram of a large sand wave and scoured depression. The end of the sand wave can be seen migrating out of the scoured depression. This suggests that the

sand waves are increasing in size. This could induce further erosion and enlargement of the scoured depression.

Figure 13. A high-resolution seismic reflection profile from the inner Bay of Fundy showing an eroded area of seabed cut into glaciomarine sediments. Small sandwaves and megaripples occur in the depression. They are interpreted as a residual product from selective erosion of the seabed by strong currents. The silt and clay sediments are transported to the northeast.

Figure 14. An interpretation of the multibeam bathymetry from the Margaretsville dunefield. Some of the sandwaves have spill over fans and associated sand ribbons that occur on the inner eastern side of the features. This suggests net transport to the east. Areas of seabed where scour is severe and where individual moats coalesce are in the upper area of the image.

Figure 15. Circulation model after Godin (1968) showing net transport along the south of the Bay to the northeast.

Figure 16. Multibeam bathymetric image of Chignecto Bay. A large deep depression occurs off Cape Enrage in the centre of the Bay. In the inner part the seabed is flat and featureless with a narrow linear zone of barchan-like sand dunes. The sand dunes indicate transport to the northeast.

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Figure 1

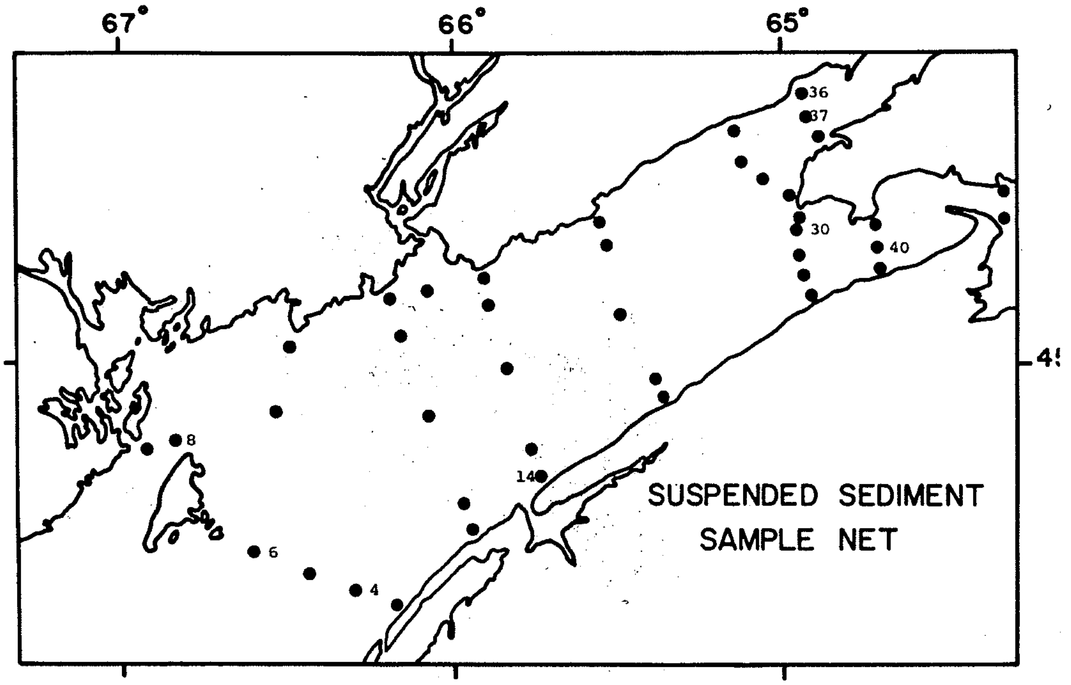
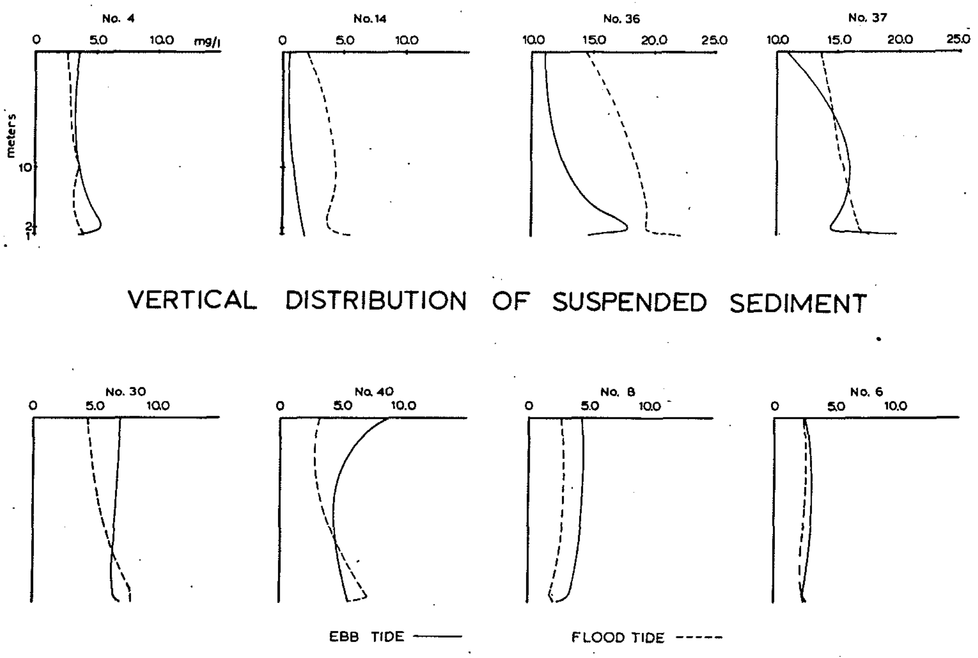
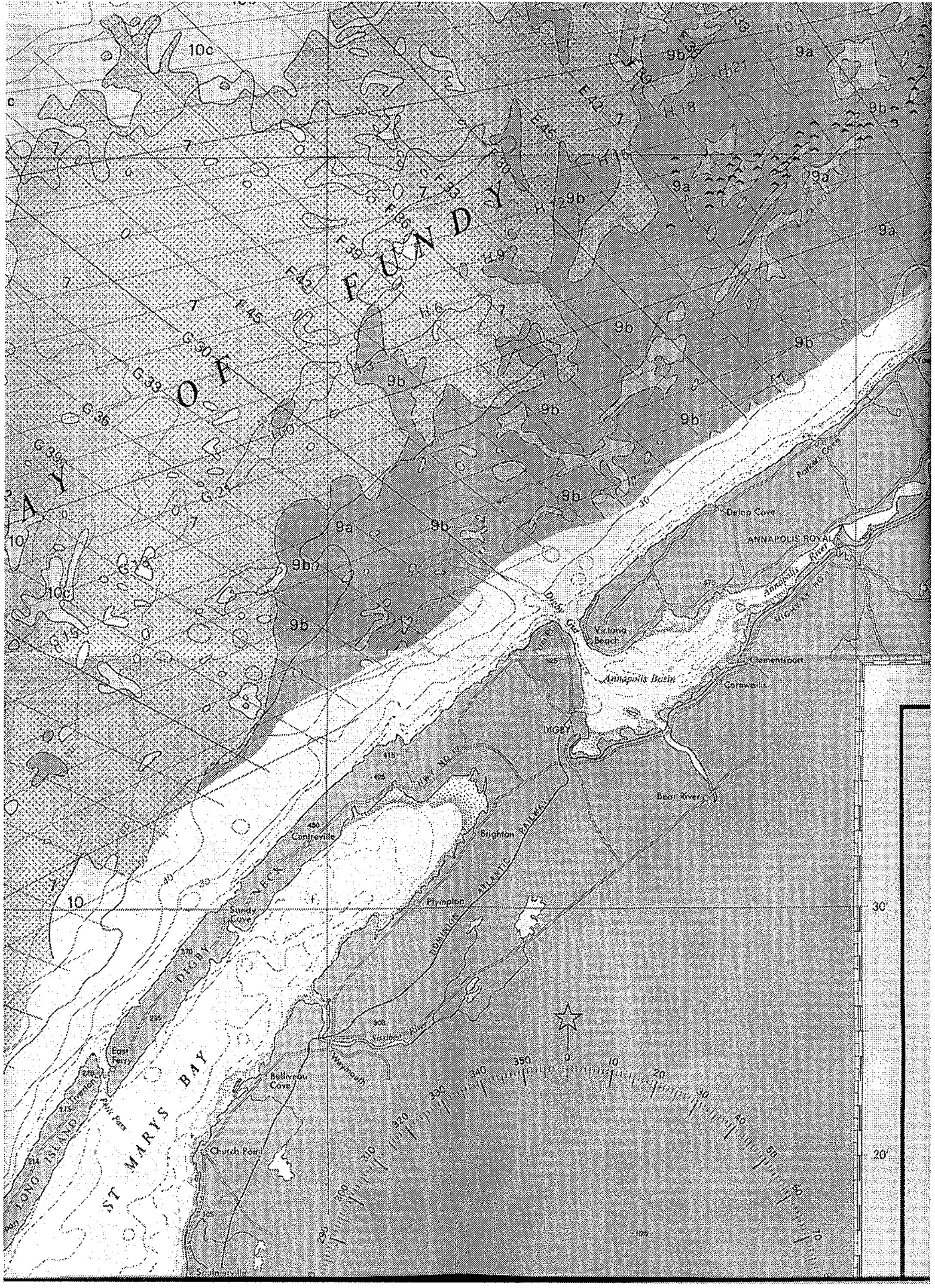


Figure 2



VERTICAL DISTRIBUTION OF SUSPENDED SEDIMENT

Figure 3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Annapolis River
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Cornwallis
DIGBY
Bear River
Brighton
Plympton
Centreville
Sandy Cove
DIGBY NECK
East Ferry
LONG ISLAND
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Belliveau Cove
Weymouth
Church Point
30'
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Figure 4

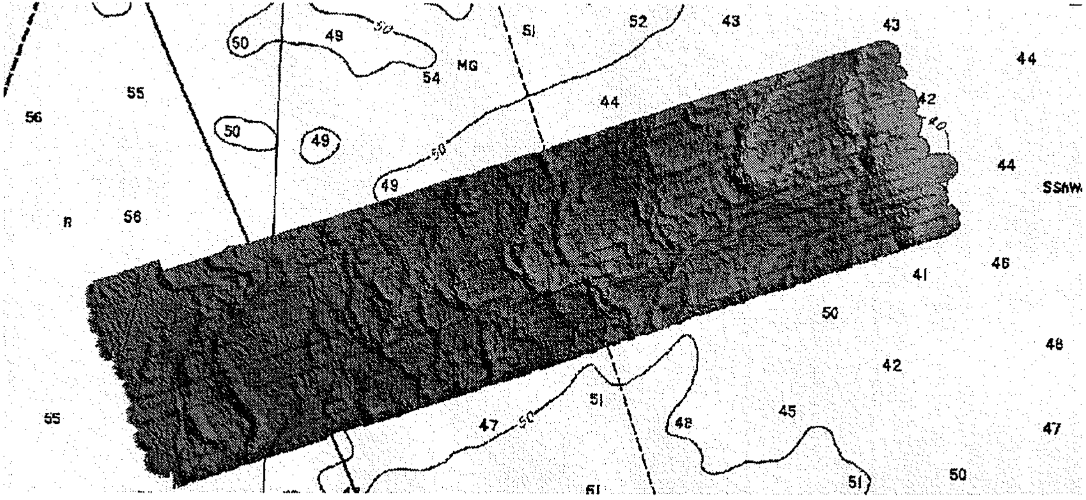

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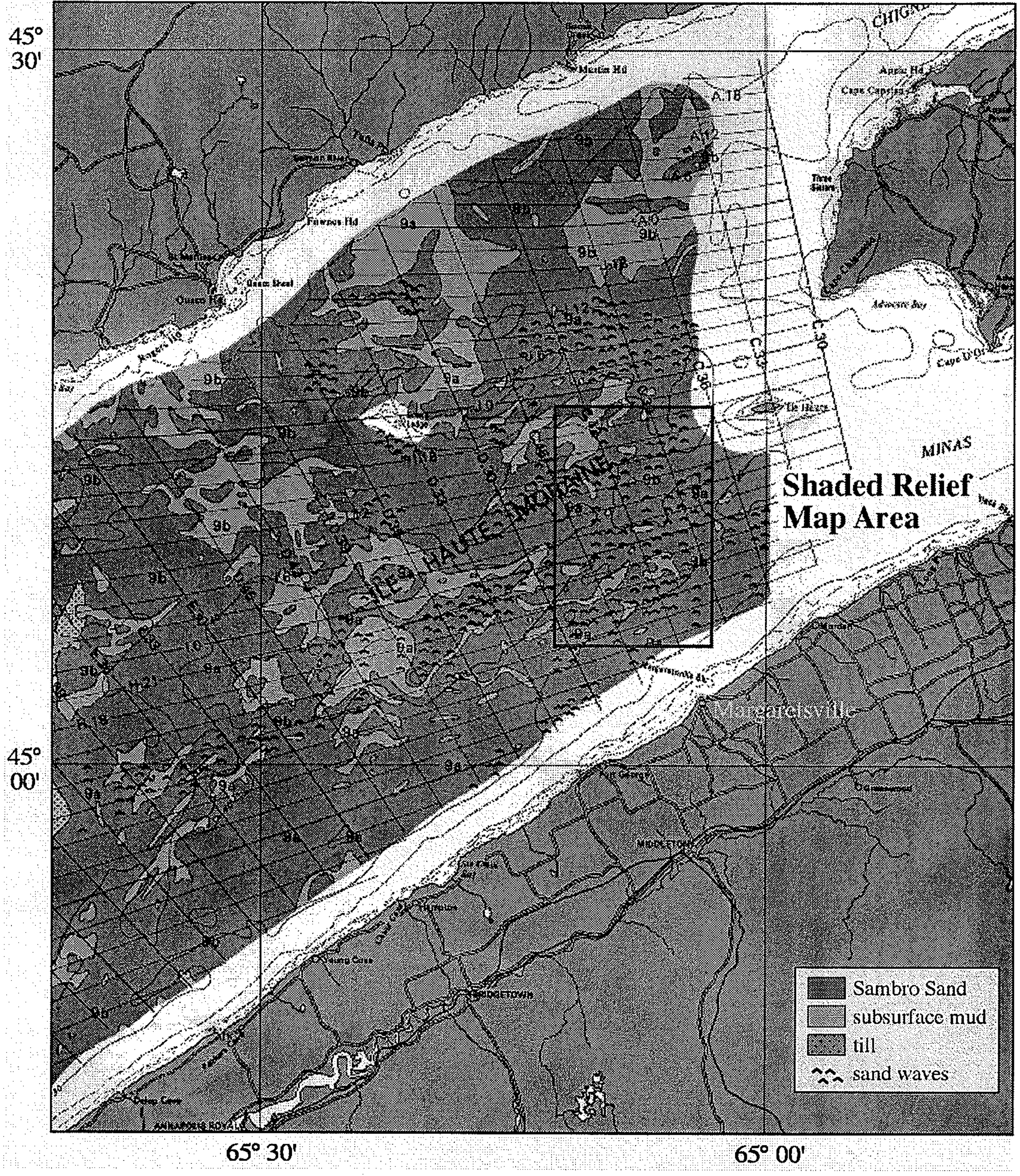
Figure 5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Shaded Relief Map Area
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sand waves

Figure 6

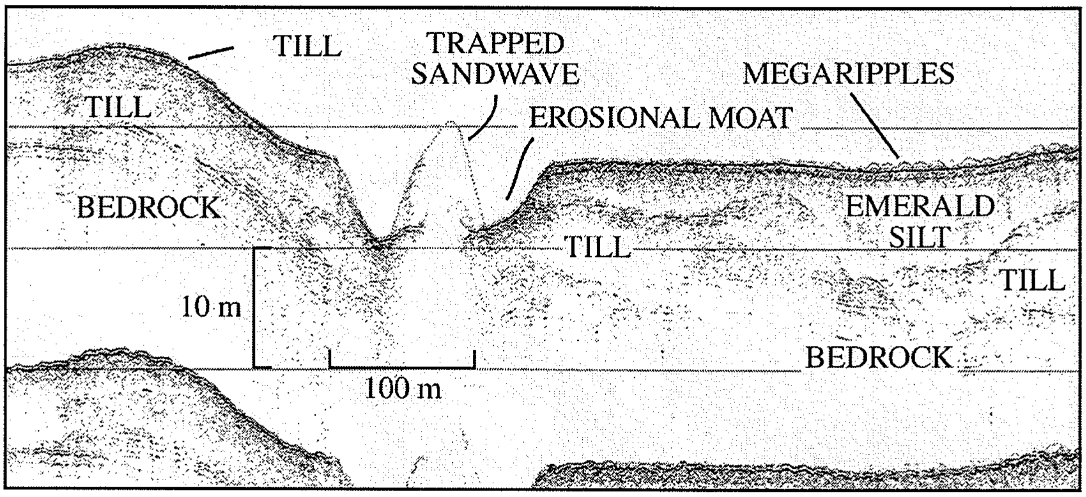

TILL
TRAPPED SANDWAVE
MEGARIPPLES
TILL
EROSIONAL MOAT
BEDROCK
EMERALD SILT
TILL
TILL
10 m
BEDROCK
100 m

Figure 7

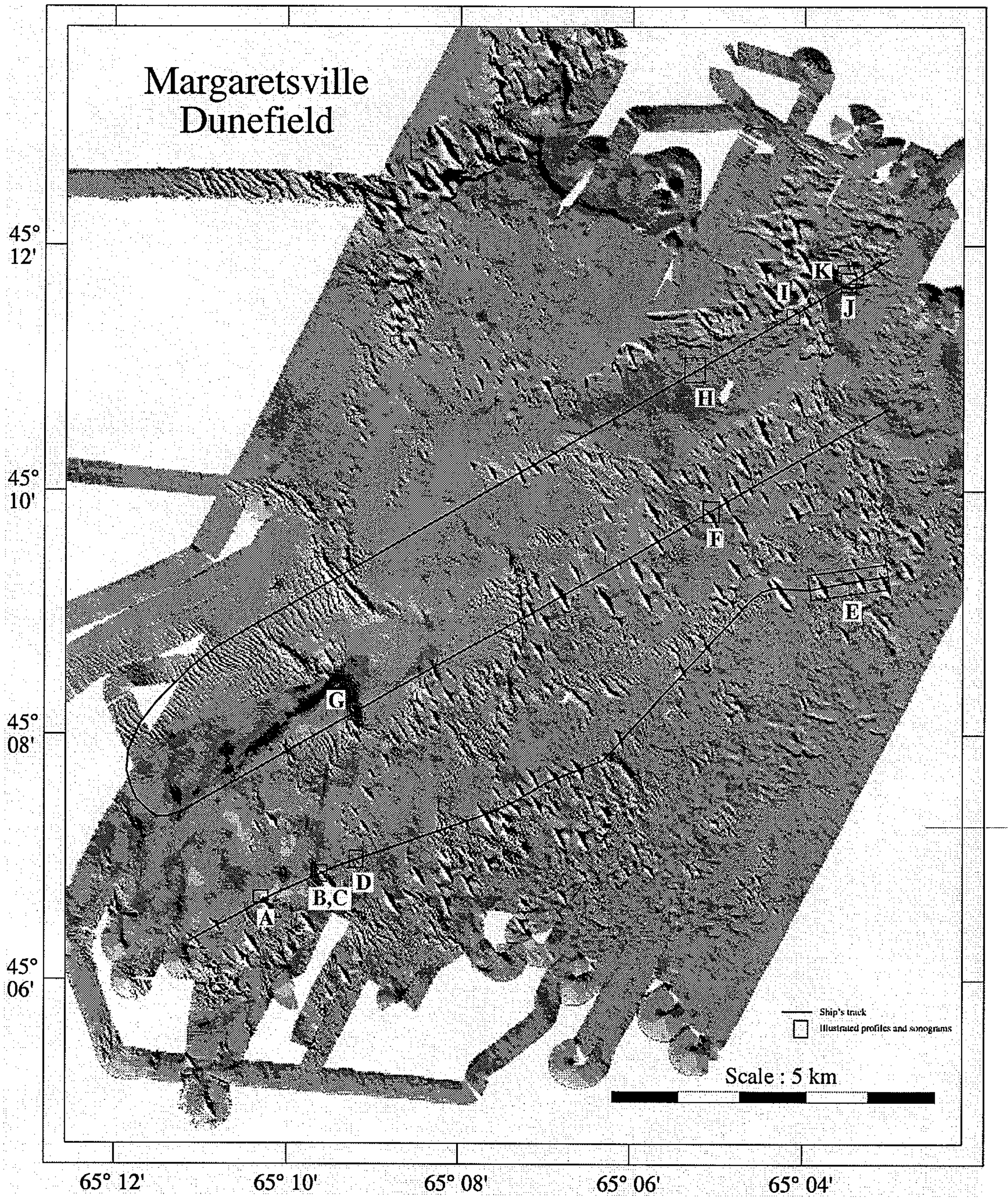
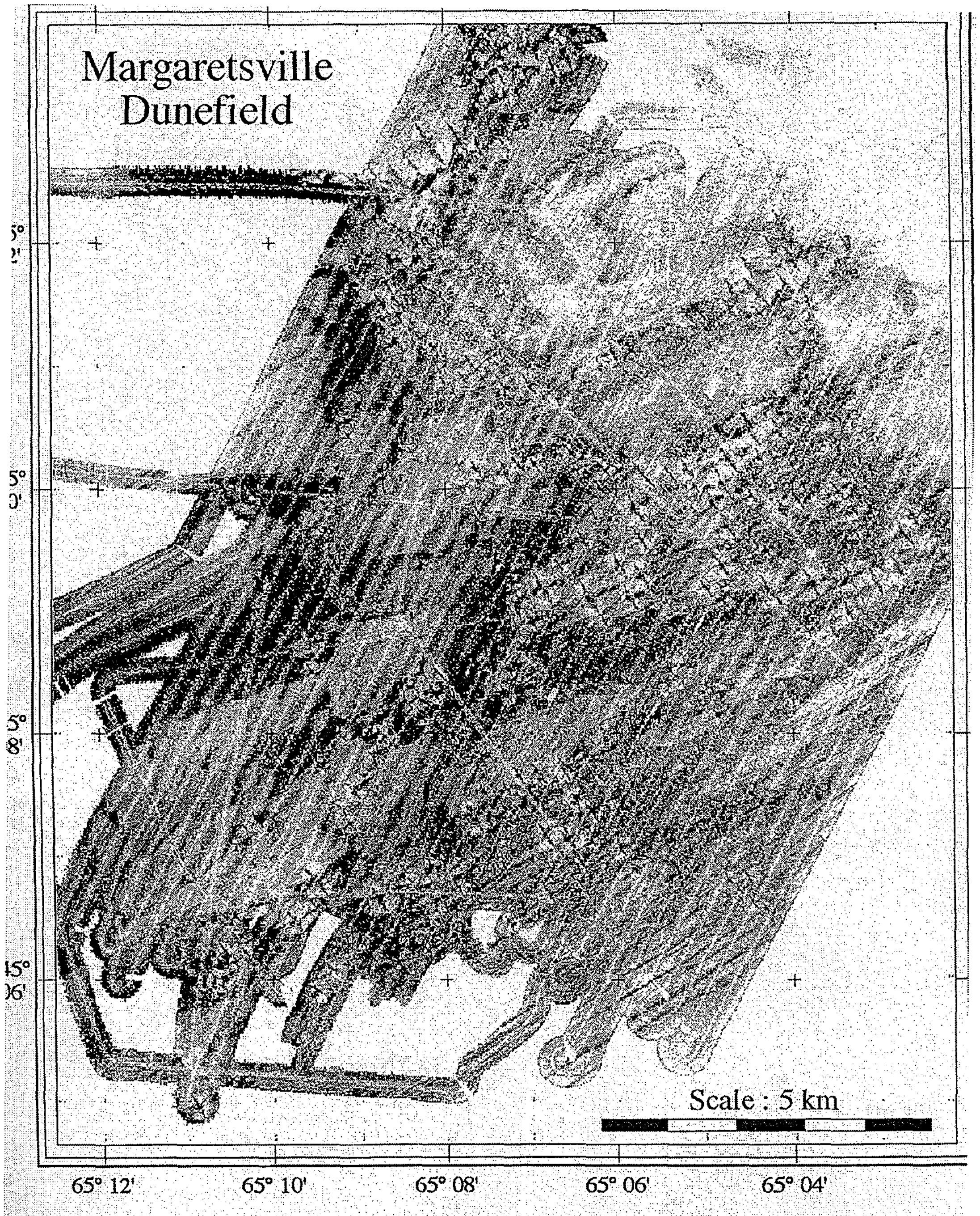

Margaretsville Dunefield
45° 12'
45° 10'
45° 08'
45° 06'
65° 12'
65° 10'
65° 08'
65° 06'
65° 04'
A
B,C
D
E
F
G
H
I
J
K
Ship's track
Illustrated profiles and sonograms
Scale : 5 km

Figure 8


Margaretsville
Dunefield
5°
2'
5°
0'
5°
8'
45°
06'
Scale : 5 km
65° 12'
65° 10'
65° 08'
65° 06'
65° 04'

8.

Figure 9

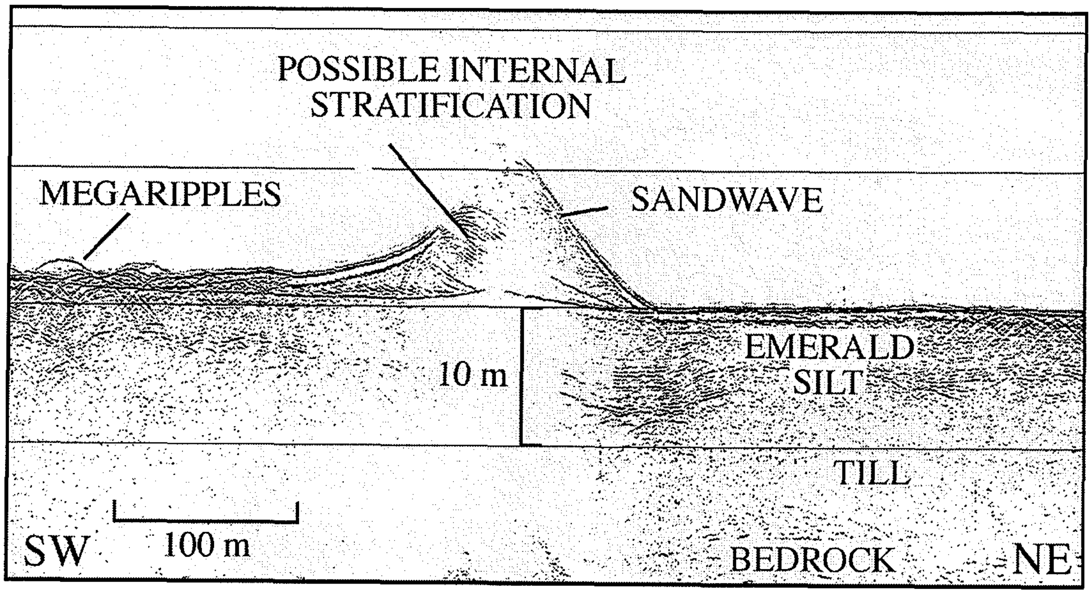

POSSIBLE INTERNAL STRATIFICATION
MEGARIPPLES
SANDWAVE
10 m
EMERALD SILT
TILL
100 m
SW
BEDROCK
NE

Figure 10

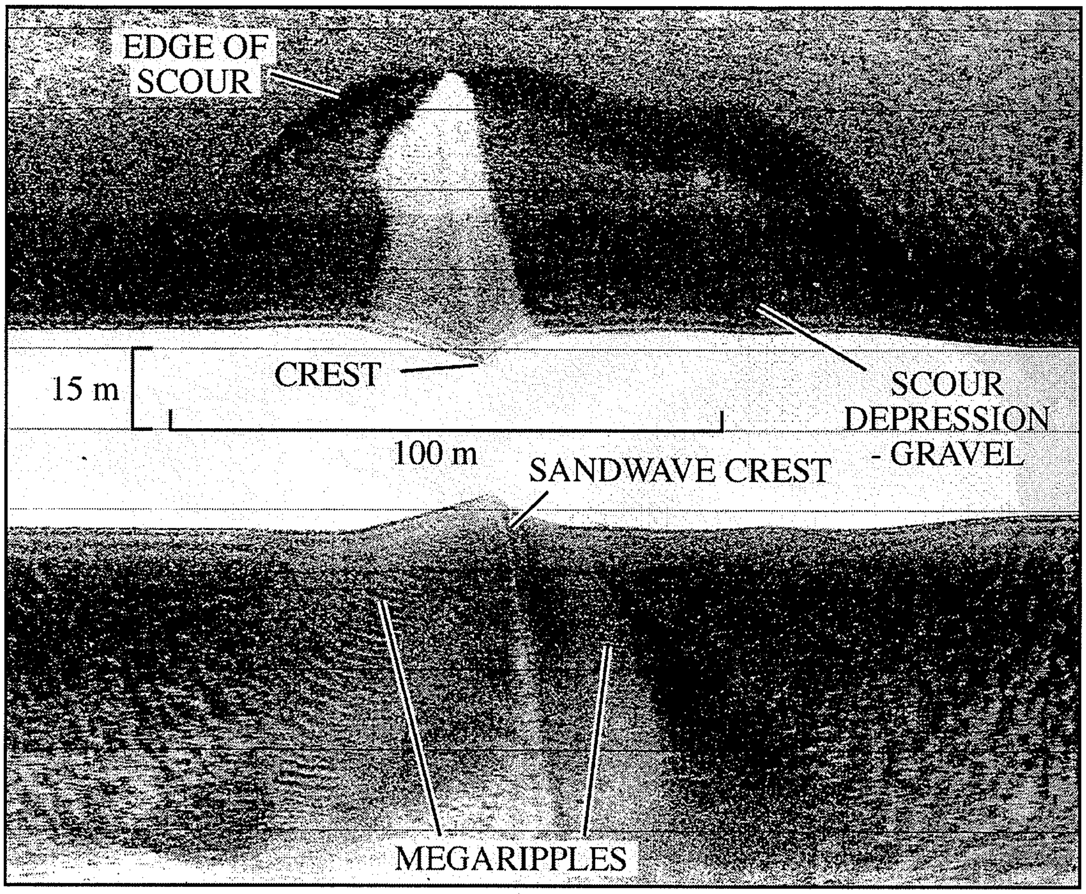
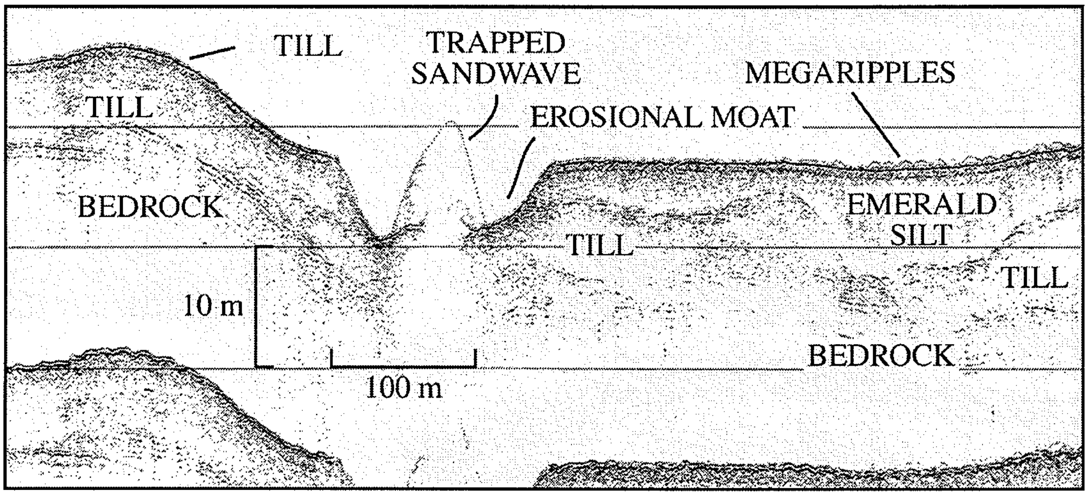

EDGE OF SCOUR
CREST
15 m
100 m
SCOUR DEPRESSION - GRAVEL
SANDWAVE CREST
MEGARIPPLES

Figure 11


TILL
TRAPPED SANDWAVE
MEGARIPPLES
TILL
EROSIONAL MOAT
BEDROCK
EMERALD SILT
TILL
TILL
10 m
BEDROCK
100 m

12.

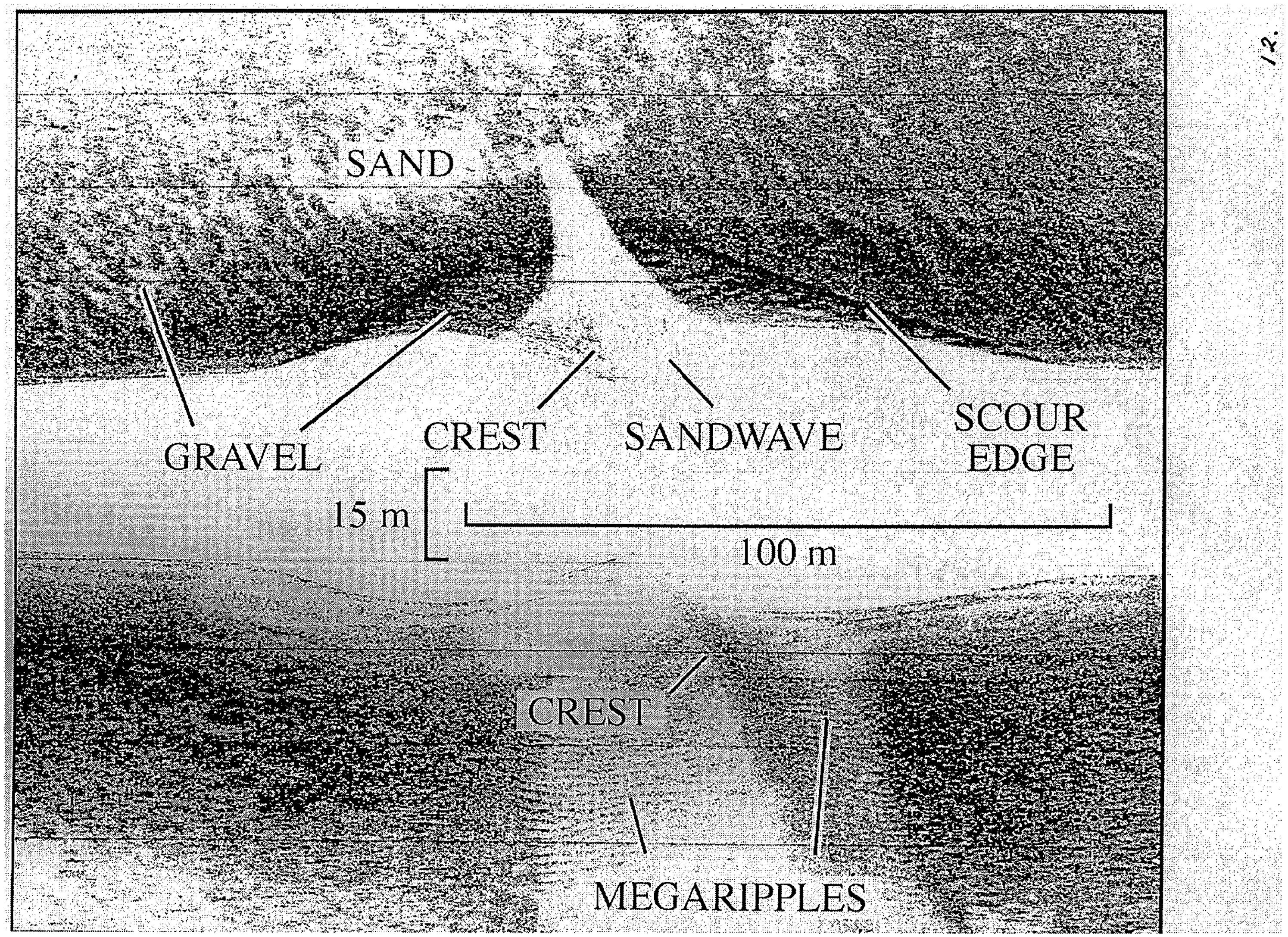

SAND
GRAVEL
CREST
SANDWAVE
SCOUR EDGE
15 m
100 m
CREST
MEGARIPPLES

Figure 12

Figure 13

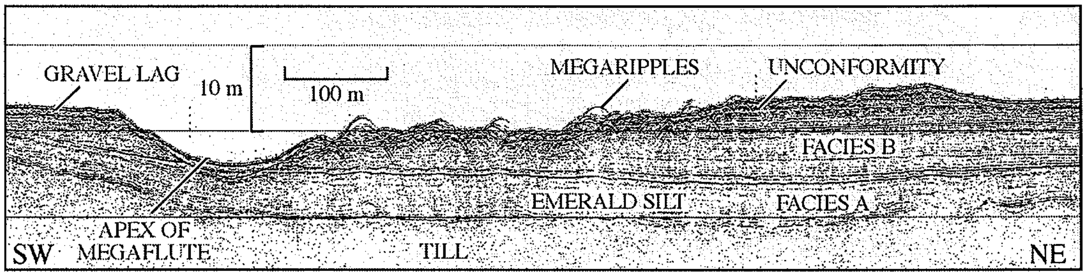

GRAVEL LAG
10 m
100 m
MEGARIPPLES
UNCONFORMITY
FACIES B
EMERALD SILT
FACIES A
APEX OF MEGAFLUTE
SW
TILL
NE

Figure 14

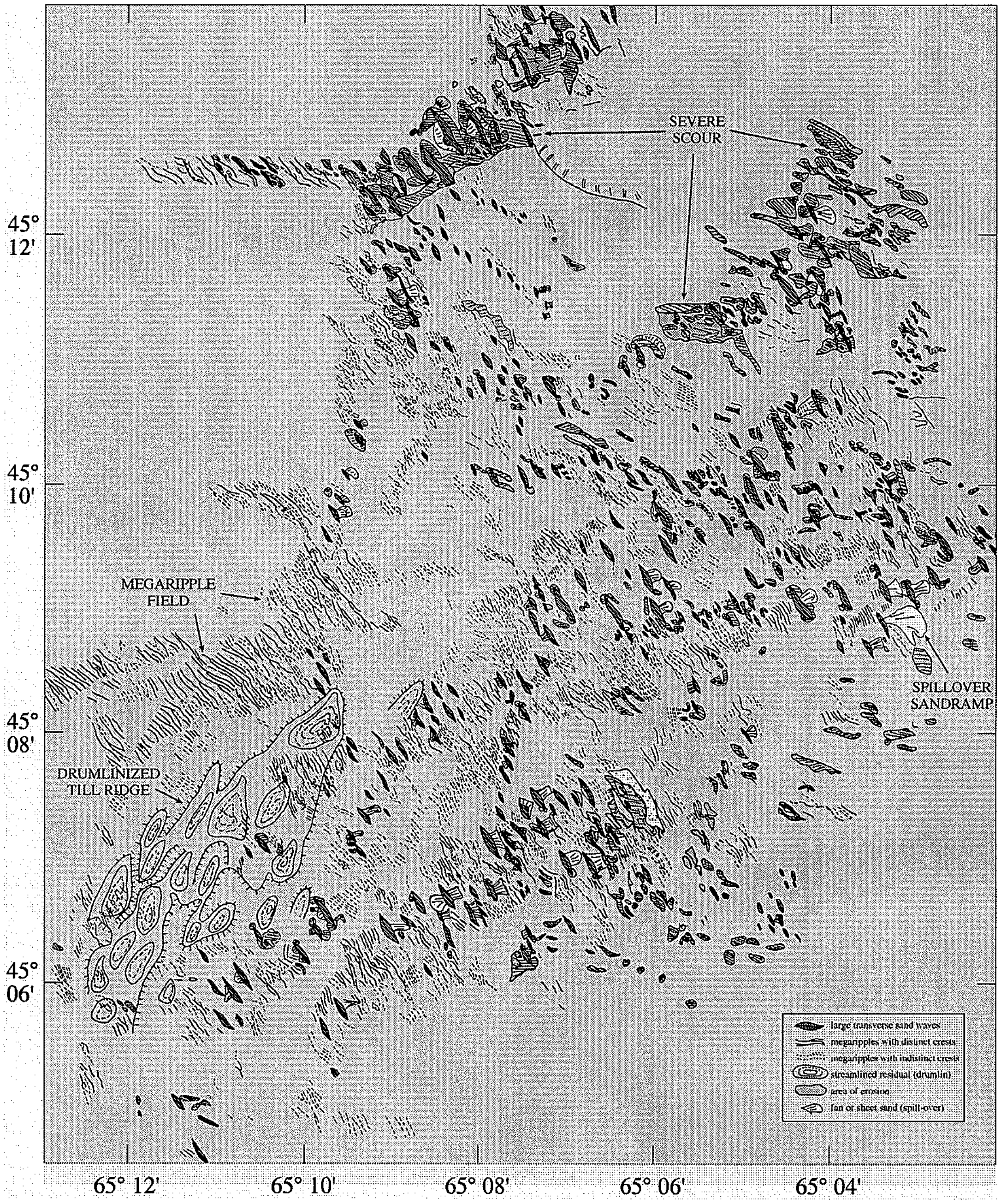

SEVERE SCOUR
MEGARIPPLE FIELD
SPILLOVER SANDRAMP
DRUMLINIZED TILL RIDGE
45° 12'
45° 10'
45° 08'
45° 06'
65° 12'
65° 10'
65° 08'
65° 06'
65° 04'
large transverse sand waves
megaripples with distinct crests
megaripples with indistinct crests
streamlined residual (drumlin)
area of erosion
fan or sheet sand (spill-over)

Figure 15

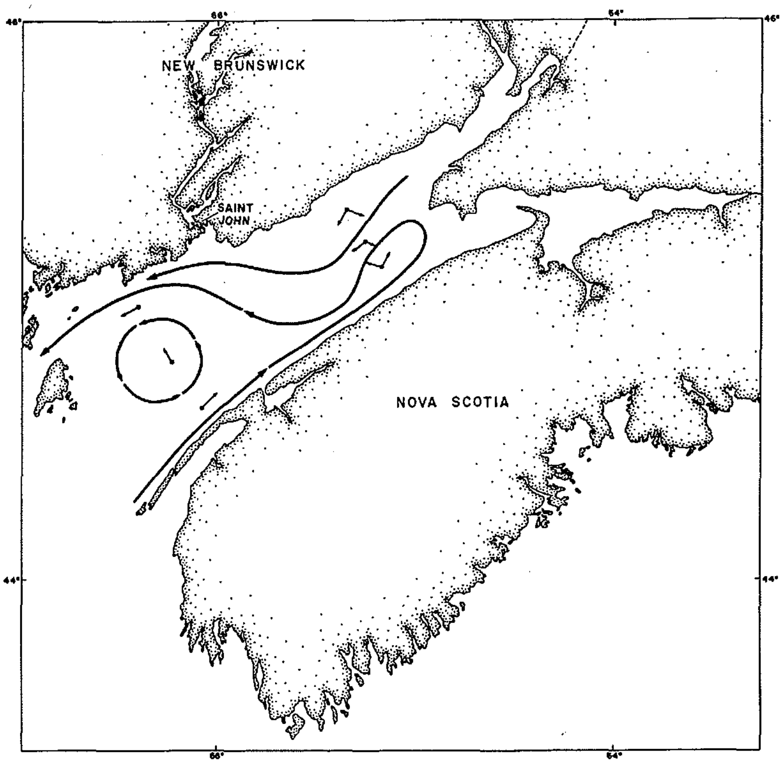
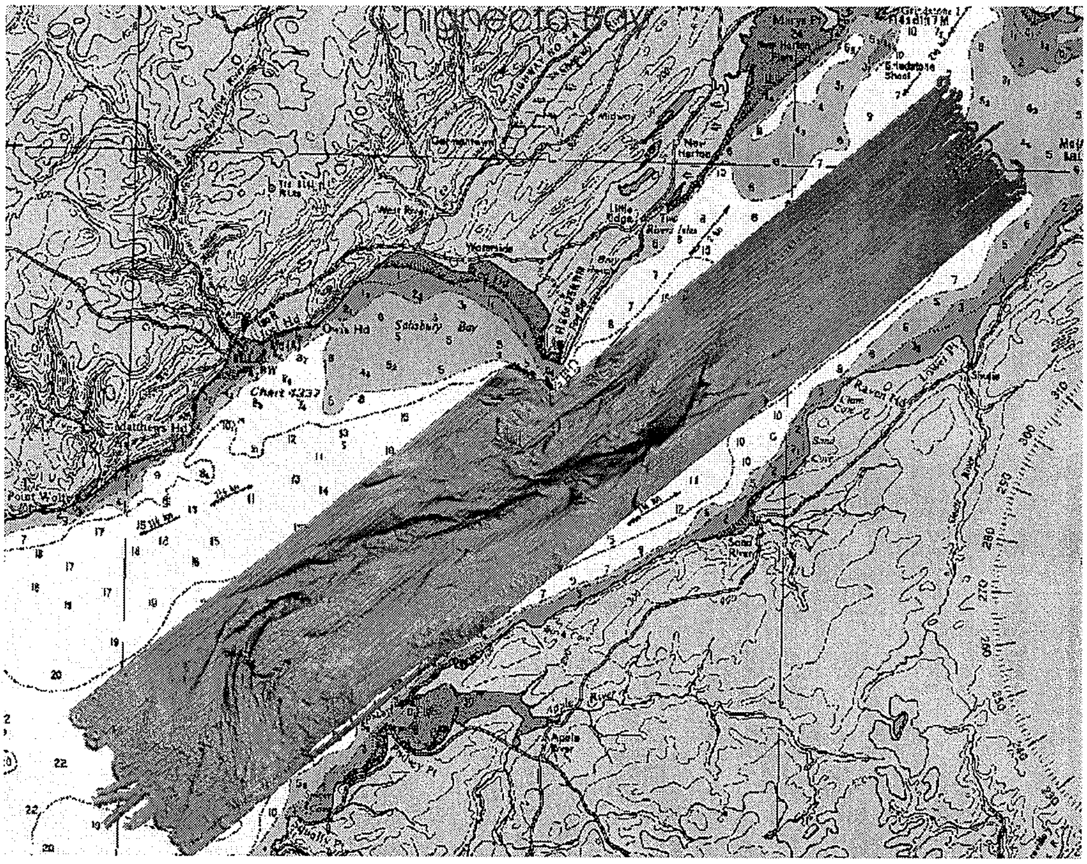


Figure 16


Chignecto Bay
Salisbury Bay
Chart 4337
Matthews Hd
Point Wolfe
Owls Hd
Waterside
West River
New Horton
Little Edge
Raven Hd
Sand Cove
Sand River
Apple River
Grindstone Shoal