

GEOLOGICAL SURVEY OF CANADA







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associated surficial geology map. GEOLOGICAL HISTORY The morphology of the Gulf of Maine and Georges Bank is the result of marine sediment deposition during the Mesozoic (65–251 million years ago) and Cenozoic (present-65 million years ago) eras, erosion during the Tertiary period (1.8-65 million years ago), and glacial erosion and deposition during the Pleistocene epoch (11,430 years to 1.8 million years ago) of the Quaternary period (Uchupi and Bolmer, 2008). Seismic reflection profiles show that beneath the surface of Georges Bank there is a prominent unconformity formed on late Cretaceous and Tertiary sedimentary rocks (King and MacLean, 1976; Lewis et al., 1980). The surficial sediment overlying the unconformity forms a veneer of glacial

debris transported to Georges Bank and other Gulf of Maine banks during the late Pleistocene epoch

from continental areas to the north (Shepard et al., 1934; Knott and Hoskins, 1968; Oldale and Uchupi,

1970; Schlee, 1973; Schlee and Pratt, 1970; Fader, 1984; Fader et al., 1988; Todd et al., 2007). During the post-glacial Holocene epoch (~12,000 years before present), sea level rose from a low stand 120 m below the present sea level (Emery and Garrison, 1967; King and Fader, 1986) and the bank was submerged ~6000 BP (radiocarbon years) (Shaw et al., 2002). Georges Bank surficial sediments were reworked and redistributed by marine processes during sea-level transgression and continue to be reworked under the modern oceanic regime (Butman, 1987; Twichell et al., 1987; Uchupi and Austin, 1987; Valentine et al., 1993). The present morphology of the Gulf of Maine, Georges Bank, and the Fundian and Northeast channels displays the imprint of multiple glaciations during the Pleistocene epoch. During the last glaciation of the Pleistocene, the Wisconsinan, the Laurentide Ice Sheet extended southeastward from entral Canada across Maritime Canada and New England to the present northern margin of Georges Bank and the continental shelf edge off Nova Scotia. The Fundian and Northeast channels were a major outlet for glacial ice to the Atlantic Ocean (Dyke et al., 2002; Schnitker et al., 2001; Hundert, 2003; Stea, 2004; Shaw et al., 2006). Based on the mapping of glacial gravel collected from the seabed in the Gulf of Maine region, Pratt and Schlee (1969) and Schlee and Pratt (1970) reported that glacial ice lapped onto the northern margin of Georges Bank. Moraines were emplaced on the northern part of the bank and sand and silt outwash spread southward. The glacial maximum was followed by a multi-phased retreat of the ice front and the incursion of marine oceanic waters into the Gulf of Maine through the Northeast Channel. Within the gulf, ice front retreat and glaciomarine deposition began as early as 18 ka with grounded ice absent from the Gulf of Maine by approximately 14 ka (King and Fader, 1986; Schnitker et

GEOSCIENTIFIC DATA

High-resolution seismic-reflection data were collected over Georges Bank, Fundian Channel and Northeast Channel in 1999, 2000 and 2002 (Fig. 3; Todd et al., 2000, 2001, 2003) in order to complement the historical geoscientific information in the area and to assist the interpretation of the multibeamechosounder data. The systems deployed included a Huntec Deep Tow Seismic (DTS) boomer, a singlechannel sleeve-gun seismic reflection system, and a Simrad MS992 sidescan sonar (120 and 330 kHz). The geophysical surveys investigated different seafloor types and features identified using the multibeam bathymetric and backscatter data (Todd et al., 2013; Todd and Courtney, 2014). Using a 0.75 m³ Institutt for Kontinentalsokkel-undersøkelser (IKU) grab sampler, seafloor sediment samples were collected at sites best suited for groundtruthing multibeam imagery and geophysical profiles (Fig. 3). The sites were chosen to collect seafloor sediment samples representative of broad areas sharing similar geomorphology (Todd et al., 2013) and acoustic backscatter response (Todd and Courtney, 2014). Grain size analysis provided the percentage of gravel, sand and mud (silt+clay) in each sediment sample. These data were augmented by sediment samples and grain size analyses from the US Geological Survey (Poppe et al., 2005). Grain size descriptions based on the samples adhere to the Ventworth size class scheme for clastic sediments (Wentworth, 1922). The multibeam bathymetric and backscatter data and the seismic-reflection profile data were used to identify locations where seafloor photographs were collected using Campod, an instrumented tripod equipped with oblique-and downward-oriented video and still cameras (Gordon et al., 2007). Campod was deployed while the ship slowly drifted across sites of geological or biological interest and was repeatedly landed on the seabed to obtain still photographs, thereby collecting high-resolution imagery along transects of 30 minutes duration that traversed up to 1000 m. depending on the current speed. About 10 still images, each showing an area of 0.96 m², were acquired per transect. In 2008, 401 seafloor photographs were acquired at 25 stations in the map area by the US Geological Survey using SEABOSS, a multi-instrumented platform equipped with a still camera (Blackwood et al., 2000). SURFICIAL GEOLOGY

features: ice-contact sediments, ice-proximal sediments, ice-distal sediments, paraglacial coastal sediments, and post-glacial sediments. The Quaternary stratigraphy of Georges Bank described here follows this deglacial sequence scheme. Earlier interpretations of surficial geological formations on Georges Bank were based on a regional understanding of the Gulf of Maine and Scotian Shelf (Fader et al., 1988; Fader et al., 2004). The formation names corresponding to the deglacial sequence names described here are noted in the legend and are shown in Figure 2. The veneer of Late Wisconsinan glacial sediment emplaced on Georges Bank likely consisted of, from north to south, ice-contact sediments, iceproximal sediments, and ice-distal sediments. This veneer is 20 to 50 m thick, is generally devoid of internal seismic reflectors, and is incised in places by channels (Fig. 4) (Lewis et al., 1980). The bank is now isolated from other sediment sources by deep basins, and the postglacial sediments that now cover the map area were derived from the reworking by currents and waves of glaciogenic deposits. The present-day sediments are equivalent to the Sable Island Sand and Gravel Formation (Fig. 2, Drapeau and King, 1972; Fader, 1984). In some areas, winnowing of finer-grained sediment (silt and sand) from postglacial sediments resulted in gravel lag deposits that effectively armour the underlying sand and gravel against erosion. The morphology and extent of postglacial sediments are interpreted from the shaded relief map (Todd et al., 2013), the backscatter strength map (Todd and Courtney, 2014), seafloor sediment samples, photographs, video transects, and geophysical data (Todd et al., 2000, 2001, 2003). Based on geophysical, geological, and photographic evidence, two Quaternary sediment units are mapped on Georges Bank. The area designated as postglacial sand and gravel (PG) is a well-sorted, generally coarse-grained sand, grading to rounded and subrounded pebble and cobble gravel (Fig. 5A), which forms a widespread surficial lag. The lag is overlain in places by well-sorted postglacial sand (PGs occurring mainly as bedforms (Fig. 5B). The bedforms are the most prominent geomorphological features on the bank, are formed through sediment transport by strong tidal currents. Multibeam echosounder sonar mapping of the Canadian portion of Georges Bank has provided unprecedented

views of the morphology and distribution of these bedforms. In areas where ground-truth data were sparse, identification of sediment units was based on nearby backscatter and topographic imagery that

had been ground-truthed using sediment samples, photographs, and video images.

Syvitski (1991) showed that a complete deglacial sequence consists of some or all of the following

At water depths of approximately 60 m or less, sediment on Georges Bank is continually reworked by tidal currents and episodically by storm-generated currents, resulting in a hierarchy of current-generated edforms in sand-rich areas. Three types of bedforms are present in this map area. The first type occurs in sand-rich areas where mobile sand waves composed of medium to coarse sand are wave-like geometric configurations of the water-sediment interface that are formed by fluid flow over an erodable granular bed. The crests of the sand waves trend is approximately southwest-northeast, normal to the major axis of the semidiurnal tidal current (Butman and Beardsley, 1987). Sand wave crests display a complex anastomosing pattern in plan view (Fig. 6, upper panel). Superimposed on the sand waves and sharing the same general crest orientation are megaripples and ripples; these features have smaller wavelengths and heights and exhibit a complex three-dimensional pattern in plan view. The sand waves have wavelengths of 50-300 m and reach heights of 19 m. In cross section they are asymmetric with gently-sloping upcurrent (or stoss) faces, and steeply-dipping downcurrent (or lee) faces (Fig. 6, lower panel). This cross-sectional attribute of the sand waves, together with their crest orientation and overall distribution on the bank, indicates that the regional direction of sediment transport is from northwest to southeast. The presence of sand waves indicates that fluid velocities on Georges Bank are sufficient to erode and transport surficial sediment. Sand waves are migratory features and their height, wavelength, and speed and direction of migration are a function of sediment grain size in the eroding bed, water depth, and current velocity (see summary of references in Whitmeyer and FitzGerald, 2008). The second style sand wave occurs within relatively small areas on Georges Bank. These bedforms have comparatively straight crests trending southwest-northeast, similar in orientation to crests within the sand wave fields (Fig. 7). although we lack direct sedimentological evidence for the composition of these features, their backscatter strength is similar to that of the sand wave fields and suggests that the are composed of well-sorted sand. These sand waves differ from those in the sand wave fields described above in that their simple, relatively straight crests show no bifurcation pattern. Also, in contrast to the symmetrical profiles of the mobile bedforms within the sand wave fields, these features are symmetrica in profile (Fig. 7). We hypothesize that they are relatively immobile. Another difference between the

mobile and immobile sand waves is their stratigraphic position. The mobile sand waves are perched on

top of the regional lag gravel surface at relatively shallow water depths (<~70 m), whereas the immobile and waves are located within bathymetric lows (>~70 m) where tidal currents velocities are presumab

weaker. Only the crests of the immobile sand waves reach the bathymetric level (<70 m) of the surrounding terrain. The ends of these features often terminate in distinct depressions, or moats (Fig. 7 giving the visual impression that they are carved out of the surrounding material. They closely resemble in their morphology and orientation to tidal current direction, sand features mapped in the Great South Channel at the western end of Georges Bank, which are immobile (but have mobile surfaces) and are separated from each other by pebble and cobble gravel lag pavements (Valentine et al., 2002). Finally, barchan dunes are present on gravel lag in sand-starved regions of the bank (Fig. 8). These dunes are composed of medium to coarse sand (Todd et al., 2000), are crescentic in planform, and are convex to the northwest, with steep lee faces facing southeastward in cross-sectional view. Their asymmetry is similar to the mobile sand waves and suggests southeastward movement. Intriguingly, the allometric relationship between barchan height and width on Georges Bank is different than the same relationship for barchan dunes measured on nearby Browns Bank (Todd, 2005). For a given barchan dune width, their height on Georges Bank is almost twice their height on Browns Bank. This marked height difference may be a result of the much more energetic current regime on Georges Bank. Observations (Moody et al., 1984) and models Xue et al. (2000) indicate that tidal current speeds on Georges Bank (up to 100 cm/s) satisfy the mean velocity required to erode and move sediment grains to cause barchan dune migration (~57 cm/s) (Miller et al., 1977), which possibly is accelerated under higher-velocity, storm-induced currents. Based on multibeam bathymetric and backscatter imagery of the region and supporting ground-truth data, we have identified three major bedform regimes on Georges Bank: (1) mobile sand waves, the most

widespread features, whose cross-sectional asymmetry suggests slow southeastward migration; (2) immobile sandwaves located in bathvmetric lows and separated by gravel lag, whose cross-sectional symmetry suggests no migration; and (3) isolated barchan dunes located on gravel lag plains with sparse

sand resources, whose cross-sectional asymmetry suggests movement to the southeast. Repetitive multibeam sonar mapping is required to detect bedform migration occurring over months or years. ACKNOWLEDGMENTS Geoscientific data were collected on Georges Bank, in Fundian Channel, and in Northeast Channel during three expeditions of the CCGS Hudson (1992-01, 2000-047, 2002-026), the CCGS Dawson (1989-001), the MV Fogo Isle (1982) and the MV Hamilton Banker (1999). As well, the US Geological Survey provided both archive data and modern data for the analysis. Multibeam sonar data were collected and processed by the Canadian Hydrographic Service. Geographical Information Systems and cartographic support was provided by S.E. Hayward, W.A. Rainey, S. Hynes and P. O'Regan. We thank J. Shaw (GSC) and Seth Ackerman (USGS) for scientific reviews of the map.



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may be gradational or conceptual in nature) . . .



Figure 1. Location map shows extent of map sheet in red. The pink shadowing shows the extent of the multibeam sonar coverage. Five-digit numbers refer to Marsden Square System used for Natural Resource Map series at 1:250 000 scale. Blue line shows 200 m



Figure 3. Data Source Map showing the distribution of geophysical tracklines (seismic reflection profiles, sidescan sonar sonograms) and seafloor sediment samples and photographs. Extent of map sheet in red.

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