

DESCRIPTIVE NOTES

INTRODUCTION The Bay of Fundy, located on the east coast of Canada between the provinces of Nova Scotia and New Brunswick (Fig. 1), is a macrotidal estuarine embayment (Amos et al., 1980) with the highest recorded tides in the world of 17 m (O'Reilly et al., 2005; Bishop, 2008). This map is one of a series of maps that show seafloor relief of the Bay of Fundy and topography of the surrounding areas in shaded-relief view (coded by colour) at a scale of 1:50 000. The maps are based on multibeam-sonar surveys completed between 1993 and 2009 to map 13 010 km² of the seafloor. Water-depth contours generated from the multibeam-sonar data are shown (in white) on the colour-coded water-depth image at a depth interval of 20 m. Bathymetric contours (in blue) outside the multibeam survey area, presented at a depth interval of 50 m, are from the Natural Resource Map series (Canadian Hydrographic Service, 1967, 1974a, b, c). The broad intertidal zone in the Bay of Fundy presented a particular surveying challenge to the collection of water-depth data. Historically, the intertidal zone was not surveyed due to the danger involved in operating vessels in coastal areas that dry between tides. As part of the multibeam-sonar mapping, the intertidal zone was surveyed at high tide using shallow-draft survey vessels, thus overcoming operational challenges associated with deeper draft survey vessels. The complete Bay of Fundy seafloor relief map coverage is composed of seventeen adjacent map areas at a scale of 1:50 000 (Fig. 1). In total, fifty-one maps constitute the Bay of Fundy map suite (three

maps per map area: seafloor relief, backscatter strength, and surficial geology). MULTIBEAM BATHYMETRY DATA COLLECTION

Multibeam-sonar water-depth data were collected by the Canadian Hydrographic Service, the Geological Survey of Canada, and the University of New Brunswick. The survey systems use a sonar beam over an arc of about 130° across the ship's track and operate by ensonifying a narrow strip of seafloor along track and detecting the seafloor by resolving the returned echo into multiple beams (Courtney and Shaw, 2000). The width of seafloor imaged on each survey line was generally four times the water depth. Line spacing was about two to three times water depth to provide ensonification overlap between adjacent lines. The survey employed a variety of survey vessels including: • the Canadian Coast Guard Ship (CCGS) Frederick G. Creed, a SWATH (Small Waterplane Area Twin Hull) vessel equipped with a Kongsberg EM1000 (prior to 2003) and a Kongsberg EM1002 (post-

2003) multibeam-sonar bathymetric survey system with 111 beams operating at 95 kHz with the

• the CCGS Matthew equipped with a Kongsberg EM710 multibeam-sonar bathymetric survey system with 200 or 400 beams operating at 70–90 kHz with the transducer mounted near the centre of the • hydrographic survey launches Plover, Pipit, and Heron equipped with Kongsberg EM3000 (prior to

and Fisheries and Oceans Canada Coastal Oceanography Group (Dupont et al., 2005).

2005) and Kongsberg EM3002 (post-2005) multibeam-sonar bathymetric survey systems with 160 to 254 beams operating at 300 kHz. The Differential Global Positioning System was used for navigation and provided a positional accuracy of ±3 m. Survey speeds averaged 12 knots (22.2 km/h) on the CCGS Creed (and slower on the other survey vessels), resulting in an average data collection rate of about 2.5 km²/h in water depths of 35–70 m. The sound velocity in the ocean was measured during multibeam-sonar data collection and used to correct the effect of sonar-beam refraction. The 1992-2006 data were adjusted for tidal variation using tidal measurements and predictions from the Canadian Hydrographic Service. During the 2008 surveys, vessel elevations were also acquired using a combination of real-time kinematic GPS systems (Church et al., 2008) and hydrodynamic tidal models developed by the Canadian Hydrographic Service

BATHYMETRIC DATA DISPLAY

transducer mounted in the starboard pontoon.

The multibeam-sonar bathymetric data are presented at 5 m per pixel horizontal resolution. The shadedrelief image is presented with a vertical exaggeration of the bathymetry of 10 times and an artificial illumination of the relief by a virtual light source positioned 45° above the horizon at an azimuth of 315°. In the resulting image, bathymetric 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 water depth, ranging from red (shallow) to violet (deep). In order to apply the widest colour range to the most frequently occurring water depths, hypsometric analysis was used to calculate the cumulative frequency of water depth. The resulting colour ramp highlights subtle variations in water depth that would otherwise be obscured. Some features in the multibeam data are artifacts of data collection and environmental conditions during the survey periods. The orientation of the survey track lines can, in some instances, be identified

by faint parallel stripes in the image. Because these artifacts are usually regular and geometric in

appearance on the map, the human eye can disregard them and distinguish real topographic features. BAY OF FUNDY GEOMORPHOLOGY

The Bay of Fundy is a southwest-trending funnel-shaped bay 155 km long that is 70 km wide at its entrance and tapers to 48 km wide at its northeastern end where it bifurcates into Chignetco Bay and Minas Channel (Fig. 1). The floor of the bay, although hummocky in detail, presents a gently dipping profile along its axis from northeast to southwest. Grand Manan Island and its adjacent southeastern shoals occupy nearly half the entrance to the bay, and divide it into two channels. Between Brier Island and Grand Manan Island lie several isolated depressions that together form Grand Manan Basin. The maximum water depth within these depressions is 233 m and the depth to the sill between Grand Manan Basin and the adjoining deeper parts of the Gulf of Maine is 160 m. The large tidal oscillations within this geomorphic setting are due to the near resonance between the principal lunar semidiurnal (M_2) component of the tide (representing 90% of the tidal energy) and the natural period (about 13 hours) of the Bay of Fundy–Gulf of Maine system. Tidal current speeds are about 0.75–1 m/s over much of the outer and central portions of the bay, but are considerably higher within

Geomorphological features revealed through mapping of the Bay of Fundy seafloor reflect the geological

history of the region. The Bay of Fundy is situated within the Carboniferous-Triassic lowland (Goldthwaite, 1924; Crosby, 1962; Williams et al., 1972) and is underlain by Triassic and Early Jurassic sandstone, shale, and basalt (Wade et al., 1996). 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 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, drumlins, and megaflutes are topographically prominent. After grounded ice retreated from the area, icebergs scoured the seafloor in the waters east and south of Grand Manan Island. After deglaciation, relative sea level fell rapidly to a lowstand of about -30 m at ca. 7 ka (Amos and Zaitlin, 1985; Shaw et al., 2002) and then rose (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 (Fig. 1). Tidal eddies produced by headlands have created banner banks (Dver and Huntley, 1999) on both sides of coastal promontories. Coastal erosion is up to 6 m/a in some areas (Amos et al., 1991). Sediment derived from this coastal erosion, coupled with sediment from seafloor 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 (Ganong, 1903; Gordon et al., 1985). Seaward of the mud flats in the subtidal zone, the seafloor 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 (Greenberg et al., 1997).

Geomorphology of this map

A series of detailed maps at a scale of 1:25 000 (Fig. 3–7) highlights geomorphological features in Minas Channel and Minas Passage. For each of these detailed maps, the colour-range values are hypsometrically optimized and differ from the 1:50 000 map sheet colour-range values. This map shows the bathymetry of the northeastern Bay of Fundy, encompassing Minas Channel, Minas Passage, and Minas Basin. The large tidal range and topographic constrictions in this part of the Bay of Fundy generates strong currents. Currents of 7–8 knots (13–15 km/h) occur on the south side of Minas Passage adjacent to Cape Split with currents of 5–6 knots (9–11 km/h) on the north side (Canadian Hydrographic Service, 2003). The harnessing of these currents to generate power has been the focus of engineering schemes dating to 1910 (Baker, 1982) and periodically has garnered attention throughout the twentieth century (Daborn and Dadswell, 1988; Desplanque and Mossman, 2004). In the 1960s, a plan to construct a tidal dam was abandoned, partly due to predicted widespread environmental effects including alteration to the tidal range throughout the Bay of Fundy and Gulf of Maine. With revived interest in renewable energy Minas Passage is now the subject of an engineering study as a site for electricity

Multibeam-sonar mapping of this region of the Bay of Fundy reveals a complex seafloor geomorphology much affected by tidal currents. During glacial and deglacial time, it is likely that sediment was deposited throughout Minas Channel and Minas Passage. As the ice sheet ablated and sea level rose, the high tidal range of the Bay of Fundy began to develop about 7000 BP (Scott and Greenberg, 1983; Gehrels et al., 1995). Powerful currents sweeping through Minas Passage eroded the Quaternary sediments and created a scour trough that reaches a depth of 170 m and splays to the west and east in a series of separate, finger-like troughs (Shaw et al., 2010) (Fig. 2, 3). The volume of Quaternary sediment removed from the trough is conservatively estimated at 4 km³. Outcropping bedrock lies at the core of the scour trough (Fig. 4).

Approximately 44 km² of bedrock is exposed in Minas Passage, almost all of which is below 50 m water depth (Todd and Shaw, 2009). Although exposed bedrock predominates in Minas Passage and Minas Channel, there are notable current-formed sedimentary features, specifically the twinned sets of bedforms, or banner banks (Dver and Huntley, 1999) that are situated on either side of the prominent headland of Cape Split. The orientation and asymetry of the bedforms in the Scots Bay banner bank (Fig. 5) indicates that bedform migration is counterclockwise, being to the south on the west side of the banner bank and to the north on the east side of the banner bank. This extensive sand deposit is surrounded by a immobile gravel seafloor (Fader and Miller, 1991), suggesting that the sand-wave field is a self-contained system, likely trapped within a large tidal eddy. South of the banner bank in outer Scots Bay is a field of barchans (Fig. 6). The geometry of these bedforms indicates net sediment transport to the northeast. The twin of the Scots Bay banner bank is a 3 km long, 20 m thick banner bank trapped in the deep bedrock trough north of Cape Split (Fig. 7). This feature is composed of gravel (Todd et al., 2010) and the bedforms on the northern flank of the banner bank are gravel waves.

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Fundy, Canada; Geo-Marine Letters, v. 4, p. 161–169.

REFERENCES

Amos, C.L. and Zaitlin, B.A., 1985. The effect of changes in tidal range on a sublittoral macrotidal sequence, Bay of

Amos, C.L., Buckley, D.E., Daborn, G.R., Dalrymple, R.W., McCann, S.B., and Risk, M.J., 1980. Geomorphology and sedimentology of the Bay of Fundy; Geological Association of Canada, Field Trip Guidebook Trip 23, 82 p. Amos, C.L., Tee, K.T., and Zaitlin, B.A., 1991. The post-glacial evolution of Chignecto Bay, Bay of Fundy, and its modern environment of deposition; *in* Clastic tidal sedimentology, (ed.) D.G. Smith, G.E. Reinson, B.A. Zaitlin, and R.A. Rahmani; Canadian Society of Petroleum Geologists, Calgary, Alberta, Memoir 16, p. 9–90. Baker, G.C., 1982. Some historical aspects of tidal power; in New approaches to tidal power, conference proceedings; Bedford Institute of Oceanography, Dartmouth, Nova Scotia, 9 p. Bishop, R., 2008. Tides and the earth-moon system; in Observer's handbook 2009, Royal Astronomical Society of Canadian Hydrographic Service, 1967. Natural Resource Chart 15136-A, bathymetry; Department of the Environment, Canadian Hydrographic Service, 1974a. Natural Resource Chart 15144-A, bathymetry; Department of the Environment, Ottawa, Ontario, scale 1:250 000. Canadian Hydrographic Service, 1974b. Natural Resource Chart 15146-A, bathymetry; Department of the Environment, Ottawa, Ontario, scale 1:250 000. Canadian Hydrographic Service, 1974c. Natural Resource Chart 15154-A, bathymetry; Department of the Environment, Canadian Hydrographic Service, 2003. Bay of Fundy, Inner Portion; Hydrographic Chart 4010, scale 1:200 000. Church, I., Hughes Clarke, J.E., Haigh, S., Santos, M., Lamplugh, M., Griffin, J., and Parrott, D.R., 2008. Using globallycorrected GPS solutions to assess the viability of hydrodynamic modeling in the Bay of Fundy; in Proceedings of the Canadian Hydrographic Conference and National Surveyors Conference, Vancouver, British Columbia, 2–5 May Courtney, R.C. and Shaw, J., 2000. Multibeam bathymetry and backscatter imaging on the Canadian continental shelf; Geoscience Canada, v. 27, p. 31–42.

Crosby, D.G., 1962. Wolfville map area, Nova Scotia; Geological Survey of Canada, Memoir 325, 67 p. Daborn, G.R. and Dadswell, M.J., 1988. Natural and anthropogenic changes in the Bay of Fundy-Gulf of Maine-Georges Bank system: in Natural and man-made hazards, (ed.) M.I. El-Sabh and T.S. Murty; D. Reidel, Dordrecht, The Netherlands, p. 547–560. $Desplanque, C.\ and\ Mossman, D.J., 2004.\ Tides\ and\ their\ seminal\ impact\ on\ the\ geology,\ geography,\ history,\ and\ socio-linear properties of the properties of th$ economics of the Bay of Fundy, eastern Canada; Atlantic Geology, v. 40, p. 1–130. Dupont, F., Hannah, C.G., and Greenberg, D., 2005. Modelling the sea level of the upper Bay of Fundy; Atmosphere-Dyer, K.R. and Huntley, D.A., 1999. The origin, classification and modelling of sand banks and ridges; Continental Shelf Research, v. 19, p. 1285-1330. Fader, G.B.J. and Miller, R.O., 1991. The Scots Bay sand wave field, Bay of Fundy: an example of potential environmental enhancement by extraction (abstract): Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Program with Abstracts, v. 16, p. A35 Ganong, W.F., 1903. The vegetation of the Bay of Fundy salt and diked marshes: an ecological study; Botanical Gazette, v. 36, p. 161–186, 280–302, 349–367, 429–455.

Gehrels, W.R., Belknap, D.F., Pearce, B.R., and Gong, B., 1995. Modeling the contribution of M2 tidal amplification to the Holocene rise of mean water level in the Gulf of Maine and the Bay of Fundy; Marine Geology, v. 124, p. 71–85. $Godin, G., 1992. \ Possibility \ of rapid changes in the \ tide of the Bay of Fundy, based on a scrutiny of the records from Saint Incomplete the street of the Bay of Fundy, based on a scrutiny of the records from Saint Incomplete the Sai$ John; Continental Shelf Research, v. 12, p. 327–338. Goldthwaite, J.W., 1924. Physiography of Nova Scotia; Geological Survey of Canada, Memoir 140, 179 p.

Gordon, D.C., Jr., Cranford, P.J., and Desplanque, C., 1985. Observations on the ecological importance of salt marshes

in the Cumberland Basin, a macrotidal estuary in the Bay of Fundy; Estuarine, Coastal and Shelf Science, v. 20, Grant, D.R., 1970. Recent coastal submergence of the Maritime Provinces, Canada; Canadian Journal of Earth Greenberg, D.A., 1990. The contribution of modeling to understanding the dynamics of the Bay of Fundy and Gulf of Maine; Chapter 5 in Modeling marine systems, (ed.) A.M. Davies; CRC Press, Boca Raton, Florida, p. 107–140. Greenberg, D.A., Petrie, B.D., Daborn, G.R., and Fader, G.B., 1997. The physical environment of the Bay of Fundy; Chapter 2 in Bay of Fundy issues: a scientific overview, (ed.) J.A. Percy, P.G. Wells, and A.J. Evans; Environmen Canada, Atlantic Region Occasional Report no. 8, Environment Canada, Sackville, New Brunswick, p. 11–36. Hundert, T., 2003. Western Scotian Slope stratigraphy: insights into late Quaternary deglaciation of the western Scotian King, L.H. and Fader, G.B.J., 1986. Wisconsinan glaciation of the Atlantic continental shelf of southeast Canada; Geological Survey of Canada, Bulletin 363, 72 p. O'Reilly, C.T., Solvason, R., and Solomon, C., 2005. Where are the world's largest tides?; 2004 in review, Bedford Institute of Oceanography annual report, (ed.) J. Ryan; Fisheries and Oceans Canada and Natural Resources Canada, Dartmouth, Nova Scotia, p. 44–46. 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; in Deglacial history and relative sea-level changes, northern New England and adjacent Canada, (ed.) T.K. Weddle and M.J. Retalle; Geological Society of America, Boulder, Colorado, Special Paper 351, p. 9–34. Scott, D.B. and Greenberg, D.A., 1983. Relative sea-level rise and tidal development in the Fundy tidal system; Canadian Journal of Earth Sciences, v. 20, p. 1554–1564. Shaw, J., Amos, C.L., Greenberg, D.A., O'Reilly, C.T., Parrott, D.R., and Patton, E., 2010. Catastrophic tidal expansion in the Bay of Fundy, Canada; Canadian Journal of Earth Sciences, v. 47, p. 1079–1091. Shaw, J., Gareau, P., and Courtney, R.C., 2002. Paleogeography of Atlantic Canada 13-0 kyr; Quaternary Science Reviews, v. 21, p. 1861–1878. Shaw, J., Piper, D.J.W., Fader, G.B.J., King, E.L., Todd, B.J., Bell, T., Batterson, M.J., and Liverman, D.G.E., 2006. Todd, B.J., Brown, O., Fromm, S.A., Hayward, S.E., Jerosch, K., Kostylev, V.E., Li, M.Z., Manning, D., Meslin, P., Middleton, G., Patton, E., Pledge, P.E., Robertson, A., Shaw, J., Spencer, P.L., and Standen, G., 2010. Expedition report CCGS *Hudson* 2009-039: Bay of Fundy; Geological Survey of Canada, Open File 6684, 413 p. Todd, B.J. and Shaw, J., 2009. International Year of Planet Earth 5. Applications of seafloor mapping on the Canadian Atlantic continental shelf; Geoscience Canada, v. 36, p. 81–94.

Wade, J.A., Brown, D.E., Traverse, A., and Fensome, R.A., 1996. The Triassic-Jurassic Fundy Basin, eastern Canada: regional setting, stratigraphy and hydrocarbon potential; Atlantic Geology, v. 32, p. 189–231. Williams, H.M.J., Kennedy, M.J., and Neale, E.R.W., 1972. The Appalachian structural province; in Variations in tectonic styles in Canada, (ed.) R.A. Price and R.J.W. Douglas; Geological Association of Canada, Special Paper 11,

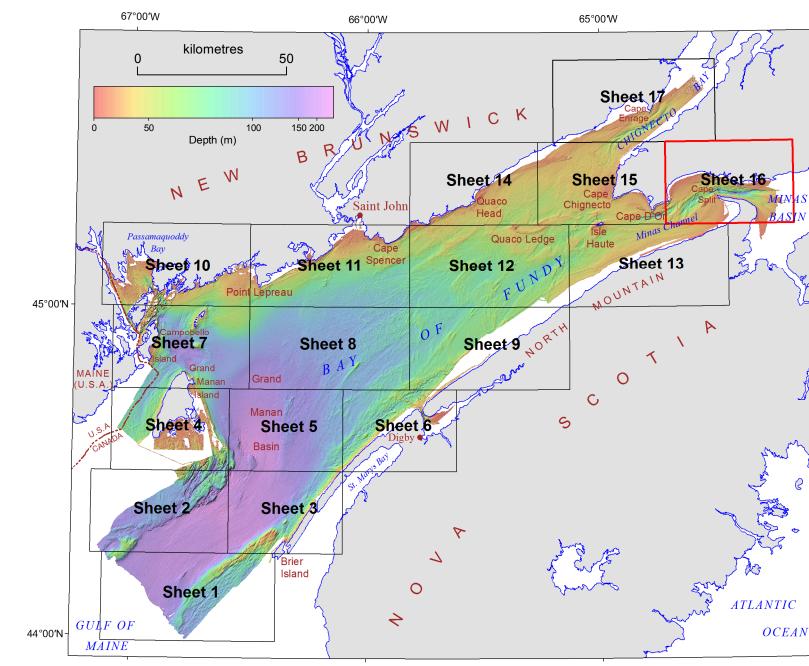


Figure 1. Location map showing seventeen 1:50 000 map sheets covering the Bay of Fundy. Sheet 16 (outlined by red box) is in northeastern Bay of Fundy encompassing Minas Passage and Minas Basin, Nova Scotia.

BAY OF FUNDY, SHEET 16 OFFSHORE NOVA SCOTIA-NEW BRUNSWICK

Scale 1:50 000/Échelle 1/50 000 Système de référence géodésique nord-américain, 1983 North American Datum 1983 © Her Majesty the Queen in Right of Canada 2011 © Sa Majesté la Reine du chef du Canada 2011 This map is not to be used for navigational purposes Cette carte ne doit pas être utilisée aux fins de navigation

Any revisions or additional geographic information known to the user would be welcomed by the Geological Survey of Canada Digital base map (land area) from data compiled by Geomatics Canada,

modified by GSC (Atlantic)

Digital bathymetric contours in metres supplied by Canadian Hydrographic Service Magnetic declination 2011, 18°20'W, decreasing 8.1' annually

> Elevations in metres above mean sea level Depth in metres below mean sea level

Authors: B.J. Todd, J. Shaw, and D.R. Parrott

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Multibeam bathymetric data collected by Canadian Hydrographic Service, 1993, 2006–2009; Geological Survey of Canada 1999–2003, 2006–2009;

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Multibeam bathymetric data compiled by Canadian Hydrographic Service,

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