

Cold-water coral habitats of Rockall and Porcupine Bank, NE Atlantic Ocean: sedimentary facies and benthic foraminiferal assemblages

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ABSTRACT

A facies model is presented for the various environmental settings presently encountered on and around carbonate mounds of Rockall and Porcupine Bank, which may be used for reconstruction of fossil coral habitats and carbonate mound development from long sediment cores. The model is based on detailed sedimentological and micropaleontological analyses of recent sediment, in combination with analysis of available multibeam bathymetric data and underwater camera footage. Our data show that a first distinction – of on-mound environments with variable coral cover, off-mound areas covered with recent mobile sediment, and relict glacial sediment – can be based on grain size distributions in combination with calcium carbonate content of the $<63\ \mu\text{m}$ fraction, even if the coral aragonite has disappeared due to downcore dissolution. Benthic foraminifera proved to be the key to distinguish different on-mound environments: hardgrounds, coral debris, isolated corals, and patchy and dense coral covers. The distribution of foraminifera is mainly related to substrate, which is governed by the presence or absence of corals and current speed. Lead-210 profiles predominantly reflect diffusive biological mixing down to 5-10 cm depth, and show that fine sediment is preferentially deposited on-mound.

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1 Introduction

1.1 Background and objectives

Cold-water coral ecosystems occur widely in all ocean basins. However, only recently have advanced acoustic mapping techniques and small submersibles revealed the spatial extent and richness of these hidden ecosystems (Freiwald et al., 2004; Roberts et al., 2006). Although they do occur globally, the available data suggest that cold-water coral mounds are most prolific along the eastern margin of the Northern Atlantic, extending from Norway to the Gulf of Cadiz (Freiwald et al., 2004). The occurrence of cold-water corals *Madrepora oculata* and *Lophelia pertusa* in the Rockall Trough area were already described in the 19th century (Thomson, 1873). However, the sheer size and expanse of the mounds off western Ireland were unknown until Hovland et al. (1994) described groups of seabed mounds appearing on bathymetric soundings and seismic images.

The mounds generally occur within a depth range of 500-1000 m (De Mol et al., 2002). The largest mounds are almost 400 m high and span several kilometers at their bases (Van Weering et al., 2003; Mienis et al., 2006). The crests of the mounds, and to a lesser extent the slopes, are covered by the common scleractinian coral species *L. pertusa* and *M. oculata*, which are the main framework builders. The frameworks provide a habitat to a diverse fauna including sponges, hydroids, mollusks, echinoderms, brachiopods, bryozoans, and ascidians. The mounds grow by the accumulation of locally produced skeletal debris and entrapment of settling pelagic material (Mienis et al., 2009; De Haas et al., 2009). Coral cover is generally patchy, and open spaces and dead corals are infilled mainly with coral debris, foraminiferal sand and carbonate mud (Akhmetzhanov et al., 2003; Van Weering et al., 2003). The seabed surrounding coral mounds consists of foraminiferal ooze or relict glacial sediments. The sand is often rippled and at the shallow upper slope of the SW Rockall Trough large

sand waves are present (Mienis et al., 2006). In many locations along the NW and SW Rockall Trough margin, the seabed is littered with dropstones, which are often also present at the base of mounds and in intramound areas (Mienis et al., 2006; Wheeler et al., 2007). The glacial dropstone pavement is part of a coarse-grained lag deposit of usually only a few cm thick, resting on top of stiff glacial silty clay (Howe et al., 2001). In off-mound areas as well as on mounds, hardgrounds are observed locally. In the present environment dropstones and hardgrounds often provide a suitable substrate for corals to settle.

The global distribution and diversity of cold-water coral mounds seem to be primarily related to carbonate chemistry and the aragonite saturation depth in particular (Guinotte et al., 2006; Roberts et al., 2006). Their occurrence is furthermore limited to deeper water with temperatures between 4-12 °C, conditions which in the North Atlantic occur down to 1000 m depth (Rogers, 1999; Roberts et al., 2006). As light does not penetrate at these depths, cold-water corals do not rely on photosymbionts for energy supply. Instead, these corals depend on filter feeding and are restricted to nutrient-rich zones in relatively low oxygen environments (Rogers, 1999; Freiwald, 2002). This explains why cold-water corals generally settle in areas where currents or downwelling provide nutrients and reduce sediment deposition (Freiwald et al., 1997; Rogers, 1999; Kenyon et al., 2003).

Presently, in the Rockall Trough area the most favorable conditions for coral growth and buildup of carbonate mounds seem to be found on Rockall Bank. Underwater camera surveys demonstrated that mound crests in this area are densely covered with corals. The mound slopes typically show a more patchy coral cover and much reduced Holocene sedimentation rates. In between the mounds, wide areas are covered with relict glacial sand littered with ice-rafted stones and boulders, indicating a lack of recent sediment deposition. At the loci of most prolific coral production, average Holocene sedimentation rates determined in sediment cores are in the order of 10 cm/ka, and recent sedimentation rates in the order of 25 cm/ka (Mienis et al., 2009). However, average long-term accumulation rates are an order of magnitude lower, about 1 cm/ka (Mienis et al., 2009). Evidence from piston cores covering the Holocene and

latest Pleistocene suggests that periods of optimum growth may have alternated with periods of non-deposition, erosion and hardground formation. These features are often attributed to glacial periods, when carbonate production was reduced or absent (Dorschel et al., 2005; Van Weering et al., 2003). The reduced coral growth has been related to a lower supply of organic material and changing currents during glaciation (Rüggeberg et al., 2007). However, it has also been shown that coral growth can be significantly reduced or cease in interglacial periods, which leads to infillment of the coral framework or erosion. These processes have been related to changing environmental or oceanographic conditions (Dorschel, 2003; Huvenne et al., 2005). At present there is no general consensus about the causes of reduced mound growth in the Rockall Trough area, and whether these occurred randomly through time or were related to distinct climatic stages.

These questions may be resolved through detailed study of long sediment cores from carbonate mounds. Crucial in such studies is a proper interpretation of sedimentary facies in terms of the original depositional environments they represent. Here we present a comprehensive facies model encompassing the various environmental settings presently encountered on and around carbonate mounds of Rockall and Porcupine Bank. The model is based on detailed sedimentological and micropaleontological analyses of box cores collected from Rockall and Porcupine Bank, in combination with analysis of available multibeam bathymetric data and underwater photos. Since the corals dominating the living community appear to suffer severely from post-mortem destructive processes (Mienis et al., 2009), benthic foraminifera, which are ubiquitous in carbonate mound sediments, were studied and evaluated as alternative proxies for habitat reconstruction.

1.2 Regional setting

Rockall and Porcupine Bank form part of the broad and strongly fragmented continental margin extending westward of Ireland and the British Isles. The margin is characterized by the presence of several large banks, separated by troughs that are generally 500-2000 m deep. This bottom topography resulted from rifting and crustal

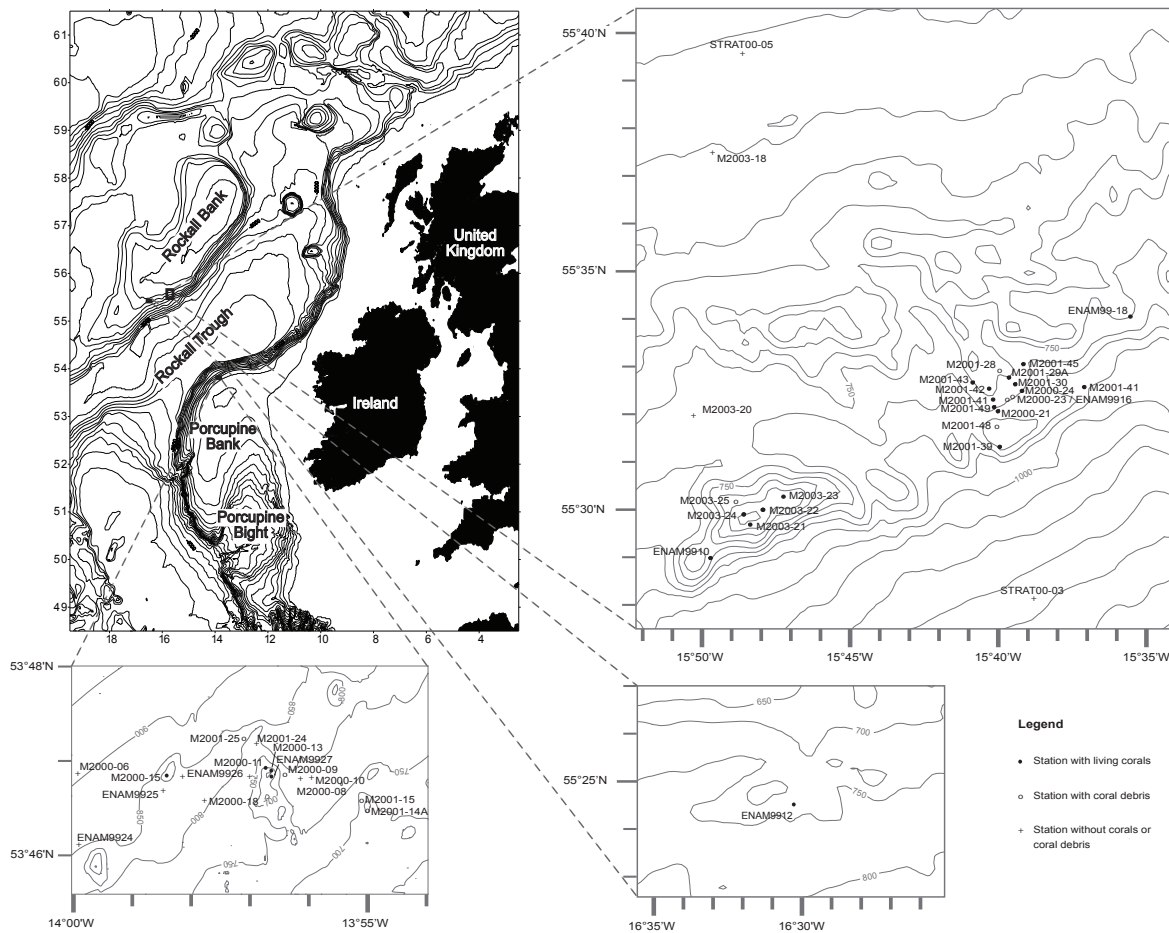


Fig. 1. Map of the Rockall Trough margin with sampling locations indicated. Depth contours are in meters.

extension accompanying the opening of the North Atlantic Ocean, which initiated in the Mesozoic (Doré et al., 1999). Foundering of the Rockall Trough in the Cenozoic isolated the Faroe-Rockall Plateau, constituting the outer part of the margin facing the Atlantic Basin, from the interior part of the margin connected to the British-Irish landmass (Boldreel and Andersen, 1998). Rockall and Porcupine Bank are located on opposite sides west and east of the Rockall Trough (Fig. 1). Rockall Trough is approximately 2 km deep in the northern part. In the SW, west of Great Britain and Ireland, it deepens to about 3 km. Further south the trough extends down to the Porcupine Abyssal plain at nearly 5 km depth.

The basement of the basins consists of stretched continental crust (Hauser et al., 1995), while banks consist of early Tertiary plateau basalts (Boldreel and Andersen,

1998). The basins are filled with up to 7 km Jurassic to recent deposits. Banks are generally only covered by a thin layer of Neogene or Holocene sediment (Morewood et al., 2004). Within the Neogene sedimentary sequence, at least two major unconformities are visible, which have been related to climatic and tectonic events. The oldest unconformity, C20, is interpreted to represent the onset of exchange of deep water masses between the Arctic and North Atlantic oceans (Stoker et al., 2001). This event was dated at early to mid Miocene (biozone NN4-5). The second unconformity, C10, is interpreted to be related to uplift and associated changes in sediment supply (Stoker et al., 2002). The event was dated at intra-Pliocene age (3.85-4.5 Ma).

Along the SW Rockall Trough margin, the Logachev Mounds form elongated ridges of several kilometers long that are arranged perpendicular to the slope. Coral mounds in this area typically occur at water depths between 600 and 1000 m. The Pelagia Mounds at the SE Rockall Trough Margin have a different morphology. They occur as isolated mounds with a base of 1-2 km long, which rise no more than 100 m above the seafloor. They generally occur on the upper slopes, within a depth range of 650 to 800 m (Akhmetzhanov et al., 2003; Van Weering et al., 2003). Seismic profiles from the SW and SE Rockall Trough margins show two strong reflectors below the mounds, which were interpreted as unconformities C10 and C20 by correlation with other seismic profiles from RT and calibration with ODP borehole data (Van Weering et al., 2003). These data imply that mound growth did not commence before mid to late Pliocene.

The occurrence and distribution of cold-water corals are related to the presence of a firm substrate to settle on, and internal tides and waves, which advect food particles to the heterotrophic corals (De Haas et al., 2009; Duineveld et al., 2007; White, 2007; White et al., 2005). Subsequently mounds grow by the in-situ production of skeletal debris and entrapment of settling pelagic material (De Haas et al., 2009; Mienis et al., 2009). Regardless of the depth of the base of the mound, mound summits along the Rockall Trough margins have grown to a specific depth level below the sea surface, at around 580 m water depth (Mienis et al., 2006). A detailed description of the morphology and sedimentology of the south Rockall Trough margins has been published in De Haas et al. (2009).

2 Materials and methods

2.1 Data collection

From 1998 to 2004 data were collected during annual research cruises with RV Pelagia of Royal NIOZ to the mounds in the Porcupine Seabight and SE and SW Rockall Trough margins. After recording of high-resolution shallow seismic and 3.5 kHz profiles (De Haas et al., 2002; Kenyon et al., 2003; Mienis et al., 2006; Van Weering et al., 2003), bottom samples were retrieved from the mound areas. Sampling locations were chosen based on bottom topography as obtained by the seismic and echo sounder studies. Samples were taken along transects reaching from the top of the mounds, across intramound areas and flanks into the areas surrounding the coral mounds. Figure 1 shows the location of the sediment sampling stations; Table 1 lists position and water depth of the stations, and gives an overview of various analyses carried out for each station.

2.2 Seabed images

Since the 2000 cruise, photo and video seabed images were acquired by a camera mounted in a frame (hopper camera). The camera was lowered on a cable that relayed the signal of a bottom detector to the deck. At each station 20 to 30 photographs were taken at approximately 1-minute intervals. All images were visually analyzed to determine sediment type, coral cover, and associated fauna. These were used, together with box core descriptions, to distinguish the environmental settings that are presently encountered.

Station	Rockall / Porcupine	Location	Depth (m)	Setting	Surface	Environment	Box core photos	Underwater footage	210Pb	Grain size	C and N	Benthic foraminifera
ENAM9910	R	-15.8261 ; 55.4823	785	flank	coral	patchy corals	*		*	*	*	
ENAM9912	R	-16.5010 ; 55.4067	750	top mound	coral	isolated corals	*		*	*	*	
ENAM9916	R	-15.6565 ; 55.5383	675	off mound	debris	coral debris	*		*	*	*	*
ENAM9918	R	-15.5923 ; 55.5667	855	on mound	coral	patchy corals	*		*	*	*	*
ENAM9924	P	-13.9977 ; 53.7675	565	off mound	pebbles	dropstones	*		*	*	*	*
ENAM9925	P	-13.9742 ; 53.7765	625	off mound	gravel	(foram) sand	*		*	*	*	*
ENAM9926	P	-13.9682 ; 53.7802	670	flank	pebbles	dropstones	*		*	*	*	*
ENAM9927	P	-13.9438 ; 53.7800	580	flank	coral	patchy corals	*		*	*	*	*
M2000-06	P	-13.9978 ; 53.7800	720	off mound	dropstone	dropstones	*		*	*	*	*
M2000-08	P	-13.9358 ; 53.7798	790	off mound	pebbles	dropstones	*	*	*	*	*	*
M2000-09	P	-13.9405 ; 53.7802	775	flank	debris	coral debris	*		*	*	*	*
M2000-10	P	-13.9325 ; 53.7800	795	off mound	coarse sand	dropstones	*	*	*	*	*	*
M2000-11	P	-13.9460 ; 53.7812	700	flank	debris	patchy corals	*	*	*	*	*	*
M2000-12	P	-13.9508 ; 53.7800	770	flank	debris	dropstones	*	*	*	*	*	*
M2000-13	P	-13.9438 ; 53.7807	680	top mound	debris	dense coral framework	*	*	*	*	*	*
M2000-15	P	-13.9735 ; 53.7800	770	top mound	debris	patchy corals	*	*	*	*	*	*
M2000-18	P	-13.9623 ; 53.7753	808	flank	pebbles	dropstones	*		*	*	*	*
M2000-21	R	-15.6687 ; 55.5345	740	on mound	coral	dense coral framework	*		*	*	*	*
M2000-23	R	-15.6593 ; 55.5375	820	flank	dropstone	coral debris	*	*	*	*	*	*
M2000-24	R	-15.6510 ; 55.5407	753	top mound	debris	patchy corals	*	*	*	*	*	*
M2001-14A	P	-13.9168 ; 53.7732	639	top mound	debris	hardground	*	*	*	*	*	*
M2001-15	P	-13.9188 ; 53.7748	685	flank	debris	coral debris	*	*	*	*	*	*
M2001-24	P	-13.9483 ; 53.7853	790	flank	pebbles	dropstones	*	*	*	*	*	*
M2001-25	P	-13.9517 ; 53.7862	754	flank	debris	coral debris	*	*	*	*	*	*
M2001-28	R	-15.6633 ; 55.5477	675	top mound	debris	coral debris	*	*	*	*	*	*
M2001-29A	R	-15.6583 ; 55.5453	687	top mound	coral	dense coral framework	*	*	*	*	*	*
M2001-30	R	-15.6548 ; 55.5435	740	flank	debris	dense coral framework	*	*	*	*	*	*
M2001-39	R	-15.6632 ; 55.5210	780	flank	debris/crinoids	isolated corals	*	*	*	*	*	*
M2001-41	R	-15.6692 ; 55.5372	695	flank	coral	dense coral framework	*	*	*	*	*	*
M2001-42	R	-15.6718 ; 55.5415	675	top mound	coral	dense coral framework	*	*	*	*	*	*
M2001-43	R	-15.6758 ; 55.5452	655	top mound	coral	dense coral framework	*	*	*	*	*	*
M2001-45	R	-15.6503 ; 55.5500	840	intermound	coral	patchy corals	*		*	*	*	*
M2001-48	R	-15.6653 ; 55.5283	853	flank	debris	coral debris	*	*	*	*	*	*
M2001-49	R	-15.6672 ; 55.5333	780	flank	coral	patchy corals	*	*	*	*	*	*
M2003-18	R	-15.8245 ; 55.6233	555	off mound	debris	(foram) sand	*	*	*	*	*	*
M2003-20	R	-15.8360 ; 55.5317	775	off mound	biogenic sand	(foram) sand	*	*	*	*	*	*
M2003-21	R	-15.8040 ; 55.4937	563	top mound	coral	isolated corals	*	*	*	*	*	*
M2003-22	R	-15.7968 ; 55.4992	618	top mound	coral	patchy corals	*	*	*	*	*	*
M2003-23	R	-15.7852 ; 55.5037	673	top mound	coral	patchy corals	*	*	*	*	*	*
M2003-24	R	-15.8075 ; 55.4975	575	top mound	coral	patchy corals	*	*	*	*	*	*
M2003-25	R	-15.8115 ; 55.5020	678	flank	debris	hardground	*	*	*	*	*	*
STRAT00-03	R	-15.6447 ; 55.4685	1180	off mound	biogenic sand	(foram) sand	*		*	*	*	*
STRAT00-05	R	-15.8082 ; 55.6587	510	off mound	foram sand	(foram) sand	*		*	*	*	*

Table 1. Overview of cores that were studied, showing the location of each station as well as its position relative to the mound, the surface lithology and the environmental setting. The data that are available for a specific core are indicated by asterisks. Coordinates are in latitude and longitude.

2.3 Sediment sampling

Twenty-six box cores were retrieved from SW Rockall Bank and seventeen box cores from NW Porcupine Bank, using a NIOZ box-corer equipped with cylindrical coring barrel with a height of 55 cm and a diameter of 50 cm. A lid on top of the coring barrel prevents disturbance of the sediment and loss of bottom water while it is retrieved. The surface of the box core was photographed and biological and sedimentological characteristics of the surface were described after recovery (Van Weering, 1999; De Haas et al., 2000; De Stigter and De Haas, 2001; De Haas et al., 2002; De Haas and Mienis, 2003; De Stigter et al., 2003). The cores were immediately subsampled by inserting wet 11 cm diameter PVC liners into the sediment. All subcores were stored at 4 °C.

2.4 Sample preparation

Subcores were frozen and then split lengthwise with a diamond circular saw to preserve the coral framework and sedimentary structures. After defrosting the split subcores were described and one half was preserved as a reference. The other core half was cut in 1 cm slices and, whenever possible, 0.5 cm slices at the top 3 cm of the core. The slices were divided into two sets of subsamples. All samples were freeze dried and weighed before and after drying. After drying, twelve subsamples of each core were wet sieved with tap water over a 63 μm mesh. The material retained on the sieve was oven dried and weighed, and used for foraminiferal studies (section 2.8). The water with the <63 μm fraction was centrifuged and the solid residue was freeze dried and weighed, and used for analysis of ^{210}Pb activity (section 2.6) and total and organic carbon and nitrogen content (section 2.7). These analyses were performed on the <63 μm fraction instead of bulk sediment in order to avoid problems associated with the often very heterogeneous texture and composition of sediments from the carbonate mounds. By eliminating scattered large pieces of coral and pebbles, more uniform results were obtained allowing better comparison between stations, and more regular downcore profiles of ^{210}Pb yielded better model fits. The second set of subsamples was used for bulk sediment grain size analysis (section 2.5).

2.5 Grain size analysis

Grain size analysis was performed with a Beckman Coulter LS230 laser particle sizer, which measures the size range of 0.4-2000 μm by laser diffraction and smaller particles between 0.04-0.4 μm by polarization intensity differential scattering (PIDS). Grain size profiles were established for 42 cores, using 12 bulk samples from each core, distributed over its entire length (Table 1). Of each freeze dried bulk sample 0.15-0.50 g of sediment was dispersed in 30 ml of tap water and ultrasonicated for 5 min to disaggregate and evenly disperse particles. After ultrasonication, samples were entered in the analyzer, using a 2 mm mesh to retain larger particles that could obstruct the flow circuit of the analyzer. Samples were measured for 2 min with internal ultrasonic switched on. A variable amount of sediment, depending on the coarseness of the

sediment, was needed to attain the optimum obscuration of the laser beam of 8-15 % required for reliable measurement. Measurements that were outside the range of optimum obscuration were discarded and measured again.

Comparisons of laser diffraction with traditional sieve and pipette measurements (Konert and Vandenberghe, 1997) show that the laser method is very accurate. They do, however, show that the clay fraction is underestimated, which is caused by the effect of grain shape. Hence, in the results that are presented here, the sediment <8 μm is treated as the clay fraction as is suggested by the aforementioned authors.

2.6 ^{210}Pb activity

Lead-210 (^{210}Pb) analysis was performed on 22 cores (Table 1). Twelve samples of each core were analyzed by α -spectrometry, where the activity is assessed indirectly through the granddaughter ^{210}Po (Boer et al., 2006). For analyses, 200-400 mg of freeze-dried, ground and homogenized sediment in the size fraction <63 μm was measured and spiked with 1 ml of 78.5 mBq/g ^{209}Po solution and leached during 7 h in 10 ml of 2M HCl at 85 °C. Subsequently 45 ml Milli-Q water and 5 ml of 40 g/l ascorbic acid were added. Polonium isotopes were collected from the solution via spontaneous electrochemical deposition on silver disks, which were held suspended in the solution. The solution was heated during 16 h at 70 °C to speed up the Po deposition. Silver plates were left in the solution for five days at room temperature to increase deposition efficiency. The alpha emission activity of Po was measured with Canberra Passivated Implanted Planar Silicon (PIPS) detectors. The 1σ counting uncertainty was 4 % on average. All activities were decay corrected for the time elapsed between sample collection and counting.

Lead-210 profiles were fitted with a conventional one-dimensional, two-layer, vertical eddy diffusion model assuming constant ^{210}Pb flux and constant sedimentation (Carpenter et al., 1982; Nittrouer et al., 1984), to establish inventories of excess (unsupported) ^{210}Pb and rates of sediment accumulation and diffusive mixing. The modified CF/CS (Constant Flux and Constant Sedimentation) model with SML (surface mixed layer) that was used assumes constant sediment deposition rates and a constant

mixing rate that is confined to the SML and is time- and depth-independent. In our model a near-zero mixing rate was assumed below the surface mixed layer. Distribution of ^{210}Pb in the sediment was considered against a vertical scale of cumulative mass depth, calculated by integration of salt-corrected dry bulk density over linear sediment depth.

2.7 Carbon and nitrogen content

Total carbon, inorganic carbon (CaCO_3), organic carbon and total nitrogen content in the $<63\ \mu\text{m}$ fraction were measured by gas chromatography using the Thermo Elemental Analyzer Flash EA 1112, according to the procedure described by Verardo et al. (1990). Six samples per box core were analyzed from 22 locations (Table 1). Total carbon and nitrogen content were established by analyzing 20 mg of freeze dried, ground and homogenized sediment from each sample, while 10 mg of sediment were used for organic carbon measurements. The latter samples were treated with 2M HCl to remove carbonates. The analyzer was calibrated by including acetanilide ($\text{C}_6\text{H}_5\text{NHCOCH}_3$) standards at the start and the end of each series, as well as after every five samples. Calcium carbonate content was calculated as $8.34 * (\text{C}_{\text{total}} - \text{C}_{\text{organic}})$, assuming that inorganic carbon was predominantly present as carbonate.

2.8 Foraminifera

Benthic foraminifera were analyzed from 14 stations (Table 1). Since benthic foraminiferal assemblages near the sediment-water interface often include a significant proportion of species that are usually not preserved in the fossil record, we chose to study foraminifera from a slightly deeper level where a taphonomically more mature, time-integrated assemblage was expected. With sedimentation rates typically on the order of a few cm/ka, however, the average age of foraminiferal assemblages will relatively rapidly increase with depth downcore, implying that they may represent environmental conditions different from those at present. As a compromise we chose to study assemblages from the 5 cm depth level, which according to ^{210}Pb profiles is at the lower reach of recent bioturbation.

Samples were washed through a 63 μm mesh. The residue was further divided into fractions 63-150 μm , 150-1000 μm , and >1 mm. Benthic foraminifera were studied from splits of the 150-1000 μm fraction. Splits were obtained with a microsplitter. At least 250 specimens were counted in each sample and determined to the highest taxonomic level possible. Fragile agglutinants that are unlikely to be preserved in the fossil record (*Textularias* and *Spiroplectinellas*) were counted but removed from the dataset prior to statistical analyses. The dataset was reduced to a practical size without considerably reducing the ecological information by omitting the species (groups) that make up less than 4 % of the fossilizing taxa in all of the samples. Before removing the less abundant species, the Miliolid taxa *Biloculina spp.*, *Triloculina spp.*, and *Quinqueloculina spp.* were grouped as well as the different *Spirillina* species. All statistical analyses were performed with PAST version 1.88 (Hammer et al., 1999). Ward's algorithm was used in the hierarchical cluster analyses.

Species diversity was computed using Shannon's index (Spellerberg and Fedor, 2003), which is defined by:

$$(1) \quad H = - \sum_{i=1}^n p_i \ln p_i$$

where H = Shannon's index and p_i = the relative abundance of a species, calculated as the proportion of the number of a species in a sample to the total number of specimen in the sample. The index is increased by either having more species or by greater species evenness. The minimum value is 0 when only one species is present. The maximum value is $\ln(N)$ when all N species are equally abundant. Species dominance was estimated by computing the Berger-Parker index d , which expresses the proportional importance of the most abundant species in a sample (May, 1975):

$$(2) \quad d = N_{\max} / N$$

where d = Berger-Parker dominance, N = total number of specimen in the sample, and N_{\max} = the number of specimen of the most abundant species in the sample.

3 Results

3.1 Environmental settings

On the basis of seabed photographs, and photographs and descriptions of box cores, seven different environmental settings were distinguished (Fig. 2; Table 1), which are described below. They are presented in the order of increasing presence of living corals.

Dropstones

This setting is generally encountered off-mound, but is also observed on mound slopes. The sediment consists of foraminiferal sand with a variable fraction of lithic fragments. The sand is littered with rounded and angular pebbles, few angular cobbles and incidentally larger dropstones. No living corals or coral fragments were encountered in this setting (Fig. 2.1).

Sand

Vast areas of seabed surrounding the coral mounds consist of foraminiferal sand. In contrast to dropstone settings, sediments in these areas are mobile as is evidenced by omnipresent small-scale current ripples and large sand waves (Fig. 2.2).

Hardgrounds

Hardgrounds occur where small coral debris and finer biogenic sediments are cemented together, forming distinct and relatively resistant strata (Fig. 2.3). Hardgrounds develop when carbonate production and sedimentation rates are low, conditions that probably occurred during glacial periods (Dorschel et al., 2005; Van Weering et al., 2003). This is corroborated by the underwater photographs, which frequently show ice rafted debris on top of hardgrounds.

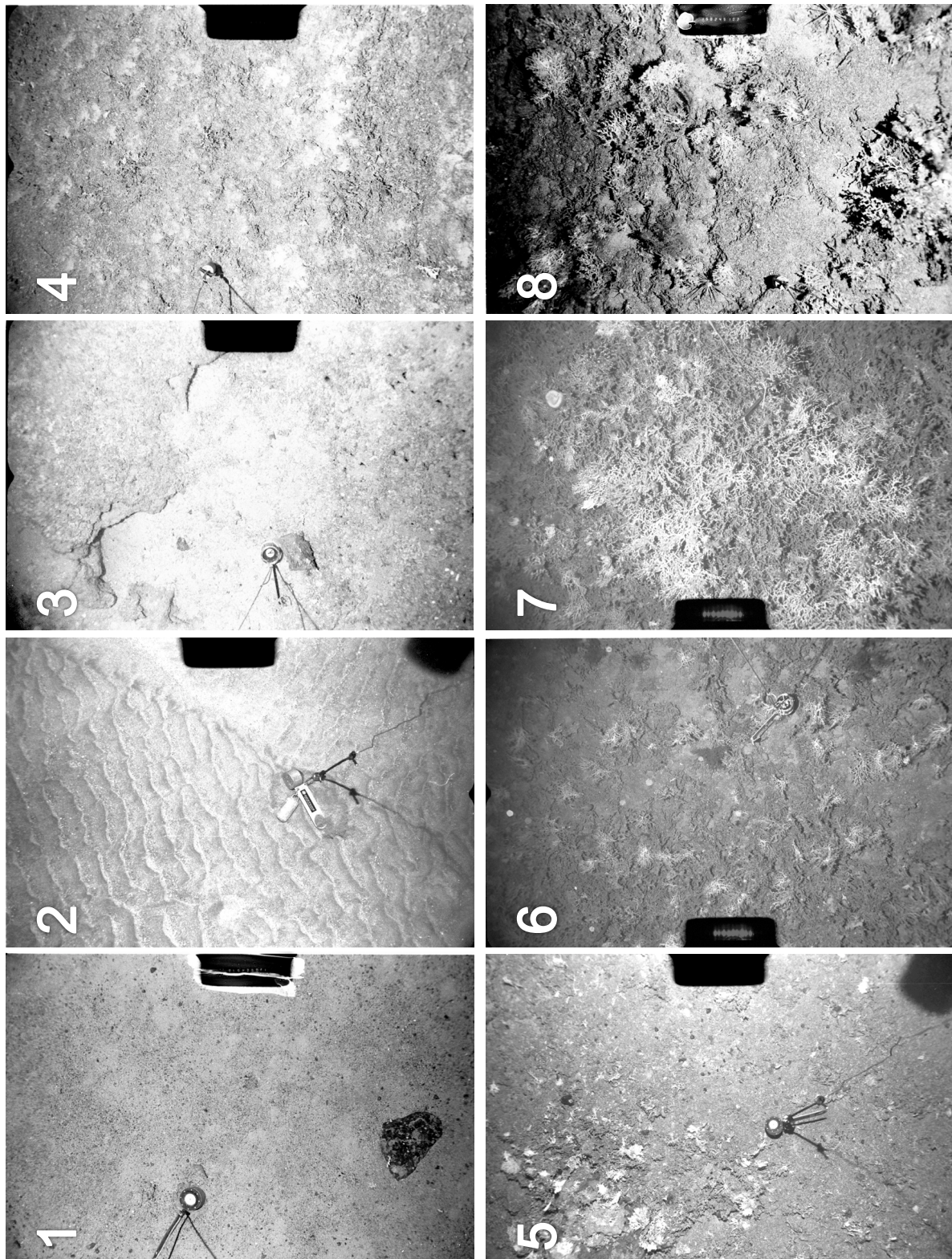


Fig. 2. Environmental settings that were distinguished in the research area. 1. Dropstones – station M2000-08 on Porcupine Bank (PB), located circa 150 m from the toe of the mound; 2. Sand – M2003-20, off-mound station on Rockall Bank (RB); 3. Hardground – M2001-14, station on mound top at PB; 4. Coral debris – M2000-24, station on mound top at RB; 5. Isolated corals – M2003-25, station on mound flank at RB; 6. Patchy coral cover – M2001-42, station on mound top at RB; 7. Dense coral cover – M2001-42, station on mound top at RB; 8. Sediment infilling as observed at station M2000-11 on a mound flank at PB. The diameter of the compass in figures 1-6 is 4 cm.

Coral debris

Sites were classified as coral debris if coral debris was present, but no living corals were observed in the vicinity of the station (Fig. 2.4). The coral debris mainly consists of fragments of *Lophelia pertusa* and few *Madrepora oculata* remains. The size of skeletal debris generally varies from sand sized to 10-15 cm long fragments. The matrix sediment mainly consists of sand-sized coral fragments and foraminiferal tests. Although the photographs show evidence that at several locations upright standing corals have been buried in situ, intact frameworks were not encountered within the box core sediments, which may be due to post-mortem destruction processes. Sediment infilling was observed on flanks and mound tops on Rockall as well as on Porcupine Bank.

Isolated corals

Living corals were classified as being isolated when only single, or few and isolated living coral specimens were observed in the vicinity of the station (Fig. 2.5). These were encountered on flanks and mound tops of Rockall Bank. There are many dead, but still upright standing corals present. The living and dead coral frameworks are surrounded by coral debris, which at various places already starts infilling the framework. Infilling was especially visible at station 2003-21. Many crinoids (*Koehlerometra porrecta*) settle on top of dying corals, while sponges fill up space in between dead corals. Our data, however, do not contain time series that can reveal if the population is presently diminishing, or whether there is a dynamic equilibrium.

Patchy coral cover

Patchy coral covers comprise at least a few living coral specimen in patches ranging in size from a few decimeters up to several meters across (Fig. 2.6). Generally multiple patches are observed within an area. Patches of corals occur on both Porcupine and Rockall Bank on mound flanks and tops. Space in between patches is covered with coral debris. Sponges are often observed in smaller open spaces in between corals and along the perimeter of patches.

Dense coral cover

These coral covers are continuous with only decimeter- to meter-sized open spaces with debris (Fig. 2.7). Although sediment infilling is sometimes observed (stations M2000-13, M2001-30, and M2001-41), corals are not completely covered and are still living. Soft corals and sponges are often present in between the calcareous corals.

3.2 Grain size distributions and sediment composition

The results of grain size measurements are summarized in Figure 3. Sediment from the only off-mound location without dropstones (ENAM 9925), classed under “sand”, contains a high percentage (>90 %) of mainly biogenic sand-sized particles and relatively small amounts of silt and clay. Grain size composition is highly homogeneous throughout the core as is reflected by the small standard deviation. At sites where dropstones are present, the sediment can generally be described as mixed lithoclastic and bioclastic sand with varying amounts of clay and biogenic debris. Variability in grain size distribution is relatively high and comparable to the variation that is observed in coralliferous sediment, although the sand fraction of the bulk sediment is higher in dropstone sediments.

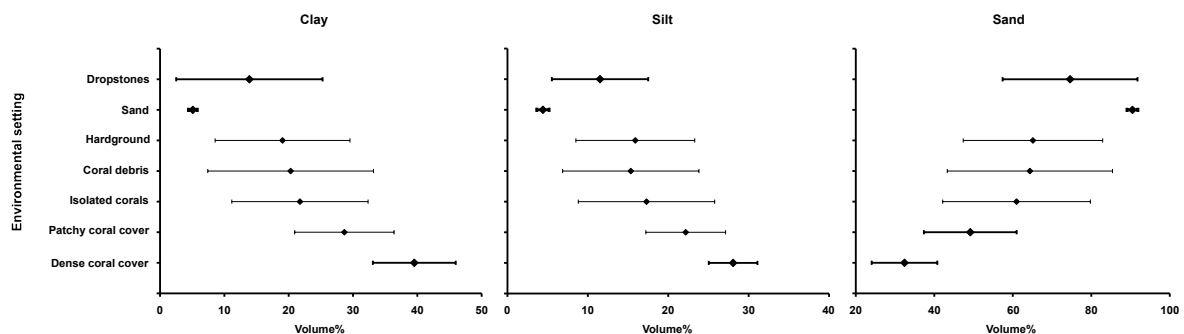


Fig. 3. Compilation of all grain size data, showing the percentage of clay, silt and sand in samples from different environmental settings that are encountered on Rockall and Porcupine bank. Heavier lines indicate a higher potential to distinguish the environment from the grain size distribution. Error bars correspond to one standard deviation.

Content of clay-sized particles is highest in areas with dense coral frameworks (40 %). Here sand contributes only 8 % to the matrix sediment and consists nearly solely of planktonic and benthic foraminifera. The amount of clay in the sediment rapidly decreases further away from the loci of framework building, with only 29 % of

clay near patchy corals and 22 % at sites with isolated corals. Silt content is also significantly lower at these locations in favor of the relative amount of sand, which increases to 49 % in patchy coral covers and 61 % near isolated corals. With respect to grain size, locations with coral debris and hardgrounds, which are interpreted as cemented coral debris based on underwater footage and box core examination, differ only slightly from sites with isolated corals. It should be noted that at these locations, where there is less influence of living coral frameworks, the variability in grain size distribution increases considerably.

3.3 ^{210}Pb profiles

Characteristic profiles for off-mound settings, stations with hardgrounds, and coral covered mounds are shown in Figure 4. Most of the sediment cores display relatively regular ^{210}Pb profiles, with maximum activity at the sediment surface ranging from 50 to 850 mBq/g, and decreasing to background levels of around 35 mBq/g further downcore. Surface activity is generally in the lower range for off-mound stations, and tends to increase toward stations with coral cover, however with considerable variation (Fig. 5a). A surface mixed layer of a few cm thick, distinguished by a less steep vertical gradient in ^{210}Pb than in the underlying sediment, is observed in a few stations, but in most cases no distinct break in gradient is present in the ^{210}Pb profile. Presumably the entire exponential part of the ^{210}Pb profile down to 5-10 cm depth is predominantly reflecting diffusive biological mixing, since Holocene sedimentation rates on the order of 10 cm/ka, reported in the literature for on-mound settings (Frank et al., 2004; De Haas et al., 2009), can not account for presence of excess ^{210}Pb deeper than 1-2 cm depth. Inventories of excess ^{210}Pb , reflecting the incorporation of recent, mostly fine-grained, sedimentary material into the sediment, range from about 250 to 4000 mBq/cm, with a tendency toward higher values for stations closer to the centers of coral growth (Fig. 5b). The highest value was found, however, at a hardground site, and values for sites with dense coral cover were at intermediate range. The correlation between environmental setting and activity at the sediment-water interface (Pearson's ρ) is 0.67 ($p < 0.001$). Inventories of excess activity do not show a significant correlation with the setting ($\rho = 0.19$; $p = 0.40$), which is mainly due to the

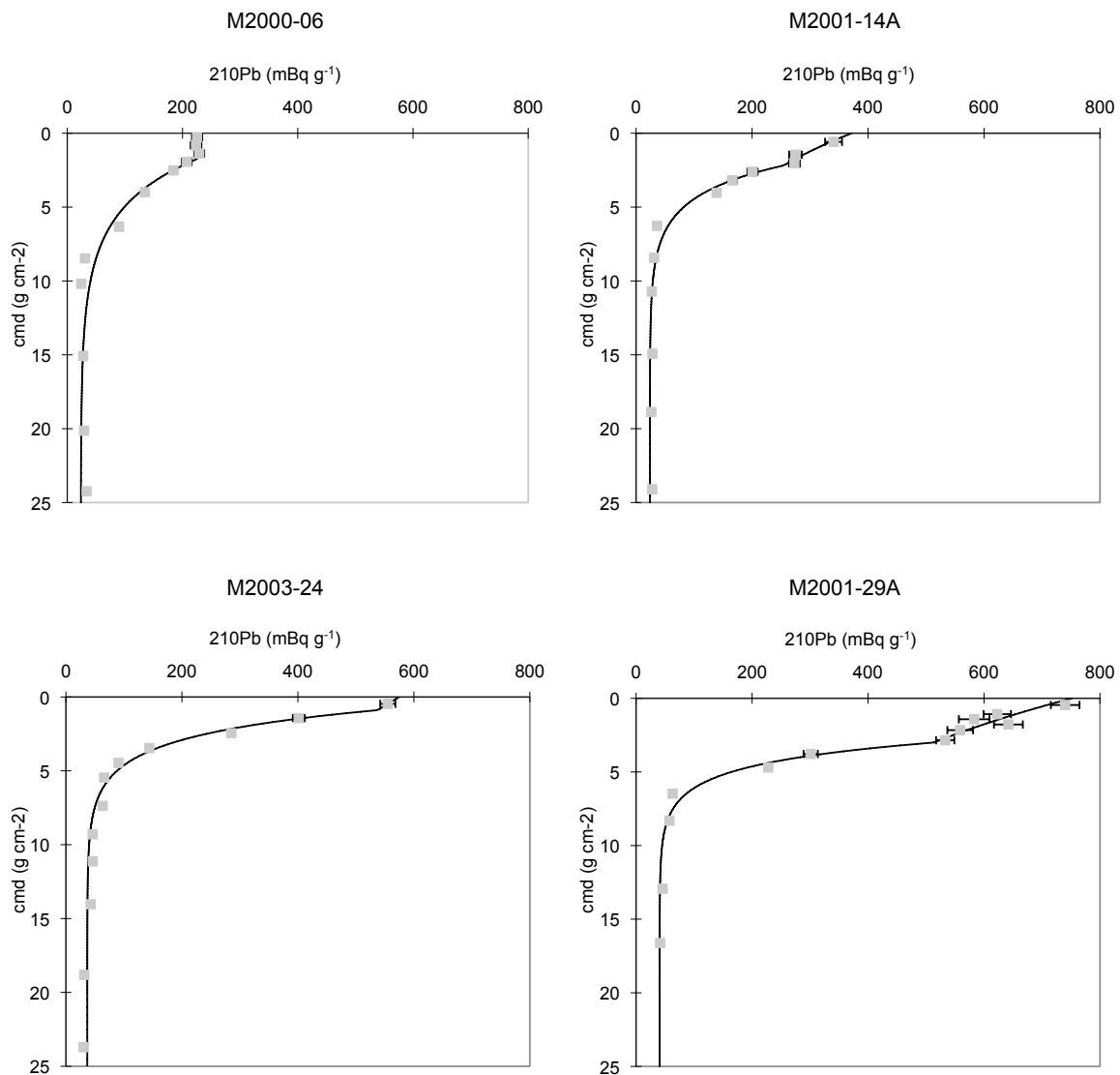


Fig. 4. Measured ^{210}Pb activities and fitted model curves for various environmental settings in the Rockall Trough area, showing a general increase in excess activity with increasing coral cover. Cmd is cumulative mass depth. Station M2000-06 is an off-mound area with dropstones on Porcupine Bank (PB). M2001-14A is from a hardground on top of a mound on PB. M2003-24 is an on-mound station with patchy coral cover on Rockall Bank (RB). M2001-29A represents a dense coral framework on top of a mound on RB. All profiles except 2003-24 show diffusive mixing just below the sediment-water interface.

very high inventory of excess activity in the hardground setting at station M2003-25 and, although to a lesser extent, by relatively high inventories at locations with dropstones. If, however, only the on-mound locations are analyzed, there is a strong and significant correlation of inventory of excess activity with the density of the coral cover ($\rho = 0.59$; $p < 0.03$).

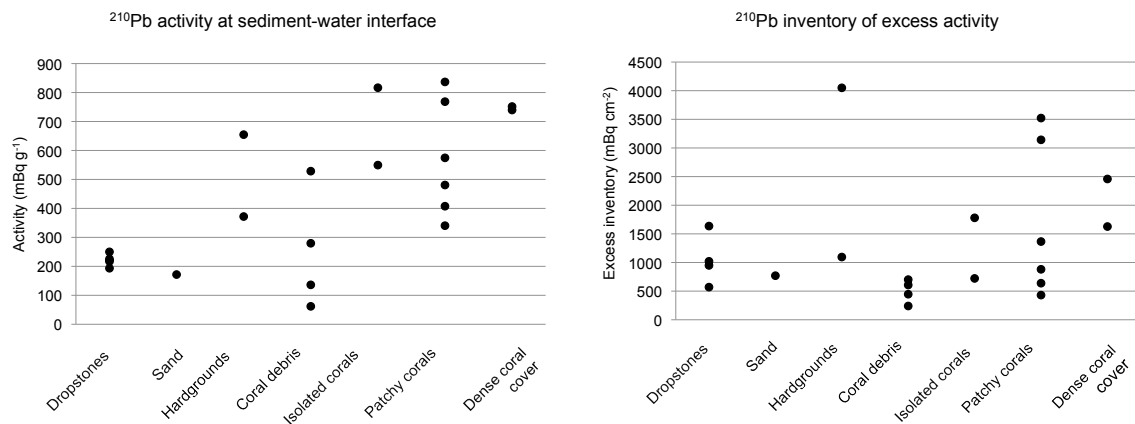


Fig. 5. Cross plots of activity at the sediment-water interface (left) and ²¹⁰Pb activity (right) versus setting, showing that activity is increasing with proximity to the centers of coral growth.

3.4 Carbon and nitrogen content

Results for inorganic carbon concentrations in the <63 μm fraction were converted to weight percentages calcium carbonate (CaCO₃) and are summarized in Figure 6. Calcium carbonate content in the <63 μm fraction varies between 41.9 and 54.8 % in sediment from Porcupine Bank. In samples from Rockall Bank, the CaCO₃ fraction is higher and generally varies within a smaller range between 74.6 and 81.4 %. There is one Rockall station with coral debris (M2001-48) where the concentration is significantly lower (60.4 %). The data from Porcupine Bank show that the CaCO₃

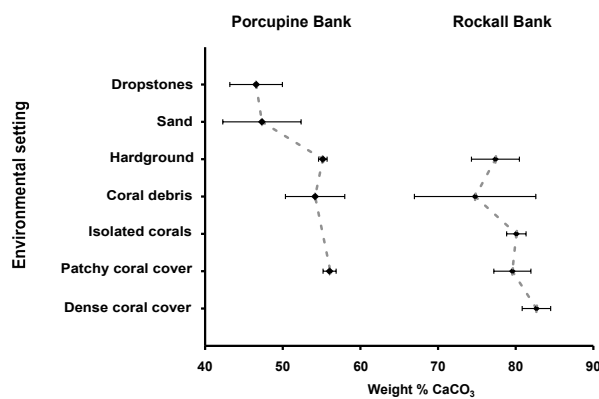


Fig. 6. Weight % CaCO₃ in box core samples from Rockall Bank and Porcupine Bank, plotted as averages for each environmental setting. Error bars correspond to one standard deviation. Table 1 shows which cores were analyzed. For stations with dropstones, characteristics are based on the top 6 cm of the core only, because of a sharp shift to lower values below this depth, which was interpreted as a transition to glacial sediment.

concentration is significantly lower in sediment from off-mound stations (weight % = 46.8; $\sigma = 3.9$) compared to on-mound environments (weight % = 55.1; $\sigma = 2.7$). Furthermore, the data show a gradual increase of CaCO₃ content with presence of corals, which is most clearly visible in data from Rockall Bank that cover all on-mound environments. Weight percentage CaCO₃ increases from 77.4 ($\sigma = 2.7$) in hardground sediment and 74.8 ($\sigma = 7.8$) in coral debris to 82.7

($\sigma = 1.8$) in sediment under a dense coral cover. The CaCO_3 content of the fine fraction is more variable in coral debris than in sediment from other settings, which can be attributed to intra-site differences. Stations with a continuous cover with relatively coarse coral debris show a higher CaCO_3 content (79.3 %; $\sigma = 1.7$), whereas sediment from station 2001-48, where coarser debris occurs patchy, has a much lower CaCO_3 content (63.9 %; $\sigma = 5.3$). The data from the Porcupine area are less complete, but suggest a similar relationship between CaCO_3 content in the $<63 \mu\text{m}$ fraction and coral cover.

The measured weight percentage of organic carbon in the box cores varies between 0.18 and 1.17 % (Fig. 7). Values for total nitrogen range from 0.04 to 0.16 %. Furthermore, total nitrogen and organic carbon content appear to vary systematically, thus C:N ratios are fairly constant (an average molar C:N ratio of 9.6 ($\sigma = 1.3$) in the Rockall Bank area and 9.4 ($\sigma = 0.9$) in the Porcupine area). In surface samples from off-mound stations, organic carbon and nitrogen content are relatively high, with average organic carbon concentrations (C_{org}) of 0.94 % ($\sigma = 0.14$) and average total nitrogen concentrations (N_{total}) of 0.11 % ($\sigma = 0.02$). Similar high values were measured in surface sediment from stations with a dense coral cover, where $C_{\text{org}} = 0.88$ ($\sigma = 0.10$), and $N_{\text{total}} = 0.12$ ($\sigma = 0.02$). Distinctly lower values were measured in sediment samples from other on-mound environments. Generally, C and N concentrations were similar in sediment from all stations with coral debris and patchy or isolated corals ($C_{\text{org}} = 0.70$; $\sigma = 0.20$ and $N_{\text{total}} = 0.09$; $\sigma = 0.03$). In samples of coral debris from Porcupine Bank, organic carbon and nitrogen concentrations fall within the same range ($C_{\text{org}} = 0.69$; $\sigma = 0.13$ and $N_{\text{total}} = 0.08$; $\sigma = 0.02$). However, much lower concentrations were measured in sediment from Rockall Bank, where $C_{\text{org}} = 0.37$ ($\sigma = 0.08$) and $N_{\text{total}} = 0.04$ ($\sigma = 0.01$).

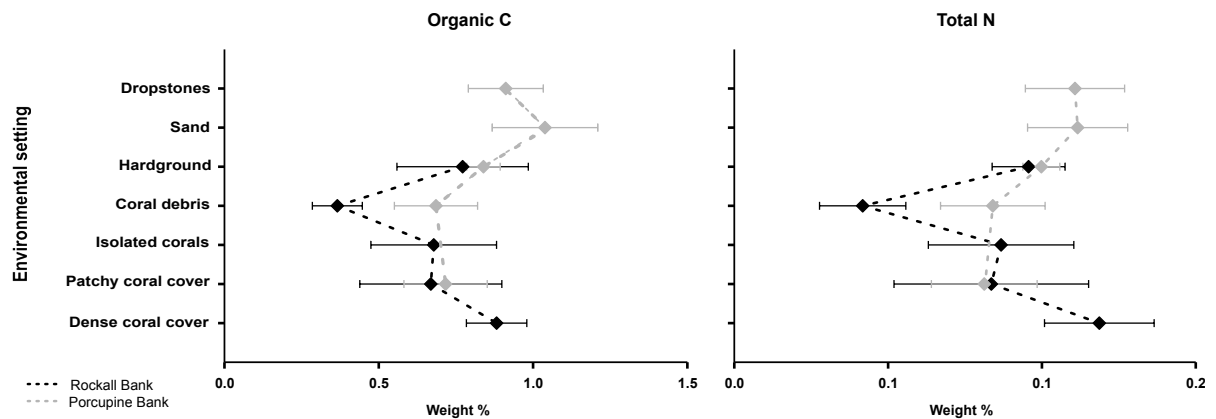


Fig. 7. Weight % organic carbon and total nitrogen in box core samples from Rockall Bank and Porcupine Bank, plotted as average for each environmental setting. Error bars correspond to one standard deviation. Table 1 shows which cores were analyzed. For stations with dropstones, characteristics are based on the top 6 cm of the core only, because of a sharp shift to lower values below this depth, which was interpreted as a transition to glacial sediment.

3.5 Benthic foraminifera

In total 86 species were identified. Species counts, split sizes and environmental settings are listed in Table 2. SEM pictures of the most abundant species in the dataset are shown in Figure 8.

Shannon's species diversity, the possible maximum diversity if all species would be equally abundant, and Berger-Parker dominance are shown in Figure 9. The results show that species diversity is lowest (2.5) in sandy sediment. The number of species in this setting is only 33 as compared to an average of 45 under patchy and dense coral covers. Secondly, the dominance in sandy sediment is much higher, which is due to the very high abundance of *Cibicides refulgens*. In hardground settings diversity is higher (2.9) and rises to 3.1 in box cores from sites with isolated corals. This increase is partly due to an increase in the average number of species from 33 to 41, but also by an increasing evenness as is illustrated by a decreasing dominance. Shannon's index shows a minor decrease with further increasing coral cover. Although the computed maximum values increase due to larger numbers of species in the samples, the diversity index decreases by a slightly higher dominance as is shown by the Berger-Parker index. The unevenness can be mainly attributed to a high abundance of *Cassidulina obtusa* and *Trifarina angulosa* at the sites with dense coral cover.

Species name	Environmental setting	Foram sand			Hard-ground		Coral debris		Isolated corals		Patchy coral cover				Dense coral cover	
	Station Split size	STRAT00-05 5/256	M2003-25 9/256	M2001-25 3/64	ENAM9916 1/64	M2001-28 1/32	M2001-39 5/256	M2003-21 5/128	M2003-22 3/128	M2003-23 5/256	M2003-24 5/128	M2000-24 5/256	ENAM9918 5/512	M2001-29A 3/64	M20001-41 3/128	
<i>Allomorphina pacifica</i>		0	0	0	0	0	1	0	0	2	0	0	0	0	0	
<i>Amphicoryna scalaris</i>		1	0	3	0	0	1	3	3	0	0	1	6	5	2	
Astronion spp.		0	4	1	2	5	7	3	11	9	12	2	6	9	4	
<i>Biloculina sp.</i>		8	3	2	8	8	0	2	1	1	4	4	3	1	3	
<i>Bolivina cf. earlandi</i>		0	0	0	0	1	0	0	1	0	1	0	2	0	0	
<i>Bolivina dilatata</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	1	
<i>Bolivina sp.</i>		1	1	1	3	0	0	0	0	0	0	0	1	0	0	
<i>Bolivina spathulata</i>		0	0	0	1	0	0	0	1	2	1	1	3	1	1	
<i>Bulimina costata</i>		0	0	0	0	0	3	0	0	0	0	2	0	0	0	
Bulimina marginata		7	5	11	17	4	26	13	17	13	9	31	25	20	24	
<i>Canceris sp.</i>		0	1	0	0	0	1	0	0	0	0	0	0	0	1	
Cassidulina laevigata		4	11	9	18	18	14	12	21	22	8	36	28	19	28	
<i>Cassidulina bradyi</i>		0	0	0	1	0	0	0	0	0	0	1	0	0	0	
Cassidulina obtusa		8	17	5	26	23	25	30	45	44	34	35	47	51	53	
<i>Cassidulinoides sp.</i>		0	0	0	0	1	1	0	1	2	1	1	2	0	0	
<i>Chilostomella oolina</i>		0	1	0	0	1	0	0	0	2	1	1	1	2	2	
<i>Cibicides kullenbergi</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	0	
<i>Cibicides lobatulus</i>		7	3	5	1	3	7	5	5	6	7	2	0	4	4	
Cibicides refulgens		116	27	13	23	18	14	11	7	8	11	11	8	8	1	
<i>Cibicides ungerianus</i>		1	1	3	5	0	1	1	0	1	1	0	1	0	0	
<i>Cibicides sp. 1</i>		1	3	8	7	7	8	10	11	9	4	4	5	4	8	
<i>Cibicides sp. 2</i>		0	0	0	0	0	1	0	0	0	0	0	0	1	0	
<i>Cibicides indet.</i>		0	0	2	0	0	0	0	1	0	0	0	0	0	0	
Cibicides variabilis		14	5	1	1	0	3	7	2	6	3	0	0	3	0	
<i>Cibicides cf. variabilis</i>		0	0	0	0	0	0	0	1	0	0	1	4	3	2	
<i>Cornuspira sp.</i>		0	0	1	1	1	0	1	5	4	2	1	0	1	1	
<i>Cristellaria sp.</i>		1	2	1	1	1	1	0	1	0	3	1	0	0	0	
Discanomalina coronata		29	63	10	10	24	9	15	18	18	22	12	2	6	2	
<i>Discorbina spp.</i>		2	0	1	1	4	0	1	0	0	1	1	1	1	0	
Eggerella sp.		14	6	6	3	2	1	0	5	1	1	2	0	6	2	
<i>Eggerella bradyi</i>		0	0	2	0	0	1	0	1	1	1	0	2	1	0	
Ehrenbergina pacifica		1	17	0	7	2	4	1	6	10	1	1	1	3	2	
<i>Epistominella sp.</i>		0	0	0	0	0	0	0	0	0	0	0	0	1	0	
<i>Eponides sp.</i>		0	0	0	0	0	0	0	0	0	1	0	0	2	0	
<i>Gavelinopsis lobatula</i>		0	0	2	2	4	2	0	2	1	2	2	1	3	3	
<i>Gavelinopsis translucens</i>		0	1	3	3	5	4	8	10	12	4	8	2	8	2	
<i>Gavelinopsis sp. 1</i>		0	0	0	0	0	0	0	0	1	0	0	0	0	0	
Globocassidulina subglobosa		21	13	9	25	14	27	22	20	14	15	18	12	11	19	
<i>Gyroidina umbonata</i>		0	0	0	0	0	0	0	0	0	0	0	0	1	0	
<i>Gyroidina orbicularis</i>		0	0	0	0	0	0	0	1	0	0	0	0	0	0	
Gyroidinoides soldanii		3	3	16	7	1	9	6	2	2	0	5	3	2	4	
<i>Hanzawaia concentrica</i>		0	0	4	0	1	0	1	1	0	0	0	0	0	0	
<i>Haplophragmoides sp.</i>		0	0	0	1	0	0	4	6	6	0	1	0	2	2	
Hoeglundina elegans		24	1	0	0	0	1	0	1	0	0	0	0	0	0	

Species name	Environmental setting	Foram sand		Hard-ground		Coral debris		Isolated corals			Patchy coral cover			Dense coral cover	
	Station Split size	STRAT00-05 5/256	M2003-25 9/256	M2001-25 3/64	ENAM9916 1/64	M2001-28 1/32	M2001-39 5/256	M2003-21 5/128	M2003-22 3/128	M2003-23 5/256	M2003-24 5/128	M2000-24 5/256	ENAM9918 5/512	M2001-29A 3/64	M20001-41 3/128
<i>Hyalinea balthica</i>		2	0	0	1	1	3	0	5	2	2	1	6	1	1
<i>Hyrrokin sarcophaga</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Lagena spp.</i>		2	4	7	5	7	7	4	4	5	4	4	4	2	6
<i>Lagenammina sp.</i>		0	0	0	0	0	0	0	0	2	0	0	0	0	0
<i>Melonis barleeanum</i>		0	2	8	4	2	4	2	4	2	4	2	0	3	1
Miliolids		5	0	0	0	0	1	2	1	1	0	1	0	3	0
<i>Neoleonticulina variabilis</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Nonion sp.</i>		0	0	0	3	0	0	0	2	0	0	2	0	0	0
<i>Nonionella bradyi</i>		0	0	1	0	3	0	2	0	0	1	0	3	3	2
<i>Nonionella tridea</i>		0	0	0	0	0	0	0	0	0	0	0	0	1	0
<i>Nonionella turgida</i>		0	0	2	2	2	2	2	11	1	3	5	8	3	8
<i>Nonionella labradorica</i>		0	0	0	0	0	0	0	0	0	1	2	0	0	1
<i>Patellina corrugata</i>		0	0	0	0	0	0	0	0	1	0	0	1	0	0
<i>Planulina ariminensis</i>		4	26	17	23	26	19	13	16	19	23	15	6	10	4
<i>Polymorphina sp. 1</i>		1	0	1	0	0	2	2	1	4	1	0	0	0	1
<i>Polymorphina sp. 2</i>		0	0	0	0	0	0	0	0	1	0	0	1	1	1
<i>Pullenia bulloides</i>		0	2	2	1	0	2	1	1	0	0	2	0	1	0
<i>Pullenia quinqueloba</i>		0	0	2	1	2	0	3	1	0	1	3	4	1	1
<i>Pulvulina sp.</i>		0	2	0	0	0	0	0	0	0	0	0	0	0	0
<i>Quinqueloculina sp.</i>		0	3	2	0	0	2	2	3	3	2	1	3	3	1
<i>Rosalina cf. floridensis</i>		0	0	0	1	0	0	0	0	0	1	2	0	0	0
<i>Robertinoidea subteres</i>		2	5	1	0	2	4	5	7	2	1	3	0	7	1
<i>Siphonina tubulosa</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Saccammina</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	1
<i>Sphaeroidina bulloides</i>		0	0	1	0	0	0	0	2	0	0	0	0	0	0
<i>Spirillina sp. 1</i>		0	0	0	0	0	3	0	1	0	0	1	0	0	0
<i>Spirillina sp. 2</i>		0	2	0	1	0	0	13	8	5	10	0	4	6	7
<i>Spiroloculina spp.</i>		0	0	0	0	0	0	1	0	1	1	1	0	1	1
<i>Spiroplectinella sagittula</i>		0	1	2	0	0	0	7	0	0	1	1	2	0	2
<i>Spiroplectinella sp.</i>		4	0	1	0	0	0	0	0	0	0	0	2	0	0
<i>Stainforthia fusiformis</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Stomatorbina concentrica</i>		0	1	0	0	0	0	2	1	0	0	0	0	0	0
<i>Techmitella sp.</i>		0	0	0	0	0	0	0	2	0	0	0	0	0	0
<i>Textularia spp.</i>		10	0	2	3	4	0	2	1	2	2	3	6	5	3
<i>Trifarina angulosa</i>		36	18	62	50	50	54	33	24	31	19	59	52	40	43
<i>Trifarina sp.</i>		0	0	0	0	0	0	0	0	0	0	1	0	0	0
<i>Triloculina sp.</i>		3	4	0	5	7	3	4	0	0	4	0	2	3	0
<i>Trochammina sp.</i>		0	0	0	0	0	1	0	3	0	0	1	0	2	0
<i>Uvigerina auferiana</i>		0	0	4	1	0	0	0	0	0	0	0	2	0	0
<i>Uvigerina cf. peregrina</i>		0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Uvigerina mediterranea</i>		7	0	18	1	0	2	0	1	2	0	0	1	0	0
<i>Uvigerina peregrina</i>		0	0	5	0	0	1	0	1	1	0	0	0	0	0
Indet.		0	0	6	3	0	7	3	0	1	2	2	1	4	2
Sum		339	258	263	279	254	289	264	307	282	234	297	274	279	258

Table 2. Benthic foraminiferal assemblages in box core samples at 5 cm below the sediment-water interface. Species that make up at least 4 % of the fossilizing taxa in one or more samples are printed in bold. Station 2001-25 is located on Porcupine Bank. Other samples are from Rockall Bank. Numbers are not standardized for a sediment volume.

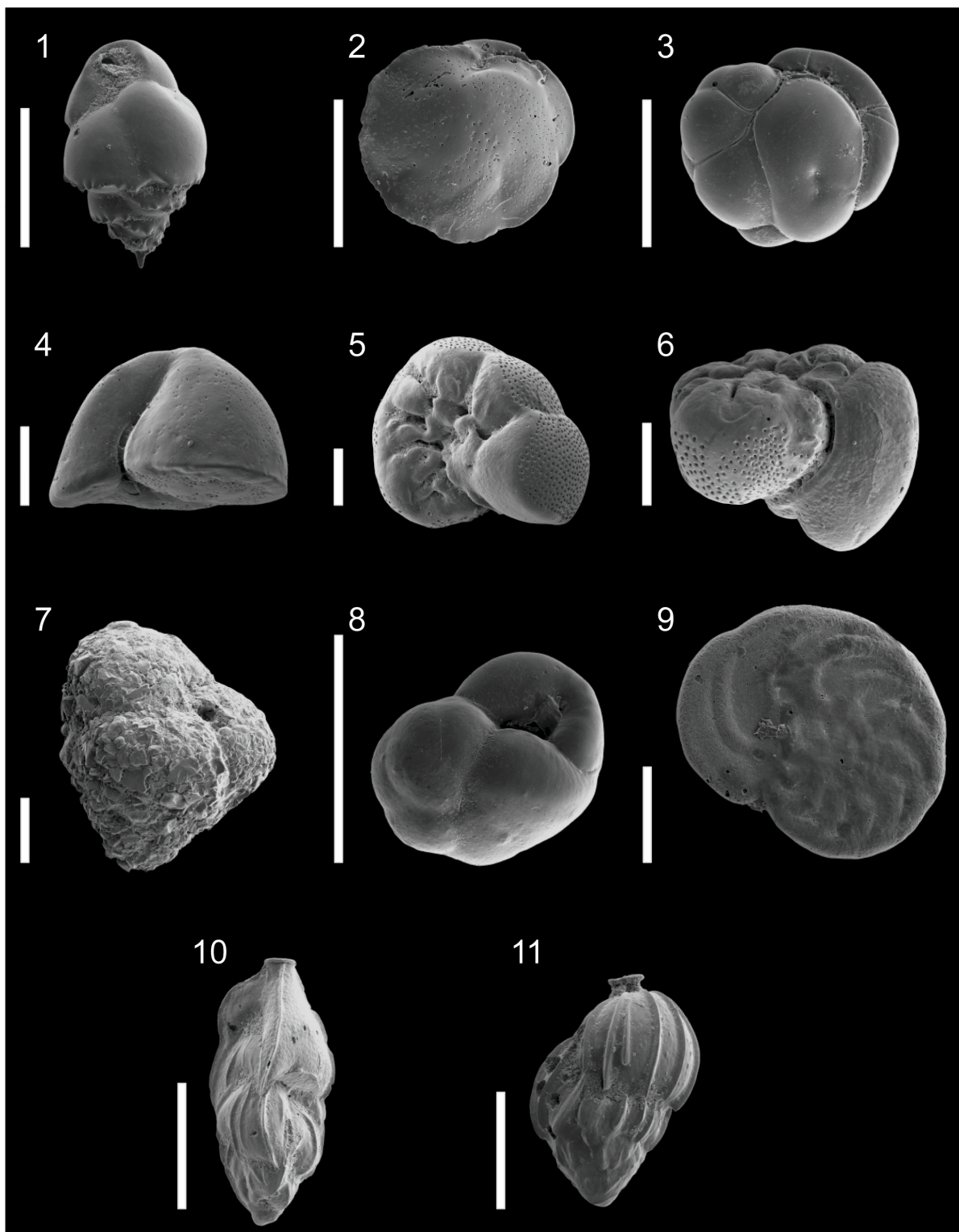


Fig. 8. Common taxa in the analyzed samples. Scale bars are 200 μm . 1. *Bulimina marginata* (d'Orbigny, 1826); 2. *Cassidulina leavigata* (d'Orbigny, 1826); 3. *Cassidulina obtusa* (Williamson, 1858); 4. *Cibicides refulgens* (de Montfort, 1808); 5 and 6. *Discanomalina coronata* (Parker & Jones, 1857); 7. *Eggerella* sp.; 8. *Globocassidulina subglobosa* (Brady, 1881); 9. *Planulina ariminensis* (d'Orbigny, 1826); 10. *Trifarina angulosa* (Williamson, 1858); 11. *Uvigerina mediterranea* (Hofker, 1932).

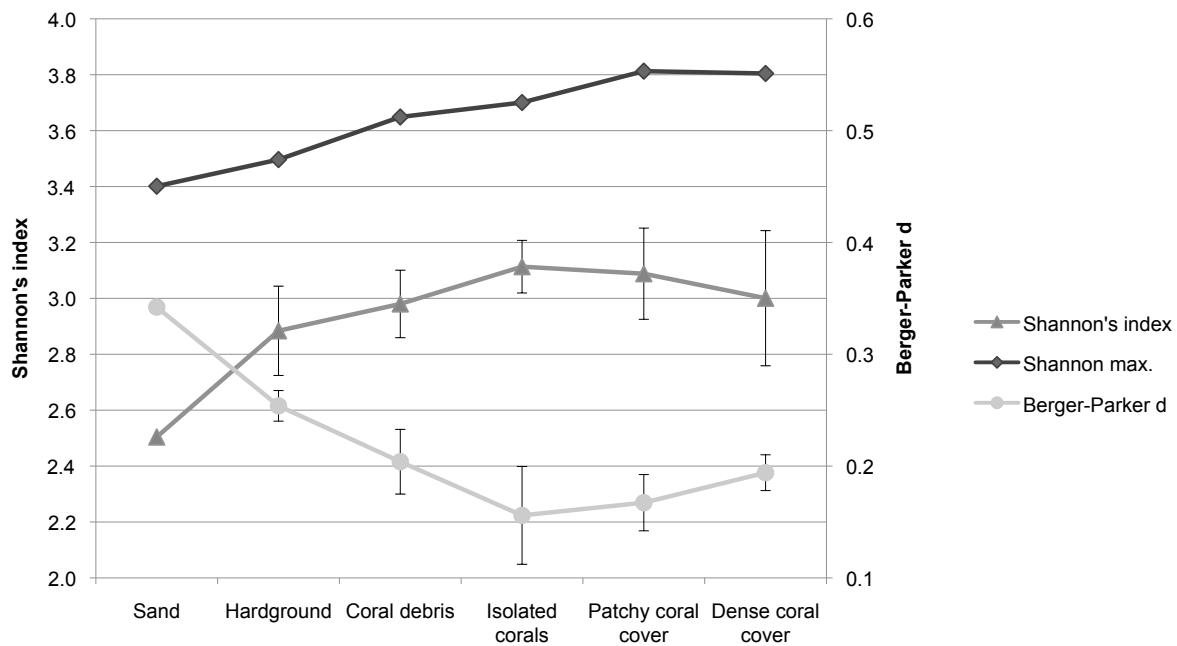


Fig. 9. Shannon's diversity index and Berger-Parker dominance per environmental setting. Error bars indicate one standard deviation. 'Shannon max' displays the maximum diversity that is attainable considering the average number of different species in each environmental setting.

Hierarchical cluster analysis (Fig. 10a) shows that foraminiferal assemblages from sandy sediment and hardground sites are significantly different from those of coral sites. Generally, sites with coral debris can be distinguished from locations with living corals. The analysis also shows that the density of the coral cover can be estimated from the benthic foraminiferal assemblages that are encountered. Hardground and sand are more closely related compared to coralline environments, although differences are sufficient to distinguish the environments on the basis of the encountered assemblages. The results of species-oriented clustering are shown in Figure 10b. Initially eight clusters were distinguished, which are indicated and labeled in the figure. If plotted against environmental setting, the following environmental preferences become visible (Fig. 11). Cluster 1, comprising only *C. obtusa*, is most abundant (20 %) in settings with a dense coral framework. The abundance decreases with diminishing presence of corals, to virtual absence in sandy off-mound areas. Cluster 2 consists of the species *T. angulosa*. This species is omnipresent, making up at least 7 % of the association in all samples. It is most abundant in coral debris (21 %) and least abundant on hardgrounds. It is also abundant in all stations with living corals, ranging from an average of 13 to

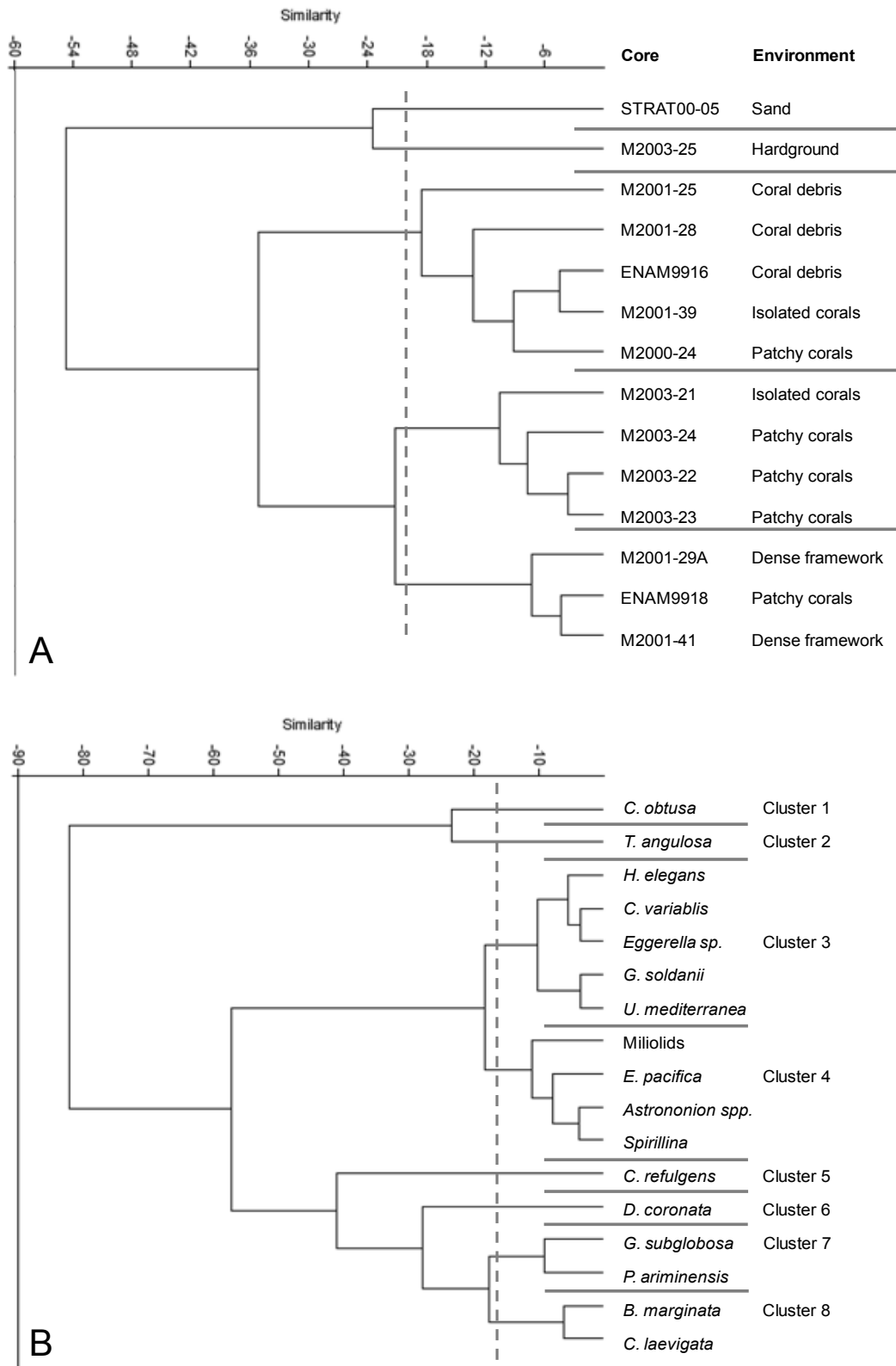


Fig. 10. Dendrograms of stations (top) and species (bottom) obtained by hierarchical cluster analyses using Ward's algorithm. Clustering is based on a data matrix with only the species that make up at least 4 % of the association in at least one of the samples and excluding fragile agglutinants.

16 % in the various settings, and is only slightly less abundant at the off-mound station (11 %). Considering the fact that there were also relatively low abundances of 8 % in two of the stations with a patchy coral cover (M2003-22 and M2003-24), the species does not appear to be endemic to a specific environmental setting. Cluster 3 contains five species that show a highly similar distribution pattern: *Hoeglundina elegans*, *Cibicides variabilis*, *Eggerella sp.*, *Gyroidinoides soldanii*, and *Uvigerina mediterranea*. These species appear to be off-mound dwellers, as their total contribution to the association is 19 % in sandy off-mound sediment, as opposed to only 3 to 8 % in the other environments. Particularly the species *H. Elegans*, *C. variabilis*, and *Eggerella sp.* contribute to the observed pattern. Cluster 4 comprises Miliolids, *Ehrenbergina pacifica*, *Astrononion spp.*, and *Spirillina spp.* These species are relatively abundant on hardgrounds (13 %) and at stations with living corals (9 %). In other environments they make up circa 5 % of the total association. A clear pattern, however, is not visible for any of the individual species. Cluster 5, composed of only *C. refulgens*, shows a strong affinity for sandy off-mound settings, where it makes up 36 % of the association. This is the highest percentage that was encountered for a single species in any of the environmental settings. Their abundance strongly declines to 11 % in hardgrounds and monotonously declines further to only 2 % at stations where the coral cover is dense. Cluster 6, another single-species cluster composed of *Discanomalina coronata*, is associated with hardgrounds, where they make up 25 % of the benthic foraminifera. In off-mound sand they are still fairly abundant with 9 %, but they are virtually absent under dense coral cover (2 %). In other settings they make up 5-6 % of the assemblage. Cluster 7 comprises *Globocassiculina subglobosa* and *Planulina ariminensis*, which thrive in a wider range of habitats. Their presence in hardgrounds, coral debris and at station with isolated corals is 15 %. The abundance declines to circa 8 % in sand and environments with a dense coral framework. Abundance of species in cluster 8, composed of *Bulimina marginata* and *Cassidulina laevigata*, shows an almost linear regression with habitat, from 3 % in sand to 18 % under dense coral cover. Although their relative abundances are distinctive, species in clusters 3 and 5 show a similar environmental preference (off-mound sand) as well as the foraminifera in clusters 1 and 8, which abundance increases with proximity to the centers of coral growth. These

clusters were grouped, resulting in 6 assemblages with different associated environments: 1. living coral assemblage, 2. on-mound assemblage, 3. coral debris assemblage, 4. hardground assemblage, 5. off-mound assemblage, and 6. an assemblage showing no environmental preference. The assemblages are plotted against environmental setting in Figure 11.

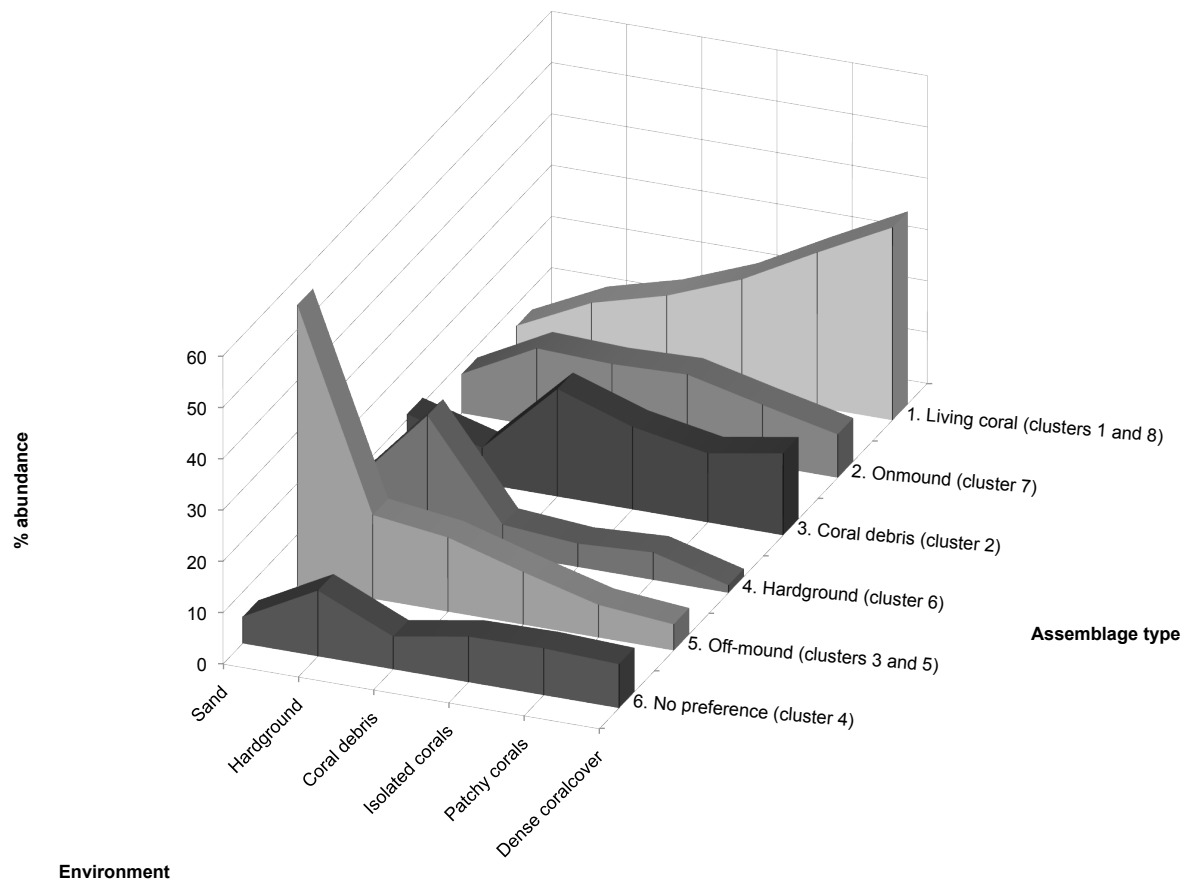


Fig. 11. Assemblages as derived from cluster analysis plotted against setting, showing the environmental preference of each assemblage. 1. Living coral assemblage = *Cassidulina obtusa*, *Bulimina marginata* and *Cassidulina laevigata*; 2. Onmound assemblage = *Globocassiculina subglobosa* and *Planulina ariminensis*; 3. Coral debris assemblage = *Trifarina angulosa*; 4. Hardground assemblage = *Discanomalina coronata*; 5. Off-mound assemblage = *Hoeglundina elegans*, *Cibicides variabilis*, *Eggerella spp.*, *Gyroidinoides soldanii*, *Uvigerina mediterranea* and *Cibicides refulgens*; 6. Assemblage without clear environmental preference = Miliolids, *Ehrenbergina pacifica*, *Astronionion spp.* and *Spirillina spp.*

The living coral assemblage, consisting of the species from clusters 1 and 8, shows an almost linear relationship with the environmental setting. They make up 38 % of the total assemblage under dense coral cover, whereas their abundance in sandy settings is only 6 %. The off-mound assemblage, with species from clusters 3 and 5, is

characteristic for sandy environments without living corals or coral debris. Their abundance increases to 55 % of the total assemblage in these settings, while the abundance drops to 16 % on hardgrounds and further decreases almost linearly to 5 % under dense coral cover.

4 Discussion

4.1 *Sediment characteristics*

The carbonate mounds of the Porcupine and Rockall Bank area are subjected to relatively strong bottom currents driven by internal (White, 2005; White, 2007; Duineveld et al., 2007). Mienis et al. (2007) retrieved long-term records of current speeds and direction, revealing current speeds up to 45 cm/s at mound crests and residual currents of 10 cm/s along the southwest slope. The study furthermore showed that near-bed currents are influenced by mound morphology and the density of the coral cover, such that different parts of the mound are subject to different current regimes and related sedimentation patterns. These different current regimes found on and off the mounds may to some extent be reflected in particle size of the sediment and contents of the <63 μm fraction. It should be taken into account, however, that apart from current sorting, particle size is also determined by local production of bioclastic material and admixture with unsorted ice-rafted material.

The grain size distributions that are summarized in Figures 3 and 12 show an overall decrease of grain size with proximity to the coral covered mounds. Clay and silt content of sediment from stations with a dense coral cover is significantly higher than in any other environmental setting and organic matter is more abundant than in any other on-mound environment (Fig. 7). While the maximum current speed of 45 cm/s at the mound crests is sufficiently high to keep clay- and silt-sized particles in suspension, Mienis et al. (2007) showed that flow speeds regularly drop below 10 cm/s during slack periods, which is sufficiently slow for deposition of clay and sand to commence (McCave and Hall, 2006). Similar speeds were measured on the neighboring Galway Mound, where maximum and mean current speeds were 51 and 16 cm/s on the top of the mound, respectively (Dorschel et al., 2007). McCave and Hall (2006) also showed that winnowing of clay and fine silts would start when bottom current speeds reach approximately 15 cm/s and will remove all but interstitial clay and silt at current

speeds exceeding 20 cm/s. The grain size data thus show that the coral cover effectively baffles the finer sediment by reducing bottom current speeds to below these threshold values. The effect of sediment baffling is also illustrated by relatively organic carbon enriched material (Fig. 7) and the ^{210}Pb measurements (Fig. 5). The generally much higher inventory of excess activity and higher ^{210}Pb activity at the sediment-water interface in areas with coral framework as compared to the other environmental settings where coral framework is absent, indicate that more recent fine material is accumulating here.

Although a trend toward a coarser grain size composition is observed with increasing density of the coral cover, as is expected due to increasing influence of winnowing processes, the variability is too large to distinguish a priori between the different environments. Considering the weight percentage of calcium carbonate in the fraction $<63\ \mu\text{m}$ (Fig. 6) does not improve the discrimination between the environments. Although a trend toward higher CaCO_3 content is visible from off-mound locations toward the mounds with thriving coral cover, the small differences and partly overlapping value ranges for the different settings, make it difficult to directly relate the CaCO_3 weight percentage to a particular mound environment. Only in rare cases, where the CaCO_3 content is extremely low, it may be possible to easily distinguish a sediment as a coral debris deposit. In addition, when applied to a paleo-environment several difficulties may arise. Firstly, when comparing data from Rockall and Porcupine Bank, it is clearly visible that CaCO_3 content in the fine fraction is significantly lower on Porcupine Bank. This can most probably be related to a higher flux of terrigenous material to the Porcupine area, as compared to Rockall Bank, which is disconnected from continental sediment supply by Rockall Trough. Secondly, further research would be necessary to establish if organic the CaCO_3 content in the $<63\ \mu\text{m}$ fraction still yield a signal related to the original depositional environment in deeper sediment layers.

In contrast to the sediment from coralline depositional environments, (foram) sands are fairly easy to distinguish from other facies. In the absence of a protecting coral cover or larger debris covering the surface, and current speeds regularly exceeding 30 cm/s (Mienis et al., 2007), these sands are sufficiently mobile to contain little clay

and silt (McCave and Hall, 2006). The grain size analyses show that the sediments have an average sand content of 90 ± 4 %, which makes them easy to identify by grain size analysis. These sediments furthermore have a relatively low CaCO_3 content, while C_{org} and N_{total} are relatively high. A relatively low ^{210}Pb activity demonstrates that these sediments do not contain much recently deposited fine material.

Lag deposits of glacial dropstones and sand, can generally be readily identified. However, if the sediment would only contain smaller debris, it will still be possible to identify these sediments based on its grain size distribution combined with the CaCO_3 content. Sand and clay content are highly variable, overlapping with the size ranges of foram sand and coralline sediments. However, variation is much larger than was observed in foram sand, and CaCO_3 content in the $<63 \mu\text{m}$ is low (Fig. 6). The relatively low CaCO_3 content may be attributed to abundance of reworked terrigenous sediment of glacial age.

4.2 *Benthic foraminifera*

Cluster analysis showed that several foraminiferal assemblages (Fig. 11) can be distinguished that represent the different sedimentary facies. The data show off-mound and on-mound dwellers, hardground, coral debris and living coral assemblages (Fig. 12). Species diversity was shown to be lowest in off-mound assemblages, while dominance was highest in these environments. Diversity increases towards the mound, attaining a maximum at stations with isolated corals. With further increasing density of the coral cover a slight decrease in diversity is observed.

Species in assemblage 3 appear to be typical off-mound dwellers. These environments have loose substrates that are constantly transported, as evidenced by current ripples, dunes and sand waves (Wheeler et al., 2005; De Haas et al., 2009). Although active sand transport may be expected to be unfavorable for settling of benthic fauna, these environments are inhabited by scattered (semi)-permanent fauna, consisting of hydroids, sponges, soft corals, and bivalves (Wienberg et al., 2008). However, this habitat seems to be favorable to only few foraminifera species. With

regard to foraminifera, they have the lowest species diversity of all environments that were distinguished, which may reflect the relatively low microhabitat variability. The foraminifera that seem to thrive well in these settings make up more than 50 % of the assemblage. The dominant species is *Cibicides refulgens* (36 %). Other typical off-mound species in the assemblage are *Hoeglundina Elegans* (7 %), *Cibicides variabilis* (4 %), and *Eggerella spp.* (4 %). These findings are in accordance with previously published results, which also describe a high abundance of (attached) epifaunal species such as *Cibicides spp.* and *G. soldanii* in similar settings (Margreth et al., 2009). The environmental preferences of the aforementioned species are compatible with the relatively high bottom current speeds and winnowing as are inferred from the grain size analyses (Gooday and Hughes, 2002; Schönfeld, 2002). The occurrence of the species may furthermore be interpreted as an indicator of well-ventilated bottom waters, although instrumental data to support this hypothesis were not available. The shallow infaunal species *H. elegans* is characteristic for relatively oligotrophic waters with ample supply of oxygen, especially high pore water oxygen concentrations, and relatively low labile organic carbon content (e.g. Gupta, 1999, Fontanier et al. 2002, Koho et al. 2008). The *Cibicides* species are in general also intolerant of reduced oxygen levels (Schönfeld, 2001). *Uvigerina mediterranea* occurred in some off-mound samples and was relatively abundant in one of the coral debris samples, which was also previously described in samples from mounds near the Porcupine Seabight (Margreth et al., 2009). Although its distribution pattern is different compared to the other species in the off-mound assemblage, *U. mediterranea* was never abundant in any on-mound samples. Studies of recent *Uvigerina* species showed that a high flux of organic material is the most important environmental factor controlling the distribution of the species (Altenbach et al., 1999; Thomas and Gooday, 1996). Since the most abundant off-mound species indicate relatively low organic matter content, the presence of *U. mediterranea* in off-mound samples may indicate slight reworking of glacial deposits.

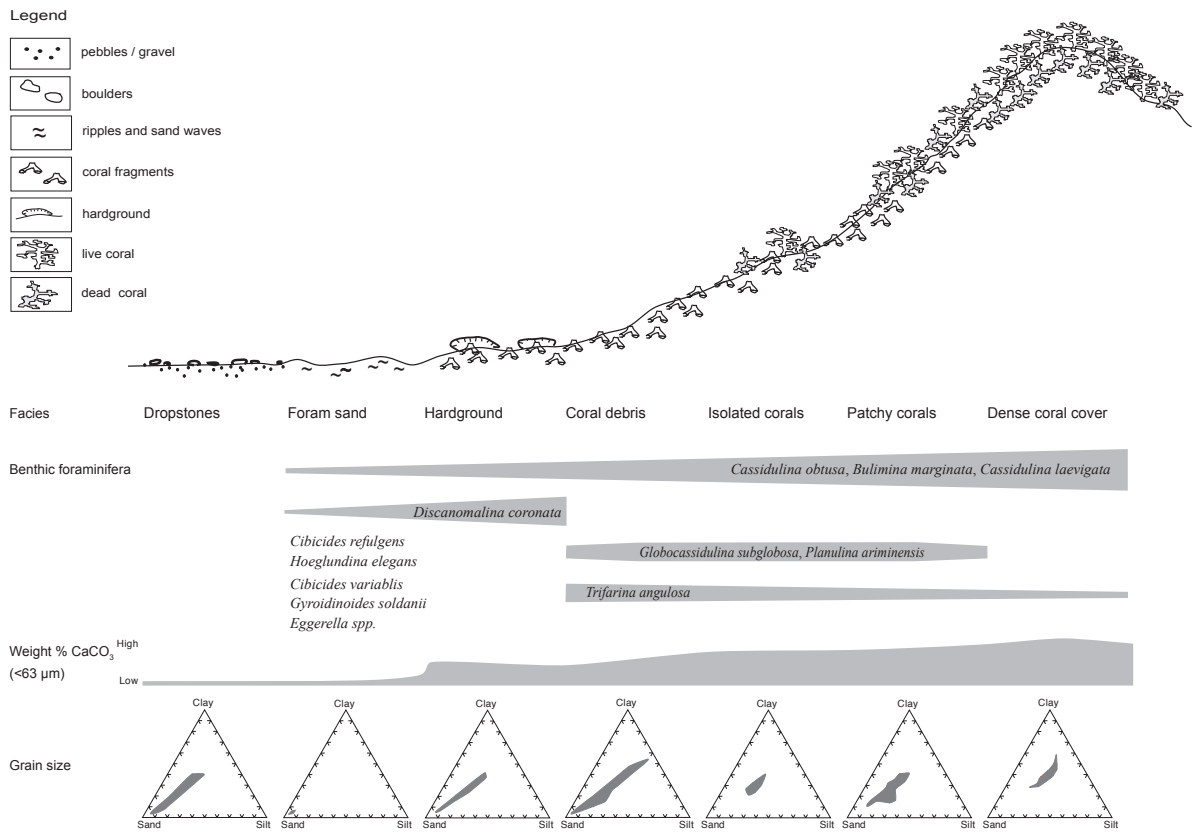


Fig. 12. Facies model showing the distribution of the most important benthic foraminiferal assemblages and the distinguishing sediment characteristics for each mound environment.

The attached epibenthic species *Discanomalina coronata* (assemblage 4) is common in off-mound sediments, but it is most abundant where hardgrounds have formed (Figs. 11 and 12). The abundance of the species in these environments may reflect hydrographic conditions in areas covered with cemented debris that are not protected by a coral cover, as the species is often observed in waters with high bottom current speeds and coarser sediments, on substrates that are slightly elevated above the seafloor (Hald and Vorren, 1987; Schönfeld, 1997; Schönfeld and Zahn, 2000). The species is often found attached to dead coral fragments and is considered endemic to mound environments (Margreth et al., 2009; Rüggeberg et al., 2007). In the former study, unstained benthic foraminifera in sediment of coral mounds along the Irish Margin were investigated. The authors found relatively high numbers of *D. coronata* in the ‘Sandwave Facies’. This is consistent with our findings in sandy off-mound settings, where the species makes up almost 10 % of the assemblage. However, when it is

considered that the species generally lives on dead coral fragments, its presence in off-mound samples may indicate reworking and transport of this species. The authors also distinguished a 'Living Coral Facies' where both infaunal and epifaunal species are present and which is dominated by *D. coronata*. In our data, *D. coronata* only made up at most 5 % of the assemblage where living corals are present and only 1.5 % under a dense living coral cover, as opposed to 25 % on hardgrounds and 9 % in off-mound sand. Although diagenetic processes may induce differences between surface sediment and our samples at 5 cm depth within the sediment, it is considered unlikely that the relatively large and robust species were much affected by these processes, whereas many fragile agglutinants and calcareous species with thin tests were preserved. It is therefore considered more likely that the observed differences between our model and that of Margreth et al. (2009) are due to the more detailed subdivision of on-mound facies types, especially with regard to the incorporation of hardgrounds and different degrees of coral cover. Whereas dead coral fragments can form a suitable elevated substrate for *D. coronata* to live on, the observed negative relationship with density of the coral cover may have to do with the inability of the species to attach to living coral. The only presently known species that can colonize the living corals is the parasitic *Hyrokkin sarcophaga* (Freiwald and Schönfeld, 1996). Secondly, with bottom current speed below the coral cover effectively reduced by the framework, the amount of suspended particulate matter that epibenthic foraminifera like *D. coronata* can feed on may be limited, and organic particles may rather accumulate below the framework favoring deposit-feeding soft-substrate dwelling foraminifera. The sedimentological and environmental conditions below a thriving coral cover apparently favor infaunal foraminifera.

The infaunal species *Cassidulina obtusa* (assemblage 1) is very abundant at stations with a dense coral cover (Figs. 11 and 12). The abundance shows an almost linear relationship with proximity to and density of living coral communities. *Bulimina marginata* and *Cassidulina laevigata* are also relatively abundant in these setting. These species, which are also shallow infaunal, generally live in muddy to fine sediments (Mendes et al., 2004; Murray, 1991), which is consistent with the results of grain size measurements and baffling of the finest sediments as evidenced by ^{210}Pb

measurements. Gooday and Hughes (2002) showed that *C. obtusa* and *B. marginata* are also abundant in phytodetrital deposits in the northern Rockall Trough, where they co-occur with other epifaunal and shallow infaunal species. Their distribution and abundance were closely linked to the deposition of labile organic matter. Considering that the interaction of local topography with hydrography is causing locally increased food supply at the mounds (Dickson and McCave, 1986; Mienis et al., 2007), the flux of organic material, combined with the muddy sediment that is baffled by the corals, may be the most important controls on the occurrence and abundance of the mound assemblage.

The relatively small infaunal species *Trifarina angulosa* (assemblage 2) is present in all samples that were analyzed (Figs. 11 and 12). It shows, however, a clear preference for sediment with coral debris, and thrives especially at sites where living corals are absent. The species has previously been described as dominant in areas with strong current activity and coarse-grained sediments in the Norwegian coastal areas (Kiltgaard-Kristensen et al., 2002). Mackensen et al. (1993) described the occurrence of *T. angulosa* in the eastern South Atlantic Polar Front region between 35° and 57° south. The species was again related to strong bottom currents, and seemed to be independent of water mass parameters and trophic conditions. Rasmussen (2002) studied millennial-scale variability in the North Atlantic and observed a co-occurrence with *Globocassiculina subglobosa*, which is also described as infaunal (Gooday, 2003). The occurrences of these species were related to periods with less organic material in the sediments, higher current velocities and better-ventilated bottom waters, where they constitute up to 20 % of the fauna. Our data show that *T. angulosa* and *G. subglobosa* together constitute 25-36 % of the assemblage in on-mound environments, which is significantly higher than is generally encountered in the North Atlantic. A higher abundance of these species may reflect the enhanced current regime. In our data, *G. subglobosa* was grouped with the epibenthic suspension feeder *Planulina ariminensis* in assemblage 2. Like *T. angulosa*, *G. subglobosa* and *P. ariminensis* occur preferentially on-mound, although our data suggests *T. angulosa* to have a preference for coral debris, whereas *G. subglobosa* and *P. ariminensis* are equally abundant in settings with few living corals. Similar results are described by (Margreth et al., 2009) who distinguish a

dead coral facies on Porcupine and Rockall Bank, where *G. subglobosa*, *Trifarina bradyi*, *T. angulosa* and *P. ariminensis* are the dominant species. Although in general epibenthic species do not appear to prefer environments with living corals, as is also visible in the distribution of species in assemblages 4 and 5, *P. ariminensis* seems to be well adapted to these settings. However, this does not refute the observation that infauna are more commonly found on-mound, while epibenthos thrive in off-mound settings. Whereas most epifaunal species encrust objects that are relatively close to the sediment-water interface, *P. ariminensis* is attached to protruding objects, such as hydroids and sponge skeletons which offers advantages in the competition for suspended food particles (Lutze and Thiel, 1989).

5 Conclusions

Foraminiferal assemblages that are encountered on Rockall and Porcupine Bank, in combination with sedimentological and geochemical data, allow to distinguish different environmental settings of cold-water corals. This can provide a method for reconstruction of fossil coral habitats and mound evolution using long sediment cores from coral mounds. An initial framework for the evolution of a mound can be obtained by grain size distributions, and CaCO₃ content of the <63 µm fraction, which can identify locations of dense coral frameworks, as well as the position of sand facies and glacial lag deposits. The framework that is provided by sediment characteristics can be further filled in and verified by the study of benthic foraminifera as species distributions appear to be primarily governed by sediment type and current speed. Typical off-mound species are *Cibicides refulgens*, *Hoeglundina elegans*, *Cibicides variabilis*, and *Eggerella spp.* The hardground assemblage is dominated by *D. coronata*, while *T. angulosa* is most abundant in coral debris. The abundance of species in the living coral assemblage, which consists of *Cassidulina obtusa*, *Bulimina marginata* and *Cassidulina laevigata*, almost linearly increases with the density of the living coral cover.

Appendix 1 – Taxonomic notes

Species name	Original notation	Citation including an illustration	Illustration in this manuscript
<i>Astrononion</i> sp.	Genus <i>Astrononion</i> , Cushman and Edwards (1937)	Ellis and Messina (1940)	
<i>Bulimina marginata</i>	<i>Bulimina marginata</i> , d'Orbigny (1826)	Jones (1994), Plate 51: 3–5	Plate 1: 1
<i>Cassidulina laevigata</i>	<i>Cassidulina laevigata</i> d'Orbigny (1826)	Jones (1994), Plate 54: 2-3	Plate 1: 2
<i>Cassidulina obtusa</i>	<i>Cassidulina obtusa</i> Williamson (1858)	Gooday and Hughes (2002), Plate 2: d	Plate 1: 3
<i>Cibicides refulgens</i>	<i>Cibicides refulgens</i> , de Montfort (1808)	Schweizer (2006), Plate 8: e-j	Plate 1: 4
<i>Cibicides variabilis</i>	<i>Cibicidella variabilis</i> , d'Orbigny (1839)	Cimerman and Langer (1991) Plate 77: 1-10	
<i>Discanomalina coronata</i>	<i>Anomalina coronata</i> , Parker and Jones (1857)	Jones (1994), Plate 97: 1-2	Plate 1: 5-6
<i>Eggerella</i> sp.	Genus <i>Eggerella</i> , Cushman (1933)	Ellis and Messina (1940)	Plate 1: 7
<i>Ehrenbergina pacifica</i>	<i>Ehrenbergina pacifica</i> , Cushman (1927)	Jones (1994), Plate 55: 4, 6-7	
<i>Globocassidulina subglobosa</i>	<i>Cassidulina subglobosa</i> , Brady (1881)	Jones (1994), Plate 54: 17	Plate 1: 8
<i>Gyroidina soldanii</i>	<i>Gyroidina soldanii</i> , d'Orbigny (1826)	Jones (1994), Plate 107: 6–7	
<i>Hoeglundina elegans</i>	<i>Rotalia (Turbinulina) elegans</i> , d'Orbigny (1826)	Koho et al. 2008 Plate 1: 3a-b	
<i>Planulina ariminensis</i>	<i>Planulina ariminensis</i> , d'Orbigny (1826)	Jones (1994), Plate 93: 10-11	Plate 1: 9
<i>Spirillina</i> spp.	Genus <i>Spirillina</i> , Ehrenberg emend. Smith and Isham (1974)	Ellis and Messina (1940)	
<i>Trifarina angulosa</i>	<i>Uvigerina angulosa</i> , Williamson (1858)	Jones (1994), Plate 74: 15-16	Plate 1: 10
<i>Uvigerina mediterranea</i>	<i>Uvigerina mediterranea</i> , Hofker (1932)	Koho et al. 2008 Plate 1: 7a-b	Plate 1: 11

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Appendix 1. List of genera and species used in the statistical analyses and facies model, including taxonomic references. Genera and species are listed in alphabetical order.

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