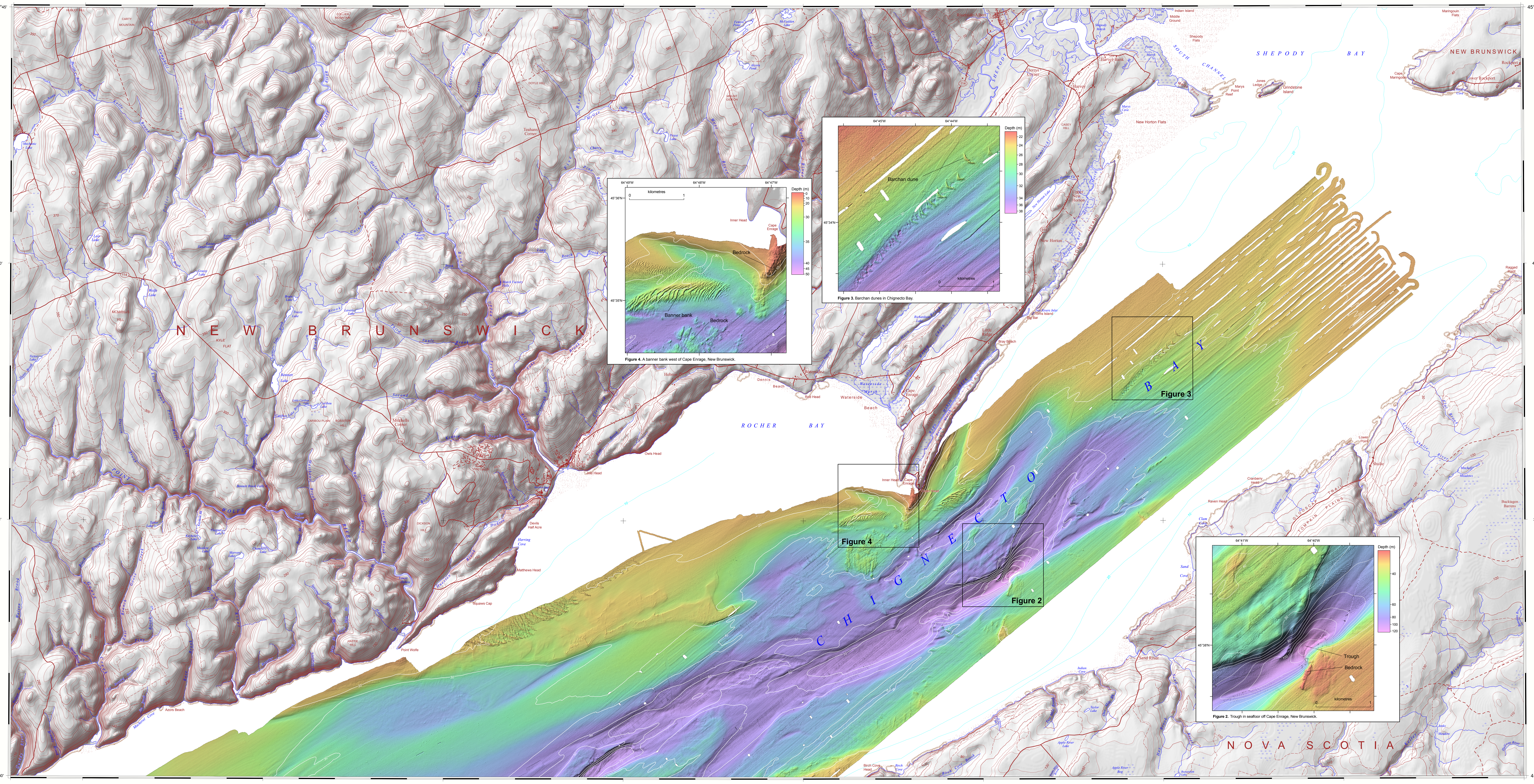

Figure 4. A banner bank west of Cape Enrage, New Brunswick.

Figure 3. Barchan dunes in Chignecto Bay.

Figure 2. Trough in seafloor off Cape Enrage, New Brunswick.

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 km^2 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 transducer mounted in the starboard pontoon,
- 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 vessel, and
- hydrographic survey launches *Plover*, *Pipit*, and *Heron* equipped with Kongsberg EM3000 (prior to 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 km^2/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 and Fisheries and Oceans Canada Coastal Oceanography Group (Dupont et al., 2005).

BATHYMETRIC DATA DISPLAY

The multibeam-sonar bathymetric data are presented at 5 m per pixel horizontal resolution. The shaded-relief 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 constricted channels and passages to the northeast (Greenberg, 1990).

Geological history

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 (Dyer 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. 2–4) highlights the geomorphological features in northeastern Bay of Fundy. 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 Chignecto Bay in northeastern Bay of Fundy (Fig. 1). Water depths reach 110 m in a trough off Cape Enrage (Fig. 2). Chignecto Bay is blanketed by glacial and postglacial unconsolidated sediment (Amos et al., 1991). In places, the sediment is organized into bedforms under the influence of the current regime in the bay. Barchan dunes, up to 3 m in height, form a train of bedforms oriented southwest-northeast in 30 m of water in the middle of the bay (Fig. 3). Sediment is often found deposited as banner banks (Dyer and Huntley, 1999), flanking prominent headlands in the Bay of Fundy, such as Cape Enrage (Fig. 4).

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REFERENCES

Amos, C.L. and Zaitlin, B.A., 1985. The effect of changes in tidal range on a sublittoral macrotidal sequence, Bay of Fundy, Canada; Geo-Marine Letters, v. 4, p. 161–169.

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. 59–90.

Bishop, R., 2008. Tides and the earth-moon system; *in* Observer's handbook 2009, Royal Astronomical Society of Canada, p. 183–187.

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

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, Ottawa, Ontario, scale 1:250 000.

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; *in* Proceedings of the Canadian Hydrographic Conference and National Surveyors Conference, Vancouver, British Columbia, 2–5 May 2008, 23 p.

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.

Dupont, F., Hannah, C.G., and Greenberg, D., 2005. Modelling the sea level of the upper Bay of Fundy; Atmosphere-Ocean, v. 43, p. 33–47.

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.

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.

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, 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, p. 205–227.

Grant, D.R., 1970. Recent coastal submergence of the Maritime Provinces, Canada; Canadian Journal of Earth Sciences, v. 7, p. 676–689.

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; Environment Canada, Atlantic Region Occasional Report no. 8, Dartmouth, Nova Scotia and Sackville, New Brunswick, p. 11–36.

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.

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?; *in* 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.

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. A conceptual model of the deglaciation of Atlantic Canada; Quaternary Science Reviews, v. 25, p. 2059–2081.

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, p. 182–261.

0 25 50 75 100

Depth (m)

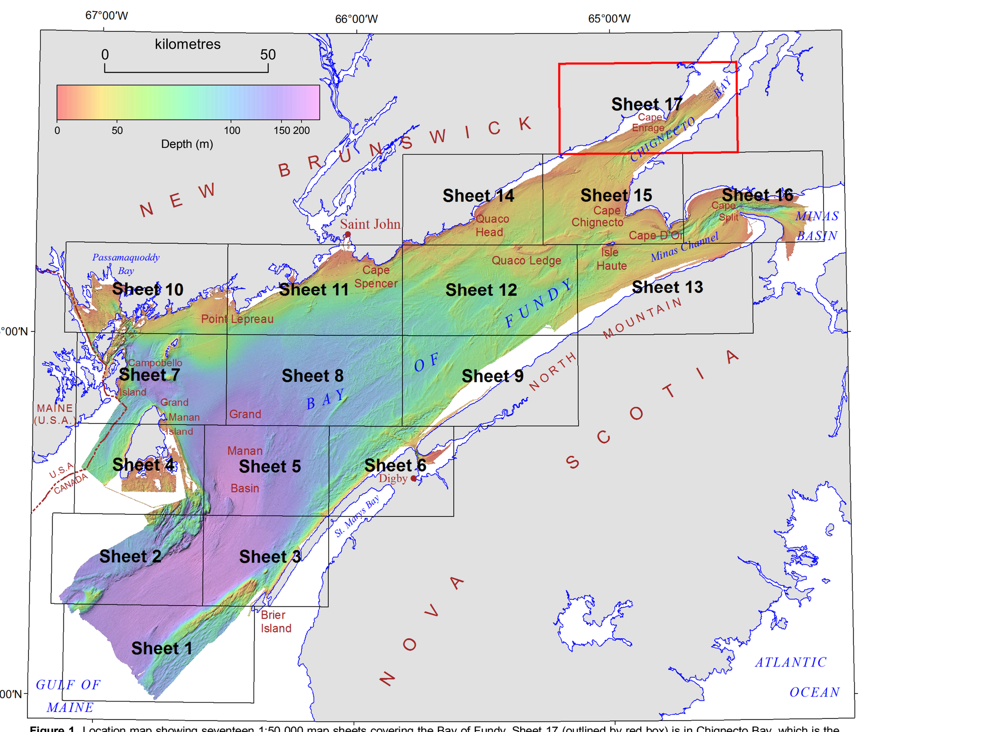

Figure 1. Location map showing seventeen 1:50 000 map sheets covering the Bay of Fundy. Sheet 17 (outlined by red box) is in Chignecto Bay, which is the northeastern extension of the Bay of Fundy.

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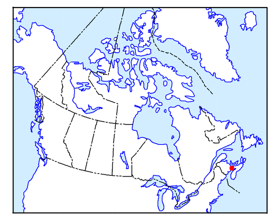
doi:10.4095/288694



LOCATION MAP

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

This map was produced by Natural Resources Canada in co-operation with Fisheries and Oceans Canada

Multibeam bathymetric data collected by Canadian Hydrographic Service, 1993, 2006–2009; Geological Survey of Canada 1999–2003, 2006–2009; and University of New Brunswick 1993, 1994, 2002–2008

Multibeam bathymetric data compiled by Canadian Hydrographic Service, Geological Survey of Canada, and University of New Brunswick 1993–2010

Digital cartography by P.A. Melbourne, Data Dissemination Division (DDD); and G. Grant, S.E. Hayward, and E. Patton, GSC (Atlantic)

MAP 2190A

SHADED SEAFLOOR RELIEF

BAY OF FUNDY, SHEET 17

OFFSHORE NOVA SCOTIA–NEW BRUNSWICK

Scale 1:50 000/Échelle 1/50 000

kilometres 1 0 1 2 3 4 kilometrès

Universal Transverse Mercator Projection	Projection transverse universelle de Mercator
North American Datum 1983	Système de référence géodésique nord-américain, 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

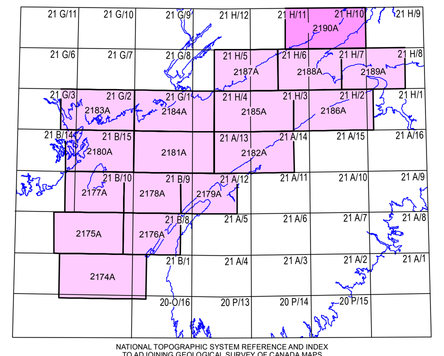
Digital base map (land area) from data compiled by Geomatics Canada, modified by GSC (Atlantic)

Digital bathmetric contours in metres supplied by Canadian Hydrographic Service and GSC (Atlantic)

Magnetic declination 2011, 18°20'W, decreasing 8.1' annually

Elevations in metres above mean sea level

Depth in metres below mean sea level



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