THE ECOLOGY OF DEEP-SEA CORALS OF NEWFOUNDLAND AND LABRADOR WATERS: BIOGEOGRAPHY, LIFE HISTORY, BIOGEOCHEMISTRY, AND RELATION TO FISHES

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by

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TABLE OF CONTENTS

Page

ABSTRACT

Gilkinson, K., and Edinger, E. (Eds.) 2009. The ecology of deep-sea corals of Newfoundland and Labrador waters: biogeography, life history, biogeochemistry, and relation to fishes. Can. Tech. Rep. Fish. Aquat. Sci. 2830: vi + 136 p.

In 2005, the DFO-Memorial University deep sea corals research group significantly expanded a core research program through a three-year International Governance Program (IGP) funded program. This funding expanded a database consisting primarily of trawl survey derived distributional data on corals to include dedicated field surveys and laboratory analyses and experiments which has yielded novel information on the ecology and biology of deep sea corals. This funding also permitted a deep sea cruise in 2007 to study, *in situ*, benthic habitats and communities of the continental slope at depths never before explored in the region. This was accomplished using the deep water remotely operated vehicle ROPOS (Remotely Operated Platform for Ocean Science). Many hours of high resolution video and still photos were collected, which are currently being processed. Specific scientific questions were addressed in this IGP study, including i) What are the inter-relationships between corals and fish? ii) At what trophic levels do deep-sea corals feed, and what do they feed upon? iii) What can biochemistry of coral tissues tell us about their 'condition'? iv) What can the 'skeletons' of corals reveal to us about historical oceanographic conditions? v) What are the growth rates and longevities of corals in our region? vi) How can past distributions of deep-sea corals be recognized and reconstructed from marine sediments vii) How do deep-sea corals reproduce and successfully recruit? Key findings of this study in relation to these scientific questions are presented. It should be stressed that while significant progress was made in answering these scientific questions as a result of IGP funding, continued research is required in these areas of study in order to better understand these sensitive deep water species. Conclusions and recommendations regarding future research priorities and conservation measures required to protect Vulnerable Marine Ecosystems (VMEs) represented by corals and their habitats are presented.

RÉSUMÉ

Gilkinson, K., and Edinger, E. (Eds.) 2009. The ecology of deep-sea corals of Newfoundland and Labrador waters: biogeography, life history, biogeochemistry, and relation to fishes. Can. Tech. Rep. Fish. Aquat. Sci. 2830: vi + 136 p.

En 2005, le groupe de recherche sur les coraux profonds formé par Pêches et Océans et l'Université Mémorial a entamé un projet de 3 ans sur les coraux financé par un fond fédéral sur la gouvernance des Océans. Ce projet a considérablement enrichi la connaissance préalablement acquise sur la distribution des coraux ainsi que d'autres aspects de l'écologie et biologie des coraux profonds. Une des conséquences du financement de ce projet fut une campagne océanographique en 2007 pour observer les habitats benthiques du plateau continental *in situ*, et ce à des profondeurs jamais atteintes auparavant. Cette campagne a nécessité l'utilisation de cameras télécommandées. De nombreuses heures de film restent encore à traiter et analyser. Durant le projet décrit ci-dessus, de nombreuses questions ont été posées et partiellement résolues : 1) Quelles sont les relations biologiques entre coraux et poissons occupant ces habitats? 2) A quel niveau trophique trouve t-on la nourriture des coraux ? 3) Que peut nous apprendre la biochimie des tissus de ces coraux ? 4) Que peuvent nous apprendre les squelettes des coraux sur l'histoire des conditions océanographiques locales ? 5) Quels sont le taux de croissance et longévité des coraux étudiés ? 6) Peut-on reconstituer la distribution passée des coraux à partir de prélèvements de sédiments marins ? 7) Comment se déroule la reproduction des coraux étudiés ? De nombreuses réponses à ces questions se trouvent dans ce rapport. Il est néanmoins important de signaler que de nombreuses questions restent sans réponse et que le financement de recherches futures dans ce domaine est primordial. Des recommandations sur le statut de protection des coraux étudiés sont également présentées dans ce document.

Background

Fisheries and Oceans (DFO) Canada recognizes that a strong scientific research program is required to make sound management decisions in order to ensure sustainability of fish stocks. In 2005, the Government of Canada announced funding of $20 m over three years for science, advocacy, policy and legal initiatives in support of Canada's international governance of high seas strategy. More than half of this funding was reserved for scientific research. This International Governance Program (IGP) report details the results of a three-year study falling under a key IGP research priority area, "At-Sea Research on Sensitive Areas and Species". This study focused on deep-sea corals. Deep-sea corals and their associated fauna can be considered straddling resources as their distributions extend both inside and outside Canada's 200 mile limit in deep-water, sensitive habitats. This project served to enhance our understanding of the distribution and biodiversity of deep-sea corals in the Newfoundland and Labrador region, and to provide novel information on the biology and ecology of corals and associated species.

Deep-sea corals are now recognized as important components of deep-sea ecosystems (Mortensen et al. 1995, Freiwald and Roberts 2005). These corals provide habitat for a variety of fish species, including some that are commercial (Jensen and Frederiksen 1992; Hosebo et al. 2002; Buhl-Mortensen and Mortensen 2004; Edinger et al. 2005). Recently, the impact of fishing on deep-sea corals has been recognized as a major environmental concern (Watling and Norse 1998; Willison et al. 2001; Hall-Spencer et al. 2002; Fossa et al. 2001; Scott et al. 2005). Their extreme longevities and slow growth rates result in estimated recovery times from disturbance measured on time scales from tens to hundreds of years (Hall-Spencer et al. 2002; Sherwood et al. 2005).

Understanding these unique species and their inter-relationships with other species in deep-sea ecosystems is crucial in order for DFO to meet conservation objectives under the *Fisheries Act* and *Oceans Act*. Coral data played a key role in the establishment of Sable Gully as Atlantic Canada's first Marine Protected Area (2003) under the Oceans Act. Furthermore, two recent fisheries closures in the Maritimes Region were established on the basis of coral hotspots in the Northeast Channel (2002) and at the site of the recently discovered, badly damaged, *Lophelia pertusa* reef at the Stone Fence (2004).

Previous and on-going collaborative DFO-Memorial University research, focusing on systematic mapping of trawl-caught corals, has significantly expanded our knowledge of deep-sea coral distributions and diversity in the Newfoundland and Labrador region (Edinger et al. 2005). This 'core' research program has provided the foundation for our knowledge of the distribution and diversity of corals. However, in order to properly manage these important and sensitive species, and the habitats they structure, detailed knowledge of their biology, as well as ecological relationships with other species, including fish, is urgently needed. Funding provided through the IGP was essential in order to address key

ecological and biological questions related to deep-sea corals (see below). In particular, IGP funding provided the opportunity to undertake a challenging deep-sea cruise in the Newfoundland region in the summer of 2007 to observe and sample corals and associated fauna in their natural habitats using a remotely operated vehicle (ROV) (see Appendix A). Data products from this IGP project, in the form of scientific publications, are listed in Appendix B.

Objectives

Scientific questions in eight major categories were addressed in the three-year study:

(1) **Coral distribution, abundance and diversity**: where do corals occur, and where are corals most abundant? Which types of environments typify coral habitat?
(2) **Inter-relationships between corals and fish**: which commercial and non-commercial invertebrate and fish species are most commonly associated with corals?
(3) **Trophic relationships:** at what trophic levels do deep-sea corals feed, and what do they feed upon?
(4) **Condition of corals:** what can biochemistry of coral tissues tell us about their 'health'?
(5) **Growth rates/longevity:** what are the growth rates and longevities of corals in our region?
(6) **Oceanographic conditions:** what can the 'skeletons' of corals reveal about historical oceanographic conditions?
(7) **Taphonomy:** how long do coral skeletons persist on the bottom? What factors affect breakdown of skeletons? How can past distributions of deep-sea corals be recognized and reconstructed from marine sediments?
(8) **Reproduction/Recruitment:** how do deep-sea corals reproduce and successfully recruit?

Part 1: Coral Biogeography and Biology

UPDATES ON DEEP-SEA CORAL DISTRIBUTIONS IN THE NEWFOUNDLAND LABRADOR AND ARCTIC REGIONS, NORTHWEST ATLANTIC

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ABSTRACT

Deep-sea coral distribution data from Newfoundland and Labrador and Arctic regions partially filled information gaps previously identified by Wareham and Edinger (2007); including that for the continental edge and slope of the NE Newfoundland Shelf, Orphan Basin, and Flemish Pass. Arctic data extended sampling coverage into, Baffin Bay, Davis Strait, Hudson Strait, and Ungava Bay. Corals were found along the continental edge and slope. Overall, there is an increase in occurrences for all species. The 2007 ROPOS cruise provided video footage of *in situ* corals, including intact and damaged corals, and documented new species to the region (n = 5 spp.) and unique habitats (e.g. *Keratoisis* thickets and sea pen and *Acanella arbuscula* fields). Data presented expands our knowledge base to 36 documented and mapped species. NAFO Div. 2G-0B remains insufficiently sampled with only one year of research data included. However, a portion of the area has been established as a *Voluntary Coral Protection Zone*. Not all areas have been surveyed sufficiently and other data sources could be considered in order to help identify and protect other important areas not captured within newly established closures (i.e. NAFO Div. 0B-2G and 3Ps). Corals are highly sensitive to fishing disturbance. Unique areas like *Keratoisis ornata* thickets observed in Haddock-Halibut Channels (NAFO Div. 3Ps) are not captured within the *CAD-NAFO Corals Protection Zone* (NAFO Div. 30), but are among the oldest and most sensitive coral habitats in the region. Newly established closures are a good first step but stronger permanent legislation is urgently needed to fully protect corals. Currently, the database is comprised of deep-sea corals only; however, other structure forming megafauna (i.e. sponges, hydrozoans, and bryozoans) should be considered and incorporated in future sampling protocols.

INTRODUCTION

In Canada, distributions of deep-sea corals have now been extensively mapped in the Northwest Atlantic (Gass and Willison 2005; Wareham and Edinger 2007). Understanding corals and their inter-relationships with other species in deep-sea ecosystems is crucial in order for Fisheries and Oceans Canada (DFO) to meet conservation objectives under the *Fisheries Act* and *Oceans Act*. Coral data played a key role in the establishment of Sable Gully as Atlantic Canada's first Marine Protected Area (MPA) (DFO 2004a) under the *Oceans Act*. Additional fisheries closures in the Maritimes Region were also established on the basis of coral hotspots in the Northeast Channel (DFO 2002) and Stone Fence (DFO 2004b).

In Newfoundland and Labrador and the Arctic no official protection under the *Oceans Act* (i.e. MPA) exists for corals. However, several other conservation measures have been taken in these regions. There are two temporary closures in the NL Region, and one in the Arctic. There is an industry lead *Voluntary Coral Protection Zone* off Hudson Strait, comprising a 12,500 km^2 area in NAFO Div. 2G-0B off Cape Chidley, Labrador, which, was initiated and implemented by industry comprised of the Groundfish Enterprise Allocation Council (GEAC), Canadian Association of Prawn Producers (CAPP) and Northern Coalition (NC). The purpose of the closure is to conserve specified species of large corals (e.g. *Primnoa resedaeformis*, *Paragorgia arborea*, *Paramuricea placomus* and *P. grandis*, and antipatharian spp.) that are known to exist in significant concentrations in the area (Bruce Chapman, pers. comm.). Secondly, a *CAD-NAFO Coral Protection Zone*, exists as a mandatory temporary closure (to 2012) on the slope of the Grand Bank in NAFO Div. 3O between 800 and 2000 m (NAFO 2007). This encompasses an area of 14,040 km^2. It was initiated by the Canadian-NAFO Working Group and implemented by NAFO. The purpose of the closure is to protect corals found in the area and 'freeze the footprint' of fishing activities in deeper waters. Finally, a 60000 km^2 *Narwhal-Coral Protection Zone*, located in the Arctic Region, is a fisheries closure for Greenland halibut in an area north of the Davis Strait in NAFO Div. 0A (DFO 2007). This was initiated and implemented by DFO Winnipeg in April 2006, and was designed to reduce fishing effort in order to help protect Narwhal over-wintering grounds and deep-sea corals.

This section provides an update on the ongoing process of identifying and mapping deep-sea corals in the Northwest Atlantic, building on the existing dataset initiated by Wareham and Edinger (2007) in order to help identify and highlight areas for protection within the Newfoundland and Labrador and Arctic Regions. This update focuses on the time period covered by this IGP program (2005-07).

METHODOLOGY

Study Area

The study area encompasses the continental shelf, edge, and slope of the Grand Banks of Newfoundland (NAFO Div. 3LNOP), Flemish Pass (NAFO Div. 3L), Flemish Cap (NAFO Div. 3M), Northeast Newfoundland Shelf (NAFO Div. 3K), Labrador Shelf (NAFO Div. 2GHJ), Southeast Baffin Shelf (NAFO Div. 0B), and Baffin Bay (NAFO Div. 0A), as outlined in Map 1.

Data Sources

Data was collected opportunistically from two primary sources: (1) annual multispecies research surveys conducted by DFO's Science Branch NL Region (2006-07), and (2) Fisheries Observer Program (FOP) data collected onboard commercial fishing vessels operating within the NAFO Convention Area (2006-07).

In addition, DFO's Arctic region began contributing coral distribution data in 2006 from multispecies research surveys conducted in that Region (NAFO Div. 0AB). All 2006-07 data, including representative coral samples, were forwarded to the NL Region and incorporated into the existing database.

Multispecies research surveys conducted by DFO in NL in 2000 (one survey in NAFO Div. 3L) and 2004 (two surveys in NAFO Div. 2J and 3KLNM) collected corals from the region but samples were originally sent to Bedford Institute of Oceanography (BIO), Maritimes Region. All samples have since been forwarded to the NL region and are now incorporated into the dataset.

The corals dataset currently contains only one research survey from The Northern Shrimp Stock Assessment Survey (2005): a five year annual survey in progress for the Arctic Region (2005-10), co-sponsored by the Northern Shrimp Research Foundation and DFO NL. Two additional research surveys were conducted in 2006 and 2007; however this data is currently unavailable.

Research survey vessels follow a standardized stratified random sampling protocol. In NL, surveys use a Campelen 1800 shrimp trawl with rockhopper footgear (McCallum and Walsh 1996). Arctic surveys are carried out with two gear types with rockhopper footgear; a Cosmos 2600 shrimp trawl for shallow water tows (100-800 m) and an Afredo otter trawl for deep water tows (400-1500 m) (T. Seiferd, pers. comm.). FOP data was collected from a variety of mobile and fixed gear types. Further details on sampling gear and methodologies can be found in Wareham and Edinger (2007).

In July 2007, high resolution video collected by a deep water ROV (ROPOS) provided *in situ* observations of corals at three deep water sites in NL: Halibut

Channel, Haddock Channel, and Desbarres Canyon. Data consisted of high resolution video, frame grabs, and still images that are currently being processed.

Limitations

A key limitation of attempting to display point data on maps covering very large areas is the associated visual misrepresentation of actual area represented by individual points. It is therefore essential to interpret the distribution maps with the aid of accompanying text. Distribution data without any measure of abundance can only be represented as a point on a map. If the study area is large, such as in this case, points appear much larger than the actual area sampled (~0.8 nmi), and as such, points can only represent occurrences; a typical method for illustrating species distributions.

Other limitations are the result of variation between data sources (i.e. multispecies surveys vs. FOP), as well as the type of habitat from which the data was collected. For example, survey trawls can only sample on relatively level sea beds leading to a bias in favor of certain types of sea floors, i.e. favoring level grounds and excluding stepper slopes and canyons (e.g. Grand Bank continental slope and edge). On the other hand, FOP data collected from commercial vessels are biased towards 'good fishing grounds' that are based on past catch rates and the level of experience of the vessel's skipper. Observer data incorporates many fisheries that use different gear classes (mobile and fixed), gear types (shrimp trawl, twin trawl), and fish in all types of marine habitats and a variety of substrates (e.g. boulders fields, mud, or sand). In short, research data can be biased towards 'trawlable' bottom types, whereas FOP data can be biased towards 'fishing effort'.

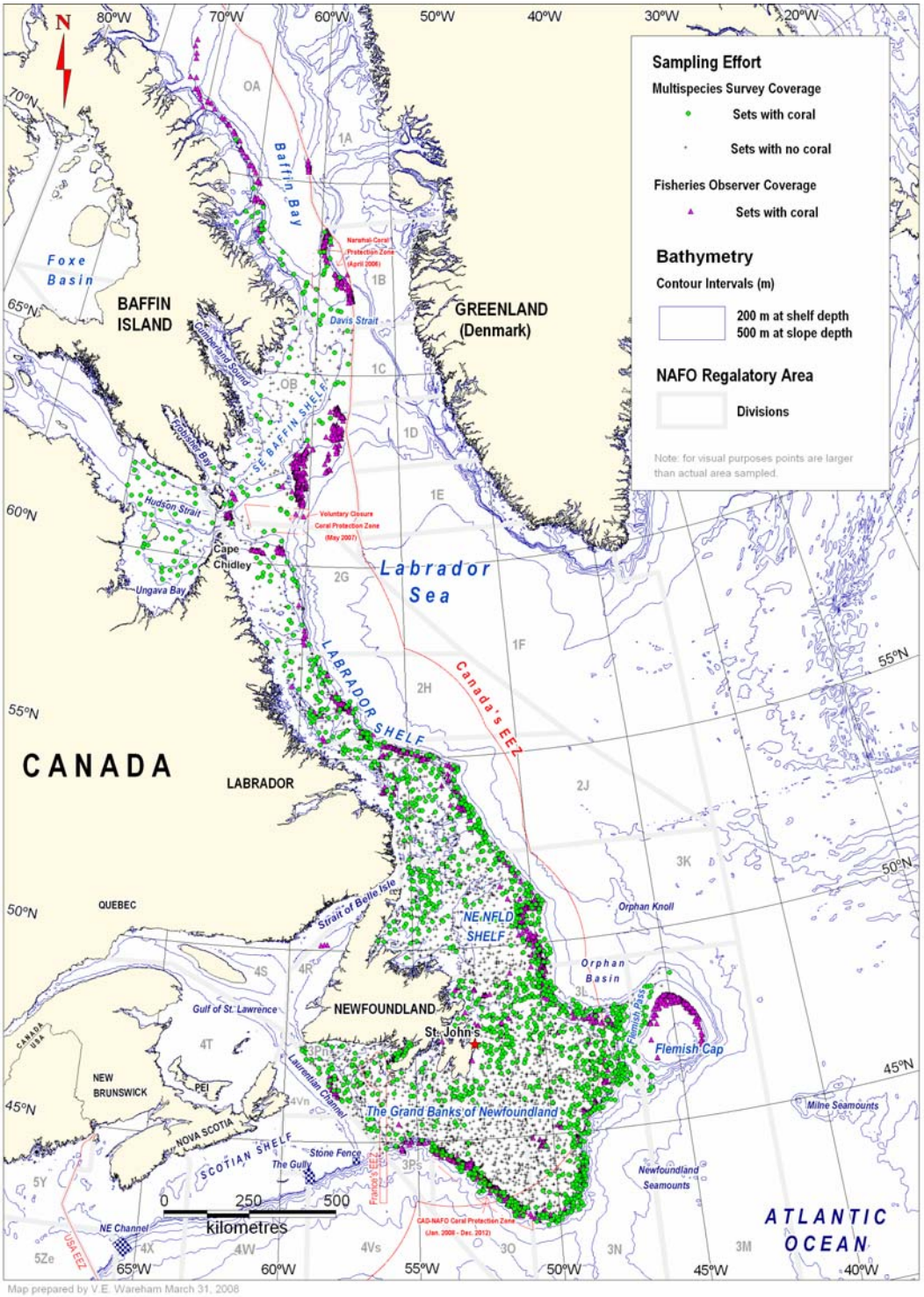
RESULTS

Results are presented as coral distribution maps that build on baseline data compiled by Wareham and Edinger (2007). New data includes; coral samples from 2000 to 2005 that were not originally included in Wareham and Edinger (NL; 2007), multispecies survey data from 2006 to 2007 (Arctic and NL Regions), Fisheries Observer data from 2006 to 07 (Arctic and NL), and preliminary results from the ROPOS Discovery Cruise 2007 (NL). Maps are broken down by overall sampling effort (Map 1), followed by coral distributions based on sub-groups; antipatharians (Map 2), alcyonaceans [large gorgonians (Map 3), small gorgonians (Map 4), and soft corals (Map 5)], scleractinians (Map 6), pennatulaceans (Map 7), and ROPOS highlights (Map 8). Voucher specimens of all pennatulaceans were sent to and verified by Dr. G. Williams of the California Academy of Sciences. Scleratinians were identified by Dr. S.D. Cairns of the Smithsonian Institute and associated documents (Cairns 1981). *Chrysogorgia agassizii* (Verrill 1883) was identified using Cairns (2001). See Table 1 for a

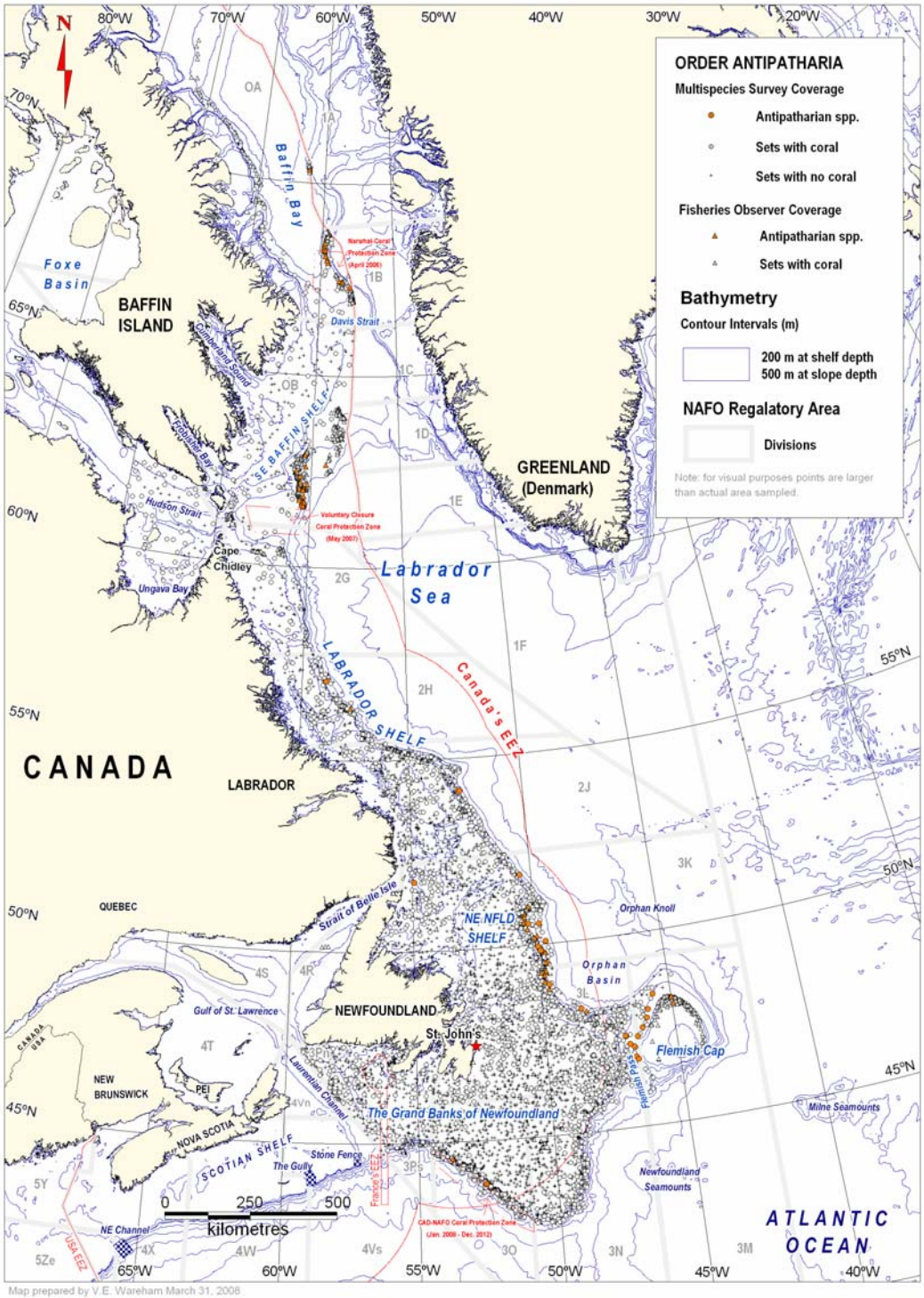
summary of data frequencies documented and mapped over the course of the project.

Table 1. Summary of coral frequencies used in distribution maps.

Order	Group	Wareham and Edinger (2007)	New data	Total
Antipatharia	black-wire corals	37	64	101
Alcyonacea	large gorgonians	134	78	212
	small gorgonians	422	502	924
	soft corals	963	1481	2444
Scleractinia	solitary stony corals	148	130	278
Pennatulacea	sea pens	577	1060	1637
	Total	**2281**	**3315**	**5596**

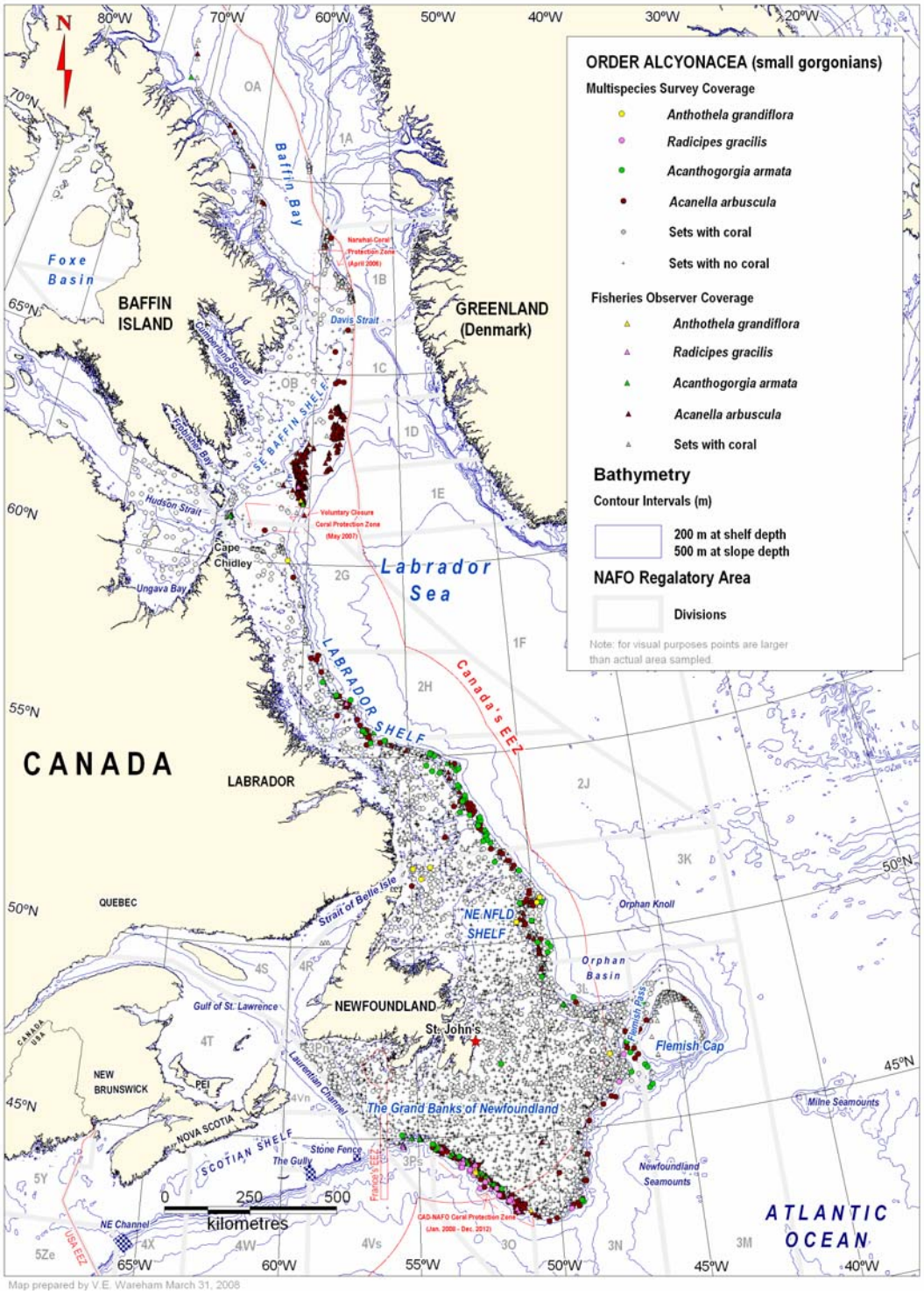


Map 1. Study area and sampling effort with distribution of deep-sea corals highlighted. Data was collected from Northern Shrimp Multispecies Survey (2005), Newfoundland Labrador Multispecies Surveys (2000-07), Arctic Multispecies Surveys (2006-07), and from Fisheries Observers aboard commercial fishing vessels (2004-07).

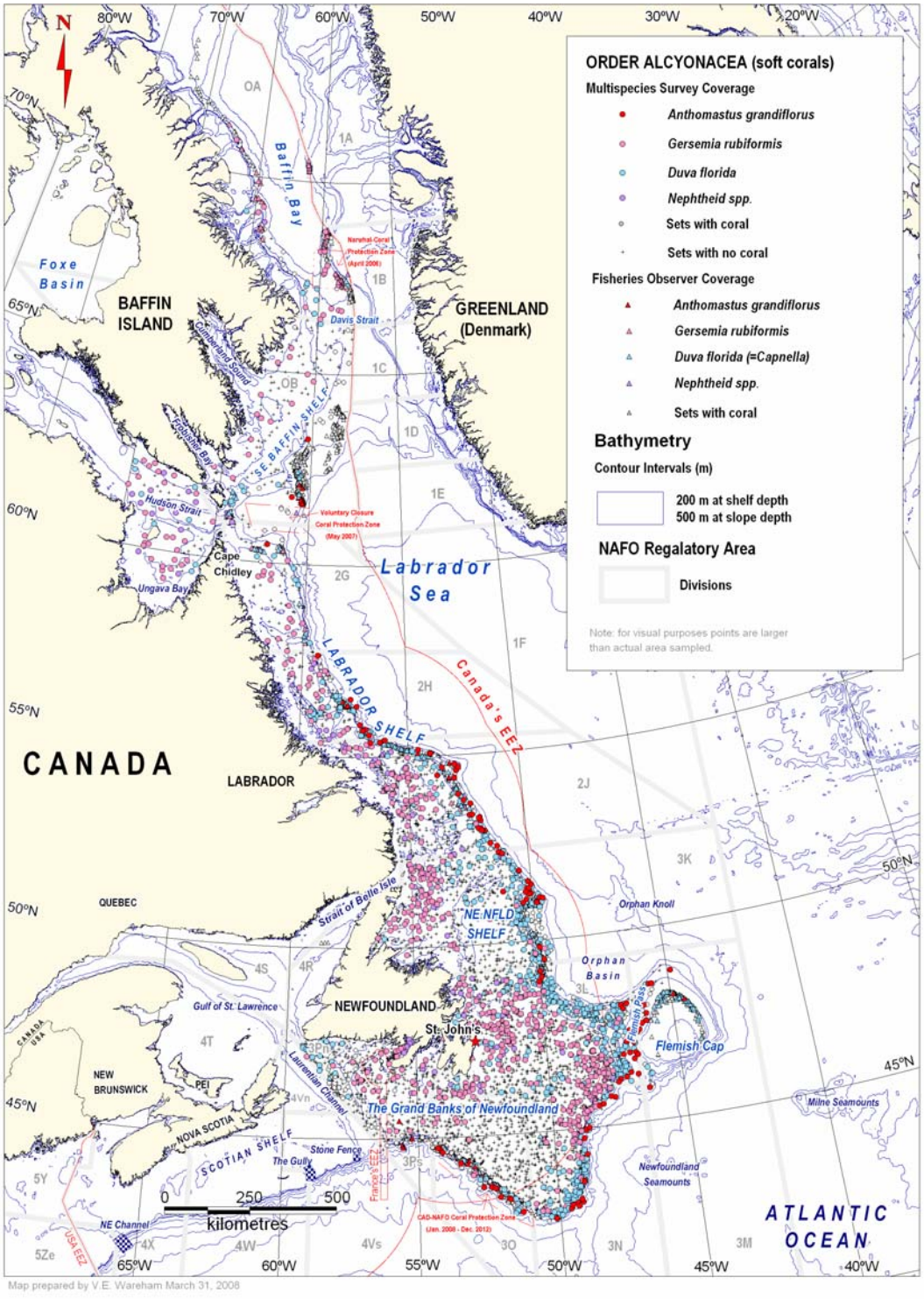


Map 2. Distribution of deep-sea corals from the Order Antipatharia (includes *Stauropathes arctica*, and *Bathypathes* spp.). Data was collected from Northern Shrimp Survey (2005), Newfoundland Labrador Multispecies Surveys (2000-07), Arctic Multispecies Surveys (2006-07), and from Fisheries Observers aboard commercial fishing vessels (2004-07).

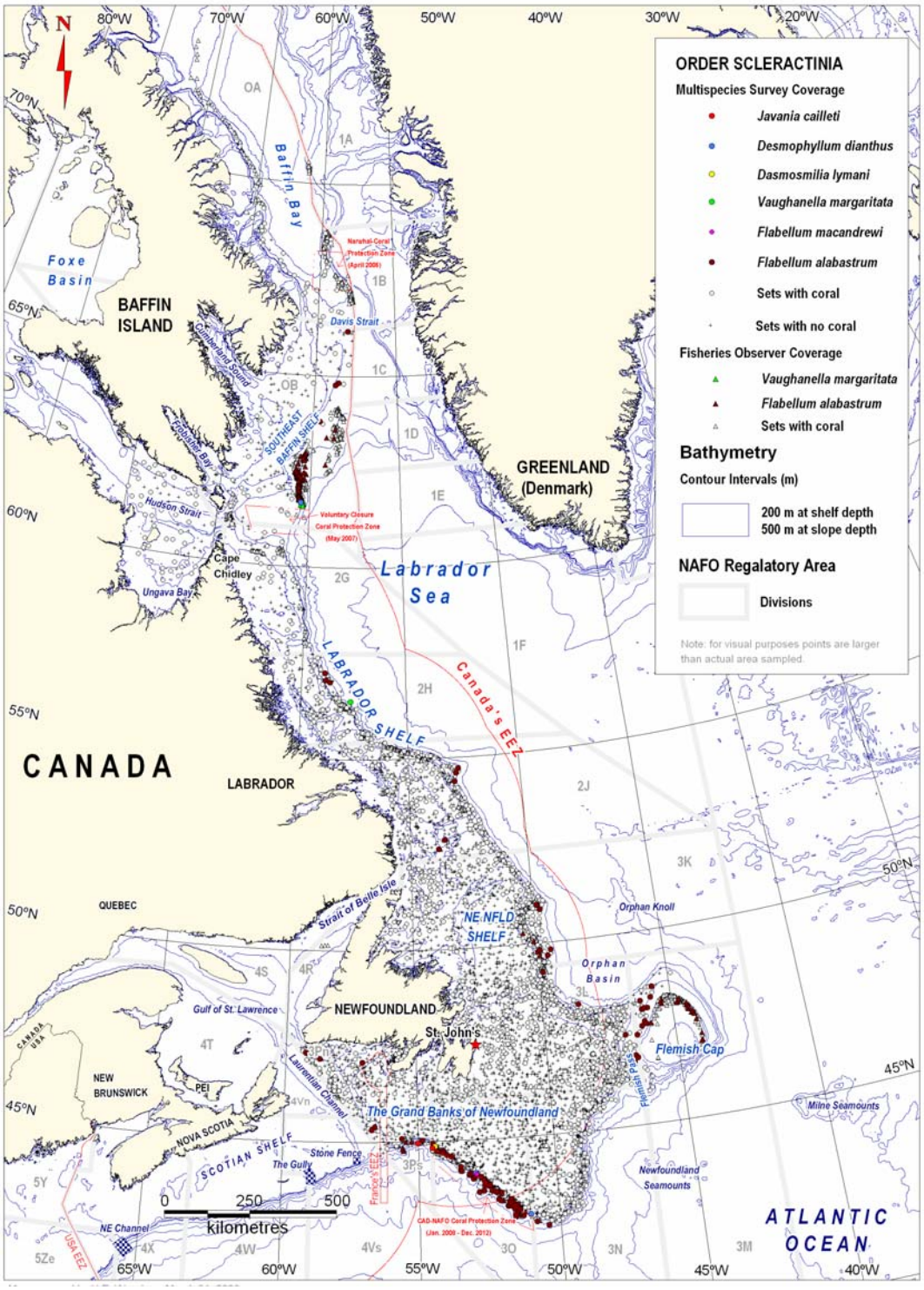
Map 3. Distribution of deep-sea corals from the Order Alcyonacea (large gorgonians). Data was collected from Northern Shrimp Survey (2005), Newfoundland Labrador Multispecies Surveys (2000-07), Arctic Multispecies Surveys (2006-07), and from Fisheries Observers aboard commercial fishing vessels (2004-07).



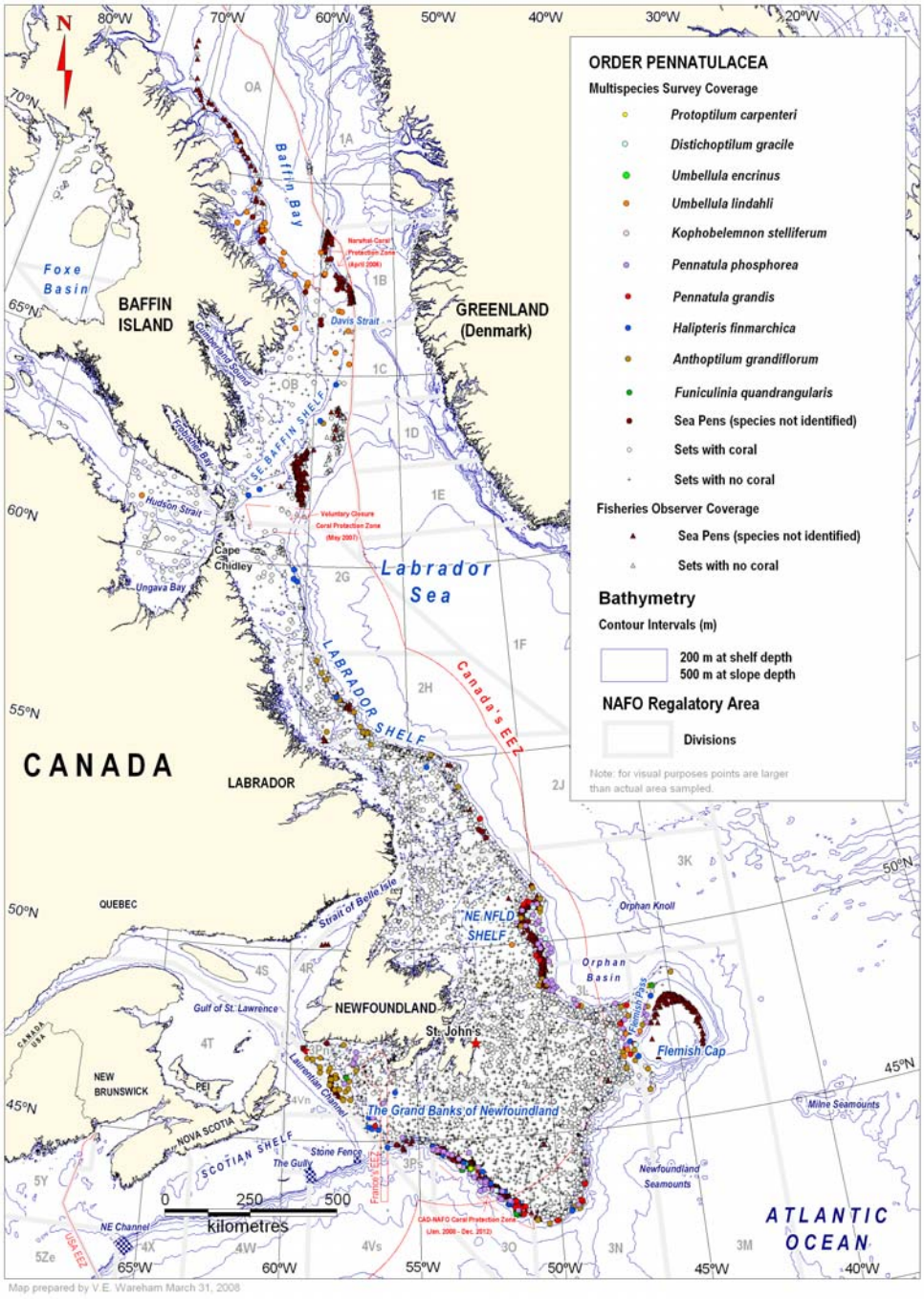
Map 4. Distribution of deep-sea corals from the Order Alcyonacea (small gorgonians). Data was collected from Northern Shrimp Survey (2005), Newfoundland Labrador Multispecies Surveys (2000-07), Arctic Multispecies Surveys (2006-07), and from Fisheries Observers aboard commercial fishing vessels (2004-07).



Map 5. Distribution of deep-sea corals from the Order Alcyonacea (soft corals). Data was collected from Northern Shrimp Survey (2005), Newfoundland Labrador Multispecies Surveys (2000-07), Arctic Multispecies Surveys (2006-07), and from Fisheries Observers aboard commercial fishing vessels (2004-07).

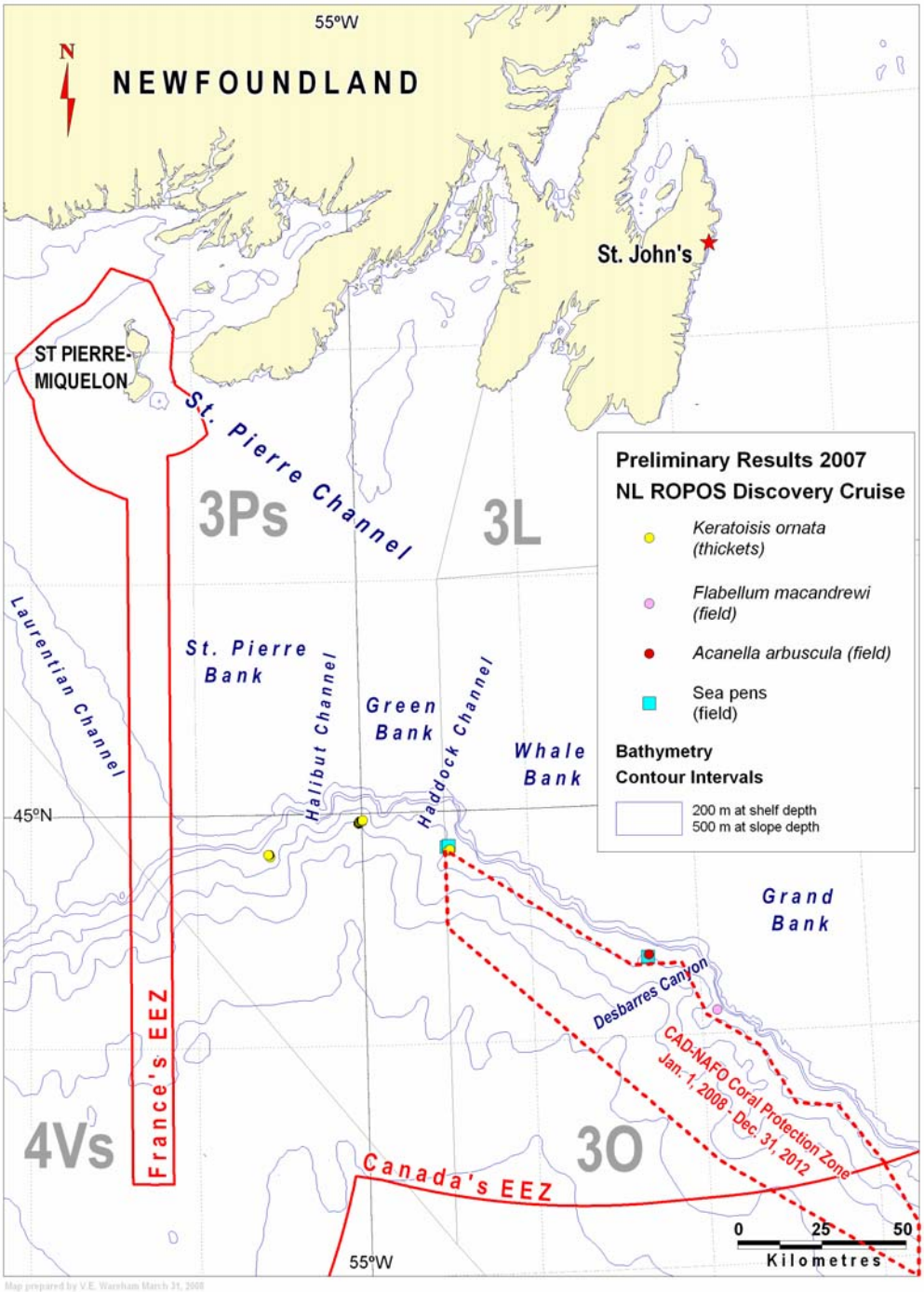


Map 6. Distribution of deep-sea corals from the Order Scleractinia (solitary stony corals). Data was collected from Northern Shrimp Survey (2005), Newfoundland Labrador Multispecies Surveys (2000-07), Arctic Multispecies Surveys (2006-07), and from Fisheries Observers aboard commercial fishing vessels (2004-07).



Map 7. Distribution of deep-sea corals from the Order Pennatulacea (sea pens). Data was collected from Northern Shrimp Survey (2005), Newfoundland Labrador Multispecies Surveys (2000-07), Arctic Multispecies Surveys (2006-07), and from Fisheries Observers aboard commercial fishing vessels (2004-07).

Preliminary results ROPOS Discovery Cruise 2007



Map 8. Preliminary results of unique deep-sea coral habitats from NL ROPOS Discovery Cruise (2007) including clusters of undisturbed *Keratoisis ornata* colonies, termed 'thickets', and large concentrations of sea pens and *Acanella arbuscula* colonies, referred to as 'fields'.

Only preliminary distribution results are presented here. However, key findings include illustration of unique coral habitats (Map 8) and five species not previously documented in this region. New species include two pennatulaceans (*Umbellula encrinus* Linnaeus, 1758; *Protoptilum carpenteri* Kölliker, 1872), one gorgonian (*Chrysogorgia agassizii*), and two scleractinians (*Flabellum macandrewi* Gray, 1849; *Javania cailleti* Duchassaing and Michelotti, 1864) (Fig. 1).

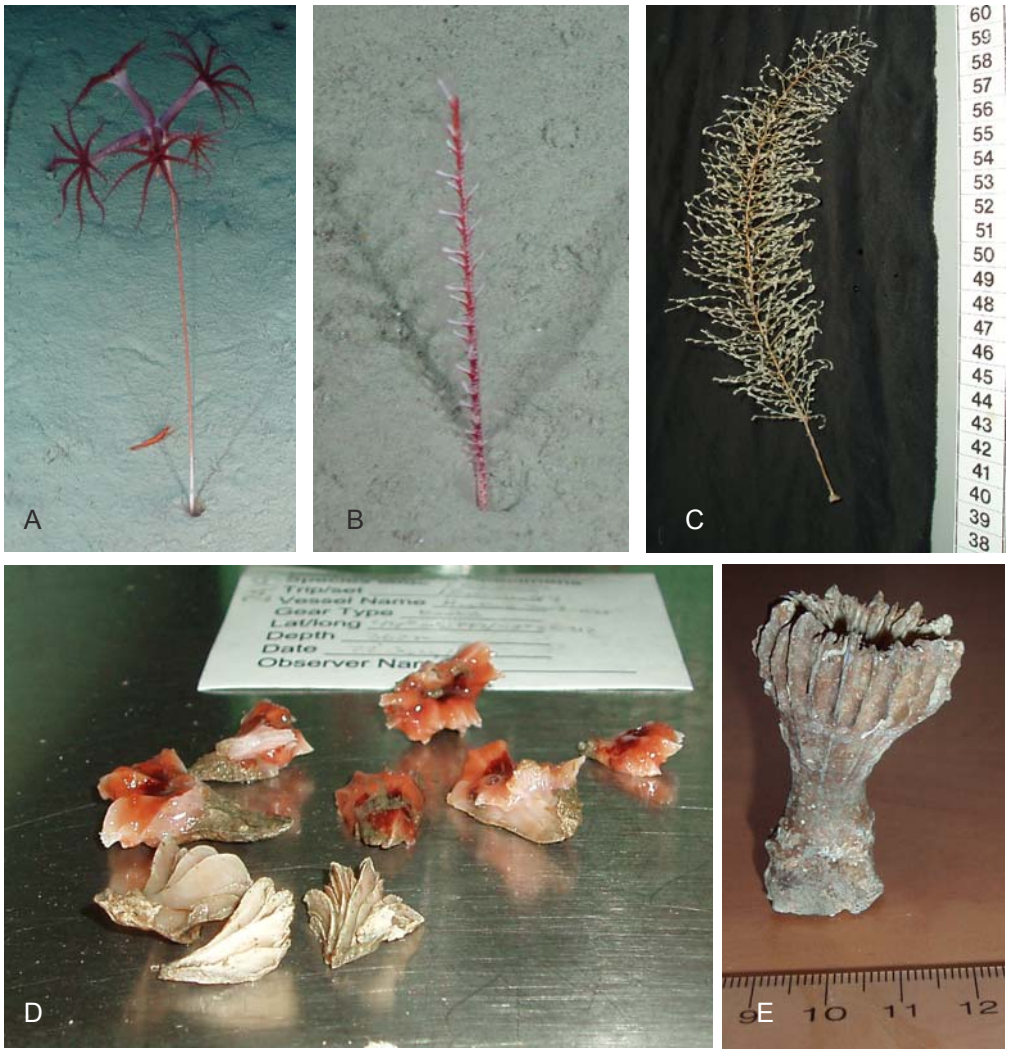


Figure 1. Deep-sea coral species documented in NL during the 2007 ROPOS Discovery Cruise; A. *Umbellula encrinus*; B. *Protoptilum carpenteri*; C. *Chrysogorgia agassizii*; D. *Flabellum macandrewi*, and E. *Javania cailleti*.

In total 36 species of coral have now been documented in the Newfoundland Labrador and Arctic Regions including; 14 alcyonaceans, two antipatharians, six scleractinians, and 14 pennatulaceans.

DISCUSSION

Newfoundland and Labrador and Arctic deep-sea coral distribution data presented here have contributed to filling data-gaps identified by Wareham and Edinger (2007). Areas such as the continental edge and slope of Northeast Newfoundland Shelf, Orphan Basin, and Flemish Pass are now represented. Data from the Arctic region represents a valuable contribution by extending sampling coverage into far northern regions including Baffin Bay, Davis Strait, Hudson Strait, and Ungava Bay. However, a significant gap still exists on the boundary line between NAFO Div. 2G-0B. This area remains insufficiently sampled with only one year of research data (Wareham and Edinger 2007). It is noted that an additional two years of data exists (Northern Shrimp Survey 2006-2007) but were unavailable for these analyses. This area, Hudson Strait-Cape Chidley, has been identified in previous studies as an important area for corals, notably *Paragorgia arborea* and *Primnoa resedaeformis* (MacIssac et al. 2001; Gass and Wilison 2005; Mortensen et al. 2006; Edinger et al. 2006; Wareham and Edinger 2007), two species not found in any great abundance within the study area. Part of this area also has temporary protection within the industry initiated *Voluntary Coral Protection Zone*.

The 2007 ROPOS cruise provided unique non-destructive sampling opportunities that included extensive video footage and photographs of corals, and unique coral habitats in Haddock Channel, Halibut Channel, and Debarres Canyon (Map 8). Pristine and damaged coral colonies, notably the long-lived species *Keratoisis ornata* (Sherwood et al., in press) were recorded on video in Haddock and Halibut Channels. This cruise also provided insight into other unique habitats not previously seen in the region, including *Keratoisis ornata* thickets, sea pen fields, and *Acanella arbuscula* fields.

In general, major patterns of deep-sea coral distributions recorded by Wareham and Edinger (2007) still hold true, with the majority of corals distributed along the continental shelf edge and slope, with a few exceptions:

- an Antipatharian was documented at the mouth of the Strait of Belle Isle and on the north side Flemish Cap (Map 2).

- *Keratoisis ornata* was documented in Flemish Pass with a high abundance of juvenile samples in both sets. Subfossilized samples of *K. ornata* were documented on the Southeast Baffin Shelf and within the *Narwhal-Coral Protection Zone*.

- *Primnoa resedaeformis* occurrences (juvenile samples only), were documented on top of the Labrador Shelf and Grand Bank (Map 3).

Overall, there was an increase in the frequencies of occurrence for all coral species (Table 1). Notably, antipatharians, a deep water group usually found at depths >1000 m (Wareham and Edinger 2007), appear to be more widely

distributed than originally recorded (Tendal 2002; Gass and Wilson 2005; Wareham and Edinger 2007). This is most likely a result of increased sampling effort from multispecies surveys carried out in 2007, which focused on deep-water areas in Flemish Pass and the Northeast Newfoundland Shelf. Fisheries Observer data also recorded higher occurrences, most likely due to commercial fishing effort targeting deeper waters where the chances of encountering corals would be higher.

The newly established temporary closures, described in the introduction, are a positive first step to coral conservation, but stronger, more permanent legislation is urgently needed to fully protect corals from anthropogenic disturbances. The need for urgency is due to the fact that corals are highly sensitive to benthic fishing disturbances and are impacted even on the first initial tow (Kreiger 2001). This was especially evident on May 23, 2007 when a Fisheries Observer documented 500 kg *Primnoa resedaeformis* and 25 kg of *Paragorgia arborea* bycatch from one set conducted within the recently established *Voluntary Coral Protection Zone*. Here, the crew was driven southwards due to pack ice and was unaware of the newly designated voluntary closure (H. Mercer, pers. com.) Based on the bycatch rates of coral in this zone, the area appears to be relatively unfished. Once damaged, slow growth rates in species like *Primnoa resedaeformis* (~0.17 mm/year; Mortensen and Buhl-Mortensen 2005), *Keratoisis ornata* (~0.06 mm/year), and antipatharians (~0.07 mm/year; Sherwood and Edinger in press) will slow recovery rates unless protection zones are established.

Keratoisis ornata thickets, captured by ROPOS video in Haddock and Halibut Channels (NAFO Div. 3Ps) were not captured within the newly established *CAD-NAFO Corals Protection Zone* (NAFO Div. 30), and, therefore, are not likely protected even though they are among the oldest species of coral found in the region (Sherwood et al., in press).

Results of this IGP funded project have significantly expanded our knowledge of coral distributions in the NL and Arctic regions and have identified key areas for coral protection. The 2007 ROPOS cruise demonstrated the value of alternative, non-intrusive sampling methods not previously used in this region. Results provide a broad overview of coral distributions, with 36 species documented and mapped. Still, not all areas have been surveyed sufficiently and other data sources could be considered in order to help fill data-poor areas further north (i.e. NAFO Div. 0B-2G).

Currently the dataset consists solely of deep-sea corals; however, other significant structure forming megafauna (i.e. sponges, hydrozoans, and bryozoans) should be considered and incorporated in future sampling collection protocols used by DFO multispecies surveys and Fisheries Observers.

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REPRODUCTIVE BIOLOGY OF DEEP-SEA CORALS IN THE NEWFOUNDLAND AND LABRADOR REGION

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ABSTRACT

The life histories of deep-sea octocorals remain largely unresolved, thereby limiting our understanding of ecological relationships and resilience of cold-water corals. Here we integrate stereological and histological investigations of preserved specimens with the long-term monitoring of live colonies and the study of larval behaviour to elucidate reproductive periodicity and larval dispersal in four species of deep-sea nephtheids (*Drifa glomerata*, *Drifa* sp*., Duva florida,* and *Gersemia fruticosa*). All samples and live specimens were collected between 100 and 1200 m off Newfoundland and Labrador (eastern Canada) from November 2004 to December 2007. Frozen samples of *D. glomerata*, used to study the reproductive cycle, revealed that the ratio of colonies with mature planulae was always >50%, suggesting the capacity to release larvae throughout the year. The average surface area of the oocytes or planulae was also consistently greater in the polyps than in the branchlets across all dates and depths, indicating that fertilization is internal and that the development of planulae is finalized in the polyps. Fecundity, expressed in planulae g^{-1}, showed a seasonal trend with an increase between November and January and lower values in June-July of a given year. Inversely, the average size of oocytes/planulae decreased from November to January in both polyps and branchlets. Based on these data, the peak breeding season is between November and February, when new planulae are produced and large mature ones are released. This was confirmed by preliminary observations of spawning in the laboratory. All four species investigated were brooders and showed a continuous pattern of planula release, over several months, without any clear periodicities. However, the peak breeding months varied between species. Planulae from different species also exhibited distinctive behaviours: most planulae from *D. glomerata* were observed to actively crawl and probe the substratum after their release; however, this proportion was significantly lower in the other three species. In settlement trials, planulae emitted by colonies of *Drifa* sp. from 1200 m typically settled faster than those from 500 m (on average 13 and 41 days, respectively). Planulae from both depths settled earlier on hard irregular substrata, i.e. shells and rough artificial surfaces, than on smooth artificial surfaces. The capacity of planulae to delay metamorphosis was noted in all species studied, with times to settlement varying

between <24 h and >2 mo. Growth of newly settled polyps was typically slow and no branching was observed in nearly one year of monitoring.

INTRODUCTION

The reproduction of deep-sea corals is a key element that can determine the level of their vulnerability or resilience to disturbances. Very little information exists on the sexual and asexual proliferation of deep-sea species worldwide and almost nothing is known of the factors that can influence these processes on a seasonal or annual basis in the NW Atlantic or elsewhere.

This research was undertaken to document the reproductive biology of deep-sea corals in the Newfoundland and Labrador region. Various species of deep-sea corals were investigated using long-term monitoring of live colonies and a combination of histological and stereological methods in an effort to elucidate their reproductive processes. The focus was on gamete development, timing and mode of spawning with respect to depth, geographical area and time of the year, as well as on larval behaviour and settlement preferences.

METHODOLOGY

SELECTION OF SPECIES FOR STUDY

Preliminary examination of many coral species stored in freezers at Fisheries and Oceans Canada revealed that nephtheid soft corals were most appropriate for this study based on the number of available specimens (i.e. from different locations, depths and dates) and on their reproductive traits (suitability for histology and microsurgical investigations). As frozen tissues are not always suitable for histological procedures, we also considered the ease with which we could get fresh specimens.

The taxonomy of nephtheids (or octocorals in general), especially those from the deep sea, is often confusing and we have therefore had to deal with unresolved identifications. We are currently working with Catherine McFadden (Harvey Mudd College) who is an octocoral systematist and co-principle investigator on the Cnidarian Tree of Life project. She is assisting us with the identification of the species we are working on. At this point, we are aware that most of the species that have been called *Gersemia* in the northern hemisphere may actually be a mix of *Drifa* spp., *Duva florida* and as yet undescribed alcyoniids (of a different family). This aspect will be clarified in the months to come. Hence, the preliminary identification may eventually change.

Reproductive Cycle (Drifa glomerata)

Collection. Samples of *Drifa glomerata* were obtained as by-catch during the DFO multi-species surveys and Fisheries Observer Program (FOP), and frozen at -20℃. All samples were collected at 103-334 m off Newfoundland and Labrador (eastern Canada) from November 2004 to July 2007.

Reproductive status and fecundity. All intact frozen specimens were examined to establish the ratio of colonies with and without visible planulae/oocytes at each sampling date. All the colonies with more than ten “reproductive” polyps (containing visible oocytes/larvae) were then divided into two groups according to depth (103-203 m; 203-334 m). For each colony, the number of visible planulae/oocytes per reproductive polyp was expressed as the average number of planulae/oocytes in ten randomly-chosen reproductive polyps. Data were then combined for samples collected at the same date and depth range.

The total number of planulae/oocytes per colony (fecundity) was calculated by multiplying the number of reproductive polyps by the number of planulae/oocytes in each of the ten randomly-chosen reproductive polyps. Again, data were pooled per sampling date and depth range. The reproductive polyp index (RPI) was expressed as the number of reproductive polyps divided by the wet weight of the colony.

The longest diameter (A) and orthogonal diameter (B) of planulae/oocytes inside reproductive polyps and branchlets of the colony were measured under a Nikon SMZ1500 stereomicroscope, using an ocular micrometer. The following formula was used to calculate the surface area of the oocytes/planulae: $SA = 4\pi*A/2*B/2$. Data were pooled by sampling date and depth range.

Histology. Six frozen colonies were prepared for histology. One branch with reproductive polyps was preserved in 4% formaldehyde. To improve the quality of the sections, the samples were embedded in Histo-Gel before standard histological preparation. Briefly, the samples were dehydrated in a series of Flex (solution of isopropyl alcohol and methyl alcohol) baths (80 to 100%). Thereafter, the samples were cleared in two stations of Clear Rite 3, infiltrated with paraffin overnight and embedded in paraffin the next morning. Sections were cut (20 µm) and mounted on glass slides. Hematoxylin and Eosin staining was used to distinguish the nuclear material from the cytoplasm. Slides were examined under a Nikon SMZ1500 stereomicroscope and Nikon Eclipse 80i microscope, both attached to a Nikon DXM1200F digital camera.

Planula Release and Settlement Preferences (Drifa sp.)

Collection. Adult colonies of *Drifa* sp. (Fig. 1A) were collected in July 2007 at depths varying between 500 and 1200 m on the continental slope of the SW Grand Banks using the remotely operated vehicle ROPOS on board the CCGS

Hudson. On the ship, the specimens were maintained in chilled seawater at a temperature of 2-3°C in darkened conditions. In the laboratory, the colonies were kept in 20 L tanks provided with running sea water (ca. 1.5 L min^{-1}) in darkened conditions. From July to November, chilled sea water was used to maintain the temperature at 5-8°C, and from December to February, ambient sea water was used (0-5°C).

Collection and culture of planulae. Free swimming planulae of *Drifa* sp. (Fig. 1B) were collected within 24 h of their release, either on the bottom of the tank or floating in the water column. The date of collection was recorded. The free-swimming planulae were reared separately in culture plates that were kept within the tank of the parent colonies, and half of the seawater was changed every day until settlement. Newly settled polyps were placed in flow-through conditions similar to the ones used for adult colonies and fed a mixture of algae (*Isochrysis* sp., *Tetraselmis* sp., *Nannochloropsis* sp.) and rotifers on a continuous basis via a peristaltic pump (ca. 40 ml min^{-1}). In addition, planulae were extracted from seven colonies to determine whether natural release was a prerequisite to settlement competency. These colonies were collected on four different dives at 495, 525, 744, and 1238 m and their size was 2.3-4.0 cm in length and 1.5-2.5 cm in width. The reproductive polyps were cut open and planulae/oocytes were gently pushed out into seawater. They were cultured in 50 ml beakers, at a density of ca. 30 individuals per beaker, in running chilled sea water, at a temperature of 5-8°C, under darkened conditions.

Settlement. After collection, naturally released planulae from each depth range were separated in six groups to analyze the settlement behaviour on different substrata (bare culture plates; culture plates with shell fragments that had been conditioned in running seawater for several months; bare culture plates with roughened surface; culture plates that were cleaned in freshwater every day; culture plates with shell fragments that were cleaned in freshwater every day; culture plates with plastic tags which were cleaned in freshwater daily). Settlement was also monitored in the planulae that had been extracted, as well as in the holding tanks where adult colonies were spawning freely.

Histology, sclerites and Transmission Electron Microscopy (TEM). During the extraction of planulae, one branch with visible reproductive polyps from each colony was preserved in 4% formaldehyde for standard histology, as described earlier. Another piece of tissue was preserved in 70% ethanol for the study of sclerites (skeletal elements), and two branches with reproductive polyps were preserved in 3% glutaraldehyde for histological preparation using standard techniques, except the embedding medium was methacrylate. Furthermore, planulae/oocytes of all stages were collected and fixed in 3% glutaraldehyde for TEM. Briefly, tissues were fixed in Karnovsky fixative and transferred to 1 m sodium cacodylate buffer, then dehydrated and infiltrated in 1% osmium tetroxide, 1 m Na cacodylate buffer, and successive ethanol baths (70-100%), followed by absolute acetone, 50:50 acetone and TAAB 812 resin. Samples were embedded in flat moulds for correct orientation and polymerized at 80°C

overnight. Polymerized blocks were trimmed, and then cut at 0.5 µm on a Leica Ultra Cut E ultramicrotome using a diamond knife. Sections were stained with 1% toluidine blue in 1% aqueous sodium borate.

Information from the field. Still images and videos footages from the 2007 expedition were analyzed to study size distribution and typical use of substrata.

Complementary observation of live Drifa glomerata. Two colonies of *Drifa glomerata* (Fig.1D) were collected at the same time as the colonies of *Drifa* sp. They were maintained as described earlier. Free swimming planulae of *Drifa glomerata* (Fig. 1E) were collected on the bottom of the tank within 24 h of their release. They were reared separately in culture plates that had been sanded and conditioned in sea water. Conditioned shells were also provided. The surface area of shells was half that of the plate. The culture conditions of larvae and polyps were identical to the ones described for *Drifa* sp.

OTHER OBSERVATIONS

Release of planulae, larval behaviour, settlement and other biological aspects were investigated on an opportunistic basis in live colonies of *Gersemia fruticosa* (collected in November 2006 at <300 m) and *Duva florida* (collected in November 2006 and July 2007 at ca. 535 m) (Fig. 1J). These colonies were maintained as described earlier for live *Drifa* sp. and *D. glomerata* specimens. Histology and TEM protocols were also similar.

RESULTS

REPRODUCTIVE CYCLE (DRIFA GLOMERATA)

Drifa glomerta is an internal brooder. Female sexual cells and planulae are pinkish in color. The early stages of female gametes developed from the mesenteries and migrated to the coelenteron of the feeding polyps. No male gametes were observed in the colonies.

TEMPORAL AND SPATIAL CHANGES IN THE REPRODUCTIVE FEATURES

The proportion of colonies with visible planulae was never less than 50% at the depths studied (103-333 m) for all sampling dates. The number of polyps containing reproductive cells within a single colony varied from 2 to 1030. The RPI increased from November (ca.10 polyps g^{-1}) to January (30-40 polyps g^{-1}), and decreased again from January to July.

Among reproductively mature specimens (i.e. with more than ten “reproductive” polyps), the number of oocytes/planulae within a single polyp varied from 1 to 10, with an average of between 2 and 4 (based on the examination of 78 colonies

and 10 polyps per colony). The number of oocytes/planulae within a single polyp varied with depths and seasons. Samples from the shallower waters (103-203 m) had a clearer seasonal trend than samples from deeper waters (204-333 m). Fecundity, expressed in planulae g^{-1}, was similarly influenced by depth. Samples from 103 to 203 m showed a seasonal trend of fecundity, with an increase between November (<50 planulae g^{-1}) and January (100-150 planulae g^{-1}) and lower values in June-July (40-80 planulae g^{-1}) of a given year. Samples from 204 to 333 m were more constant from January to July (150-250 planulae g^{-1}); however, data from November (ca. 50 planulae g^{-1}) were the lowest. Furthermore, the average fecundity was greater in deeper water samples for all the sampling dates.

The average size (surface area) of oocytes/planulae showed a seasonal trend. A decrease from November to January was detectable in both reproductive polyps and branchlets (Fig. 2). The average surface area of the oocytes or planulae was consistently greater in the polyps than in the branchlets across all dates and depths (Fig. 2).

PLANULATION, LARVAL BEHAVIOUR AND SETTLEMENT (DRIFA SP.)

Reproductive features of Drifa sp.

Drifa sp. is a hermaphroditic internal brooder. Large colonies (i.e. extended colony size during spawning season of ca. 11 X 7 X 7 cm) were observed to spawn on a continuous basis from August 2007 to March 2008; however, several smaller colonies (ca. 3 X 2 X 2 cm) were spent after several weeks of' spawning. Female sex cells and planulae tend to be pinkish in colour, while the male sex cells (spermaries) are white. All stages of female gametes exist throughout the year in the populations studied; however, the sperm sacs are rarely found (i.e. observed only twice between July and December 2007).

The early stages of female gametes developed from the mesenteries and the maturing gametes migrated to the coelenteron. All colonies examined for histology contained all four stages of oocyte development: Stage I, oogonia budding from the mesenteries; Stage II, previtellogenic oocytes containing a large nucleus; Stage III, viitellogenic oocytes, characterized by the rapid accumulation of yolk; Stage IV, late vitellogenic oocytes are mature and filled with yolk droplets, which stain a conspicuous pink colour. No male gametes were identified in histological sections.

Mature planulae are reared in what appears to be specialized reproductive polyps which do not possess well-developed tentacles for feeding. When they contain planulae/oocytes, these specialized polyps are visibly larger than the feeding polyps and exhibit a smoother surface. They seem to be analogous to siphonozoids but this morphological feature has not yet been clarified (as it is apparently not characteristic of nephtheids).

PLANULA RELEASE, BEHAVIOUR, METAMORPHOSIS AND SETTLEMENT PREFERENCE

The first evidence of planula release in *Drifa* sp. was observed in July 2007, several days after collection from the field. The number of planulae released in a single episode varied from 1 to 14 in six colonies from 500 m, and from 1 to 5 in eleven colonies from 1200 m. The large planulae (ca. 3-6 mm long) were released through the anterior opening of the reproductive polyp at the capitulum surface that is shaped like a trunk. The process lasted about 15 min. In subsequent monitoring, there was no obvious trend in the timing of planula release, which was observed at any time of the day. Adult colonies were found to be able to release more than one planula at a time, generally from different polyps. Furthermore, when more than one mature planula occurred in the same polyp and were released simultaneously, one could be released from the opening while the other could exit through a tear in the polyp.

During planulation, the adult colonies were never fully contracted. If the adult colony was somehow disturbed and the polyps retracted, the planula release process was prolonged and could last up to several days.

Just after release, the planulae exhibited a very plastic shape (Fig. 1B). They underwent cycles of contraction and expansion that allowed them to alternately sink to the bottom and float in the water column. On average, fully extended planulae were 4-5 mm long and 1 mm wide. They were rod-shaped, and covered with ciliae (Fig. 1B).

Five stages have been defined for the development of planulae/juveniles after their release. Stage 1, free-swimming elongated planula; Stage 2, settled cone-shaped or flattened planula; Stage 3, the *Edwardsia* stage, differentiated flattened or elongated planula, (metamorphosis occurs at this stage: the oral disc and eight tentacles develop; pinnules also appear at this stage); Stage 4, early polyp with tentacles and pinnules well developed; Stage 5, branching polyp.

For naturally released planulae, settlement occurred after 1-29 d, though a small portion of larvae took >2 mo to settle. The type of substratum clearly influenced the time and rate of settlement: for instance, only 5 of 39 planulae settled on sterile plates (after 12-50 d), whereas 15 of 32 planulae settled on shell fragments (after 2-24 d). A few planulae were observed to settle on adult colonies and other planulae. The eight primary mesenteries typically appeared within 24 h, and polyps developed eight pinnulated tentacles after 12-75 days. Typically, planulae of colonies from 1200 m were observed to settle faster than those from 500 m (on average 13 and 41 days, respectively). Planulae from both depths settled earlier on hard irregular substrata (i.e. shells and rough artificial surfaces) than on smooth artificial surfaces. Settlement occurred more rapidly on

cleaned shells than fouled ones in planulae from 500 m but not in those from 1200 m. Pair-wise trials of settlement preferences are in progress

In extracted planulae, settlement also occurred after 1-30 d (over a single month of monitoring). The number of settled planulae was always lower than the number of available planulae found in the colonies (Table 1).

Table 1. Settlement of planulae extracted from colonies of *Drifa* sp. The depth at which the adult colony was collected, the number of elongated (mature?) and round (immature?) planulae extracted and the number of settled planulae after one month (August 2007) are presented.

Depth (m)	Number of elongated planulae	Number of round planulae	Number of settled planulae
495	33	34	15
525	23	65	15
744	0	44	0
744	20	33	15
1238	9	72	9
1238	40	142	23

EARLY GROWTH

The growth rates of *Drifa* sp. recruits (Fig. 1C) are very slow: polyps reached 5 mm in length, and had a stalk diameter of ca. 1 mm 7 months after settlement. Branching of polyps has not yet been observed.

ULTRASTRUCTURE OF PLANULAE

TEM sections are currently being studied to compare changes in cell types within planulae/oocytes at different stages of development.

FIELD OBSERVATIONS

At depths shallower than 500 m, most of the colonies were observed on cobbles, rocks or rocky cliffs. At 1200 m, the substratum was mainly mud, with very few occurrences of cobbles or rock surfaces. Colonies were found to grow sparsely on mud and were also observed to occur in clusters when appropriate hard substrata were available, such as sponges, empty shells, tube worms, etc.

Complementary information on Drifa glomerata

Two colonies of *Drifa glomerata* were kept alive in the laboratory. One had visible planulae and the other did not. The first release of planula occurred on January 4, 2008, when a single planula was expelled through the anterior opening of a polyp. Its maximum length was about 5 mm (Fig. 1E). The planula was covered with cilia and actively probed the substratum. It used the mucus-covered oral extremity as an anchor to position the aboral extremity for attachment. Also, the demersal planula displayed complex crawling behaviours, and was able to circle vertically and horizontally by contracting and expanding rapidly within minutes. Since then, more planulae have been emitted. Studies of time to settlement and substratum preference are currently in progress.

OTHER OBSERVATIONS

Duva florida

Duva florida did not spawn naturally in the laboratory. However, planulae were successfully extracted from dying colonies collected in December 2006 and July 2007. When the extracted planulae were fully extended, their length was ca. 1.5-2.5 mm and their width was ca. 0.5 mm (Fig. 1G). Settlement was observed in both groups and polyps (Fig. 1I) had reached a similar stage in September 2007 (ca. 3-4 mm long). No branching of polyps was observed over 11 months.

Gersemia fruticosa

The release of planulae by colonies of *Gersemia fruticosa* was observed from April to June 2007 in the laboratory. The size of fully extended planulae was ca. 1.5-2.5 mm long and 0.5 mm wide (Fig. 1L). Time to settlement varied from 3 to 54 days. Polyps reached up to 10 mm in length after 7 months growth.

DISCUSSION

Planula release by colonies of *Drifa* sp. in the laboratory was observed from July 2007 to March 2008, with a peak between September and November. Spawning of *Gersemia fruticosa* was from April to June 2007, with a peak in April-May. *Drifa glomerata* started releasing planulae in January 2008 and were still spawning in March 2008. All three species showed a continuous planula release process, without any clear lunar or monthly pattern. Colonies of *Duva florida* have never been observed to release planulae. However, the successful culture of new polyps from planulae obtained from dying colonies between December 2006 and July 2007, indicates that mature planulae may be produced all year long at the population level.

Planulae exhibited distinctive behaviours in the four species of soft corals that were investigated. A majority of planulae from *Drifa glomerata* were observed to actively crawl and probe the substratum after their release; however, this proportion was significantly lower in the other three species. The proportion of planulae with complex searching activities will likely increase the local recruitment of new polyps. However, the less mature planulae, which need more time before settlement, probably favour dispersal on a larger scale and complement local aggregation (Sebens 1983).

Hard substrata are very important for the settlement of soft coral planulae. In locations where mud is the dominating substratum, corals were observed in clusters when firm substrata, such as sponges, shell debris, tube worms, etc., were found. This was also observed in deep-water scleractinians (Wilson 1979). Many soft coral colonies were also observed to occur on cliffs or rocky outcrops at shallower depths in the field. This is probably due to: 1) a greater likelihood of settlement on vertical surfaces; 2) the lower probability of suffocation on vertical substrata, which increases the survival rate of polyps (Rogers 1990).

Though the production of recruits seems to occur on a nearly continuous basis, with seasonal trends at shallower depths only, opportunities for settlement may be limited and the growth of settled polyps appears to be incredibly slow, further highlighting the vulnerability of deep-sea coral ecosystems.

ACKNOWLEDGMENTS

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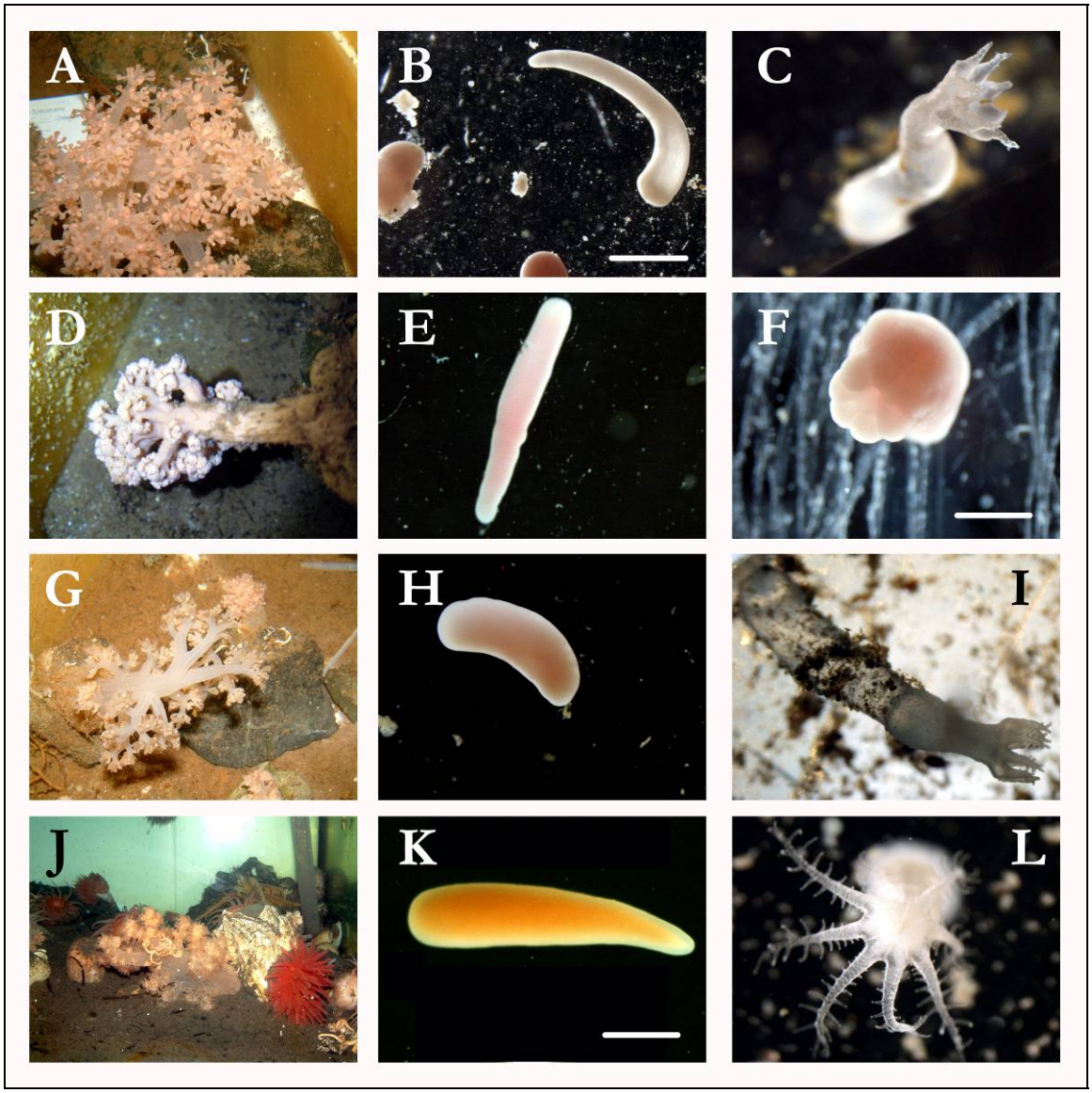

Figure 1. Live colonies, planulae and newly settled polyps of four soft coral species. A-C) *Drifa* sp. Extended colony size is ca. 11X7X7 cm. D-F) *Drifa glomerata.* Extended colony size is ca. 7X4X3 cm. G-I) *Duva florida.* Extended colony size is: 6X3X3 cm. J-L) *Gersemia fruticosa.* Extended colony size is ca. 10 cm. The bar in B corresponds to 1 mm and applies to C, E, H, I and L. The bars in F and K correspond to 0.5 mm.

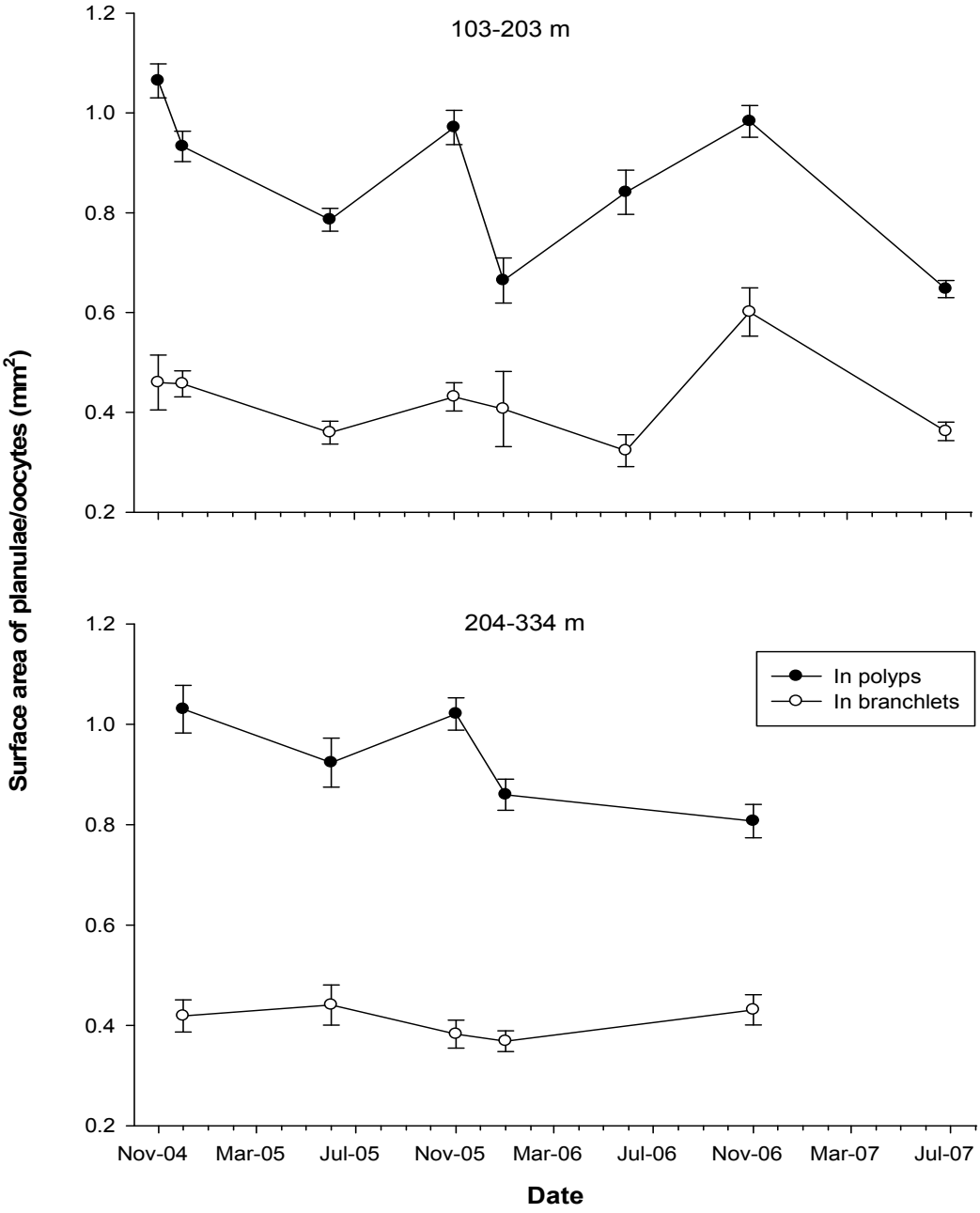

Figure 2. Surface area of visible planulae/oocytes in polyps and branchlets of *Drifa glomerata* at two different depths, from November 2004 to July 2007. For each colony, planulae/oocytes were measured in ten reproductive polyps and three branchlets; data from the same date were combined (Mean±SE).

SUMMARY OF ONGOING CORAL RECRUITMENT EXPERIMENTS

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INTRODUCTION

During the 2007 ROPOS cruise, an experiment was designed and deployed to explore recruitment of corals, especially large gorgonian corals. The focus of the ongoing experiment is to investigate the importance of substrate limitation of coral habitat, and the question of substrate limitation to coral distributions. The experiment was designed to test three hypotheses: (1) large gorgonian corals are substrate-limited, such that corals, especially large gorgonian corals, will recruit to experimental hard substrates placed in soft sediment (sandy-muddy) environments; (2) sediment mobility limits coral recruitment, such that corals will recruit more successfully to experimental hard substrates elevated above the sediment-water interface than to those at the sediment-water interface; and (3) corals will preferentially recruit to vertical surfaces of hard substrates over upward-facing horizontal surfaces, as observed among scleractinian corals on tropical coral reefs (Maida et al. 1994).

METHODOLOGY

Six experimental settlement arrays were deployed at depths of between 350 m and 1000 m on the SW Grand Banks and the Stone Fence, on the margin of the Scotian shelf. Two settlement arrays were deployed in sites inhabitated by large gorgonian corals (Stone Fence at 350 m depth, and Haddock Channel at 700 m; Fig. 1), one array was deployed in a muddy sand environment close to areas with large gorgonians (Haddock Channel at 700 m depth) and three were deployed in sites without large gorgonians, all at 1000 m (Halibut Channel, Haddock Channel, and Desbarres Canyon). Of the three arrays not in coral habitat, two were in canyons in Haddock Channel, and one was on a canyon ridge in Desbarres Canyon). All arrays were deployed by the ROV ROPOS during the 2007 cruise.

Settlement arrays were modified from the design of Kelly and Metaxas (2006), and consisted of sixteen substrata. Eight substrata consisted of 10 cm x 7 cm x 7 cm blocks of gabbro ("black granite"), with one smooth-cut surface and the remaining surfaces broken, exposing the fresh mineral surfaces. The other eight substrata were commercial scrubbing pads, which expose high amounts of surface area, and have a successful record of larval recruitment in deep-sea environments (Kelly and Metaxas 2006). All substrata were attached to a 3-1-6 stainless steel frame, in arrangements that had four stone blocks elevated 15 cm above the frame, and four attached directly at the level of the frame, with the same numbers of high and low scrubbing pads. All substrata were attached to the frame, smooth side down, using marine epoxy and plastic cable ties. Arrangement of the blocks and scrubbing pads on the frame was randomized using a latin squares design.

Figure 1. Experimental settlement array deployed at site HC3-2 at a depth of 700 m (Haddock Channel, SW Grand Banks), in a thicket of *Keratoisis ornata* and other corals.

The intended duration of the Newfoundland portion of the experiment is three years followed by recovery of the settlement arrays in 2010, using an ROV.

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RELATIONSHIPS BETWEEN DEEP-SEA CORALS AND GROUNDFISH

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ABSTRACT

Patterns of association between deep-sea corals and commercial and non-commercial fish and invertebrate species were studied using DFO survey trawl data, and *in situ* observations using the ROV ROPOS. Patterns of coral biomass in trawl surveys were non-random, with the highest quantities of bycatch recovered in the Hudson Strait region. Coral biomass and fish biodiversity were significantly correlated, as were coral species diversity and fish species diversity. Trawl survey data revealed statistically significant associations between corals and several species of groundfish, and also between soft corals and juvenile shrimp and crab. Patterns of association could reflect biological interactions, or could reflect coincidence, with overlapping habitat preferences for corals and the various fish species. Ongoing analysis of ROPOS coral-and-fish transect data may help to resolve this uncertainty.

INTRODUCTION

Possible relationships between deep-sea corals and a variety of groundfish, especially commercial and endangered species, have received considerable attention in the Eastern Atlantic (Husebø et al. 2002, Costello et al. 2005), the Florida and Gulf of Mexico region (Reed et al. 2005, Sulak et al. 2007) and in the Pacific (Kreiger and Wing 2002, Stone 2006), but less in the Northwest Atlantic (Auster et al. 2005, Mortensen et al. 2005). Fish utilization of coral habitat can be in terms of juvenile fish habitat, feeding areas, resting areas, or refuges from predation (Auster 2007, Costello et al. 2005). Alternatively, certain fish species may be more abundant in sites with abundant corals than in otherwise similar areas only by coincidence, i.e. habitat conditions that favour corals also favour abundance of certain fish species, but with no direct functional connection

between the corals and the fish (cf. Auster et al. 2005).

Studies of the relationships between corals and fish have three components: (1) comparison of groundfish diversity and abundance were compared among coral classes within an initial dataset of standardized trawl surveys (Edinger et al. 2007b), (2) multivariate statistical analysis of fish community composition in relation to presence or absence of different coral classes (ongoing), and quantitative analysis of the trawl survey complemented by qualitative observations of fish and corals based on the 2007 ROPOS cruise in the southwest Grand Banks. Quantitative analysis of ROPOS coral-fish transect data is ongoing.

METHODOLOGY

TRAWL SURVEY DATA ANALYSIS

Coral distributions and definition of coral classes

Coral distributions and abundances were mapped in two sources of quantitatively analyzed research trawl surveys (Wareham and Edinger, this volume): (1) 2003-05 Fisheries and Oceans Canada trawl survey by-catch, covering the area south of latitude 58°N (NAFO Zone 2H and south); (2) 2005 Shrimp Industry scientific survey of northern Labrador and the Davis Strait, covering the area north of latitude 58°N (NAFO Zones 2G and 0B). Although the Northern Shrimp Survey was conducted in 2006 and 2007, data resulting from these surveys was unavailable for this publication.

Coral species were divided into five functional groups: Large long-lived gorgonians and antipatharians, small gorgonians, soft corals, sea pens, and cup corals (Table 1). Most large and small gorgonians occurred in multiple species assemblages, as did many of the sea pens and cup corals, while nephtheid soft corals often occurred as single records, particularly in shallow water.

Presence or absence of each coral species in each set, coral species richness, total wet weight of corals, wet weight of each class of coral, and coral class scores were determined for each set. Coral class scores were assigned on a hierarchical scale of 0 to 4, in which 0 indicates absence of corals, 1 indicates presence of soft corals, but no other functional groups, 2 indicates sea pens or cup corals, but no gorgonians, 3 indicates presence of small gorgonians, and 4 indicates presence of large gorgonians or antipatharians (Table 1).

Table 1. Coral class definitions.

Coral class	***Definition***
4	Sets containing 1 or more large gorgonian or antipatharian corals *Primnoa resedaeformis* (Gunnerus 1763)*, Paragorgia arborea* (L.)*, Keratoisis ornata* (Verrill 1878)*, Acanthogorgia armata* (Verrill 1878)*, Paramuricea placomus* (L.) or *P. grandis* (Verrill 1884)*, Bathypathes arctica* (Lütken 1871)*,* usually with other, smaller, corals.
3	Sets containing 1 or more small gorgonian corals, *Acanella arbuscula* (Johnson 1862)*, Radicipes gracilis* (Verrill 1884), usually with soft corals, sea pens, or cup corals.
2	Sets containing 1 or more sea pens (*Distichophyllum gracile* (Verrill 1882), *Funiculina quadrangularis* (Pallas 1766)*, Halipteris finmarchia* (Sars 1851)*, Pennatula grandis* (Ehrenberg 1834)*, Pennatula* sp., *Umbellula lindahli* (Kölliker 1875), and five other species of sea pens as yet unidentified), sometimes with cup corals (*Flabellum alabastrum* (Moseley 1873)*, Vaughanella margaritata* (Jourdan 1895), or *Desmophyllum dianthus* (Esper 1794).
1	Sets with soft corals (*Gersemia rubiformis* (Ehrenberg 1834)*, Gersemia* sp.*, Duva (Capnella) florida* (Verrill 1869), *Anthomastus grandiflorus* (Verrill 1878), but no other coral groups.
0	No corals

Groundfish Abundance Data Analysis

Abundance of groundfish was compared among coral classes. All sets (n=1614) were 15 min. tows, covering a distance of 1.4 km, and conducted with a Campelen 1800 shrimp trawl equipped with rockhopper footgear. Groundfish were identified and quantified by DFO fisheries technicians, trained in fish identification by DFO fisheries scientists, using standard protocols. Abundance of groundfish was compared among the five coral classes. To account for variation in fish abundance with depth, sets were divided into six depth classes: (0-200 m, 200-400 m, 400-600 m, 600-800 m, 800-1000 m, and 1000 m+; Edinger et al. 2007b).

Twelve groundfish species chosen for analysis were characteristic of, and often dominant on the continental slope (Koslow et al. 2000), and include commercial species, potential (Devine et al. 2006) or recognised (COSEWIC 2005) species-at-risk, and sedentary species (O'Dea and Haedrich 2002) known to be associated with benthic structures (Table 2).

Numbers and weights of each fish species were square-root transformed prior to analysis. Numerical abundance per tow and wet weight per tow of fishes were compared among the six depth classes and the five coral classes using 2-way ANOVA of square-root transformed numerical abundances and wet weights, followed by Tamhane's post-hoc test assuming unequal variances. Since square-root transformation did not normalize all data, comparisons of fish abundance between coral classes were repeated using the non-parametric Kruskall-Wallis test on untransformed numerical abundance and weight data. Correlations between the abundance of each fish species and coral biodiversity, coral biomass, and coral class were estimated using Spearman rank correlation (Edinger et al. 2007b).

Table 2. Groundfish and commercial invertebrate species analyzed in 2003-05 DFO and Northern Shrimp Survey data.

Common Name	Scientific Name
Atlantic Cod	*Gadus morhua*
Roughhead grenadier	*Macrourus berglax*
Rock grenadier	*Coryphaenoides rupestris*
Deepwater redfish	*Sebastes mentella*
Golden redfish	*Sebastes marinus*
Greenland halibut	*Reinhardtius hippoglossoides*
Wolffish	Anarhichadidae
Lumpfish	*Cyclopterus lumpus*
Eelpouts	*Lycodes* spp.
Witch flounder	*Glyptocephalus cynoglossus*
Northern Shrimp	*Pandalus borealis, P. montagui*
Snow Crab	*Chionocetes opilio*

RESULTS AND DISCUSSION

CORAL BIOMASS HOTSPOTS

Peaks of coral wet weight per tow were found along the southwestern edge of the Grand Banks, along the northeast edge of the Northeast Newfoundland Shelf, especially near the tip of Funk Island Bank (51°N, 50°30′W), along the continental slope off the central and southern Labrador shelf, near Cape Chidley, Labrador (60°N, 61°W), and in the Davis Strait (62°N, 61°W) (Fig. 1). Coral species richness and wet weight per tow were significantly correlated. Wet weight of all corals was significantly higher in sets containing large gorgonians and antipatharians than in sets containing small gorgonians, which in turn had higher weights than sets containing only soft corals, sea pens, or cup corals.

The sampling gap near the Hudson Strait (61-62°N, 62-64°W) was deliberate: the vessel conducting the Northern Shrimp Survey avoided this area because reported rough bottoms brought too high a risk of net damage. Several sets

conducted in this region during the 2006 Northern Shrimp Survey yielded up to 500 kg of coral per 15 minute tow (Edinger et al. 2007b). However, these data, including precise locations of these sets, were unavailable for this publication.

The sampling gap on the western edge of Orphan Basin has since been filled, showing considerable concentrations of large and small gorgonians, and antipatharians, near Funk Island Spur and near the location known colloquially as Tobin's Point, at roughly 49.5°N, 50°W.

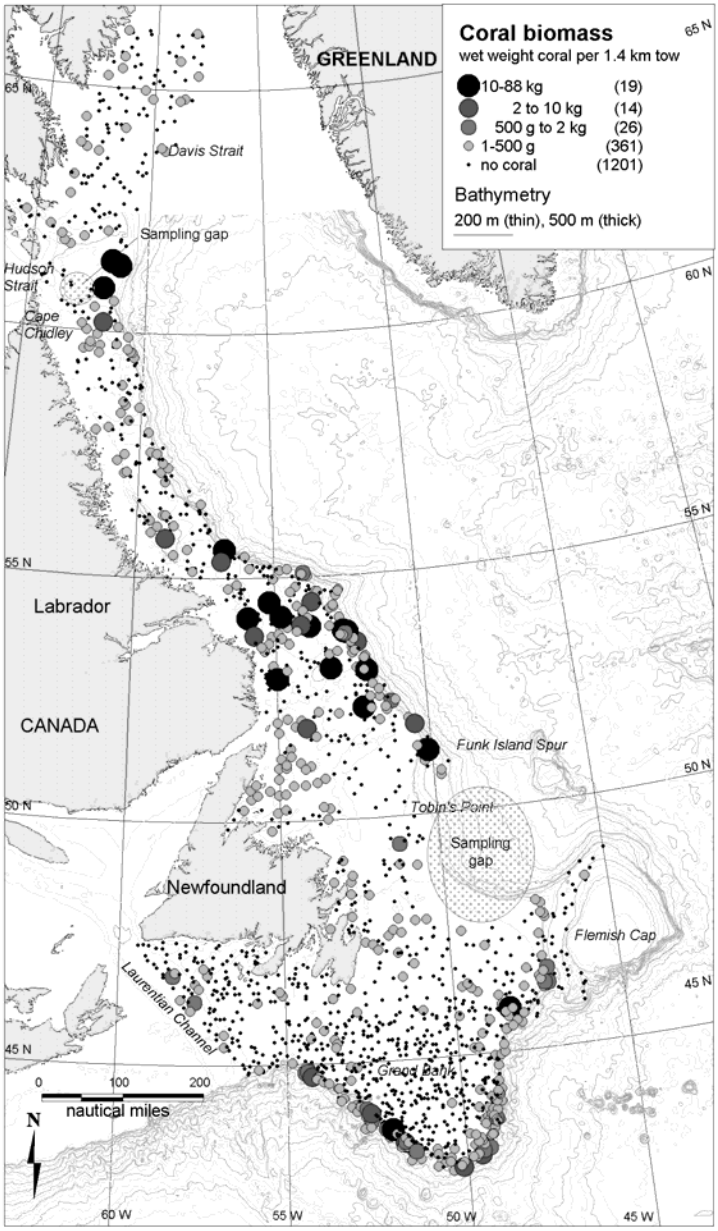

Figure 1. Geographic variation in coral wet weight (kg/15 minute trawl) in research survey trawls.

CORAL DIVERSITY AND FISH DIVERSITY

Fish diversity was significantly higher in sets with corals than in sets without corals, and was highest in sets defined by small gorgonians. Fish species richness and coral species richness were significantly correlated.

GROUNDFISH ABUNDANCE VARIATION WITH CORAL CLASS AND DEPTH

Most fish species did not show a strong preference for one coral class over all others, and their abundance patterns were not uniform among depth classes. Rock grenadier abundances were not significantly different among coral classes in tows deeper than 1000 m, where this species was most abundant. In intermediate depth waters (400-600 m), Rock grenadier were most abundant in sets containing large skeletal corals, but in 600-1000 m, Rock grenadier were less abundant in soft coral sets than in all other sets. Roughhead grenadier were most abundant in sets defined by large gorgonians or antipatharians at 200-400 m depths, but at 400-600 m and 600-1000 m depths they were most abundant in soft coral sets (Fig. 2). Deepwater redfish, weight per tow was greatest in the small gorgonian coral class sets in the 200-400 m and 400-600 m depth ranges.

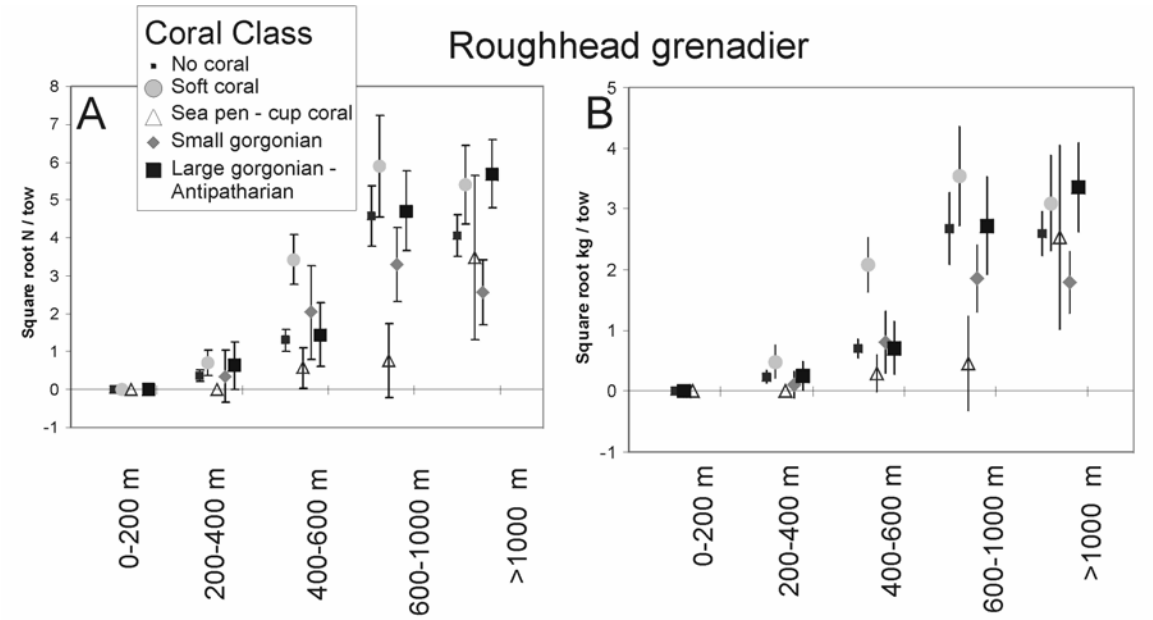

Figure 2. Square-root transformed abundance of roughhead grenadier, *Macrourus berglax*, in trawl sets characterized by the presence of different types of deep-sea corals. A: number per tow. B: biomass per tow.

In shallow waters (<200 m), Greenland halibut were more abundant in sets with corals of various classes than in sets without corals. In the 200-400 m depth range, Greenland halibut were most abundant in large gorgonian sets or soft coral sets, followed by small gorgonian or non-coral sets, and were least abundant in sea pen sets (Fig. 3). By contrast, in the 400-600 m depth range, Greenland halibut had greatest numbers in sets without corals, with abundance decreasing with coral class. Wolffishes, *Anarhichas* spp. (L.), were most abundant in sets with small gorgonians in 200-400 m depth, and weakly displayed a similar pattern in the 400-600 m depth range, but a weak trend toward higher numbers in soft coral and sea pen sets in the 600-1000 m depth range.

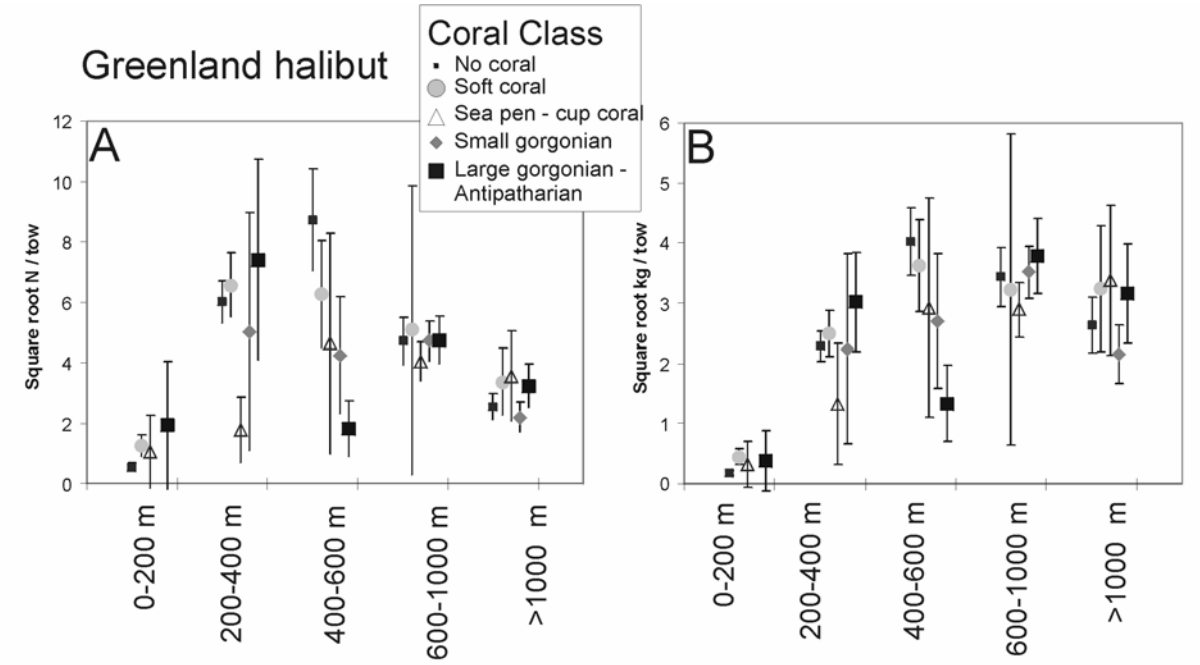

Figure 3. Square-root transformed abundance of Greenland halibut, *Rheinhardtius hippoglossoides*, in trawl sets characterized by the presence of different types of deep-sea corals. A: number per tow. B: biomass per tow.

Shrimp numbers were highest in soft coral sets, in water shallower than 200 m, with roughly equal numbers in the few shallow water sets containing large corals (Fig. 4). By contrast, shrimp weights were greatest in sets with soft corals at 200-400 m, and lowest in sea pen and small gorgonian sets in that depth range.

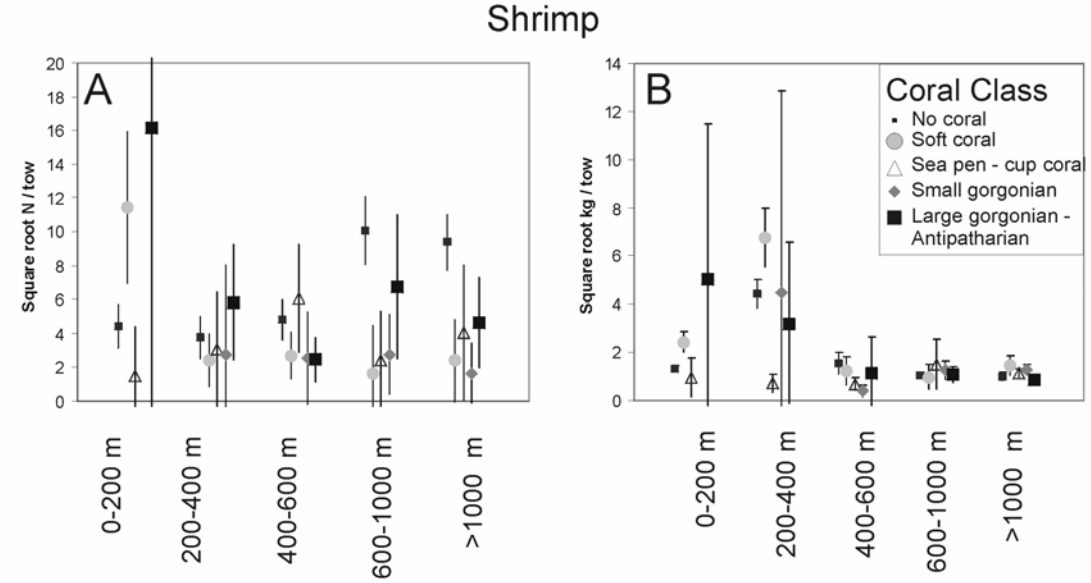

Figure 4. Abundance of shrimp, *Pandalus borealis* and *P. montagui*, in trawl sets characterized by different types of deep-sea corals. A: number, B: biomass per tow.

Snow crab numbers followed a similar pattern, but weights were greater in sets with sea pens in the 200-400 m depth range and highest in sets with large gorgonian corals in waters deeper than 400 m.

Numbers and weights of Atlantic cod, both grenadier species, Greenland halibut, wolffish weight, and shrimp weight were significantly correlated with coral species diversity and total coral wet weight per tow. The fish species that showed positive correlations with corals also had stronger correlations with depth and/or bottom temperature. For results of all statistical tests for all species, see Edinger et al. 2007b).

Nearly all fish species considered were more abundant in coral classes than non-coral classes in at least one depth range. Many fish species had their greatest abundances in soft coral sets, particularly in waters shallower than 400 m. Very few fish species had greatest abundances in large gorgonian/antipatharian sets. Greatest fish species richness was observed in small gorgonian sets, not in the large gorgonian/antipatharian sets. Together, these observations suggest that the fish and invertebrate species considered do not have strong or obligate relationships with large skeletal corals, but also suggests the importance of soft corals, sea pens, and small gorgonians as potential contributors to fish and invertebrate habitat, especially for juveniles, should not be overlooked.

Groundfish and commercial invertebrate abundances on the shallow (<200 m) or deep (200-400 m) shelf were often greatest in soft coral sets. The contrasting patterns between numbers and weights per tow, as observed in wolffish, shrimp and snow crab, implies that juveniles may occupy one depth range and coral habitat while adults occupy another. Both shrimp and crab recruit in shallow gravelly habitats, then migrate to soft bottom habitats on maturity (Bergström 2000). Thus corals, or physical habitats that support corals, may be more important as juvenile fish and invertebrate habitat than as habitat for adults, which could benefit from size refuge from predation. Distinguishing biological structuring of habitat from coincidental occurrence of corals and fish in the same environment will require *in situ* observations (e.g. Costello et al. 2005), but may still leave some ambiguity (cf. Auster et al. 2005).

That neither species of redfish showed differences in numerical abundance between coral classes was surprising, as redfish are among the fish species generally thought to be most strongly associated with deep-sea corals (Mortensen et al. 1995; Husebø et al. 2002; Costello et al. 2005; Mortensen et al. 2005). Previous coral-redfish associations have been described for *Lophelia pertusa* (L.) reefs (Husebø et al. 2002; Costello et al. 2005), large skeletal gorgonians near the Aleutian Islands (Kreiger and Wing 2002; Stone 2006) and the Scotian margin (Mortensen et al. 2005). Similarly, the lack of a clear association between corals and Greenland halibut weight in deep water was surprising because many of the large coral specimens from Fisheries Observer

Program (FOP) derive from the Greenland halibut fishery. (Wareham and Edinger 2007; Edinger et al. 2007a).

The lack of strong associations between large skeletal corals and most groundfish species in our analyses differs from the results of studies of fish-scleractinian deep-sea reefs in the Northeast Atlantic (Husebø et al. 2002, Costello et al. 2005; Roberts et al. 2006), and the Gulf of Mexico (Sulak et al. 2007), and gorgonian coral habitat in Alaska (Kreiger and Wing 2002; Stone 2006). Scleractinian deep reefs, in which the corals build a geological structure, may be much more likely to host endemic or specialized fish fauna than gorgonian coral habitats, in which the geological features of the habitat are formed from bedrock or cobble-boulder fields, and not by living organisms (cf. Auster et al. 2005, Tissot et al. 2006, Auster 2007). The contrast between our results and previous studies may also be due to the scale difference between trawl survey data and direct observations using gillnet fishing in reef and nearby off-reef settings (<200 m scale, Husebø et al. 2002) or video observations (Auster et al. 2005; Costello et al. 2005; Mortensen et al. 2005). In the trawl surveys used here, each point represents the aggregate organism occurrence within a trawl path 1.4 km long and 17 m wide, further reduced according to the catchability of the various species (cf. Schneider et al. 1987). The different results and difference in scale highlight the importance of *in situ* observations and collections, especially for studying juvenile fish, crustaceans, and other fauna potentially associated with corals (cf. Buhl-Mortensen and Mortensen 2005). Other important patterns, such as a quantification of coral biomass per unit area, can only be achieved through *in situ* observations.

Although there were no dramatic relationships between corals and abundance of the 10 groundfish species studied, there was a weak but statistically significant positive correlation between coral species richness and fish species richness, suggesting that habitats that support diverse corals are also likely to support diverse assemblages of fishes. The correlation between coral species richness and fish species richness may be coincidence, may reflect greater abiotic structural variation in coral-rich areas, or may reflect diffuse effects of corals on fish habitat and fish communities similar to those observed on shallow water reefs (cf. Sale et al. 1994). For example, most tropical reef fish do not have an obligate relationship with individual coral species, but depend on the reef environment (e.g. Sale 2004). By increasing the spatial and hydrodynamic complexity of habitats, deep-sea corals may provide important, but not obligate, habitat for a wide variety of fishes. Diffuse effects of deep-sea corals on fish habitat and communities could include higher prey abundance, greater water turbulence, and resting places for a wide variety of fish size classes (Auster et al. 2005; Costello et al. 2005). Ongoing multivariate statistical analysis of fish community composition in relation to corals, based on from trawl survey data, may elucidate some of these patterns.

SHIFTING BASELINES: FISHING HISTORY AND CORAL BIOMASS PER TOW

The average coral biomass in all coral classes were two to three orders of magnitude lower than those reported from previously untrawled areas in the Gulf of Alaska (Kreiger 2001 or the Tasmanian Seamounts). The relatively low average coral biomass per tow observed in this study may result from habitat limitations on coral density, low coral catchability, or past damage to coral populations from several decades of intensive bottom trawling (Pauley 1995; Watling and Norse 1998; Kulka and Pitcher 2002; Anderson and Clarke 2003; Stone 2006). Of these, trawling damage may be the most likely explanation. The highest wet-weight-per-tow values were recorded on the margins of the northern sampling gap in the Hudson Strait. Previously untrawled sites in this area sampled in August 2006 recovered up to 500 kg of *Primnoa resedaeformis* and other corals in a single tow (Northern shrimp survey data not available for this publication). These bycatch rates are as high as the highest reported values of coral biomass bycatch per trawl duration in previously unfished waters of Alaska (Kreiger 2002) or the Tasmanian Seamounts (Anderson and Clarke 2003). A 12, 500 km^2 portion of the Hudson Strait coral hotspot was given informal protection through a fishing industry voluntary closure declared in May 2007 (MPA News 2007), although many areas with high incidence of coral bycatch surrounding the Hudson Strait area are not included in this voluntary closure.

Fisheries observer reports suggest that the largest corals being recovered currently are far smaller than the largest corals caught ten years ago aboard commercial trawlers in the Davis Strait (R. Beazley, SeaWatch, pers. comm.). These observations are consistent with exponential decline in size and wet weight of corals recovered in trawl fisheries through time, as documented on seamounts affected by the Orange roughy fishery (Anderson and Clarke 2003). These patterns match the concept of shifting baseline syndrome (Pauly 1995), in that the abundances of corals observed in most parts of the region's waters may be several orders of magnitude lower than pre-fishing levels, and corals in many areas may have lost their former ecological importance. The general lack of strong patterns of association between corals and fish may also result from a reduced abundance of corals caused by trawling damage (cf. Koslow et al. 2000, 2001). Although coral distributions are unlikely to have changed due to trawling damage, coral abundance, and particularly the abundance of large corals, is likely to have been diminished (cf. Fosså et al. 2001, Gass and Willison 2005, Mortensen et al. 2005). If large, long-lived corals have the greatest importance in structuring habitat, and have been greatly reduced in frequency due to fisheries impacts, patterns of association between fishes and corals are likely to have been obscured.

QUALITATIVE *IN SITU* OBSERVATIONS OF FISHES IN RELATION TO DEEP-SEA CORALS, SW GRAND BANKS, 2007

The most common fish species observed during the SWGB cruise were grenadier (*C. rupestris* and *M. berglax*), redfish (probably mostly *S. mentella*, although different redfish species can be difficult to distinguish in video), black dogfish (*Centroscyllium fabricii*), and chimaera (mostly deep-water chimaera, *Hydrolagus affinis*). Interesting observations included wolffish (*Anarhichas sp.)* and redfish resting near boulders covered in a diverse suite of corals (Fig. 5), Orange Roughy (*Hoplostethus atlanticus*) resting among the branches of *Keratoisis* thickets (Fig. 6), skates among beds of the small gorgonians *Acanella arbuscula* and *Acanthogorgia armata*, deep-water chimaera (*Hydrolagus affinis*) and other fish species among sea pen meadows (Fig. 7) and the false boarfish *Neocyttus* sp. (Fig. 8) resting among corals near a deep-water vertical bedrock exposure at the Stone Fence, along the NE edge of the Scotian Shelf. Orange roughy and false boarfish are normally seamount-associated species. Many of these were rare or single observations, consistent with other reports that direct close relationships between fish and corals are the exception, rather than the rule (Auster 2007; Sulak et al. 2007). Quantitative analysis of fish transect data from the 2007 SWGB cruise is ongoing.

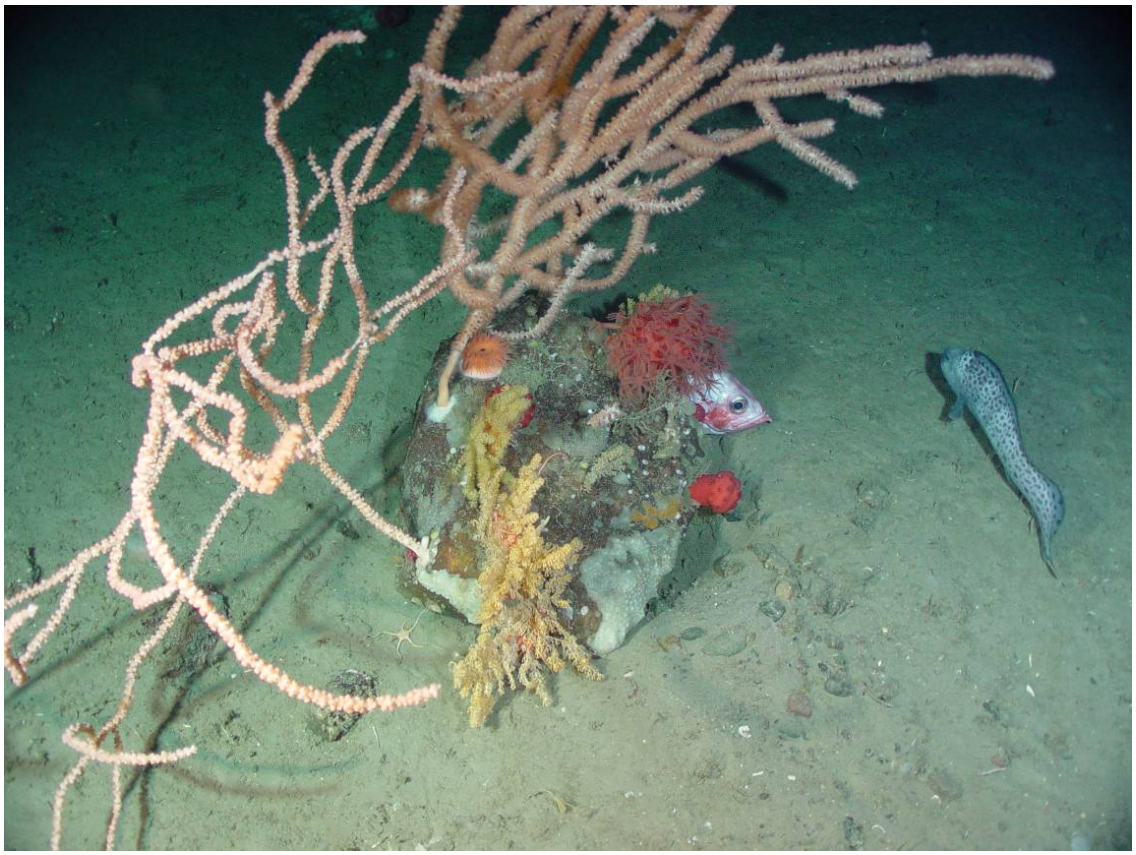

Figure 5. Wolffish, *Anarhichas* sp. and redfish, *Sebastes* sp., resting near a boulder with numerous attached corals, Halibut Channel, SW Grand Banks

(667 m). Corals include gorgonians (*Keratoisis ornata* and *Acanthogorgia armata*) and soft corals (*Anthomastus grandiflorus* and nephtheids).

Figure 6. Orange roughy, *Hoplostethus atlanticus*, observed in a *Keratoisis ornata* thicket, Haddock Channel, SWGB at a depth of 660 m. The fish changed from a pale colour to a brilliant red shortly after this photo was taken.

Figure 7. A grenadier swimming within a sea pen meadow, mostly *Pennatula grandis*, at a depth of 899 m in Desbarres Canyon, SW Grand Banks.

Figure 8. False boarfish, *Neocyttus* sp., observed on a bedrock wall, near gorgonian and antipatharian corals, Stone Fence, at a depth of 1036 m.

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Part 2: Coral Biochemistry and Geochemistry

MAIN LIPID CLASSES, ATP AND PROTEIN DATA IN SOME SPECIES OF DEEP-SEA CORALS IN THE NEWFOUNDLAND AND LABRADOR REGION

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ABSTRACT

Despite the fact that deep-sea corals are recognized as a crucial part of the deep marine ecosystem, little information is available on the general physiology and biochemistry of these species. As part of an IGP-funded project, measurement of lipids, ATP and protein amounts of deep-sea corals were completed. Decision-tree analysis (DTA) revealed a link between coral groups and total lipid percentages, showing that species within the same group were characterized by similar lipid amounts. Depth did not seem to impact the total lipid percentages suggesting that deep-sea corals adapt to the differential access to food by changing the proportion of lipid classes while maintaining equivalent lipid levels. The overall results obtained after decision tree analysis of ATP and protein data show strong differences between species with low seasonality in the data (despite some non-significant variations). This suggests a weak influence of reproductive cycles on general metabolism. The absence of trend with depth and season in protein data remains surprising considering its link with food availability but could suggest a stronger reliance on lipid storage for survival of the species.

INTRODUCTION

To date, most studies on lipid composition concern shallow water corals. Changes in the amounts of lipids present in coral tissues can be an indicator of stress. For example, amounts of lipids in corals decreased during the El Niño warming event of 1983 (Glynn et al. 1985). In addition to producing a change in total lipids, environmental conditions could have an impact on lipid allocation, i.e. reproductive lipid versus storage lipid (Ward 1991). Lipid amounts can give insights into coral physiology and provide information on species general health status. Lipid percentages of 81 specimens were measured and the presence and ratios of 6 major classes of lipids were assessed. Results of lipid analysis conducted on coral samples were summarized in a manuscript published in 2008 (Hamoutene et al. 2008a).

ATP is the most basic and universal energy-supplying molecule. Effect of tidal flows (Fang et al. 1987), as well as light (Al Horani et al. 2003), have impacted ATP levels in shallow water corals. Al Horani et al. (2003) highlighted the link

between ATP levels and calcification processes thus proving that ATP can bring direct information on coral vitality. Increased sedimentation due to trawling can impact this vitality. Corals can remove sediment from their surface in a variety of ways, including using tentacles and cilia to move debris, and trapping particles in mucus, which is subsequently sloughed off (Hubbard and Pocock 1972). These cleansing processes are not without energetic cost and therefore contribute to coral stress (Bak 1978). ATP can bring information on energy budgets of coral and allow us to investigate potential impacts of fishing activities (and pollution) on species sampled in areas under different fishing pressures. Tissue protein levels were also evaluated in this study in relation to season, depth and sample location. In addition, species-related trends in protein data distribution were investigated (Hamoutene et al. 2008b).

METHODOLOGY

CORAL SAMPLES

Coral samples were collected opportunistically from three sources: Fisheries and Oceans Canada multispecies stock assessment surveys, the Northern Shrimp Survey (DFO and Industry collaboration), and the Fisheries Observer Program (FOP). All specimens were assigned a species code, bagged with locator number, and frozen. Samples used for lipid analysis were collected in the fall of 2004 and 2005. Samples collected in the fall, summer and spring of 2005, as well as the fall of 2007 were used fort ATP and protein analysis. Sampling depths varied between 50-1500 m, but not all species were represented at all depths. Sampling sites comprised Cape Chidley (61^{o}N, 63^{o}W), Southwest Grand Banks (43^{o}N, 53^{o}W), Southeast Grand Banks (45^{o}N, 49^{o}W) and the Flemish Cap (47^{o}N, 47^{o}W). A total of 18 species were sampled (not all species were sampled both years). The coral samples acquired belonged to the order Alcyonacea which is subdivided into 3 informal groups: soft corals, gorgonians with a consolidated axis, and gorgonians without a consolidated axis. Soft corals consisted of 1 alcyoniid (*Anthomastus grandiflorus* (Ag), and 2 nephtheids (*Gersemia rubiformis* (Gr), and *Capnella florida* (Cf)). When nephtheids were difficult to identify, they were designated by the general term of nephtheids (nepht). Gorgonians with a consolidated axis considered for this study were: *Acanella arbuscula* (Aa), *Paramuricea* spp. (Ps), *Primnoa resedaeformis* (Pr), *Keratoisis ornata* (Ko), *Acanthogorgia armata* (Aar), and *Radicipes gracilis* (Rg). One species of gorgonian without axis was considered: *Paragorgia arborea* (Pa). The order Antipatharia was represented by (*Bathypathes* spp. (Bs). In one instance, one sample was designated as Anti due to identification difficulties. The order Pennatulacea was represented by 3 species *Anthoptilum grandiflorum* (Agr), *Halipteris finmarchia* (Hf), and *Pennatula grandis* (Pg). Some samples were designated by the common name: sea pen (Ss) because of some identification difficulties. Finally, the order Scleractinia was represented by one species *Flabellum alabastrum* (Fa).

LIPID EXTRACTION AND ANALYSIS

Frozen polyp samples were processed and extracted according to Ward (1995). After 24 hours in the fume hood, samples were placed in glass tubes and centrifuged for 1 min to remove debris. For analysis of total lipid composition, lipid extracts were applied to 10x10 cm HPTLC plates processed according to Brod et al. (1991). The chromatograms were scanned by an image scanner, and percent composition of the lipids was determined on the basis of band intensity (Yamashiro et al. 2001). Image analysis was performed using GEOMATICA software. The spot intensity by this method was found to be linear up to 5 µg of all standard lipids. The classes of lipids identified on the plates are sterols (STEROLS, standard lipid=cholesterol), free fatty acid (FFA, standard=oleic acid), triacylglycerol (TG, standard=glycerol trioleate), monoalkyldiacyl glycerol (MADAG, standard=1-o-hexadecyl-2,3-dihexadecanoyl-rac-glycerol), wax (WAX, standard=stearyl oleate) and sterol esters (SE, standard=cholesterol oleate). Results are expressed as percentages of the total lipid content for each lipid class.

ATP ASSAY

ATP from coral polyps was extracted according to Fang et al. (1987). The volume of 0.6N H_2SO_4 used was determined according to the amount of coral tissue available for extraction; 5ml of H_2SO_4 was used for 5g of tissue or less, a volume of 10ml H_2SO_4 for more than 5g tissue. ATP detection was performed by using an ATP kit (SIGMA). ATP was expressed as 10^{-13} moles/g of tissue (wet weight).

PROTEIN DETERMINATION

Prior to protein extraction, decalcification was carried out according to Yamashiro et al. (1999) without use of formaldehyde. Proteins were extracted according to Yamashiro et al. (2005) with some modifications (multi-step extraction). Protein determination was performed according to Lowry et al. (1951).

STATISTICAL ANALYSIS

Decision tree analysis (DTA) was carried out to explore trends and differences in lipid composition, ATP and protein data resulting from variations in water depth, sampling location, species, year and season of sampling. DTA was carried out using the procedure described by Breiman et al. (1984). At every level of the tree, stepwise splitting is performed by examining each of the predictor variables in turn and selecting the predictor resulting in the smallest within-group sum-of-squares for a binary split. The splitting criterion is expressed as

proportional reduction in error (PRE), with a minimum PRE of 0.05 required for a split to result for any given predictor variable. The procedure supports both continuous and categorical variables. Categorical predictor variables used in the analysis include sampling site location ("*Location*") and coral species ("*Species*"). Water depth measured in meters ("*Depth*") was included as continuous predictor variable, as well as "*Season*" and "*Year*" for ATP and protein data. The risk of over fitting was minimized by specifying a minimum number of cases, or stop size, for the creation of new nodes (Puestow et al. 2001). That is, if a given node contained fewer observations than the specified stop size (n=5) it was not further partitioned. DTA was applied to lipid composition data, as well as to ATP and protein values. One way ANOVA was subsequently applied to all terminal nodes (for lipid analysis only) to reveal statistically significant differences between all subsets. The Holm-Sidak method was used for multiple comparisons.

RESULTS AND DISCUSSION

The technique used for lipid extraction resulted in a coefficient of variation (CV) of 10%. Harland et al. (1993) found between 5-10% variation in lipid percentages between samples from the same colony (CV of 6-17%), confirming the importance of replicating lipid extraction. Lipid percentages of deep-water corals were lower than values obtained for their shallow-water counterparts. Values ranged from 2.4 to 38.8% for deep-water spp. while lipid percentages found in shallow-water species vary between 6 and 47% (Harland et al. 1993, Grottoli et al. 2004). Shallow-water corals are essentially photoautotrophic with respect to carbon, have high rates of growth compared to deep-water corals (Huston 1985) and are therefore able to maintain high lipid levels (Stimson 1987). DTA revealed a link between coral groups and differences in total lipid percentages showing that species within a group had similar lipid amounts. The following sequence was found: total lipids in gorgonians < soft corals and sea pens < Order Antipatharia (Fig. 1).

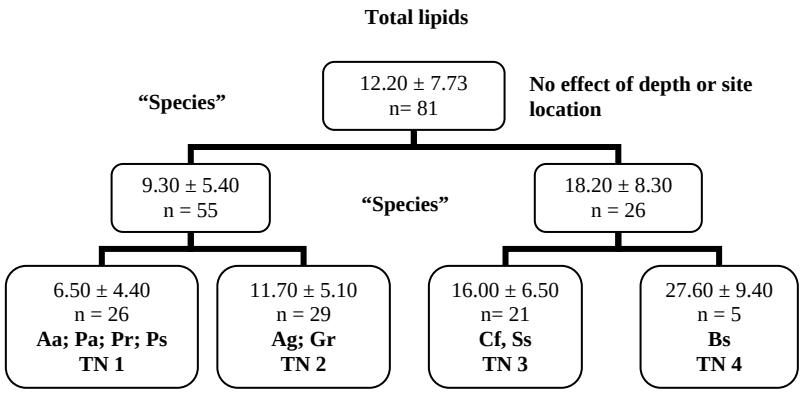

Figure 1. Decision tree analysis for total lipids with three predictors: depth, species and location. Ag: *Anthomastus grandiflorus*, Gr: *Gersemia rubiformis*, Cf: *Capnella florida*, Aa: *Acanella arbuscula*, Ps: *Paramuricea* spp, Pr: *Primnoa*

resedaeformis, Pa: *Paragorgia arborea*, Bs: *Bathypates* spp, and Ss: Sea pens. TN: tree node. All data are expressed as mean percentage ± standard deviation.

The results of this investigation suggest that the deep-sea corals considered here are storing energy mostly as MADAG (14.4%) and WAX (14.0%). Wax esters and triacylglycerols are the main storage lipids in shallow corals and can account for 40 to 73% of total lipids (Harland et al. 1993, Yamashiro et al. 1999). Alkyldiacylglycerols (like MADAG) can be metabolized to yield energy but at a much lower rate than triacylglycerols (Sargent et al. 1973). The study of lipoproteins of sharks (Sargent et al. 1973, Mills et al. 1977) as well as some primitive coelacanth (Mills and Taylaur 1973) shows that MADAG is a feature of 'primitive' lipid metabolism which has been lost during the evolution of teleosts and higher classes of animals (Mills et al. 1977).

Depth-related trends were seen for FFA, TG and SE with an increase in their levels deeper than 800m and for FFA and TG a subsequent decrease below 1000 m (Fig. 2). The increase observed in FFA, TG and SE at depths greater than 800 m could suggest a need for storage because of a decrease in food availability. Analysis of particulate organic matter reaching the deep-sea floor shows a high percentage of fatty acids and sterols (Kiriakoulakis et al. 2004). Free sterols form a part of membranes and play an important role in regulating their viscosity and permeability (Nes 1974). In mollusks, a decrease in sterols has been observed following spawning suggesting that sterols are required for forming new cellular membranes during gametes proliferation (De la Parra et al. 2005). The decrease in sterols observed in corals living at depths deeper than 1000 m could be associated with low growth rates (Watling and Norse 1998) and increased longevity (Sherwood et al. 2005), resulting in decreased requirements in structural lipids. The effect of bleaching and stress on shallow-water corals has shown that corals have two strategies for lipid use: 1) to use available lipid stores therefore depleting total percentages, or 2) to shift the lipid class composition (Grottoli et al. 2004). The fact that depth did not seem to impact the total lipid percentages could suggest that deep-sea corals adapt to differential access to food by changing the proportion of lipid classes but maintaining equivalent lipid levels.

The highest ATP value obtained in our study is 513.00 10^{-13} moles of ATP/g; this value is lower than levels obtained by other authors in shallow corals. Fang et al. (1987) obtained an average of 697.96 10^{-13} moles/g in the species *Acropora gravida*. In Fang et al. (1991), 4 species of *Acropora* as well as *Montipora aequituserculata* and *Porites nigrescens* revealed ATP levels between 14.30 10^{-9} to 91.80 10^{-9} moles/g. Shallow-water corals are essentially photoautotrophic with respect to carbon, displaying high rates of growth compared to deep-water corals (Huston 1985). Shallow water corals have therefore higher energy requirements than deep-sea species which may be reflected in higher ATP levels. Moreover, preservation of samples could have impacted ATP levels measured in this study. Samples were preserved at -20ºC in 2005 and in liquid nitrogen first followed by -20ºC in 2007. It is important that sampling should minimize handling stress

before freezing in liquid nitrogen (Fang et al. 1991). Corals samples obtained for this study were acquired opportunistically, not always minimizing handling stress of samples. Therefore, any comparisons of ATP values between shallow and deep water corals should be interpreted with caution.

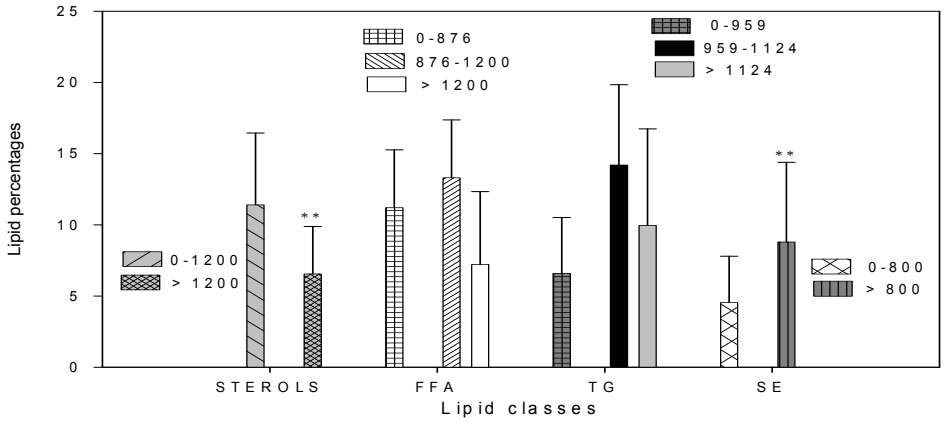

Figure 2. Depth profiles of 3 classes of lipids (all species are included).
** Significant statistical difference when compared to values < 800m, or < 1200m (t-test, $p < 0.05$). [a]groups with significant differences after application of Holm-Sidak multiple comparison procedure.

Protein levels recorded in deep-sea coral tissues were higher than values found in the literature for shallow water corals. Harithsa et al. (2005) found values between 3 and 8 mg/g tissue in two coral species (*Porites lutea* and *Acropora formosa*) from the Arabian Sea. Similarly, Fang et al. (1987) recorded 2 mg of protein/g of tissue in the shallow water species *Acropora gravida*. Values found in this study varied between approximately 22 and 2180 mg/g of tissue. However, differences between extraction techniques could also explain these dissimilarities. In Harithsa et al. (2005), homogenization in a saline solution, followed by a centrifugation, was used. Fang et al. (1987) used a one-step boiling in NaOH to extract protein. In both cases, no decalcification was conducted. In this study, decalcification was performed in 10% acetic acid to ensure access to tissue for protein extraction. The extraction technique performed in this study on deep-sea corals was more “aggressive” (multi-step process), therefore resulting in more protein being extracted from the tissue.

The overall results obtained after DTA of ATP and protein data show strong differences between species with low seasonality in the data. Even though they are congeners, strong differences were found in reproductive strategies between three deep-water species (*Caryophyllia ambrosia*, *C. cornuformis*, *C. sequenzae*) examined by Waller et al. (2005), showing the importance of the “species”

predictor in explaining differences. Moreover, these authors identified asynchronous, cyclical hermaphroditism with no evidence of seasonality in these three deep water species. These results could suggest less influence of reproductive cycles on general metabolism in these deep water species. Nonetheless, the absence of any trends with depth and season in the protein data is a surprising result considering its link with food availability and some of the observations found on lipid data in deep-sea corals by Hamoutene et al. (2008).

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STABLE CARBON AND NITROGEN ISOTOPIC COMPOSITION OF DEEP-SEA CORALS FROM THE NEWFOUNDLAND AND LABRADOR CONTINENTAL SLOPE: EXAMINATION OF TROPHIC LEVEL, DEPTH AND SPATIAL EFFECTS

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ABSTRACT

Stable isotopic analysis of deep-sea corals has the potential to provide information on their feeding habits as well as on productivity and nutrient dynamics in the deep ocean. To assess inter-species differences in feeding habits, the C and N isotopic compositions were analyzed for 11 species of deep-sea corals collected along the Newfoundland and Labrador continental slope. Geographic variability was addressed by examining specimens from three regions (Hudson Strait, Labrador Slope and the Southern Grand Banks) with a range of depths (50-1400 m) for each site. Species was the most important controlling factor for both the C and N isotopic compositions. This is likely linked to substrate control of food availability and quality. Species, such as *Paragorgia arborea*, were at the lowest trophic level, ingesting a greater proportion of "fresh" sinking particulate organic matter (POM). Other species, such as *Bathypathes arctica* and the Alcyonacean soft corals occupied higher trophic levels with a greater proportion of resuspended POM. The highest $\delta^{15}N$ values were observed for *Flabellum*, indicating a carnivorous diet. Depth was not a significant factor for $\delta^{15}N$ values, while only $\delta^{13}C$ values correlated with latitude with a slight increase (<1‰) from north to south in the study area.

INTRODUCTION

Despite the great deal of recent interest in deep-sea corals (see Roberts et al. 2006), little is known about what they eat. Previous research on the feeding habits of deep-sea corals has focused mainly on the scleractinian *Lophelia* reefs of the Northeast Atlantic. Aquarium and field observations, and chemical markers in preserved tissues, show that these corals feed on a diet ranging from detrital particulate organic matter (POM) to live zooplankton (Mortensen et al. 2001, Kiriakoulakis et al. 2005). Much less is known about the feeding habits of deep-sea gorgonian and antipatharian corals common to Eastern Canada (Sherwood et al. 2005).

With the aim of understanding of the feeding habits of deep-sea corals of Newfoundland and Labrador, we investigated the carbon and nitrogen stable isotopic composition among 11 different species collected from different depths and regions. Stable C isotopes ($\delta^{13}C$) reveal information about the source of an organism's food, while stable N isotopes ($\delta^{15}N$) reflect an organism's position in the food web (trophic level). Stable isotopic composition therefore has the potential to provide information about the diets of deep-sea corals (Fry 1988, Hobson et al. 1995, Vander-Zanden and Rasmussen 2001). This is particularly useful when traditional methods of diet analysis, such as gut contents or incubations are impracticable.

We also explored geographic and bathymetric patterns in $\delta^{13}C$ and $\delta^{15}N$ in coral tissues. Isotopic composition of primary consumers provides time-integrated data on processes operating near the base of the food web, such as eutrophication (Heikoop et al. 2000) and nutrient dynamics across oceanographic gradients (Dunton et al. 1989). A previous study from Newfoundland and Labrador reported higher $\delta^{15}N$ fish and invertebrates inhabiting the inner reaches of the continental shelf than in fish and invertebrates living near the shelf break (Sherwood and Rose 2005). We assessed the strength of similar isotopic gradients along the main axis of the outer Labrador Current, from its origin near the Hudson Strait to the southern Grand Banks.

METHODOLOGY

CORAL SAMPLES

Coral samples were gathered opportunistically as part of an ongoing deep-sea coral collection program (Wareham and Edinger 2007). For stable isotope analysis, 169 coral tissue samples were obtained, representing 11 species collected over a depth gradient from 47 to 1433 m over three regions. The three regions represented were Hudson Strait, Labrador Slope, and southern Grand Banks (Fig. 1). The Hudson Strait and Labrador Slope are located along the main axis of the cold and low salinity Labrador Current. The southern Grand Banks is

located at the southern extent of the Labrador Current, and is also influenced by warmer and higher salinity Gulf Stream waters and Warm Slope Waters.

STABLE ISOTOPIC AND C:N ELEMENTAL ANALYSIS

To carry out the isotopic analysis, several polyps were removed from each coral to provide a composite sample. These were then freeze-dried and ground to a powder using an agate mortar and pestle. Samples for elemental (%N and %C) and carbon isotope analysis were treated with 5 % (v/v) HCl to remove carbonates, triple rinsed in de-ionised water and dried at 60^{o}C. Samples for nitrogen isotope analysis were left untreated and analysed separately. Approximately 0.7 mg samples were weighed into 10 x 10 mm ultra light Sn capsules. The analyses were carried out using a Carlo Erba 1500 elemental analyzer connected by a ConFlo-II interface to a Finnigan™ MAT252 isotope ratio mass spectrometer in the Department of Earth Sciences, Memorial University. The carbon and nitrogen isotopic values are reported in the standard δ notation:

$$\delta X = [(R_{sample}/R_{standard}) - 1] \times 10^{3}$$

where X is ^{13}C or ^{15}N and R is ^{13}C/^{12}C or ^{15}N/^{14}N. Values are in per mil (‰) units with respect-to Vienna Pee Dee Belemnite (VPDB) standard and the N_2 in air respectively. Calibration of the mass spectrometer data was carried out using external reference materials. Replicate analyses were also carried out on selected coral samples. The average standard deviation between replicates was ±0.20 ‰ for δ^{13}C and 0.24 ‰ for δ^{15}N. Elemental concentrations (%C and %N) were analysed in conjunction with the isotopic analyses. Replicate analyses on selected coral samples had an average standard deviation of ±0.76 for % C and ±0.30 for % N.

Interpretation of δ^{13}C data is potentially complicated by lipid content, because lipids are isotopically depleted relative to proteins (DeNiro and Epstein 1977). Consequently, δ^{13}C data were corrected for lipid content using C:N as a proxy for lipid content according to equations in McConnaughey and McRoy (1979):

$$\text{Lipid (L)} = 93 / [1 + (0.246\ \text{C:N} - 0.775)^{-1}]$$

$$\delta^{13}C' = \delta^{13}C + 6 [-0.207 + 3.90 / (1 + 287 / L)],$$

where, δ^{13}C' represents lipid-corrected δ^{13}C.

STATISTICAL ANALYSIS

The distribution of species with respect to regions and depths was unbalanced. Data were therefore analysed in the following manner. First, the effect of species

on each of $\delta^{13}C'$ and $\delta^{15}N$ over the entire dataset was tested using 1-way ANOVA. Then, the effects of region and depth were tested for each level of species using ANCOVA. Where necessary, non-significant interactions were eliminated and models were refit sequentially. Model residuals were checked to verify assumptions of normality and homogeneity of variance; transformations were not required. Post-hoc comparisons were performed with Tukey's honestly significant differences (HSD) test. Statistical significance is reported at the $p < 0.05$ level.

RESULTS AND DISCUSSION

Species was by far the strongest predictor of $\delta^{13}C'$ ($F_{10,138} = 15.14$, $p < 0.001$) and $\delta^{15}N$ ($F_{10,154} = 16.81$, $p < 0.001$). To compare feeding habits among species, data were plotted in a graph of $\delta^{15}N$ vs. $\delta^{13}C'$ (Fig. 1). Here, the vertical axis represents a continuum of trophic level, with $\delta^{15}N$ increasing by about 3 ‰ per trophic level (Fry 1988, Sherwood and Rose 2005). The horizontal axis represents a continuum of food "freshness", from relatively fresh, recently exported POM (lower $\delta^{13}C'$) to older, re-worked POM (higher $\delta^{13}C'$). Also plotted are data for fish and other invertebrates from the continental slope foodweb off Newfoundland (Sherwood and Rose 2005). The distribution of data in Figure 1 provides a convenient way to visualize trophic relationships among different taxa, with each $\delta^{13}C'$-$\delta^{15}N$ pair corresponding to a unique trophic niche.

Coral data plotted along a relatively tight trendline ($r^2 = 0.71$, $p < 0.001$) extending from *Paragorgia* to *Flabellum*. At the lower end of the trendline, *Paragorgia* and *Primnoa* plotted closer to zooplankton (amphipods and euphausiids). These species therefore consume a similar diet as zooplankton: recently exported phytoplankton remains (i.e. sinking POM). The remaining gorgonian species (*Acanella*, *Keratoisis*, *Acanthogorgia*, *Anthomastus*, *Paramuricea*, *Capnella*), as well as Pennatulacea and *Bathypathes,* displayed higher values of $\delta^{13}C'$ and $\delta^{15}N$. This suggests that re-suspended POM and benthic meiofauna make up a greater proportion of their diet. At the higher end of the trendline, *Flabellum* plotted closer to snow crab, suggesting a primarily carnivorous diet, and consistent with aquarium observations showing that *Flabellum* can ingest swimmers up to 1.5 cm in length (Buhl-Mortensen et al. 2007). The range of $\delta^{13}C'$ and $\delta^{15}N$ values in the dataset shows that deep-sea corals occupy a wide range of trophic niches, likely as a strategy to reduce competition in the food limited, deep-sea environment (e.g. Iken et al. 2001).

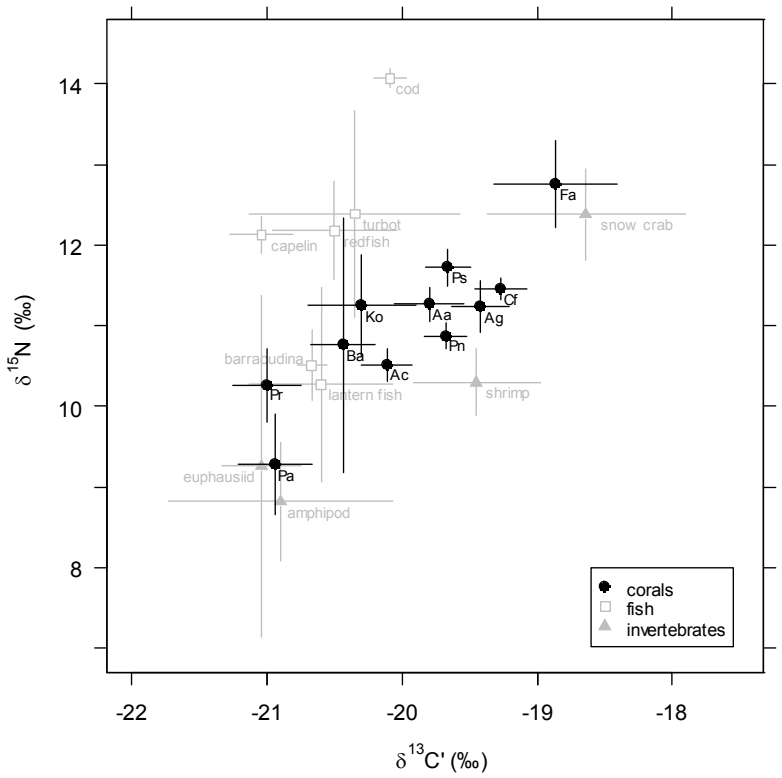

Figure 1. Distribution of deep-sea coral data in $\delta^{15}N$ vs. $\delta^{13}C$' space; *Anthomastus* (Ag), *Capnella* (Cp), *Acanella* (Ac), *Acanthogorgia* (Aa), *Keratoisis* (Ko), *Paragorgia* (Pa), *Parauricea* (Ps), *Primnoa* (Pr), Pennatulacea (Pn), *Bathypathes* (Ba), *Flabellum* (Fa). Also shown are data for fish and other invertebrates from Sherwood and Rose (2005). Error bars are 95% conf. intervals.

Depth had an overall insignificant effect on stable isotopic composition of deep-sea coral tissues (Fig. 2). This is consistent with the results of Hamoutene et al. (2008), where depth had no effect on lipid composition, and suggests that substrate, rather than depth, controls the availability and quality of food.

Values of $\delta^{13}C$ increased slightly (<1‰) from Hudson Strait to Grand Banks, although the effect was statistically significant only for *Capnella*, *Acanella* and Pennatulacea. This pattern is consistent with lower values of phytoplankton $\delta^{13}C$ in colder, high latitude waters, relating to higher concentrations of dissolved CO_2 (Rau et al. 1989). There were no significant differences in coral $\delta^{15}N$ between the Hudson Strait, Labrador Slope or Grand Banks.

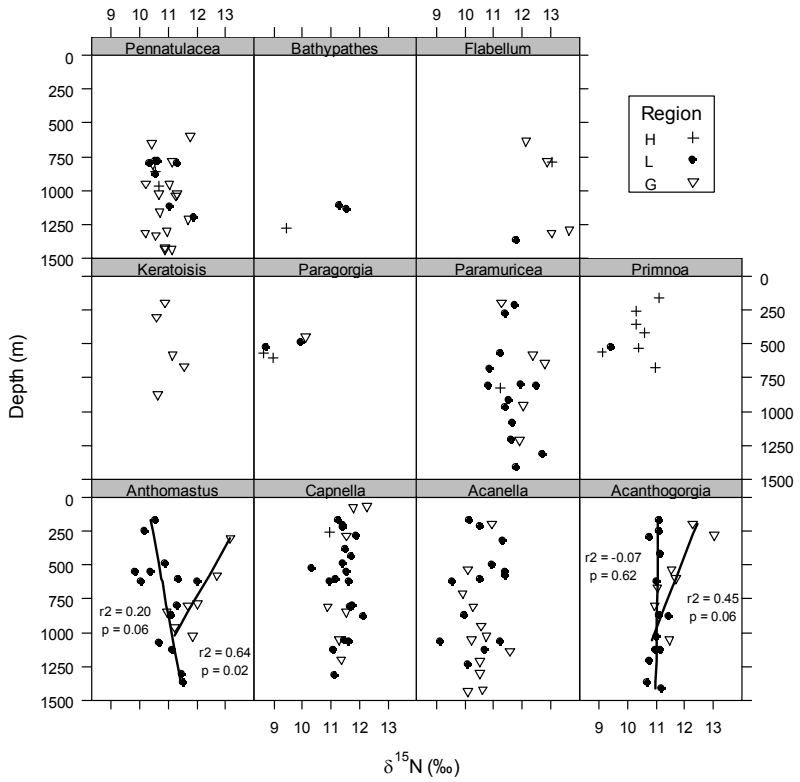

Figure 2. Plots of δ^{15}N vs. depth, grouped by region. H = Hudson Strait; L = Labrador Slope; G = Grand Banks. The region × depth interaction was significant for *Anthomastus* and *Acanthogorgia*; linear fits are shown separately for each region. All other region and depth effects and interactions not significant at the p = 0.05 level.

FUTURE WORK

Given a better understanding of stable isotopic composition in deep-sea corals, we are ready to examine long-term records of isotopic composition preserved in the organic endoskeletons of older, radio-metrically dated specimens. These records have the potential to provide information on productivity and nutrient cycles over extended time periods (Sherwood et al. 2005, Williams et al. 2006). We are pursuing a compound-specific isotope approach that allows us to disentangle the effects of trophic level and the isotopic composition of source nutrients. A colleague in Germany (C. Ostertag-Hemming) is running preliminary tests for us using GC-MS. If successful, we hope to replicate the method using instruments available in the lab of S. Zeigler at Memorial University. It is expected that records of δ^{15}N spanning the last 100 years will shed new light on the effects of decadal climate change on trophic dynamics of plankton and zooplankton in the Northwest Atlantic.

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CARBON-14 COMPOSITION OF DEEP-SEA CORALS OF NEWFOUNDLAND AND LABRADOR: PROXY RECORDS OF SEAWATER ^{14}C, AND QUANTIFICATION OF DEEP-SEA CORAL GROWTH RATES

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ABSTRACT

Deep-sea gorgonian corals secrete a two-part skeleton of calcite and protein. The calcite is comprised of dissolved carbon sources at depth, while the protein is made from sinking particulate organic matter (POM), which originates in surface water. Radiocarbon (^{14}C) content of the calcite and protein provide direct measures of seawater ^{14}C both at depth and in the overlying surface waters, respectively. We measured radiocarbon (^{14}C) in colonies of *Primnoa resedaeformis* and *Keratoisis ornata* collected off Eastern Canada to reconstruct seawater ^{14}C contents over the last 1200 years. Along the Newfoundland and Labrador slope, convective mixing of the water column homogenizes the ^{14}C signature to at least 1000 m depth. Off southwest Nova Scotia, the vertical gradient in ^{14}C is much stronger, because subsurface waters mix with ^{14}C-depleted Antarctic Intermediate Water (AAIW) originating from the south. We also produced a reference chronology of nuclear bomb produced ^{14}C representing the offshore branch of the Labrador Current. Using this, we calibrated the ages and growth rates of colonies of 6 different species of gorgonian and antipatharian corals. All species were slow growing and long lived. Since all of the corals were from heavily fished areas, it is likely that age distributions are biased towards smaller and younger colonies. Recovery of deep-sea corals from fishing-induced damage will likely take decades to centuries.

INTRODUCTION

The radiocarbon (^{14}C) content of seawater is an important tracer of oceanic mixing. The ^{14}C age of a deep water mass reflects the length of time since it was last exposed to, or "ventilated" with the atmosphere. Additionally, the difference in ^{14}C between surface and deep waters reflects the extent of vertical mixing. Uptake of bomb-^{14}C produced by atmospheric nuclear weapons testing in the

late 1950s and early 1960s has amplified the natural ^{14}C gradient between surface and deep waters. While seawater ^{14}C distribution has been mapped on a global scale, spatial and temporal variability is better revealed through study of biogenic archives, such as corals, whose skeletal ^{14}C contents closely reflect that of the seawater in which they grow (Druffel 1980). Time series ^{14}C records are useful for constraining marine reservoir ages (Guilderson et al. 2005), vertical and lateral mixing (Druffel 1997) and air-sea CO_2 exchange (Fallon et al. 2003).

We measured ^{14}C composition in independently-dated colonies of *Primnoa resedaeformis* and *Keratoisis ornata* to reconstruct past levels of oceanic ^{14}C. Skeletons of these gorgonian corals comprise both calcite and proteinaceous gorgonin. The calcite is derived from dissolved inorganic carbon at depth, while the gorgonin is tightly coupled to recently fixed and exported particulate organic matter (POC; Roark et al. 2005, Sherwood et al. 2005). Radiocarbon content of the calcite and gorgonin fractions therefore provide direct measures of seawater ^{14}C both at depth and in the overlying surface waters, respectively. Records of pre and post bomb-^{14}C were generated for surface and deep (i.e. upper intermediate water) slope water masses along a latitudinal gradient from 42^{o}N to 60^{o}N. Additional measurements from recent and subfossil specimens were used to assess vertical ^{14}C gradients over the last 1200 years.

Bomb-^{14}C is also useful for calculating ages and growth rates of deep-sea corals (Sherwood et al. 2005; Roark et al. 2006). Information on ages and growth rates is important for the conservation and management of deep-sea corals. These parameters are vital for assessing the vulnerability of deep-sea corals to natural and anthropogenic disturbances, and the timescale of their recovery. One of dominant gorgonian species off Eastern Canada, *Primnoa resedaeformis*, is known to live for at least 700 years (Sherwood et al. 2006). We measured growth rates and life span of the gorgonians *Acanella arbuscula*, *Keratoisis ornata*, *Paramuricea* sp., *Paragorgia arborea* and antipatharian *Bathypathes arctica* collected off Newfoundland and Labrador, using the bomb-radiocarbon dating method. We also compared radial and linear growth rates in a suite of colonies of *P. resedaeformis* collected during a single tow in the Northern Labrador Sea to growth rates from the Northeast Channel, southwest of Nova Scotia.

METHODOLOGY

CORAL SAMPLES

Specimens were collected with the remotely operated vehicle *ROPOS* and as fisheries bycatch (Wareham and Edinger 2007). To reconstruct seawater ^{14}C study, live samples of *P. resedaeformis* from the Hudson Strait, a live specimen of *K. ornata* from the southwest Grand Banks, and subfossil *K. ornata* from Baffin Bay, Davis Strait, Hudson Strait, southwest Grand Banks and Sable Gully were used. Samples of *P. resedaeformis* from the Northeast Channel, southwest of Nova Scotia, were also used (Sherwood et al. 2005). For the growth rates study,

colonies of *A. arbuscula*, *B. arctica*., *K. ornata*, *P. arborea*, *P. resedaeformis* and *Paramuricea* sp. were selected (Table 1).

RADIOCARBON ANALYSIS

To obtain samples for ^{14}C analysis, approximately 0.5 cm thick cross sections were cut from the bases of colonies with an Isomet™ low speed saw or a hand saw. The sections were ground and polished using silicon carbide films, ultrasonically cleaned in de-ionised water, then photographed with a Nikon™ Coolpix 900 digital camera attached to a Nikon™ SZ 1000 binocular microscope. Incandescent or ultraviolet light was used to image growth rings and resulting images were used to guide sampling. Gorgonin samples were isolated either by peeling apart growth rings, cutting with a stainless steel scalpel, or using a manual micromill fitted with a 0.3 mm bit, depending on the size and architecture of the coral skeletons, after dissolving away the calcite fraction 5% HCl. Calcite samples were milled along radial transects of the massive calcite growth zones of *K.ornata* and *P. resedaeformis.*

For ^{14}C analyses, CO_2 aliquots evolved from calcite and decalcified gorgonin samples were reduced to graphite in the presence of iron catalyst. Delta-^{14}C was determined on graphite targets at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Results include a background and $\delta^{13}C$ correction and are reported as $\Delta^{14}C$ according to Stuiver and Polach (1977).

DATING METHODS

To generate reference chronologies of seawater ^{14}C, colonies of *K. ornata* and *P. resedaeformis* were dated using independent methods. Recently living colonies of *P. resedaeformis* from the Hudson Strait were dated by counting annual growth rings in transverse section, as described in Sherwood et al. (2005). An older *P. resedaeformis* from the NE Channel and colony of *K. ornata* were dated with ^{210}Pb dating (Full details provided in O.A. Sherwood, E.N. Edinger, T.P. Guilderson, B. Ghaleb, M.J. Risk and D. Scott. 2008, *Earth and Planetary Science Letters* 275).

RESULTS AND DISCUSSION

Paired gorgonin and calcite ^{14}C records spanning pre- and post-nuclear bomb eras were generated for Hudson Strait, Grand Banks and Northeast Channel (Fig. 1). Gorgonin records showed a steeper bomb-^{14}C response because this reflects the ^{14} content of surface waters, transmitted to the deep-sea corals via sinking POM. Calcite bomb-^{14}C signals were lagged and damped because this reflect the ^{14}C content of deep waters, which take longer to equilibrate with atmospheric ^{14}C levels. During the pre-bomb (pre-1957) era, levels of ^{14}C in

surface and deep waters were the same at the Hudson Strait and Grand Banks, due to both areas being under the influence of the same water mass, Labrador Slope Water, which over decadal timescales is well mixed to at least 1000 m depth. At the NE Channel, deep-water ^{14}C values were significantly depleted to -105‰, reflecting periodic intrusion of Warm Slope Water (WSW) originating from the south. Warm Slope Water is partly derived from Antarctic Intermediate Water (AAIW) which causes its low ^{14}C signature. These results show that ^{14}C profiles from corals collected along the Scotian Slope could be used to reconstruct the movements of WSW vs. LSW over centennial to millennial timescales. Slopewater movements in this area have profound "bottom-up" effects on fisheries ecology in this region (Drinkwater et al. 2002); detailed proxy records could help to resolve the details of these effects on marine populations over extended time periods.

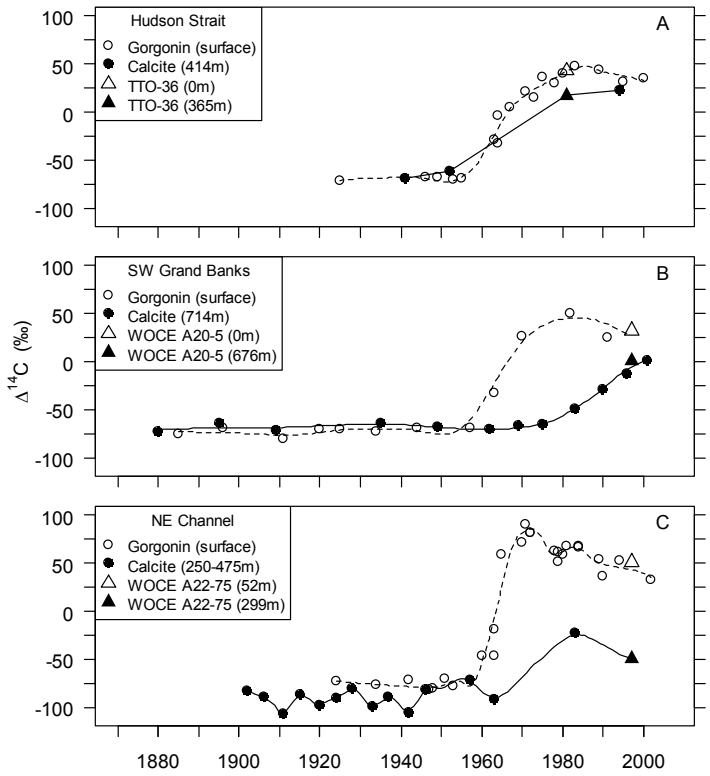

Figure 1. Paired gorgonin (surface water) and calcite (sub-surface water) $\Delta^{14}C$ records. (A) Hudson Strait records generated from 3 growth ring-dated colonies of *P. resedaeformis* (1525-1, 1525-3, 1525-10; depth = 414 m). (B) Southwest Grand Banks records generated from a single ^{210}Pb-dated *K. ornata* (1343; depth = 713 m). (C) Northeast Channel records from specimens of *P. resedaeformis* collected between 250-475 m. Gorgonin record from Sherwood et al. (2005); calcite record from the massive calcite zone of an older ^{210}Pb-dated colony (COHPS2001-1). TTO and WOCE data represent seawater $\Delta^{14}C$ at the indicated depths.

We used the surface water bomb-^{14}C profiles from the Hudson Strait and Grand Banks to calibrate the ages of samples of other species of deep-sea coral of unknown age. Bomb-^{14}C chronologies from the 2 sites were identical, so the data were merged to produce a single reference chronology representing surface waters of the offshore branch of the Labrador Current off Newfoundland and Labrador. This more accurately reflects bomb-^{14}C levels in the waters overlying our deep-sea corals than a previously published reference chronology based on otoliths of fish collected mainly from shelf waters of southern Newfoundland (NAFO Div. 3Ps; Campana 1997; Campana et al. 2002). For each coral section to be dated, between 2 and 4 samples were isolated for Δ^{14}C, representing some combination of pre-bomb, bomb-increase, and post-bomb data points. If any of these Δ^{14}C values were typical of the period of bomb- increase (Δ^{14}C = -50 to +25 ‰) then the year of formation was determined from the intersection of that Δ^{14}C value (± 1 SE) with the 95% prediction intervals enveloping the reference chronology. Alternatively, if only pre-bomb and post-bomb data points were available, the most recent sample with pre-bomb Δ^{14}C was assigned to the year 1957 (e.g. Roark et al. 2005). For each coral, we then had 2 tie-in points: a calibrated bomb-^{14}C age from somewhere inside the axial skeleton, and the year of collection at the outer margin of the skeleton. From these, we calculated an average radial growth rate across the radius of the axial skeleton, and a corresponding age of the colony.

Ages and growth rates are summarized in Table 1. With the exception of *P. arborea*, all of the species grew at exceptionally slow growth rates (<200 µm yr^{-1} radially, and <2 cm yr^{-1} vertically). *P. arborea* grew at a faster radial growth rate of 800 µm yr^{-1}, apparently to provide extra support for its weak, unconsolidated skeleton. Calibrated growth rates also provided proof that concentric growth rings in the species *B. arctica* (Fig. 2), *A. arbuscula*, and *K. ornata* (Fig. 3) form with annual periodicity (Fig. 2), but not in *P. arborea* or *Paramuricea* sp. (Fig. 4).

Ages of colonies ranged from a few decades, up to 200 years for a subfossil colony of *K. ornata*. All of the specimens reported on here were collected from heavily fished areas, with the exception of the Hudson Strait (Edinger et al. 2007). The largest and oldest colonies are likely to have already been removed from the population, thereby biasing age distributions toward smaller and younger colonies (cf. Anderson and Clarke 2003). Little is known about the frequency of recruitment events in deep-sea gorgonians and antipatharians; however, knowledge of shallow-water taxa (Lasker et al. 1998) and preliminary evidence from deep-sea species (Mills and Mullineaux 2005) suggests that it may be infrequent. The combination of slow growth rates and infrequent recruitment implies that populations of deep-sea corals damaged by fishing gear will take centuries to recover. Conservation measures to protect deep-sea corals of Newfoundland and Labrador should be designed and implemented immediately.

Table 1. Collection details, ages and growth rates (GR) of antipatharian and gorgonian (Order Alcyonacea) specimens collected off Newfoundland and Labrador.

Order/Family/Species	Sample ID	Lat (N)	Long (W)	Depth (m)	Year of Coll.	Dating method	Age (yrs)	Radial GR ($\mu m \cdot yr^{-1}$)	Vertical GR ($cm \cdot yr^{-1}$)
Antipatharia									
Schizopathidae									
B. arctica	465	44°34.02'	53°46.02'	876	2005	bomb-^{14}C	56 ± 8	65 ± 11	1.34 ± 0.19
B. arctica	2440	44°57.45'	55°1.19'	812	2007	bomb-^{14}C	75 ± 21	36 ± 14	1.33 ± 0.37
Alcyonacea									
Isididae									
A. arbuscula	1591	65°7.86'	58°27.12'	526	2006	bomb-^{14}C / growth rings	30 ± 20	70 ± 40	1.00 ± 0.67
K. ornata	2452	44°49.96'	54°28.13'	601	2007	bomb-^{14}C	97 ± 9	72 ± 7	0.93 ± 0.08
K. ornata	1449	61°36.00'	60°22.98'	1193	2007	^{14}C [a,b]	200 ± 30	75 ± 11	n/a
K. ornata	1343	44°7.98'	52°55.98'	713	2006	^{210}Pb [a]	138 ± 23	53 ± 9	n/a
Plexauridae									
Paramuricea sp.	1348	44°13.02'	53°0.00'	814	2006	bomb-^{14}C	80 ± 14	92 ± 21	0.75 ± 0.13
Paramuricea sp.	1886	55°13.14'	55°10.98'	850	2006	bomb-^{14}C	71 ± 7	206 ± 24	0.56 ± 0.06
Paragorgiidae									
P. arborea	1523	60°29.88'	61°23.70'	414	2006	bomb-^{14}C	80 ±13	833 ± 151	1.62 ± 0.27
Primnoidae									
P. resedaeformis	1525-3	60°29.88'	61°23.70'	414	2006	growth rings	100	90	1.00
P. resedaeformis	1525-4	60°29.88'	61°23.70'	414	2006	growth rings	72	146	n/a
P. resedaeformis	1525-5	60°29.88'	61°23.70'	414	2006	growth rings	31	165	1.71
P. resedaeformis	1525-6	60°29.88'	61°23.70'	414	2006	growth rings	23	215	2.61
P. resedaeformis	1525-7	60°29.88'	61°23.70'	414	2006	growth rings	24	188	2.50
P. resedaeformis	1525-8	60°29.88'	61°23.70'	414	2006	growth rings	24	167	2.29
P. resedaeformis	1525-10	60°29.88'	61°23.70'	414	2006	growth rings	44	125	1.86
P. resedaeformis	1526-1	60°10.56'	61°47.40'	257	2006	growth rings	50	130	n/a
P. resedaeformis	1526-2	60°10.56'	61°47.40'	257	2006	growth rings	57	105	n/a
P. resedaeformis	1534	61°29.28'	61°49.14'	608	2006	growth rings	52	83	n/a
P. resedaeformis	1536-1	61°12.12'	61°22.68'	585	2006	growth rings	18	194	1.94
P. resedaeformis	1536-2	61°12.12'	61°22.68'	585	2006	growth rings	20	170	1.80
P. resedaeformis	1539	60°19.38'	62°8.94'	285	2006	growth rings	18	181	n/a
P. resedaeformis	1567	62°9.66'	61°32.22'	456	2006	growth rings	62	121	n/a
P. resedaeformis	2370-1	61°21.00'	60°40.98'	640	2006	growth rings	42	194	1.90

[a] Data from O.A. Sherwood, E.N. Edinger, T.P. Guilderson, B. Ghaleb, M.J. Risk, and D.B. Scott, submitted manuscript
[b] Subfossil specimen

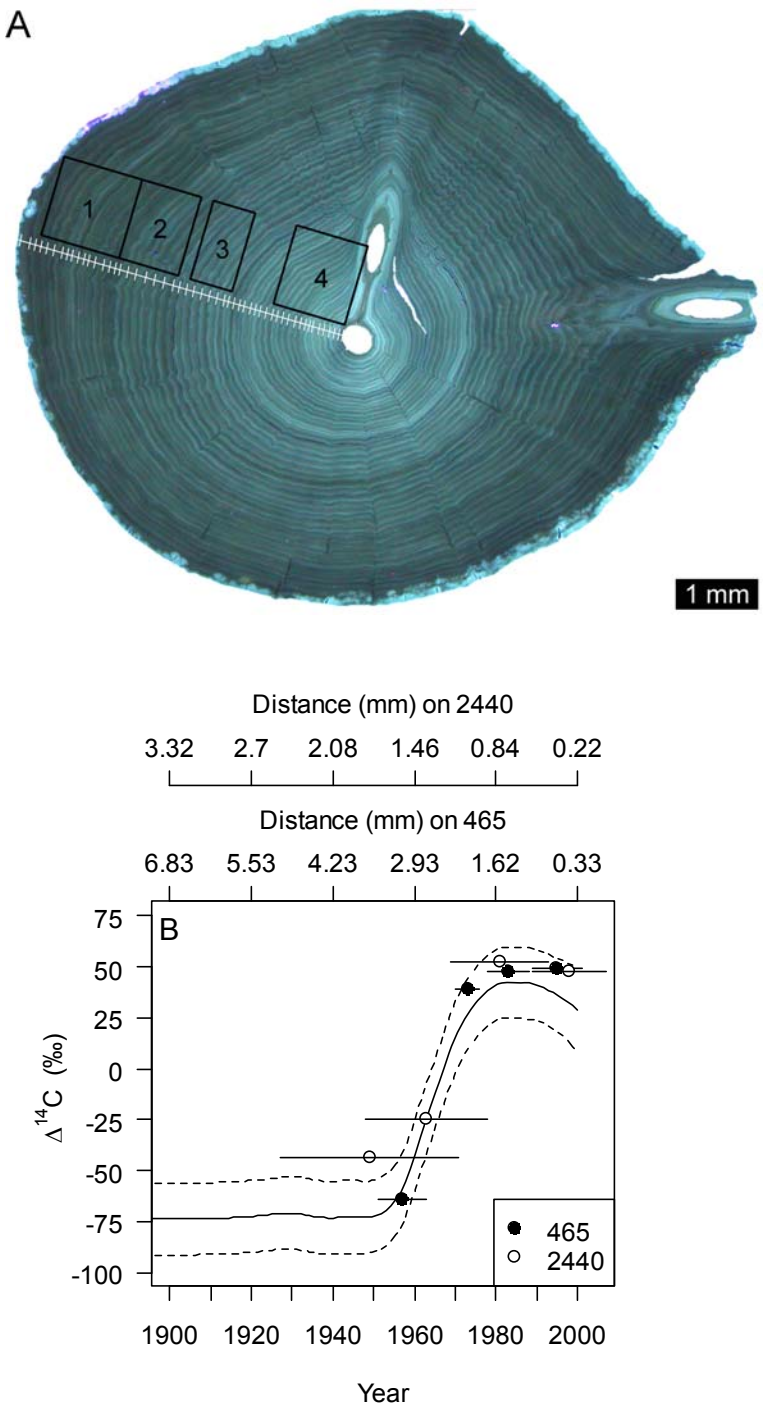

Figure 2. **(A)** Basal thin section through the axial skeleton of *B. arctica* #465, illuminated with ultraviolet light. Growth rings delineated by white hatches. Numbers 1-4 indicate samples milled for ^{14}C analysis. **(B)** The reference bomb-^{14}C chronology overlain with data for colony #465 and an additional *B. arctica* colony (#2440) at constant radial growth rates of 65 μm·yr^{-1} and 31 μm·yr^{-1}, respectively. Upper horizontal axes represent sample distances on colonies #465 and #2440. Horizontal error bars represent width of samples. Vertical error bars are smaller than symbols.

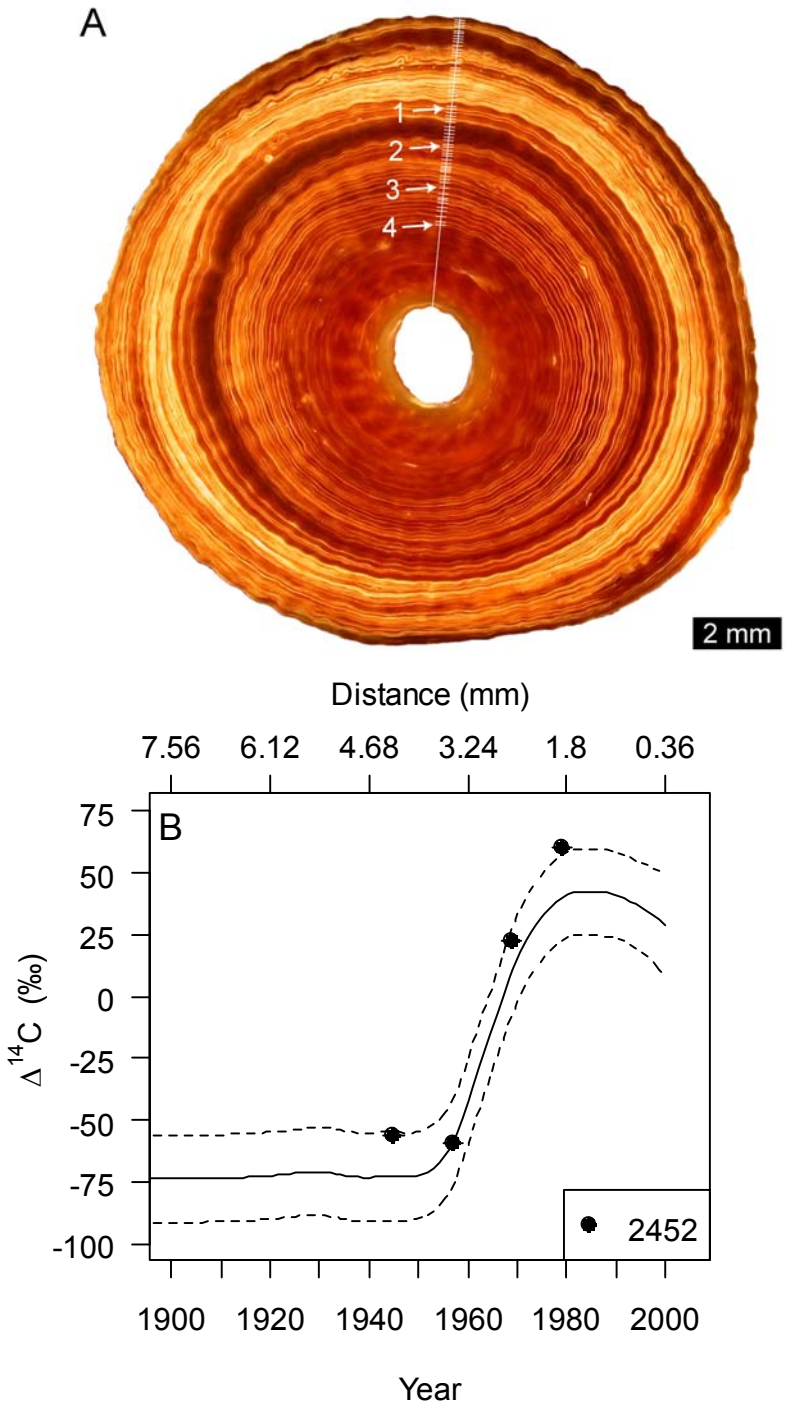

Figure 3 (A): Thick section through a basal node of *K. ornata* #2452. Growth rings, where visible, delineated by white hatches. Numbered arrows point to individual rings isolated for ^{14}C analysis. Growth rings delineated by white hatches. (B) Reference bomb-^{14}C data overlain with data for colony #2452 at a growth rate of 72 μm·yr^{-1}, as for Figure 2B.

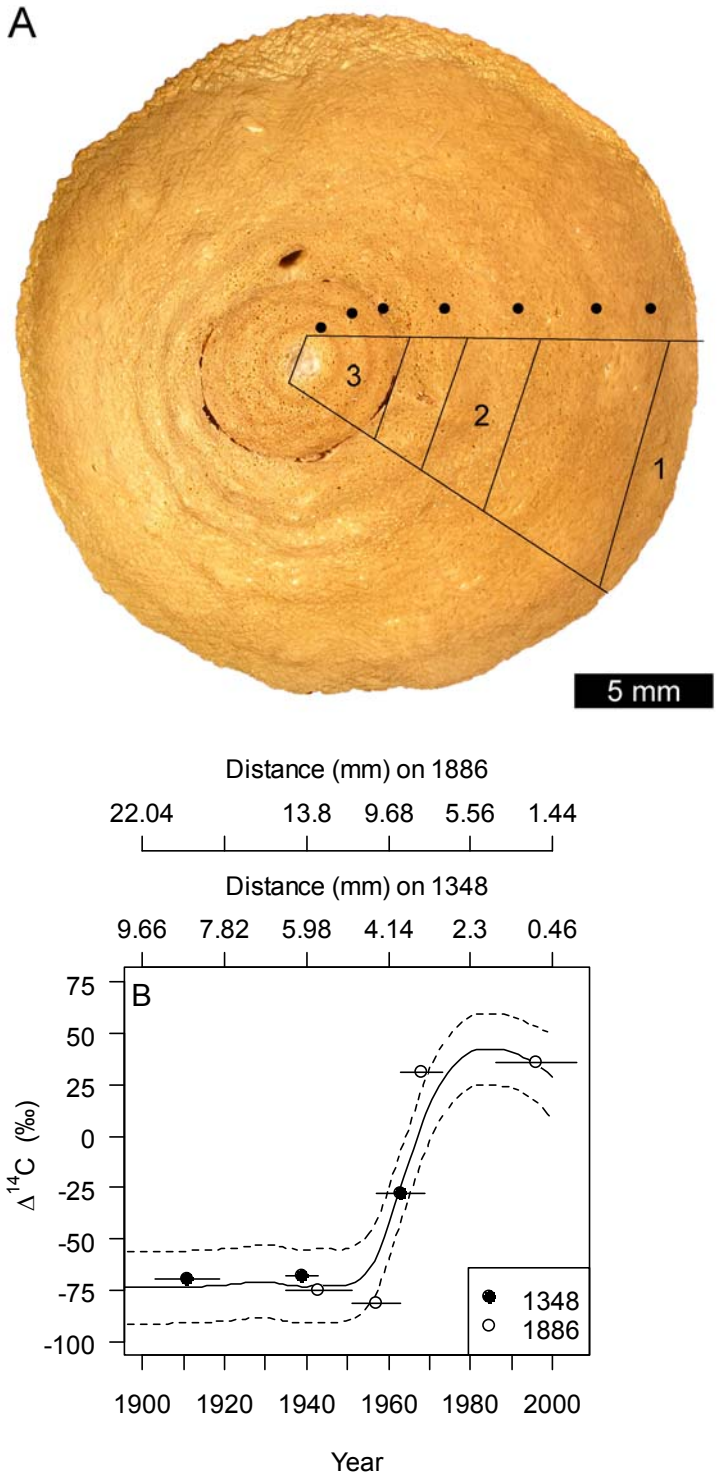

Figure 4. (A) Basal thick section of *Paramuricea* sp. #1886. Numbered segments indicate samples isolated for $\Delta^{14}C$ analysis. Black dots indicate concentric growth rings forming with an apparent periodicity of ~10 years. (B) Reference bomb-^{14}C data overlain with data for colonies #1348 and an additional *Paramuricea* sp. colony (#1886) at growth rates of 92 μm·yr^{-1} and 230 μm·yr^{-1}, respectively, as for Figure 2B.

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Part 3: Coral Taphonomy, Physical Oceanography, Conclusions and Recommendations

TAPHONOMY OF GORGONIAN AND ANTIPATHARIAN CORALS IN ATLANTIC CANADA: EXPERIMENTAL DECAY RATES AND FIELD OBSERVATIONS

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ABSTRACT

Taphonomy includes the processes of organism and skeleton preservation and degradation, prior to and during fossilization. Taphonomy of deep-sea corals is relevant to coral conservation because broken and dead corals of most species are rarely observed on the sea floor, even in areas that are subject to heavy bottom-contact fishing effort. Coral taphonomy studies in this project sought to understand the longevity of dead coral skeletons of several species on the sea floor using aquarium experiments and *in situ* observations using the ROV ROPOS. Aquarium experiments showed that the gorgonian *Paragorgia arborea* degraded to disaggregated spicules within 3-6 months, in striking contrast to the other species studied, which were all relatively stable. The skeletons of the carbonate- or carbonate-gorgonin skeletonized gorgonians *Keratoisis ornata* and *Primnoa resedaeformis* experienced no significant weight change in the first seven months of the experiment, while the pure gorgonin skeletons of *Paramuricea* actually increased in weight, as a consequence of more complete hydration of the skeleton. Exposed skeletons and buried skeletons followed nearly identical patterns. Exposed carbonates in the skeletons of *Keratoisis ornata* became slightly chalky and pitted, similar to subfossil specimens of this species recovered as fisheries bycatch and by the ROV. *In situ* observations matched those of the laboratory experiment. Dead skeletons of *Paragorgia* were extremely fragile, and crumbled in the manipulator arms of the ROV, while dead skeletons of *Primnoa* and *Keratoisis* were much stronger although they appeared to be somewhat more brittle than live-collected skeletons of the same species. The lack of dead corals observed on the seafloor in heavily trawled areas may be explained by rapid degradation of *Paragorgia* skeletons, and removal of skeletons of other species by strong currents.

INTRODUCTION

While underwater video footage has documented Atlantic Canadian deep-sea corals damaged by fishing gear (Mortensen et al. 2005), dead corals (i.e. recently dead or skeletons) are rarely observed lying on the sea floor. This contradiction, in striking contrast to shallow water coral reefs or deep-water *Lophelia* reefs, where dead corals persist and contribute significantly to the observed calcium carbonate accumulations (e.g. Bueck and Freiwald 2005), poses a challenge for quantifying historical impacts of bottom-contact fishing on deep-sea gorgonian 'coral forests'. Trawl bycatch sampling has retrieved heavily weathered subfossil bases of *Primnoa resedaeformis* and *Keratoisis ornata*, that have been radiocarbon dated to 1200 and 1600 years old (Sherwood et al., In press, EPSL). Dead or subfossil specimens of *Paramuricea, Acanthogorgia*, and *Paragorgia* are rarely or never observed. To explain the gaps in our knowledge of the persistence of skeletonized gorgonian corals on the sea floor, we performed laboratory experiments on the taphonomy of deep-sea corals, and collected observations on coral taphonomy and the presence of dead corals of various species during the 2007 ROPOS cruise.

Taphonomy includes all the processes of fossilization, especially the degradation and alteration of skeletal remains prior to or during burial (Behrensmeyer and Kidwell 1985). There are numerous observational and experimental studies of taphonomy in shallow water (e.g. Briggs 1995; Best and Kidwell 2000; Lescinksy et al. 2002; Estrada et al. 2004). In contrast, deep-water observational (Boerboom et al. 1998) or experimental (e.g. Parsons et al. 1999; Callender et al. 2002; Powell et al. 2006) studies are rare. Rates of burial are crucial, as burial, even to shallow depths within the sediment, prevents most biological alteration of skeletons (e.g. through encrustation and bioerosion processes) (e.g. Lescinsky et al. 2002). Furthermore, redox potential (Eh) and pH conditions within marine muds are quite different from those in the overlying water column, generally lacking dissolved oxygen leading to reducing conditions (i.e. negative Eh) and slightly more acidic conditions (lower pH) than within the water column. Furthermore, the organic or compound organic-carbonate composition of gorgonian coral skeletons has profound implications for gorgonian coral taphonomy that likely distinguishes patterns observed for these organisms from those with simple mineralized skeletons such as scleractinians corals or molluscs.

In order to understand coral skeletal breakdown, we examined both physico-chemical and biological processes of skeletal degradation in skeletonised deep-sea corals. In particular, we compared patterns of weight change, physico-chemical skeletal degradation, biological encrustation, and bioerosion among five species of gorgonian and antipatharian corals. Our experimental results complement observations of dead and decaying corals from the Scotian margin and Southwest Grand Banks continental slope.

METHODOLOGY

EXPERIMENTS

Because environmental characteristics, especially burial rates, nutrient levels, and light availability, have a profound impact on rates and patterns of skeletal degradation (Callender et al. 2002), a shallow-water experimental field deployment was considered inappropriate for studying deep-sea coral taphonomy in the field. Rather, an experimental approach was established in the laboratory, and field activities were purely observational.

The laboratory experiment consisted of a series of replicated treatments on skeletal fragments and tissue of five species of gorgonian and antipatharian corals: two with compound calcite and organic skeletons (*Primnoa resedaeformis, Keratoisis ornata*), two with purely organic skeletons (*Paramuricea* spp., *Paragorgia arborea*.) and one antipatharian with a proteinaceous organic skeleton (*Bathypathes arctica*). All samples were selected from among the collection of frozen trawl bycatch material collected from DFO multispecies surveys and the fisheries observer program (Wareham and Edinger 2007). Treatments included skeletal remains buried ~1 cm within muddy sand (Fig. 1), skeletal remains elevated above the sediment-water interface, and a handling control of samples cut, weighed, and returned to the freezer. Individually photographed and pre-weighed 5-7 cm long skeletal pieces were tagged with labelled plastic cable ties prior to deployment. Because coral skeletal samples were frozen prior to preparation for the experiment, samples were hydrated by soaking in seawater before being measured for initial weights, lengths, and diameters. Skeletons were deployed for durations of 3.5, 7, and 12 months, with the 12 month deployments yet to be collected. In addition, segments of skeleton with attached tissue were also deployed in order to observe rates of tissue degradation and loss. Tissue degradation was observed visually both above and below the sediment-water interface.

Muddy sand was collected from Holyrood Bay, Newfoundland, by Ocean Sciences Centre divers approximately 1 week before the start of the experiment. Sediments were homogenized in aquaria prior to addition of skeletons. Aquaria were equipped with flow-through filtered running seawater, which was left running at a low rate for the duration of the experiment. Aquaria were covered with black plastic garbage bags to exclude light in order to simulate dark conditions found in deep water. Water was not chilled, such that water temperatures varied seasonally, reaching as high as 9^{o}C in summer, and as low as -1^{o}C in winter.

Figure 1. Half-buried pieces of *Paramuricea* sp. deployed in a tissue degradation experiment. Rusty colour of sediment surface is caused by oxidation of iron in muds; black colour below indicates lack of dissolved oxygen below sediment-water interface.

FIELD OBSERVATIONS

Field observations of dead corals were made in Sable Gully and the Stone Fence, on the Scotian margin and in Haddock Channel and Desbarres Canyon on the slope of the SW Grand Banks (SWGB) during the 2007 ROPOS ROV cruise. Six of the eight SWGB dive sites spanned the depth range of 400-1000 m, and were arranged along a gradient of trawling intensity as indicated by fisheries observer records of fishing effort (Edinger et al. 2007).

RESULTS AND DISCUSSION

WEIGHT CHANGE

Gorgonian corals consisting of combined carbonate-organic skeletons (*Primnoa resedaeformis*, *Keratoisis ornata*) experienced no statistically significant weight change during the initial 7 months of the experiment. Patterns of weight change were identical in exposed (Fig. 2) and buried (Fig. 3) specimens of these species, although buried samples of *Keratoisis ornata* appeared to have undergone a greater degree of pitting than exposed samples (Fig. 4).

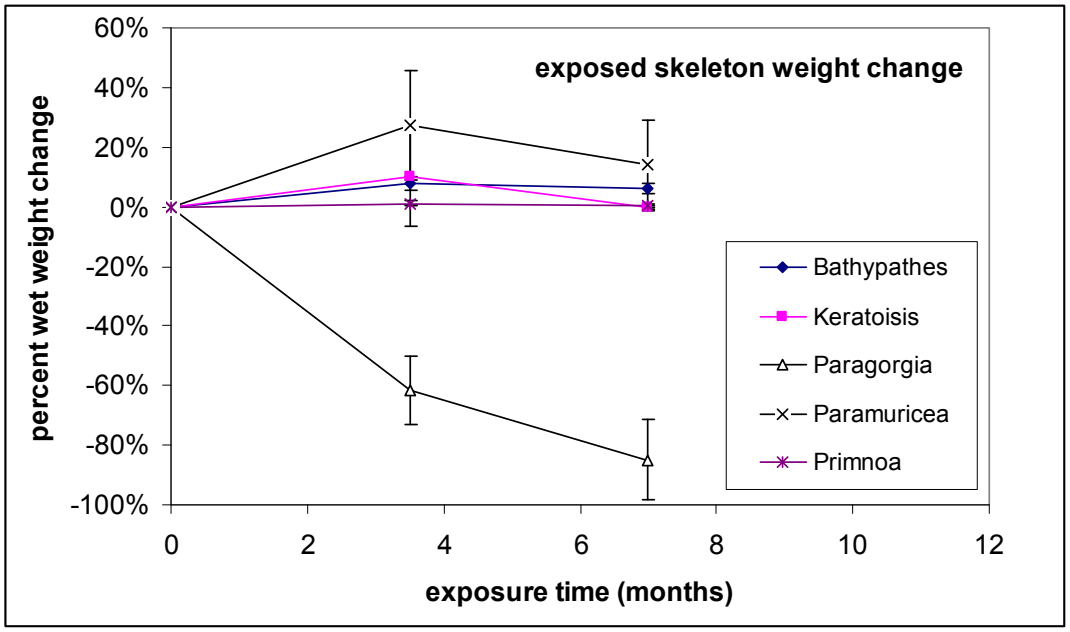

Figure 2. Percent weight change in exposed skeletal samples. N=5 in all cases. All *Paragorgia* samples were completely consumed after 7 months. Apparent weight gain in other species results from wet weight measurement in samples that were frozen and incompletely hydrated at the beginning of the experiment.

Gorgonian and antipatharian corals with dense, purely organic skeletons (*Paramuricea, Bathypathes*) both experienced slight, but significant, weight gain during the initial 7 months of the experiment. Weight gain was greater and more variable in *Paramuricea* than in *Bathypathes*, and was greater in exposed samples *Paramuricea* than in buried samples. As no biological encrustation was observed on samples of either species in either treatment, weight gain in these species was probably an artifact resulting from incomplete hydration of samples prior to recording initial weights. *Paramuricea* samples also swelled, increasing slightly in length and diameter from the initial deployment to removal.

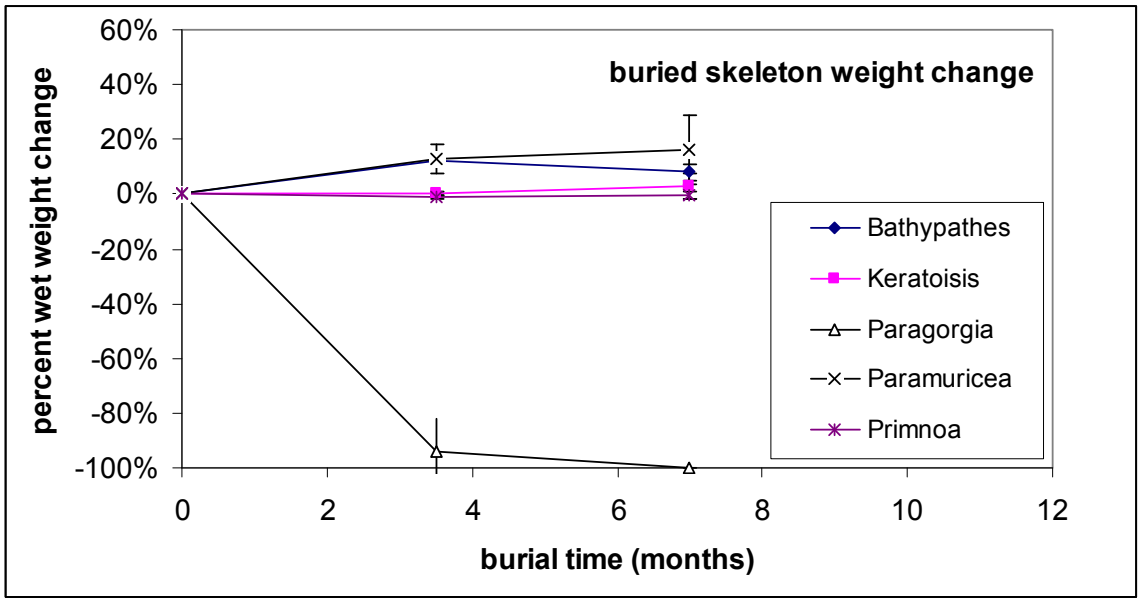

Figure 3. Percent weight change in buried skeletal samples. N=5 in all cases. All *Paragorgia* samples were completely consumed after 7 months. Apparent weight gain in other species results from wet weight measurement in samples that were frozen and incompletely hydrated at the beginning of the experiment.

Contrasting radically with the other experimental species, *Paragorgia arborea* experienced rapid weight loss in both exposed and buried treatments. Weight loss was more complete in buried treatments than in exposed treatments, at both time intervals sampled. After 3.5 months, exposed samples of *Paragorgia* were degraded down to spicules (Fig. 5) sometimes with a slight remnant of orange tissue on the outer surface of the coral. After 7 months, all buried samples of *Paragorgia* had completely disintegrated, as had most of the exposed samples.

Tissue degradation. Exposed tissues of all species were completely degraded within two months.

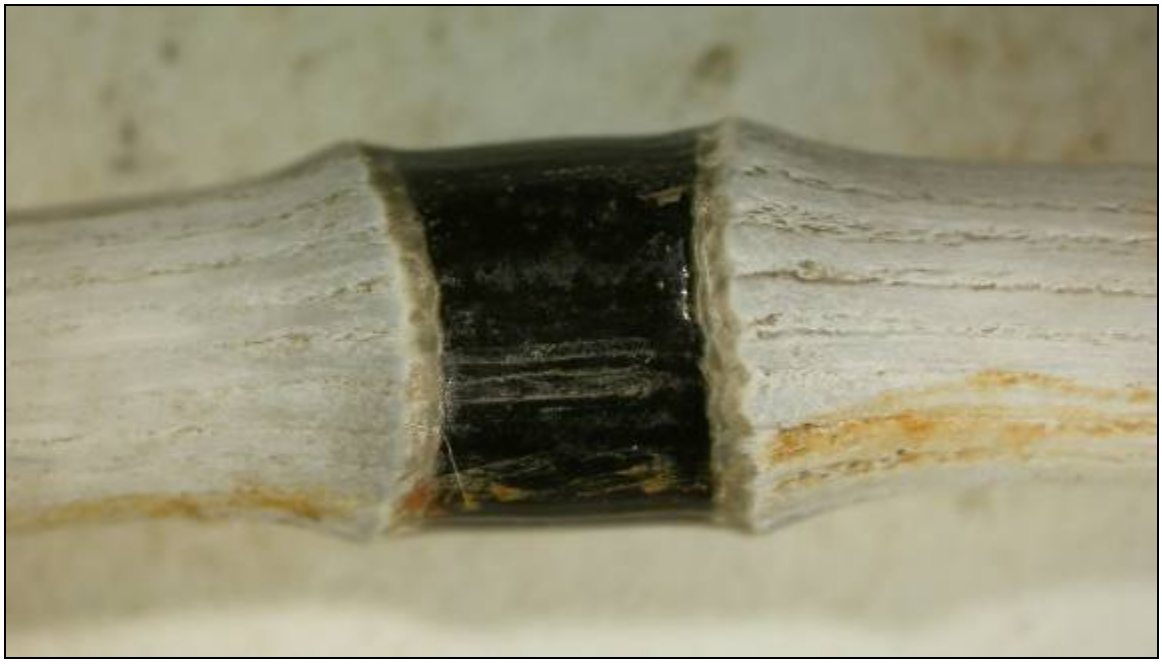

Figure 4. Chalky weathering, pitting, and iron-staining observed on buried skeletal fragment of *Keratoisis ornata* from taphonomy experiment. Diameter of organic node (black) is approximately 4 mm.

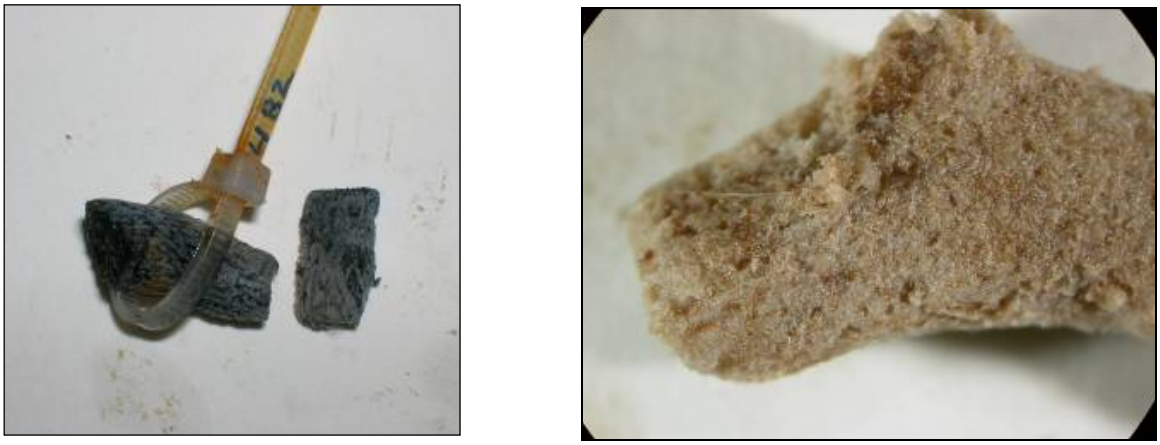

Figure 5. *Paragorgia arborea* experimental taphonomy samples. Left: Buried treatment degraded to friable spicule mass after 3 months. Dark discolouration results from burial in anoxic sediment. Right: Close-up of degraded spicule mass from exposed treatment after 7 months. Diameter approximately 1 cm.

FIELD OBSERVATIONS

Dead, chalky weathered samples of *Keratoisis ornata* were observed and collected at The Gully, the Stone Fence, and Haddock Channel, SWGB (Fig. 6). Slightly chalky dead *Primnoa* were also observed at the Gully. In some cases, heavily weathered dead corals were observed at greater depth than live corals, but most dead corals were found in the same areas as live corals. Dead and

decaying *Paragorgia arborea* were observed in The Gully, often with the upper portion of a broken-off colony live, but the lower portion dead (Fig. 7). When collection attempts were made of dead *Paragorgia*, the dead portions of the skeletons invariably crumbled within the jaws of the ROV manipulator arm, regardless of the grip strength. When the manipulator arm grasped live portions of the colony the skeleton was rigid and collectible.

Figure 6. Degraded, subfossil sample of *Keratoisis ornata* skeleton being collected by ROV manipulator arm from a deep portion (1827 m) of The Gully.

Figure 7. Broken and dying colonies of *Paragorgia arborea* (left, upper centre, and life colony of *Primnoa resedaeformis*, collected from the upper Gully (675 m). Dead portions of broken colonies were extremely fragile, and could not be gripped with ROV manipulator arms without breaking.

IMPLICATIONS FOR ASSESSING FISHING IMPACTS ON CORALS, AND EFFECTS OF PAST FISHING EFFORT ON CURRENTLY OBSERVED CORAL DISTRIBUTION AND ABUNDANCE

Skeletons, especially bases, of calcified gorgonians like *Primnoa resedaeformis* and *Keratoisis ornata* can persist on the sea floor for long periods of time, from centuries to millennia, although in high current settings they are likely to be exported downslope. In contrast, broken colonies of the non-calcite forming *Paragorgia arborea* are likely to be degraded to spicules within a matter of months, probably less than one year. Broken colonies of *P. arborea* resulting from fishing activities would be evident only if observed recently after the disturbance. Although the post-mortem duration of dense, consolidated organic skeletons, such as *Paramuricea* and *Bathypathes*, remains unknown, the results of weight loss experiments suggest that colonies of these two species should persist for years on the sea floor. Dead colonies of neither species were observed during the 2007 cruise.

Although *K. ornata* has been recorded by various trawl surveys surrounding Desbarres Canyon, in a more heavily trawled area on the SWGB, neither live nor dead colonies of *K. ornata* were observed in the three dives conducted in Desbarres Canyon. Dislodged colonies of the small gorgonian *Acanella*

arbuscula were observed, along with both upright and overturned *Acanthogorgia armata*. In addition, trawl scars were abundant, particularly at depths shallower than 600 m. The habitat in Desbarres canyon was generally similar to that in Haddock Channel, where abundant *Keratoisis* thickets were observed, but trawling intensity was lower, according to fisheries observer records of fishing effort (Edinger et al. 2007). The lack of *K. ornata* observations in Desbarres Canyon may result partly from the cumulative effects of intensive trawling for redfish, and other forms of bottom-contact fishing. Naturally broken corals were observed in the Gully, which is now protected from fishing, although older colonies were mostly exported downslope, while freshly dislodged or broken colonies were observed in areas surrounded by the same species of corals, suggesting minimal transport.

Processes of coral taphonomy likely limits the length of time that fishing-induced damage to deep-sea gorgonian coral habitats can be observed, particularly in high-current areas with strong numerical dominance of corals with spongy skeletons such as *Paragorgia arborea*.

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COMPARISON OF BOUNDARY LAYER CURRENT PROFILES IN LOCATIONS WITH AND WITHOUT CORALS IN HADDOCK CHANNEL, SOUTHWEST GRAND BANKS

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ABSTRACT

Deep-sea coral habitat was characterized in Haddock Channel, on the southwest slope of the Grand Banks, using two 2 mHz doppler current profilers. Instruments were deployed from CCGS *Hudson* using the ROPOS remotely operated vehicle. The profilers were deployed for 85 hours, at a depth of 700 m, beginning July 17th, 2007. The vertical profiling range was 4 m, with 1 m depth resolution, with a sampling frequency of 2.7 minutes. One instrument was placed in an area where bamboo corals (*Keratoisis ornata*) extended approximately 1 m in height and occurred at a density on the order of 1 colony per square meter. The second instrument was deployed 60 m away in an area containing no corals but having visually similar sea floor characteristics. Observed currents showed some evidence of tidal forcing but other processes clearly influence the current regime: speeds remained below 10 cm/s. Comparison of current profiles between the two sites indicated that the presence of bamboo coral modifies the boundary layer structure such that at a height of 1 m above the seabed, velocities are reduced by 13% compared to non-coral habitat.

INTRODUCTION

An important aspect in understanding the distribution of coldwater corals involves the characterization of coral habitat. Factors such as depth, available substrate, and food supply influence coral distribution. Ocean current regimes are also believed to play an important role in determining the suitability of coldwater coral habitat (Mortensen and Buhl-Mortensen 2004).

Corals occurring in the deep ocean are located in the benthic boundary layer. The boundary layer occurs due to the interaction of local currents near the sea floor with the sea floor topography. Essentially, the roughness of the sea floor creates drag or bottom friction which influences how currents near the bottom behave, i.e. reducing the speed of there currents or altering where they flow. In accordance with boundary layer theory the currents at the interface between the ocean and sea floor must have zero velocity (Kundu 2004). The boundary layer can extend between 5 and 20 m above the sea floor. Newfoundland and

Labrador coldwater corals are mainly distributed along the slope of the continental shelf (300-2000 m) where tidal interactions can create mixing events and turbulence within the bottom boundary layer (White 1994, Reidenbach 2006).

The presence or absence of such mixing events is important in determining the available food supply for coldwater corals. Coldwater corals themselves also modify the sea floor roughness. Thus it becomes important to characterize the structure of the local bottom boundary layer current regime in areas where coldwater corals are found.

The present study was conducted to characterize the local boundary layer currents in an area of Haddock Channel, southwest slope of the Grand Banks, which contained the large gorgonian coldwater species Bamboo Coral (*Keratoisis ornata).* Boundary layer characterization was carried out using two Nortek acoustic doppler current meters (ADCP) designed for deep water deployment. The goal is to determine if the presence of coral alters the boundary layer, and if so in what way.

METHODOLOGY

SITE DETERMINATION

Locations in Haddock Channel for the experiment were chosen based on earlier visual surveys by ROPOS during the 2007 Cruise. An area inhabited by Bamboo coral (Site 2) was chosen as the experimental site and a second area approximately 60 m away containing no coral (Site 1), but identified as suitable for coral habitation, was chosen as a control site.

DEPLOYMENT OF INSTRUMENTS FROM *CCGS HUDSON* VIA ROPOS

The ROPOS remotely operated deep water submersible was used to deploy two Nortek Aquadopp doppler current profilers (ADCPs) which were each attached to stainless steel platforms or 'settlement plates' as shown in Figure 1. Location, depth, and other deployment parameters are given in Table 1 below.

Table 1. Haddock Channel Deployment Parameters.

Site name and characteristics	Location (Lat. and Long.)	Date of deployment	Date of recovery	Depth (m)
Site 1 no coral present	N 44 49.8023 W 54 29.0484	July 17, 2007 17:10 UTC	July 21, 2007 17:24 UTC	707
Site 2 bamboo coral thicket	N 44 49.7639 W 54 29.1070	July 17, 2007 21:10 UTC	July 21, 2007 17:30 UTC	696

The ADCPs were configured for optimum data acquisition given the short term deployment. Table 2 below lists configuration parameters.

Table 2. ADCP configuration parameters.

Transducer frequency	Sample rate	Number of profile cells	Cell size	Deployment time *in situ*
2 mHz	Profile every 166 seconds (2.7 minutes)	8	1 meter	~ 85 hours

Figure 1. Settling plate with Nortek Aquadopp 2 mHz doppler profiler during initial fitting of the profiler at Oceans Science Center, Logy Bay. The settling plate is approximately 121 cm (48 inches) long, 45 cm (18 inches) wide, and 30 cm (12 inches) high.

DATA PROCESSING

The power spectral densities for all profile cells were plotted to help identify any periodic processes that are present in the velocity time series data. Figure 2 is a plot of the power spectrum of the velocity time series of beam 2, bin 3 for instrument 2. At frequencies greater than $3\times10^{-3}\,Hz$, the power spectrum has the spectral characteristic of white noise and the red spectrum characteristic of geophysical processes at lower frequencies. $3\times10^{-3}\,Hz$ was then used as a cutoff frequency for low-pass filtering of the velocity time series using a 3rd order Butterworth filter.

An unfiltered velocity time series in beam coordinates is shown in Figure 3 along with the same time series after application of the Butterworth filter for comparison. The values recorded by the doppler current profilers are components of the water velocities which are parallel to the axis of the acoustic beams hence the term beam coordinates. These velocities must then be resolved into U, V, W (East, North, Z) components by a coordinate transformation. Final velocity time series were sampled at 0.006 Hz with an uncertainty in the velocity of approximately 0.05 cm/s.

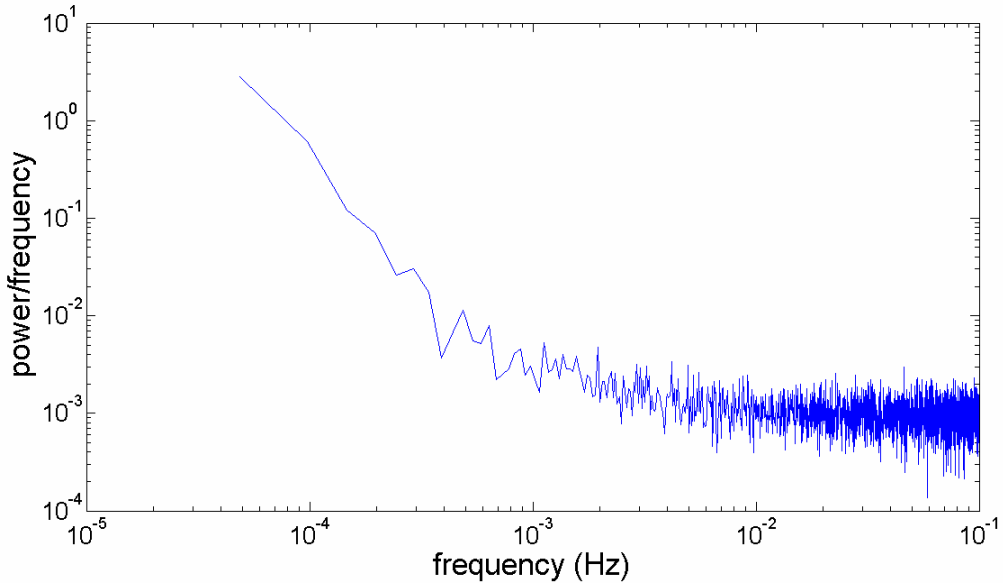

Figure 2. Power Spectrum of velocity time series: Beam 2, bin 3, instrument 2 (Site 2 - Coral Area).

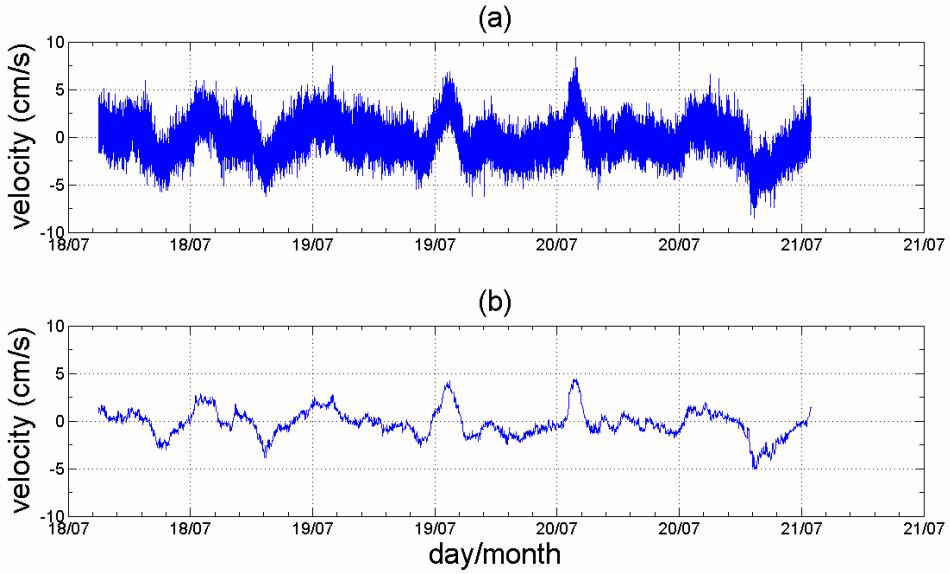

Figure 3. Time series of (a) unfiltered velocity profiles taken at site 2 (coral area) from transducer beam 1, profile bin 1 (1 meter above the instrument) and (b) same time series after filtering with Butterworth low pass filter cutoff frequency of $3\times10^{-3}\,Hz$.

TECHNICAL ISSUES

Battery voltage and data acquisition

The Nortek Aquadopp profilers used in the deployment were new and untested in this environment - deep water, low temperature, high duty cycle. Analysis of the onboard battery voltage record showed a voltage drop from 8.5 V at the time of deployment, to 8.1 V, approximately 40 minutes thereafter. The battery then showed some voltage recovery but approximately 78 hours after the initial battery drop the voltage began cycling between 8 and 8.3 V which was insufficient to maintain the original sampling rate. Profiles taken after the battery voltage began to fluctuate were subsequently removed from the data set. Based on personal communication with the manufactures it was determined that the low voltage is due to a combination of high duty cycle (short period between profiles) and low temperature (<10^{o}C). Essentially, the low temperature environment combined with a configuration for short term deployment and maximum data acquisition, resulted in insufficient time for the "cell chemistry to recover and avoid the excessive voltage drop." For future deployments using these instruments it is recommended that the sampling rate be decreased to mitigate the effects of the low temperature (~4^{o}C) environment on the battery voltage.

RESULTS

VELOCITY TIME SERIES

East (U) and North (V) time series for site 2 (coral area) are shown below in Figure 4.

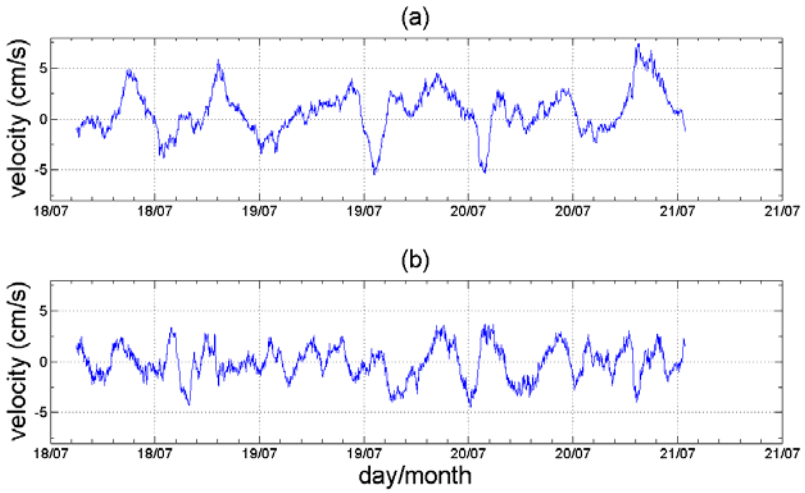

Figure 4. Time series of (a) East velocity for site 2 (coral area), the magnitude of observed velocities was between 0-10 cm/s, which is low compared with currents observed in other coral habitat (10-30 cm/s), evidence of tidal signals and non-linear processes is also identified, and (b) North velocity time series for site 2 (coral area).

MEAN VELOCITY PROFILE COMPARISON

Analysis of acoustic backscatter intensity from both instruments showed insufficient backscatter intensity from the upper four bins (5-8 m above the instruments). This meant that data for the velocity profile comparison was selected from only the lower four bins (1-4 m above the instruments). The data from the upper four bins may still be useful for analysis of other parameters such as suspended organic material.

Figure 5 is a comparison of mean boundary layer velocity profiles for sites 1 and 2. Mean velocity vectors for each of the four profile bins were rotated to point in the same direction as the mean velocity vector of bin 3 in order to compare their magnitudes as a function of height above the sea floor averaged over the entire deployment period.

Both profiles indicate decreasing velocity with depth as expected from boundary layer theory. However, the coral area (site 2) profile is significantly different from the non-coral area (site 1). Comparison of profiles between the two sites indicates that in this environment the presence of bamboo coral modifies the

boundary layer structure: at 1 m above the bottom velocities are reduced by 13% with the presence of coral relative to the area without coral.

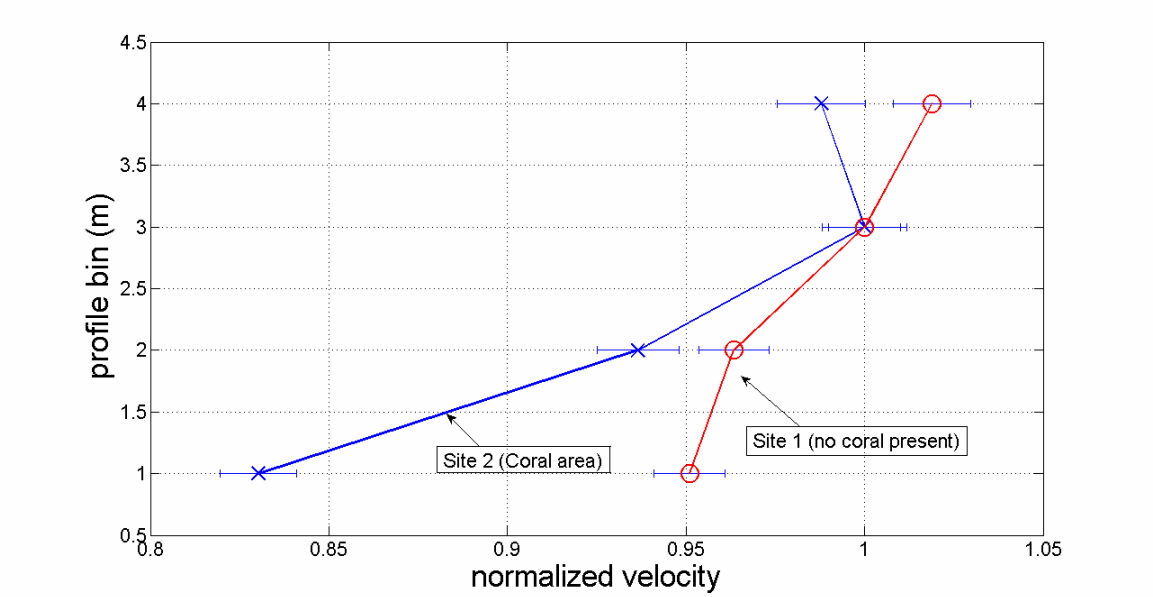

Figure 5. Mean velocity profile comparison for the coral area (Site 2, 'X') and non-coral area (Site 1, 'O'). The x axis is the velocity normalized by the bin 3 velocity. The y axis is the height above the profiler in meters.

CONCLUSIONS

The lack of suspended material in the water column may be responsible for the insufficient acoustic backscatter and reduced depth resolution (useful maximum profile height was 4 m above instrument as opposed to the optimal capability of 8 m). Local bottom current speeds were observed to be relatively low (5-10 cm/s) in this coral habitat compared with currents observed by researchers on board CCGS Hudson in other coral areas, e.g. the Gully, Stone Fence, etc. Most importantly, the presence of coral appears to be altering the local bottom boundary layer. Further analysis will include fitting observations to boundary layer theory and use of backscatter intensity data as a proxy for suspended organic material.

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CONCLUSIONS AND RECOMMENDATIONS

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CORAL DIVERSITY, DISTRIBUTION, AND ABUNDANCE

Results of coral distribution research show that only one species was common in shelf-depth waters: the nephtheid soft coral *Gersemia rubiformis*. All other coral species were restricted to the continental shelf edge and continental slope. Five broad areas of highest diversity and abundance of deep-sea corals were identified along the continental margin of Newfoundland and Labrador (Fig. 1). Proceeding from south to north:

(1) Southwest Grand Banks Slope (SWGB). In particular, the area surrounding Halibut and Haddock Channels contained the highest diversity of coral species per survey trawl tow, and hosts a unique habitat type. The area was characterized by low-current strength and thickets of golden bamboo coral, *Keratoisis ornata* and other associated corals, including *Acanthogorgia armata*, *Anthomastus grandiflorus*, and soft corals, which were observed living on scattered boulders derived from Pleistocene glaciomarine debris flows, referred to as "till tongues" (Piper et al. 2005, Edinger et al. 2007c). *Keratoisis* thickets on scattered boulders, surrounded by muddy sand, have not been observed at any of the important coral areas of the Scotian Margin, and do not apparently exist north of the SWGB. Quantification of coral densities in these *Keratoisis* thickets, based on video transect data, is ongoing, as is quantification of the relationships between corals and fish and other invertebrates.

Although habitat characteristics similar to those in Halibut Channel were observed in Desbarres Canyon, including trawl survey and observer records of *Keratoisis*, no live or dead *K. ornata* were observed in Desbarres Canyon during the 2007 ROPOS cruise. Rather, the gorgonian coral fauna in the Desbarres Canyon area was dominated by *Acanthogorgia armata* and *Acanella arbuscula*, with relatively rare

occurrences of *Radicipes gracilis* in deeper water. Sea pens were particularly diverse in the Desbarres Canyon area.

The southwest slope of the Grand Banks was one of three priority areas for coral conservation identified by Edinger et al. (2007a) based on the combination of high coral diversity and high rates of coral bycatch. A portion of the southwest Grand Banks slope has been protected by an interim (in effect to 2012) NAFO coral protection closure established in November 2007 in waters deeper than 800m in NAFO Div. 3O (see conservation measures, below).

(2) Flemish Pass. Flemish Pass contained moderate levels of coral biodiversity with high abundance of *Keratoisis ornata* and frequent occurrences of antipatharians, mostly *Stauropathes arctica*. Sponges were also highly abundant in Flemish Pass. Here, many of the areas with a high abundance of corals appear to have experienced relatively low levels of fishing effort, based upon European Union VMS data (Javier Murillo Perez, personnel communication, 2008). A significant gap in our knowledge of coral distributions exists on Flemish Cap, where most research trawl surveys are carried out by the European Union. An area of particular interest is the south side of Flemish Cap, which is steeply sloping and heavily incised with submarine canyons. One European NAFO scientist referred to this area as “untrawlable”, which gives it a high probability of being good coral habitat, and in good condition, if it has largely escaped trawling impacts to date.

(3) Northeast Edge of the Northeast Newfoundland Shelf. This region contained moderate levels of biodiversity, based on many records of large and small gorgonians and antipatharians from both DFO multispecies trawl surveys and the Fisheries Observer Program (FOP). The two most important sites within this area were Funk Island Spur (also known as Orphan spur, see Piper 2005), and Tobin’s Point. Orphan Spur appears to be a relict Pleistocene sand and gravel spit (Piper 2005), while Tobin’s Point lies along the shelf edge near the mouth of a shelf-crossing trough, Funk Island Deep (Shaw et al. 2006). A large *Paragorgia* colony was collected from Tobin’s point in DFO trawl surveys conducted in late 2006. Both sites appear to provide the gravelly substrates required to support populations of large gorgonian and antipatharian colonies. This was the second priority area for coral conservation identified in Edinger et al. (2007), primarily due to very high rates of coral bycatch identified by fisheries observers.

(4) Labrador Shelf Edge and Upper Slope. This area, located along the southeastern and central Labrador Shelf has a high diversity of corals of all types, with diversity in the region surpassed only by the southwest Grand Banks slope. Large gorgonian corals identified here are mostly *Paramuricea* and *Acanthogorgia*. Small gorgonians, especially *Acanella*

arbuscula, are also abundant. Large corals appear to be most abundant close to the mouths of shelf-crossing troughs, such as Hawke Saddle, Cartwright Saddle, and Hopedale Saddle (Wareham and Edinger 2007). In northern Labrador, Ogak Saddle appears to have a greater abundance and diversity of corals than surrounding areas. A number of corals other than *Gersemia* were recorded from the shelf-crossing troughs themselves, and not just where these troughs debouche on the continental slope. Coral distributions in these shelf-crossing troughs are likely to be influenced primarily by substrata and bottom temperature, with most corals requiring water temperatures above 0°C.

(5) Hudson Strait, between northern Labrador and Southern Baffin Island. This is the fourth and most important coral diversity and abundance hotspot in the region. This area was originally identified from DFO multispecies survey trawl and Observer Program trawl records as a Cape Chidley hotspot (MacIsaac et al. 2001, Gass and Willison 2005), but has since been shown to extend more or less continuously from the northern edge of Saglek Bank northward to the southeast shelf of Baffin Island (Wareham and Edinger 2007, Edinger et al. 2007a). This area has the highest recorded biomass of corals in survey trawls throughout the region, and is the only area with abundant *Primnoa resedaeformis* and *Paragorgia arborea* north of the Stone Fence off Nova Scotia.

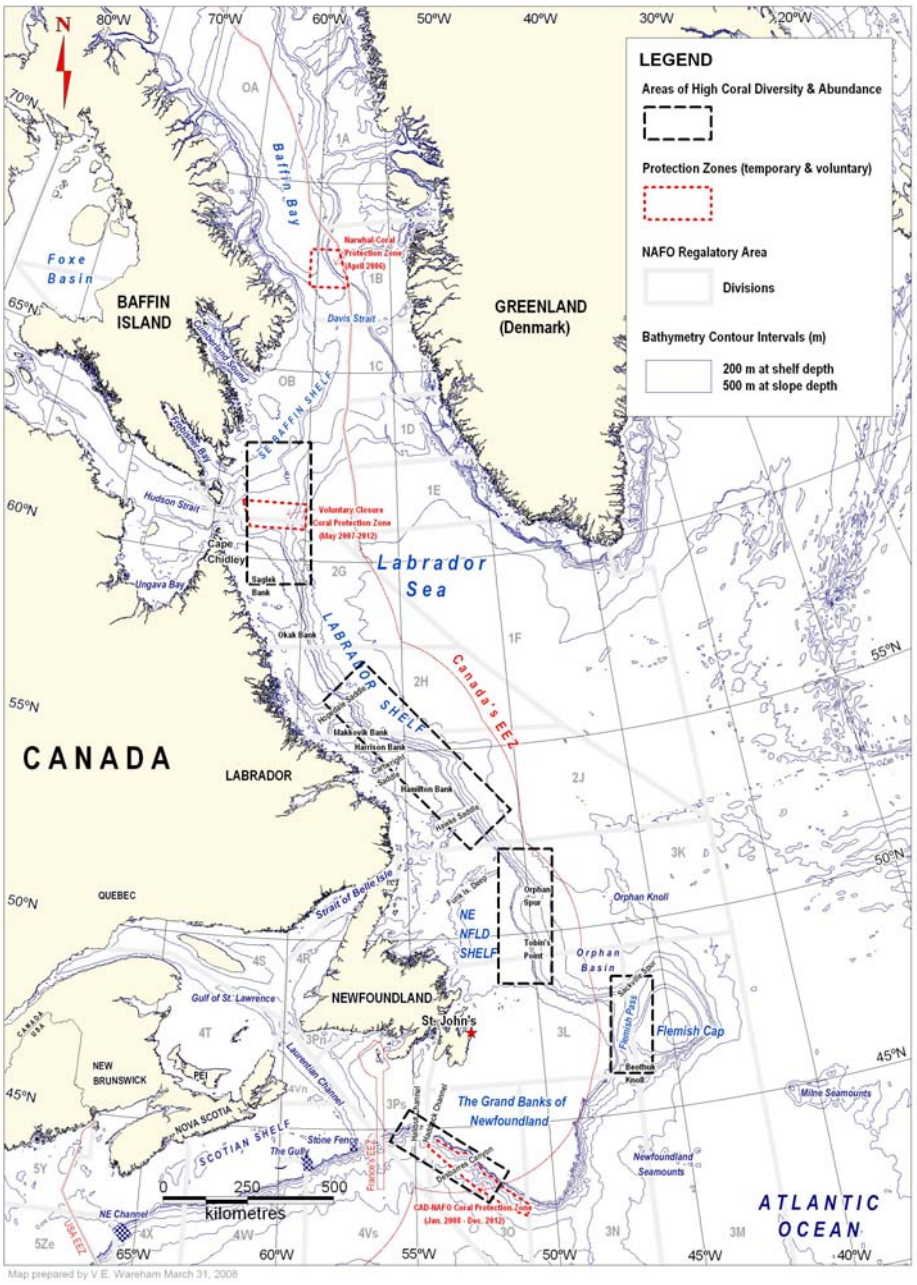

Figure 1. Areas of high coral diversity and abundance in the NL region.

Figure 2. Contents of an otter trawl set recovered after a 2-hour commercial trawl for Greenland Halibut in the Hudson Strait coral hotspot, May 2007. The pink colonies are all *Primnoa resedaeformis*; also visible are grey-white sponges. Bycatch of corals in this trawl tow was more than 500 kg. Photo credit: Harry Mercer, photo property of DFO.

Three factors probably contribute to the high abundance and moderately high diversity of corals recorded off Hudson Strait (Figs. 2 and 3). Hudson Strait has a high current regime, as Arctic through-flow water joins the Labrador Current. Hudson Strait also has an abundance of coarse substrates as a function of Quaternary geology: the Hudson Strait was one of the principal ice streams draining the Laurentide ice sheet, as recorded by abundant stacked tills between Cape Chidley, Labrador, and Resolution Island, Nunavut (McLean et al. 2001; Piper 2005). Finally, the deeper portions of Hudson Strait have experienced very little fishing pressure, as fishermen have avoided some portions of the strait due to gear damage. Several fisheries observers and former fishermen have commented that large gorgonian corals used to be common on the grounds between Cape Chidley and Resolution Island, but that large corals are no longer observed there, a likely consequence of intense shrimp trawling activity.

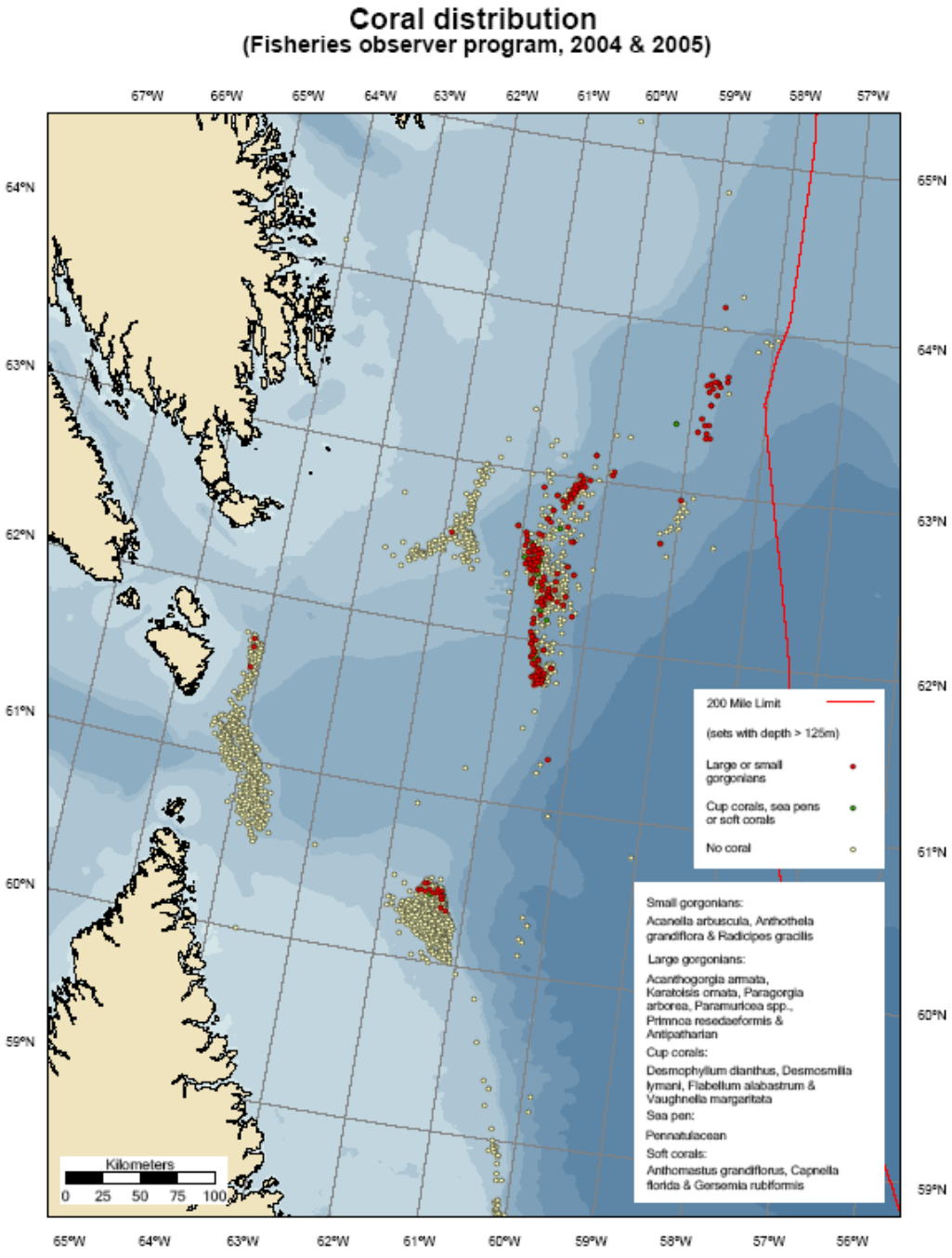

Figure 3. Map of coral bycatch patterns in the Hudson Strait area. The concentration of large gorgonian coral bycatch at roughly 60°N, 60°W, on the northern margin of Saglek Bank, had been previously identified as the Cape Chidley hotspot.(MacIsaac et al. 2001; Gass and Willison 2005). The large area without observer records centred around 61°30′N, 62°W indicates the largely untrawled area in Hudson Strait, with abundant *Primnoa resedaeformis* and *Paragorgia arborea*. This area has recently been the subject of a voluntary closure (MPA News 2007; see *Conservation Measures* below).

The Hudson Strait coral hotspot may represent the only remaining largely untrawled area on the continental shelf-edge and upper slope in the Newfoundland and Labrador region. Therefore, this area and other northern areas should receive the highest priority for conservation action. A voluntary closure announced by three commercial fishing organizations in May 2007 protects part of the Hudson Strait hotspot, but leaves most of the area open to continued fishing (see *Conservation Measures* below). It is also apparent that further refining of the definition of 'frontier areas', as it relates to fishing activity, is required to protect this area as well as others. The current use of the term appears to be too general and could lead to northern regions or deep-water areas being dropped from frontier area status due to even a very limited amount of fishing activity within large geographic regions, i.e. spatial scales of coral habitat and fishing activities need to be incorporated into a definition of "frontier area". This could be developed in connection with DFO's Sensitive Areas Policy.

CORAL-ASSOCIATED BIODIVERSITY

Biodiversity of invertebrates and fish associated with deep-sea gorgonian corals remains an active field of research worldwide including, more recently, the Newfoundland and Labrador region. Research to date has revealed statistical associations between corals and some species of commercial groundfish, and suggests that corals are likely to provide facultative habitat for groundfish and commercial invertebrates, especially juveniles, or at least improve habitat quality (Koslow et al. 2001; Stone 2006; Edinger et al. 2007b). Alternatively, statistical associations between groundfish and corals could be the result of shared habitat preferences for similar characteristics, but in the absence of direct biological interactions (Tissot et al. 2006; Edinger et al. 2007b). Analyses of *in situ* observations of fish and invertebrates in relation to corals from the SWGB 2007 ROPOS cruise are ongoing and these analyses will contribute to our understanding of these associations.

Qualitative viewing of *in situ* observations during the 2007 SWGB ROPOS cruise suggested stronger associations between corals and a number of rare fish species than associations between corals and commercial fish species. These observations support the argument that coral conservation should be promoted on the basis of the intrinsic value of the corals themselves and their contribution to deep-sea biodiversity, rather than potential links between corals and abundance of commercially-exploited groundfish (Auster 2005). It is noted that there is ample evidence elsewhere that many species of invertebrates are directly associated with deep-sea corals (i.e. living on or amongst corals) at various life stages (Buhl-Mortensen and Mortensen 2004, 2005).

Research on coral-associated biodiversity will be enhanced through the soon-to-be initiated Canadian Healthy Oceans Network (CHONe) research

program, to which DFO has committed in-kind support in the form of ship time. (see *Research Priorities* below).

CORAL BIOCHEMISTRY AND GEOCHEMISTRY

Analysis of lipid patterns in deep-sea corals found a lack of geographic or depth-related patterns, but significant inter-specific variation in major lipid classes. A finding of particular interest is the presence of very ancient types of storage lipids in a number of corals (Hamoutene et al. 2008), reinforcing the idea that the deep-sea is evolutionarily conservative (Jablonski and Bottjer 1990).

Stable isotope analysis of corals, used to infer the nature of food supply, similarly found a lack of major geographic or bathymetric trends in stable isotope composition of coral tissues, but significant inter-specific variation in both d15N and δ^{13}C. The interspecific patterns of δ^{13}C and d15N composition can best be interpreted as a consequence of differences in feeding habits controlled by environment, especially substratum and current strength (Sherwood et al., 2008, Deep-Sea Research I).

CORAL SCLEROCHRONOLOGY: GROWTH BANDING, GROWTH RATES, RADIOCARBON ANALYSIS, AND PALEOCEANOGRAPHY

Coral sclerochronology has been a major focus of laboratory research under the IGP corals project, with emphasis on coral skeletal banding patterns, coral growth rates and longevities, radiocarbon analysis of coral skeletons, and applications to paleoclimatology and paleoceanography. Annual growth banding had already been established in *Primnoa resedaeformis* (Sherwood et al. 2005), and was demonstrated in current research for *Keratoisis ornata*, *Acanella arbuscula*, and *Bathypathes arctica*. Growth bands in *Paramuricea* spp. were shown not to be annual, and the lack of growth banding in *Paragorgia* (Mortensen and Buhl-Mortensen 2005) was re-affirmed. Application of bomb radiocarbon analysis to these gorgonian and antipatharian coral species showed slow radial and linear growth rates, and that individual corals of each species can live for several decades to several centuries (Sherwood et al., submitted, CJFAS). Analysis of a population of *Primnoa* collected from a single trawl showed that the average maximum age of the corals collected in the Hudson Strait hotspot was approximately 40 years, even though *Primnoa* can live to an age of 700 years (Sherwood et al. 2006). The astonishing longevity of gorgonian corals is generally reiterated, indicating the long recovery time required for coral habitats following trawling or other anthropogenic disturbance. Age-stem diameter regressions are being developed for the most common gorgonian corals to allow estimates of population structure based on stem diameter observed in video. Age-height regressions are likely to be less reliable than age-stem diameter, due to the highly variable branching patterns observed in many coral species.

Bomb radiocarbon analysis of gorgonian coral skeletons along the geographic gradient Hudson Strait through the SW Grand Banks to the Northeast Channel (SE Scotian shelf) showed the striking contrast between Newfoundland and Labrador corals, consistently influenced by the Labrador current, and Nova Scotia corals, with more surface water influence of the Gulf Stream, and intermittent bottom-water influence of Antarctic Intermediate Water. Skeletal stable isotope and trace element analysis is more likely to reveal decadal-scale paleoclimatic or paleoceanographic trends on the Scotian shelf and slope, where various water masses change in their relative importance, than in Newfoundland and Labrador waters, where the dominance of the Labrador current, and Labrador Slope Water remains largely unaltered. Planned compound-specific stable isotope analyses of gorgonian skeletons should help to elucidate such patterns.

CONSERVATION MEASURES

Since the inception of the deep-sea corals IGP project, three significant conservation measures have been implemented for corals in the Newfoundland and Labrador region; two under the auspices of NAFO, and one voluntary closure established by the fishing industry. These include the protection of several seamounts, an interim coral closure off the SW Grand Banks, and an industry-sponsored voluntary closure in the Hudson Strait. These conservation measures complement existing measures in the Maritimes region (Northeast Channel coral conservation area, Sable Gully Marine Protected Area, and Stone Fence *Lophelia* conservation area; Breeze and Fenton 2007) and the Arctic region (Fisheries and Oceans Canada 2007).

In 2006, NAFO established protection of the Newfoundland Seamounts, Orphan Knoll, and waters below 2000 m depth in general, from fishing activities (NAFO 2006). An important caveat on this protection is the permission for experimental trawl fisheries of up to 20% of the fishable areas in each of these locations. Recent video observations showed that the impacts of the 1960s and early 1970s fishing activity on the Corner Rise Seamounts (New England Seamounts) is still evident, particularly in relation to deep-sea corals (Waller et al. 2007), and implies that the permission for experimental fisheries could lead to considerable destruction of corals, sponges, and other long-lived biogenic structures in these environments.

In September 2007, NAFO established an interim coral protection closure (~ 14,00 km^2) in NAFO Div. 3O, on the southwest Grand Banks slope, between 800 and 2000 m depth, in effect from 2008 through to 2012. This closure was established partly in response to Canada and NAFO's, UN General Assembly Resolution 61/105 (2006) commitments to preserve habitats for deep-sea corals (NAFO 2007). Unfortunately, because this closure is established only in NAFO Div. 3O, which straddles the 200-mile limit, it does not protect the highly

significant *Keratoisis* thicket habitats identified in the Haddock and Halibut Channels, which are located in NAFO Div. 3Ps. Furthermore, by adopting a depth-limited closure below 800 m, much of the most important rocky habitat for the longest lived gorgonian corals, which are most abundant at depths shallower than 800 m, is not protected. Comparison of the boundaries of the NAFO Div 3O closure with rates of coral bycatch in observed fisheries in 2004 and 2005 shows that the majority of the areas in which more than 25% of fishing sets recovered corals occur outside of the NAFO coral protection area (Fig. 4).

In May 2007, three fishing industry organizations, Groundfish Enterprise Allocation Council (GEAC), Canadian Association of Prawn Producers (CAPP), and the Northern Coalition (NC) announced a voluntary closure adjacent to Hudson Strait (MPA News, 2007) (Fig. 5). The boundaries of this 12,500 km^2 closure were determined through consultation with fishing captains, who indicated the areas they avoided in order to escape gear damage by hard rocky bottom characterized by abundant corals. This voluntary closure included many, but not all, of the 2006 Northern Shrimp Survey sets that contained very high quantities of coral bycatch. The voluntary closure does not include the previously identified Cape Chidley hotspot on the northern edge of Saglek Bank nor the area with high incidence of coral bycatch on the southeast Baffin Shelf. Later in May 2007, a commercial vessel fishing for Greenland Halibut trawled through this voluntary closure area and recovered more than 500 kg of corals, primarily *Primnoa resedaeformis*. The authors consider the voluntary closure inadequate in size and location. Since the first pass of a bottom trawl does the most damage to structure-forming biota (Koslow et al., 2000, Anderson and Clarke 2003, Rice et al., 2006), protection of ‘unfished’ (or marginally fished) coral habitat in northern frontier areas (and possibly coral-rich “spillover” areas), including Hudson Strait, should be a top priority

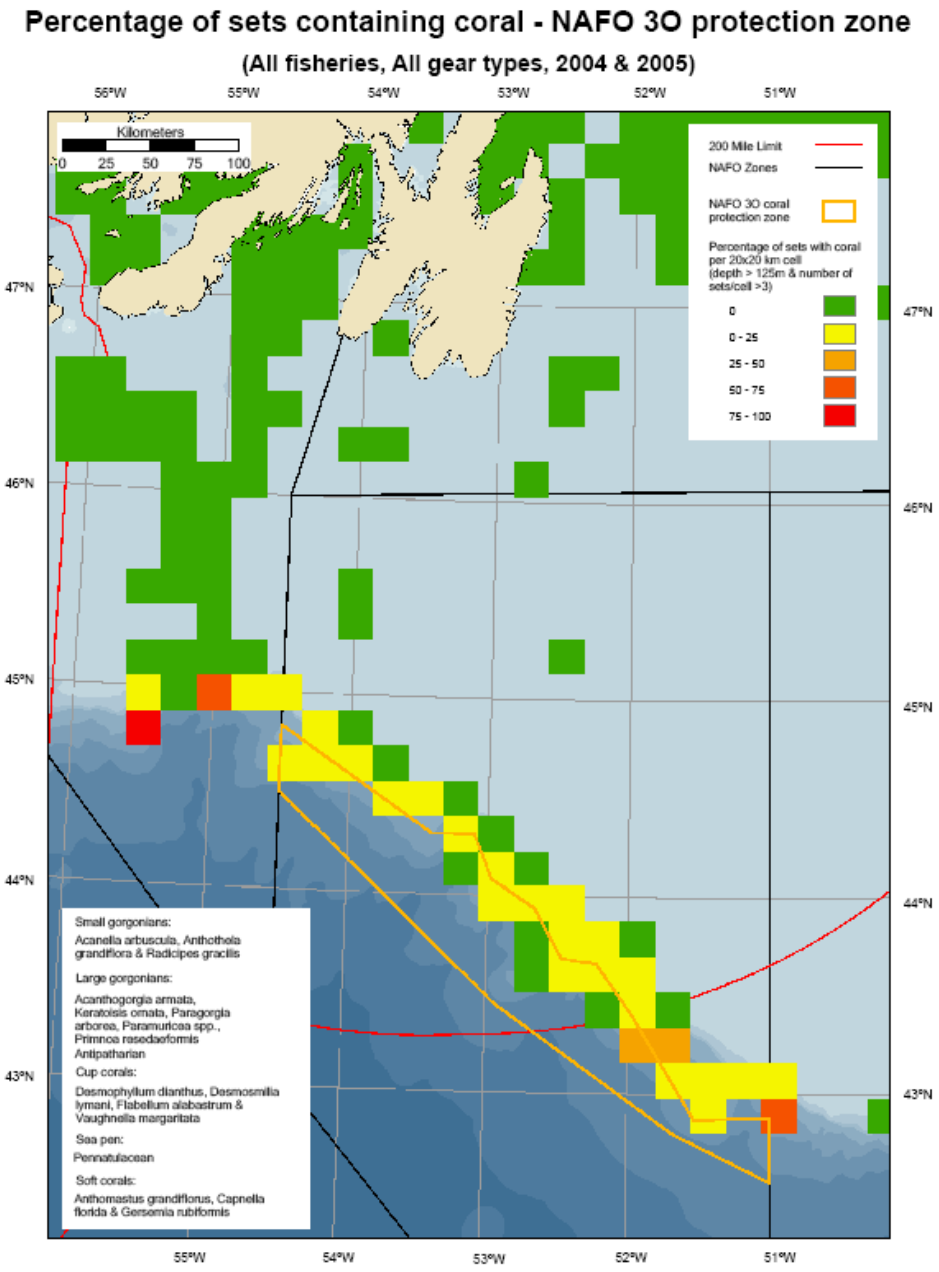

Figure 4. Position of NAFO Div. 3O coral protection area in relation to the percentage of commercial fisheries sets containing corals. Many of the most important areas for corals, especially in the Haddock and Halibut channels (NAFO Div. 3Ps, upper left) are not protected by this measure.

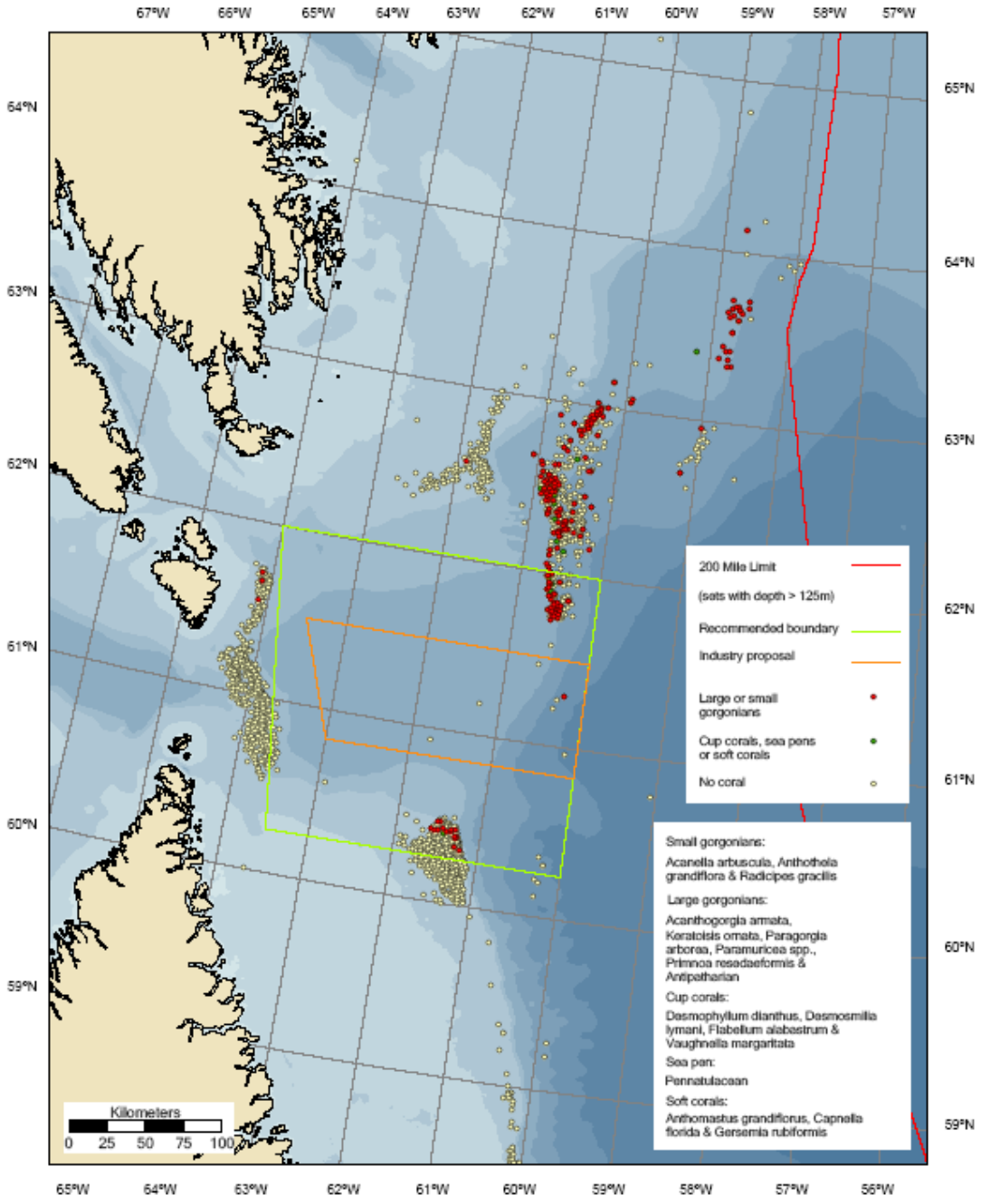

Figure 5. Boundaries of the 2007 Hudson Strait voluntary closure (orange line) in relation to 2004-05 coral bycatch (Edinger et al. 2007b). Also shown is minimum recommended closure to protect known coral hotspots in the Hudson Strait (green line).

RESEARCH PRIORITIES

FIELD STUDIES

Identified research priorities for deep-sea corals in the Newfoundland and Labrador region emerge primarily from coral distribution studies, including the coral diversity and abundance hotspots identified, and knowledge gaps on Flemish Cap, Orphan Knoll, and Newfoundland Seamounts.

IDENTIFIED CORAL DIVERSITY AND ABUNDANCE HOTSPOTS

1. Hudson Strait coral hotspot. *In situ* observations of the Hudson Strait coral hotspot is recommended as a high priority for research in the Newfoundland and Labrador region. A research cruise is currently being planned for the summer of 2009 using the CCGS *Amundsen*, with capabilities for multibeam sonar, acoustic sub-bottom profiling, and dedicated ROV deployment. Cruise objectives will include characterization of the geological basis of coral habitat in Hudson Strait, quantification of coral diversity and abundance and coral-associated biodiversity, and comparison of coral diversity and abundance between fished and unfished areas.

2. Southeastern Labrador slope and Northeast Newfoundland Shelf edge coral hotspots. *In situ* observations of the coral diversity and abundance hotspots along the continental slope of Labrador, from Makkovik Bank southward, and the shelf edge of the Northeast Newfoundland shelf, is the second recommended field research priority for corals in the Newfoundland region.

External research support for biodiversity-related research in these areas and the Orphan Knoll has already been approved through the Canadian healthy Oceans Network (CHONe) NSERC Strategic Network grant. DFO has committed to $100,000 in ship-time in support of this research in each of the next three years.

KNOWLEDGE GAPS: FLEMISH CAP AND SEAMOUNTS

1. Studies of corals on Flemish Cap and Flemish Pass, especially the steep and deeply incised south side of the Flemish Cap, is a third recommended field research priority for the Newfoundland region. Increased knowledge of these areas can be gained through greater cooperation with European Union fisheries research surveys and European Union fisheries observers. Ultimately, however, an ROV cruise for *in situ* observations of corals on the south side of the Flemish Cap will be required.

2. Orphan Knoll has been identified as a key target for deep-sea coral research since the first studies on paleoclimate records from *Desmophyllum cristagalli* (= *D. dianthus*) solitary corals from Orphan Knoll were published more than a decade ago (Smith et al. 1997). The debate continues over the geological origins of Orphan Knoll (Enachescu 2004). Attempts to recover corals from Orphan Knoll in 2004 using a rock dredge were unsuccessful. Limited multibeam data, and considerable seismic profiling data have already been collected for the Orphan Knoll by the Government of Canada (multibeam, for UNCLOS purposes) and by the offshore oil and gas industry. Research questions to be investigated during an ROV-equipped cruise to the Orphan Knoll would include: i) the possible role of cold-seeps and authigenic carbonate formation in supporting corals and coral habitat on the Orphan Knoll; ii) the composition, diversity and abundance of corals and sponges on Orphan Knoll, and, iii) the associated fish and invertebrate faunas.

3. Newfoundland Seamounts. While the New England Seamounts have been the focus of considerable exploration by researchers in the United States, the Newfoundland Seamounts have never been the subject of *in situ* investigations. Observer reports from experimental fisheries on the Newfoundland seamounts suggest abundant deep-sea coral populations. In addition, the extent of fisheries impacts on the Newfoundland seamounts remains unclear.

LABORATORY STUDIES

Ongoing research priorities for laboratory research on deep-sea corals include biochemical and geochemical analyses. Biochemical research priorities include fatty acid analysis to give precise indications of food sources (cf. Parrish et al. 2005). Geochemical research priorities include sclerochronology applied to paleoclimate and paleoceanography related questions. Time-series analysis of stable isotope composition in gorgonin, and elemental ratios in coral calcite or aragonite should be analyzed using secondary ion mass spectrometry (SIMS) (Cohen et al. 2002, Rollion-Bard et al. 2003).

RECOMMENDATIONS

RESEARCH

1. Fisheries and Oceans Canada should continue its significant commitment and support to deep-sea coral research in the Newfoundland and Labrador region, especially through ship time support for *in situ* investigations of coral habitats using ROV and drop video camera.

2. Now that a solid base of research on shelf and slope environments has been established, expanded research on continental shelf-break and continental slope environments should occur, as these are the environments where most of our corals and fishing activities co-occur. Top priority should be given to the Hudson Strait coral hotspot. Comparisons between continental slope and seamount environments will also be informative.

3. Fisheries and Oceans Canada should explore scientific collaborations with European Union and U.S. scientists for field research on the Flemish Cap and other areas. Access to coral distribution data and fisheries data for the Flemish Cap would greatly improve scientific knowledge and management capability. Increasingly, the importance of international research collaborations is being recognized as an important tool to share resources (e.g. funding, shiptime) and exchange information at basin scales. The recent TRACES (Trans-Atlantic Coral Ecosystem Study) initiative is an example of collaboration between Canada, the European Union and the US scientists.

CONSERVATION

1. *Keratoisis* thicket habitats in the Haddock and Halibut Channels (NAFO Div. 3Ps) should be protected from fisheries impacts.

2. *Primnoa*- and *Paragorgia*-dominated coral habitats in the Hudson Strait (NAFO Div. 0A) should be protected. The current voluntary closure established by the fishing industry should be expanded and made mandatory.

3. Conservation requirements/actions for the southern Labrador and northeast Newfoundland shelf edge areas should be investigated.

4. Fisheries and Oceans Canada should reconsider its policy on frontier areas, to discourage exploratory trawling in areas that are likely to be prime coral habitat (cf. Koslow et al. 2000).

ACKNOWLEDGMENTS

We would like to thank the many colleagues who contributed to making this three-year project a success. We especially thank the Newfoundland and Labrador DFO multispecies survey technicians and Offshore Observers for assisting in the collection of corals. We thank colleagues at the Bedford Institute of Oceanography, and in particular Dr. Ellen Kenchington, for contributing to make the 2007 ROPOS cruise a success. We thank George McGuire for his assistance in contracting outside sources of expertise. Reviews of this report by Nadine Templeman and Jason Simms are greatly appreciated. This project was funded by Fisheries and Oceans Canada and National Sciences and Engineering Research Council (NSERC).

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Appendix A

Biogeography, Biodiversity, and Reproductive Ecology of Deep-sea Corals

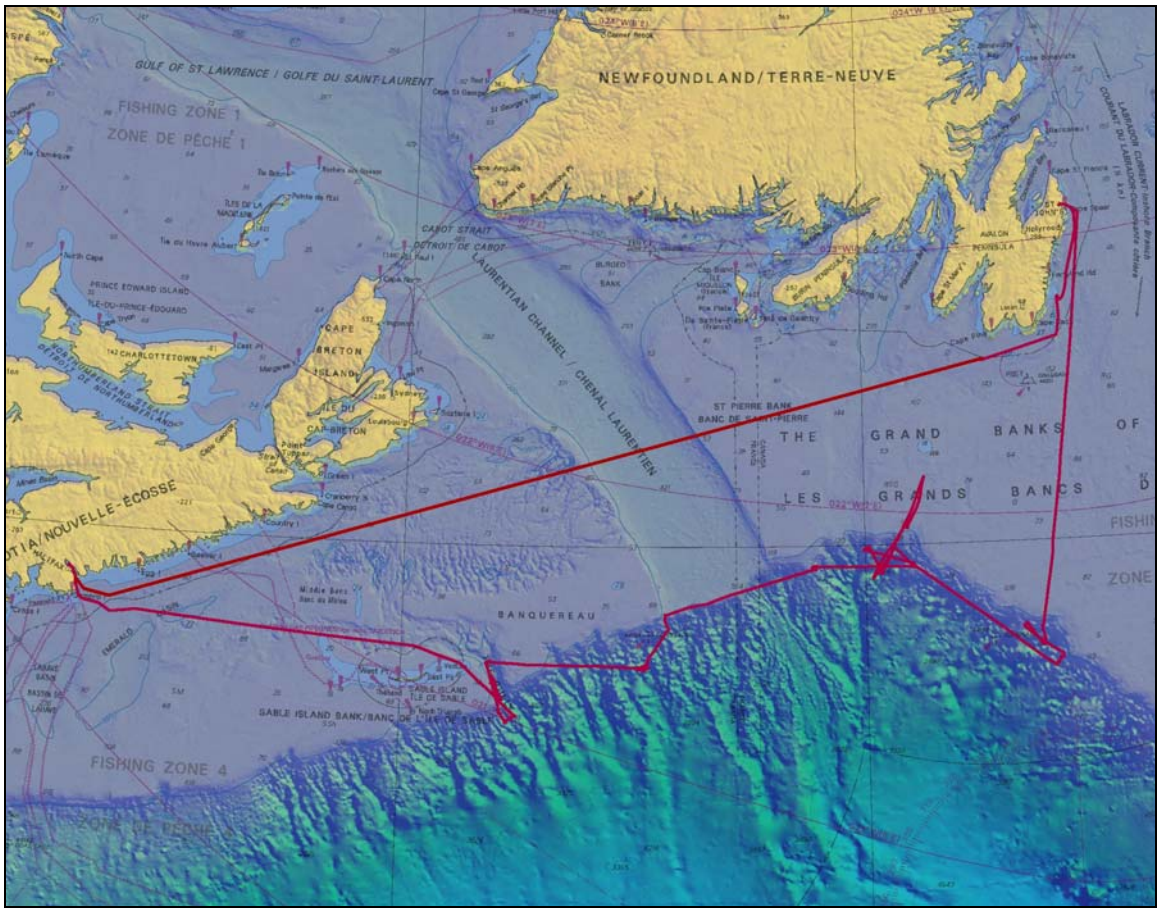
NSERC Discovery Ship Time Cruise Report
Fall 2007

A. Mercier, E. Edinger, P. Snelgrove and L. Zedel

Type of Cruise: Dedicated.
Dates: July 6-27, 2007.
Platform (vessel and submersible): *CCGS Hudson* and ROPOS (Canadian Scientific Submersible Facility, Victoria B.C.).
Portion of cruise funded by NSERC STAC: 5 days of 24-h ROPOS operation in the NL segment of the cruise (between July 15 and July 24, 2007).

Location of dive sites

Sable Gully (NS), Stone Fence (NS), Haddock Channel (NL), Desbarres Canyon (NL). Location of dives funded by NSERC STAC: Haddock Channel (NL), Desbarres Canyon (NL). See map of cruise track below:



Cruise Summary

This three-week cruise was funded by the DFO International Governance of High Seas Program (IGP, Newfoundland region), Science Branch and Oceans Branch of DFO Maritimes region, and by NSERC. Its general goal was to investigate the deepwater fauna of the continental slopes including several aspects of deep-sea corals (i.e., geological basis of their habitats, reproductive ecology, biodiversity associated with corals and coral habitats) in four regions of the Scotian Margin and Southwest Grand Banks (SWGB) of Newfoundland. Overall, the cruise was highly successful, and achieved most of its objectives, despite loss of several days to weather.

- **Total cruise length**: 17 operational days, 4.5 days steaming;
- **Length of NL segment**: 9 operational days (5 days partly funded by NSERC);
- **Days lost to weather in NL**: 2;
- **Number of dives planned in NL**: 11;
- **Number of dives fully completed in NL**: 8;
- **Dives missed/shortened due to weather or technical problems in NL**: 3.

General objectives for NSERC-funded portion of the cruise

1. Describe diversity and abundance of deep-sea corals in relation to habitat features in two locations on SWGB continental slope (Edinger, Gilkinson, Wareham);
2. Compare diversity and abundance of fishes in coral and non-coral habitats, and between canyons and ridges, on SWGB continental slope (Snelgrove, Baker, Gilkinson);
3. Compare diversity and abundance of infauna in coral and non-coral habitats (Snelgrove, Baker);
4. Compare diversity and abundance of megafauna in coral and non-coral habitats (Kenchington, Edinger, Wareham);
5. Collect long-lived skeletal corals for sclerochronology and taphonomy analysis (Sherwood, Edinger);
6. Collect deep-sea corals and return them live to Memorial University for studies of coral reproduction, development and settlement (Mercier, Sun);
7. Deploy experiments to assess recruitment of corals to rock and artifical substrates in coral and non-coral habitats (Snelgrove, Baker);

Funding allocation.

DFO Maritimes region provided ship time aboard *CCGS Hudson*, DFO IGP grant (NL region) covered ROPOS mobilization costs and 4 operational days, and NSERC STAC funded 5 of the 9 operational days scheduled for the NL region. DFO Maritimes Region also provided the technical expertise (refrigeration unit, data management, Multicorer) and staff for the entire mission.

Scientific staff

- Chief scientist: E. Kenchington (DFO);
- NSERC principal investigators on board: A. Mercier (MUN), E. Edinger (MUN);
- NSERC PIs participating from shore: P. Snelgrove (MUN), L. Zedel (MUN);
- DFO Collaborators: K. Gilkinson (DFO);
- Post-doctoral fellows: O. Sherwood (MUN);
- Graduate students: K. Baker (MUN), W. Fowler (MUN), Z. Sun (MUN), V. Wareham (MUN);
- Undergraduate students: L. Beazley (Dal), D. Ferguson (Dal), T. Jordan (Dal);
- DFO staff: L. Paon, R. Benjamin, S. Roach, B. MacDonald, A. Cogswell, K. Bentham, C. Bourbonnais-Boyce, K. MacIsaac (BIO), V. Wareham, N. Templeman (NAFC).

Of the principal investigators on the NSERC proposal, only Metaxas was unable to participate as planned. P. Snelgrove and L. Zedel, and graduate student Fowler, were unable to go to sea, however they sent experiments to be deployed, and/or directed sampling remotely via satellite link and/or graduate students.

Work accomplished and plan for scientific analysis

(1) Coral habitat characterization (Edinger):

The geological nature of coral habitat in the locations visited was investigated by visual examination of substrates, coupled with qualitative analysis of multibeam bathymetry lent by the Geological Survey of Canada in the Stone Fence and Haddock Channel.

Gorgonian corals in the Halibut and Haddock Channel area were mostly observed growing on or near cobbles and boulders on the ridges lying to the east and west of the channels. Feeder canyon thalwegs were typically composed of silty mud, while ridges were composed of muddy sand with pebbles, cobbles, and boulders. Our dive planned for the principal channel of Haddock Channel was cancelled due to weather, as were the intermediate depth dive (HC6, 1600-1000 m) and the final ridge dive (HC4, 1000-400 m).

Habitats in the Desbarres Canyon area generally had fewer cobbles and boulders than equivalent-depth habitats in the Haddock Channel area, and slopes were generally of lower gradient. Most of the sites below 700 m were muddy sand, with few or no boulders; boulders became more common at depths shallower than 600 m, many of the boulders in deeper depths had

colonies of *Acanthogorgia* growing on them, but boulders at shallower depths tended to be barren of corals.

(2) Coral diversity and abundance (Edinger, Wareham):

The most common large gorgonian in the Haddock Channel area was *Keratoisis ornata*, which invariably grew atop pebbles, cobbles, or boulders, mostly in the 800-500 m depth range. Colonies typically reached a maximum height of 1.5 m, and were usually clustered on rocks into open thickets, separated by muddy sand. The smaller gorgonians *Acanthogorgia armata* and *Acanella arbuscula* were common from 900-500 m, and became less common in waters shallower than 400 m. Sea pens were abundant and diverse in deep waters, with abundance apparently decreasing in shallower waters. Soft corals were most common in shallower waters, but occurred at all depths. Several species of solitary cup coral were observed, including *Flabellum alabastrum*, *F. macandrewi*, *Desmophyllum dianthus*, and an unknown cup coral. One individual of an antipatharian coral, probably *Stauropathes arctica*, was observed in the Haddock Channel.

The most common corals in the Desbarres Canyon area were a variety of sea pens and the smaller gorgonians *Acanthogorgia armata* and *Acanella arbuscula.* Although the larger gorgonian *Keratoisis ornata* was recorded in the Desbarres Canyon area in DFO trawl surveys, it was not observed on our ROPOS dives. The sea pens observed were: *Umbellula* sp., several Pennatulidae (including *Pennatula grandis* and *P. phosphorea*), *Funculinia quadrangularis*, *Anthoptilum grandiflorum*, *Distichoptilum gracile*, *Halipteris finmarchia*, *Kophobelemnon* sp. and an unidentified retractable species. Voucher specimens of sea pens were collected to be sent to Dr. Gary Williams of the Academy of Sciences for official classification. Shallower portions of the dives in the Desbarres Canyon area showed extensive trawl scours and other evidence of fishing disturbance, including overturned rocks, and *Acanella* corals uprooted and overturned lying on the sea bed.

(3) Long-lived coral skeleton collections (Sherwood, Edinger):

Approximately 40 colonies of long-lived coral species with growth rings and the potential to record oceanographic conditions were collected, including both live and dead colonies. Live colonies of *Keratoisis ornata* and *Acanella arbuscula* included a range of colony sizes with which to calculate regressions of age to stem diameter and colony size. Additional species collected included *Primnoa resedaeformis* (from Nova Scotia sites), *Paragorgia arborea* (also from Nova Scotia sites, for taphonomic analysis), *Desmophyllum dianthus* (from both Nova Scotia and Newfoundland sites), and an antipatharian coral, probably *Stauropathes arctica*. Many of the larger samples were dead bases of long-lived colonies of *K. ornata* and *P. resedaeformis*. Collection of a range of sizes of colonies would not be

possible by any means other than direct sampling with an ROV. Calculation of age to size regressions will allow estimates of gorgonian coral population structure.

(4) Biodiversity analysis of fish, infauna (Snelgrove, Baker, Gilkinson):

Fish transects were completed during all but one dive in Newfoundland waters. They were conducted as 1 km transects along contours every 200 m between 2200 and 500 m depths and along contours every 100 m in waters shallower than 500 m. Approximately, 29 fish transects were completed. Video will be analyzed to determine if additional, shorter transects can also be used from other portions of the dives. Although all fish identifications must be verified by video analysis, common species encountered included various macrourids, *Antimora rostrata*, *Harriotta raleighana*, *Sebastes sp*., *Pollachius virens*, and *Synaphobranchus kaupi*.

The results of these transects will be used to determine small scale changes in fish diversity and abundance in relation to coral, bottom sediments, bottom heterogeneity, depth, and overall region. These transects will also be used to quantify manmade debris in the deep-sea off Newfoundland.

(5) Infauna diversity and abundance (Snelgrove, Baker):

A total of 32 push cores were collected for analysis of infaunal diversity and abundance. These cores were collected during 13 dives in both Nova Scotia (n=9) and Newfoundland (n=23) portions of the cruise. The samples were sieved and preserved upon retrieval. Macrofauna will be sorted, identified and the results analyzed for changes in infauna diversity and abundance over various scales.

(6) Megafauna diversity and abundance (Edinger, Gilkinson, Snelgrove):

Quantitative and qualitative video data on large megafauna were collected as part of the fish transects, and as part of the explorer-collection mode of diving in the up-slope components of the dives between the fish transects. As megafauna observed did not appear different from those encountered on the Scotian Margin portion of the cruise, additional voucher specimens were not collected.

(7) Collection/maintenance of live coral and other invertebrates (Mercier, Sun):

Some collections of soft corals were made during the NS segment, although the method used (arm/claw) was found to be inappropriate (the specimens were crushed or otherwise damaged). Only 2 specimens of nephteid corals survived from that segment. While onboard, another sampling instrument was

designed with the help of the ROPOS staff. This “scoop” was much more efficient and allowed us to collect several healthy specimens during the NL segment. The claw was still used but only to collect small rocks on which corals grew. The samples included: 9 colonies of *Capnella florida* from 3 different locations/depths; 31 colonies of *Drifa glomerata* from 4 different locations/depths; 37 *Flabellum alabastrum* from 2 different depths on the same dive (i.e., 25 from ca. 950 m and 12 from ca. 600 m); 3 *Anthomastus*; 6 sea pens of various sizes; as well as 3 colonies of *Keratoisis*, 12 holothurians (*Mesothuria* sp.), 6 sea stars (*Tremaster mirabilis*), 8 sea urchins (*Phormosoma placenta*), and various other small invertebrates that were attached the main samples (brittle stars, worms, etc.).

While onboard, all the live specimens were maintained in a holding facility which consisted on 2 X 1000-L and 4 X 250-L covered tanks placed inside a refrigerated container. The two larger tanks were used as reservoirs; they were filled with ambient sea water and chilled to 3-5 °C on a regular basis, so as to provide a constant supply of cold sea water to the smaller tanks (on a flow-through basis). The 250-L tanks were subdivided with buckets and baskets to hold the various live specimens. The animals were transferred to our laboratories during the stopover in St. John’s, NL. All of them did well except for the holothurians and sea urchins, which were either dead upon arrival or died within the first 48 hours, most probably as a result of injuries or greater sensitivity to temperature variations.

Analysis has begun with the colonies of *Capnella* and *Drifa*. Some specimens were dissected to extract planula larvae, and to collect tissue samples for histology and confirmation of identification. Planulae were placed in culture and the settlement successfully studied on several occasions. More trials are planned in the next few weeks to compare colonies from different provenances/depths. Some of the colonies will also be kept alive to monitor natural planula release. The *Anthomastus* colonies were dissected and preserved for histological analysis (there were too few samples for any other type of study). The *Flabellum*, *Keratoisis*, sea pens and seat stars are being kept alive for further study; all of them are doing well.

(8) Current meter deployments for turbulence analysis (Zedel, Fowler):

Two Nortek Aquadopp 2 MHz current profilers were successfully deployed and recovered by the ROPOS remotely operated submersible operating from the *CCGS Hudson*. Following the experimental approach used by Reidenbach et al. (2006)[1], one instrument was deployed within a group of

[1] Reidenbach, M.A., S.G. Monismith, J.R. Koseff, G. Yahel, and A. Genin, 2006: Boundary layer turbulence and flow structure over a fringing coral reef, Limnol. Oceanogr., 51(5), 1956-1968.

Keratoisis ornata coral (individual corals observed were approximately 1-1.5 m in height) while the other was deployed approximately 60 m from that group in an area with similar bottom structure but lacking corals. Zedel and Fowler were not present on the cruise but were able to direct the placement of the current meters using a live video and voice feed through a satellite link: this was the first time ROPOS had been able to offer this capability. Both instruments were placed at a depth of 700 m and recorded data on station for 85 hours between July 17 and July 21, 2007. We had hoped for a longer deployment that would have allowed for characterization of the long term current regime but could not secure an acceptable recovery opportunity for the instruments. The short deployment has allowed us to optimize the data acquisition to pursue the cruise objective of characterizing the boundary layer in which corals occur: velocity profiles were acquired every 5 seconds for the duration of the deployment. This is the first deployment for this type of current meter in this environment and it was not known how well it would perform i.e. over what range the instrument would successfully recover data. Acceptable data was recovered to a maximum height of 4 meters above the bottom in 1 meter depth cells. Acoustic backscatter strength has also been recorded with this instrument and shows substantial variability; it is possible that this backscatter data can be interpreted as a proxy for changes in suspended organic matter concentration.

(9) Coral recruitment arrays (Baker):

Six settlement arrays (1 in NS, 5 in NL) consisting of 16 settlement surfaces (8 sponge and 8 rocks) were deployed during the cruise. Three were deployed in areas known to have corals and three were deployed in non-coral habitats. Efforts will be made to retrieve these arrays after 1 or 2 years. The results will be used to help determine if corals are not recruited to areas because of lack of substrate or other factors. Two of the arrays were deployed in the vicinity of current meters to aid in the future analysis of recruitment dynamics.

Problems encountered

Aside from the dives lost to weather or technical problems with the ROPOS, the only other major problem occurred with the multicorer, which was deployed on three occasions during the cruise. There was a recurrent mechanical problem with the unit which failed to trip and collect benthic cores. We were able to contact the manufacturer for advice and they advised us that the problem was not unique to us and that for successful sampling of some bottom types, modifications to the instrument would be necessary. We did make efforts between each deployment to circumvent the problem but these were unsuccessful and therefore no multicore samples were collected.

Plans for publication

Data described in (1) and (2) will be used to prepare two multi-author papers: the first will describe the surficial geology of coral habitats in the Gully, Stone Fence, Haddock Channel, and Desbarres Canyon; the second will document coral diversity and abundance on the southwest grand banks sites, including the habitat characteristics of the individual coral species observed.

The data/samples described in (4), (5) and (9) will comprise a portion of the PhD thesis of Krista Baker, who will analyze the samples and video over the next 18 months. The data from push cores will be combined with similar types of data collected during a Hudson cruise in 2006 to compare diversity patterns over multiple geographic scales. These results will form the basis for a manuscript to be submitted to an international journal such as *Deep-Sea Research* or *Marine Ecology Progress Series*. The data from fish transects will also be analyzed over the next 18 months with the objective of preparing a second manuscript for an international, peer-reviewed journal. The coral settlement arrays will only provide useful data once they are recovered and it is therefore difficult to predict if and when that will happen given that there are currently no cruises planned to that region. The arrays will therefore be recovered and analyzed as opportunity permits.

Data gathered in (6) will be compiled into a paper on megafauna diversity and abundance, in relation to habitat characteristics and coral abundance, in conjunction with the Nova Scotia leg of the cruise.

The soft coral data/samples described in (7) will comprise a portion of the MSc thesis of Zhao Sun. Data on fecundity, planula settlement and polyp survival/growth will be compiled and compared between species. This will complement data already gathered using live, preserved and frozen samples from previous expeditions. The aim is to understand and compare the reproductive strategies and the development/settlement processes of 3 or 4 species of corals. Such an extensive study of live specimens allowing behavioural monitoring and the culture of larvae and juveniles as never been reported thus far. The results will be published in the appropriate peer-reviewed journals and presented at international conferences over the next 12-18 months.

For the data described in (8), velocity time series will be analysed to determine velocity structure with depth and to identify spectral content. This data will tell us how much the bottom boundary is mixing the water and will give us some idea of the volume of water (and therefore food) sampled by the corals. The instruments also measure acoustic backscatter which will be proportional to the concentration of suspended material in the water: we will look for any significant time structure in this data. We will compare the data between the two instruments to see if the corals perceptibly alter the flow.

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APPENDIX B
PRODUCTS OF RESEARCH

PUBLICATIONS

Science Journals

Edinger, E.N., V.E. Wareham and Haedrich, R.L. 2007. Patterns of groundfish diversity and abundance in relation to deep-sea coral distributions in Newfoundland and Labrador waters. Bull. Mar. Sci. 81, Suppl. 1: 101-122.

Hamoutene, D., T. Puestow, J. Miller-Banoub and Wareham, V. 2008. Main lipid classes in some species of deep-sea corals in the Newfoundland and Labrador region (Northwest Atlantic Ocean). Coral Reefs 27: 237-246.

Sherwood, O.A. and Edinger, E.N. 2009. Ages and growth rates of some deep-sea gorgonian and antipatharian corals of Newfoundland and Labrador. Can. J. Fish. Aquat. Sci. 66: 142-152

Sherwood, O.A., E.N. Edinger, T.P. Guilderson, B. Ghaleb, M.J Risk and Scott, D.B. 2008. Late Holocene radiocarbon variability in Northwest Atlantic slope waters. Earth and Planetary Science Letters 275: 146-153.

Sherwood, O.A., R.E. Jamieson, E.N. Edinger and Wareham, V.E. 2008. Stable C and N isotopic composition of cold water corals from the Newfoundland and Labrador continental slope: examination of trophic level, depth, and spatial effects. Deep-Sea Res. I 55: 1392-1402.

Wareham, V.E. and Edinger, E.N. 2007. Distributions of deep-sea corals in the Newfoundland and Labrador region, Northwest Atlantic Ocean. Bull. Mar. Sci. 81, Suppl 1: 289-312.

Reports

Edinger, E., K. Baker, R. Devillers and Wareham, V. 2007. Cold-water corals off Newfoundland and Labrador: distributions and fisheries impacts. World Wildlife Fund Canada, Toronto, 41 p.+map CD.

Hamoutene D., Burt K., Samuelson S., Wareham V. and Miller-Banoub, J. 2008b. ATP and Protein Data in Some Species of Deep-Sea Corals in the Newfoundland and Labrador Region (Northwest Atlantic Ocean). Can. Tech. Rep. Fish Aquat. Sci. 2801

Mercier, A. and Hamel, J-F. 2008. Voyage to the slope of the deep dark sea. Canadian Geographic, April 2008.

CONFERENCE ORAL PRESENTATIONS/ ABSTRACTS/POSTERS

Presented

Edinger, E.N., Sherwood, O.A., Gilkinson, K.D. and Wareham, V.E. 2007. Geological basis of deep-sea coral habitat in Atlantic Canada. 17th Canadian Paleontology Conference, St. John's, NL, Sept. 2007. Poster presentation.

Edinger, E.N., Sherwood, O.A., Gilkinson, K.D., and Wareham, V.E. 2008. Geological Basis of Large Gorgonian Coral Habitat in Atlantic Canada. at 9th international GEOHAB meeting: Geological and biological marine habitat mapping. Sitka Alaska, 28 April-1 May, 2008. (Oral presentation).

Fowler, W. 2008. Boundary layer velocity structure in a cold-water coral area of Haddock Channel, Southwest Grand Banks. ASLO summer meeting, June 8-13, 2008, St. John's, NL. Oral presentation.

Jamieson, R.E., Sherwood, O.A., Edinger, E.N. and Wareham, V.E. 2008. Carbon and nitrogen stable isotope composition of deep-sea corals from offshore Newfoundland and Labrador. ASLO summer meeting, St. John's, NL, June 2008.

Sherwood, O.A. and Edinger, E.N. 2007. Bamboo corals (*Keratoisis ornata*) from the Northwest Atlantic: growth rates, radiocarbon variability, and a new archive of Holocene Paleoclimate. 17th Canadian Paleontology Conference, St. John's, NL, Sept. 2007. Poster presentation.

Sherwood, O.A., Edinger, E.N., Risk, M.J., Scott, D.B., Ghaleb, B. and Guilderson, T. 2007. Late Holocene radiocarbon variability in northwest Atlantic slope waters. American Geophysical Union Annual Meeting, San Francisco, Dec. 2007. Poster presentation.

Sherwood, O.A. and Edinger, E.N. 2008. Ages and growth rates of some deep-sea corals of Newfoundland and Labrador. ASLO summer meeting, St. John's, NL, June 2008. Poster presentation.

Sun, Z., Hamel, J.-F. and Mercier, A. 2008. Settlement preferences and planula behaviour in deep-sea soft corals. ASLO summer meeting. June 8-13, 2008, St. John's, NL. Poster presentation.

Sun, Z., Hamel, J.-F. and Mercier, A. 2008. Reproductive cycle of the deep-sea coral, *Drifta glomerata*, (Octocorallia: Alcyonacea), in the NW Atlantic. 11th

International Coral Reef Symposium (ICRS), July 7-11, 2008, Fort Lauderdale, Florida, USA. Oral presentation.

Sun, Z., Hamel, J.-F. and Mercier, A. 2008. Planula release, settlement, metamorphosis and growth of deep-sea soft corals. 11th International Coral Reef Symposium (ICRS), July 7-11, 2008, Fort Lauderdale, Florida, USA. Poster presentation.

Wareham, V.E., J.R. Firth and Beazley, R. 2007. Utilization of fisheries observers in mapping the distribution of deep-sea corals in the northwest Atlantic. Proceedings of the 5th International Fisheries Observer Conference Victoria, BC, Canada 15-18 May, 2007. Edited by T.A. McVea, and S.J. Kennelly.