

Benthic foraminifera distribution in the Ross Sea (Antarctica) and its relationship to oceanography

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ABSTRACT - Modern deep-water benthic foraminiferal assemblages were studied from box cores collected in four areas of the Ross Sea, during the oceanographic cruise ANTA05 within the framework of the Italian Antarctic Research National Programme (PNRA). The investigated sites are characterised by different oceanographic settings. Samples from the Drygalski (site BC 33) and Lewis Basins (site BC 22) contain exclusively agglutinants taxa with high abundance of *Miliammina arenacea* (Chapman, 1916), *Trochammina* gr., *Portatrochammina* gr., *Lagenammina difflugiformis* (Brady, 1879), *Recurvoides contortus* Earland, 1934 and *Reophax* gr. On the other hand, samples from the Joides Basin (site BC 01) and from the Pennell Trough (site BC 38) are characterised by a higher species richness and by the presence of calcareous species (*Astrononion echolsi* Kennett, 1967, *Nonionella bradii* [Chapman, 1916] and *Fursenkoina fusiformis* [Williamson, 1858]). The absence of calcareous foraminifera, in the westernmost areas of the Ross Sea, may be attributed to the strong influence of the High Salinity Shelf Waters rich in CO₂ and to the presence of a shallow Calcite Compensation Depth. Microfaunal content observed in the Joides Basin (site BC 01) and in the Pennell Trough (site BC 38) is associated to the intrusion of the relatively warm, salty and rich in nutrients Modified Circumpolar Deep Waters. The study highlights that foraminiferal species composition and areal distribution is strongly related to local variation in water mass characteristics and provides evidence on the relationship between *Trochammina* gr. and biogenic silica content at the seafloor.

RIASSUNTO - [Distribuzione dei foraminiferi bentonici nel Mare di Ross (Antartide) e relazioni con l'oceanografia] - Il lavoro riguarda la distribuzione attuale dei foraminiferi bentonici presenti nei sedimenti superficiali (0-1 cm) di quattro box cores prelevati nel settore occidentale del Mare di Ross, durante la campagna oceanografica ANTA05, nell'ambito del Programma Nazionale di Ricerche in Antartide (PNRA). Il confronto tra i dati quantitativi e l'assetto idrografico delle aree investigate, caratterizzate da diverse condizioni oceanografiche, ha evidenziato la stretta relazione tra la tipologia e la variabilità areale della microfauna a foraminiferi bentonici e le masse d'acqua. Nel dettaglio, un'associazione con basse concentrazioni di foraminiferi e diversità specifica, caratterizzata dalla quasi esclusiva presenza di forme resistenti a guscio agglutinante e dominata dalla presenza di *Miliammina arenacea* (Chapman, 1916), *Trochammina* gr., *Portatrochammina* gr., *Lagenammina difflugiformis* (Brady, 1879), *Recurvoides contortus* Earland, 1934 e *Reophax* gr., è stata riscontrata nei box cores dei siti BC 33 e BC 22 situati rispettivamente nel Drygalsky e nel Lewis Basins, ovvero in aree fortemente interessate dalla presenza delle High Salinity Shelf Waters e da una minore profondità del livello di compensazione della calcite. Le associazioni con maggiore diversità specifica sono state invece notate nei box cores dei siti BC 01 e BC 38 prelevati nel Joides Basin e nel Pennell Trough, dove si ha l'intrusione della Modified Circumpolar Deep Water, una massa d'acqua relativamente calda, salata e ricca in nutrienti. In particolare, in corrispondenza del sito BC 01 sono presenti anche taxa a guscio calcareo, prevalentemente bentonici, quali *Astrononion echolsi* Kennett, 1967, *Nonionella bradii* (Chapman, 1916) e *Fursenkoina fusiformis* (Williamson, 1858). Questo studio evidenzia che la presenza e la distribuzione delle associazioni a foraminiferi in questa area del Mare di Ross è strettamente connessa alle condizioni oceanografiche locali. Il confronto tra la presenza delle specie più abbondanti ed i principali parametri abiotici in ambiente antartico (tenore di carbonio organico, contenuto in silice biogenica e presenza di carbonato di calcio) ha permesso di ampliare le conoscenze esistenti sull'ecologia della microfauna a foraminiferi bentonici in questa area, informazioni utili per paleo-ricostruzioni ambientali ed oceanografiche. In questo studio viene documentata una stretta relazione tra la distribuzione di *Trochammina* gr. e la disponibilità di silice biogenica sul fondale.

INTRODUCTION

The study of the ecosystem state in the Antarctic region has become increasingly important, because this area is more vulnerable to Ocean Acidification (OA), due to its relatively low total alkalinity and the increased CO₂ solubility in cold water (Orr et al., 2005). Modeling studies predict that surface waters in the Southern Ocean may start to become under-saturated with respect to aragonite and calcite (DeJong et al., 2015, and reference therein). Benthic foraminifera are traditionally considered as good environmental indicators since their distribution is related to the habitat physical, chemical and biological

characteristics, such as organic matter availability, bottom water dissolved oxygen concentration, nature of substrata, and water depth (Barras et al., 2014). The investigation of the relationships between benthic foraminifera and the surrounding environment in the Antarctic region has gained importance mainly because this area is characterised by high accumulation rates of silica and organic carbon (Dunbar & Leventer, 1989; Nelson, 1992; Murray & Pudsey, 2004). Changes in water masses with depth are clearly identified as the primary factor that influences the distribution of foraminifera in Antarctica (Anderson, 1975; Milam & Anderson, 1981). In some cases, even local variations of water masses and the seasonal melting of

the ice cover may affect the composition of foraminiferal associations (Massom & Stammerjohn, 2010).

Majewsky & Anderson (2009) have also indicated the ice cover, the activity of bottom currents, and the intensity of primary production as factors influencing the distribution of benthic foraminifera. Moreover, the conservation of calcareous foraminifera also depends on the Calcium Carbonate Compensation Depth (CCD) that in the Ross Sea is shallower because of the low temperature, the high CO₂ content and the low surface primary productivity, which are reduced owing to the presence of a thick pack-ice (Kennett, 1966, 1968; Anderson, 1975; Kellogg et al., 1979).

During the last fifty years, several authors carried out detailed studies on the foraminiferal distribution in Antarctic areas (e.g., McKnight, 1962; Finger & Lipps, 1981; Ishman & Domack, 1994; Murray & Pudsey, 2004); however, few investigations exist on the distribution of recent benthic foraminifera in the Ross Sea (Pflum, 1966; Osterman & Kellogg, 1979; Bernhard, 1987; Ward et al., 1987; Violanti, 1996) and on their relationships with local variation in water mass characteristics (D'Onofrio & Pugliese, 1989; Asioli, 1995; Bertoni et al., 2012).

In the sediments of the Ross Sea, the assemblage is often characterised by high numbers of agglutinants with respect to calcareous taxa. This distribution is the result of CO₂ accumulation at the seafloor, leading to higher solubility of CaCO₃. Moreover, the dissolution of calcareous test is strongly controlled by the presence of a shallow CCD, thus leading to increasing abundances of agglutinated taxa or even to the absence of foraminifera (Milam & Anderson, 1981; Schröder-Adams, 1990). Studies performed on living and dead specimens of benthic foraminifera also show, in some cases, the presence of taphonomic effects that determine the dissolution of calcareous tests and the loss of fragile agglutinated tests (Mackensen et al., 1993; Asioli, 1995; Violanti, 1996; Murray & Pudsey, 2004). For all the aforementioned reasons, the preserved fossil assemblages (tanatocenosis) can potentially differ from the living microfaunas (biocenosis) (Mackensen et al., 1993; Violanti, 1996).

In order to obtain modern analogues to be used for reconstruction in the geological record, additional knowledge on recent assemblages from several environment with different water depth and oceanographic settings is needed.

This work aims at describing and better understanding the spatial distribution and composition of recent benthic foraminiferal microfauna from the Ross Sea collected during the oceanographic cruise ANTA05. We select four sites characterised by different oceanographic regimes as key areas to monitor the formations and transit of dense shelf waters in this region (Jacobs et al., 1985). The results from this study increase the current knowledge on the relationships between benthic ecosystems and oceanographic regime in the Antarctic region.

REGIONAL SETTING

Geographical and bathymetric setting

The Ross Sea is located in the Pacific sector of the Southern Ocean, between Cape Colbeck at 158°W and

Cape Adare at 170°E. On the southern side, it is bounded by the Ross Ice Shelf, at around 78.5°S. This broad ice cover, which extends over nearly half the continental shelf, is about 250 m thick on its northernmost side (Budillon et al., 2002). The Ross Sea is characterised by a deep and irregular continental shelf with a mean depth of 500 m. Its eastern region is composed by slightly elevated reliefs, while the western side shows an extremely irregular topography, largely due to glacial erosion (Anderson et al., 1984). The central western sector is characterised by alternating reliefs and depressions, some of which are deeper than the shelf edge. Indeed, the bottom topography in this zone is rather irregular, with the ~ 500 m deep shelf isolated from the shore by a canyon, oriented north-eastward and deeper than 1000 m, the Drygalsky Basin (Budillon et al., 2002).

Water Masses

The circulation on the Ross Sea shelf is rather complex; here we report the most important water masses that influence the benthic faunal distribution in this area. Variations in physical properties along the seawater column determine a vertical structure from the surface to the bottom (Fig. 1).

At the sea-surface, the Antarctic Surface Waters (AASW) enter in the Ross Sea around Cape Colbeck as part of a narrow coastal flow that, in addition to importing sea ice and icebergs, also incorporates continental meltwater derived from sea ice-air interactions farther upstream (Jacobs et al., 1985). In summer, AASW is a warm (temperature up to 2.0 °C) and fresh (salinity 33.5–34.5 per mil) water mass produced from the mixing of shelf waters and ice meltwater, or from the up-welling of the Circumpolar Deep Waters (CDW). It is the most variable water mass in the Ross Sea (Cincinelli et al., 2008). Low Salinity Shelf Water (LSSW), characterised by relatively high temperatures and low salinities (~ 34.4–34.6 per mil), flows below the AASW mainly on the eastern part of the Ross Sea Shelf (Jacobs et al., 1985). The intermediate waters are usually characterised by oceanic waters, entering in the Ross Sea from outside the shelf. The CDW is the greatest volume water mass in the Southern Ocean (SO), it is a mixture of Atlantic Deep Water and Antarctic Water, as well as recirculated deep water from the Indian and Pacific Oceans (e.g., Callahan, 1972; Georgi, 1981; Charles & Fairbanks, 1992; You, 2000). CDW is a relatively warm, salty and nutrient-rich water mass carried around Antarctica by the Antarctic Circumpolar Current (ACC) (Whithworth & Nowlin, 1987), that evolves by mixing, cooling and by inputs from precipitation, melting and brine formation into several new water masses on and near the Antarctic Continental Shelf (Jacobs et al., 1985; Catalano et al., 2000; Russo, 2000). In the Ross Sea, the mixing of the CDW with the surface and shelf waters forms the Modified CDW (MCDW; Fig. 1), or Warm Core (WMCO), characterised by a temperature between +1.0 and -1.5 °C (Cincinelli et al., 2008). MCDW intrudes into the continental shelf in several locations, mostly along the east side of troughs (Joides & Drygalsky Basins), but also in the Glomar Challenger Basin (Jacobs & Giulivi, 1999; Budillon et al., 2003; Orsi & Wiederwohl, 2009; Dinniman, 2011; Kohut et al., 2013). MCDW waters form warmer and saltier layer in the water column.

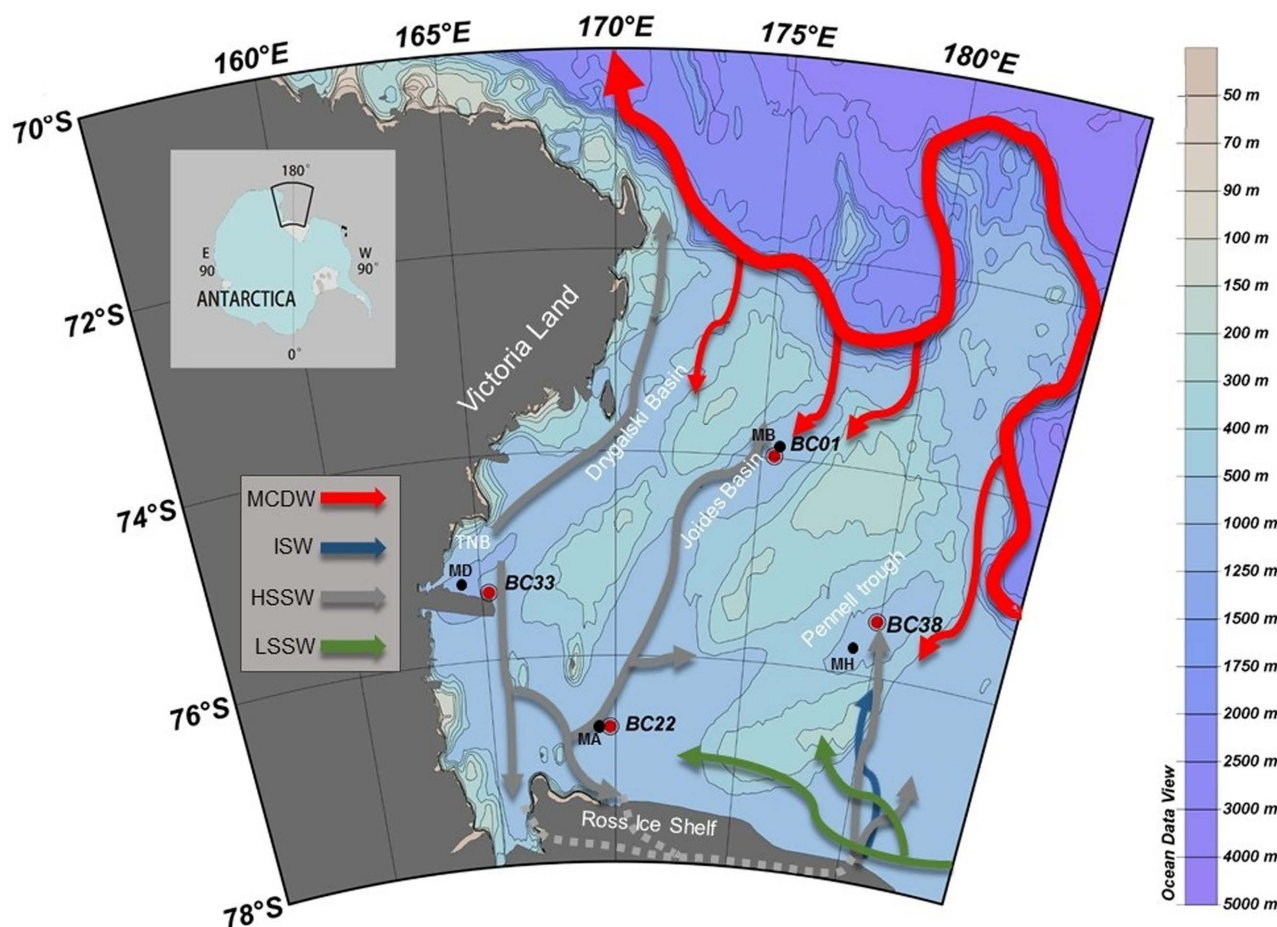


Fig. 1 - Study area with the location of investigated sites (BC 01, BC 22, BC 33 and BC 38; red circles) and the mooring (MA, MB, MD, MH) locations (black circles). The main water masses horizontal pathways on the Ross Sea shelf are also indicated. MCDW: Modified Circumpolar Deep Waters; ISW: Ice Shelf Water; HSSW: High Salinity Shelf Waters; LSSW: Low Salinity Shelf Water (LSSW). TNB: Baia Terra Nova Italian scientific station.

Below this layer, temperatures decreased gradually with depth, while salinities increased (Cincinelli et al., 2008); this was probably due to the intrusion of MCDW and to its mixing with colder and saltier waters in the bottom. Deeper waters were mostly derived from High Salinity Shelf Waters (HSSW; Fig. 1) and were characterised by low temperatures (-1.9°C) and high salinities (34.7 per mil) (Jacobs et al., 1985). HSSW are the densest waters of the Ross Sea (Jacobs et al., 1985) and are formed during the Austral winter (Jacobs et al., 1985) on the wind-generated coastal polynyas of Victoria Land, particularly in Terra Nova Bay (TNB) and then move northward following the clockwise circulation (Budillon et al., 1999). This water mass plays a crucial role in the formation of Antarctic Bottom Water (AABW) (Kurtz & Bromwich, 1985; Jacobs and Comiso, 1989; Van Woert, 1999), thus contributing to deep ocean ventilation and the global thermohaline circulation (Jacobs et al., 1985; Orsi et al., 1999; Jacobs, 2004). MCDW intruding under the Ross Ice Shelf (RIS) interacts actively at its base (Budillon et al., 2000; Budillon & Spezie, 2000) to form the Ice Shelf Water (ISW; Fig. 1), characterised by temperature and salinity lower than the surface freezing point (Jacobs et al., 1985; Trumbore et al., 1991; Locarnini, 1994; Hofman & Klink, 1998; Budillon et al., 2000).

The four investigated sites are characterised by different oceanographic regimes (Fig. 1). Site BC 01 is located in the Joides Basin, in an area influenced by strong lateral advection, and low vertical sedimentation (Langone et al., 2000). The surface mixed layer at this station is occupied by the AASW, while between 70 and 200 m, a warmer and saltier layer is present, probably due to the intrusion of MCDW. Below this layer, temperatures decrease gradually with depth, while salinities increase. Bottom waters (> 450 m depth) are mostly derived from the cold and salty HSSW (Langone et al., 2000).

Site BC 22 is located in a quite flat area characterised by high biogenic fluxes through the water column (Langone et al., 2003) and by weak currents at the bottom flowing from Terra Nova Bay (TNB) polynya. In this region, the seasonal increase in sea ice extent inhibits fine sediment and organic matter accumulation at the sea-floor.

Site BC 33 is located in the western sector of the Ross Sea, inside the wind-driven TNB polynya and just north of the Drygalski Ice Tongue. The polynya opening results principally from the synergy of meteorological, oceanographic, and geographic features of this region. Especially during winter, the TNB polynya is frequently forced by cold and strong katabatic downslope flows that push new-formed sea ice away from the coast (Sansiviero

et al., 2017); it is considered to be the largest producer of HSSW (Kurtz & Bromwich, 1983, 1985; Jacobs et al., 1985; Van Woert, 1999a, b; Budillon & Spezie, 2000; Budillon et al., 2003; Fusco et al., 2009). The vertical structure of the water column at this station, shows a thin surface layer, characterised by relatively high temperature and low salinity, corresponding to AASW (Jacobs et al., 1985). The HSSW lies below the surface layer, extending down to the bottom (Cincinelli et al., 2008). Most of the HSSW produced in the polynya move northward along the Victoria Land coast and escape from Cape Adare down to the slope. However, part of the HSSW flows southward until reaches Ross Island and the RIS and divides into two branches (Fig. 1). The first one moves around the southern part of the Mawson Bank and goes back to the north through the Joides Basin (Budillon et al., 2002, 2011; Orsi & Wiederwohl, 2009; Gordon et al., 2015). The second branch flows under the RIS and operates glacial ice melting, contributing to originate the Ice Shelf Water (ISW; Jacobs et al., 1970); this water mass, characterised by temperatures below the sea surface freezing point emerges from beneath the RIS in the central-eastern sector of the Ross Sea (Jacobs & Giulivi, 1999), and moves northward, where site BC 38 is positioned, reaching the shelf break near 75°S just to the east of the dateline (Jacobs et al., 1985).

MATERIALS AND METHODS

Sediment samples were collected using a box corer from four different sites of the Ross Sea continental shelf (sites BC 01, BC 22, BC 33 and BC 38) (Fig. 1, Tab. 1) during the oceanographic cruise ANTA05 in the framework of the Italian Antarctic Research National Programme (PNRA). Actually, our sample sites correspond (or are near) to four mooring sites active since

Site	Latitude	Longitude	Water depth (m)	Mooring site
BC 01	73° 58.95' S	175° 02.59'	578	Mooring B
BC 22	76° 41.59' S	169° 04.68'	790	Mooring A
BC 33	75° 20.44' S	165° 16.52'	687	Near Mooring D
BC 38	75° 27.45' S	179° 52.52'	559	Near Mooring H

Tab. 1 - Details of sample locations (name, geographical coordinates, water depth and mooring site).

1994 in the frame of different national research projects of the PNRA (Tab. 1).

Penetration of the box-corer was approximately 40 cm and the samples retrieved were undisturbed, with clear water overlying the sediment surface. Then, plastic tubes of 10 cm of diameter were inserted in the central area of each box cores to obtain short cores. In the laboratory, one core for each site was split in half, visually described and sub-sampled at 1-2.5 cm intervals for sedimentological, geochemical and micropalaeontological analyses prior to archiving.

Micropalaeontological analyses

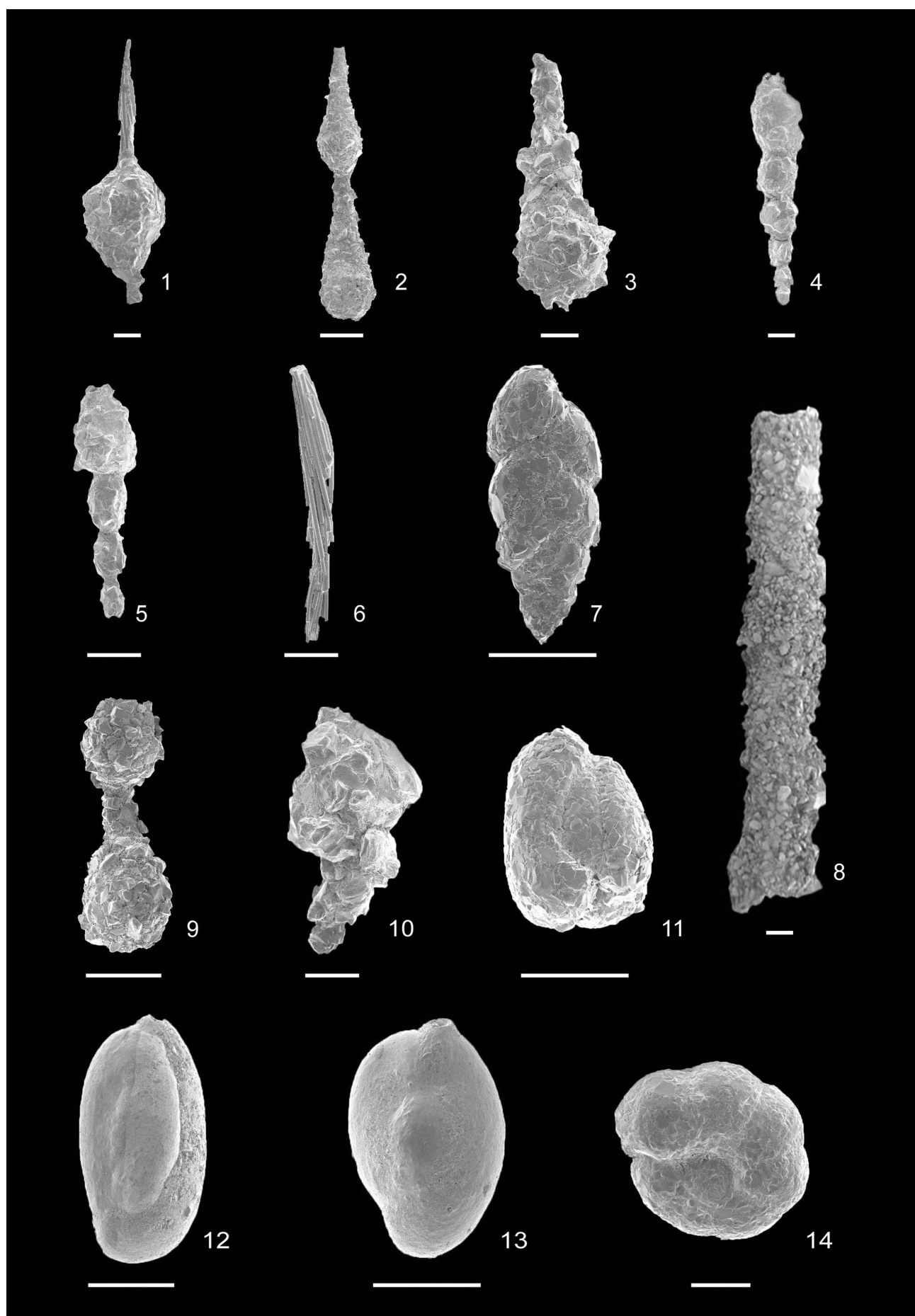
Samples were gently washed through a 63 µm sieve and dried at 50 °C. Quantitative analyses were performed on the > 63 µm size fraction with an optical stereomicroscope. All the foraminiferal specimens were picked up, counted and identified following Loeblich & Tappan (1987), Violanti (1996), and Murray & Pudsey (2004). The taxa not determined at species level are left in open nomenclature (e.g., *Hyperammina* sp.). *Portatrochammina* gr. includes *Portatrochammina antartica* (Parr, 1950) and *Portatrochammina wiesneri* (Parr, 1950); *Trochammina* gr. corresponds to *Trochammina* cf. *quadricamerata* (Echols, 1971) and *Trochammina multiloculata* Höglund, 1947. The list of identified species is reported in Appendix A and the most common taxa are illustrated in Plates 1

EXPLANATION OF PLATE 1

Scanning electron micrographs of the main foraminifera specimens identified in the core-top samples (level 0-1 cm) from four sites of the Ross Sea continental shelf (Antarctica).

- Fig. 1 - *Hormosinella distans* (Brady, 1881); site BC 01. Repository Code n. 23896 b 1.
- Fig. 2 - *Hormosinella ovicula* (Brady, 1879); site BC 01. Repository Code n. 23896 b 2.
- Fig. 3 - *Lagenammina difflugiformis* (Brady, 1879); site BC 01. Repository Code n. 23896 b 3.
- Figs 4-5 - *Reophax subfusiformis* Earland, 1933; site BC 01 and site BC 22. Repository Code n. 23896 b 4 and Repository Code n. 23589 b 1, respectively.
- Fig. 6 - *Reophax spiculifer* Brady, 1879; site BC 01. Repository Code n. 23896 b 5.
- Fig. 7 - *Pseudobolivina antarctica* Wiesner, 1931; site BC 01. Repository Code n. 23896 b 6.
- Fig. 8 - *Rhabdammina* sp.; site BC 01. Repository Code n. 23896 b 7.
- Fig. 9 - *Reophax guttifer* Brady, 1881; site BC 01. Repository Code n. 23896 b 8.
- Fig. 10 - *Reophax scorpiurus* de Montfort, 1808; site BC 01. Repository Code n. 23896 b 9.
- Fig. 11 - *Adercotryma glomerata* (Brady, 1878); site BC 01. Repository Code n. 23896 b 10.
- Figs 12-13 - *Miliammina arenacea* (Chapman, 1916); site BC 01 and site BC 22. Repository Code n. 23896 b 11 and Repository Code n. 23589 b 2, respectively.
- Fig. 14 - *Recurvoides contortus* Earland, 1934; site BC 01. Repository Code n. 23896 b 12.

Scale bar corresponds to 200 µm. All figured specimens are stored at the Institute of Marine Sciences (ISMAR) Bologna - micropaleontology collection, Antarctic section.



and 2. In this study, we report data on the foraminiferal assemblages collected in the topmost subsamples (0-1 cm interval of sediment) of each core. The investigated material is stored at the Institute of Marine Sciences (ISMAR) Bologna - micropalaeontology collection, Antarctic section (Archive repository numbers 23896 and 23897 for site BC 01; repository numbers 23589 and 23590 for site BC 22; repository number 24326 for site BC 33; repository numbers 23667 and 23668 for site BC 38).

Geochemical analyses

Calcium Carbonate content (CaCO_3) was calculated following the equation of Heussner et al. (1990): $\% \text{CaCO}_3 = (\% \text{C}_{\text{tot}} - \% \text{C}_{\text{org}}) \times 8.33$ where C_{tot} and C_{org} are total and organic carbon contents of the sample, respectively, and were determined with a FISONs NA2000 Elemental Analyzer.

Biogenic silica contents were obtained by the progressive dissolution method (Mortlock & Froelich, 1989), using NaOH 0.5 M as extractant, due to the supposed large amount of SiO_2 in the samples (DeMaster et al., 1981). The leaching was carried out on 20 mg of sediment at 85 °C, taking 0.2 ml aliquots for analysis every hour for four hours.

Statistical analyses

In order to quantifying the diversities of the benthic foraminiferal assemblage, the most common indices were calculated (Taxa Diversity, Shannon Index and Evenness) for each site. Additionally, to highlight the relationships between the most abundant/dominant species and/or group of species (*L. diffugiformis*, *M. arenacea*, *Portatrochammina* gr., *Reophax* gr., *Rabdamminella* sp., *Trochammina* gr.) and the main environmental parameters at the sea floor in this area (organic carbon, biogenic silica and CaCO_3 content), a Correlation Analysis was carried out

on the dataset. For this test, the agglutinated foraminifera were calculated as relative percentages (%) on the total agglutinated specimens in each site (Appendix B).

Statistical analyses were performed using the PAST-PALaeontological STatistics (version 3.14b) software. The obtained correlation coefficient (r), is a measure of the strength and direction of the linear relationship between two variables and is defined as the covariance of the variables divided by the product of their standard deviations.

RESULTS

Sediment features and chronology

The surficial sediments are mud/sandy silt-rich likewise the lithofacies that drapes the seafloor of the Ross Sea (Prothro et al., 2018). The sandy fraction increases in the easternmost part of the investigated area (site BC 33) and can be interpreted as ice-rafted debris (sensu Anderson et al., 1980). The description of the lithology > 63 micron for each box core is summarised in Tab. 2 together with the main geochemical parameters measured in the first centimeter of the sediment (0-1 cm). Maximum concentration of biogenic silica is found at site BC 01 and the organic carbon reveals little variation without distinctive trends. The CaCO_3 content is generally low and decreases with water depth in sites BC 38, BC 33 and BC 22 that are influenced by the transit of HSSW.

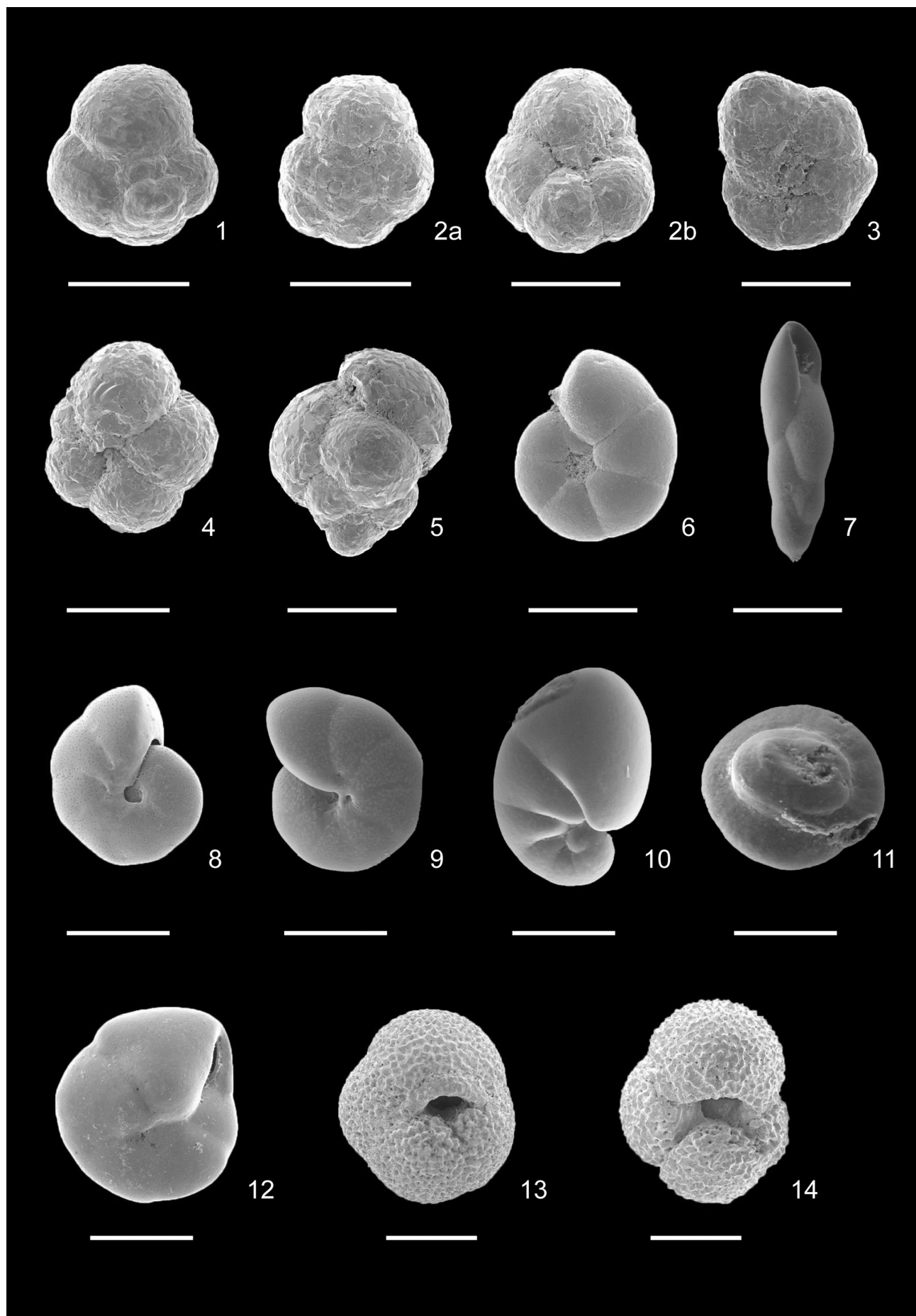
The age control of the sediments is based on ^{210}Pb analysis carried out at ISMAR-CNR Bologna following the procedure reported in Frignani & Langone (1991) and Frignani et al. (1993). The $^{210}\text{Pb}_{\text{excess}}$ profiles given in Fig. 2 document that the upper part of the sediments (about 10 cm in depth at site BC 01 and BC 22, 7 cm at site BC 33 and 6 cm at site BC 38) represents the material accumulated during the last 100-150 yrs, in agreement

EXPLANATION OF PLATE 2

Scanning electron micrographs of the main foraminifera specimens identified in the core-top samples (level 0-1 cm) from four sites of the Ross Sea continental shelf (Antarctica).

- Fig. 1 - *Portatrochammina wiesneri* (Parr, 1950); site BC 01. Repository Code n. 23896 b 13.
- Fig. 2 - *Portatrochammina antartica* (Parr, 1950) (a: spiral view; b: umbelical view); site BC 01. Repository Code n. 23896 b 14.
- Fig. 3 - *Deuterammina grisea* (Earland, 1934); site BC 01. Repository Code n. 23896 b 15.
- Fig. 4 - *Trochammina* cf. *quadricamerata* (Echols, 1971); site BC 01. Repository Code n. 23896 b 16.
- Fig. 5 - *Pseudotrochammina bullata* (Höglund, 1947); site BC 01. Repository Code n. 23896 b 17.
- Fig. 6 - *Labrospira wiesneri* Parr, 1950; site BC 01. Repository Code n. 23896 b 18.
- Fig. 7 - *Fursenkoina fusiformis* (Williamson, 1858); site BC 01. Repository Code n. 23896 b 19.
- Fig. 8 - *Pullenia subcarinata* (d'Orbigny, 1839); site BC 01. Repository Code n. 23896 b 20.
- Fig. 9 - *Astrononion echolsi* Kennett, 1967; site BC 01. Repository Code n. 23896 b 21.
- Fig. 10 - *Nonionella bradyi* (Chapman, 1916); site BC 01. Repository Code n. 23896 b 22.
- Fig. 11 - *Glomospira charoides* (Jones and Parker, 1860); site BC 01. Repository Code n. 23896 b 23.
- Fig. 12 - *Epistominella exigua* (Brady, 1884); site BC 01. Repository Code n. 23896 b 24.
- Fig. 13 - *Neoglobobulimina pachyderma* (Ehrenberg, 1861) sinistral (sin); site BC 01. Repository Code n. 23896 c 1.
- Fig. 14 - *Globigerina bulloides* d'Orbigny, 1826; site BC 01. Repository Code n. 23896 c 2.

Scale bar corresponds to 200 μm . All figured specimens are stored at the Institute of Marine Sciences (ISMAR) Bologna - micropalaeontology collection, Antarctic section.



Site	Level (cm)	Sediment composition and description	Organic carbon (%)	Biogenic Si (%)	CaCO ₃ (%)
BC 01	0-1	• Diatomaceous silty clay	0.33	29.9	6.10
		• Light brown in color			
		• Many sponge spicules and radiolarians			
BC 22	0-1	• Silty clay	1.51	22.1	0.00
		• Olive-brown in color			
		• Sponge spicules and radiolarians			
		• Rare millimetric pebbles			
BC 33	0-1	• Sandy silt	0.55	18.1	0.40
		• Olive brown in color			
		• Silty clay			
BC 38	0-1	• Brown-gray in color	1.18	16.8	0.50
		• Sponge spicules and radiolarians			

Tab. 2 - Surface sediment characteristics for each box core and geochemical parameters (organic carbon, biogenic silica and CaCO₃ content).

with the accumulation rates known for these areas (see Langone et al., 1998; Frignani et al., 2003). Based on these results, the foraminiferal content discussed in this study, from the first centimeter (0-1 cm), is representative of the recent assemblage occurring today in the sediment-water interface of the investigated sites.

Foraminiferal distribution

Foraminiferal assemblages in the four core-top samples are dominated by benthic taxa: 23 agglutinated species and seven calcareous species were identified (Fig. 3 and Tab. 3). The sample from site BC 01 is the only containing few planktic foraminiferal species; samples from sites BC 22 and BC 33 are exclusively composed of agglutinated benthic foraminifera. In all samples, the H index value ranges between 2 and 3 and the population show an Evenness index increasing from 0.55 (site BC 01) to 0.77 (site BC 22) (Tab. 3).

Benthic microfauna identified in sample from the Joides Basin (site BC 01) (Fig. 1) is characterised by the highest foraminiferal species richness (15 specimens/gram of sediment), with 22 agglutinated species, seven calcareous species (*A. echolsi*, *Epistominella exigua* [Brady, 1884], *Fursenkoina fusiformis* [Williamson, 1858], *Globocassidulina bitor* [Crespin, 1960], *N. bradii*, *Pullenia subcarinata* [d'Orbigny, 1839], and *Trifarina angulosa* [Williamson, 1858]), and three planktic species (*Neogloboquadrina pachyderma* [Ehrenberg, 1861] sinistral (sin), *Globigerina bulloides* d'Orbigny, 1826 and *Turborotalita quinqueloba* [Natland, 1938]) (Fig. 3, Tab. 3, Pls 1 and 2). The most abundant agglutinated taxa are *T. cf. quadricamerata* (~ 17% of the total benthic assemblage), *L. difflugiformis* (12%), *Reophax* gr. (~ 11%), *M. arenacea* (11%), *Pseudotrochammina bullata* (Höglund, 1947) (7%), and *Adercotryma glomerata* (Brady, 1978) (4%) (Pls 1 and 2). The tests (both benthic and planktic) are generally well preserved and also some

fragile species are present (e.g., *Adercotryma glomerata* [Brady, 1978] and *Reophax spiculifer* [Brady, 1979]).

Foraminiferal assemblage in sample from the Lewis Basin (site BC 22) (Fig. 1) is characterised by low abundances (7.4 specimens/gram of sediment) and low diversity (14 species with 13 agglutinated taxa) (Fig. 3, Tab. 3, Pls 1 and 2). The assemblage is dominated by *M. arenacea* (22%) with *Hyperammina* sp. (13%), *T. multiloculata* (13%), *L. difflugiformis* (9%) and different species belonging to the *Reophax* gr. (each species ~ 7%).

In the sample from site BC 33, collected in the Drygalski Basin (Fig. 1), foraminiferal microfauna is

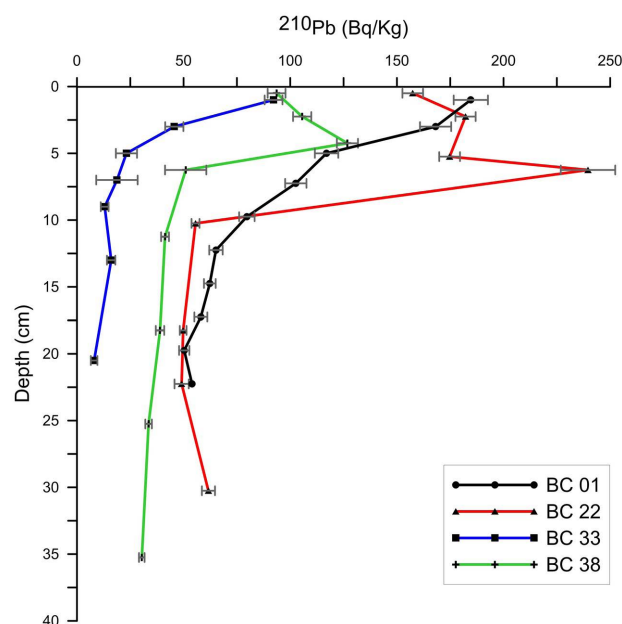


Fig. 2 (color online) - Total ²¹⁰Pb vs. depth in the investigated box cores.

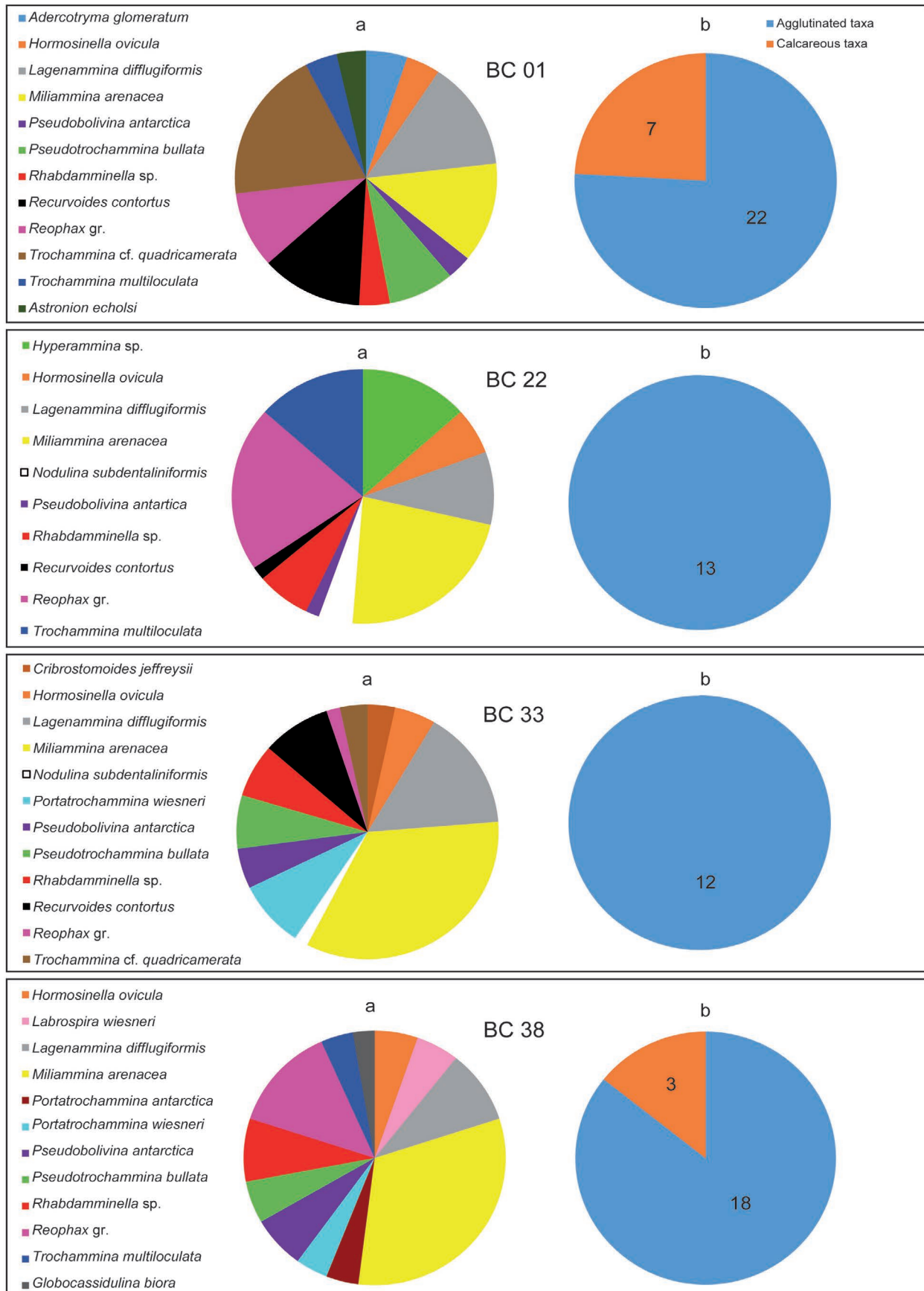


Fig. 3 - a) Benthic foraminiferal components (% of the total assemblage) from core-top samples (0-1 cm) (for graphical reason, species with an occurrence < 1% are not reported). b) Number of calcareous and agglutinated benthic foraminiferal species from surface samples (0-1 cm).

Sample	BC 01	BC 22	BC 33	BC 38
Sediment interval (cm)	0-1	0-1	0-1	0-1
gram of dry sediment	40.06	16.25	19	16.8
Agglutinated species				
<i>Adercotryma glomerata</i>	27			
<i>Cribrostomoides jeffreysii</i>	4	1	2	1
<i>Deuterammina grisea</i>	6			1
<i>Glomospira gordialis</i>	1			
<i>Hyperammina</i> sp.		16		
<i>Hormosinella distans</i>	2			
<i>Hormosinella ovicula</i>	21	7	3	4
<i>Labrospira wiesneri</i>	9			4
<i>Lagenammina difflugiformis</i>	73	11	9	7
<i>Miliammina arenacea</i>	67	27	20	24
<i>Nodulina subdentaliformis</i>	1	5	1	
<i>Portatrochammina antartica</i>	7			3
<i>Portatrochammina wiesneri</i>	8		5	3
<i>Pseudobolivina antarctica</i>	16	2	3	5
<i>Pseudotrochammina bullata</i>	43		4	4
<i>Recurvoides contortus</i>	66	2	5	1
<i>Reophax scorpiurus</i>	15	9	1	1
<i>Reophax subfusiformis</i>	16	8		1
<i>Reophax guttifer</i>	11			4
<i>Reophax spiculifer</i>	9	8		4
<i>Rhabdammina</i> sp.	20	8	4	6
<i>Trochammina</i> cf. <i>quadricamerata</i>	102		1	1
<i>Trochammina multiloculata</i>	21	16		3
Calcareous species (Benthic)				
<i>Astronion echolsi</i>	19			1
<i>Epistominella exigua</i>	6			
<i>Fursenkoina fusiformis</i>	4			1
<i>Globocassidulina biora</i>	2			2
<i>Nonionella bradii</i>	7			
<i>Pullenia subcarinata</i>	1			
<i>Trifarina angulosa</i>	1			
Calcareous species (Planktic)				
<i>Globigerina bulloides</i>	4			
<i>Turborotalita quinqueloba</i>	2			
<i>Neogloboquadrina pachyderma</i> (sin)	15	1		1
Total of counted specimens	606	121	58	82
No. of benthic specimens/g sediment	15	7.4	3.1	4.9
No. of agglutinated species	22	13	12	18
No. of calcareous species (Benthic)	7	0	0	3
No. of calcareous species (Planktic)	3	1	0	1
Taxa Diversity	29	13	12	21
Shannon Index (H)	2.76	2.30	2.08	2.57
Evenness (E)	0.55	0.77	0.67	0.62

similar to the one observed at BC 22 in terms of both abundance (three specimens/gram of sediments) and diversity (12 species) (Fig. 3 and Tab. 3). The benthic microfauna is entirely composed of agglutinated taxa, with high abundance of *M. arenacea* (34%), *L. difflugiformis* (15%), *R. contortus* (8%), *P. wiesneri* (8%), *P. bullata* (~ 7%) and *Rhabdamminella* sp. (~ 7%) (Fig. 3, Tab. 3, Pls 1 and 2).

The sample from site BC 38, located in the Pennell Trough (Fig. 1), contains 18 agglutinated species, three calcareous species (*G. biora*, *A. echolsi*, *F. fusiformis*) and one planktic taxon (*N. pachyderma* [sin]) with low frequencies (4.9 specimens/gram of sediments) (Fig. 3 and Tab. 3). The most common taxa are *M. arenacea* (29%), *L. difflugiformis* (9%), and *Rhabdamminella* sp. (8%) (Fig. 3, Tab. 3, Pls 1 and 2).

DISCUSSION

Recent benthic foraminiferal fauna collected in four areas of the Ross Sea is dominated by agglutinated taxa. However, the content of calcareous species is difficult to evaluate as it can be significantly affected by post core-recovery dissolution. In fact, the presence of corrosive interstitial water might cause the post depositional dissolution of calcareous foraminifera, prior to the core sampling as already documented by Osterman et al. (2001). Previous investigations (Murray & Pudsey, 2004), performed on total (living and dead) foraminiferal assemblages in the surface sediment samples (0-1 cm), suggest that the main differences between living and dead assemblages could be related to taphonomic changes such as dissolution of calcareous tests and loss of the more fragile agglutinated forms. Therefore, here we focus principally on the agglutinated taxa that characterise and dominate the benthic assemblages.

Relatively high abundances, richness and diversity are common in the northernmost site (BC 01). Here, the assemblage is dominated by *Trochammina* gr., *L. difflugiformis*, *M. arenacea* and *R. contortus*, as already documented in this region in late-Holocene sediments by Melis & Salvi (2009). The preservation of the test of different species of benthic calcareous foraminifera and the relatively high species diversity suggest favorable environmental conditions for the benthic microfauna. In addition, the occurrence of *Epistominella*, *Fursenkoina* and *Nonionella*, opportunistic species, associated with the availability of organic matter (Gooday, 1996) indicates high organic flux to the bottom. These observations may be explained with the inflow of MCDW in this site as this water mass is relatively warm, salty and rich in nutrients. In addition, the presence of planktic species such as *N. pachyderma* (sin) and *G. bulloides* can be diagnostic of the intrusion of open-ocean surface water in this area. However, the comparison of the planktic assemblage observed in this study with the results obtained from plankton tows collected in the same station (Bergami et al., 2009) highlights the low abundance of calcareous shells in

the sediment. Also, in other studies from Antarctica, living calcareous specimens are not always present in the dead assemblages (e.g., Violanti, 1996). The higher resistance to dissolution of agglutinated forms compared to the calcareous tests, the latter being more prone to dissolution, could explain the observed anomaly as suggested by previous investigations (Osterman & Kellogg, 1979; Milam & Anderson, 1981; Anderson, 1999; Mikhalevich, 2004). Furthermore, other benthic calcareous groups such as cold-water corals and bivalves are documented to occur just northwestern of the studied area (Elverhoi & Roaldset, 1983; Taviani et al., 1993; Anderson, 1999) and their presence has been linked to abundant nutrients delivered by the intruding MCDW. The inferred relationship between the presence of the MCDW and a higher preservation of calcareous specimens can explain the occurrence of some calcareous taxa observed also in the Pennell Trough at site BC 38. In fact, in this area of the Ross Sea, the influence of MCDW is prominent, especially considering that the corrosive HSSW is mitigated by the contact with other water masses (Castagno et al., 2017). These assumptions are in agreement with previous studies that invoked the MCDW as a factor controlling the higher productivity and the improved preservation of calcareous foraminifera in different areas of Antarctica (Mackensen et al., 1990; Domack et al., 1995; Igarashi et al., 2001; Pudsey et al., 2006).

By contrast, samples collected in the Drygalski Basin (site BC 33) and in the Lewis Basin (site BC 22) contain poor assemblages characterised by the absence of calcareous foraminifera and the presence of the more resistant agglutinated taxa with the dominance of *M. arenacea*, *L. difflugiformis*, *Rhabdamminella* sp., *R. contortus* and *Portatrochammina* gr. The observed foraminiferal assemblage reflects the presence of a shallower CCD and the influence of the HSSW at the bottom. In fact, *M. arenacea* is reported to be common in cold saline shelf water of the Antarctic continental margin (Milam & Anderson, 1981; Murray, 1991; Ishman & Domack, 1994) as it shows high tolerance to cold corrosive bottom waters and to fluctuations in salinity (Ishman & Sperling, 2002). The foraminiferal species observed at these sites are very similar to the assemblages documented in recent sediments studied by Violanti et al. (1996) and Murray & Pudsey (2004), who attributed their composition mainly to post-mortem calcareous dissolution and to the shell deposition at, or below, the CCD (Kennett, 1968). The investigated sites are intensely affected by the presence of the HSSW at the bottom and by the presence of a shallow CCD (~ 550 m in this region; Kennett, 1968). In the Drygalski Basin (site BC 33), the high frequency of suspension feeder tubular species, such as *R. contortus* and *Rhabdamminella* sp., which are taxa preferring deep-water habitats where bottom currents deliver food sources (Linke & Lutze, 1993), is interpreted as the result of the lateral advection of detrital particles. These particles are transported by bottom currents triggered by the movement of salty and cold waters (HSSW) especially during winter season. The composition of sedimentary fluxes in this

Tab. 3 - Counting list of Foraminifera in core-top samples (0-1 cm) from sites BC 01, BC 22, BC 33 and BC 38 and ecological indices in the benthic assemblages (Taxa Diversity, Shannon Index and Evenness).

area shows seasonal changes: the alternation of biogenic particles from biological production in summer and the increase of the detrital input from the adjacent Drygalski glacier in winter. The presence of relative high values of *Portatrochammina*, a taxon less robust compared to *M. arenacea* but with similar ecological requirements (Majewsky et al., 2016, 2018), together with the complete absence of calcareous foraminifera (both planktic and benthic) and to the low diversity of the assemblage, may also suggest dissolution of the calcareous tests and the loss of the more fragile agglutinated species shortly after burial.

The statistical analysis provides additional information on the relationships between the environmental variables and the composition of the benthic foraminiferal assemblages. The CaCO_3 content results a significant parameter that influences the abundances of foraminifera both calcareous and agglutinated while it does not show any relationship with the dominant species of agglutinated foraminifera (Fig. 4). The biogenic silica content correlates well with the abundance of *Trochammina* gr. and does not influence the *Rhabdamminella* sp. and *M. arenacea* distribution. This relation suggests that *Trochammina* gr. occurrence is sensible to the phytoplankton availability, as the biogenic silica accumulation at the seafloor is strongly linked to the temporal and spatial phytoplankton growth in surface (Dunbar & Leventer, 1989). Moreover, the study of Peloquin & Smith (2007), shows that enhanced surface phytoplankton production is associated with MCDW intrusions. Together with the assumption above (correlation between *Trochammina* gr. and phytoplankton), their finding may explain the high

percentages of *Trochammina* gr. in the Joides Basin (site BC 01), where MCDW is documented. However, additional investigations in other areas of the Ross Sea and ecological studies on *Trochammina* gr. are required in order to confirm this evidence.

Finally, the relative abundances of *M. arenacea* and of the *Trochammina* gr. show inverse correlation (Fig. 4) suggesting different environmental requirements of these two taxa. *Miliammina arenacea* is abundant at sites (BC 33, BC 38 and BC 22) where the presence of HSSW is well documented and the assemblage is generally depleted in calcareous taxa and is characterised by a low to medium diversity of agglutinated species. In contrast, *Trochammina* gr. displays high abundances at site BC 01, which is strongly influenced by the presence of the MCDW, and the associated foraminiferal assemblage is composed by highly diversified agglutinated taxa and by the presence of few calcareous specimens (both planktic and benthic).

CONCLUSIONS

Recent foraminiferal assemblages from different oceanographic areas of the Ross Sea were analysed to investigate their areal distribution in relation to the oceanographic regime. Generally, the benthic microfauna is dominated by resistant agglutinated tests. Our results document that diversity and abundances of the taxa are strongly influenced by the regional differences in water mass properties.

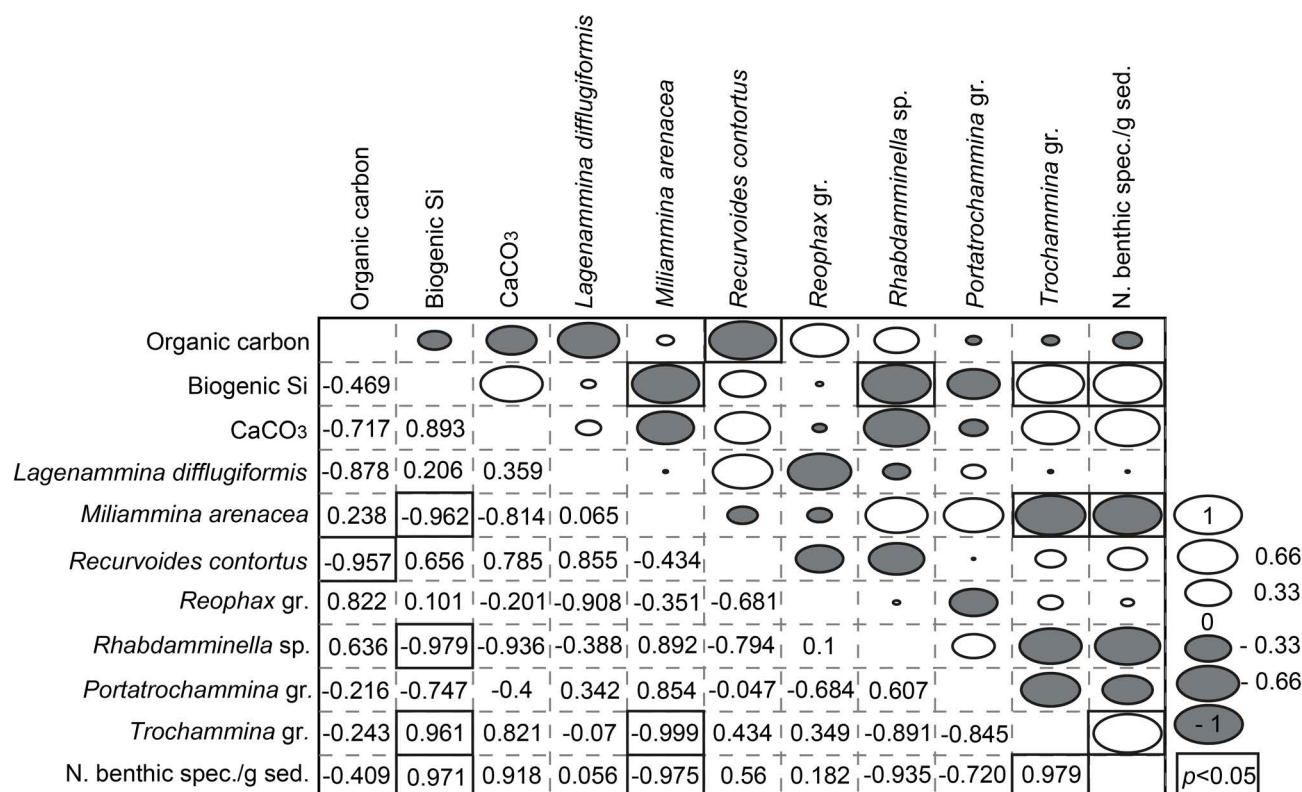


Fig. 4 - Graphical (white and grey ellipses) and correlation coefficient matrix values between environmental parameters (organic carbon, biogenic silica and CaCO_3 content) at the sea floor in the investigated sites and the most abundant species and/or group of agglutinated species. Black boxes highlight the correlation coefficients with $p < 0.05$ (n. benthic spec./g sed.: number of benthic specimens/g sediment).

The exclusive presence of agglutinated taxa and the low abundance in the assemblages observed in the Drygalski (site BC 33) and Lewis Basins (site BC 22) may be attributed to cold, saline, CO₂-rich bottom waters and to the presence of a shallow CCD, conditions unfavorable to carbonate precipitation and preservation.

The presence and/or increase in abundance of calcareous taxa documented in the samples collected from the Joides Basin (site BC 01) and the Pennell Trough (site BC 38) is strongly correlated with the intrusion of the warmer and nutrient-rich MCDW, which is also not corrosive for carbonates.

Our results provide new ecological information about the distribution of *Trochammina* gr. This genus results correlated with the biogenic silica availability at the seafloor and occurs in areas influenced by the presence of MCDW. Consequently, it can be used as a key group in palaeoenvironmental and palaeoceanographic reconstruction.

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APPENDIX A

Foraminiferal species list in alphabetical order.

Agglutinated

Adercotryma glomerata (Brady, 1878)
Cribrostomoides jeffreysii (Williamson, 1858)
Deuterammina grisea (Earland, 1934)
Glomospira charoides (Jones & Parker, 1860)
Hyperammina sp.
Hormosinella distans (Brady, 1881)
Hormosinella ovicula (Brady, 1879)
Labrospira wiesneri Parr, 1950
Lagenammina difflugiformis (Brady, 1879)
Miliammina arenacea (Chapman, 1916)
Nodulina subdentaliformis (Parr, 1950)
Portatrochammina antarctica (Parr, 1950)
Portatrochammina wiesneri (Parr, 1950)
Pseudobolivina antarctica Wiesner, 1931
Pseudotrochammina bullata (Höglund, 1947)
Recurvoides contortus Earland, 1934
Reophax guttifer Brady, 1881
Reophax scorpiurus de Montfort, 1808

Reophax spiculifer Brady, 1879
Reophax subfusiformis Earland, 1933
Rhabdammina sp.
Trochammina cf. *quadricamerata* (Echols, 1971)
Trochammina multiloculata Höglund, 1947

Calcareous (Benthic)

Astrononion echolsi Kennett, 1967
Epistominella exigua (Brady, 1884)
Fursenkoina fusiformis (Williamson, 1858)
Globocassidulina bionia (Crespin, 1960)
Nonionella bradii (Chapman, 1916)
Pullenia subcarinata (d'Orbigny, 1839)
Trifarina angulosa (Williamson, 1858)

Calcareous (Planktic)

Globigerina bulloides d'Orbigny, 1826
Turborotalita quinqueloba (Natland, 1938)
Neoglobobulimina pachyderma (Ehrenberg, 1861)

APPENDIX B

Relative abundance of the most common agglutinated taxa (% calculated vs. total agglutinated specimens), number of benthic specimens per gram of sediment and the values of the environmental parameters. Data used for the Correlation Analysis (see Fig. 4).

Site	Organic carbon	Biogenic Silica	CaCO ₃	<i>Lagenammina difflugiformis</i>	<i>Miliammina arenacea</i>	<i>Recurvoides contortus</i>	<i>Reophax</i> gr.	<i>Rhabdammina</i> sp.	<i>Portatrochammina</i> gr.	<i>Trochammina</i> gr.	Number benthic specimens/g sed.
BC 01	0.33	29.90	6.10	13.39	12.29	12.11	9.36	3.67	2.75	22.57	15.00
BC 22	1.51	22.10	0.00	9.02	22.13	1.64	20.49	6.56	1.64	13.11	7.40
BC 33	0.55	18.10	0.40	15.52	34.48	8.62	1.72	6.90	8.62	1.72	3.10
BC 38	1.18	16.80	0.50	9.09	31.17	1.30	12.99	7.79	7.79	5.19	4.90