Integration of Multibeam Bathymetry and LiDAR Surveys of the Bay of Fundy, Canada

D. Russell Parrott[1], Brian J. Todd[1], John Shaw[1], John E. Hughes Clarke[2],
Jonathan Griffin[3], Bruce MacGowan[3], Michael Lamplugh[3] and Timothy Webster[4]

[1]Geological Survey of Canada (Atlantic), Bedford Institute of Oceanography, Dartmouth, NS. (Russell.Parrott@NRCan.gc.ca, Brian.Todd@NRCan.gc.ca, John.Shaw@)NRCan.gc.ca)
[2]Ocean Mapping Group, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, NB. (jhc@omg.unb.ca)
[3]Canadian Hydrographic Service, Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, NS. (griffinj@mar.dfo-mpo.gc.ca, macgowanb@mar.dfo-mpo.gc.ca, lamplughm@mar.dfo-mpo.gc.ca)
[4]Applied Geomatics Research Group, Centre of Geographic Sciences, Lawrencetown, NS. (Timothy.Webster@nscc.ca)

Abstract

Canadian vessels equipped with multibeam bathymetry systems are in high demand by the Canadian Hydrographic Service (CHS) and by researchers from the Geological Survey of Canada (GSC). For several years, survey time for geological mapping was allocated in relatively small blocks of 10-20 days to provide as many applicants as possible the opportunity to collect multibeam bathymetry data. The resulting small-area surveys provided tantalizing glimpses of the wide diversity of the character of the seafloor but did not provide the regional context required for a full understanding of the features discovered.

In 2006, the GSC, in conjunction with CHS and several universities, commenced a three year program to map the Bay of Fundy on the east coast of Canada. The Bay of Fundy has the largest recorded tides in the world, with a maximum range of about 17 metres at the head of the bay. Tidal current velocities that exceed 4.5 m s^{-1} in restricted narrow passages at various points in the bay could be harnessed for electrical power generation. To date about 10,000 km^2 of multibeam bathymetry have been collected in the bay. Sub-bottom profiler data were collected simultaneously to provide information on the character and thickness of the sediments on the sea floor. Large drying areas were surveyed using airborne terrestrial laser (LiDAR), providing an opportunity to generate a continuous map of the marine, intertidal and terrestrial areas. CHS will use the data to generate improved navigation charts and GSC will integrate information from geophysical surveys, seafloor samples, photographs and video transects to produce surficial geology and benthic habitat maps. The resulting 1:50,000 scale maps will be released as part of a new Canadian national marine map series. The presentation will focus on the status of the project after the first two years of data collection, challenges and future plans of the project with an interpretation of the most recent data.

Introduction

In 2004 the Canadian government committed " …*to move forward on its Oceans Action Plan by maximizing the use and development of oceans technology,.*.". The Bay of Fundy, located on the east coast of Canada between the provinces of Nova Scotia and New Brunswick, was identified as one of the priority areas under Canada's Oceans Action Plan. In response to this national priority, the Geoscience for Ocean Management (GOM) program within Natural Resources Canada (NRCan) initiated a regional multibeam mapping effort to provide multibeam bathymetry data for the majority of the Bay of Fundy. This work was performed under a project called Geoscience for Management and Economic Development in the Bay of Fundy. The project was designed to apply new mapping technologies to the sea floor and the water column in the Bay of Fundy in a multidisciplinary approach to produce a series of new, digital map products upon which ecosystem management decisions could be made and future scientific endeavours could be based. A systematic compilation of existing surficial sea floor geoscience data was made and supplemented with integrated multibeam bathymetry and geophysical surveys, field measurements and model predictions to produce maps, data bases and interpretive reports to empower stakeholders, clients and partners with the knowledge base to implement integrated ocean management. The approaches of the Bay of Fundy were scheduled to be mapped initially, followed by the outer and central Bay of Fundy, and selected portions of the inner Bay of Fundy. In 2007, the schedule was modified to allow collection of data in the Minas Passage area, where an in-stream tidal generation project was under consideration.

Background

The Bay of Fundy is an estuarine embayment (Amos et al., 1980) with a resonant period of about 13 hours. This resonance is close to the 12 hour and 25 minute dominant lunar tide of the Atlantic Ocean and results in the largest recorded tides in the world, with a range that increases from about 4 m at the mouth of the bay to a maximum of 17 m at the head of the bay (O'Reilly et al., 2005). These extremely large tides generate strong current velocities that exceed 4.5 m s^{-1} in restricted narrow passages at various points in the bay and have been the focus of plans to harness tidal power as long ago as 1910 (Daborn and Dadswell, 1988). With revived interest in renewable energy, Minas Passage has been selected as the site of an engineering study for in-stream electrical power generation, and the new imagery and other data are contributing to the process of site selection.

Canadian vessels equipped with multibeam bathymetry systems have been collecting data in the Bay of Fundy since 1992. These vessels are in high demand by the Canadian Hydrographic Service (CHS) for detailed bathymetry surveys and by researchers from the Geological Survey of Canada (GSC) of Natural Resources Canada (NRCan) for geological seafloor mapping. For several years, survey time for geological mapping was allocated in relatively small blocks of 10-20 days to provide as many applicants as possible the opportunity to collect multibeam bathymetry data. The resulting small-area surveys provided tantalizing glimpses of the wide diversity of the character of the seafloor but did not provide the regional context required for a full understanding of the features discovered. In 2006, the GSC, in conjunction with CHS and several universities, commenced a three year program to map the Bay of Fundy on the east coast of Canada. To date about 10,000 km^2 of multibeam bathymetry have been collected in the bay. Sub-bottom profiler data were collected simultaneously to provide information on the character and thickness of the sediments on the seafloor. Various points in the bay are presently being studied to determine the suitability to be harnessed for electrical power generation.

Current meters, suspended sediment sensors and time lapse photographs will be used to provide information on seafloor properties and the dynamics of the water column. These data, in conjunction with the improved bathymetry data, will be used to improve the resolution and accuracy of tide and current prediction models.

The broad intertidal zone in the Bay of Fundy presents a challenge to collection of marine geophysical and bathymetry data. Traditionally, this area has not been surveyed due to the significant time requirements and inherent danger involved in operating vessels in coastal areas that dry between tides. These large drying areas were surveyed using airborne terrestrial laser known as LiDAR (Light Detection And Ranging), that also provides very high resolution elevation models. The combination of these techniques enables the generation of a continuous map of the marine, intertidal and terrestrial areas. The data were collected during an extreme low tide to provide detailed elevation measurements of the inter-tidal areas. LiDAR surveys performed between 2000 and 2007, mapped about 4000 km^2 of the surrounding land. Multibeam bathymetry data will be collected during high tides to provide a seamless digital elevation model across the intertidal zone.

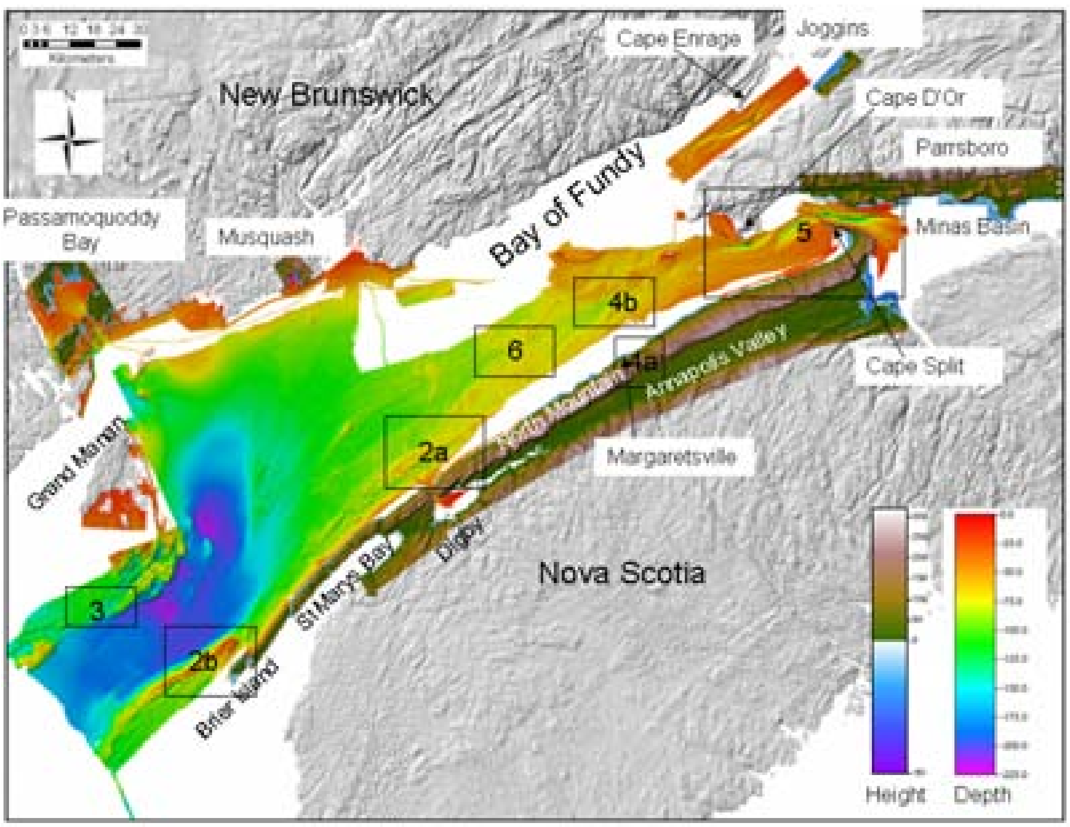


Fig. 1: Extent of multibeam bathymetry and LiDAR data collected in the Bay of Fundy since 1992, overlain on an image generated from radar topographic data. The colour bars for the LiDAR elevations and bathymetry are shown in the lower right portion of the image. The rectangles show the location of subsequent figures in the text.

Fig. 1 shows the extent of multibeam bathymetry and LiDAR coverage of the Bay of Fundy to the end of September 2007, as a shaded-colour-relief image and the locations of subsequent figures in the text.

Multibeam Bathymetry Data Collection

Multibeam bathymetric data were collected by the Canadian Hydrographic Service, the Geological Survey of Canada and the University of New Brunswick. The survey systems use a beam over an arc of about 130° across the ship's track and operate by ensonifying a narrow strip of seafloor and detecting the seafloor by resolving the returned echo into multiple beams. The width of seafloor imaged on each survey line was four times the water depth. Line spacing was about two to three times water depth to provide ensonification overlap between adjacent lines. The survey utilized a variety of survey vessels and multibeam bathymetry systems including:

- the CCGS *Frederick G. Creed*, a SWATH (Small Waterplane Area Twin Hull) vessel equipped with a Kongsberg EM1000 (prior to 2005) and Kongsberg EM1002 (2005 onwards) multibeam bathymetric survey system with 111 beams operating at 95 kHz with the transducer mounted in the starboard pontoon,
- the CCGS *Matthew* equipped with a Kongsberg EM710 multibeam bathymetric survey system with 200 or 400 beams operating at 70–100 kHz with the transducer mounted near the centre of the vessel, and
- hydrographic survey launches *Plover*, *Pipit*, and *Heron* equipped with Kongsberg EM3000 (prior to 2005) and Kongsberg EM3002 multibeam bathymetric survey systems with 160 to 254 beams operating at 300 kHz.

The Differential Global Positioning System was used for navigation, providing positional accuracy of ±3 m. Survey speeds averaged 12 knots (22.2 km hr^{-1}), resulting in an average data collection rate of about 2 km^2 hr^{-1} in water depths of 35–70 m. The sound velocity in the ocean was measured during multibeam data collection and used to correct the effect of sonar beam refraction. The 1992 to 2006 data were adjusted for tidal variation using tidal measurements and predictions from the Canadian Hydrographic Service. During the 2007 survey, vessel elevations were also acquired using a combination of real-time kinematic GPS systems (Church et al., 2008, this volume) and hydrodynamic tidal models developed by the Canadian Hydrographic Service and Fisheries and Oceans Canada Coastal Oceanography Group (Dupont et al., 2005).

Multibeam Backscatter Intensity Data

Most modern multibeam sonar systems provided a measure of the peak or average backscattered intensity (measured as a voltage on the receiver array), a property that can indicate the nature of the material on the seafloor. This value is a function of the geometric parameters of the survey, characteristics of the multibeam bathymetry system which can vary from system to system, and the nature and shape of the sediments being surveyed. In order to obtain useful information about the seafloor sediments, it is paramount to remove the system effects and geometric parameters from the data. The Bay of Fundy surveys have involved five different Kongsberg Simrad EM multibeam sonar systems, from five different survey platforms with over fifteen years of software and hardware upgrades. To process the backscatter data to a common level, assumptions are required about absolute source level, pulse length, absolute and time-varying receiver gains, seawater attenuation coefficients and sonar transmission and reception sensitivities. Because of uncertainty in all of these, the standard output value is effectively a relative measure. As a result, inter-survey consistency can be poor. A method is therefore required to pick an arbitrary reference (sonar hardware and software configuration) and adjust all other surveys, through overlapping coverage, to that reference (Hughes Clarke et al., 2008, this volume) which has addressed the problems associated with integration of data for each configuration, adjustments needed to refer backscatter data to absolute levels, variations by angle, by pulse length settings and correcting for applied attenuation coefficients. They concluded that once all these corrections have been made, a second set of adjustments needs to account for the spatially-variable shape of the inherent seabed angular response curves. Imperfections in each of the backscatter intensity processing algorithms and assumptions provide uncertainty in the absolute estimate of bottom backscatter strength making automated seafloor characterization difficult. Nevertheless, the processed imagery is amenable to subjective interpretation and illustrate the regional delineation of the main surficial sediment types.

LiDAR Data Collection

LiDAR is a remote sensing technique that involves an aircraft equipped with a laser rangefinder that emits pulses of light towards the earth, and by measuring the two-way travel time, determines the distance or range from the aircraft to the earth's surface. Precise positioning of the aircraft by GPS and an inertial measurement unit allows the land elevations to be determined. The Bay of Fundy coastal LiDAR data were acquired by the Applied Geomatics Research Group, Nova Scotia Community College (NSCC), starting with the Annapolis Valley in July 2000 (LaserMap, ALTM1200 sensor, May 2003 (Terra Remote Sensing, Mark I sensor), and April 2004 (Terra Remote Sensing, Mark II sensor), followed by the remaining coastal areas in October 2006, and April and May, 2007 (AGRG, ALTM3100 sensor). The typical LiDAR configuration consisted of flying at 1500 m altitude at 120 km hr^{-1}, with a laser pulse repetition of 70 kHz resulting in the earth's surface being measured every 1 to 2 m horizontally with a vertical accuracy within 0.20 m. Ground returns are classified from the resultant LiDAR point cloud and a ‘bald earth’ Digital Elevation Model (DEM) is constructed. The DEM has been processed to have heights relative to the Canadian Geodetic Vertical Datum of 1928 (CGVD28) which is a close approximation of Mean Sea-Level (MSL).The key survey areas are shown in Fig. 1, and include the large drying areas in Passamaquoddy Bay (a tidal power model test site), Musquash (a federal Marine Protected Area), Parrsboro and northern Minas Basin (the landfall for tidal power development in Minas Passage), Joggins (a World UNESCO heritage site applicant), the entire North Mountain of Nova Scotia and St. Marys Bay.

Data Display

The multibeam bathymetric and LiDAR data were processed to 1 to 5 m horizontal resolution and then presented at resolutions ranging from 1 to 30 m per pixel, depending on the scale of the map or image being produced. The shaded-relief images were created by vertically exaggerating the bathymetry 10 times and then artificially illuminating the relief by a virtual light source positioned 45° above the horizon at an azimuth of 315°. In the resulting image, bathymetric and topographic features are enhanced by strong illumination on the northwest-facing slopes and by shadows cast on the southeast-facing slopes. Superimposed on the shaded-relief image are colours assigned to depth and height. The bathymetry colour bar ranges from red (shallow) to blue-violet (deep) and the topography colour bar ranges from green (at sea level) to brown-white (in the highlands) as shown in Fig. 1.

Geomorphology

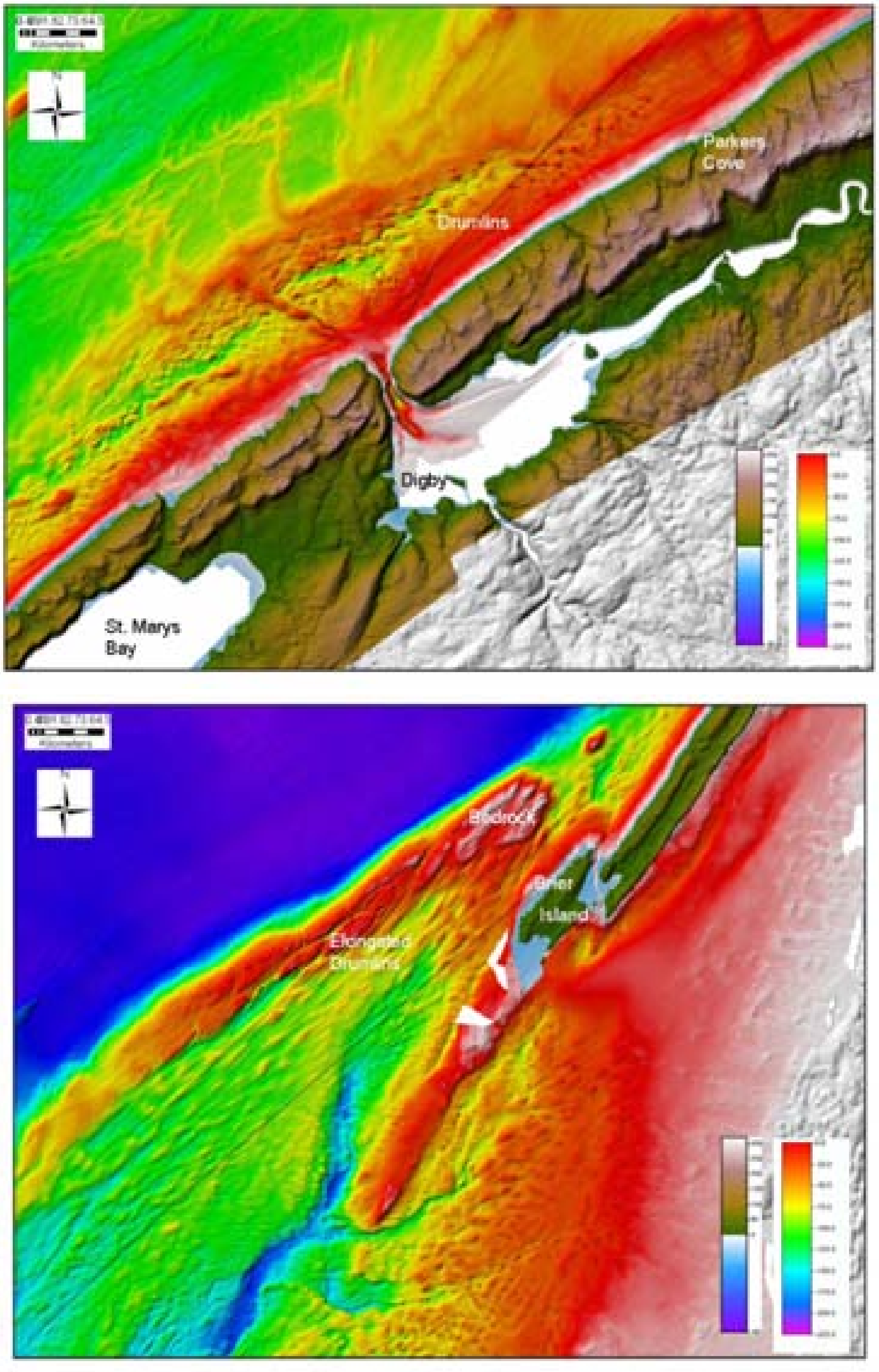
The Bay of Fundy occurs within the Carboniferous–Triassic lowland (Goldthwaite, 1924; Crosby, 1962; Atlantic Tidal Power Programming Board, 1969; Williams et al., 1972; Amos et al., 1980, Fader et al., 1977) and is underlain by Triassic sandstones, shales and basalts. Exposed bedrock has been modified by glacial erosion and exhibits a rugged surface.

During the late Wisconsinan glacial maximum, culminating in the Gulf of Maine region at approximately 20 ka (20,000 radiocarbon years BP), the Bay of Fundy was covered by a regional ice sheet that terminated to the south on the Scotian Slope (Schnitker et al., 2001; Hundert, 2003). The glacial maximum was followed by a multiphased retreat of the ice front. In the Gulf of Maine, ice-front retreat and glaciomarine deposition began as early as 18 ka. Grounded ice was absent from the Gulf of Maine and Bay of Fundy by approximately 14 ka (King and Fader, 1986; Schnitker et al., 2001; Shaw et al., 2006). The Bay of Fundy exhibits geomorphological features formed during the Quaternary glaciation and deglaciation of the area. Moraines and drumlins are topographically prominent. Large icebergs scoured and pitted the seafloor in the waters east and south of Grand Manan Island during this period.

The sea level in the Bay of Fundy has varied considerable during, and since, the last glaciation. Approximately 13 ka, relative sea level was 30 m above present levels (Amos et al., 1991, Shaw et al., 2002). After deglaciation, relative sea level fell rapidly to a lowstand 25 to 30 below the present level at c. 7 ka (Amos and Zaitlin, 1985) and then rose to present levels (Grant, 1970). From about 6.3 ka, tidal amplitude started to increase. This effect is continuing today (Godin, 1992). These high tides have resulted in large zones of erosion in areas with high current velocities such as Cape Split, Cape D'Or and Cape Enrage (see Fig. 1 for locations). Tidal eddies produced by headlands have created banner banks (Dyer and Huntley, 1999) on both sides of coastal promontories. Coastal erosion is up to 1 m a^{-1} in many areas (Amos et al., 1991). Sediment transported by this erosion, coupled with sediment from sea floor erosion and sediment delivered by rivers, has contributed to the development of broad intertidal mud flats in the inner Bay of Fundy. The coastlines of the bay also host salt marshes and dykelands. Seaward of the mud flats in the subtidal zone, the sea floor is variable in character, consisting of exposed bedrock, gravel, sand and mud. In places, strong tidal currents create sand waves several metres in height and hundreds of metres in length (Percy et al., 1997).

Interpretation of the bathymetry and LiDAR data

The new multibeam bathymetry and LiDAR imagery enables interpretation of processes relating to both ancient and modern geological processes in the bay and on the shoreline. In many cases strong correlations exist between the nature of the geological features seen onshore and offshore, although in many places the changes in sea level that have occurred in the past 14,000 years have erased evidence of features in the transgression zone. Many of the modern processes are reworking sediments that were deposited during the last glaciation.



a)

b)

Fig. 2. Multibeam bathymetry and LiDAR images of drumlins in the onshore and offshore areas between a) Parkers Cove and Digby and b) southwest of Brier Island. Bathymetry data north of the thin black line in each of the images was collected using multibeam bathymetry systems. Data south of these lines were collected using the Olex system. Locations are shown in Fig. 1.

A series of drumlins can be seen both onshore and offshore on the Nova Scotia side of the Bay of Fundy. Onshore, these features indicate an ice-flow direction that radiates from the areas of high topography in the south-central portion of Nova Scotia. Near Digby, ice appears to have flowed north from the high topography towards the Bay of Fundy. Drumlins are present in the offshore of Nova Scotia near Parkers Cove (Fig 2a) and continue southwest within about 8 km of the coast to the mouth of the Bay of Fundy. The shape of the drumlins indicates that the direction of ice flow changes from perpendicular to the coast in the nearshore, to parallel to the coast at about 8 km offshore. These drumlins change in shape from being almost circular near Digby and Parkers Cove, to elongated south of Brier Island (Fig 2b). These fields of elongated glacial landforms indicate an ice stream adjacent to the coastline of Nova Scotia during the last glacial period (before 14,000 years ago). Note the thin black line on the images in Figure 2. Bathymetry data north of the thin black line in each of the images was collected using multibeam bathymetry systems. Data south of these lines were collected using the Olex electronic chart system and made available for scientific research by the Olex AS (www.olex.no)

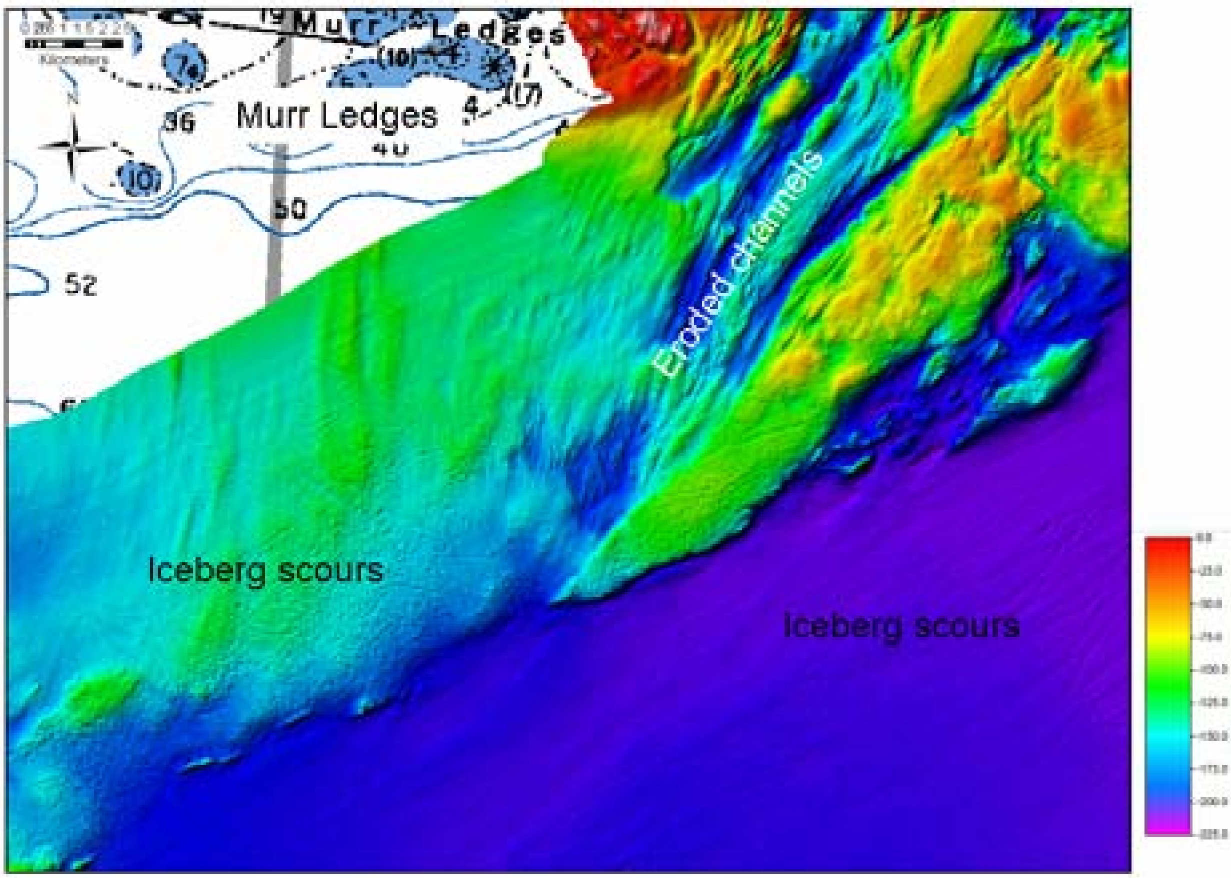


Fig. 3. The seafloor south of the Murr Ledges offshore of Grand Manan Island shows deep trenches eroded into the bedrock and iceberg scours and pits are present in the sediment covered areas, and the deep basins. Locations are shown in Fig. 1.

Fig. 3 shows an example of the iceberg scours and pits have been observed on the seafloor in the waters east and south of Grand Manan Island. Scours and pits have been observed in water depths ranging from 225 to 90 metres. We have measured scours with lengths of up to 14 km with depths ranging from < 1 to 6 m. Scour widths up to 300 m have been measured. The seafloor south of Grand Manan also shows deep trenches, eroded into the bedrock (Fig. 3) and may indicate grounded ice stream flow from the northeast.

LiDAR data indicate that the section of North Mountain near Margaretsville has the lowest elevation along this section of the range and that glacial ice likely flowed from the Annapolis Valley to the Bay of Fundy for a period, from this area. The three volcanic flow units of the North Mountain basalts can be resolved on the LiDAR (Webster et al., 2006). Large deposits of glacial material, in the form of kames and eskers, are evident onshore (Fig. 4a). Offshore is a large field of sand dunes (Fig. 4b). The largest of the sandwaves have lengths of about 1 km, widths of 100 to 200 m and heights up to 17 m.

a) b)

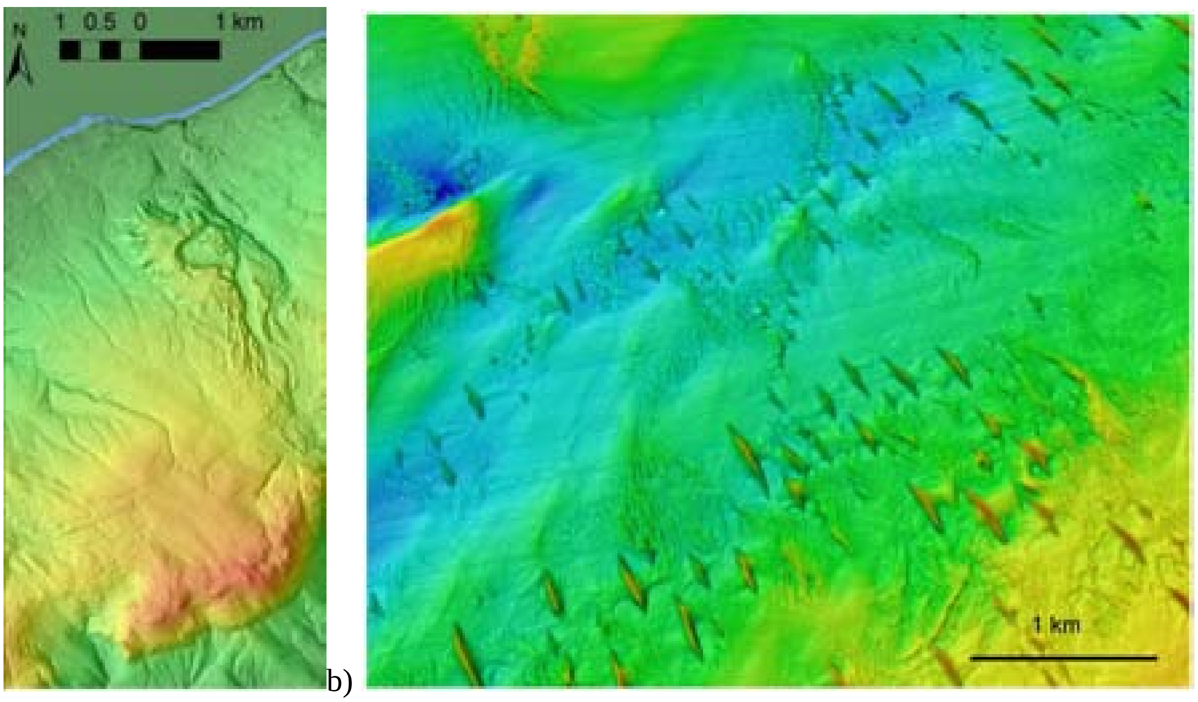


Fig. 4. a) LiDAR image of the onshore glacial deposits near Margaretsville, NS. B) Oblique aerial view of field of trapped sand dunes in the central Bay of Fundy offshore from Margaretsville, NS. Width of view is approximately 5 km. Locations are shown in Fig. 1.

Erosional trenches, formed in zones with high current velocities, are prominent in the seafloor morphology of Minas Passage shown in Fig. 5. The total volume of Quaternary sediment removed from the trenches at Cape Split and Cape D'Or, is conservatively estimated at 4 km^3. Near Cape Enrage, in Chignecto Bay (Fig. 1), an estimated 0.8 km^3 of material has been removed. This sediment volume has never featured in estimates of sediment sources in the bay (e.g., Amos and Zaitlin, 1991) and may lead to a rethinking of the origin of the amount of suspended sediments in the bay, and indeed the even larger amounts that have been sequestered in salt marshes and mud flats. The multibeam surveys have revealed the complexity in the 170 m deep scour trench in Minas Passage, north of Cape Split. To the east and west, it splays into series of separate, finger-like troughs eroded into the Quaternary sediments. At many of these sites, the tidal eddies produced by the headlands have created banner banks (Dyer and Huntley, 1999), on both sides of the coastal promontory. A pair of these 'banner banks' is seen off Cape D'Or and Cape Split. The large Scots Bay sand wave field has sand waves on the west that migrate south, and sand waves on the east side that migrate north, and the sand body is entirely surrounded by hard gravel seafloor, so that the dune field appears to be a self-contained system. The twin of the Scots Bay field is a 3 km-long, 20 m-thick body of gravel ripples, trapped inside the deep trough north off Cape Split. A field of barchan dunes located to the south of the Scots Bay dunes appears to be migrating to the north. Tidal processes likely control the location of the scour trenches and bedform fields. The Scots Bay dune field is trapped in a tidal gyre in the lee of Cape Split that appears on numerical tidal models (D. Greenberg, Pers. Comm., 2008).

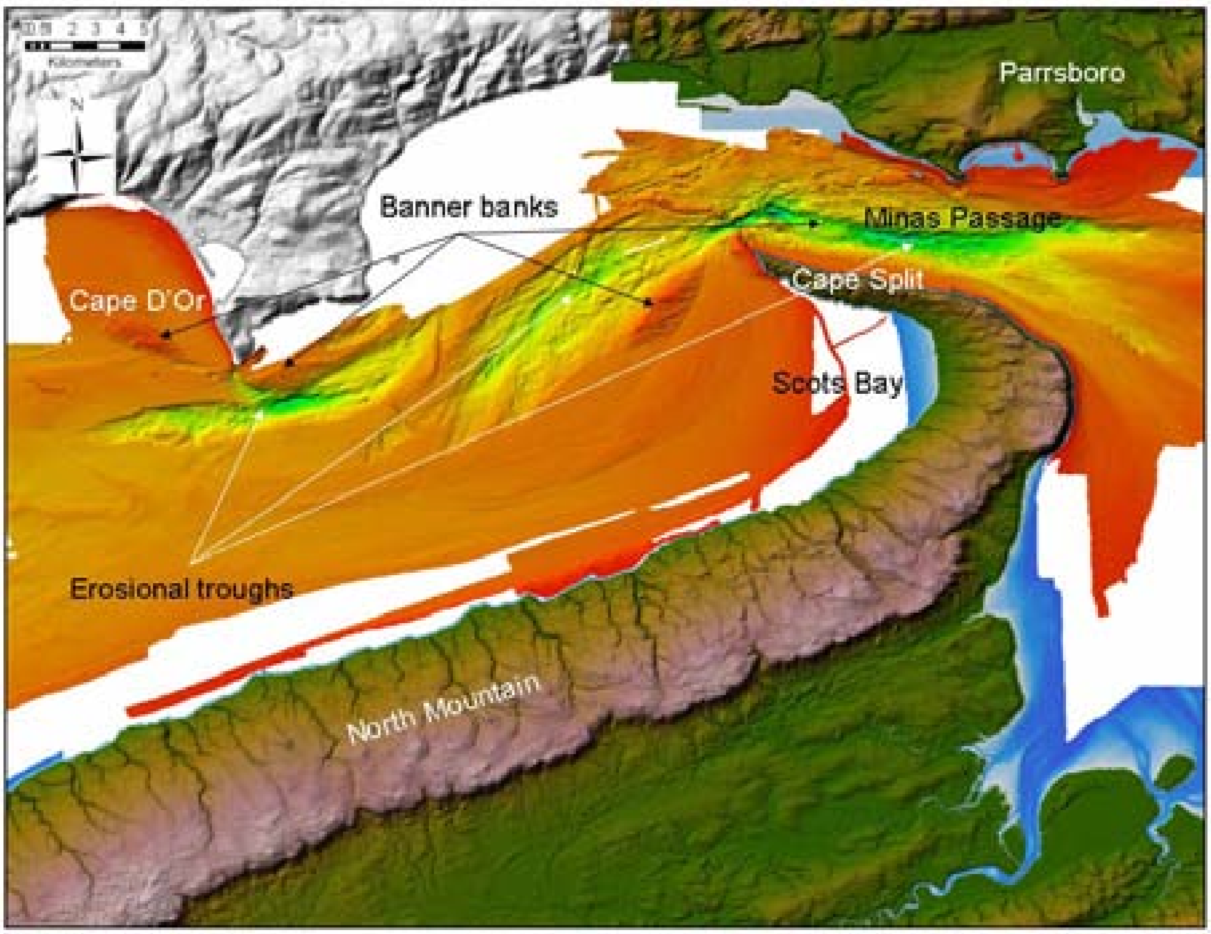


Fig. 5. The seafloor in Minas Passage has been eroded in many areas exposing bedrock. Banner banks are visible near the promontories at Cape D'Or and Cape Split. Locations are shown in Fig. 1.

Another notable feature of the upper Bay of Fundy is the presence of long and narrow, flow-parallel raised bioherms formed by horse mussels, *Modiolus modiolus* (Wildish et al, 1998) (Fig. 6). Originally described from sidescan sonograms and high-resolution seismic reflection profiles, the new multibeam bathymetry coverage indicates that the bioherms are associated with a region of low backscatter strength sediments. Horse mussels in the Bay of Fundy (Fig.6) are a key ecosystem engineer species involved in pelagic-benthic coupling (Wildish & Fader 1998). The mussel reefs appear on the multibeam bathymetric and backscatter maps as a field of raised, linear, continuous to discontinuous narrow ridges that form parallel to the dominant current direction. The mussel reefs are superimposed on the regional seabed and rise up to 3 m high above the seabed. We have measured reef lengths ranging from < 100 m to > 1000 m, and widths of 50 m. The reefs that lie on a dominantly gravel bottom appear muted without sharp edges and are lower in height as compared to those in the region of sand. This variance suggests that the proximity of sand in transport may be an essential control on the formation of the reefs (Wildish & Fader 1998).

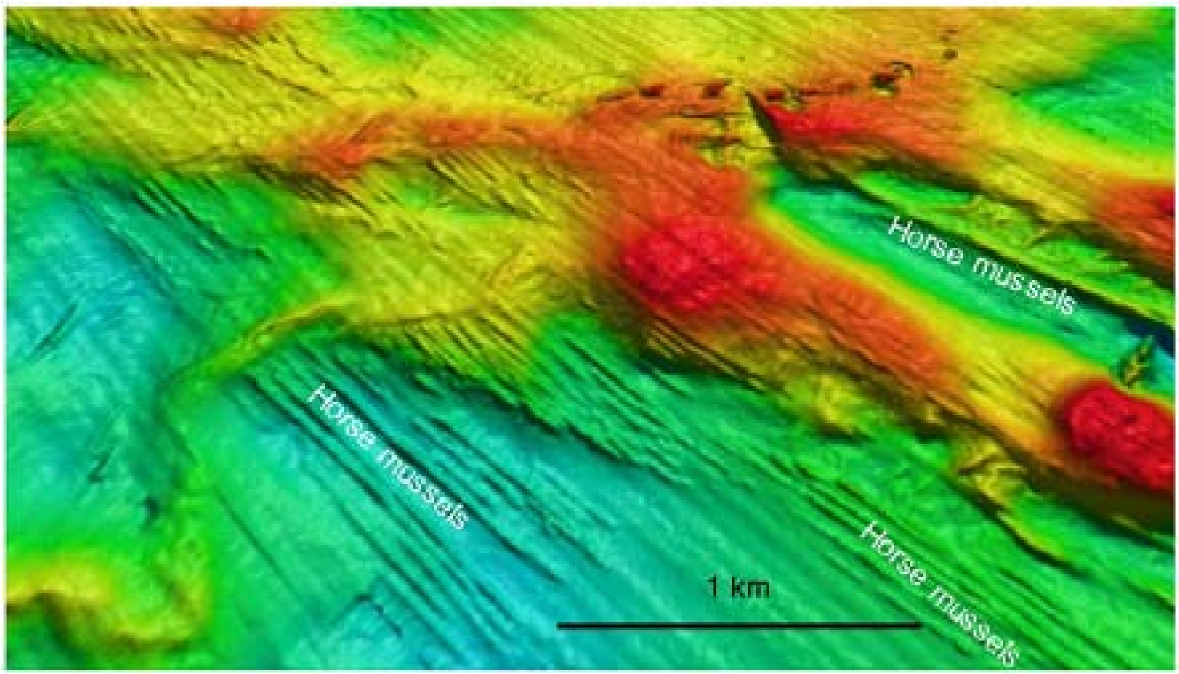


Fig. 6. Oblique view (looking west) of reefs of horse mussels which appear on the multibeam bathymetry data as a field of raised, linear, narrow ridges. The mussel ridges are aligned to the northeast, parallel to the dominant tidal current flow.

Future Work

Additional bathymetry and sub-bottom profiler data will be collected in 2008, during a 30-day survey using the CCGS *Creed* and a 60-day survey using the CCGS *Matthew* and two hydrographic launches. The focus will be to expand the existing coverage, resurvey zones of suspected seabed mobility, and provide overlap with terrestrial LIDAR in nearshore areas. Benthic and sampling surveys are planned for 2009. Bottom current and sediment transport measurements are planned for 2008.

References

Amos, C.L., Buckley, D.E., Daborn, G.R., Dalrymple, R.W., McCann, S.B., and Risk, M.J. 1980. Geological Association of Canada Field Trip Guidebook Trip 23: Geomorphology and sedimentology of the Bay of Fundy. 82p.

Amos, C.L. and Zaitlin, B.A. 1985. The Effect of Changes in Tidal Ranges on a Sublitoral Macrotidal Sequence, Bay of Fundy, Canada. Geo-Marine Letters, v. 4, p. 161-169.

Amos, C., K.T. Tee, and B.A. Zaitlin. 1991. The Post-glacial Evolution of Chignecto Bay, Bay of Fundy, and its Modern Environment of Deposition. In: D.G. Smith, G.E. Reinson, B.A. Zaitlin and R.A. Rahmani (Eds.). Clastic tidal sedimentology. Can. Soc. Petroleum Geol. Memoir 16: 59-90.

Atlantic Tidal power Programming Board. 1969. Feasibility of tidal power development in the Bay of Fundy. Board Report and Committee Report, Halifax, NS.

Canadian Hydrographic Service
1967: Natural Resource Chart 15136-A, bathymetry; Department of the Environment, Ottawa, Ontario, scale 1:250 000.

Crosby, D.G. 1962. Wolfville map area, Nova Scotia (21-H1) Geological Survey of Canada Memoir 325: 67 pp.

Church, I., Hughes Clarke, J.E., Haigh, S., Santos M., Lamplugh M., Griffin, J. and Parrott, D.R., 2008, Using Globally-Corrected GPS Solutions to Assess the Viability of Hydrodynamic Modeling in the Bay of Fundy. Proceedings of the Canadian Hydrographic Conference and National Surveyors Conference Vancouver BC, 2-5 May 2008.

Churchill, F.J. 1924. Recent changes to the coastlines in the County of Kings. Proceedings and Transactions of the Nova Scotia Intitiute of Science, v. 16: pp. 84-86.

Daborn, G.R., and Dadswell, M.J., 1986. Natural and Anthropogenic Changes in the Bay of Fundy - Gulf of Maine - Georges Bank System. in Man-Made Hazards, 1988, pp. 547-560

Dupont, F., Hannah, C.G., and Greenberg, D. 2005. Modelling the Sea Level in the Upper Bay of Fundy. Atmosphere-Ocean. 43(1), 33-47

Dyer, K.R. and David A. Huntley, D.A 1999: The origin, classification and modelling of sand banks and ridges. Continental Shelf Research. 9, pp 1285-1330

Fader, G.B., King, L.H., and MacLean, B. 1977. Surficial Geology of the eastern Gulf of Maine and Bay of Fundy. Marine Sciences Paper 19. Geological Survey of Canada Paper 76-17: 23 p.

Godin, G. 1992. Possibility of rapid changes in the tide of the Bay of Fundy, based on a scrutiny of the records from Saint John. *Continental Shelf Research,* 12, 327-338.

Goldthwaite, J.W. 1924. Physiographic of Nova Scotia. Geological Survey of Canada, Memoir 140: 179 pp.

Grant, D.R. 1970. Recent coastal submergence of the Maritime Provinces, Canada. Canadian Journal of Earth Sciences, v. 7: pp. 676-689

Hundert, T. 2003 Western Scotian Slope stratigraphy: insights into late Quaternary deglaciation of the western Scotian Shelf, eastern Canada; M.Sc. thesis, Dalhousie University, Halifax, Nova Scotia, 154 p.

Hughes Clarke, J.E., Iwanowska, K.K., Parrott, D.R., Duffy, G., Lamplugh, M., and Griffin, J., 2008. Inter-calibrating multi-source, multi-platform backscatter data sets to assist in compiling regional sediment type maps: Bay of Fundy. Proceedings of the Canadian Hydrographic Conference and National Surveyors Conference Vancouver BC, 2-5 May 2008

King, L.H. and Fader, G.B.J. 1986 Wisconsinan glaciation of the continental shelf-southeast Atlantic Canada; Geological Survey of Canada, Bulletin 363, 72 p.

Olex SA. Website at www.Olex.no. Accessed 2008-04-17.

O'Reilly, C.T., Solvason, R. and Solomon, C. (2005). "Where are the World's Largest Tides?" BIO Annual Report "2004 in Review", Editor Judith Ryan, ISBN:0-662-40330-4, pp 44 -46.

Percy, J.A., Wells, P.G., and Evans, A.J. (eds) 1997: Bay of Fundy issues: a scientific overview, Workshop Proceedings, Wolfville, Nova Scotia, January 29 to February 1, 1996. Environment Canada, Atlantic Region Occasional Report no. 8, Environment Canada, Sackville, New Brunswick, 191 p.

Schnitker, D., Belknap, D.F., Bacchus, T.S., Friez, J.K., Lusardi, B.A., and Popek, D.M. 2001: Deglaciation of the Gulf of Maine; Deglacial History and Relative Sea-level Changes, Northern New England and Adjacent Canada, (ed.) T.K. Weddle and M.J. Retalle; Boulder, Colorado, Geological Society of America, Special Paper 351, p. 9–34.

Shaw, J., Gareay, P. and Courtney, R.C., 2002. Paleography of Atlantic Canada 13-0 kyr. Quat. Sci. Rev. 21, 1861-1878.

Webster, T.L., Murphy, J.B., Gosse, J.C., and Spooner, I. 2006. The application of LIDAR-derived DEM analysis for geological mapping: An example from the Fundy Basin, Nova Scotia, Canada. Canadian Journal of Remote Sensing, Vol. 32, No. 2, pp. 173-193.

Williams, H.M.J., Kennedy, M.J., and Neale, E.R.W. 1972. The Appalachian structural province. In Variations in Tectonic Styles in Canada; edited by R.A. Price and R.J.W. Douglas. Geological Association of Canada Special Paper 11: pp. 182-261

Wildish, D.J., and Fader, G.B. 1998. Pelagic-benthic coupling in the Bay of Fundy. Hydrobiologia 356/357: 369-380.

Author biographies

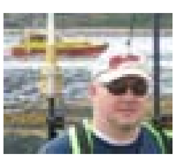
Russell Parrott is a marine geophysicist specializing in high resolution survey techniques at the Geological Survey of Canada, Atlantic. He is the project leader for the Bay of Fundy project. He holds an M.Eng degree in Applied Geophysics from McGill University, Montreal.

Geological Survey of Canada, Natural Resources Canada
Box 1006, Dartmouth, NS, Canada, B2A 4A2, Phone 901-426-7059, rparrott@nrcan.gc.ca

Brian Todd is a marine geoscientist at the Geological Survey of Canada at the Bedford Institute of Oceanography. He is part of the GSC group developing a new marine map series based on multibeam bathymetric data in conjunction with geological and geophysical information. These maps are used to interpret the glacial and deglacial history of Canada's continental shelves. He has a Ph.D. in geology from Dalhousie University in Halifax

John Shaw is a research scientist with the Geological Survey of Canada, part of Natural Resources Canada, and is based at the Bedford Institute of Oceanography. Research interests include the glacial history of Atlantic Canada, postglacial sea-level changes and their effects on coastlines, and making geological maps based on multibeam data.

John E. Hughes Clarke is the Chair in Ocean Mapping at the University of New Brunswick. With a background in marine geology and oceanography, his prime interest is in taking advantage of the limits of resolution and accuracy achievable with both the bathymetry and backscatter from swath sonar systems to examine marine sediment transport.



Jon Griffin is a hydrographer with the CHS-Atlantic, and is currently a Chief Hydrographer aboard the CCGS Matthew for the 2008 survey season. Jon joined the CHS in 1991, and has been primarily involved with field programs in support of science and hydrography since then. He has a Masters of Engineering from UNB.

Bruce MacGowan is a senior hydrographer with the CHS-Atlantic, who has been involved in traditional and multibeam bathymetric surveys for over 30 years.

Michael Lamplugh has been a field hydrographer in CHS-Atlantic since 1977. He was H-I-C aboard the *F G Creed* until he moved (2002) to the *CCGS Matthew*. Starting in 2003 he worked hard to upgrade the sounding capability of the *Matthew* from an EM100 to the high-resolution EM710, this was achieved in 2006 (& both launches have EM3002 systems).

Tim Webster is a Research Scientist with the Applied Geomatics Research Group at the Nova Scotia Community College. He obtained his PhD from Dalhousie University where he used high-resolution LIDAR DEMs to investigate landscape evolution through fluvial and glacial processes. Other research includes coastal flood risk mapping from storm-surge events and long term sea-level rise.