Appendix 3:

Geology, Bathymetry, Ice and Seismic Conditions

(Fader 2009)

Geological Report for the Proposed In Stream Tidal Power Demonstration Project in Minas Passage, Bay of Fundy, Nova Scotia

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Regional Physiography, Geography and Bathymetry of Minas Passage, Inner Bay of Fundy

Physiography

The location of the proposed tidal power demonstration facility falls within one major physiographic province of eastern Canada known as the Appalachian Region (Figure 1). Within the Appalachian Region there are two divisions: the Atlantic Uplands and the Carboniferous-Triassic Lowlands. The proposed tidal power demonstration site (Minas Passage) falls within the Carboniferous- Triassic Lowlands that is named because it is underlain largely by rocks of Carboniferous and Triassic age. A further subdivision of the Carboniferous – Triassic Lowlands is known as the Fundian Lowlands (Williams et al., 1972).

The development of the Appalachian Region began during the late Jurrassic to early Cretaceous time with the modification of the landscape by fluvial drainage systems and today is considered a mature surface. The Fundian Lowlands cover most of the Bay of Fundy continuing into the deeper parts of the Gulf of Maine. They extend inland in Nova Scotia to include the Annapolis and Minas Lowlands. Both the uplands and lowlands of the Appalachian Region are thought to have developed together in response to a long and continuous cycle of erosion. Subsequent glacial erosion of these surfaces has been minor in nature. It only altered local regions of the former landscape previously developed by subaerial erosion.

Geography

Minas Passage occurs in the inner part of the Bay of Fundy connecting Minas Channel with Minas Basin, (Figure 2). Minas Channel connects with the inner Bay of Fundy to the west. The Bay of Fundy is part of a much larger regional marine system that includes the Gulf of Maine and Georges Bank and is referred to as the FMG for research purposes. The Bay of the Fundy is a linear embayment, 155 km in length that tapers to 48 km wide at its northeastern end where it bifurcates into Chignecto Bay and Minas Channel. The Bay also shallows in a northwest direction from 233 m water depth in Grand Manan Basin at the entrance, to 45 m at the bifurcation. The Bay of Fundy connects to the northeastern corner of the Gulf of Maine between the islands of Grand Manan, New Brunswick; and Brier Island, Nova Scotia.

Divisions of the Bay of Fundy

The Bay of Fundy has been divided into a variety of geographic regions for research and fisheries purposes. One system divides the Bay into what is referred to as the "Upper Bay" and the "Lower Bay" with the dividing line running from Cape Spencer east of Saint John, NB, to Parkers Cove northeast of Digby, NS. A further subdivision is sometimes used to divide the Bay into four quadrants separating the north and south portions. Other divisional systems define the boundary between the inner and outer Bay of Fundy as a line that runs in a more southerly direction from Cape Spencer in NB to the Digby Gut area (Figure 3). Dadswell et al, (1984), in a review of fisheries in the Bay of Fundy, divided it into three geographic regions: lower, mid and upper. Fisheries divisions of the Bay of Fundy term the Inner Bay as area 55 and the Outer Bay as area 54. The dividing line in this case is between Digby and Musquash Head in NB, slightly to the west of the other divisions. The Minas Passage project area occurs within the inner or upper Bay of Fundy.

Minas Passage

Minas Passage is a rectangular – shaped body of water that connects Minas Channel to Minas Basin (Figure 2). Minas Channel is the area of the inner Bay of Fundy east of a line that extends from Cape Chignecto in the north, to Harbourville in the south. The entrance to Minas Channel lies east of Ile Haute, a prominent Island of the inner Bay of Fundy.

Minas Passage is approximately 14 km long. At its narrowest constriction, it is 5 km wide between Cape Sharp and the southern shore of North Mountain and is 10 km wide at its widest point between Parrsboro and Cape Blomidon. The Passage is oriented northwest – southeast. The four corner points and boundary lines of Minas Passage are Ramshead Point west of the mouth of the Diligent River in the northwest, south to the western tip of Cape Split, southeast to Cape Blomidon and northeast across the passage to Second Beach, at the eastern headland of the entrance to Parrsboro Harbour. Black Rock is a small basalt island that lies in the northern part of Minas Channel to the east of Cape Sharp, located approximately 0.5 km offshore. Some maps present Minas Passage as a minor geographic component of Minas Channel that occurs to the west.

Coastline of Minas Passage

The southern shoreline of Minas Passage is a straight coastline with steep basalt cliffs of North Mountain basalt extending from Cape Split to Blomidon, where the coastline turns to the south as part of the western shoreline of Minas Basin. There are few bays, indentations and headlands along the southern shore of Minas Passage and this is the result of the bedrock geology of this coastal segment that consists of uniform North Mountain basalt.

In contrast, the coastline of the northern part of Minas Channel is much different, largely the result of varying bedrock lithologies at or near the shoreline. Partridge Island and Cape Sharp are prominent steep sided, high-relief basalt promontories that resisted erosion in comparison to the adjacent siltstone and shale softer rocks of the Carboniferous Parrsboro Formation and the Triassic to Jurassic Blomidon Formation that have been more heavily eroded. Additionally, the overlying glacial and post glacial sediments of the region were formed in a complex environment resulting from caving ice fronts and raised sea levels that have produced terraced regions of glacial outwash, gravel barriers, till cliffs and bedrock exposed coastal segments. These processes and materials have resulted in a coastline that is highly irregular with some straight coastal segments and a large embayment called West Bay controlled by the resistant headlands of Cape Sharp and Partridge Island.

Welsted, 1974 undertook a study of the shorelines of the Bay of Fundy to produce a series of maps showing a coastal classification based on the interpretation of air photos. Shaw et al., 1998 undertook a regional sensitivity study of the coastlines of Atlantic Canada to rising sea levels (Figure 4). The shoreline region of Minas Passage is classified as moderate in this assessment.

Bathymetry

The Canadian Hydrographic Chart for Minas Passage is Chart # 4010 (Figure 2). The sparse bathymetry presented on this chart is in fathoms and it depicts Minas Passage as a narrow body of water constricted to the north of Cape Split as defined by the 20 fathom contour that broadens toward the east to the north of Cape Blomidon. The deepest depths in the Passage are 61 fathoms in the central area to the south of Cape Sharp.

Chart #4010 also shows a number of current velocity vectors with the highest values of 7 - 8 knots off Cape Split and Cape Sharp (Figure 2). A current velocity of 5 – 6 knots is plotted on the north side off Ram Head. Minas Passage is the region of highest currents in the Bay of Fundy.

Minas Passage had previously been studied as part of early tidal power proposals in the 1960s and 70s and geological/geophysical surveys were conducted to investigate seafloor conditions and sediment distributions. Two tidal barrages were proposed for construction in the passage at both ends termed the B4 and B5 crossings.

Multibeam Bathymetry

Modern bathymetric mapping technologies have significantly evolved over the past several decades and present methods utilize multibeam sonar systems that provide for 100% seabed coverage, precise measurements of depth and location, and an ability to present the information in a variety of interpretation friendly images and fly-throughs. At the start of this project, multibeam bathymetry had just been collected from the Minas Channel and Minas Passage region of the Bay of Fundy by the Geological Survey of Canada and the Canadian Hydrographic Service. That information was obtained at the start of this project and subsequent multibeam surveys were conducted in the region of Minas Passage by the proponents to obtain very high-resolution information for project needs and infrastructure micro-siting. Multibeam bathymetry not only provides water depth information, but through processing of the data, images of backscatter (proxy for seabed hardness) and seabed slope can be generated.

The bathymetric imagery can be presented as shaded-relief maps that depict the seabed as a digital terrain model with an artificial sun shining across the imagery to enhance relief. They are similar to aerial photographs of land surfaces. The data can also be displayed using conventional, but very precise bathymetric contours. These maps and images can be interpreted in conjunction with seabed samples and photographs, and seismic reflection and sidescan sonar data to understand seabed materials and processes active on the seabed. The following is a description of the regional bathymetry of Minas Passage based on multibeam bathymetry.

Minas Passage

The regional multibeam bathymetric shaded relief image in Figure 5 shows the water depths of Minas Passage in a colour depth-coded presentation. The image extends from the western tip of Cape Split in the south to Black Rock in the northeast – key geographic components of the Minas Passage area. The bathymetry was collected by the Geological Survey of Canada and provided to the project. A major feature of Minas Passage is a deep narrow linear depression that runs throughout Minas Passage oriented parallel to the southern shoreline of North Mountain and has been termed the "Minas Scour Trench" by researchers during the first round of tidal power development. This deep channel begins in an area to the north west of Cape Split where it is oriented southwest and turns to the south east to the north of Cape Split. Here the Channel is 0.6 km wide. The channel broadens to 1.5 km wide toward the east and largely occurs in the southern part of Minas Passage. As the channel approaches Minas Basin, it shallows, bifurcates into three deep regions, and gradually merges with the seabed. The north and south flanks of this channel are steep and bedrock controlled. The southern area of Minas Passage near North Mountain consists of a narrow platform that continues to the southern shoreline.

To the north of the deep channel lies a broad bedrock controlled platform 3 km wide with a very rough surface of exposed bedrock ridges and some fields of ripples in gravel. A prominent series of three, 30 – 40 m shallow flat topped platforms extend to the west from Black Rock and collectively form a ridge that is over 4 km in length. These represent areas of volcanic outcrop of North Mountain Basalt on the seabed confirmed by magnetic maps of the region and bottom photographs. Directly to the south of the volcanic platform is a prominent linear fault that runs east-west parallel to the trend of the platform extending from the southern area of Cape Sharp to the west. The region to the north of the volcanic ridge consists of rough morphology similar to the area to the south of the platform and is a region of outcropping bedrock. The seabed shallows abruptly toward the north shore of Minas Passage with a shore platform at about 10 m water depth that is approximately 0.5 km wide from the low water shoreline. Sand and gravel bedforms occur on this surface. In the north west region of Minas Passage the seabed is smoother (Figure 5) in comparison to the rough bedrock ridged region in the central part. This suggests a cover of surficial sediments overlying the bedrock as the Passage gradually shallows to the northwest. To the east of Cape Sharp, a similar shallow region extends further offshore and its edge presents a steep slope to the deep channel.

Minas Channel Bathymetry

Minas Passage connects to Minas Channel in the west and the bathymetry of this region is more complex (Figure 6). To the northwest of Cape Split lie a series of shallow offset faulted volcanic ridges that are likely a seaward continuation of North Mountain basalt projecting from Cape Split across the adjacent seabed. This series of shallow platforms that together make up a northwest trending ridge, are similar in shape, composition and morphology to the volcanic platforms that lie to the west of Black Rock in Minas Passage. Minas Channel consists of both broad flat shallow regions mainly in the southeast and deeper scoured depressions in the central region with a high degree of roughness. The bottom of the broad scoured regions display only a few small areas of exposed bedrock directly to the south of the volcanic ridge suggesting that the remaining scoured areas are cut into glaciomarine sediments and till. The scouring process has not been as severe as that in Minas Passage where vast regions of exposed bedrock have been exhumed.

Two prominent linear northeast trending ridges cut across the seabed of the northern area of Minas Channel and may represent boulder covered moraines that were originally deposited by receding glaciers and have survived the subsequent scouring process. Other isolated scour depressions occur in Minas Channel and contain large symmetrically-shaped sandy bedforms or dunes. A very large deposit of sand, termed a banner bank, lies to the southwest off Cape Split and is referred to as the Cape Split Dunefield (Miller and Fader, 1990). It has been studied in considerable detail and contains large sand waves or dunes on its surface that shift orientation, shape and height with every tidal cycle, all while maintaining the general location of the dune field.

Most Recent Multibeam

An interpretation of the Minas Channel and Minas Passage region was first undertaken utilizing previous published material and reconnaissance seismic reflection, sidescan sonar and sample data collected by the Geological Survey of Canada. This analysis determined that the most appropriate location for a demonstration tidal power project was located in Minas Passage and that such a location occurred to the west of Black Rock in the northern area of Minas Passage. The siting analysis was based on criteria such as avoidance of seabed hazards, preference for hard and stable seabed, water depth limits for devices, length reductions for marine cables, avoidance of shipping lanes and fishing zones, proximity to the electrical grid and distance from adjacent parkland. Once the area was selected, it was necessary to conduct very high-resolution seabed surveys in order to characterize the seabed in considerable detail and to determine appropriate sites for device micro-siting.

The prime system utilized for survey was a Reson multibeam bathymetric sonar system that had an ability to represent the morphologic information at approximately 0.5 m resolution, considerably higher than the previous multibeam data collected by the Geological Survey of Canada that was girded at 2 m. The multibeam information from the high resolution survey was collected over a smaller region that contained potential candidate sites to characterize details of seabed relief and to provide detailed contoured imagery of bottom topography and seabed slope information. The following is a general description of the bathymetry based on the detailed multibeam information (Figure 7).

The high resolution multibeam bathymetric survey was conducted in an area in and around Black Rock extending to the west across the volcanic platform and to the north to an area south of Ram Head (Figure 7). It also continued to the low water shoreline to the north of Black Rock and was conducted at high water to provide near shore coverage. The survey covers a region of approximately 4 km by 1.6 km.

The high resolution multibeam bathymetric shaded-relief map, Figure 7 shows the east west trending volcanic ridge as the dominant morphologic feature of the southern part of this study region. Water depths across the ridge show that it is defined by the 30 m contour in the eastern portion near Black Rock, and increases in depth to 35 m at the western tip of the feature. It is a broad flat platform with very minor relief of a few m across its surface and is 500 m wide at its widest location tapering to a triangular-shaped western end. Several broad deep channels occur across the surface of the platform near the western part of the feature and reach over 50 m water depth. A few localized linear depressions occur along the northern flank of the volcanic ridge and appear as erosional moats. The volcanic ridge protrudes above the surrounding areas by as much as 15 m but averages 5 m in height and has very steep slopes. The slopes are steeper and higher in the western portion of the platform area. Some local scouring appears to occur around the volcanic ridge flank in the west.

A broad region of northwest trending bedrock ridges lies to the north, south and west of the volcanic platform in deeper water. The ridged region to the north has water depths that range between 35 and 40 m in the east and is slightly deeper in the west, ranging between 40 and 45 m. A few intervening deeper regions between ridges approach 50 m water depth. The ridges are rough and undulating with flat regions occurring between ridges.

In the northern region of the study area at approximately 45 m water depth, the seabed becomes smoother and the bedrock ridges appear to be buried beneath sediments as the region approaches the shoreline. Continuing to the north and northeast, the seabed presents a gradual shallowing slope with increasing steepness, and at 10 m water depth a scarp occurs where the seabed flattens to the north. This flat region is a broad platform that continues to the shoreline across the intertidal zone. The edge of the scarp is convoluted in places and only a few areas are straight and well-defined. These regions of convoluted scarp are interpreted to represent possible slump scars.

To the northwest and south east of Black Rock are a series of prominent ridges on the seabed that are interpreted as gravel bedforms. On the nearshore platform in water depths around 5 m are a variety of sand and gravel bedforms as defined by crests and troughs that are oriented normal to the adjacent shoreline.

A detailed interpretation and discussion of the bathymetry and how it relates to the bedrock and surfical geology and seabed processes will be presented in other sections of this report.

Figures

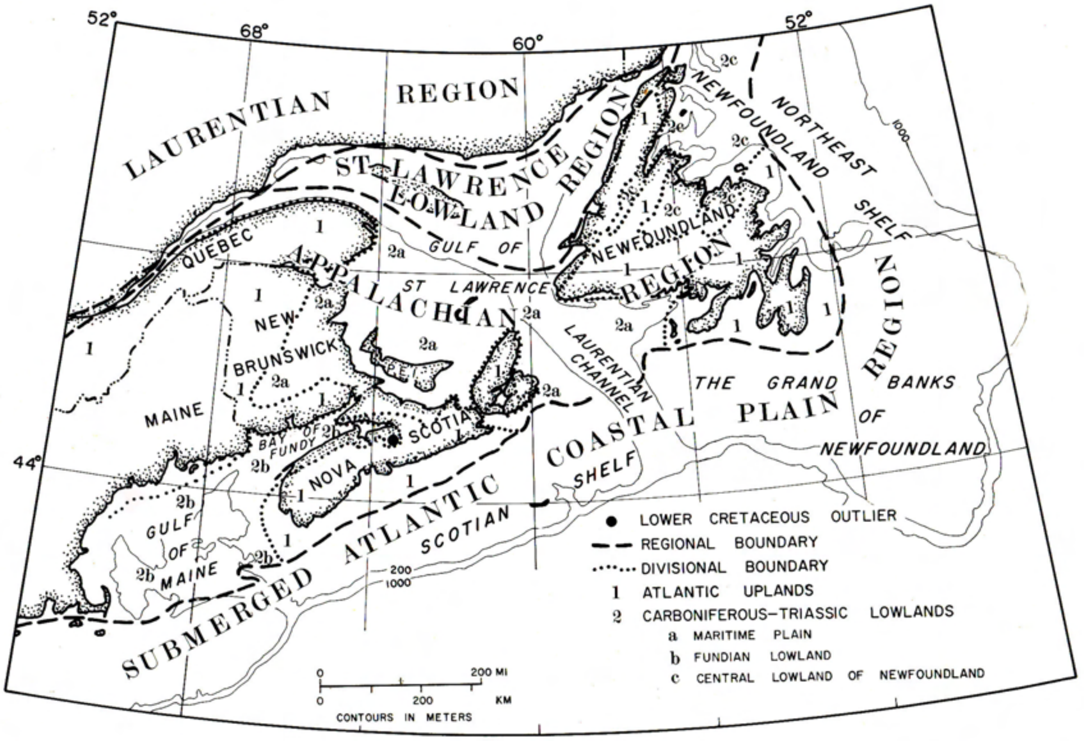

Figure 1. Major Physiographic divisions of Atlantic Canada from Williams et al., (1972).

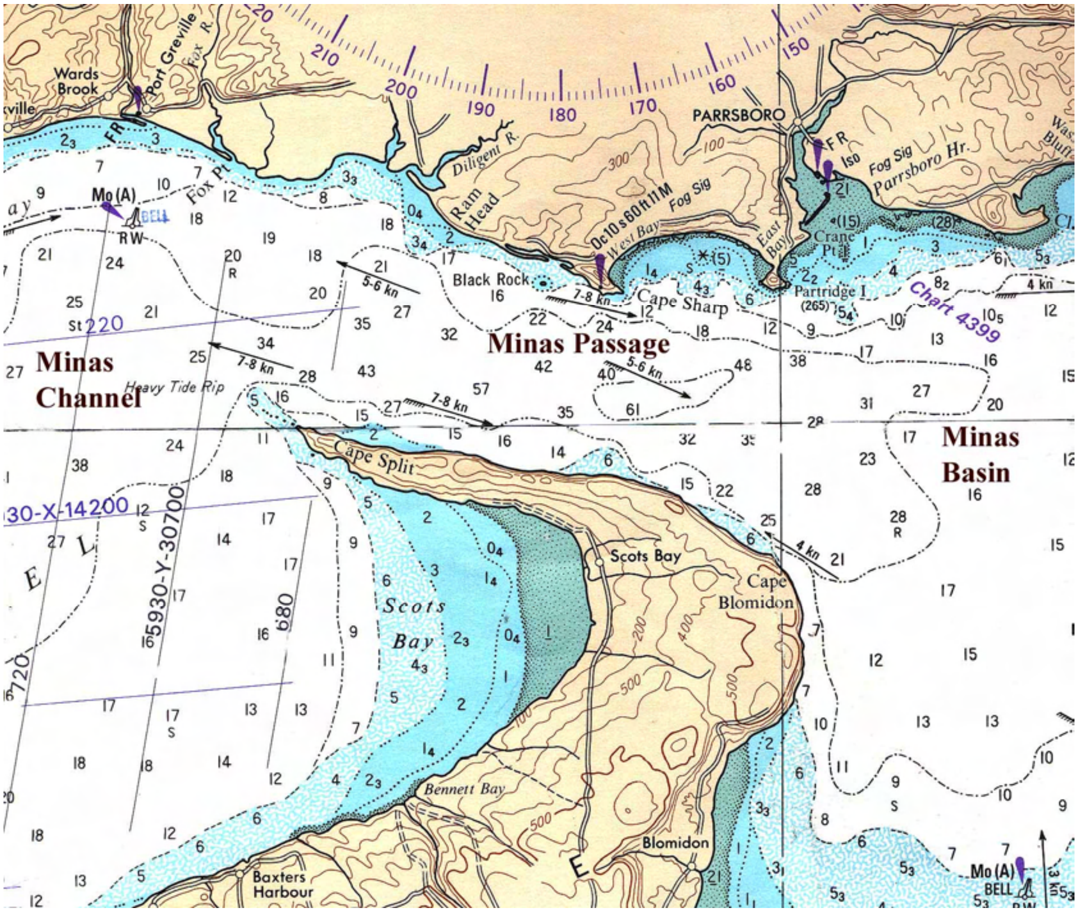

Figure 2. A section of Canadian Hydrographic Chart 4010 that shows the relationship of Minas Passage to Minas Channel in the west and Minas Basin in the east. See text for detailed description.

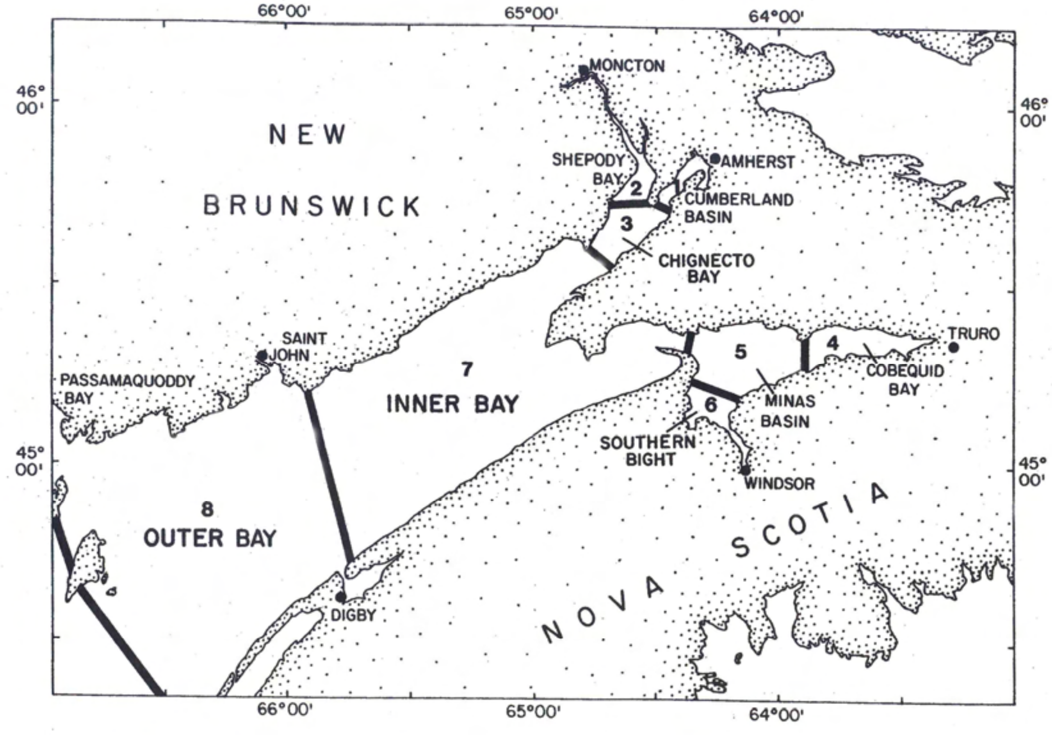

Figure 3. Divisions of the Bay of Fundy into inner and outer, and other geographic regions of the inner Bay.

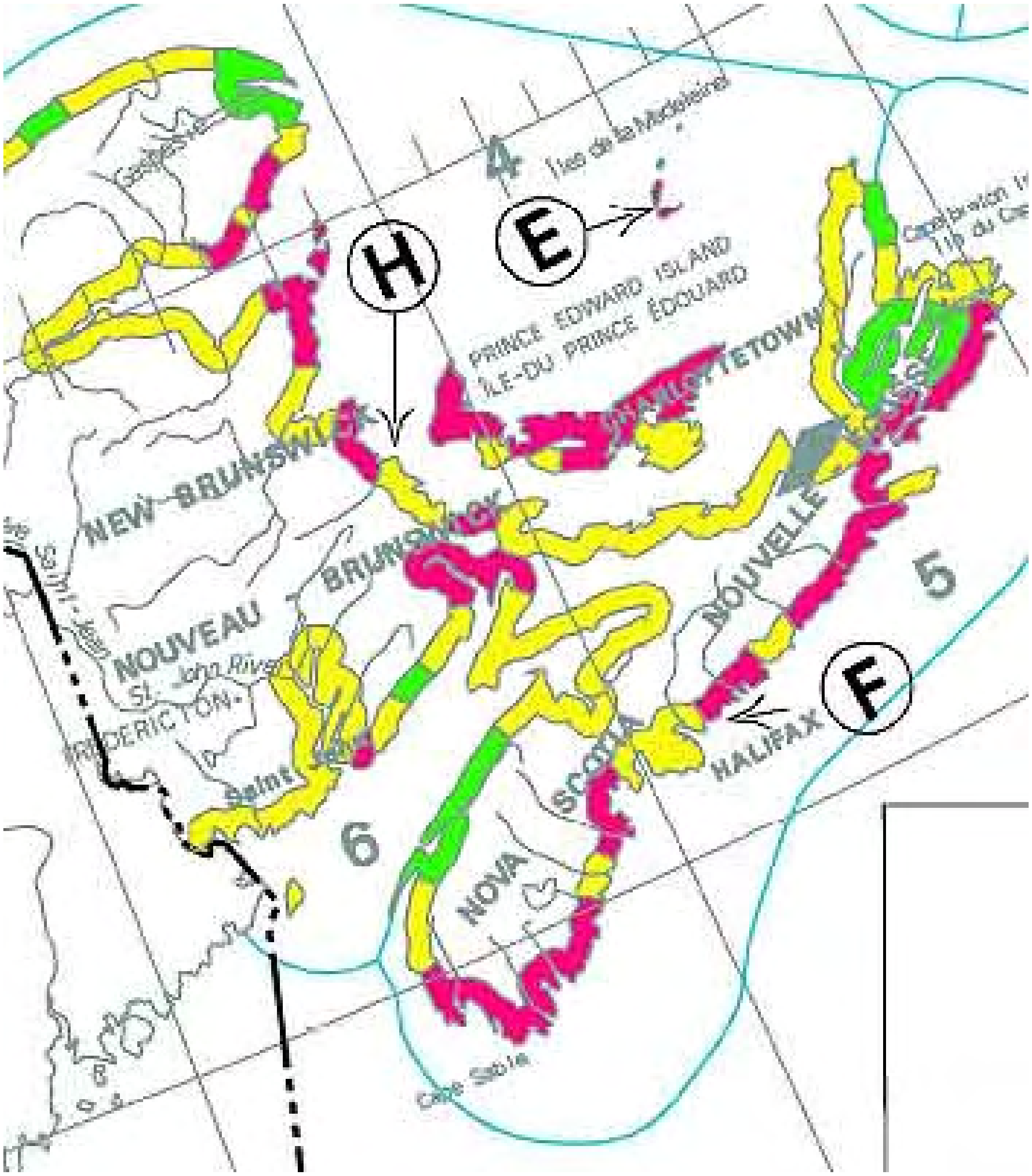

Figure 4. Sensitivity index for coasts of Atlantic Canada vulnerable to the effects of global sea level rise, from Shaw et al., 1998. The shorelines of Minas Channel, Passage and Basin are shown in yellow indicating moderate sensitivity.

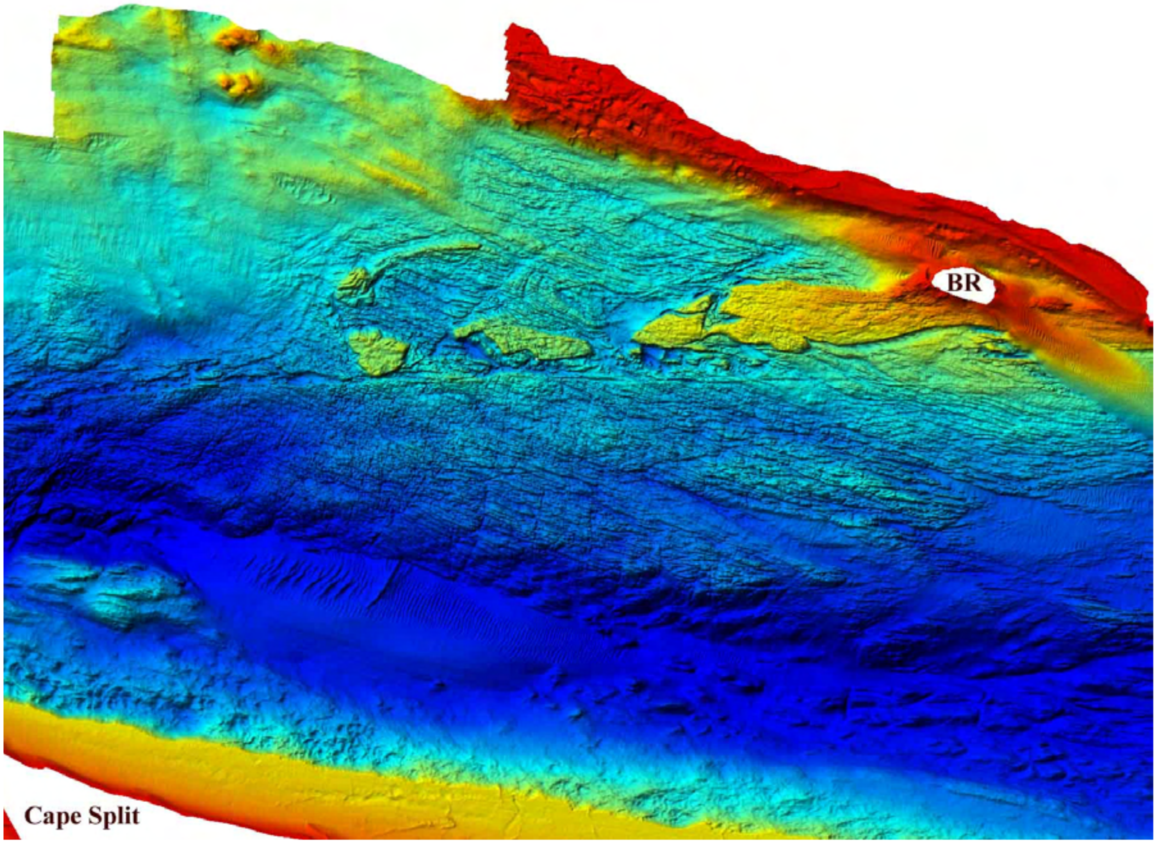

Figure 5. Multibeam bathymetric shaded-relief image of Minas Passage from data collected by the Geological Survey of Canada and the Canadian Hydrographic Service.

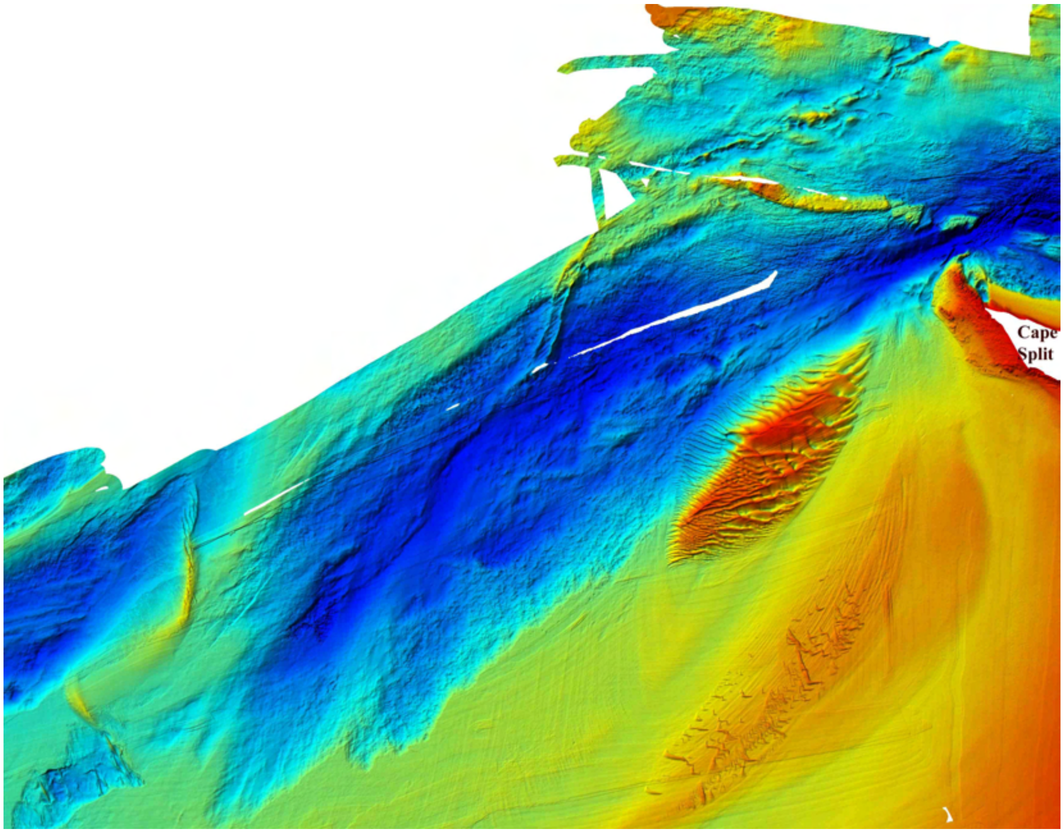

Figure 6. Multibeam bathymetric shaded-relief image of Minas Channel from data collected by the Geological Survey of Canada and the Canadian Hydrographic Service.

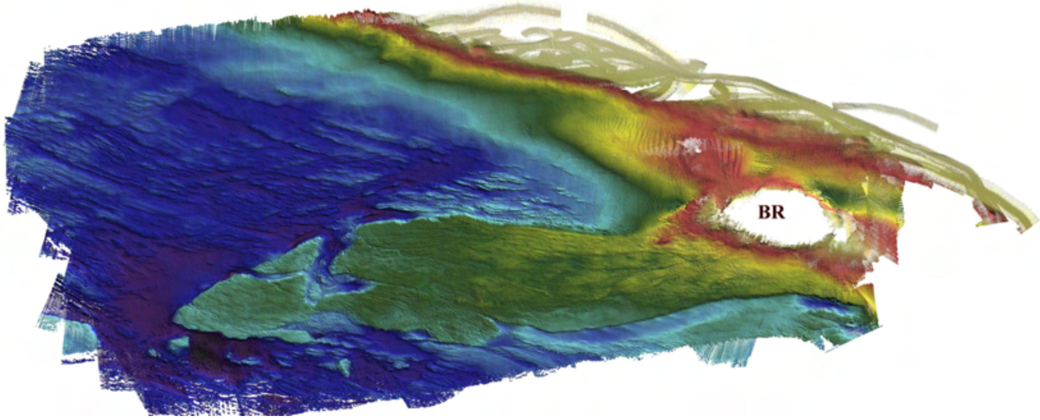

Figure 7. High resolution multibeam bathymetric map of the area to the west of Black Rock produced by Seaforth Engineering where the in-stream tidal power demonstration test sites are proposed to be located.

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Bedrock and Surficial Geology of Minas Passage

Bedrock Geology

Prior to studies associated with this tidal power demonstration project, a limited amount of research had been conducted in the Minas Passage region of the Bay of Fundy. Most was undertaken to evaluate environmental and engineering aspects of the previous round of tidal power development in the 1980s that envisioned the construction of tidal power barrages or dams across regions of the inner Bay of Fundy. Surveys were conducted using low-resolution acoustic systems and details of the seabed morphology, bedrock, sediments, seabed features and bathymetry were lacking.

The most recent study (2008) for this project has had the advantage of the development and application of many new and improved seabed mapping systems and technologies over the past two decades. These included high-resolution seismic reflection systems, sidescan sonars, multibeam bathymetric sonars, cameras, and navigation systems. As part of the proposed tidal power demonstration project, surveys have been conducted in Minas Passage using these systems and the data has provided a characterization of the seabed with resolutions of decameters.

The following is a description of the bedrock geology and surficial sediments of Minas Passage as well as the proposed sites for tidal power device and associated cable placement. The present study has been integrated with results of previous research.

Data Base

Seismic reflection surveys have previously been undertaken in Minas Passage to support bedrock mapping by the Geological Survey of Canada and by the Atlantic Development Board for the 1980s tidal power assessment (Huntec Ltd., 1966). The marine bedrock geology of the region has been mapped by King and MacLean, (1976) and in a subsequent digital revised map released by King and Webb (in press) (Figure 8). The geology was interpreted on the basis of structural and stratigraphic relationships and acoustical reflectivity from a grid of high-resolution seismic reflection profiles collected in the 1960s and 70s. Bedrock information from adjacent land areas, well data, dredged samples, and gravity and magnetic and seismic refraction data were also used. The bedrock geology of the adjacent land in Nova Scotia has been studied by the Nova Scotia Department of Natural Resources over many years and the land geology assessment in this report was extracted from map ME 2000-1 (Keppie, 2000) and map 82-7 by Donohoe and Wallace, 1982.

The most recent geophysical survey in the Bay of Fundy was conducted by Fader, 1998, from the CCGS Hudson that collected sidescan, airgun and Huntec high-resolution seismic reflection data from a survey that extended from Minas Basin through Minas Passage and Minas Channel.

Previous Research

Earliest research on the bedrock of the Bay of Fundy and adjacent Gulf of Maine suggested that the Bay was a graben (Upham, 1894 and Johnson, 1925). Koons (1941, 1942), proposed that the Bay formed by fluvial erosion followed by submergence and that glacial erosion played a minor role. Shepard (1930, 1931) interpreted that the deep basins in the Bay were glaciated and that glaciation was responsible for its overall shape. Swift and Lyall (1968) investigated Triassic sediments in the Bay of Fundy using sparker seismic reflection techniques and defined a broad open syncline as well as the Fundian Fault along the northern flank of the Bay. The sparker seismic reflection profiles from that survey have been published and preserved in Geological Survey of Canada Open File Report #898 (Fader, 1983) and were assessed for this study.

Based on a study of industry wells and seismic reflection profiles, Wade et al., 1996 assessed the subsurface geology of the Fundy Basin and determined that the Basin has been influenced by major pre-existing transverse faults. Deep penetrating seismic reflection profiles were interpreted and show that it is a half-graben that lies south of the Cobequid-Chedabucto Fault System (Glooscap Fault, King and MacLean, 1976) in Nova Scotia, at the boundary between the major Avalon and Meguma lithotectonic zones of the northern Appalachians. The Basin formed at the eastern margin of North America during the Triassic/Jurassic rifting of Pangaea. Continental derived red clastic rocks and Triassic and Early Jurassic basalt flows crop out along the Bay of Fundy and Minas Basin coast of Nova Scotia and are comprised of four formations: Wolfville, Blomidon, North Mountain Basalt and Scots Bay.

The most recent geological map of Nova Scotia, Map ME 2000-1 (Keppie, 2000) describes the North Mountain Basalt that borders the southern part of the Bay of Fundy as tholeiitic plateau basalt. Based on a U-Pb concordant zircon age of 202+- 1 Ma, the basalt is considered to be Jurassic in age. This therefore controls the age of the overlying Scots Bay Formation as Jurassic as well. The entire suite of sedimentary rocks extending from North Mountain across the Bay of Fundy is now accepted to be Jurassic in age in contrast to the earlier Triassic assumption (King and MacLean, 1976) and others. The recent geological map of Nova Scotia (Keppie, 2000) indicates they the rocks of the Scots Bay Formation are lacustrine limestone, siltstone, chart, fluvial sandstone and contained vertebrate fossils. The dominant structure of the Acadian Basin is a syncline defined by the hook of Cape Split to the northeast that plunges to the southwest along the entire Bay. The thickness of the Triassic sediments are up to 900 m as measured from seismic reflection profiles and regionally there may be as much as 2000 m of section present.

Minas Passage

The bedrock geology of most of the floor of Minas Passage is mapped as Triassic/Jurassic sedimentary bedrock (King and Webb, in press), (Figure 8). This compilation is regional in nature and presents the geology at a scale of 1:1,000,000 and does not show details at any given location. The passage is depicted as being underlain mostly by Triassic sedimentary rocks but a long linear volcanic deposit occurs parallel to the passage just south of the north shore and is mapped as the Triassic McKay Head Basalt. Along the northern coast the bedrock is complex and consists of the McCoy Brook Formation of fluvial, deltaic, lacustrine, playa and aeolian clastic rocks. Lacustrine limestone and basalt agglomerate are common.

1980 Surveys

As part of the studies for the first round of tidal power development in the Bay of Fundy, Huntec Ltd. prepared a report in 1966 on the marine geology and geophysics of Minas Channel, Minas Passage and Minas Basin for the Atlantic Development Board. It was intended as an overview engineering evaluation of Minas Passage. The systematic grid survey resulted in bathymetric, sediment, and bedrock maps that were prepared to assess the feasibility of constructing a dam across Minas Passage as it was considered the most probable location for a tidal dam. Bedrock structural and stratigraphic assessments were undertaken as part of this study and although of low resolution, some of this information provides a regional framework in which to place the present study and is summarized here.

The bedrock surface was found to be highly irregular and rough and interpreted to occur at the seabed in places and to have been modified by glacial erosion. Much of Minas Channel was found to have been swept clean of sediments attributed to strong tidal currents. Sediments up to 330 feet in thickness, however, occur in adjacent Minas Basin outside of the scoured region.

A map of the distribution of bedrock was prepared for the Minas Passage region (Huntec Ltd., 1966) (Figure 9). This showed that three different bedrock types occurred: Carboniferous and Triassic sedimentary rocks as well as Triassic basalt. Carboniferous rocks were interpreted to occupy the northern two thirds of Minas Passage and Triassic rocks occur in the southern third. Volcanic ridges extended to the west from both Cape Sharp and Cape Split. They interpreted that Minas Passage is part of the north limb of the Fundy Syncline with the centre of the syncline occurring in the curving ridge of North Mountain south of Cape Split.

The contact between the Triassic Blomidon Formation in the south and Carboniferous rocks in the north was interpreted to partially coincide with a regional fault in the deepest part of Minas Passage and was thought to be responsible for the origin of the deep channel. The contact was suggested to contain fractured and crushed rock that was prone to severe differential erosion by fluvial and glacial processes.

The sedimentary rocks were found to consist of gently to steeply dipping sandstones and shales that are weathered on the seabed exhibiting highly variable properties. They are described as being well–compacted and sound. The southern Blomidon formation was found to have better engineering properties for the foundation of a tidal barrage in the offshore then on adjacent land.

Based on the Huntec 1966 studies, bedrock mapping on the adjacent land, and the new results obtained on bedrock by the 2008 round of surveys, it appears that the stratified bedrock at the seabed of the proposed facility represents the Parrsboro Formation (Mossman and Grantham, 2000). It consists of a lower red facies and a thicker coarser overlying grey facies (Belt, 1962, 1965). The upper part is a predominantly lacustrine unit composed of grey and red mudrock, dark coloured shale, with intervals of red and grey sandstone. Vertebrate tracks have been found in the upper section along with rooted horizons, raindrop impressions, dessication cracks and dewatering structures. Tree stems and roots are common in some sections.

Faults

The Huntec Ltd. 1966 report identified several faults in Minas Passage that trend east–west. The North Mountain Basalt to the west of Black Rock is portrayed as being in fault contact with the surrounding Carboniferous rocks. A number of smaller northeast trending shear faults also occur in this area.

The main fault zone within the inner Bay of Fundy is part of a major system that occurs along the north flank of the Bay and connects with the Chedabucto-Cobequid system in Nova Scotia. These faults are all part of the Glooscap Fault System (King and MacLean, 1976) that continues further to the west in the Bay of Fundy and east across the Scotian Shelf. Within Minas Passage a large fault is clearly seen on the multibeam bathymetry (Figures 5,10). It occurs to the south of the volcanic ridge that projects to the west from Black Rock and extends from an area off Cape Sharp in the east, to an area to the northwest of Cape Split, for a distance of over 13 km. It is manifest on the multibeam bathymetry (Figure 5) as a linear depression that varies in width up to 50 m. Along some parts of the fault, both northern and southern flanks consist of prominent ridges. The depression associated with the fault is interpreted to arise from preferential erosion of weaker and fractured rocks. It is difficult to determine the horizontal offset along this fault as the strike of the exposed bedrock on both sides is the same. Wade et al., (1996) have mapped a prominent fault on land to the east that may be the same one as identified from the multibeam bathymetry. It is the Portapique Fault that begins in the west near Cape D'Or and extends to the east past Truro, sub parallel to the Cobequid Fault further to the north. The Portapique Fault on land sets the Carboniferous rocks against the Triassic deposits which surround Cobequid Bay. In the offshore the strata exposed on both sides of the fault have the same strike so it is difficult to determine the amount of strike slip offset. The character of the bedrock exposure on either side of the fault is quite similar suggesting that the rocks may be of the same age. This is in agreement with the bedrock geology interpretation from the 1966 Huntec Ltd. survey but not in agreement with the interpretation by King and MacLean, 1976 that suggested that all the rocks in

Minas Passage are Triassic (Jurassic).The Huntec Ltd. 1966 survey suggests that the contact between the Carboniferous rocks and Triassic rocks is interpreted to be further to the south in the deepest part of Minas Passage in what has been termed the "Minas Passage Scour Trench". Therefore the age of the bedrock in the central and southern area of Minas Passage is not yet resolved.

Several sets of prominent joints occur within the exposed bedrock that trend almost north-south and southwest – northeast. These features occur as linear deeper regions and may represent suitable locations for routing of project cables as protection in regions of lower hydrodynamic conditions, low relief and flat gravel surfaces.

Surficial Sediments

With the exception of the nearshore regions of Minas Passage, much of the seabed consists of exposed bedrock. In the northwest region thick surficial sediments overlie the bedrock and have large linear furrows, ridges and isolated scour depressions on their surface (Figure 5). An area of bedforms in gravel termed gravel waves occurs in the deepest part of Minas Passage. Other areas of gravel waves occur in the eastern part of Minas Channel and to the northwest and southeast of Black Rock (Figure 10). These gravel waves overlie a thicker deposit of surficial sediments that are thought to represent coarse deposits in the lee of the island associated with strong currents. They may also represent a remnant of a deposit of till or glaciomarine sediment that once covered much of the seabed of Minas Passage but has survived erosion in this area.

On the north side of Minas Passage is a narrow flat shelf that extends from the shoreline dipping gently seaward to a depth of approximately 10 m. Gravels and sands occur on this shelf and are formed into a variety of bedforms with an orientation normal to the shoreline. The shelf dips steeply from its seaward edge to 40 m water depth where bedrock begins to crop out on the seabed and continues to the south. This slope is covered in gravel consisting of granules, pebbles, cobbles and boulders. Samples are difficult to collect across this surface because of a dominance of large boulders at the seabed. Seismic reflection profiles across this area (Figure 11) show that the thickest material below the slope is largely stratified glaciomarine sediment and till is thin or absent. Overlying the glaciomarine sediment is a more recent deposit of sand and gravel that continues to the shoreline. The western part of the inner shelf and adjacent slope as well as the region to the north of Black Rock has features interpreted as bedforms and slumped sediments. Circular depressions are common and suggest current scouring. The inner shelf outer edge appears to be incised with circular features that are the headwall scarps of slumped sediments. Cable routes from the offshore devices have been chosen to avoid these features.

The volcanic flat ridge that extends to the west from Black Rock is mostly exposed bedrock but pebbles, cobbles and boulders are common. No fine-grained clays, silts and sands appear to be present. In the region of exposed bedrock sedimentary ridges to the north and south of the volcanic platform, sediments occur in the flat areas between the exposed ridges. They have a gravel cover of granules, pebbles, cobbles and boulders.

Several seismic reflection systems were used to determine the nature and thickness of the surficial sediments between the exposed bedrock ridges. Little acoustic penetration was achieved and side echoes were common acoustic artifacts on the profiles that result from the hardness and steepness of the nearby bedrock ridges. A covering of boulders also scattered the acoustic energy from the systems degrading penetration and resolution of subsurface events. Regional interpretations of the seismic reflection data from the Minas Channel region and indeed the inner Bay of Fundy show that glaciomarine stratified sediments are widespread and very thick, in contrast to thin or absent glacial till. This suggests that Minas Passage once contained thick glaciomarine sediments in early post glacial time and today it is a large scoured depression formed by beach erosion during times of lowered sea level and strong currents. The surficial material that occurs between the bedrock ridges and underlies the gravel is more likely to represent glaciomarine muddy sediments than till. Wider areas of seabed between bedrock ridges would be expected to contain thicker glaciomarine sediments.

Crown Lease Area and Device Site Bedrock and Surficial Geology

The proposed Crown Lease Area and three device sites occur to the west of Black Rock and south east of Ram Head, Minas Passage. They all occur in the northern part of Minas Passage. Device areas B and C occur over stratified outcropping bedrock and site A lies over North Mountain basalt. The new survey information on the nature of the bedrock geology comes from a study and interpretation of multibeam bathymetry, sidescan sonograms and mosaics, a few samples, and bottom photography and video. Samples of the bedrock are difficult to collect as the bedrock is very hard and covered with boulders in many places. The following is a more detailed description of the bedrock and overlying surficial sediments at each of the proposed device locations each of which covers an area defined by a 200 m diameter circle (Figure 12).

Site A

Site A occurs over a volcanic shallow flat ridge that extends to the west from the Black Rock region. It is located approximately 1400 m from the centre of Black Rock on the northern part of the volcanic ridge. The northern part of A also covers the northern flank of the volcanic platform and extends to water depths of 45 m over a steep bedrock surface. The water depths at site A average 30 m and the surface is largely exposed bedrock with gravel (boulders, cobbles and a few pebbles). Many boulders larger than 1 m in diameter can be seen on the high resolution multibeam bathymetric imagery. The bedrock surface is rounded and hummocky with a roughness of less than 1 m and differs from sites B and C that display sharp eroded edges of upturned bedrock strata. The multibeam bathymetry and the sidescan sonograms show a slight linearity to the surface that may represent variations in the volcanic flows, glacial erosional grooves, or patterns of subaerial erosion that were developed when the area was exposed at lower sea levels in post glacial time. The slope map of site A shows that it is a very flat surface and the backscatter imagery indicates that it is an area of very uniform high reflectance – hard.

Bottom photographs from nearby area A on the volcanic platform show that the bedrock surface is gently rounded and hummocky much like exposures of North Mountain Basalt in the shoreface of the region. Crevasses are filled with pebbles, cobbles and some granules and biogenic growth is quite extensive.

Site B

Site B occurs 2 km to the west of Black Rock north of the volcanic ridge over a region of largely exposed sedimentary bedrock as the furthermost offshore test site. Water depths over this region are the deepest of the three device locations and average 45 m. This area has a slightly greater exposure of bedrock than site C. Nearby bottom photographs show the bedrock to consist of Carboniferous Parrsboro Formation grey and red beds. The bedrock beds are upturned strata with a rough and undulating surface and the strike of the beds is northwest, close to the direction of the prevailing current. This is considered to be coincident rather than controlled. The beds appear to dip to the northeast based on the geometry of exposed bedrock ridges on the seabed. This is contrary to the dip of the beds presented in the early Huntec Ltd. 1966 study. The relief on the bedrock surface is less than in other areas of the region and was one of the criteria for site selection. Both the northern and southern regions of area B have zones of flat seabed. These regions are gravel covered with boulders. The flatness arises from the presence of surficial sediments that fill the deeper regions between bedrock ridges. The composition of the material underlying the gravel is not well known because of sampling problems associated with bouldery seabeds and a lack of penetration and resolution of the high-resolution seismic reflection systems. Based on a regional distribution of sediments throughout Minas Passage interpreted from seismic reflection profiles and a few samples collected by bottom dredge, it appears that the subsurface sediments are either till or glaciomarine muds. The regional relative distribution of till and glaciomarine sediment indicates that glaciomarine sediment is more prevalent. Although in both cases the surface of these materials is heavily armoured with gravel including boulders. Dredge samples collected in the region penetrated the gravel lag in a few places and sampled stiff, dry, and red muddy sediment that is similar to glaciomarine sediments cored in the inner Bay of Fundy.

Site C

Site C lies 1 km to the west of Black Rock just north of the volcanic ridge with the southern boundary of the area encroaching on the northern flank of the volcanic ridge. Average depths across this area are 40 m and it consists of exposed bedrock ridges and several flatter regions of gravel with boulders and is similar to site B. The northern part of the area has the largest region of flat seabed. Bottom photographs from Area C show both exposed bedrock at the seabed as well as gravel regions with granules, pebbles, cobbles and boulders. Broken shell debris occurs in some areas. The bedrock is similar to that of Site B and the overlying surficial sediments that lie beneath the flat areas of seabed are interpreted as erosional remnants of both till and glaciomarine sediment. Gravel occurs over the flat regions of the seabed and boulders are common within the gravel and on the bedrock.

Cable Corridor Geology

The selection of the cable corridor is largely controlled by seabed characteristics and engineering design criteria. One of the criteria for route selection requires that the cable must be able to be removed if required. This results in a route that avoids regions of moving seabed gravel bedforms that could bury it and make recovery difficult. It is important to lay the cable on seabeds that would not abrade the cable and as a result, the crossing of exposed bedrock ridges is not a preferred route. The chosen cable route also takes advantage of bedrock structure to minimize hazards. A main route through the sedimentary bedrock region has been chosen in a wide gravel covered flat region of seabed that represents an eroded joint in the bedrock. The individual cables to each of the devices have been chosen to run parallel to bedrock strike in the slightly deeper and protected depressions between bedrock ridges that are flat and gravel covered. Steep slopes were avoided and routes were chosen to traverse the terrain with the lowest slopes to place the cable on the seabed and avoid suspensions.

At the northern end of the sedimentary bedrock region, the cable route crosses the slope and adjacent inner shelf edge in a region with no bedforms, slumps or headwall scarps and crosses the shelf edge at right angles. The cable route then turns to run southeast on the shallow inner shelf approximately parallel to the shoreline. Areas of bedforms, and rock outcrop are avoided along this part of the route and the cable route takes a final turn to the shoreline in an area north of Black Rock.

Figures

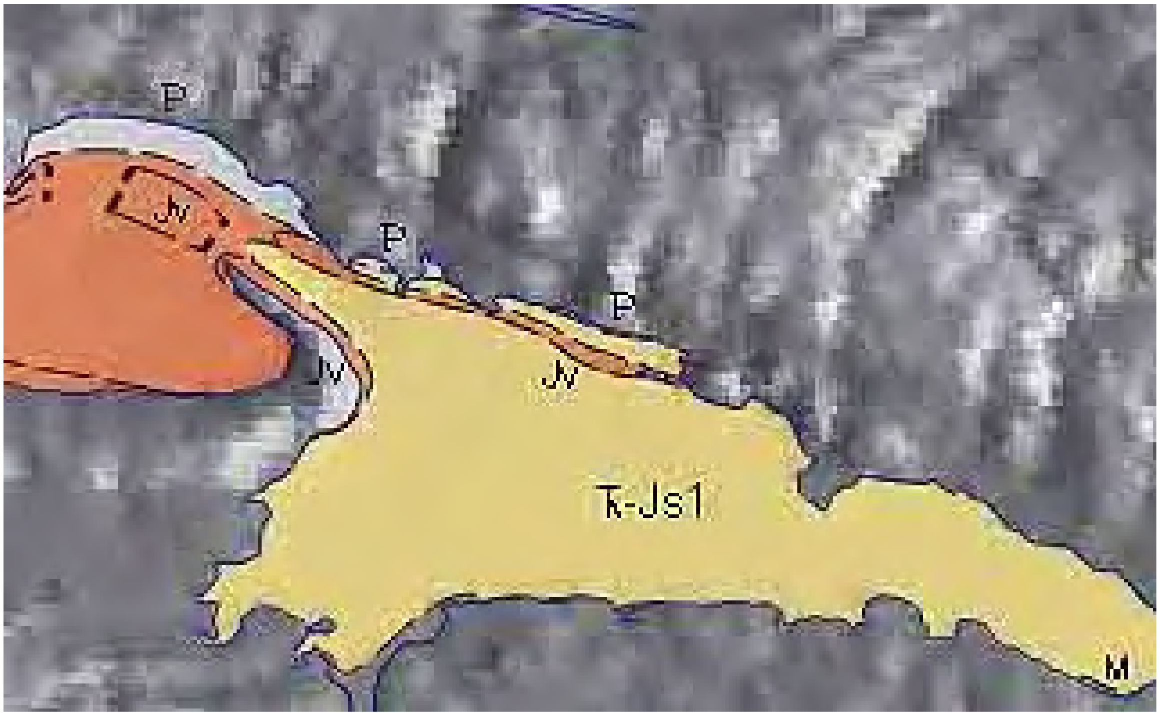

Figure 8. A map of the inner Bay of Fundy portion of a new digital bedrock compilation by King and Webb, (in press). Minas Passage is mapped as being underlain by Triassic to Jurassic sedimentary bedrock. Some areas of volcanic Jurassic North Mountain basalt have been mapped in this regional compilation. 8B is the index for the bedrock of this region.

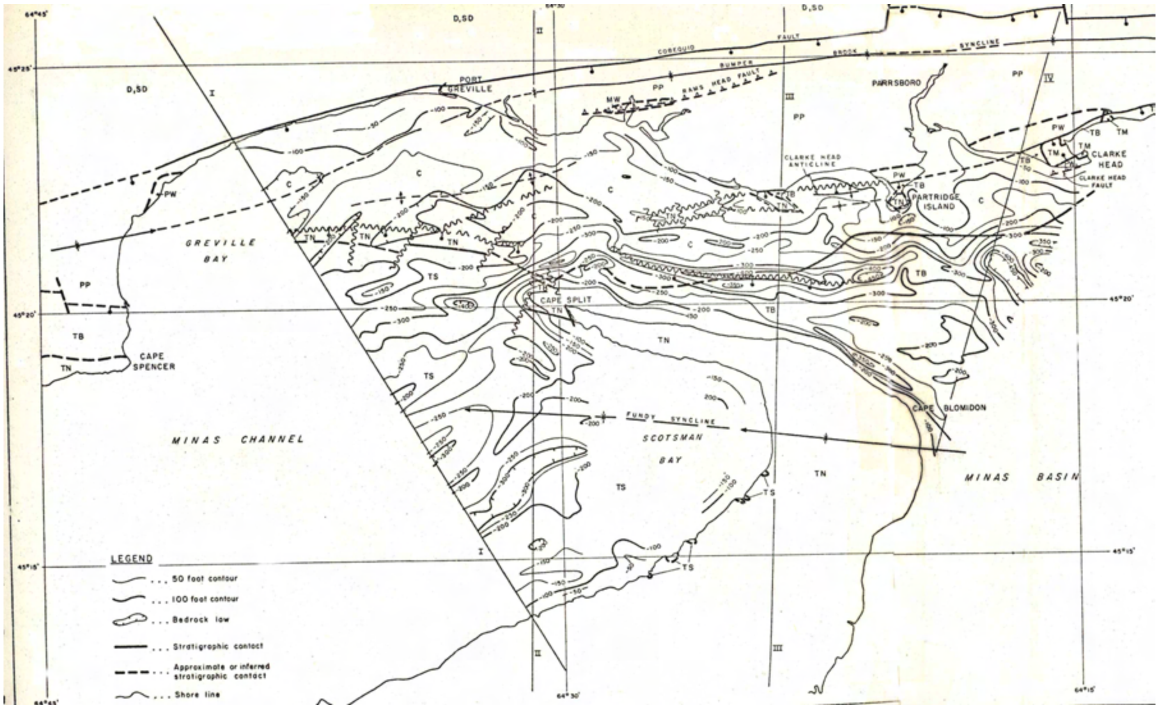

Figure 9. Huntec Ltd., (1966) interpreted bedrock map of the Minas Passage region. The site of the tidal power test project overlies Carboniferous sediments and the contact between the Triassic Blomidon Formation and the Carboniferous sedimentary bedrock is presented as occurring in the southern part of Minas Passage in the area of the "Minas Scour Trench". Contours are drawn on the bedrock surface as interpreted from seismic reflection data.

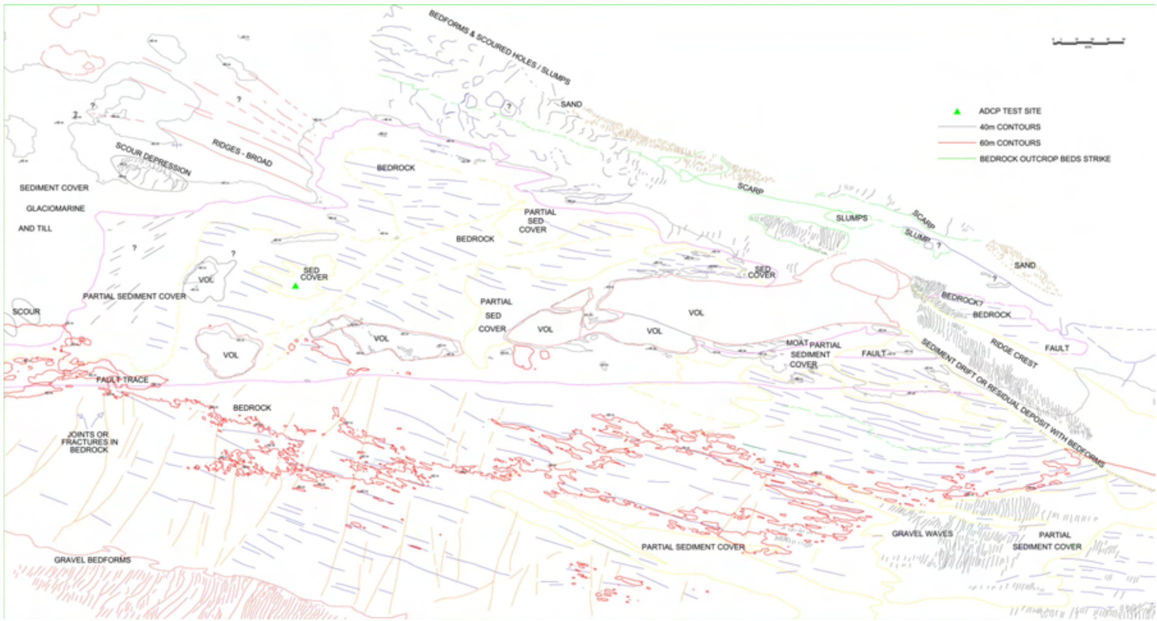

Figure 10. An interpretation of multibeam bathymetry for the Minas Passage region showing both bedrock and surfical geological characteristics. The major regional fault, likely the Portapique Fault, lies just to the south of the volcanic platform that extends to the west from Black Rock. The fault runs east – west.

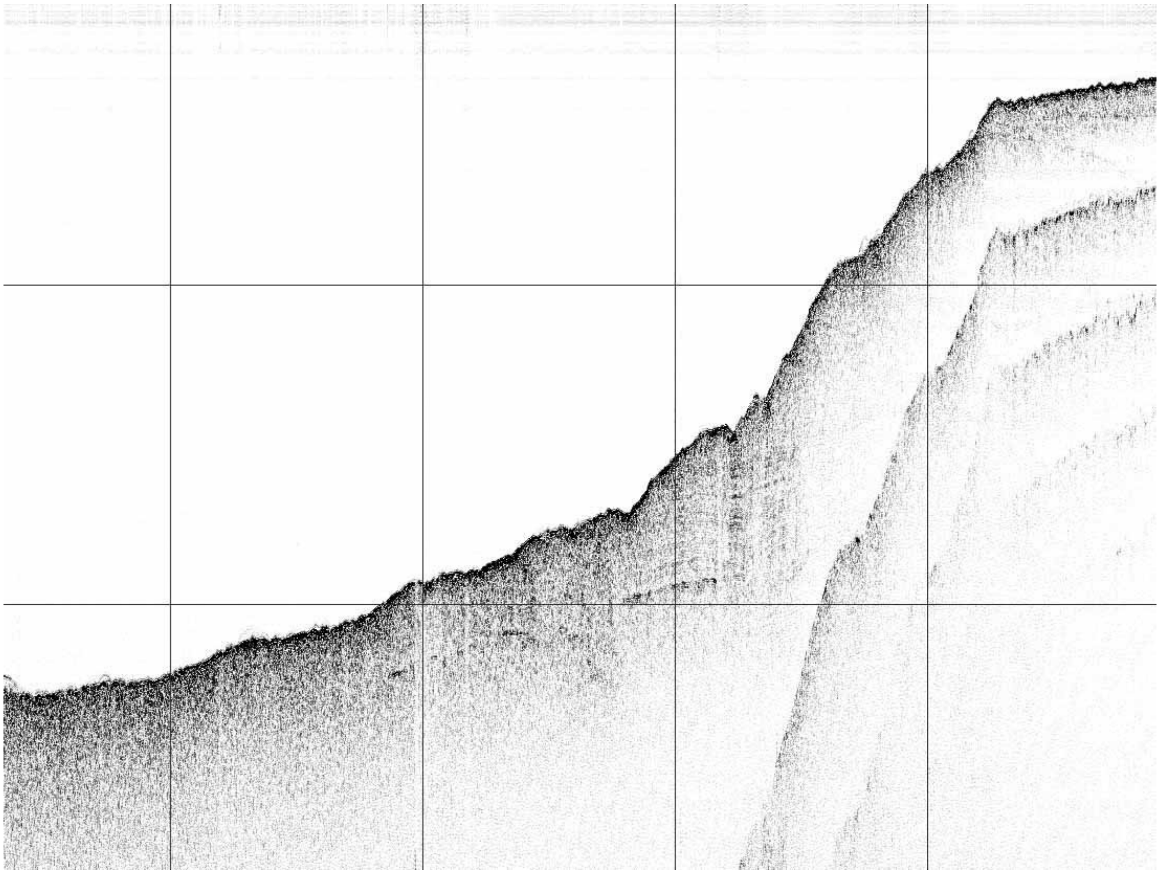

Figure 11. A Seistec Line in Cone seismic reflection profile from the inner shelf of the north shore of Minas Passage extending down the slope to the deeper water in the south. The stratified material beneath the seabed is interpreted as glaciomarine sediment deposited at the time of glacier recession from the region. It has been eroded during times of lower sea level and marine transgression as the sea level rose. Strong currents also played a major role in removing the glaciomarine sediments from Minas Passage. Much of the Passage was likely filled with these sediments at the end of the last glaciation, the Wisconsinan.

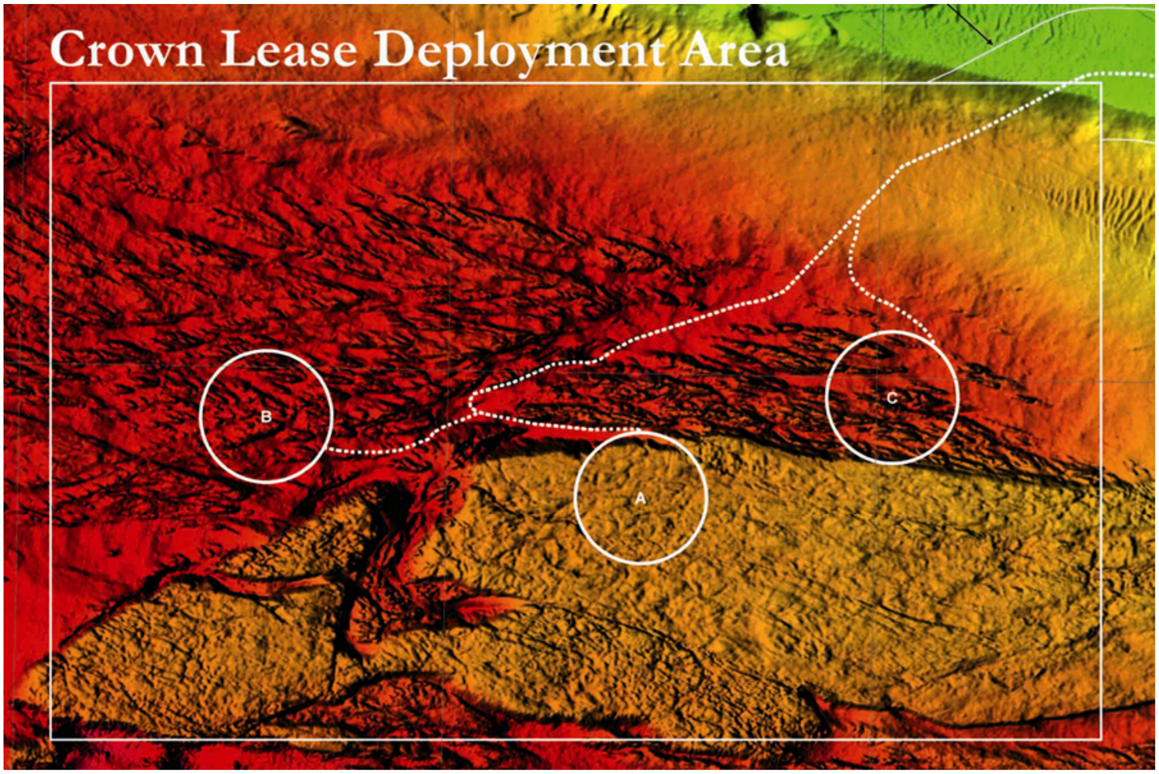

Figure 12. A multibeam bathymetric map of the northern part of Minas Passage showing the Crown Lease area as a rectangle and the proposed device sites as circles. The dashed line represents a potential cable corridor to shore.

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Sediment Transport and Suspended Sediments

Introduction

Sediments in Minas Passage can be transported in the water column as suspended sediments; ice rafted at the sea surface and released through melting to the water column and seabed, and transported directly on the seabed as bedload. Sediment transport, seabed stability, sediment deposition and erosion, and suspended sediments are considered important components of the in-stream tidal power demonstration project that must be understood in order to determine the effects of the infrastructure on the environment and the effects of the environment on the infrastructure. Sources of fine-grained material (silt and clay) are provided to the Bay of Fundy from both natural and anthropogenic sources that include ocean dumping activities, rivers, seabed bottom fishing activities, natural erosion of the seabed, shorelines, the adjacent land, and by ice rafting. In order to understand issues associated with sediment transport in Minas Passage, particularly at the site of the proposed in stream tidal power demonstration project, an understanding of the seabed, its characteristics and the processes that are active there are essential components.

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; Amos, 1984)). Increased sedimentation seaward of the Windsor Causeway, near the gypsum dock in Hantsport, and associated with the Petitcodiac River has further focused research on sediments in the inner Bay of Fundy.

In the outer Bay, a large project has been underway for over many years to investigate the fate of sandy and muddy dredge spoils disposed to the seabed off Black Point derived from dredging activity in Saint John Harbour (Parrott et al., 2006). This study used a modern multibeam bathymetric and modeling 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 provided 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 the early study in the Bay of Fundy during the 1990s. The first collected information off Margaretsville, in Minas Channel, and in Scots Bay of the inner Bay of Fundy by the University of New Brunswick and the Canadian Hydrographic Service 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 multibeam 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 large scoured region off Cape Enrage is similar morphologically to Minas Passage. 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 surveys, new insights have been gained into present conditions of erosion, sediment transport and deposition at the seabed and complex relationships associated with large sand waves that were not previously known.

The Petitcodiac River, New Brunswick, is the largest river discharging into the upper Bay of Fundy. The hydrological and geological characteristics of the river have been altered dramatically by the construction of a causeway between the City of Moncton and the Town of Riverview in 1968. This has changed the hydrodynamics and accelerated the deposition of fine-grained sediment in the upper reaches of the estuary. In 2002 and 2003, the Science Branch of Fisheries and Oceans Canada, Maritimes Region, conducted field surveys on the Petitcodiac River Estuary (Curran et al., 2004). 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 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 (Byrne et al., 2002). The experiment was designed 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 (Daborn and Dadswell, 1988). 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.

An important sediment transport study using a 2-dimensional tidally-forced model was undertaken by Greenberg and Amos, 1983, for Minas Passage and Minas Basin that combined a numerical model and a sediment budget analysis. It involved an assessment of the tides and currents, suspended sediments, bottom sediments, sediment sources and the postglacial evolution of the system. The study was mainly concerned with cohesive clay and silt sized sediments and was intended to assess sedimentation associated with the construction of a tidal barrage in inner Minas Basin. They suggest that the only significant source of suspended sediment was from the open boundary to Minas Basin (through Minas Channel and Minas Passage). This study was undertaken before the development of multibeam sonars that can provide digital terrain models of seabed relief and can be assessed for an understanding of processes of erosion and deposition. From the study of the multibeam bathymetry it is clear that fine-grained sub-surface sediments are eroding from the seabed of the inner Bay of Fundy, from Minas Channel and the entrance to Minas Basin. Minas Passage is not a major contributor of fine-grained sediment as it has largely been removed from this mature scoured region. It is merely a conduit for the transfer of suspended sediment.

Sediment Transport

Minas Channel and Minas Passage

From a morphological perspective, most of the area of the Bay of Fundy is a gently sloping surface from west to east with several anomalous deep scoured regions. The largest of these occurs between Grand Manan Island and southwestern Nova Scotia at the entrance to the Bay of Fundy where it is narrow and restricted. Such deep depressions are attributed to fluvial followed by glacial erosional processes of over deepening. For the inner Bay of Fundy, deep regions occur in central Chignecto Bay, two off Cape D'Or in Minas Channel and in Minas Passage. These deep regions are characterized by rough topography, linearity, occurrence in narrow restricted bodies of water or near projecting headlands and strong currents. They possess many other morphological hallmarks of current scoured depressions. Some depressions are scoured completely through sediments to bedrock while others contain sediments and are only partially eroded. The common characteristic of these deep depressions is that they lie in narrow passages with strong currents. Adjacent regions at broad ends of these depressions are usually flat areas of thick sediments suggesting that material has been eroded from the deep scoured regions and transported and deposited in adjacent regions with lower velocity currents.

The scoured regions of the inner Bay of Fundy represent anomalous areas and cover only a small proportion of the seabed. The in-stream tidal power demonstration project is proposed to be located in Minas Passage which is one of these scoured depressions. The history of development of the scoured regions indicates that they have been initially formed by glacial erosion with subsequent sediment deposition. Fluctuating sea levels and modern high current processes have continued to scour the sediments. The following is a description of Minas Passage and the proposed development area that includes the geological history, materials at the seabed, and observations on sediment deposition and transport based on modern marine surveys.

Seabed of Minas Passage

The surficial sediments at the seabed of the Crown Lease area are all gravel – that is granules, pebbles, cobbles and boulders. This is interpreted from the MB backscatter that indicates no mud or sand at the seabed. The sidescan sonograms also show high reflectivity indicating that the seabed is very hard – gravel. The high-resolution multibeam bathymetry shows large boulders on the gravel and exposed bedrock surfaces. Boulder measurements indicate that some are up to 5 m in diameter and they often appear in clusters. Indeed, conditions that occur at the demonstration site are similar to those of much of Minas Passage.

Questions have been posed about the stability and nature of the device sites and the potential for local scour and effects on sediment transport and regional morphology associated with device installations. Sediment samples are a very important component of sediment modeling but they are very difficult to collect in Minas Passage. Subsurface sampling is even more difficult because of the widespread occurrence of protective lag gravel with rounded boulders. Large areas of the seabed of the demonstration site are exposed bedrock in the form of upturned jagged ridges or flat volcanic areas. Attempts were made at sampling the gravels and were only partially successful returning a few gravel clasts in most cases. For an understanding of sediment transport, sediment deposition and erosion, bottom photographs and video of the seabed provide critical evidence. Bottom photographs have been collected regionally in the area and over 600 have been analyzed for particle size, shape, sorting, distribution, stability and biological growth. This information has been integrated with the results from the interpretation of the sidescan sonograms and high resolution multibeam bathymetry.

No sand sized sediments or silts and clays were observed on the seabed of the Crown Lease area. Most of the photographs were taken during times of slack water or close to it, and sand sized material that may have been in suspension as well as silts, clays and organic matter would be expected to settle temporarily on the seabed. This was not observed on the photographic data suggesting that in the study area little sand is in suspension and that silt and clay are either in low concentration in the water column or don't settle to the seabed. Greenberg and Amos (1983) measured and modeled suspended sediments in the inner Bay of Fundy and showed that suspended sediments in Minas Passage were less than 5 mg/l and stable at 2 mg/l throughout the Bay of Fundy to the west. Additionally, pebbles, cobbles and small boulders have no attached biological growth (Figure 13). Larger boulders and adjacent bedrock have broad coverings of low growth that appears to start at about 20 cm above the seabed (Figure 14). This suggests that the smaller gravel sizes that have clean surfaces may be moving and rolling around as bedload and preventing growth in the zone immediate to the seabed. The movement is likely local and confined by the bedrock ridges and large boulders of the region. No boulders on the photographic imagery showed tilted sediment lines that would indicate recent movement and repositioning. The seabed therefore, appears as a mature hard scoured bottom of bedrock and gravel.

Most of the gravel clasts in the study area are round to subround in shape. A few clasts are angular and may have been transported by ice. A simple interpretation is that the rounding is due to present day active movement. However the larger rounded boulders that occur in the same area do not move. The rounding is interpreted to have occurred during times of lowered sea levels. Relative sea level in the region could have fallen as low as 40 m in early post glacial time as the land quickly rebounded from the removal of nearby glaciers. At times of lowered sea levels, large regions would have been above or near sea level and beach processes of high energy during regressions and transgressions would have produced the roundness of the boulders. Additionally the lowered sea level would have resulted in erosion of both tills and glaciomarine fine grained sediments that were previously deposited over bedrock. Thus the present seabed is largely a relict bottom with modern elements of granule, pebble and cobble bedload movement as well as sediment deposition by ice rafting. The lag gravel surfaces are termed “relict”, that is, they reflect deposition and formation under differing conditions (very high energy) in the past and have maintained these characteristics for thousands of years to the present. They are not in dynamic equilibrium with present energy conditions. For these reasons, samples of the gravel cannot be used in transport models that consider that the entire seabed is in equilibrium with present conditions and responding to those energy conditions.

Sediment Bedforms

Within Minas Passage there are five areas of bedforms in sand and gravel. On the shallow nearshore shelf west of Cape Sharp and on the shelf off North Mountain there are a series of small amplitude sand and mixed gravel bedforms oriented normal to the shoreline. To the northwest and southeast of Black rock are areas of gravel waves (Figure 15). Bottom photographs show that these sediments are mostly pebble to cobble in size and repetitive multibeam mapping shows that they alter their orientation and wavelength but remain in the same area. Another large area of gravel bedforms occurs in the deep Minas scoured trench close to the southern shore off Cape Split. This area of bedforms may be part of a pair located to the west and east of the projection of Cape Split into the Bay. These paired bedform features are termed banner banks, although in this case the one in the Minas scour trench is gravel while the one to the west of Cape Split is composed of coarse sand and fine gravel. The final area of gravel ripples occurs to the south and southwest of Black Rock in deep water overlying bedrock ridges. Repetitive multibeam bathymetric surveys over ten years show that these bedforms have slightly changed their distribution and orientation with time. There are a few bedforms in gravel within the Crown Lease proposed area in the northeast corner but none within the actual device site proposed locations. Thus an interpretation of the sediment bedload transport potential of the proposed area is that the seabed is very stable. Granules, pebbles and cobbles may move locally but are not thick and abundant enough to form bedforms or the flow conditions are not strong enough. The gravel is confined between bedrock ridges and amongst large boulders that are widespread. None of the boulders show evidence for movement or reorientation.

Sub Surface Sediments

What lies beneath the gravel and how thick the gravel and the underlying sediments are, remains an issue that is not clearly understood. Two of the best high-resolution seismic reflection systems available were used to penetrate the gravel layer and resolve the layering and structure to bedrock. This was only successful in a few areas and is the result of acoustic scattering from the presence of the hard rounded gravel clasts. The seismic data from adjacent areas, as well as from the slope area to the north clearly shows that stratified sediments interpreted as glaciomarine muds are the dominant glacial sediment of the region and not till (Figure 11). Till normally contains over 50% gravel and in strong currents is only slightly eroded and armoured by the cover of gravel, and further erosion is suppressed. The fact that Minas Passage is a large deep scoured depression means that till was not the dominant material that originally filled this depression as it is not easily eroded in strong currents. Also the fact that the gravel is relatively thin suggests that it was not derived from till where gravel makes up to 50 % of that material. Glaciomarine sediments are thick regionally and this suggests that beneath the gravel lag with boulders, remnants of the glaciomarine sediment could occur that were once much more extensive. The thickness of the material over bedrock could be greater closer to shore than further offshore. The wider the flat area between exposed bedrock ridges, the greater likelihood that the surficial material is of greater thickness. Some of the material beneath the gravel to the west was sampled with a robust dredge and the material consisted of a very stiff red marine sediment, likely glaciomarine mud (Figure 16). Typically this sediment consists of silt, clay, sand and a few gravel clasts. It was deposited as the glaciers receded from the region through transport by water of sub ice and englacial debris. Some of the gravel in Minas Passage could also have been transported to the area by recent ice rafting.

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. 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.

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. The northwest nearshore zone was described 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.

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 consisted of fine and 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 the Minas Basin system. The major contributor is the Avon, Salmon and Shubebacadie and other smaller rivers that dump into Minas Basin. They considered Minas Basin as almost a closed system which is filling up with fine-grained sediment.

Greenberg and Amos, 1983, studied the size, shape and composition of suspended particulate matter in Minas Basin through analysis of 48 samples. The majority of the material consisted of composite sedimentary particles. The modal diameter of the particles was 30 um. The length of time the critical sheer stress is less than the value for deposition in Minas Basin is approximately 1 h at high and low water slack periods. This suggests that suspended particles that move through Minas Passage should fall to the seabed for this period of time. In contrast to the study of Pelletier and McMullen (1972), they suggested that the rivers in Minas Basin were not the main source for suspended sediments and that the sediments came from the open ocean (the Bay of Fundy proper to the west).

Inner Bay of Fundy Geological History and Suspended Sediments

In the inner Bay of Fundy, sediments, morphology, features and seabed processes are much different than in the outer area. In the 1977 study of Fader et al., the inner seabed was mapped as sand and gravel (Sambro Sand) with fields of large sand bedforms. This sedimentary unit was considered to have 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 is glaciomarine Emerald Silt (Figure 17). This sedimentary formation is coarser than the Holocene 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 as is till. Cores of these stratified 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 including in Minas Channel. 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 either a low sea level stand associated marine transgression, or the onset of tidal dynamics, the inner Bay of Fundy seabed has been greatly modified and reflects more the dynamics of present conditions in contrast to the iceberg scoured relict tills in the outer Bay which have remained unchanged. Multibeam Bathymetry was collected off Margaretsville Nova Scotia in the inner Bay of Fundy west of Minas Channel over a field of large sandy bedforms. An interpretation of these bedforms and associated erosional moats has provided new insights into modern processes which are thought to contribute large amounts of glacial age mud to the water column (Fader, 1996). This represents a 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 over deepening.

Based on interpretation of the new multibeam bathymetry (2006 – 2008) collected by the Canadian Hydrographic Service and the Geological Survey of Canada (Atlantic), fine-grained sediment in suspension in Minas Passage is interpreted to be sourced from the inner part of the Bay of Fundy, from adjacent Minas Channel in the west, from the entrance to Minas Basin in the east and from near shore slope areas of the northern part of Minas Channel where slumped deposits occur. The multibeam bathymetry from Minas Channel and the entrance to Minas Passage shows that scouring of the seabed in glaciomarine sediments is a continuing process over very large areas and that the seabed has not been scoured down to the bedrock as has Minas Passage. Some sediment may also be eroded from the northwestern area of Minas Passage where thick sediments cover the bedrock surface and show evidence of elliptically-shaped scour features with internal bedforms. This suggests a selective erosion of silt and clay and the formation of bedforms in residual sand and gravel. Similar scoured depressions and large sand bedforms occur in Minas Channel to the west (Figure 18).

Sediment traps were placed on the ADCP systems to sample and determine the nature of sediments in suspension in Minas Passage. Samples from these traps contained fine-grained muds, minor sand and granules and a few pebbles. It is not clear if the material in the traps was collected by settling during slack water or inadvertently during difficult recovery efforts through system dragging. The dominance of marine growth on bedrock and boulders above a 20 cm exclusion zone suggests that the bedload zone is confined to the immediate seabed so that granules, pebbles and cobbles would not likely be transported above that level. Repetitive multibeam bathymetric comparisons show that the water depths have not changed over a two year interval except in small areas in a moat region along the north flank of the volcanic platform where granules exist. Such a lack of erosional and depositional change is also evidence for a stable seabed. Current measurements at the seabed have a maximum velocity of 5 knots that is not enough to transport boulders.

The potential for seabed scour associated with gravity platforms depends on the design that includes the area and shape of the platform feet and whether they are located on bedrock or gravelly seabeds. The thickness of the gravel at the seabed and the presence if any of subsurface till or glaciomarine muddy sediments is an important component of such an assessment. Based on the regional distribution of sediments above bedrock and between bedrock ridges it is interpreted that the subsurface material would be patchy in distribution and have a variable thickness.

Figures

Figure 13. A bottom photograph of the seabed in Minas Passage showing a typical bottom of gravel – granules, pebbles and cobbles. The clasts consist of a variety of lithologies ranging from metasedimentary to igneous rocks. Note a lack of growth on the clasts and an absence of a thin cover of sand or mud despite being collected at slack water.

Figure 14. A bottom photograph from Minas Passage showing a gravel seabed consisting of granules, pebbles, cobbles and boulders. The larger clasts are small boulders and have a sponge growth cover above a clean zone that is interpreted as the bedload transport zone approximately 20 cm in height. This suggests that the granules, pebbles and cobbles may move in response to currents.

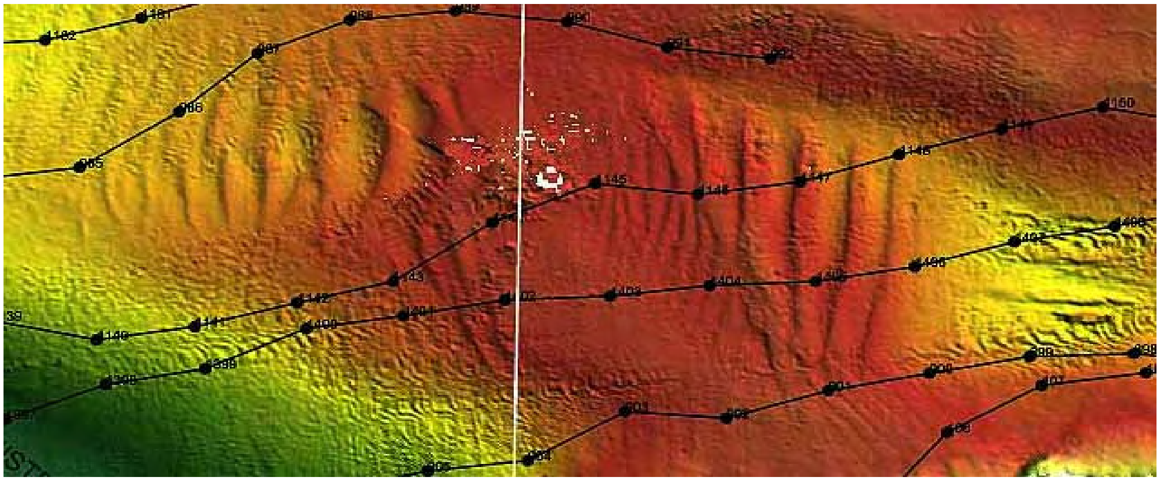

Figure 15. A multibeam bathymetric image of the seabed to the northwest of Black Rock, Minas Passage showing a zone of gravel ripples. Repetitive multibeam mapping across these features shows that they have altered their pattern of distribution but that the field has not changed location. Bottom photographs from this area show the clasts in the bedforms are pebbles and cobbles.

Figure 16. Photograph of a sample of stiff red mud collected by a rock dredge that penetrated the gravel lag surface in the northern area of Minas Passage. The material is similar to cored glaciomarine sediments in other areas of the inner Bay of Fundy that were deposited approximately 13 000 years ago during the retreat of the glaciers from the region. This material may underlie other areas of flat gravel lag in Minas Passage.

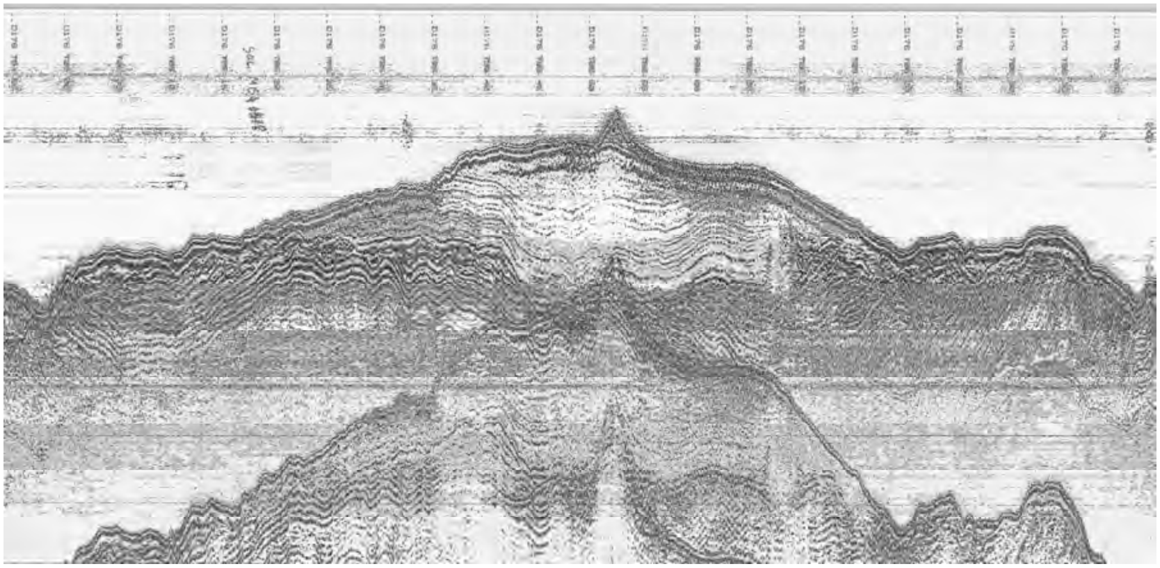

Figure 17. A seismic reflection profile from Minas Channel that shows thick glaciomarine sediments beneath gravel lag surfaces and sand bedforms. Thin till overlies the bedrock surface and the glaciomarine sediments are very thick and widespread in this area of the inner Bay of Fundy.

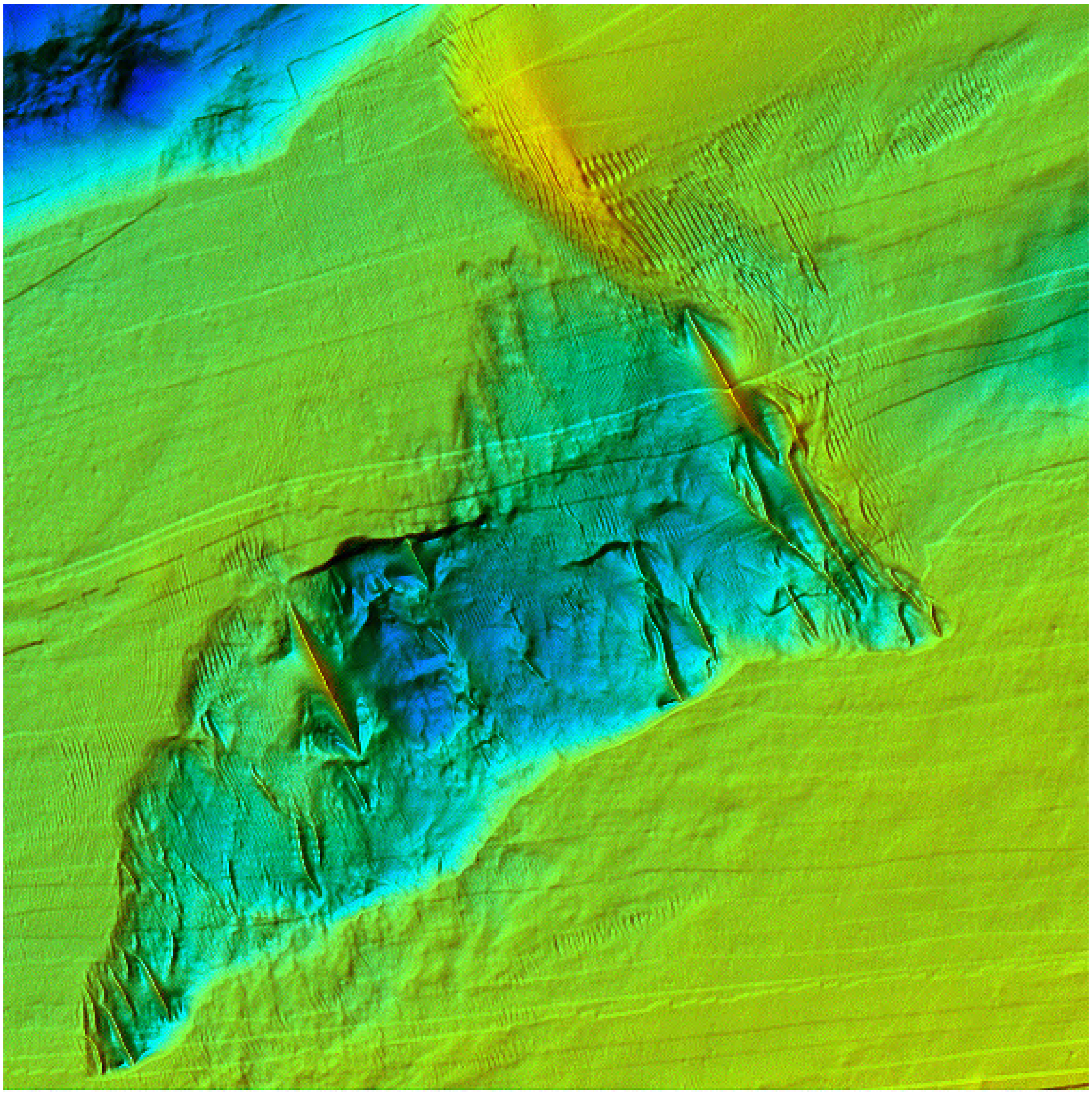

Figure 18. A multibeam bathymetric image of the seabed of Minas Channel. The region is flat gravel covered glaciomarine sediment. A large scoured region of seabed is shown that contains many singular symmetric sand waves within the depression. This is an area of active erosion but the currents are likely not strong enough to transport the sand sized material out of the depression. Large quantities of silt and clay are eroded from this feature and are likely transported as suspended sediments.

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Seismic Hazard, Faults and Earthquakes: Inner Bay of Fundy

Introduction

This report provides an assessment of the seismic hazard for the area of the proposed tidal power demonstration project in Minas Passage, Bay of Fundy, as well as the regional and local distribution of faults and earthquakes. Within Canada, the Bay of Fundy area occurs within the Northern Appalachian Seismic Zone (NAN). Figure 19 shows the historical seismicity in eastern Canada and Figure 20 is a more detailed map of the location of seismicity in NAN during varying time periods.

The Geological Survey of Canada (NRCan) has produced a new seismic hazard model (GSC Open File #5813, 2008) and a suite of new seismic hazard maps for Canada and this report draws on the excellent information provided by the GSC that is available on their web site.

http://earthquakescanada.nrcan.gc.ca/hazard/index_e.php

GSC Open File # 4459 presents the development and rationale for the model, the detailed model itself, and results for selected cities and areas of Canada. Open file #5813 makes available seismic hazard values for a grid of more than 200,000 points over Canada and surrounding areas. They were computed using the final methods and model used for the 2005 National Building Code of Canada. These values represent median ground motion on firm soils for a probability of exceedance of 2% in 50 years for the five ground motion parameters (5% damped spectral acceleration of 0.2, 0.5, 1 and 2 second periods plus peak ground acceleration.

The Northern Appalachians Seismic Zone **(NAN)** includes most of New Brunswick, western Nova Scotia and extends into New England. No earthquakes are shown to occur in the Minas Channel, Minas Passage and Minas Basin region of Nova Scotia on this compilation.

Background on earthquakes in eastern Canada

The continual movement of large segments of the earth's tectonic plates is the cause of more than 97% of the world's earthquakes. Eastern Canada is located in a stable continental region within the North American Plate and has a relatively low rate of earthquake activity. Nevertheless, large and damaging earthquakes have occurred there in the past and may occur in the future.

Rate of Activity

Approximately 450 earthquakes occur in eastern Canada each year. Of this number, perhaps four will exceed magnitude 4, thirty will exceed magnitude 3, and about twenty-five events will be reported just as felt. On average, a decade will include three events greater than magnitude 5. A magnitude 3 event is sufficiently strong to be felt in the immediate area, and a magnitude 5 is generally the threshold of damage. The seismograph network in Canada can detect all events exceeding magnitude 3 in eastern Canada and all events magnitude 2.5 or greater in densely populated areas.

Causes

The causes of earthquakes in eastern Canada are not well-understood. Unlike plate boundary regions where the rate and size of seismic activity is directly correlated with plate interaction, eastern Canada is part of the stable interior of the North American Plate. Seismic activity in areas like these tends to be related to the regional stress fields, with the earthquakes concentrated in regions of crustal weakness. Although earthquakes can and do occur throughout most of eastern Canada, years of instrumental recordings have identified certain clusters of earthquake activity. In these clusters, earthquakes occur at depths varying from surface to 30 km deep.

Seismic Hazard in Canada

Although earthquakes occur in all regions of Canada, certain areas have a higher probability of experiencing damaging ground motions. This probability is used in the National Building Code to help design and construct buildings that are as earthquake proof as possible. Figure 21 provides an idea of the likelihood of experiencing strong earthquake shaking at various locations. This map shows the relative seismic hazard across Canada for single family dwellings (1-2 story structures). The map indicates that the site of the proposed tidal power demonstration project in Minas Passage occurs in an area where the relative hazard is considered to be low.

The damage potential of an earthquake is determined by how the ground moves and how the buildings within the affected region are constructed. Expected ground motion can be calculated on the basis of probability, and the expected ground motions are referred to as seismic hazard.

The evaluation of regional seismic hazard for the purposes of the National Building Code of Canada (NBC) is the responsibility of the Geological Survey of Canada. The seismic hazard maps prepared by the Geological Survey are derived from statistical analysis of past earthquakes and from advancing knowledge of Canada's tectonic and geological structure. On the maps, seismic hazard is expressed as the most powerful ground motion that is expected to occur in an area for a given probability level. Contours delineate regions likely to experience similarly strong of ground motions. The simplified seismic hazard map (Figure 21) indicates the relative hazard across Canada.

The seismic hazard maps and earthquake load guidelines included in the National Building Code are used to design and construct buildings to be as earthquake proof as possible. The provisions of the building code are intended as a minimum standard. They are meant to prevent structural collapse during major earthquakes and thereby to protect human life. The provisions may not, however, prevent serious damage to individual structures.

Seismic Hazard Information in the National Building Code (NBC)

Building design for various earthquake loads is addressed in sections 4.1.8, 9.20.1.2, 9.23.10.2, 9.31.6.2, and 6.2.1.3 of the 2005 NBC. In addition, a table in Appendix C starting on page C-11 of Division B, volume 2 of the Code provides ground motion design values for many of the larger communities across Canada. While the National Building Code is chiefly intended for new buildings (Article 1.1.1.1 of Division A), appendix A (appendix note A-1.1.1.1) outlines the principles by which the code should also be applied to the use and modification of existing buildings.

The seismic hazard is described by spectral-acceleration values at periods of 0.2, 0.5, 1.0 and 2.0 seconds (Figures 22 -25). Spectral acceleration is a measure of ground motion that takes into account the sustained shaking energy at a particular period. It is a better measure of potential damage than the peak measures used by the previous 1995 code, and thus will improve earthquake-resistant design. Peak Ground Acceleration is still used for foundation design. All parameters are expressed as a fraction of gravity. The four spectral parameters allow the construction of uniform hazard spectra (UHS) for every place in Canada.

Ground motion probability values are given in terms of probable exceedence, that is the likelihood of a given horizontal acceleration or velocity being exceeded during a particular period. The probability used in the 2005 NBC is 0.000404 per annum, equivalent to a 2-per-cent probability of exceedence over 50 years. This means that over a 50-year period there is a 2-per-cent chance of an earthquake causing ground motion greater than the given expected value.

Calculation of Seismic Hazard

The seismic hazard at a given site is determined from numerous factors. Canada has been divided into earthquake source regions based on past earthquake activity and tectonic structure. The relation between earthquake magnitude and the average rate of occurrence for each region is weighed, along with variations in the attenuation of ground motion with distance. In calculating seismic hazard, scientists consider all earthquake source regions within a relevant distance of the proposed site. The four spectral acceleration seismic hazard maps show levels of ground shaking at periods of 0.2, 0.5, 1.0 and 2.0 seconds (equivalent to frequencies of 5, 2, 1, and 0.5 Hertz). This is important because different buildings are susceptible to different frequencies of earth motion, and damage is frequently associated with a resonance between earthquake ground motion and the building's own natural frequency. A high-rise of ten stories or more may sway with a natural period of 1 or 2 seconds, whereas in response to the same earthquake a brick bungalow across the street may vibrate at nearly 10 Hertz. The UHS is a description of the seismic hazard at a site in terms of building height.

In building construction and design, not only the size of a probable earthquake should be considered, but also the nature of the ground motion most likely to occur at the site. Seismic hazard calculations provide part of this information. As our understanding of earthquakes and of their effects on engineered structures continues to develop, the seismic provisions of the National Building Code are revised to enhance public safety and minimize earthquake losses.

Earthquakes in New Brunswick

A summary of the historical earthquake activity in the province of New Brunswick is contained in a report by Burke, (2005). Most of New Brunswick lies within the Northern Appalachian Zone (NAN), as shown on the map of earthquakes in Eastern Canada and has experienced several earthquakes in the magnitude 5 to 6 range. The exception is the northwestern part of the province with a few smaller magnitude earthquakes, which lies within the Eastern Background Zone. New Brunswick has also felt the effects of larger events from the Charlevoix-Kamouraska Zone, Lower St. Lawrence Zone and the Laurentian Slope Zone.

In New Brunswick, epicentres cluster in three regions (Burke, 1984); Passamaquoddy Bay region, Central Highlands (Miramichi) region, and the Moncton region. Earthquakes have been more frequent in these regions and sometimes of a size to be potentially damaging (larger than magnitude 5). Figure 29 shows the distribution of earthquakes from 2004 to the present and two small ones are located to the west and east of the proposed tidal power demonstration area.

Faulting in the Bay of Fundy Region

The most widespread and significant fault or fault zone in the Bay of Fundy region is the Chedabucto-Cobequid fault system. It is part of a much larger transform fault system that extends from the Grand Manan area of the outer Bay of Fundy, north of Minas Basin, across Nova Scotia, through Chedabucto Bay to the Laurentian Channel. The name “Glooscap Fault System” has been proposed for this system that also includes the marine sector (King and MacLean, 1976). They further proposed that it might join with the Newfoundland fracture zone in deep water to the east and involve oceanic crust. The fault system is essentially Triassic/Jurassic and earlier in age but there is evidence for additional faulting in Cretaceous time and perhaps recent activity on the eastern Scotian Shelf and in the adjacent Laurentian Channel.

Map 812H (King and Maclean, 1976) shows the distribution of faults of the Glooscap Fault System in the Bay of Fundy. It consists of a linear continuous – discontinuous fault that extends from Ile Haut in the east, westerly to a few kilometers off the south coast of New Brunswick at Cape Spencer where it changes direction and continues southwesterly to Grand Manan Island in the outer Bay of Fundy. There it joins a series of other faults bordering pre-Pennsylvanian acoustic basement. North of this western area of the fault, the Triassic sediments are structurally disturbed in a broad zone that continues to the Passamaquoddy Bay region in the north.

As reported in King and MacLean 1976, in the disturbed zone the aeromagnetic data shows considerable variation in contrast to the typically smooth signature of the Triassic/Jurassic rocks through the remainder of the basin. Fader (1989) conducted a high-resolution seismic reflection survey over the northern part of the disturbed zone to determine if any of the faults had affected the Quaternary overlying sediments in order to assess recent activity. The faulted Triassic/Jurassic sediment is overlain by thick glaciomarine stratified sediments that would record any activity on the faults below. The survey showed that the overlying sediments were not disturbed in any way indicating no activity of the faults over the past 15 – 18 000 years. This is contrast to the eastern Scotian Shelf were north of Banquereau, both glaciomarine Emerald Silt and LaHave Clay Holocene sediments are faulted and contorted along the offshore extension of the Glooscap Fault System.

Seismic activity along the Chedabucto-Cobequid fault near the proposed development site consists of two small earthquakes epicentres. One occurred off Cape Chignecto in the Bay of Fundy near the entrance to Chignecto Bay and the other occurred 17 km south east of Springhill. Appendix 1 shows a map of the earthquakes in the region over the past five years as well as a listing of the dates, times, locations, depths, magnitudes and regions from the GSC earthquake data base.

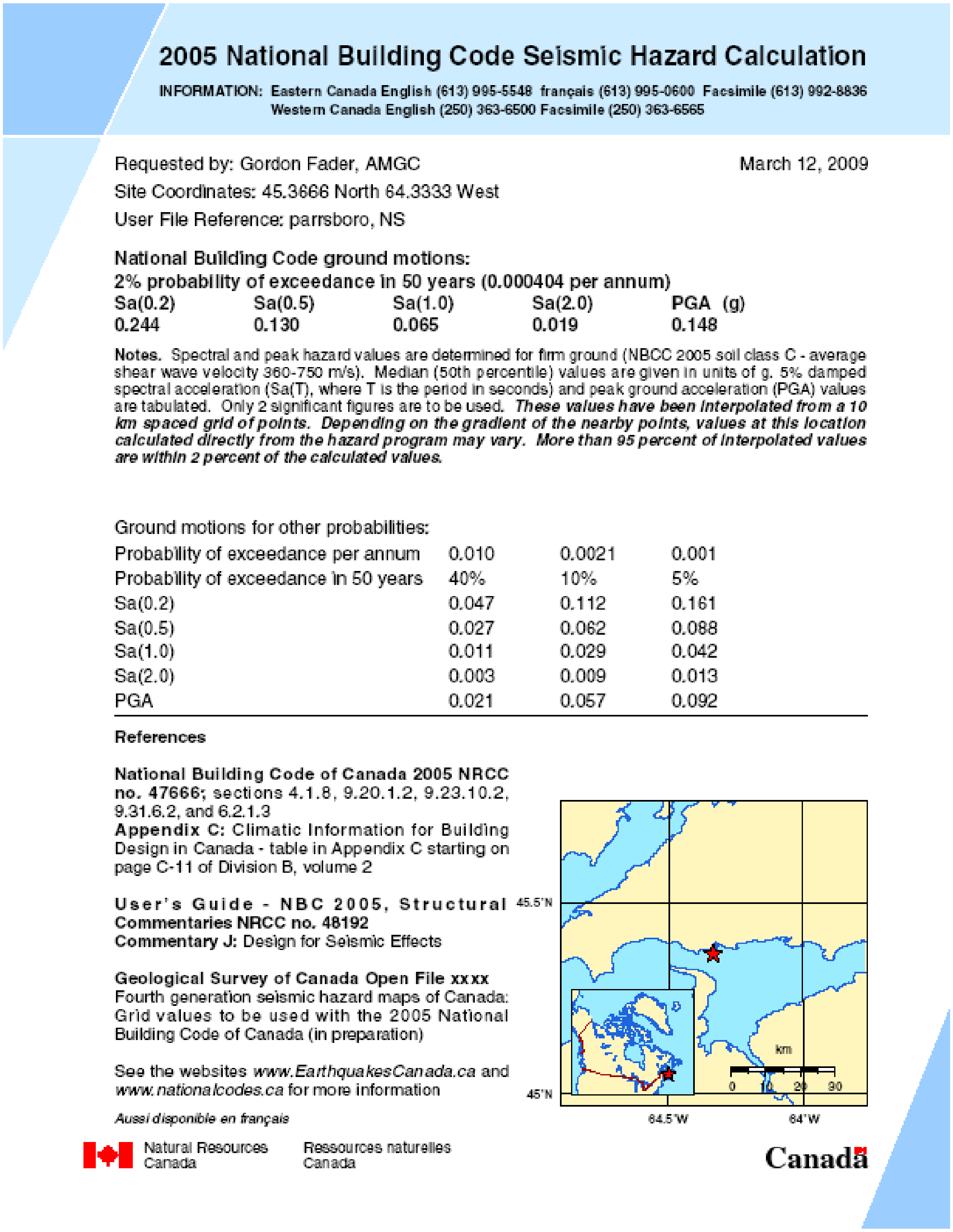
Portapique Fault

Within Minas Passage the most evident fault is the Portapique Fault. It lies to the south of the volcanic platform that projects to the west from Black Rock and extends from an area off Cape Sharp in the east, to an area to the northwest of Cape Split for a distance of over 13 km (Figures 5,10). It is manifest on the multibeam bathymetry as a linear depression that varies in width up to 50 m. Along some parts of the fault, both northern and southern flanks consist of prominent ridges. The depression associated with the fault is interpreted to arise from preferential erosion of weaker and fractured rocks. It is difficult to determine the horizontal offset along this fault as the strike of the exposed bedrock on both sides is the same. Wade et al., (1996) have mapped a prominent fault on land to the east that may be the same as the one identified from the multibeam bathymetry. It is the Portapique Fault that begins in the west near Cape D'Or and extends to the east past Truro, sub parallel to the Cobequid Fault but further to the north. The Portapique Fault on land sets the Carboniferous rocks against the Triassic deposits which surround Cobequid Bay. In the offshore the strata exposed on both sides of the fault on the multibeam bathymetry have the same strike so it is difficult to determine the amount of strike slip offset. The character of the bedrock exposure on either side of the fault is quite similar suggesting that the rocks may be of the same age. This is in agreement with the bedrock geology interpretation from the 1966 Huntec Ltd. survey but not in agreement with the interpretation by King and MacLean, 1976 that suggested that most of the rocks in Minas Passage are Triassic (Jurassic).The Huntec Ltd. 1966 survey suggested that the contact between the Carboniferous rocks and Triassic rocks is interpreted to be further to the south in the deepest part of Minas Passage in what has been termed the "Minas Passage Scour Trench". Although the Portapique Fault is a prominent fault on the multibeam bathymetry, there is no evidence for seismic activity on this fault.

Deformed proglacial deltaic sediments have been found at Economy Point – Lower Five Islands, Nova Scotia (Broster and MacDougall, 1996). Fluid escape structures were attributed to the expulsion of groundwater during post glacial seismic shaking of saturated sediments. Dating of charcoal associated with the fluid escape structures suggests significant seismic shaking around 1870+- 70 years. The deformation may have resulted from the 1855 M5+ earthquake that occurred in New Brunswick, 100 km to the northwest near Moncton.

Minas Passage Proposed Tidal Power Site Assessment

An assessment of the proposed tidal power demonstration site has been evaluated against the 2005 National Building Code of Canada. Appendix 1 below shows the spectral and peak hazard values for firm ground. The values have been interpolated from a 10 km spaced grid of points. More than 95% of the interpolated values are within 2% of the calculated values.



2005 National Building Code Seismic Hazard Calculation

INFORMATION: Eastern Canada English (613) 995-5548 français (613) 995-0600 Facsimile (613) 992-8836
Western Canada English (250) 363-6500 Facsimile (250) 363-6565

Requested by: Gordon Fader, AMGC
March 12, 2009
Site Coordinates: 45.3666 North 64.3333 West
User File Reference: parrsboro, NS

National Building Code ground motions:
2% probability of exceedance in 50 years (0.000404 per annum)

Sa(0.2)	Sa(0.5)	Sa(1.0)	Sa(2.0)	PGA (g)
0.244	0.130	0.065	0.019	0.148

Notes. Spectral and peak hazard values are determined for firm ground (NBCC 2005 soil class C - average shear wave velocity 360-750 m/s). Median (50th percentile) values are given in units of g. 5% damped spectral acceleration (Sa(T), where T is the period in seconds) and peak ground acceleration (PGA) values are tabulated. Only 2 significant figures are to be used. ***These values have been interpolated from a 10 km spaced grid of points. Depending on the gradient of the nearby points, values at this location calculated directly from the hazard program may vary. More than 95 percent of interpolated values are within 2 percent of the calculated values.***

Ground motions for other probabilities:

Probability of exceedance per annum	0.010	0.0021	0.001
Probability of exceedance in 50 years	40%	10%	5%
Sa(0.2)	0.047	0.112	0.161
Sa(0.5)	0.027	0.062	0.088
Sa(1.0)	0.011	0.029	0.042
Sa(2.0)	0.003	0.009	0.013
PGA	0.021	0.057	0.092

References

National Building Code of Canada 2005 NRCC no. 47666; sections 4.1.8, 9.20.1.2, 9.23.10.2, 9.31.6.2, and 6.2.1.3
Appendix C: Climatic Information for Building Design in Canada - table in Appendix C starting on page C-11 of Division B, volume 2

User's Guide - NBC 2005, Structural Commentaries NRCC no. 48192
Commentary J: Design for Seismic Effects

Geological Survey of Canada Open File xxxx
Fourth generation seismic hazard maps of Canada: Grid values to be used with the 2005 National Building Code of Canada (in preparation)

See the websites *www.EarthquakesCanada.ca* and *www.nationalcodes.ca* for more information

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Appendix 2

Summary and Conclusions

Seismic zoning maps for Canada are derived from the analysis of past earthquakes and advancing knowledge of Canada's tectonic and geological structure. Canada is divided into earthquake source regions based on past earthquake activity and tectonic structure. The relation between earthquake magnitude and the average rate of occurrence for each region is considered, along with variations in the attenuation of ground motion with distance. In calculating seismic hazard, scientists consider all earthquake source regions within a relevant distance of the proposed site. On the maps, seismic hazard is expressed as the maximum ground motion that is expected to occur in an area with a given probability. Contours delineate zones likely to experience similar intensities of shaking.

Minas Passage is located within the Northern Appalachian Seismic Zone (NAN). Maps of seismic risk in the 2005 code show the area occurs within Zone 1 and is considered to have a low earthquake risk. In fact, Canada to the east of the Cordillera, extending north from the United States border to the Arctic Ocean, comprises about two-thirds of the stable craton of the North American plate. Much of this large area appears to be substantially aseismic, although it contains several zones of significant seismicity and a few other regions of lower-level seismicity. Historically, earthquakes in the Minas Passage region have been infrequent and of small magnitude. The nearest zone of earthquake activity is likely associated with the Chedabucto-Cobequid Fault System and consists of two small earthquakes to the west and east. These did not occur within the proposed tidal power demonstration area.

Figures

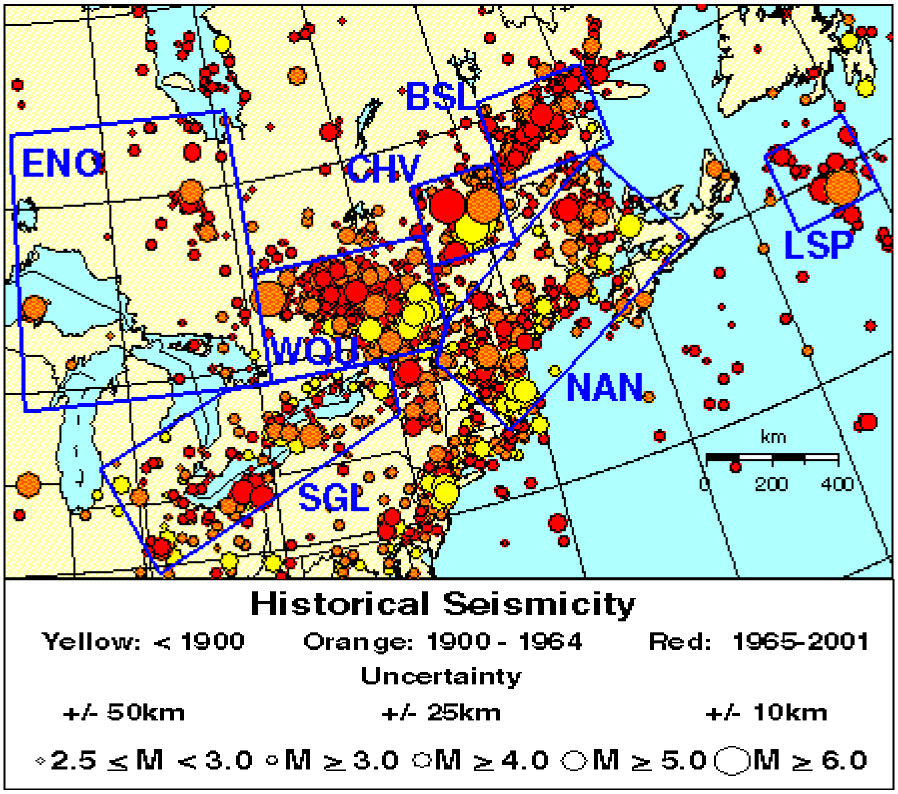

Figure 19. A map of the historical seismicity in eastern Canada.

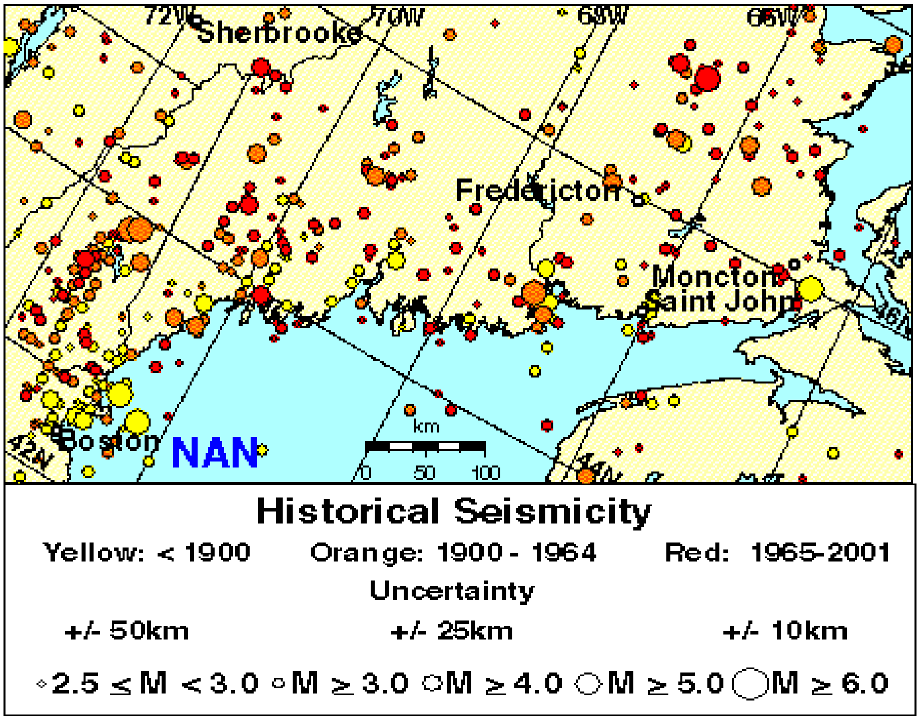

Figure 20. A more detailed map of the location of seismicity in the NAN area of eastern Canada.

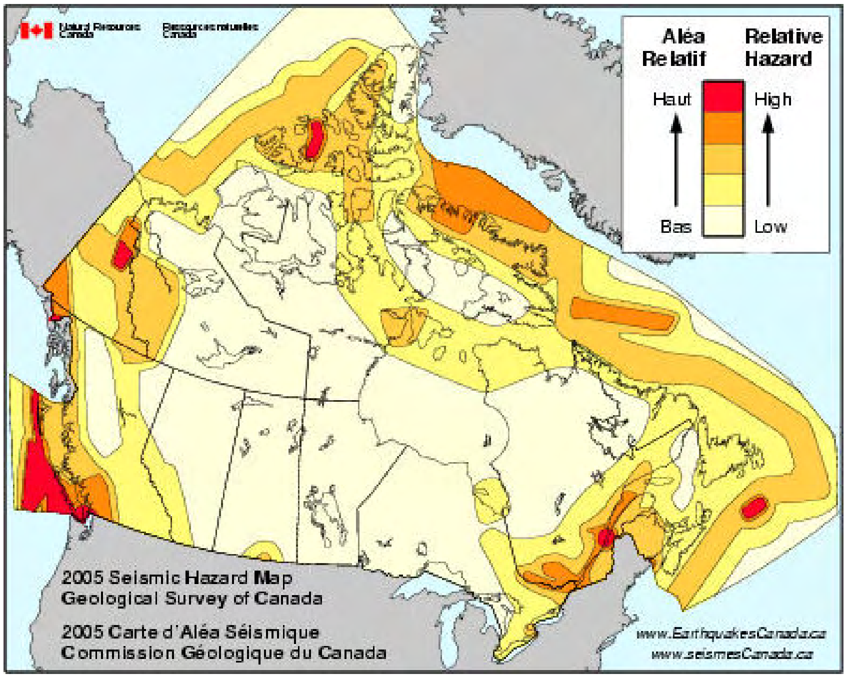

Figure 21. A simplified seismic hazard map of Canada.

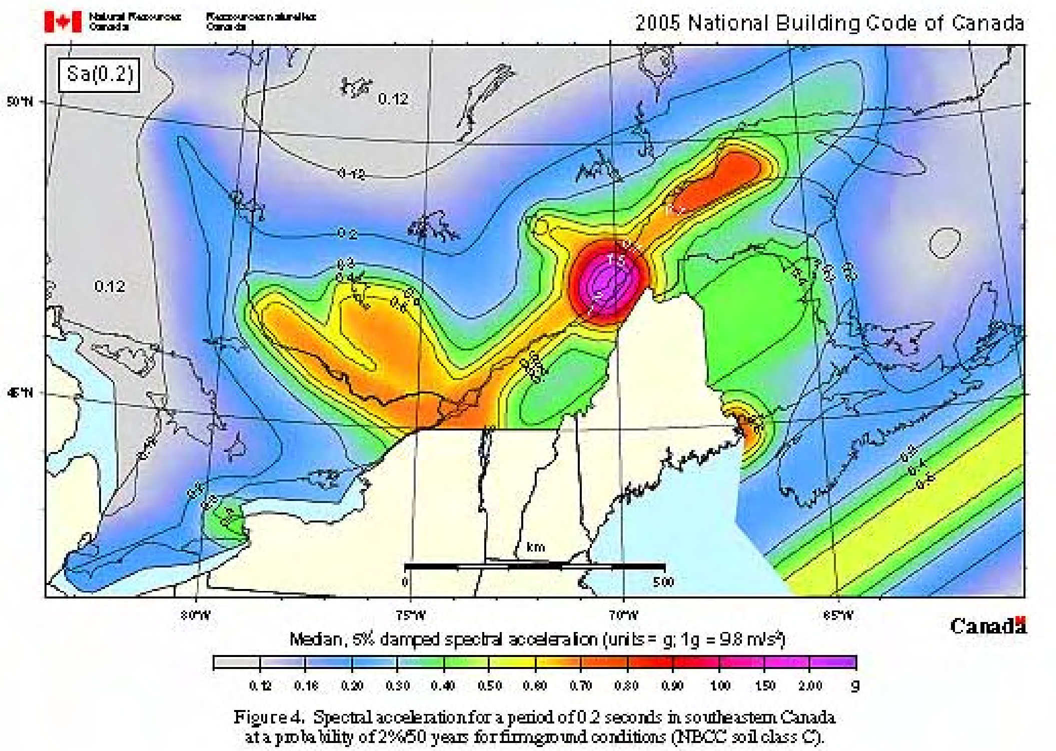

Figure 22. Spectral acceleration for a period of 0.2 seconds in southeastern Canada at a probability of 2%/50 years for firm ground conditions (NBCC soil class C).

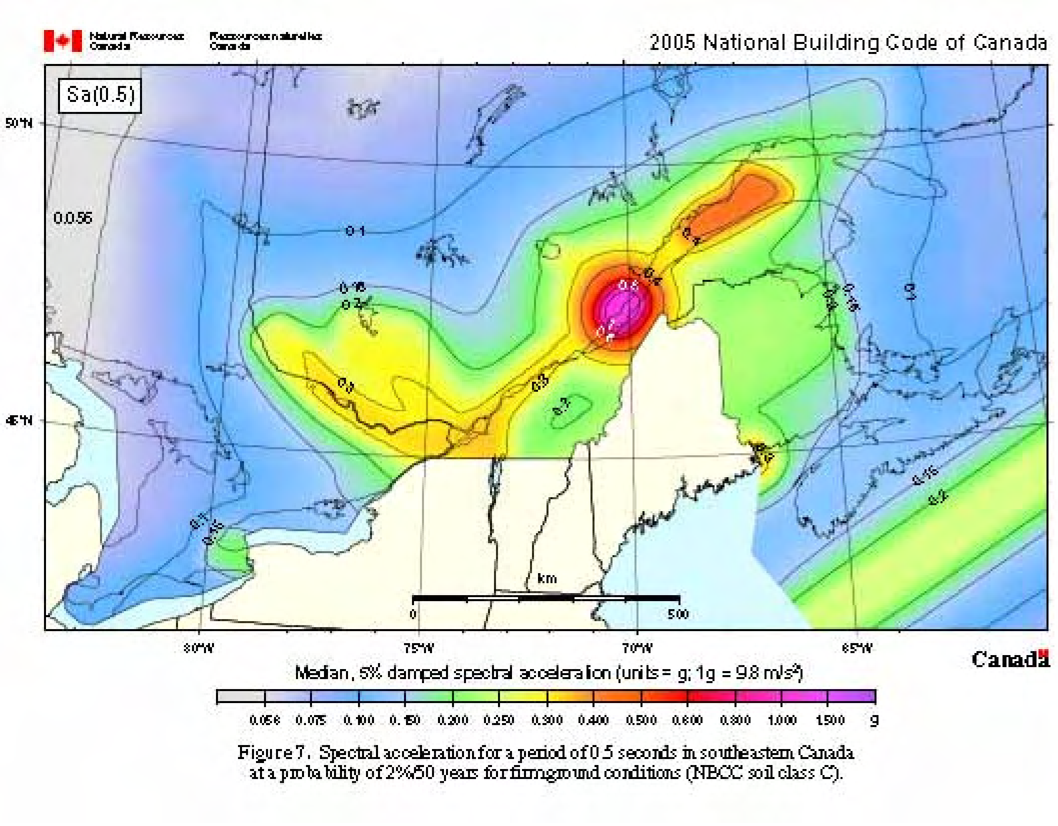

Figure 23. Spectral acceleration for a period of 0.5 seconds in southeastern Canada at a probability of 2%/50 years for firm ground conditions (NBCC soil class C).

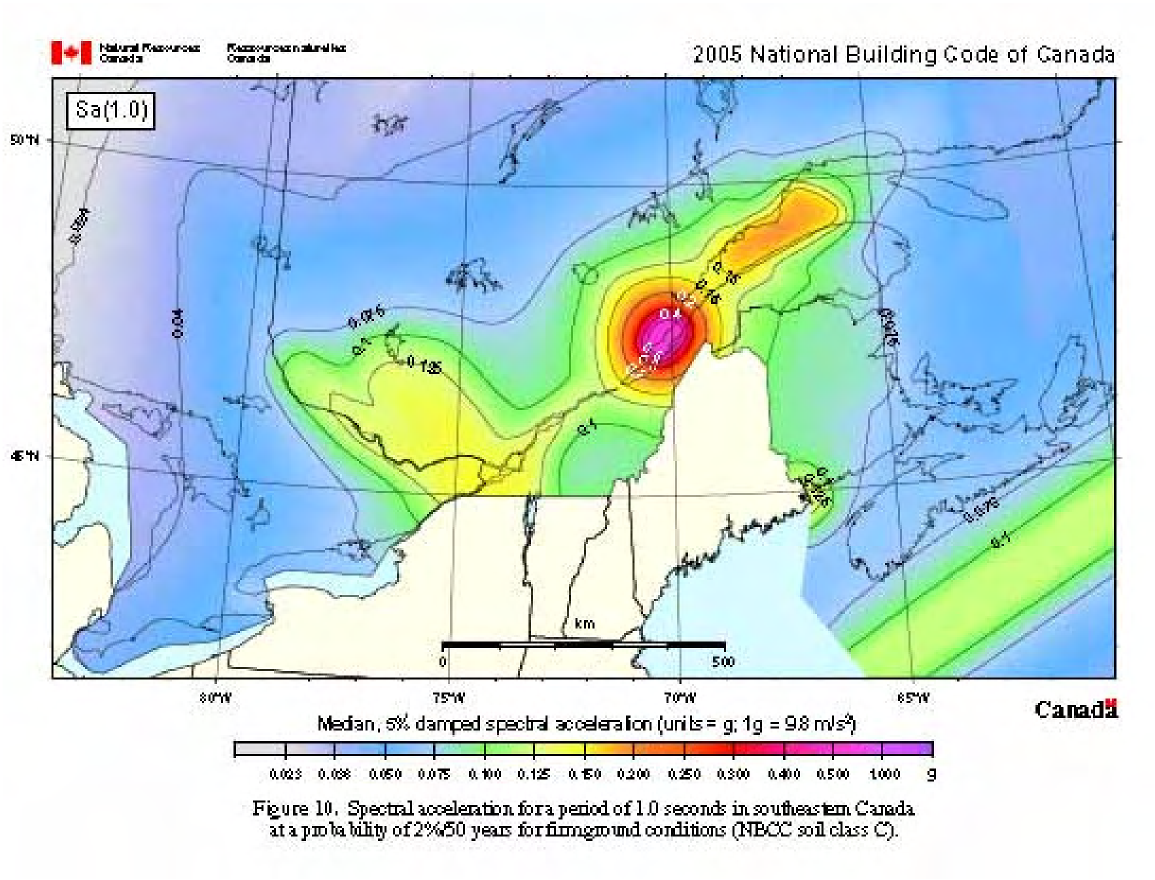

Figure 24. Spectral acceleration for a period of 1.0 seconds in southeastern Canada at a probability of 2%/50 years for firm ground conditions (NBCC soil class C).

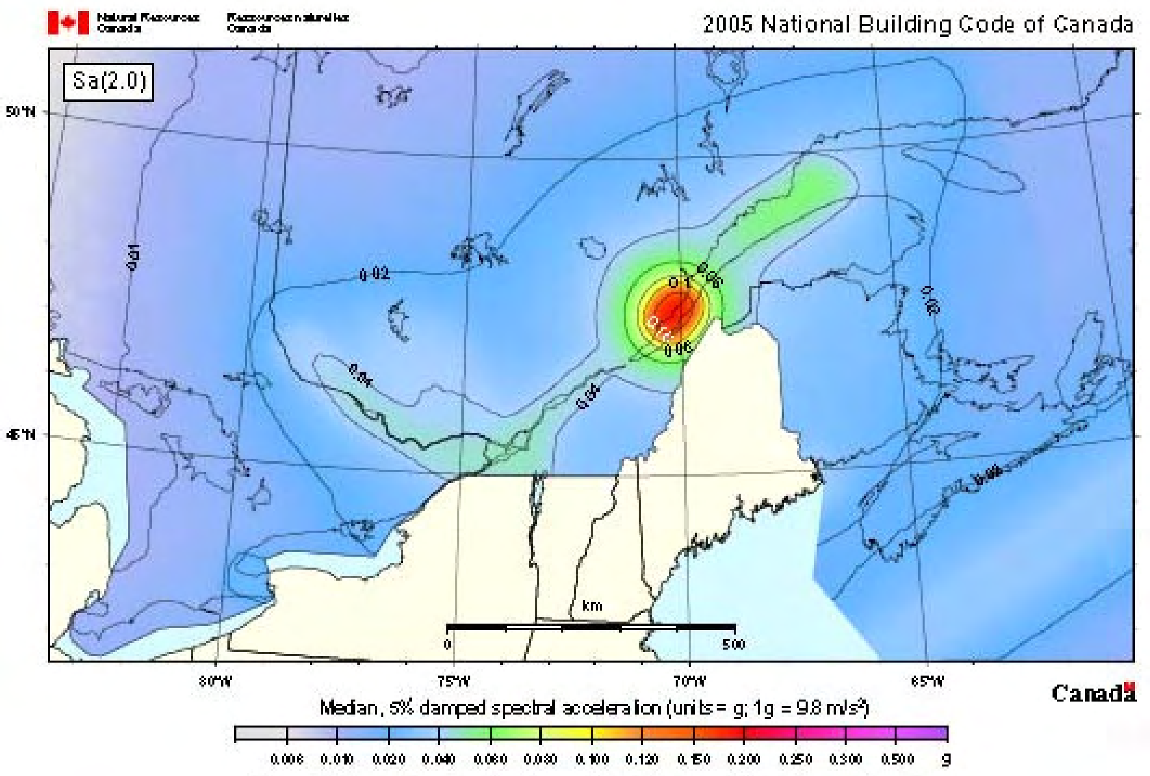

Figure 13. Spectral acceleration for a period of 2.0 seconds in southeastern Canada at a probability of 2%/50 years for firm ground conditions (NBCC soil class C).

Figure 25. Spectral acceleration for a period of 2.0 seconds in southeastern Canada at a probability of 2%/50 years for firm ground conditions (NBCC soil class C).

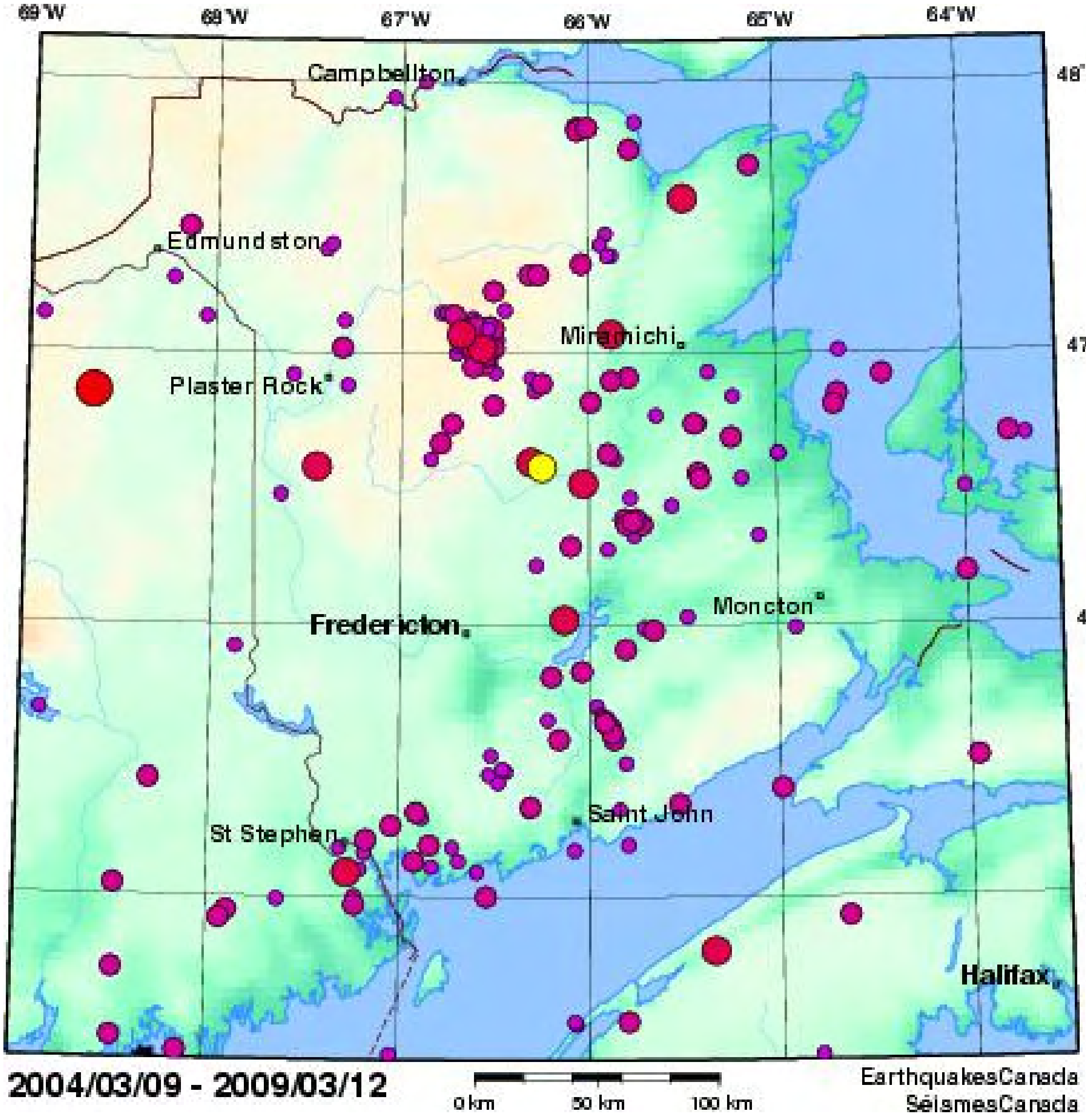

Figure 26. Distribution of earthquakes from 2004 to 2009 in the Bay of Fundy region.

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Glacial, Post Glacial, Present and Projected Sea Levels: Bay of Fundy

Relative Sea level Change - the Bay of Fundy Region

Former Quaternary shorelines have been identified at elevations as high as 75 m above present sea level and over 100 m below in Atlantic Canada. In contrast to the glacial and early post glacial history of sea level change, sea level appears to be rising in Maritime Canada today at a rate of between 20 and 30 cm/100 years. This has been attributed to long term climate change and crustal subsidence (Scott et al., 1995). A summary of the glacial history of the region over the past 100 ka provides an understanding of the relative sea level change and a perspective on future potential change.

The sea level history of the region also controls to a large degree the characteristics of materials deposited in association with both high and low sea level stands and the intervening areas that have been transgressed and regressed. Within recent years, an understanding of sea level change associated with global warming has added an additional amount of potential sea level rise to that predicted from crustal movements alone. For the proposed tidal power demonstration project in Minas Passage, former sea level positions have controlled to a large degree the characteristics of the materials on the seabed and on the adjacent land. An understanding of the future projected change in sea level that includes effects of global warming is important for the design of project infrastructure.

Quaternary glaciers played a major role in sea level change and for Atlantic Canada two opposing glacial models termed maximum and minimum models were put forth. The maximum model suggests that ice extended across the entire region to the continental slope from a Laurentide ice centre in Quebec, (Goldthwait, 1924, Denton and Hughes, 1981, Shaw et al., 2002). The minimum model suggests the presence of only local thin glaciers during the late Wisconsinan (Grant, 1977; Dyke and Prest, 1987). Through mapping of the glacial landforms and materials both on land and in the offshore, a more complex model of Wisconsinan glaciation (the last major ice advance in Atlantic Canada) has been developed and it appears to be closer to the maximum model.

The following discussion is a summary of findings in Stea et al., 1998; Shaw et al., 2002 and the results of mapping of sediments in the Bay (Fader et al., 1977, Fader, 1989) and adjacent coastal areas with an emphasis on the Bay of Fundy region. Recently collected seismic reflection data and multibeam bathymetry in Minas Passage have provided high resolution information for an understanding of the relative sea level low stand at the proposed tidal power demonstration site.

Sea Levels during the Previous Interglacial

A regional former sea level position prior to the Wisconsinan glaciation has been mapped and interpreted as an abrasion surface 4 – 6 m above present sea level in parts of Nova Scotia. It is overlain in places by peat and wood beyond the range of radiocarbon dating (Grant 1980). This rock platform has been interpreted as an erosional surface formed during the last interglacial period (marine isotope stage 5e) approximately 120 000 ybp. Grant interpreted that it represents an important former equilibrium position of sea level due to glacier melting and crustal subsidence after the previous major glacial episode. Marine sands have been found in both northern and southern Nova Scotia at elevations of 25 m and provide further evidence for higher sea levels.

The amount of relative sea level rise during the last interglacial may be an important indicator of present and future sea level rise in Maritime Canada. Based on the present rate of sea level rise, and not considering effects of global warming on sea level rise, it would take approximately 2 ka to raise sea levels by 6 m (the height of the old abrasion platform). Such estimates represent a minimum as the rate of subsidence is expected to decrease exponentially (Pirazzoli, 1996).

Late Wisconsinan Sea Levels 20 – 10 KA

During the earliest Wisconsinan phase of ice flow, ice extended across the region to the continental slope where it was grounded in over 300 m of water depth and perhaps as much as 800 m. Deglaciation began earliest in the southwest (outer Gulf of Maine) as early as 21 ka and progressed across the continental shelf in a time transgressive manner with the last ice remaining on the eastern Scotian Shelf. Ice retreated rapidly out of the Gulf of Maine and up the Bay of Fundy because of their great depths and linear morphological connection to the ice centres. This removal isolated an ice mass on Nova Scotia (Scotian Ice Divide) that later became an active ice centre. The isolated ice cap was drawn into the deeper Bay of Fundy where it formed streamlined deposits of till on the seabed.

In the Bay of Fundy there is an anomalous northeast trend to lower marine limits from over 40 m at the mouth to 0 near the Bay head (Figure 27). The shorelines are tilted toward a local late ice centre, the source of the ice flow out of the Bay of Fundy. Stea (1982) suggested that shorelines around the Bay of Fundy are diachronous and the marine limit may not be a function of ice thickness but of protracted ice retreat to local ice centres. This may have prevented the formation of beaches in some areas. Widely varying ages on raised marine deposits from both sides of the Bay support this idea.

Relative Sea Level History of the Bay of Fundy

The relative sea level history in the Bay of Fundy is very complex with the lowstand shoreline shallowing from southwest to northeast (Fader, 1989, Fader et al., 1977, Shaw et al., 2002). The following is a discussion of the high and low stand history of sea levels and new ideas resulting from the collection and interpretation of multibeam bathymetry in the Bay. Former high sea level stands are relatively easy to locate, interpret and map. Most are associated with rock platforms, beach sediments of well-sorted sand and rounded gravel, terraces and sometimes deltaic sediment deposits where rivers and streams entered the former sea. Lidar imagery and aerial photographs also show vegetation changes possibly related to textural properties of the sediments that affect water content and the presence of subtle terrace and beach morphological features. They are difficult to interpret from on-land field investigations alone.

Determining the position of former lower sea level stands that are presently submerged is a much more difficult problem. Seabed features indicative of low sea level stands and subsequent transgressions include: terraces, erosional surfaces and unconformities, sediment textural characteristics of winnowing, absence of fine-grained sediment, erosion of glacial till and glaciomarine sediment, muted topography and relative greater exposures of bedrock. Dating these low sea level stands is also very difficult as material suitable for dating, such as marine shells, must be confirmed to have formed in situ in low stand deposits. With the advent of multibeam bathymetric mapping, subtle morphologic characteristics of low sea level stands are becoming easier to recognize and interpret. However, in areas of high energy, such as the Bay of Fundy, overprinting by modern sediment transport processes has resulted in the burial of low stand features or their removal, making recognition more difficult. The following is a summary of the low stand sea level evidence from the Bay of Fundy (Fader et al., 1977) and a discussion and interpretation of recent multibeam bathymetry.

The lowest position of sea level in post glacial time prior to the Holocene marine transgression is critical to the distribution of sediments, their stratigraphic relationships, sediment texture and seabed features such as exposed bedrock, former channels, etc. For the Scotian Shelf and outer Gulf of Maine, this position has been interpreted to occur at a depth of approximately 115 – 120 m in the offshore and 65 -70 m in the near shore.

Within the Bay of Fundy, the low sea level stand has been interpreted to occur at a depth of between 40 to 60 m gradually decreasing in depth from 110 m near German Bank, Gulf of Maine to the southwest of Yarmouth. In the Fader et al. (1977) study, glacial till and glaciomarine sediments were found in the Bay of Fundy well above the depth of occurrence of the low stand on the adjacent Scotian Shelf. At the entrance to the Bay of Fundy a noted increase in the silt and clay component from sediment samples supports a decrease in the former sea level position. The grain shape of the gravels in the outer Bay of Fundy also supports this model. Transgressed gravel surfaces consist of well-rounded to rounded clasts and the gravels in the Bay below are angular to subangular in shape.

Along the south-western and south-eastern coasts of Nova Scotia there is no evidence for a postglacial marine limit higher than the present shoreline. Studies by Goldthwait (1924), Hickox (1962), Bloom (1963), Swift and Borns (1967), Grant (1971) and others have found widespread raised marine strandlines and marine deposits in the area to the north of Yarmouth and along the south and north coasts of the Bay of Fundy and the Gulf of Maine. These features attest to late and post glacial significant rebound. In Nova Scotia the marine limit increases in elevation from a hinge line slightly north of Yarmouth and trends generally northeastward on land parallel to the geographic axis of the Bay of Fundy. Along the Nova Scotian side of the Bay, the highest marine limit is 45 m at Digby Gut (Grant 1971 and Stea et al., 1998). In contrast, the height of the marine limit in New Brunswick is 73 m above present sea level (Gadd, 1973). A minimum age for this limit is 13 325 ybp. In central Maine the height of the marine limit is even higher at 135 m (Stuvier and Borns, 1975) and is dated at 13 000 ybp. This shows that a tilt existed across the Bay of Fundy due to greater depression of the crust in New Brunswick and Maine as a result of closer approximation to the Laurentide ice centre. Although formed at the same time, there is approximately a 30 m difference in the present elevation of the marine limit in a line of section across the Bay of Fundy from Digby to Saint John.

Sea Level History Post Marine Limit Formation

The marine limit (highest level of marine water on land) formed some time after the ice retreated or is coequivalent with the timing of ice retreat. In some areas ice cover may have prevented the formation of raised marine features, hence, they are discontinuous. The early post glacial body of water that existed in the area of the Bay of Fundy has been termed the “DeGeer Sea” and was considerably larger than the present Bay extending up the Annapolis Valley and the St. John River Valley flooding large areas of present land.

After 13 500 ybp, isostatic rebound exceeded the rate of eustatic sea level rise resulting in a marine regression across the former sea bed (elevations presently to a maximum of 45 m) with a resulting emergence of the land. Through this process of rapid isostatic rebound, the relative sea level in the Bay of Fundy fell during the time period of 13 000 to approximately 9 500 ybp. Grant (1971) studied aggraded material in intertidal estuaries and estimated that sea level fell to a position 20 - 30 m below the present level. Recent studies in coastal and nearshore Maine by Belknap et al. (1989) show the presence of a widespread unconformity at a present water depth centered around 60 m. Studies of the surficial geology of Passamaquoddy Bay using seismic reflection profiles by Pecore and Fader (1991), also recognized a regional unconformity at a depth of 60 below Holocene pockmarked muds that was developed on glaciomarine sediments. Recently collected multibeam bathymetry from several areas of the Bay of Fundy shows a variety of previously unrecognized seabed features such as iceberg furrows, fluted till and sub parallel transverse moraines in water depths greater than 60 m that are likely too delicate to have survived a marine transgression intact and support the interpretation of a higher low sea level position. Deltaic deposits have also been found in similar depths with high-resolution seismic reflection profiles.

After formation of the low sea level stand at approximately 9 500 ybp, relative sea level began to rise and transgressed areas above 60 m water depth continuing to the present shoreline. Transgressions can be very effective erosional mechanisms compared to regressions where sediments tend to be armoured and not undercut and are thus preserved. In the Bay of Fundy, tills and previously deposited glaciomarine sediments were eroded, armoured with lag gravels and the topography was smoothed and muted in this transgressed zone of between 60 m water depth and the present shoreline. Subsequent strong currents resulting from the development of high tides in the Bay of Fundy further armoured this surface and continue to do so at present.

Amos and Zaitlin (1985) studied the sea level history for the inner Bay of Fundy in Chignecto Bay. They suggested a relative sea level fall from a high of 48 m at about 13,500 ybp to a low of 25 m at 7000 ybp. Additionally, Amos et al., (1991) suggested that there were actually two times of macrotidal conditions in Fundy: the first as the relative sea level fell from the high stand across the present position, and another as the sea level returned to its former preglacial position sometime after 6000 ybp. Shaw et al., 2002 combined isobase maps with a digital terrain model of Atlantic Canada to map coastlines from 13 000 ybp to the present. Their map of the Bay of Fundy inner region for 9000 ybp (Figure 28) shows that much of Minas Basin was subaerially exposed.

Short Term Relative Sea Level Trends in the Bay of Fundy

Tide gauge data from Atlantic Canada extends back almost 100 years and contains a strong signal of rising sea level (Shaw and Forbes, 1990) (Figure 29). Grant (1970, 1975) cited rates of 46, 41 and 26 cm/century for St. John, N.B. Carrera and Vanieck gave rates of 31.4 cm/century for the time period 1966 – 1985 for Yarmouth, south of the entrance to the Bay of Fundy.

The sources for compiling tide gauge trends discussed in Shaw and Forbes, 1990, are Tidal Publication No. 30 published in 1951 by the Canadian Hydrographic service. They also used data obtained from Marine Environmental Data Services (MEDS), a branch of the Department of Fisheries and Oceans. The Yarmouth data set from MEDS sources includes some isolated values for 1900 and 1956 with the continuous set beginning in 1967. The rate for the period 1900 -1988 is 26.3 cm/century. Excluding the 1906 value, the rate is 26.8. For St. John, N.B. and the rate includes 24 values predating 1929, the first year of MEDS recordings. The record gives a rate of 21.2 cm/century. A regression using only data from 1929 onwards provides a rate of 28.4 cm/century.

From the above values it is clear that along with many other areas in Atlantic Canada, the Bay of Fundy is experiencing a rise in relative sea level. The calculated rise does depend on the length of the record. The two most important causes of sea level rise are crustal subsidence and eustatic sea level rise. The fact that rates change regionally suggests regional variations in the crustal component. Grant (1975) also reached this conclusion. Global climatic warming may play an even larger role in sea level rise than amounts associated with responses to glacial offloading and crustal movements. This is discussed in the following section.

Global Warming Associated Sea Level Rise

The most recent research on sea level change was presented at the International Scientific Congress on Climate Change in Copenhagen in March 2009. It showed that the upper range of sea level rise by 2100 could be in the range of about one meter, or possibly more. In the lower end of the spectrum it appears increasingly unlikely that sea level rise will be much less than 50 cm by 2100. The following is a summary of the Copenhagen meeting.

Dr. John Church of the Centre for Australian Weather and Climate Research, Australia and the lead speaker in the sea level session, told the conference, "The most recent satellite and ground based observations show that sea-level rise is continuing to rise at 3 mm/yr or more since 1993, a rate well above the 20th century average. The oceans are continuing to warm and expand, the melting of mountain glaciers has increased, and the ice sheets of Greenland and Antarctica are also contributing to sea level rise."

New insights reported at the meeting include the loss of ice from the Antarctic and Greenland Ice Sheets. "The ice loss in Greenland has accelerated over the last decade. The upper range of sea level rise by 2100 might be above 1m or more on a global average, with large regional differences depending where the source of ice loss occurs", says Konrad Steffen, Director of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado, Boulder and co-chair of the congress session on sea level rise.

The last assessment report from the IPCC from 2007 projected a sea level rise of 18 - 59 cm. However the report also clearly stated that not all factors contributing to sea level rise could be calculated at that time. The uncertainty was centered on the ice sheets, how they react to the effects of a warmer climate, and how they interact with the oceans, explains Eric Rignot, Professor of Earth System Science at the University of California Irvine and Senior Research Scientist at NASA's Jet Propulsion Laboratory.

"The numbers from the last IPCC are a lower bound because it was recognized at the time that there was a lot of uncertainty about ice sheets. The numerical models used at the time did not have a complete representation of outlet glaciers and their interactions with the ocean. The results gathered in the last 2-3 years show that these are fundamental aspects that cannot be overlooked. As a result of the acceleration of outlet glaciers over large regions, the ice sheets in Greenland and Antarctica are already contributing more and faster to sea level rise than anticipated. If this trend continues, we are likely to witness sea level rise one meter or more by year 2100".

"Measurements around the world show that sea level has risen almost 20 cm since 1880," explained Professor Stefan Rahmstorf of the Potsdam Institute for Climate Impact Research, who gave the plenary speech on sea level rise at the 2009 congress. These data also reveal that the rate of sea level rise is closely linked to temperature: sea level rises faster the warmer it gets. "If sea level keeps rising at a constant pace, we will end up in the middle of that 18-59 cm IPCC range by 2100," says Rahmstorf. "But based on past experience I expect that sea level rise will accelerate as the planet gets hotter."

The results of the 2009 International Scientific Congress on Climate Change in Copenhagen demonstrate that a clear assessment of the amount of sea level rise due to global climate warming does not exist and a range of values of between 18 and 100 cm by 2100 have been proposed. The infrastructure for the tidal power demonstration project in Minas Passage that includes buildings, cables, gravity based structures and perhaps water surface piercing structures will use the most up to date information on sea level rise as a component of the design criteria.

Tidal Variations

Sea surface elevation records taken at Saint John, New Brunswick were analyzed by Godin (1992) who noted that the amplitude of the M2 tide was increasing at a rate of 10 -15 cm/century. He interpreted this to be the result of changes in resonance resulting from sea level rise or sediment redistribution at the head of the Bay. Scott and Greenberg (1983) estimated a 1.5% increase in tidal amplitude for each 1 m rise in sea level. This would only translate into a 1-2 cm/century increase based on the present knowledge of sea level rise. Greenberg (1979) suggested that such high increases in tidal amplitude as suggested by Godin could only occur with major tidal power installations and not changing sedimentation patterns. Greenberg and Petrie suggested that more study was required to sort out magnitudes and causes of changing amplitude of the M2 tide. The tidal range expansion was interpreted as most rapid after 7000 ybp and that it had decreased by 4000 ybp (Scott and Greenberg, 1987). John Shaw (personal communication, 2008, in prep.) has proposed a novel idea suggesting that tidal expansion was delayed in Minas Basin by the existence of a barrier at the junction between Minas Passage and Minas Basin. This barrier was destroyed perhaps by a large storm in one event and may represent the legend recorded in the First Nations accounts of the great flood in the stories of Gloosecap.

Summary of Sea Level History and Implications for the proposed development of Tidal Power in Minas Passage

The glacial, post glacial and historical sea level knowledge has implications for the construction of offshore infrastructure as well as on land components. Of utmost importance to the design of structures that may pierce the sea surface is consideration of the continued projected rise in sea level. Based on the knowledge of sea level change over the past 50 years, the facilities will be designed and constructed to anticipate a sea level rise of 30 cm/century for natural crustal changes combined with a further 18 to 100 cm associated with global climate change. Such a design will also take into consideration potential change in tidal heights and storm waves associated with higher sea levels.

With regard to the design and construction of the land based facilities, knowledge that former sea levels were as high as 26 m near Cape Sharp will also be considered in the design and construction. These former and higher sea levels have controlled the characteristics of glacial outwash and other materials in the near shore zone.

Figures

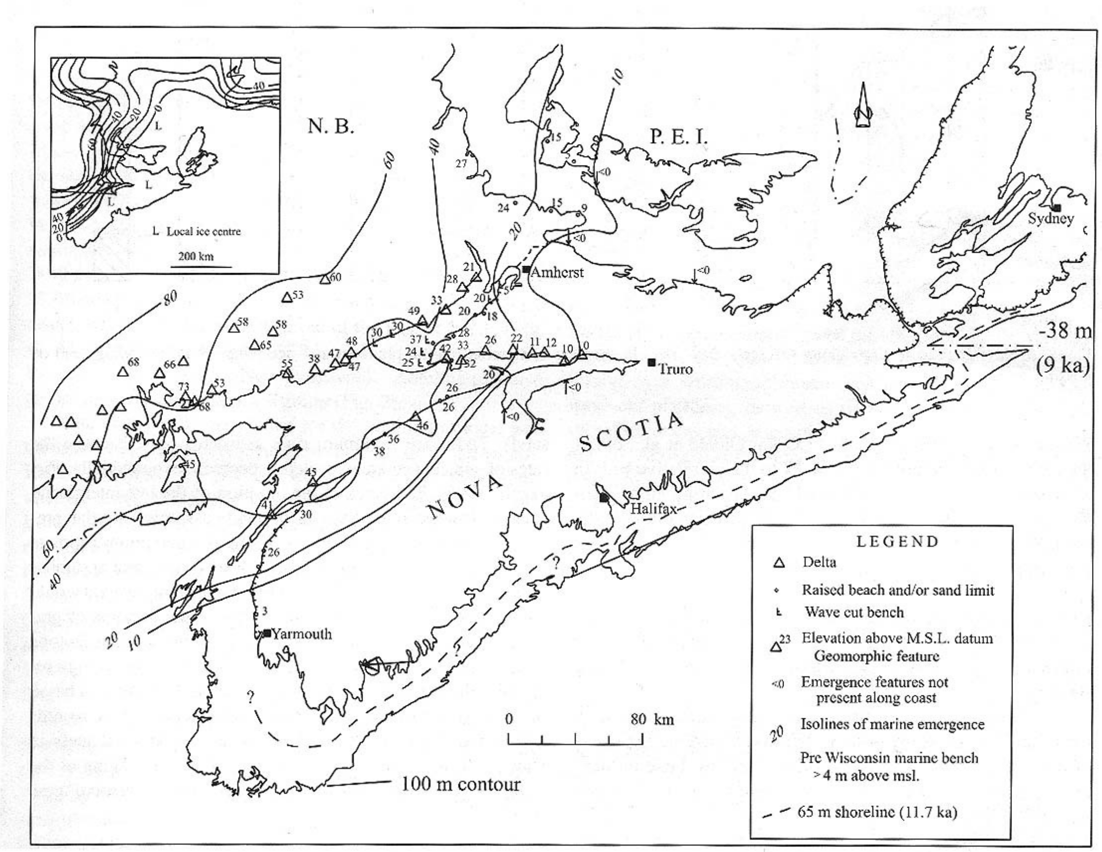

Figure 27. Lines of equal emergence (isopleths) of elevations of the marine limit in Nova Scotia and New Brunswick. The marine limits are represented by wave-cut terraces, beaches and deltas. Former interglacial shorelines occur around Cape Breton Island and north of Yarmouth. In contrast, the low stand shoreline offshore east Nova Scotia at 65 m is shown. From Stea et al., 2001.

Figure 28. A map of the distribution of Atlantic Canada at approximately 9000 ybp showing the paleogeography of the region. Areas in green represent offshore regions of subaerial exposure resulting from the position of relative sea level at this time. Note that most of Minas Basin was land at this time. From Shaw et al., in press (2005).

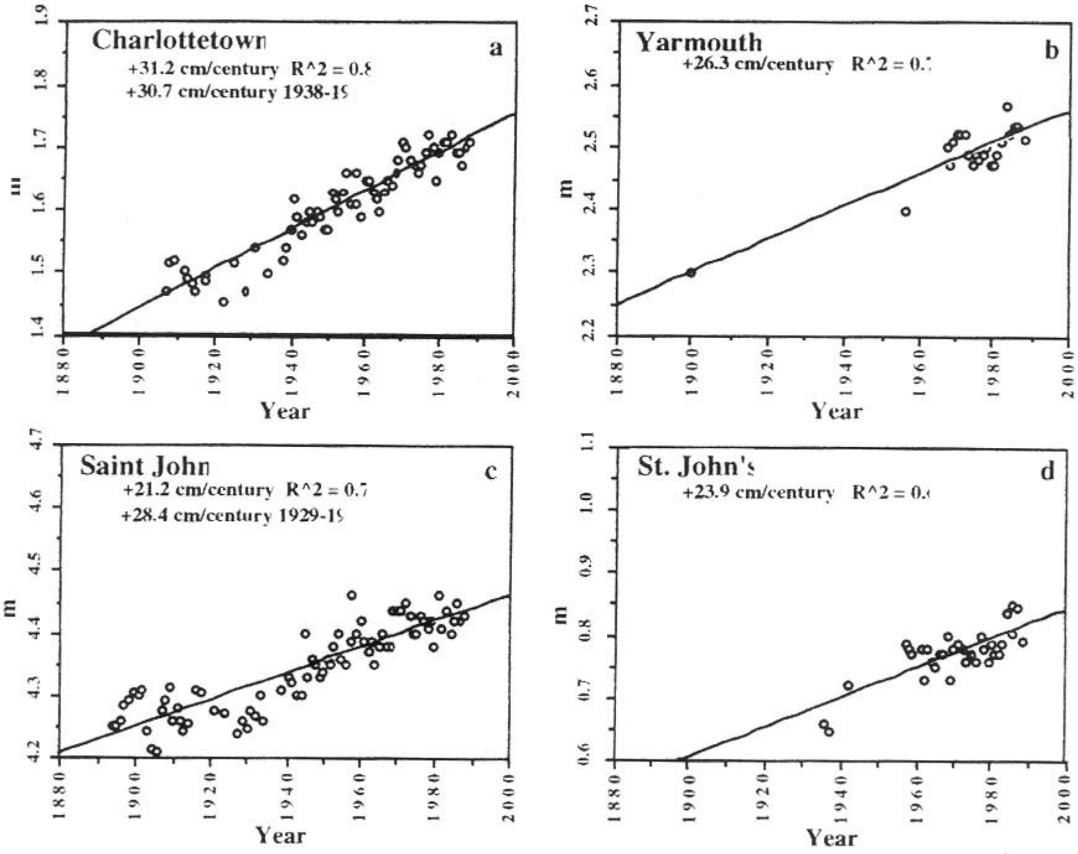

Figure 29. Tidal records and rates of change for a) Charlottetown, P. E. I., b) Yarmouth, N. S., c) Saint John, N.B., and d) St. John's, Newfoundland and Labrador. From Shaw and Forbes, 1990.

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