Geological features supporting deep-sea coral habitat in Atlantic Canada

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1. Introduction

Deep-sea corals have gained considerable scientific and conservation attention in the past decades as long-lived and vulnerable habitat-structuring organisms (Hall-Spencer et al., 2002; Roberts et al., 2006). The worldwide decline of fisheries vulnerable habitat-structuring organisms (Hall-Spencer et al., 2002; Buhl-Mortensen and Mortensen, 2006; Stone, 2006; Edinger et al., 2007a) and invertebrate habitat for fish (Husebø et al., 2002; Auster, 2005; Costello et al., 2006) has prompted an examination of the role deep-sea corals serve as shelter and refuge. The great life-spans of deep-sea corals (Sherwood and Edinger, 2009) and their susceptibility to damage from fisheries and other activities have made them objects of great conservation concern in Atlantic Canada (Gass, 2003; Mortensen et al., 2006a; Edinger et al., 2007b) and elsewhere (Fossà et al., 2002; Hall-Spencer et al., 2002; Ardron et al., 2007; and many others).

Because many types of corals require hard substrates, surficial geology has considerable influence on their distributions. The geological origins of the features that create coral habitat have been an object of study in the European margin (Freiwald et al., 2002; Freiwald and Risk, 2007) and the Gulf of Mexico ( Schroeder et al., 2005; Schroeder, 2007), but not previously in Atlantic Canada. Some Norwegian deep-sea reefs...
have grown on the berm left by Pleistocene iceberg scours (Freiwald et al., 1999), similar to the berm that support some hexactinellid sponge reefs in British Columbia (Conway et al., 2005). The nature of the features that support coral growth varies considerably among regions, particularly between paraglacial continental margins, continental margins not subject to glacial effects, and seamounts or other non-continental margin settings.

This paper has three objectives. First, we review the distribution of skeletal deep-water coral species and in relation to geology of the continental margin in Atlantic Canada. Second, we qualitatively describe the nature and origins of several kinds of geological features that provide habitat for deep-sea corals in Atlantic Canada as observed during recent ROV cruises in Atlantic Canada. Finally, we briefly compare the geological features supporting coral growth in Atlantic Canada with the features that support cold-water coral growth on paraglacial and non-paraglacial settings in other regions of the world.

1.1. Corals in Atlantic Canada

Deep-sea corals in Atlantic Canada include more than 30 species of gorgonian octocorals with calcitic and/or organic skeletons (“gorgonians”), non-skeletal alcyonacean octocorals (“soft corals”), pennatulacean octocorals (“sea pens”), antipatharians with organic skeletons (“black corals”), and solitary and colonial scleractinians (“stony corals”) (Maclsaac et al., 2001; Gass and Willison, 2005; Wareham and Edinger, 2007). Large gorgonian, antipatharian, and most scleractinian corals are generally dependent on hard substrates, while sea pens, some small gorgonians, and some soft corals can occupy sand and mud bottoms, along with reclining solitary scleractinians such as Flabellum. Using fishermen’s knowledge, museum collections, and coral bycatch data from scientific surveys and commercial fisheries, the distribution of > 30 species of octocoral, antipatharian, and scleractinian corals has been mapped off Nova Scotia and Newfoundland (Breeze et al., 1997; Maclsaac et al., 2001; Gass and Willison, 2005; Mortensen et al., 2006b; Wareham and Edinger, 2007; Fig. 1). Habitat characteristics of coral-rich areas shallower than 1000 m have been described from the shallow (Mortensen and Buhl-Mortensen, 2004, 2005a) and deeper (Watanabe et al., 2009) areas of the Northeast Channel, and The Gully (Mortensen and Buhl-Mortensen, 2005b; Cogswell et al., 2009), but not from other locations.

Most large gorgonian corals are concentrated along the shelf break from 200 to 800 m depth, but the depth ranges of many of the smaller gorgonians and sea pens extend well below 1000 m, and some species live deeper than 2000 m (Wareham and Edinger, 2007; Baker et al., 2008). Areas with greatest density of deep-sea coral records coincide with submarine canyons such as The Gully, and the mouths of shelf-crossing troughs of the Scotian Shelf, Grand Banks, Northeast Newfoundland Shelf, and Labrador Shelf. Major deep-sea coral sites in Labrador waters include the Hudson Strait and northern edge of Sagleik Bank, and sites close to the mouth of Okak Saddle, Hopedale Saddle, Cartwright Saddle, and Hwke Channel (Fig. 1). Coral assemblages in the Northeast Channel, The Gully, and the Stone Fence, which have been identified as the key areas for deep-sea corals in Nova Scotia, are dominated by two large gorgonian corals, Primnoa resedaeformis and Paragorgia arborea, but these species are rare in most parts of Newfoundland and Labrador, with the exception of the Hudson Strait coral hotspot near the northern tip of Labrador (Mortensen et al., 2006b; Wareham and Edinger, 2007; Wareham, 2009). The most common skeletal corals in other parts of Newfoundland and Labrador waters are the large gorgonians Keratoisis ornata and Paramuricea spp. (a mix of Paramuricea placomus and Paramuricea grandis), the small gorgonians Acanthogorgia armata, Acanella arbuscula, and Radicipes gracilis, the antipatharian coral Stauropathes arctica, and the solitary cup corals Desmophyllum dianthus and Flabellum spp. Most of these species are thought to tolerate low-current settings more effectively than Primnoa and Paragorgia (Bryan and Metaxas, 2007; Cogswell et al., 2009).

Unfortunately, many areas of known coral habitat have been extensively fished by trawl, gillnet, and bottom longline (Kulka and Pitcher, 2002; Mortensen et al., 2005; Edinger et al., 2007b) and much of the original coral habitat may have been damaged or destroyed. Efforts at coral conservation depend on accurate distribution data, an understanding of the factors controlling distribution, and the anthropogenic threats to corals (Breeze and Fenton, 2007). Statistical approaches to defining the factors controlling coral distribution in Atlantic Canada have identified substrate and bottom water temperature as key variables (Mortensen et al., 2006b). Ecological niche factor analysis modeling identified slope, temperature, surface chlorophyll A concentration, and bottom current strength as the dominant predictors of large gorgonian coral distribution (specifically Primnoa and Paragorgia, Bryan and Metaxas, 2006, 2007), while recognizing that slope may be a proxy for distribution of hard substrates, rather than a biologically meaningful variable (Metaxas and Bryan, 2007). Similar analysis with geographically weighted regression found slope to be significant to gorgonian coral distributions in the Newfoundland and Labrador region at the regional scale, because corals are concentrated along the continental slope, but not important at the local scale (Jones, 2008). Because finely resolved continuous spatial data on surficial geology are not available for most parts of Atlantic Canada, most attempts to analyze factors controlling coral distribution either have not considered substrate at all (Bryan and Metaxas, 2007), or consider substrate only by grain size, without consideration of the geological origins of hard substrate features (Mortensen et al., 2006b).

This article reviews the geology of the Atlantic Canadian continental margin, and compares the geology with the broad distribution of cold-water corals in Atlantic Canada. This paper also presents qualitative in-situ observations of the geological features that support coral habitat, and using bottom photographs from the 2007 cruise to the eastern Scotian Shelf and Southwest Grand Banks. Observations presented here include the nature of the habitat-supporting features, and the coral species observed on each type of feature. This paper does not present quantitative results of video analyses of coral abundance, depth distribution, and species composition (e.g. Baker et al., 2008; Cogswell et al., 2009), which will be published separately.

2. Geological setting

The entire continental margin of Atlantic Canada has been affected by Pleistocene glaciations, which eroded the continental shelf and strongly influenced depositional features both on the shelf and in deep water beyond the ice limit (Boyd et al., 1988; Scott et al., 1989; Shaw et al., 2002; Piper, 2005; Shaw et al., 2006). Glacial ice reached the shelf edge at the last glacial maximum (LGM) along much of the eastern Canadian margin (e.g. Stea et al., 1998; Piper and Brunt, 2006) but may not have crossed wide shelves such as the Grand Banks since the previous glacial maximum in marine isotope stage 6 (Huppertz and Piper, 2009). Major erosional physiographic features left by glaciation include shelf-crossing troughs associated with ice streams across the Scotian Shelf, Grand Banks, Northeast Newfoundland Shelf, and Labrador Shelf (Piper, 2005; Shaw et al., 2006). The largest of
these include the Northeast Channel, the Laurentian Channel, and the Hudson Strait, which contained the principal ice streams in Atlantic Canada. In contrast, ice domes formed on some of the outer banks (Gipp, 1994; Fig. 1).

Almost the entire upper continental slope off Atlantic Canada is underlain by glacial till. It is lacking only off parts of the southern Grand Banks and at Flemish Cap. In places, the till is buried up to tens of metres beneath younger proglacial and Holocene sediment. It is recognized in seismic-reflection profiles as wedge-shaped acoustically incoherent sediment packages, commonly termed till tongues, that pinch out generally between 500 and 700 mbsl (King and Fader, 1986; Piper et al., 2005; Piper, 2005). Where sampled, till tongues are either not penetrated by a 1 tonne piston corer, or return overconsolidated diamict with shear strengths of 60–100 kPa characteristic of lodgement till. Only at the seaward pinch out of the till tongues does the diamict appear normally consolidated (Piper and Macdonald, 2002). These upper slope till tongues thus differ from similarly named features in continental shelf basins that are principally debris-flow deposits (Stravers and Powell, 1997). Locally, debris flow deposits apparently derived at least in part from glacial till are found immediately downslope from till tongues, for example off St. Pierre Slope (Bonifay and Piper, 1988) and off Whale Bank (Piper and Gould, 2004). Seaward of some transverse troughs, notably off Hudson Strait (Rashid and Piper, 2007) and off Trinity Trough (Tripsanas and Piper, 2008), upper slope till tongues pass directly into continuous glaciogenic debris-flow deposits. Many sampled tills on the continental shelf and upper slope are sandy or muddy, substantially derived from reworking of Pleistocene or Late Tertiary sediments on the shelf, but include a small proportion of bedrock pebbles to boulders. Such large clasts are also transported to the continental slope by icebergs. In many cases, upper slope till has been scourred and pitted by icebergs, and the surface commonly has been reworked by shelf-edge currents and storms (Mosher et al., 2004).

Within transverse troughs, acoustically incoherent stacked tills commonly have been deposited at the seaward end of the trough near the shelf break, creating a low ridge that is shallower than the trough on the central part of the shelf (King, 1996; Stea et al., 1998; Piper and MacDonald, 2002; Rashid and Piper, 2007). In the case of the Laurentian Channel, late glacial and Holocene sediment has covered the stacked till in the center of the channel (Josenhans and Lehman, 1999), but strong currents at the SW margin of the channel maintain cobble-boulder environments at an area called the Stone Fence, where thick tills have been plastered over the bedrock edge of Laurentian Channel. Similarly, strong tidal currents in the Northeast Channel sweep the end moraine (Ramp et al., 1985), and outflow of Arctic water generates strong currents seaward of Hatton Basin off Hudson Strait (Straneo and Saucier, 2008).

Seaward of the till tongues, the heads of submarine canyons show dendritic drainage patterns, which are particularly evident in multibeam sonar-derived bathymetry (Fader and King, 2003; Mosher et al., 2004; Piper, 2005). Some canyons appear to connect with buried tunnel valleys on the adjacent shelf (Piper et al., 2007, their Fig. 13) and have flat broad floors, interpreted to result from erosion by subglacial meltwater. Similar broad valleys extending from near the shelf break are found seaward of some transverse troughs, including Laurentian Channel and Halibut Channel (Mosher and Piper, 2007a). In places, these broad valleys diverge into spillover channels and have eroded residual buttes (Hughes-Clarke et al., 1990). The deep incision of canyons at the mouth of Northeast Channel and The Gully has also been ascribed to the effect of subglacial meltwater (Piper et al., in press). In these settings and in the fan valleys off Laurentian Channel, eroded bedrock is widespread. Seaward of the shelf-crossing troughs of Newfoundland and Labrador, eastward and northward from Halibut Channel, there has been Quaternary progradation of glacial till, and bedrock outcrops are rare or absent. Strong tidal currents in Northeast Channel and The Gully have kept eroded bedrock, and at the shelf-edge also till, free of surficial cover. Elsewhere, late Pleistocene and Holocene sediment has mantled the floors and walls of most channels, yielding mud and fine sand surficial cover atop the underlying dendritic drainage (Piper and Campbell, 2002; Mosher and Piper, 2007b).

3. Methods

In 2001, 2006 and 2007 researchers from Dalhousie University, Memorial University of Newfoundland and Fisheries and Oceans Canada surveyed deep-sea coral habitat in Atlantic Canada with the remotely operated submersible ROPOS. Surveys were conducted along the upper continental slope between southwest Nova Scotia and the southwest Grand Banks of Newfoundland (Fig. 1).

3.1. Qualitative photographic and video observations.

Surveys were performed with the remotely operated vehicle (ROV) Remote Operated Platform for Ocean Science (ROPOS), deployed from CCGS Martha Black (2001) and CCGS Hudson (2006, 2007). The 2001 cruise was limited to a depth of 500 m, while during the 2006 and 2007 cruises, the vehicle was configured to a maximum depth of 2500 m. In Nova Scotia waters, surveys targeted known areas of coral abundance in the Northeast Channel, The Gully and Stone Fence, based on previous reports (Breeze et al., 1997; MacIsaac et al., 2001; Gass and Willison, 2005), and following upon previous in-situ investigations using drop-video (Mortensen and Buhl-Mortensen, 2004, 2004a, b; Mortensen et al., 2006b). In Newfoundland, knowledge of coral distribution was more limited (Wareham and Edinger, 2007), so depth-stratified 1 km transects for fish abundance and diversity (along contour) and up-slope transects (for invertebrate identification and collections) were carried out along pre-determined routes, based on reports of coral bycatch (Wareham and Edinger, 2007; Edinger et al., 2007b). Depth-parallel transects in the Newfoundland were generally conducted at 1000, 800, 700, 600, 500, and 400 m depths, with intervening up-slope transects for megafauna identification and collections. Additionally, at least 1 dive to 2000 m or greater was conducted in the Northeast Channel, The Gully, the Stone Fence, Haddock Channel, and Desbarres Canyon.

Video was recorded continuously during each dive, and digital still photographs were taken opportunistically. Parallel lasers placed 10 cm apart were used to indicate scale, and to estimate sizes of substrates coarser than sand, and of corals, other macrofauna, and fishes. Manipulator arms and collection boxes fitted on the vehicle were used to collect samples for species identification and for biological and paleoceanographic studies.

Video analysis of substrates at sea, and post-processed in the lab, used the Bedford Institute of Oceanography’s in-house video analysis program “Class-Act Mapper”, in which substrates, corals, sponges, other invertebrates, fishes, and anthropogenic features such as lost fishing gear were recorded, along with position, depth, and any other qualitative observations. The field of view was quantified from the lasers, allowing estimates of the total area surveyed, and the relative abundance of different substrates. Substrates were identified and described visually, with some collection of rocks where attached to corals. Visual identification of substrates used the scaling lasers, relative to the Udden–Wentworth grain size scale for substrates coarser than sand. Substrates were classified as bedrock, boulders, cobbles, gravel,
sand, and fine-grained sediment (muddy sand and mud); relative abundance of substrate types was estimated visually to the nearest 10% throughout each dive, with up to three substrates recorded at any one time. Rock types were assessed visually, and with rare collections. Dip angle of exposed bedrock or semi-consolidated sediments was assessed visually in relation to the position of the ROV, and checked against the attitude sensors (roll, pitch, heave) of the ROV.

Coral species were identified visually using colour photographic identification guides, with collection of some species for verification by spicule analysis or reference to taxonomic experts (Baker et al., 2008; Cogswell et al., 2009; Wareham, 2009). Coral species lists and depth distributions were compiled for each location studied (Baker et al., 2008; Wareham, 2009; Cogswell et al., 2009). Relative and absolute abundance of coral taxa, while not presented in this paper, were quantified as \( N \) colonies/m², using the estimated area of each video transect.

Precise tracking of ROV position allowed matching of in-situ geological observations with archival sub-bottom profiles and multibeam bathymetric data of three-dimensional geological structures. Positions of seismic lines and bottom photographs presented here are indicated in the location map and insets in Fig. 2. Multibeam bathymetry in inset maps of Fig. 2 is derived from previously published datasets (Mosher and Piper, 2007b; Cameron and King, 2008; also available at http://gdr.ess.nrcan.gc.ca/multibath/e/viewer.htm).

4. Qualitative field observations

Four principal types of geological features were observed to support coral growth on hard substrates along the Scotian Margin and Southwest Grand Banks of Newfoundland. These were (1) current-winnowed moraine-derived till deposits on the outer continental shelf and uppermost slope; (2) till tongues on the upper slope; (3) eroded friable Tertiary bedrock and Quaternary consolidated glaciomarine sediments; and (4) authigenic carbonate crusts. Unconsolidated post-glacial sediments supported corals not dependent on hard substrates. The geological features supporting coral habitat are described in order below.

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Fig. 2. (A) Location map showing areas of in-situ qualitative observations, and positions of figures. Inset maps show positions of sub-bottom profiles or bottom photographs in relation to detailed bathymetry. (B) Northeast Channel, Fundian Channel. (C) The Gully. (D) Stone Fence. (E) Haddock and Halibut Channels. Multibeam bathymetry courtesy of Geological Survey of Canada and Canadian Hydrographic Service.
4.1. Shelf-break and upper slope winnowed till

Winnowed till, or ice-contact sediments, derived from end moraines, provides the primary habitat for large gorgonian corals in the Northeast Channel and the Stone Fence along the Scotian Margin. These till deposits are visible in sub-bottom profile as acoustically incoherent deposits with a rough seabed expression (Figs. 2B and 3). Lithology, assessed visually, included abundant crystalline basement rocks resembling granite and gneiss. Visually assessed grain size in these environments was mostly cobbles, small boulders, and pebbles, with coarse sand patches in places between cobbles and boulders (Fig. 4; Mortensen and Buhl-Mortensen, 2004; Watanabe et al., 2009). These areas are swept by strong currents that keep them clear of fine-grained sediments and maintain the habitat suitable for growth of large gorgonian corals. Corals were observed growing on the tops and sides of boulders and cobbles. Lophelia pertusa corals were also observed in the current-swept boulder environment at the Stone Fence, mostly in the form of dead Lophelia rubble (Fig. 5). In the upper reaches of the thalweg of The Gully, in both side feeder canyons (Figs. 2C and 6) and the main thalweg (Figs. 2C and, 7) boulders of crystalline basement rock were observed. Many of these boulders had been colonized by large colonies of Paragorgia, Primnoa, Keratoisis, and other corals (Figs. 6 and 7).

4.2. Deep-water till tongues

Deep-water till tongues, provide large gorgonian coral habitat seaward of Halibut and Haddock Channels, and in Desbarres Canyon, Southwest Grand Banks (Figs. 2E and 8). Till tongues are recognized in sub-bottom profiles as downslope continuations of acoustically incoherent reflecting bodies that have since been buried by post-glacial sediment. In acoustic profiles, these acoustically incoherent sediment bodies extend to about 650 m water depth (Fig. 8). The surficial expression of the till tongues is pebbles, cobbles, and

Fig. 3. Seismic profile crossing the outer edge of Northeast Channel and the adjacent upper slope. Shows progradational till sheets and the youngest seismically resolvable till tongue. The upper slope is cut by canyons and gullies both at the seafloor and in the subsurface (GI sleeve gun profile from cruise HU2005023).

Fig. 4. Current-swept cobble-boulder habitat supporting abundant small colonies of Primnoa resedaeformis. Stone Fence, 305 m.
boulders resting in a matrix of sand and mud (Fig. 9). In examples
along the margins of Haddock and Halibut Channels, on the
southwest Grand Banks, cobbles and boulders in a mud matrix,
interpreted as till tongues or their related dropstone or debris-flow
deposits, extended to approximately 800 m depth. In this facies,
individual cobbles and boulders were commonly covered by single or
multiple colonies of hard-substrate dependent corals, especially the
gorgonians K. ornata and A. armata and the soft corals Anthomastus
grandiflorus and Duva florida (Fig. 9). The scattered boulder and cobble
in muddy sand matrix facies, interpreted as till tongues, was also
observed at Desbarres Canyon, to the southeast of Haddock Channel,
along the southwest margin of the Grand Banks (Fig. 2), where nearby
seismic profiles show well-developed till tongues (Piper and Gould,
2004, their Fig. 3). The gorgonian coral fauna commonly observed at
Desbarres Canyon included the smaller rock-inhabiting gorgonian A.
armata and the soft-sediment inhabiting gorgonians A. arbuscula and
R. gracilis, but K. ornata was only rarely observed in Desbarres Canyon.

4.3. Eroded friable bedrock and Quaternary glaciomarine sediments

Eroded bedrock was commonly observed in The Gully, and in a
few locations in approximately 1000 m water depth near the
Stone Fence. In both these environments, corals were observed
growing on vertical and steeply inclined surfaces. In The Gully, it
was often difficult to determine the orientation of bedding planes
in the friable bedrock, although some locations appeared to have
shallowly dipping bedding (Fig. 10). Where bedding planes were
visible in the exposed mudstone and sandstone bedrock in the
deeper areas of the Stone Fence, many of the outcrops appeared to
have near-vertical dip (Fig. 11).

On the eroded friable bedrock in The Gully, large gorgonians
(Paragorgia, Primnoa, Keratoisis) and attached scleractinian cup
corals (Desmophyllum) were commonly observed growing hori-
zontally from eroded bedrock walls. Soft corals (Anthomastus,
Duva, Drifa) were observed growing on the pinnacle tops (Fig. 10).
Corals observed on these bedrock exposures near the Stone Fence
included a large antipatharian coral, the soft coral A. grandiflorus,
and Desmophyllum (Fig. 11).

A small ‘gully’ eroded into horizontal, thinly bedded, semi-
consolidated sediments was observed at approximately 800 m
depth seaward of Haddock Channel (Figs. 2E and 12). Although
the gully was less than 10 m deep, its exposed walls were covered
with a variety of corals, including the gorgonian Keratoisis, the soft
coral Anthomastus, and the scleractinian cup corals Desmophyllum
and Javania cailleti. Similarly, semi-consolidated slumped
sediments in the same area provided firm substrates for the
gorgonian Keratoisis, the solitary scleractinians Desmophyllum and
Javania, and the large antipatharian S. arctica (Fig. 13).

4.4. Authigenic carbonate crusts

Thin authigenic crusts of cemented sediment, probably
calcium carbonate, were observed immediately adjacent to the
small gully excavated into the flat-lying semi-consolidated
glaciomarine sediments seaward of Haddock Channel (Fig. 14).
The crusts appeared to be less than 2.5 cm thick, where exposed
in cross-section along the margins of the small gully. The solitary
cup corals D. dianthus and J. cailleti were observed growing on the
underside of eroded crusts of partially lithified surficial sediment
(Fig. 14). Attempts to collect the crust for mineralogical and stable
isotopic analysis were unsuccessful, as were attempts to collect
the cup corals growing on its lower side.
4.5. Fine-grained post-glacial sediments

Fine-grained post-glacial sediments were observed in many areas of the Stone Fence, Haddock and Halibut Channels, and Desbarres Canyon. Some of these fine-grained sediments supported dense aggregations of sea pens (Pennatulaceans; Fig. 15), referred to as meadows (cf. Brodeur, 2001), as observed in Desbarres Canyon (Fig. 15) and several species of the solitary scleractinian cup coral Flabellum.

5. Discussion

5.1. Shelf-break and upper slope winnowed till

Coral assemblages in these environments are dominated by the large bushy or fan-shaped gorgonians P. resedaeformis and P. arborea, with lesser abundances of the organic-skeleton gorgonians A. armata and Paramuricea spp. Cobble size may limit the size of coral colony, as current drag on corals causes smaller cobbles to overturn, hence limiting the growth of the coral colonies (Mortensen and Buhl-Mortensen, 2005a, b; Watanabe et al., 2009).

Below 750 m in the valleys off Northeast Channel, asymmetrically rippled sand dominates, with rare large boulders and outcrops of friable bedrock, which are colonized by gorgonian and other corals (Sameoto et al., 2008; Watanabe et al., 2009). Although the abundance of hard substrates and the abundance of Primnoa and Paragorgia corals were significantly correlated, Watanabe et al. (2009) concluded that hard substrate was not limiting to corals in the current-swept boulder environments, because uncolonized hard substrates were observed at most depths.

The current-swept boulder environment of the Stone Fence also hosts the only known Atlantic Canadian deep-water coral reef, built by the colonial scleractinian L. pertusa (Mortensen et al., 2006a). This reef, covering an area of roughly 1 km², has been severely damaged by trawling, and is now mostly reduced to rubble (Mortensen et al., 2006a; Cogswell et al., 2009). The boulders composed of crystalline basement rock observed in the upper part of The Gully were probably derived from downslope transport of till from the shelf (cf. Fader and King, 2003). The lithology of large clasts in the apparent end moraines observed at...
the Northeast Channel, The Gully, and the Stone Fence can be compared with clast lithologies reported from cores by Piper and deWolfe (2003) and Hundert and Piper (2008), derived principally from Appalachian basement.

Seismic profiles and drop camera studies suggest that the high abundance of corals in the Hudson Strait coral hotspot is probably supported by a combination of moraine-derived current-swept boulders and deep-water till tongues (Josenhans and Barrie, 1989; Andrews et al., 1994, 2001; Rashid and Piper, 2007). This area has the highest coral bycatch rates observed in Newfoundland and Labrador waters (Edinger et al., 2007a, b), matching those of untrawled areas in the Gulf of Alaska (Krieger, 2001) or the Tasmanian seamounts (Anderson and Clarke, 2003), and has been suggested to be the most important coral site in the Newfoundland and Labrador region (Gilkinson and Edinger, 2009). The very high abundance of the large gorgonians Primnoa and Paragorgia in the Hudson Strait coral hotspot (MacIsaac et al., 2001; Gass and Willison, 2005; Wareham and Edinger, 2007; Edinger et al., 2007a, b) contrasts dramatically with the rest of the shelf break and slope off Newfoundland, where these two species are quite rare (Wareham and Edinger, 2007; Wareham, 2009). The marine geological studies in the area (Andrews et al., 1994, 2001; Rashid and Piper, 2007) and oceanographic predictions of high current flow (Straneo and Saucier, 2008) suggest that the Hudson Strait coral hotspot is also supported by a current-swept boulder environment similar to that of the Northeast Channel and Stone Fence. This prediction would be consistent with the importance of the Hudson Strait as the principal ice stream through which
Laurentide ice sheet glaciers reached the Labrador Sea (MacLean, 2001; Piper, 2005; Shaw et al., 2006).

5.2. Deep-water till tongues

Presence of till tongues in Halibut and Haddock Channels and Desbarres Canyon is confirmed by seismic-reflection profiles (Halibut and Haddock Channels, Mosher et al., 2010, their figures 3.2.15 and 3.2.16; Desbarres Canyon, Piper and Gould, their Fig. 3). Trough-mouth tills are associated with the locations of ice streams during deglaciation of Atlantic Canada (Shaw et al., 2006), and are expected to provide the basis for concentrations of Paramuricea and the antipatharian coral S. arctica in deep waters near trough mouths along the Northeast Newfoundland Shelf (upper slope off Trinity Trough, locally known as Tobin’s Point, Aksu and Hiscott, 1992; Tripsanas and Piper, 2008) and Labrador Shelf margins (Josenhans et al., 1986) (Fig. 1).

The apparent difference in depth-limit between the acoustically-recognizable till tongue facies (~650 m) and their surface expression as the matrix-supported cobble-boulder facies near Haddock and Halibut Channels may be a function of the resolution of the acoustic profiler, but is more likely related to enhanced meltout of dropstones from attached ice along the ice margin. Where lithology could be assessed visually from video, and based on limited rock samples recovered, the cobbles and boulders appeared to be well-indurated sedimentary rocks, probably from the late PreCambrian sequences on the Avalon and Burin Peninsulas of Newfoundland, the areas that supplied glacial debris to the Haddock and Halibut Channels (Piper and deWolfe, 2003). These are lower-current environments, with general bottom current model predictions of 10–20 cm/s (as opposed to ca. 100 cm/s in the tidally influenced Northeast Channel off Nova Scotia), and directly measured bottom currents of 8–15 cm/s in the Haddock Channel (Zedel and Fowler, 2009).

Seismic profiles from Desbarres Canyon show well-developed till tongues (Piper and Gould, 2004; their Fig. 3), supporting our observations of extensive areas of cobbles and boulders in mud matrix within the Desbarres Canyon area. Although we observed very few of the large gorgonian K. ornata in Desbarres Canyon, this species was recorded in fisheries bycatch from the Desbarres Canyon area (Wareham and Edinger, 2007). Fishing effort, especially trawling effort, is much higher around Desbarres Canyon than in the Haddock and Halibut Channel areas (Edinger et al., 2007b), suggesting that the dearth of K. ornata in the 2007 surveys of Desbarres Canyon may be a function of fisheries-induced damage. Although there are several records of fisheries bycatch of P. arborea in the Haddock Channel, very few of these larger corals were observed during our surveys, and none during the 2002 drop video surveys conducted in the area in waters shallower than 500 m (Mortensen et al., 2006b). The rarity or absence of Primnoa and Paragorgia from the Southwest Grand Banks sites may also reflect the low current regime; Primnoa and Paragorgia tend to be found in areas of high current flow (Bryan and Metaxas, 2006). Alternatively, the rarity of these species, which tend to be found shallower than Keratoisis and Acanthogorgia (Gass and Willisson, 2005; Mortensen et al., 2006b; Wareham and Edinger, 2007), may also reflect the result of decades of trawling (Kulka and Pitcher, 2002) on the continental shelf and upper slope.
5.3. Eroded friable bedrock and Quaternary glacimarine sediments

Deep-sea corals in The Gully were commonly observed on eroded friable Tertiary mudstone, in an environment resembling underwater badlands. The exposed mudstone outcrops in The Gully are thought to be a product of subglacial meltwater erosion (Fader and King, 2003; Piper, 2005). Coral growth on similar eroded bedrock was reported from The Gully by Mortensen and Buhl-Mortensen (2005b). Coral growth on eroded bedrock was also noted in the Northeast Channel (Scott, 2003; Watanabe et al., 2009).

We hypothesize that low shear strength of the bedrock may limit size, shape and species composition of deep-sea corals in many parts of The Gully. Friable bedrock outcrops frequently had large colonies of the elongate gorgonian *Keratoisis*, but only small colonies of the bushier gorgonians *Paragorgia* and *Prisma*. These bushy corals exert a much higher shear stress on the bedrock than would *Keratoisis*, given the same current regime. Detached moderate size colonies of *Paragorgia* were observed lying at the base of outcrops, having detached from the friable bedrock with their holdfasts intact, but often with a thin layer of bedrock remaining on the bottom part of the holdfast. This limitation also likely applies to exposed bedrock in the Northeast Channel (Scott, 2003); although bedrock exposures in the Northeast Channel are relatively uncommon in comparison with The Gully (Cogswell et al., 2009; Watanabe et al., 2009). Single colonies of the solitary scleractinian *D. dianthus* were also observed on eroded bedrock features in The Gully during a 2006 cruise using the Canadian Navy DSIS ROV (D.B. Scott, unpublished).

The near-vertical dip of the exposed bedrock outcrops seaward of the Stone Fence suggests that they may represent near-surface slumps of the type described by Hughes-Clarke et al. (1989). The antipatharian corals photographed on the deep eroded bedrock facies in the Stone Fence (Fig. 11) may represent a new species of *Puranihipathes* (Cogswell et al., 2009).

The horizontally bedded semi-consolidated sediment observed seaward of Haddock Channel is probably composed of Pleistocene glacimarine sediments (Mosher et al., 2010). Off Haddock Channel, both the small gully eroded into the semi-consolidated sediment, and the weakly consolidated slumped material may be related to the 1929 Grand Banks earthquake and turbidity current, although regionally no failures have been previously confirmed east of Halibut Channel (Armitage et al., in press).

A colony of *S. arctica* growing on top of the weakly consolidated slumped material was aged at 82 ± 31 years using bomb radiocarbon (Sherwood and Edinger, 2009). The slumped material may have originated as a rotational slump (cf. Piper et al., 1999), but no slump headscarp was observed, and the slump was not discernable in multibeam sonar, which had a pixel size of approximately 40 m (Fig. 2E).

5.4. Authigenic crusts

Growth of corals on authigenic crusts has been reported elsewhere in cold seeps and other deep-sea environments (e.g. Howland and Risk, 2003; Schroeder, 2007; Foubert et al., 2008a). White filamentous slime related to hydrocarbon release has been found on the Grand Banks (Fader, 1989).

The origin of the crusts off Halibut Channel is unknown, but may be related to seabeamed seepage of hydrocarbon and associated formation waters (Mosher et al., 2004), perhaps accelerated by seabed failure in 1929 (Piper et al., 1999). The relationship between the crusts and the excavation was unclear, as was the potential relationship between the crusts and cold seep activity, which is widely recognized as a trigger for deep-sea carbonate or other mineral crust formation (e.g. Bohrmann et al., 1998). The thinness of the authigenic crusts, apparently limited spatial extent and existence along the margins of an erosional feature within horizontally bedded semi-consolidated sediment suggest cementation related to cold seep activity. Cold seep activity has been reported at much greater depths in the Laurentian Fan (Mayer et al., 1987).

5.5. Coral assemblages on fine-grained post-glacial sediments

The abundance of post-glacial mud in many areas was not surprising. A dramatic difference in the coral assemblages between muddy environments and the various hard-substrate environments was also expected. Sea pens anchor in soft sediments using hydrostatically inflatable pedicles, while *Neomelin* lies semi-reclined in the mud. Because antipatharians, most gorgonians, and most scleractinians require hard substrates, they were not observed in muddy habitats, with the exceptions of the smaller gorgonian *A. arbuscula* and *R. gracilis*, both of which have root-like holdfasts that anchor the corals within sandy sediment. These two gorgonian species occur at much greater depth than the other gorgonians, which depend on hard substrates (Wareham and Edinger, 2007; Baker et al., 2008; Wareham, 2009; Cogswell et al., 2009).

5.6. Overview of interpreted relationship between geology and coral distributions.

As indicated in Fig. 1, there is a general correspondence between major glacial geological features that provide hard substrates at shelf-break and slope depths and the abundance of skeletal deep-water corals along the continental margin of Atlantic Canada. Fig. 16 summarizes the relationships among the geological features discussed in this paper, and between the geological features and the corals growing on them, in the form of a block diagram. The block diagram depicts the relative, rather than absolute, depth distributions of the five types of geological features discussed in this paper. For example, the current-swept ice-contact sediments are found at considerably greater depth in the Hudson Strait, Northern Labrador than in the Northeast Channel and Stone Fence, Nova Scotia (see Piper, 2005). Necessarily, the till tongues are always found at greater depths than the current-swept ice-contact sediments, and have been described from the mouths of many of the shelf-crossing troughs of the Newfoundland and Labrador continental margin (Piper, 2005; Shaw et al., 2006, and references therein). The exposed steep bedrock outcrops are found at a variety of depths in the Northeast Channel, The Gully, and The Stone Fence (Watanabe et al., 2009; Mortensen and Buhl-Mortensen, 2005b; Cogswell et al., 2009, respectively), not necessarily at depths below 1000 m.

Eroded consolidated Quaternary sediments and authigenic carbonates are suggested to be related to fluid flow along fault lines, consistent with our understanding of the Laurentian Fan region (Mayer et al., 1987; Mosher et al., 2004) and elsewhere. In general, eroded Quaternary sediments are thought to be more common than eroded Tertiary bedrock along the shelf break and upper continental slope of Newfoundland and Labrador (Piper, 2005). Authigenic carbonates may also occur on Orphan Knoll (Enachescu, 2004), although exposed pinnacles on Orphan Knoll could also be eroded remnants of Paleozoic bedrock (Parson et al., 1984; van Hinte et al., 1995).

The large skeletal coral fauna depicted on the different geological facies represents a summary of previously published research on coral distributions in relation to substrates (Mortensen and Buhl-Mortensen, 2004, 2005a, b; Mortensen et al., 2006a, b;
Cogswell, et al., 2009; Watanabe et al., 2009) and our qualitative in-situ observations. The large gorgonians Primnoa and Paragorgia and the colonial scleractinian Lophelia appear to be most common on the winnowed till facies (Mortensen et al., 2006a, b; Watanabe et al., 2009), and on the eroded bedrock facies in sites such as The Gully (Fig. 16). These sites coincide with strong bottom currents, suggesting that current strength is a strong predictor of these species distributions (Bryan and Metaxas, 2006, 2007). Without the moraines or bedrock to provide hard substrates, however, strong currents may not be sufficient to sustain populations of these corals (see Etnoyer and Morgan, 2007). Both current strength and geological facies probably influence the distribution of these species (Mortensen et al., 2006a, b).

The gorgonians K. ornata and A. armata, and the antipatharians, are all dependent on hard substrates, and were observed on a wide range of geological features, with K. ornata and A. armata the most common large skeletal corals on the till tongues seaward of Haddock and Halibut Channels (in-situ observation Mortensen et al. 2006 and this paper, and coral bycatch data, Mortensen et al., 2006b; Wareham and Edinger, 2007; Baker et al., 2008; Wareham, 2009; Cogswell et al., 2009). These species are generally found over a greater depth range than Primnoa and Paragoria (Wareham and Edinger, 2007; Baker et al., 2008; Cogswell et al., 2009). Many of these species can tolerate the high current strengths at the winnowed till and eroded bedrock facies, yet also grow in low current environments found on some of the till tongues (e.g. Zedel and Fowler, 2009). Till tongues may be the most common features that deliver hard substrates to deeper, lower current, areas of the upper continental slope along paraglacial continental margins. Ice-rafted debris may be another important source of hard substrates upon which corals can grow in paraglacial settings.

The eroded Quaternary sediments and authigenic crusts were each observed at only 1 site in our 2007 mission, although both types of features have been previously reported in Atlantic Canada, especially in the Laurentian Fan region (Mayer et al., 1987; Piper et al., 1999; Mosher et al., 2004; Piper, 2005). Observations on the coral fauna of these features are necessarily
limited, but included a variety of skeletal and non-skeletal species on the eroded Quaternary sediments, but only solitary scleractinian corals on the exposed underside of the authigenic crusts (see Sections 4.3 and 4.4). The solitary scleractinian coral D. diadophus often occurs on vertically exposed hard substrates that shelter it from sedimentation (Cairns, 1981; D.B. Scott, unpublished observations, 2006; Cogswell, et al., 2009). In our observations, these vertical hard substrates included eroded bedrock, eroded and/or slumped Quaternary sediments, and authigenic crusts. As a summary of the published literature and our qualitative observations, the illustrated distributions of corals among the geological facies represent hypotheses to be tested in future publications using quantitative data on coral species composition among the geological facies, from the various regions we have studied.

5.7. Comparison with other regions

With the exception of the seafloor meadows, hard substrates are fundamental to all the types of coral habitat described. The general origins of coral habitats observed along the Atlantic Canadian continental margin are similar to origins observed along other paraglacial continental margins. The origins of the hard substrate features differ markedly among paraglacial continental margins, continental margins not subject to glacial erosion and sedimentation, and non-continental regions such as seamounts.

5.7.1. Paraglacial continental margins

The patterns of erosion and sedimentation observed along the Atlantic Canadian margin are typical of paraglacial continental shelves, with transverse shelf-crossing troughs, shelf-break till deposits, deep-water till tongues, and yet deeper trough-mouth fans (O’Cofaigh et al., 2003). Cold-water corals are common in paraglacial shelf and slope settings such as the Norwegian continental margin and the Canadian Pacific and Atlantic continental margins. Along the continental shelf and slope of Norway, cold-water L. pertusa reefs have become established on a variety of bottom features, including bedrock ridges (Mortensen et al., 2001; Freiwalld et al., 2002), elevated hard substrates in glacial till associated with Pleistocene iceberg ploughmark berms (Freiwalld et al., 1999), cold seeps (Hovland and Risk, 2003), or even isolated boulders in sandy channels subject to strong unidirectional currents (Mortensen et al., 2008). On the Sula ridge, offshore Norway, variation in bedrock resistance to erosion contributes to the shape of the ridge on which the corals grow, although iceberg ploughmarks appear to have had a greater influence on reef distribution than the bedrock itself (Freiwalld et al., 2002). Although iceberg ploughmarks and associated berms have been recorded in great abundance from the Newfoundland and Labrador shelves (Josenhans and Barrie, 1989; Cameron and Sonnichsen, 1992) and on the upper Scotian Slope (Piper and Campbell, 2002), very few of the coral occurrences observed to date along the Atlantic Canadian margin has been recognized as associated with iceberg ploughmark berms.

In some fjords and coastal inlets in Norway, British Columbia, New Zealand, and Chile, corals and sponges are concentrated in locations where tidal currents are amplified by sills or other restrictions (e.g. Nordgård, 1921; Mortensen et al., 2001; Tunnicliffe and Syvitski, 1983; Grange, 1985; Haussermann and Forsterra, 2007). Large gorgonian and scleractinian corals and reef-forming sponges on Canada’s Pacific continental margin occur on a variety of hard-substrate features, including boulder-sized fragments of glacial drift (Tunnicliffe and Syvitski, 1983; Conway et al., 2005; Edinger et al., 2008) and bedrock ridges (Conway et al., 2007; Edinger et al., 2008). Of the coral species observed along the Atlantic Canadian continental margin, only one species, the nephtheid soft coral Gersemia rubiformis, has also been recorded in shallow water or in fjords (Dale et al., 1989; Maelisaac et al., 2001; Copeland et al., 2008). On Banquereau, a sandy bank offshore Nova Scotia, the soft coral G. rubiformis was observed to attach to empty mollusk shells at frequencies > 84% (Gilkinson et al., 2005). In Newfoundland and Labrador waters, most other coral species are probably restricted from fjords and shallow shelf environments by seasonal sub-zero surface water temperatures associated with the Labrador Current. An exception to this pattern are a few of the deep “warm-water fjords” along the south coast of Newfoundland, which contain Labrador slope water that remains 5°C or warmer year round, in which the soft coral A. grandiflorus was recorded (Haedrich and Gagnon, 1991). Off Nova Scotia, warm surface waters in summer restrict many coral species to slope depths (Mortensen et al., 2006b).

5.7.2. Non-paraglacial continental margins

Where cold-water coral reefs and concentrations have been described from areas outside major glacial influence, the origins of hard substrates supporting coral growth are generally exposed bedrock, eroded semi-consolidated sediment, shelf-break fluviodeltic gravels, and current-winned hardgrounds (Wheeler et al., 2007). In Alaskan waters, coral density is highest on bouldery island-arc shelf and slope features of the Aleutian Islands (Stone, 2006), but these environments experienced little or no direct impact of glaciation, and are isolated from continental turgrogenous sedimentation. Along the European margin south of Scandinavia, Lophelia reefs initiated upon coarse gravels associated with lowstand paleo-deltas (e.g. Stewart et al., 2006) and erosional features. Corals commonly occur along the flanks of submarine canyons, on eroded bedrock scarps (e.g. Huvenne et al., 2008), analogous to the erosional features supporting coral growth in The Gully as described here and by Mortensen and Buhl-Mortensen (2005b). For many of the large carbonate mounds on banks at the edge of the European margin (e.g. Porcupine Bank, Hatton Bank, Rockall Bank), cold-water coral reef growth initiated on bedrock, coarse siliciclastic deposits, or hardgrounds (Noël et al., 2006; Wheeler et al., 2007; Weinberg et al., 2008), but beneath larger mounds the original settlement surface has been obscured by successive generations of carbonate mound development, with corals re-establishing reef growth upon the mound after a hiatus of thousands of years or more (e.g. Foubert et al., 2008b).

In the Gulf of Cadiz, cold seeps contribute to formation of hard substrates that supported coral growth (e.g. Foubert et al., 2008a; Mienis et al., 2008). Similarly, cold seeps are the primary mechanism generating hard substrates that support L. pertusa reef development in the Gulf of Mexico (Schroeder et al., 2005; Schroeder, 2007), and support a wide variety of hard-substrate dependent epifauna surrounding cold seeps (e.g. Callender et al., 1990). Although the authigenic carbonates described from Haddock Channel may have been related to a small cold seep, most of the coral habitat encountered along the Canadian continental margin was paraglacial in origin. Similarly, while most of the coral habitat in the Hudson Strait and Baffin Bay is probably derived from ice-contact sediments or till tongues (see Section 4.1), a spatial correspondence between apparent hydrocarbon seepage and concentrations of cold-water corals in the Hudson Strait area has been recently documented (C. Jauer, Geological Survey of Canada, pers. comm., March 2009).

5.7.3. Non-continental-margin settings

In non-continental-margin settings, seamounts often harbour dense growth of cold-water octocoral and colonial and solitary scleractinian corals (e.g. Koslow et al., 2001; Stone, 2006; Rogers et al., 2007; Cairns, 2007). Isolation from continental sources of
sediment appears to favour growth of corals and other long-lived sessile benthos on seamounts (Rogers et al., 2007). Although several sets of seamounts occur off the continental margin of Atlantic Canada, most are quite deep and have not been investigated by drop-video, submersible, or ROV. The Newfound-land Seamounts, Fogo Seamounts, and Orphan Knoll have some corals including recent and subfossil D. diadum (e.g. Smith et al., 1997), and have been studied geologically, but coral habitats in these areas have yet to be investigated using in-situ means. The Newfoundland Seamounts, near the boundary between Canadian and US waters, support dense communities and diverse assemblages of corals and other sessile epifauna (e.g. Moore et al., 2004; Cairns, 2007), except where they have been impacted by fishing (Waller et al., 2007).

6. Conclusions

Quaternary and surficial geology exert a crucial influence on the features that support growth of many types of cold-water corals, particularly along paraglacial continental margins. In Atlantic Canada, glacial and glaciomarine processes that transported coarse-grained sediment onto the continental slope are particularly important. Most areas with high densities of gorgonian and antipatharian corals along the Atlantic Canadian continental margin are associated with shelf-crossing glacial troughs and trough-mouth fans, both characteristic features of ice streams, as observed in other paraglacial settings. Glacial and paraglacial deposits supporting coral growth included winnowed boulders and cobbles derived from ice-contact sediments, and isolated cobbles and boulders within a fine-grained matrix, derived from till tongues. Ice-contact derived boulders and cobbles in relatively current-swept environments support the gorgonian corals Primnoa, and Paragorgia, in the Northeast Channel, The Gully, the Stone Fence, and the eastern margin of the Hudson Strait, near the northern tip of Labrador. Till tongue derived cobbles and boulders in a fine-grained matrix in lower-current environments apparently provide habitat for gorgo-nian and antipatharian corals in the Haddock and Hallibut channels, SW Grand Banks, and probably near the mouth of the Trinity channel (Tobin’s Point), and near the mouths of several shelf-crossing troughs along the Labrador shelf edge.

Erosional environments composed of weakly consolidated Tertiary siliciclastic sediments provide substrates for cold-water coral habitat, especially in The Gully. Erosional exposures of Quaternary sediments can also support coral growth locally. Authigenic carbonate crusts, probably associated with cold seep activity, were observed to support coral growth in one location in Haddock Channel, but are likely to be more widespread, particularly around the Laurentian Fan.

Most of the continental slope is composed of fine-grained unconsolidated sediments, and provides suitable habitat for sea pens, reclining solitary scleractinians (mostly Flabellum), and smaller gorgonian corals with root-like holdfasts, such as Acarella arbuscula. Understanding cold-water coral distributions depends in part on understanding the geological origins of their habitats. Predictive models of deep-sea coral distributions along paraglacial continental margins should consider glacial history, especially the position of major ice streams, and other geological features, in addition to oceanographic factors.

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