



Benthic foraminifera from West Antarctic fiord environments: An overview

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Abstract: After several years of research, the foraminiferal fauna of Admiralty Bay (King George Island, South Shetland Islands) has become the most studied fiord in West Antarctica with respect to foraminifera. As such, it provides actualistic data for better understanding of paleoenvironmental records from this dynamically changing area. Over a few years, the bay was systematically sampled down to 520 m water depth, for multi-chambered and monothalamous benthic foraminifera, including soft-walled allogromiids often overlooked in former studies. Altogether, 138 taxa were identified, and three new taxa described. This paper aims to integrate these results, put them into a broader perspective, and supplement them with information that was not presented to date. Most notably, a record of the vertical distribution of Rose Bengal stained foraminifera below the sediment surface and the proportions of soft and robustly-testate forms at different sites are described.

Key words: Antarctica, King George Island, Admiralty Bay, Foraminifera.

Introduction

Study area. — Admiralty Bay, with a total area of 120 km², is the largest fiord of King George Island and the entire South Shetlands archipelago. It is formed by a more than 500 m deep main channel, which opens to Bransfield Strait, and three inlets with water depths down to 100–200 m (Fig. 1). The hydrography of Admiralty Bay is typical for the South Shetlands. It is characterized by a well-mixed, rather uniform (except in the coastal zone) and well-ventilated water column (Lipski 1987). The upper 15–35 m is significantly freshened during the summer by meltwater (Sarukhanyan and Tokarczyk 1988). Water circulation in the bay is driven by strong winds predominantly from WSW and NNW which, together with tides, push surface waters out to sea and intensify inflow of open seawater along the south-west shore (Robakiewicz and Rakusa-Suszczewski 1999). Winter freezing of Admiralty Bay is extremely variable (Kruszewski 2002). The bay freezes in 2 for every 3 years for up to 3 months. Its better sheltered inlets are ice covered for considerably longer periods than the main channel.

The South Shetland Islands, are on Bransfield Strait, on the western side of the Antarctic Peninsula. They are affected by relatively warm ($>1.5^{\circ}\text{C}$) Upper Circumpolar Deep Water, in contrast to the Weddell Sea, on the eastern side of the Antarctic Peninsula, which is influenced by colder and more saline Weddell Sea Transitional Water (Shevenell and Kennett 2002; Domack *et al.* 2003). The Bransfield Strait side of the Antarctic Peninsula is relatively warm, receives more precipitation (500–1000 mm per year; Van Lipzig *et al.* 2004), and experiences less extensive sea ice coverage, which results in a rather low-altitude glacial equilibrium-line (<100 m) on the western side of the Antarctic Peninsula in contrast with the eastern side (>400 m) (Turner *et al.* 2002; King *et al.* 2003). In Admiralty Bay, glacial equilibrium lines are at ~ 150 m above sea level (Domack and Ishman 1993). Almost half of its shoreline is occupied by tidewater glaciers and icefalls that have been retreating for at least the last few decades (Braun and Gossmann 2002; Pudełko 2008).

During the last 50 years, the western Antarctic Peninsula has been the most rapidly warming region in the Southern Hemisphere and is considered to be a “hot spot” of global warming. The atmospheric warming is up to $0.5\text{--}0.6^{\circ}\text{C}$ per decade (Meredith and King 2005). This warming affected numerous fragile environments due to increased coastal melt-water run-off, rapid retreat of glacier fronts, and disintegration of ice shelves (Braun and Gossmann 2002; Cook *et al.* 2005). Benthic foraminifera constitute an important element of changing biocenoses. Owing to their small size, high abundance, and robust skeletal elements, they provide a great tool for analyzing future and past environmental changes in that dynamic region. However, our knowledge of their recent distribution and ecology, especially in coastal and near-shore areas of the Antarctic Peninsula is far from complete. The ongoing research in Admiralty Bay, as one of major fiords of the South Shetlands, attempts to bridge this gap.

Former studies on benthic foraminifera from the Antarctic Peninsula region.

— The up to date foraminiferal research in the Antarctic Peninsula was rather fragmentary. It was initiated by Earland (1934) and continued by rather random distribution studies from few locations by Cushman (1945), McKnight (1962), and most notably by Herb (1971). Several brief taxonomic reports of the U.S. Antarctic Program (Lipps *et al.* 1972; Stockton 1973; Lipps and DeLaca 1974; Finger 1975, 1977; Temnikow and Lipps 1975; Temnikow 1976; Lena 1980; Ishman 1989) followed. Chinese studies (Li and Zhang 1986a, b; Li *et al.* 1987; Zhang 1994; all in Chinese) focused on foraminifera from surface sediment in the area of Great Wall Bay on King George Island. More comprehensive studies were completed by Ishman and Domack (1994), who investigated recent foraminiferal assemblages from Marguerite Bay, Palmer Archipelago, and Bransfield Strait; all on the western side of the Antarctic Peninsula. They found two assemblages closely associated with the distribution of the two dominant water masses; Upper Circumpolar Deep Water and Weddell Sea Transitional Water. On the other hand, Finger and Lipps (1981) and Gray *et al.* (2003) focused on foraminiferal repopulation of the volcanic caldera of Deception Island, after its eruptions in 1967, 1969, and 1970.

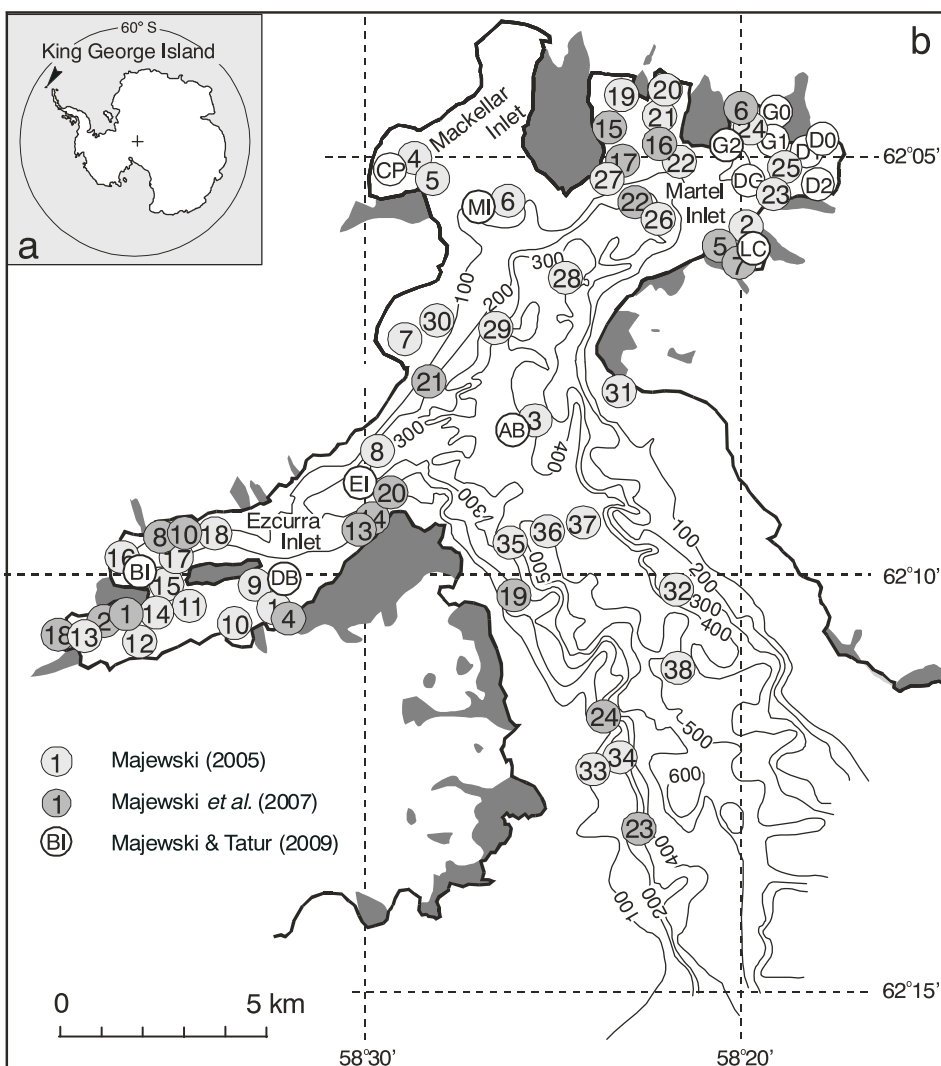


Fig. 1. The location of King George Island (a) and sampling stations from different surveys throughout Admiralty Bay (b). Dark gray indicates inland glacier-free areas (Battke 1990). The bathymetric contour lines in meters after Straten (1996). Note three sets of sampling stations collected for different investigations.

More recent studies targeted foraminifera in fiords of King George Island (Chang and Yoon 1995; Mayer 2000); however, they were limited to small areas and water-depths less than 100 m. In the area of South Shetlands, studies on foraminifera from short, Holocene sediment cores were also carried out by Li *et al.* (2000) and Yoo *et al.* (2006), also involving stable isotope analyses (Khim *et al.* 2001). Ishman and Sperling (2002) analyzed down core foraminiferal record in 43 m long Holocene section from Palmer Deep south off Anvers Island.

Investigations on the eastern side of the Antarctic Peninsula were less frequent. In the Weddell Sea area, they were carried out by Anderson (1975a, b), and Mackensen *et al.* (1990). They noted a widespread presence of deep water and early diagenetic conditions unfavorable for preservation of calcareous and some agglutinated foraminifera in most of the area. More recent investigations in the areas exposed by the retreat of Larsen Ice Shelf showed the presence of distinct biofacies including one associated with the ice edge (Ishman and Szymcek 2003), however, no clear assemblage changes associated with the ice shelf collapse was noted (Murray and Pudsey 2004).

Benthic foraminifera in Admiralty Bay

The first report including foraminiferal assemblages (39 taxa) from Admiralty Bay was that of Ishman and Domack (1994). Although it was regional in scope, it included two sites from the inner part of the bay, and 135 m and 285 m water-depth (mwd), sampled during *Polar Duke* 1988-II cruise. Subsequently, Gaździcki and Majewski (2003) analyzed 3 samples from inner part of Ezcurra Inlet (20, 35, and 75 mwd), collected during the austral summer of 1986/1987. They reported 24 foraminiferal species.

The first systematic survey of Admiralty Bay (Majewski 2005) was based on 38 samples from 8 to 520 mwd (Fig. 1) collected during the 2002/2003 austral summer. From those, some 105 testate species of benthic foraminifera were catalogued. However, in that survey only the >125 μ m fraction was investigated. Another set of 20 samples from 8 to 254 mwd (Fig. 1) was collected in Admiralty Bay in early 2007 (Majewski *et al.* 2007). This study focused primarily on monothalamous (single chambered) agglutinated and soft-walled allogromiid foraminifera that were not investigated in the preceding studies. It revealed the presence of at least 40 morpho-species. Additionally, the finer fractions (63–125 μ m), from the samples collected for the soft-walled foraminifera (Majewski *et al.* 2007), were investigated. In those residues, seven more multi-chambered benthic foraminifera were encountered. They are fragile and minute Textulariina: *Leptohalysis scottii*, *Textularia tenuissima*, *Textularia antarctica*, and *Eggerella minuta*, as well as calcareous Rotaliina: *Neoeponides* sp., *Epistominella exigua* and a single specimen resembling *Stainforthia concava* of Höglund (1947) (Fig. 2).

The complete list of benthic foraminifera recognized in Admiralty Bay is presented in Appendix 1. Among them, 53 taxa of agglutinating monothalamous and allogromiid foraminifera, 27 of multi-chambered agglutinated, and 58 taxa of calcareous foraminifera are recognized (Majewski 2005; Majewski *et al.* 2007, and this study). Based on that material, one new genus (*Bowseria* Sinniger, Lecroq, Majewski *et* Pawłowski, 2008) and two new species (*Bowseria arctowskii* Sinniger, Lecroq, Majewski *et* Pawłowski, 2008 and *Cribrorhaphidium webbi* Majewski,

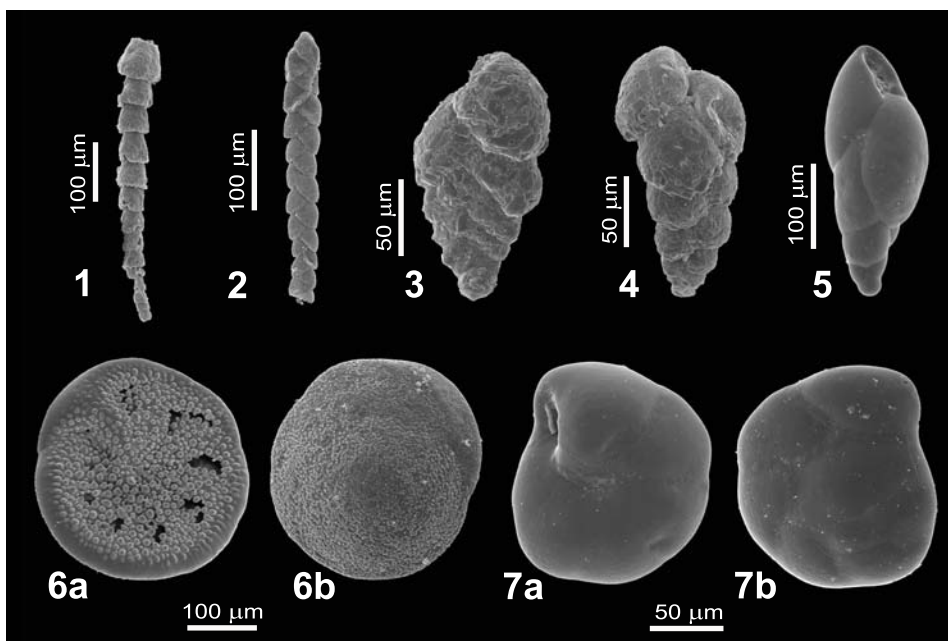


Fig. 2. SEM images of multi-chambered foraminifera from Admiralty Bay, not included in Majewski (2005) **1.** *Leptohalysis scottii* (Chaster 1892), KG16. **2.** *Textularia tenuissima* Earland 1933, KG13. **3.** *Textularia antarctica* (Wiesner 1931), KG14. **4.** *Eggerella minuta* (Wiesner 1931), KG14. **5.** *Stainforthia* cf. *concava* (Höglund 1947), KG22. **6.** *Neoeponides* sp., KG19. **7.** *Epistominella exigua* (Brady, 1884), KG19.

2009) were established, and detailed discussions of ecology and morphologic and/or molecular diversity of *Criboelphidium webbi* (Majewski and Tatur 2009) and *Globocassidulina biora* (Majewski and Pawlowski in press) presented.

Despite describing several new taxa, foraminifera found in Admiralty Bay have no endemic elements. They represent species typical of coastal benthic communities recognized not only from West but also East Antarctica (e.g. Milam and Anderson 1981; Gooday *et al.* 1996; Igarashi *et al.* 2001). Also *C. webbi*, that may seem unique to Admiralty Bay, was reported under various names from recent (Mayer 2000) and sub-recent sediments of Maxwell Bay, King George Island (Woo *et al.* 1996; Li *et al.* 2000), as well as from Late Quaternary deposits of Ross Sea (Ward and Webb 1986) and western Weddell Sea (Majewski and Anderson 2009).

Vertical distribution of benthic foraminifera within the sediment. — Majewski (2005) showed distribution of dead (sub-fossil) and “living” (Rose Bengal stained) assemblages throughout Admiralty Bay. The 38 short sediment cores analyzed in that survey were sliced and picked for foraminifera every 1 cm. This enabled tracking of vertical distribution of the “living” foraminifera below the sediment surface. Distribution of the most common “living” species from all cores combined is presented on Fig. 3.

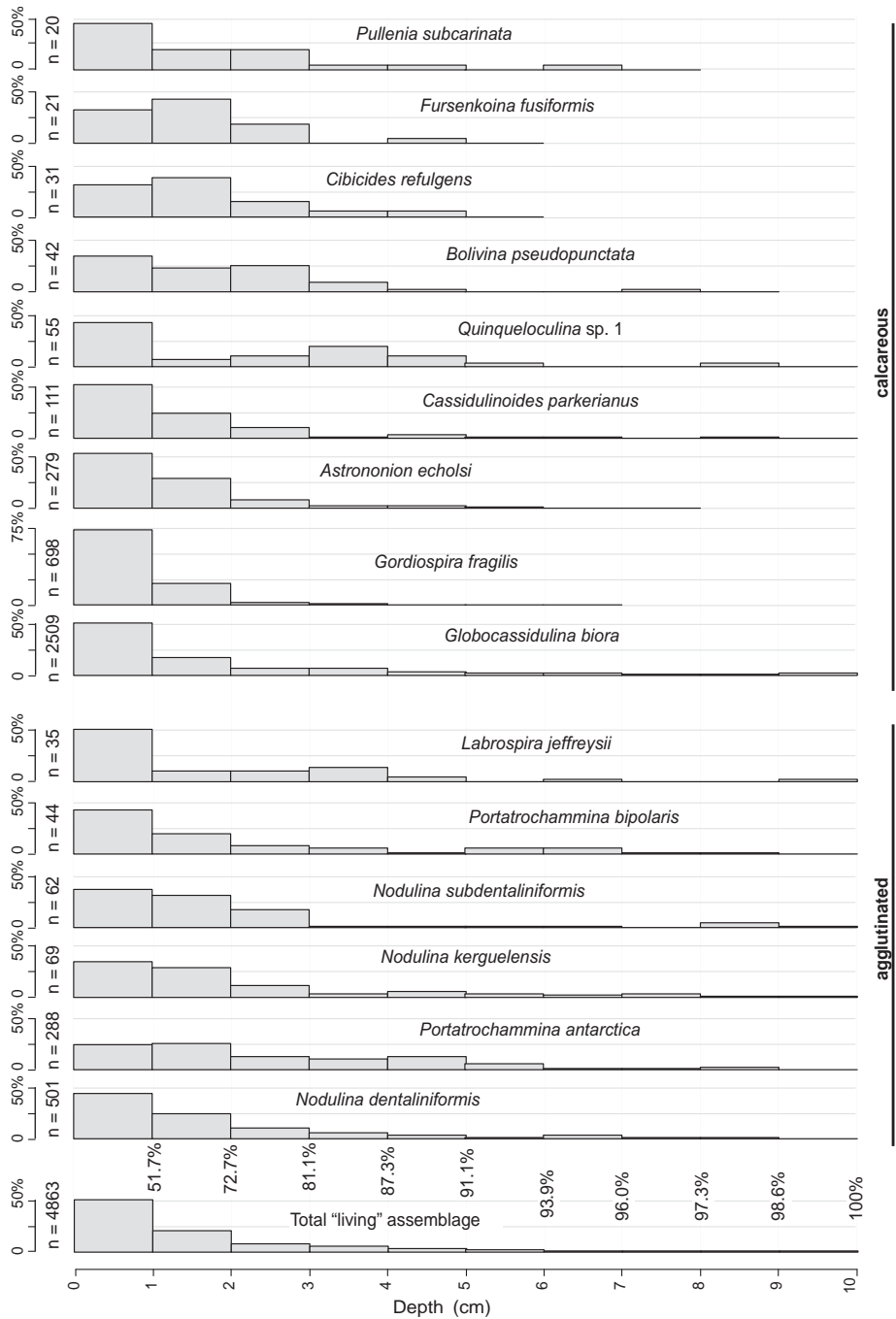


Fig. 3. Vertical distribution patterns of the most abundant "living" benthic foraminifera reported in Majewski (2005) expressed in percentages calculated from abundances from all cores combined. Note number of specimens of each taxon presented (n) and cumulative percentages of the total benthic foraminiferal assemblage marked next to the first graph from the left.

Despite limitations of the staining technique (*e.g.* Corliss 1991), these results show that none of benthic foraminifera inhabiting Admiralty Bay shows a typical deep-infaunal distribution. Over 80% of all calcareous and agglutinated stained specimens were found in the upper 3 cm of sediment. Taking into account suggested sedimentation rates for Admiralty Bay, of 0.13 cm y⁻¹ to 0.36 cm y⁻¹ (Khim *et al.* 2001; Straten 1996; Majewski and Tatur 2009), the 3-cm thick interval corresponds to 23 to ~8 years time span.

None of the benthic species, reported on Fig. 3, shows the highest abundances below 2 cm below sediment surface, so all may be considered shallow-infaunal (Jorissen 1999). All, except *Cibicides refulgens*, *Fursenkoina fusiformis*, and *Portatrochammina antarctica*, show the highest abundances in the top 1 cm of the sediment. It may seem surprising that *Cibicides refulgens* falls within this group as it was found commonly growing on the free-swimming Antarctic scallop (Alexander and DeLaca 1987) and thus to prefer predominantly epibenthic habitats. However, Hohenegger *et al.* (1993) reported on common among foraminifera inhabiting of burrows created by infaunal macrobenthic organisms. On the other hand, the recent observations could suggest that *Cibicides refulgens* is not strictly epibenthic, or they represent just one more example of the imperfection of the Rose Bengal staining technique for discriminating truly living specimens.

Monothalamous foraminifera. — Previous studies on South Shetland Island faunas (*e.g.* Ishman and Domack 1994; Finger and Lipps 1981; Chang and Yoon 1995; Mayer 2000; Gray *et al.* 2003; Majewski 2005) focused on robust, testate foraminifera, which could be preserved in the fossil record. Except for the work of Earland (1934), practically nothing was known about the monothalamous, and especially allogromiid, foraminifera, characterized by single-chambered organic or agglutinated tests, despite the fact that they are particularly abundant in high latitude settings (Gooday 2002). Antarctic monothalamous foraminifera are known mainly from a few older studies (*e.g.* Pearcey 1914; Heron-Allen and Earland 1922; Wiesner 1931; Earland 1934). There are also some more recent reports (Ward and Webb 1986; Violanti 1996; Majewski 2005), however, they have not included the organic-walled allogromiid species, poorly preserved in alcohol-fixed or dried samples.

Recently, a growing interest in the diversity and ecology of Antarctic foraminifera led to a more detailed description of both organic-walled and agglutinated monothalamous species from the McMurdo Sound (Gooday *et al.* 1996) and the Weddell Sea (Cornelius and Gooday 2004). Several new morphospecies have been described from those localities (Gooday *et al.* 1995, 2004; Bowser *et al.* 2002; Delaca *et al.* 2002; Gooday and Pawlowski 2004; Sabbatini *et al.* 2004). Some studies suggest that their diversity is largely underestimated not only in cold (Pawlowski *et al.* 2002, 2005) but also in warm-water environments (Habura *et al.* 2008). The same is observed in Admiralty Bay (Majewski *et al.* 2007). At least half of the 53 taxa of those foraminifera listed in Appendix 1 of this overview are of unclear or unknown taxonomic identity. Despite some efforts (Majewski *et al.* 2007; Sinniger *et al.* 2008;

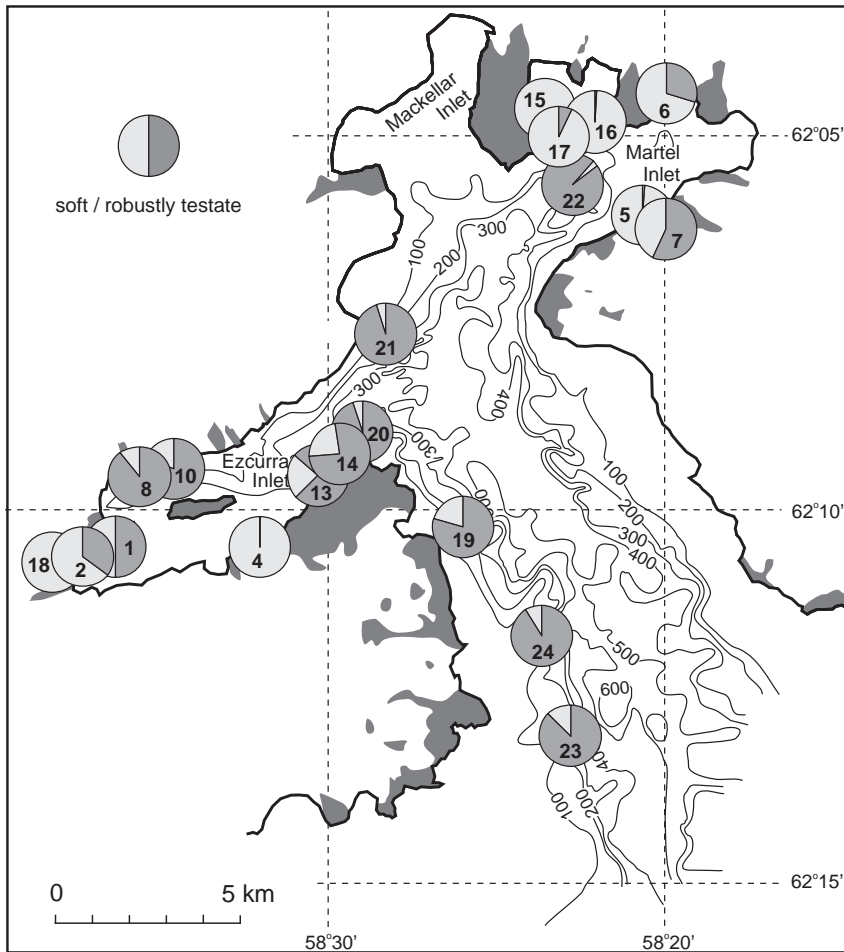


Fig. 4. Relation between soft and robustly-testate living foraminifera throughout Admiralty Bay, based on data from Majewski *et al.* (2007).

Pawlowski and Majewski submitted), allogromiid foraminifera from the deep, central part of Admiralty Bay await to be investigated, and numerous monothalamous taxa found already in shallower areas of Admiralty Bay are to be established.

An important aspect of monothalamous foraminifera is that, despite the fact that they are practically absent from the fossil record, they constitute an important part of living foraminiferal communities (*e.g.* Gooday 1996). In some environments, they may actually dominate the benthic foraminiferal assemblages (*e.g.* Korsun 2002). Based on the samples studied by Majewski *et al.* (2007), the abundances of monothalamous foraminifera in the >125 mm fraction were compared with Rose Bengal stained robustly-testate foraminifera from the same fraction (Figs 4, 5). Despite some weaknesses of such a comparison, *i.e.* the possibility of inclusion of some dead *Psammospaera* and *Lagenammina* in the otherwise truly

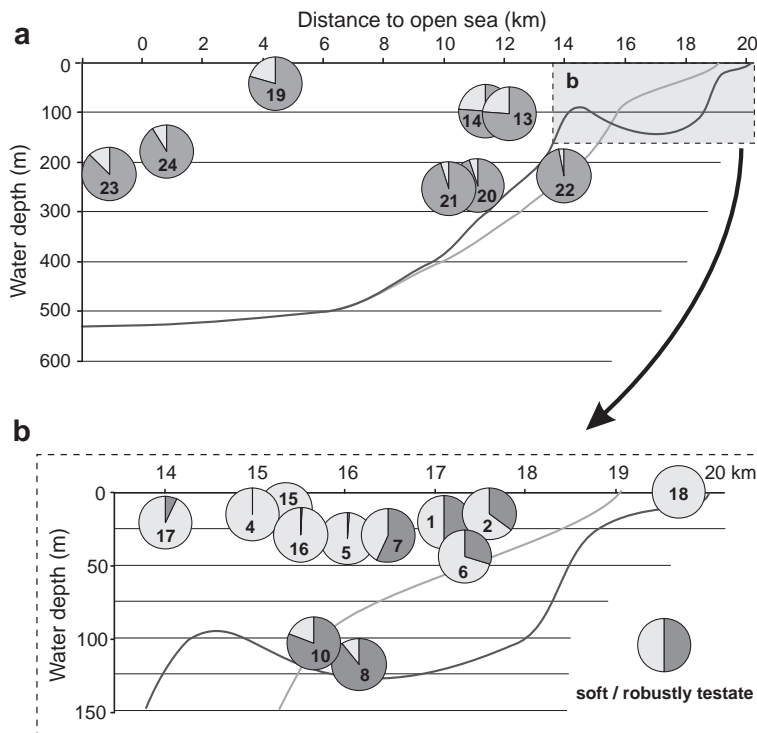


Fig. 5. Soft to robustly-testate living foraminiferal ratios from Fig. 4 versus water depth and distance to open sea. Gray lines show bathymetric profiles along Admiralty Bay main axes, dark gray for the main channel and Ezcurra Inlet, bright gray for Martel Inlet.

living monothalamous assemblage, and overestimation of frequencies of living testate forms by the staining technique (Corliss 1991), such comparison provides a good estimate of the environments in which the monothalamous foraminifera are the most prominent. In Admiralty Bay, monothalamous foraminifera are dominant (>50% of living assemblage) at the great majority of sites from less than 50 mwd. They constitute ~20% at most sites from ~100 mwd and <10% at most sites from ~200 mwd (Fig. 5). Monothalamous foraminifera are also most common at sites far within the inlets (Fig. 4) at locations the most affected by glacier retreat and turbid conditions due to sediment and melt-water discharge. In that respect, they show similar affinities as the allogromiid foraminifera from Arctic fiords (*e.g.* Korsun and Hald 2000; Korsun 2002; Sabbatini *et al.* 2007).

Bipolar distribution of benthic foraminifera

Bipolar distribution is observed in many polar and subpolar protists. For example, 44 morphospecies of free-living, limnetic ciliates were found to occur in Arctic and Antarctic freshwater bodies (Petz *et al.* 2007). Bipolarity has also been observed

in some groups of marine invertebrates, *e.g.* five common genera of amphipods were found in Arctic and Antarctic fiords (Jazdzewski *et al.* 1995). However, Dell (1972) was strongly doubtful about the possibility that some benthic species occur now in the Arctic and Antarctic as a kind of relict of a once widely dispersed fauna. In his review, he concluded that bipolarity was considered to occur in “difficult” groups, with still unresolved taxonomy. Although it was demonstrated that meticulous morphologic investigations could lead to differentiation between Arctic and Antarctic forms (*e.g.* Schmiendl and Mackensen 1993), it is also true that morphological characters may be often inadequate to detect interspecific variations leading to the identification of bipolar species. Using molecular methods has helped to unravel many uncertainties for example the Arctic and Antarctic planktonic foraminifera *Neogloboquadrina pachyderma* has been shown to differ genetically (Darling *et al.* 2006).

Among monothalamous foraminifera, several morphotypes appeared to be very similar between Admiralty Bay (Majewski *et al.* 2007) and Svalbard (Gooday *et al.* 2005; Majewski *et al.* 2005). The same names were applied to their identification; however, it was uncertain whether these morphospecies were genetically identical, or their identification was biased by a lack of distinctive morphological features. Up to date, no biogeographic investigations were based on the foraminiferal DNA from Admiralty Bay. Nevertheless, Pawlowski *et al.* (2008) conducted genetic analyses of four monothalamous morphotaxa (the genera *Micrometula*, *Psammophaga*, and *Gloioquillum*) and the species *Hippocrepinella hirudinea* from coastal areas of McMurdo Sound (East Antarctic). Other specimens came from western Svalbard (Arctic), as well as from the deep Southern and Arctic Oceans and Northern European fiords. Analyses of partial SSU rDNA sequences revealed substantial cryptic diversity within each of these morphotypes, and showed that Arctic and Antarctic isolates differ genetically and probably represent distinct species. In all cases, the bipolar populations were clearly distinct genetically. Not surprisingly, Arctic specimens were generally more closely related to those from Northern Europe than to their Antarctic relatives. The deep-sea specimens from the Weddell Sea branched as sister group to the McMurdo Sound population, while those from the Arctic Ocean clustered with those from Norwegian fiords (Pawlowski *et al.* 2008).

Among multi-chambered forms that have more distinctive morphological features than monothalamous foraminifera, McKnight (1962) noted at least 12 species common to the Antarctic and Arctic areas and many forms comparable in both polar regions. Comparison of robust foraminifera from Admiralty Bay with those from Arctic fiords, for example from Svalbard (Hansen and Knudsen 1995; Hald and Korsun 1997; Majewski and Zajączkowski 2007) showed several species present in both regions *i.e.* *Reophax scorpiurus*, *Spiroplectammina biformis*, *Portatrochammina bipolaris*, *Adercotryma glomerata*, *Procerolagena gracilis*, *Hyalinonetrion gracillima*, *Cornuspira involvens*, *Rosalina globularis*, *Fursenkoina fusiformis*, *Cibicides lobatulus*. However, at least some if not all of these taxa are known to be cosmopolitan species that occur also at lower latitudes. Moreover, as among the

monothalamous foraminifera (Pawlowski *et al.* 2008), they may be in fact not truly bipolar species but morphologically similar and/or yet undistinguished groups of cryptic species. It is also worth noting, that there are common similarities at supra-specific level. A typical form from Antarctic fiords *Miliammina arenacea* may resemble Arctic *Silicosigma groenlandica*, *Recurvoides contortus*–*Recurvoides turbinatus*, *Paratrochammina haynesi*–*Paratrochammina bartrami*, *Labrospira jeffreysii*–*Labrospira crassimargo*, *Globocassidulina biora*–*Cassidulina reniforme*, *Criboelphidium webbi*–*Criboelphidium excavatum*. Moreover, at least in the case of the last two pairs, they also share distinctively similar ecologies.

Benthic foraminifera as paleoenvironmental indicators

In Majewski (2005), four benthic foraminiferal assemblages were identified from water depths down to ~500 m. They are briefly reviewed in Table 1. They may be defined by association of different foraminiferal species and faunal diversities, which seem to be affected by environmental factors closely related to water depth, most likely decreasing food levels with increasing water depth. However, the same or simi-

Table 1
Benthic foraminiferal assemblages typical for Admiralty Bay,
modified from Majewski (2005)

Assemblage	Water depth	Typical taxa	Abundances (upper 10 cm of sediment)	Diversity, Shannon Index **
Restricted coves	usually <20 m	<i>Quinqueloculina</i> sp. 1, <i>Hemispaerammina bradyi</i> , at some locations <i>Globocassidulina biora</i>	low; total well below 10 spec./cm ²	very low; ~0.7
Open inlets	up to 250 m usually <100 m	<i>Globocassidulina biora</i> , <i>Psammosphaera fusca</i> * less important: <i>Criboelphidium webbi</i> , <i>Quinqueloculina</i> sp. 1, <i>Hippocrepinella hirudinea</i> , <i>Cassidulinoides parkerianus</i> , <i>Spiroplectammina biformis</i> , and to some extent <i>Hemispaerammina bradyi</i>	high; up to 260 dead and 20 “living” spec./cm ²	low; 0.7–2.0, rarely 2.3
Intermediate zone	~100 m, outer main channel at its junction with inlets	<i>Portatrochammina antarctica</i> , <i>Cassidulinoides parkerianus</i> less important: <i>Cibicides refulgens</i> , <i>Spiroplectammina biformis</i> , and <i>Globocassidulina biora</i>	intermediate; few dozen spec./cm ²	intermediate; 1.7–2.1, rarely 1.1
Deep-water zone	200–400 m	<i>Miliammina arenacea</i> , <i>Angulogerina earlandi</i> , <i>Pullenia subcarinata</i> , <i>Portatrochammina bipolaris</i> , <i>Cassidulinoides porrectus</i>	intermediate; few dozen spec./cm ²	high; 1.8–2.7
	>400 m	<i>Lagenammina arenulata</i>		

* *Psammosphaera fusca* seems to prefer higher sedimentation rates and/or slightly more diverse communities than *Globocassidulina biora*

** Shannon Index $H = -\sum \frac{n_i}{n} \ln \frac{n_i}{n}$

lar assemblages appear to be also indicative of glacial influence, *i.e.* the shallow-water assemblages being typical for glacier-proximal conditions (*e.g.* Majewski and Anderson 2009). Only few species, *i.e.* *Quinqueloculina* sp. 1, *Hemisphaerammina bradyi*, *Psammosphaera fusca*, and *C. webbi*, from water depths shallower than 200 mwd, are restricted to a single assemblage. Most species are present in more than one assemblage; however, in different proportions to other taxa.

It appears that high abundance of *Globocassidulina biora* is the most characteristic element of the inner fiord foraminiferal assemblages. This foraminifer also dominated shallow-water records from other locations on King George Island. In fact, Li *et al.* (2000) and Yoo *et al.* (2006) showed variations with core-depth in abundances of two large *Globocassidulina* morphotypes (*G. biora* and *G. crassa rossensis*). According to molecular investigations on living *Globocassidulina* populations from Admiralty Bay performed on SSU and ITS rDNA sequences, these two morphotypes are in fact a single species (Majewski and Pawlowski in press) with the largest, fully grown specimens having predominantly doubled apertures, typical of *G. biora* (Quilty 2003). Nevertheless, the dominating morphologies within this genus fluctuate in down-core records (Li *et al.* 2000; Yoo *et al.* 2006). The specimens of single, branched (Yoo *et al.* 2006), or doubled (Li *et al.* 2000) apertures were suggested to be more abundant in glacier-proximal sediment with higher gravel content. Therefore, the validity of those observations is not certain. However, they may still suggest a potential usefulness of the intraspecific morphologic variations within *G. biora* for paleoenvironmental studies.

Together with water-depth, the total abundance of living populations seems to change as well (Majewski 2005). However, in the geological record, fossil foraminiferal abundances are strongly affected by accumulation rates, reworking, and diagenetic processes, therefore minor variations in the total abundances are of little use for paleoenvironmental reconstructions. In Admiralty Bay, a trend of decreasing test size with deepening water-depth is also obvious. It is well demonstrated for *G. biora* populations (Majewski and Pawlowski in press), where the largest in test-size (~0.6 mm on average) populations are present at shallowest water depth (30 m), while the smallest in test-size (< 0.2 mm) occur at the greatest depths (223–254 mwd) investigated in that survey. The same trend of decreasing test-sizes with water depth seems to affect entire foraminiferal assemblages in Admiralty Bay as well and it could relate to decreasing food levels with increasing water depth. However, Milam and Anderson (1981) noted opposite test-size trends from the Adelie-George V Coast of East Antarctica indicating that it may be more of local importance.

Among multi-chambered foraminifera from Admiralty Bay, a single member of the family *Elphidiidae* attracts special attention. It was found exclusively in relatively shallow water, usually < 100 mwd, and glacier-proximal settings (Majewski and Tatur 2009). Its strictly defined distribution carries precise ecological implications for palaeoenvironmental research. As the only adequately documented modern elphidiid known to date from Antarctic waters, it was established as the new species *Cribo-*

elphidium webbi Majewski, 2009. In 7 out of 14 short sediment cores analyzed, this foraminifer is abundant during short-lived events recorded only 10–20 cm below the sediment-surface, and seems to be associated with retreating tide-water glaciers (Majewski and Tatur 2009). A very similar foraminifer, was encountered in Unit 2 (Michalchuk *et al.* 2009), in the Firth of Tay, Holocene section from the Weddell Sea side of the Antarctic Peninsula, from ~9400 to ~8300 yr BP, and especially before ~8800 yr BP. *Criboelphidium* cf. *webbi* is present at the very base of that sequence, providing a record of initial glacial retreat and the most near-glacier conditions for this unique Holocene record (Majewski and Anderson 2009).

Future studies of benthic foraminifera in West Antarctic fiords

The investigations of benthic foraminifera in Admiralty Bay has increased our knowledge of foraminifera from coastal and near-shore areas of the Antarctic Peninsula, but also showed how much more needs to be revealed. The most striking gap in our knowledge is that of monothalamous and especially allogromiid foraminifera. Very little is known about their taxonomy, true diversity, and distribution throughout Antarctica, not to mention their biology and ecology. There are large numbers of species awaiting to be discovered and described for science in this poorly known group of meiofauna.

Despite decades of research, not enough is yet known about the ecology of testate foraminifera, so important for paleoenvironmental studies. For considerable improvement, studies of foraminiferal distribution in Antarctic fiords needs to be performed along with thorough multi-proxy environmental surveys. Up to date, no detailed studies of seasonal population dynamics have been conducted. Although some studies have utilized stable isotopic composition of foraminiferal tests (*e.g.* Khim *et al.* 2001; Majewski and Tatur 2009) the seasonal population blooms can influence their interpretations. Year-around, seasonal studies in polar environments would be demanding and require sophisticated methodology and strong logistic support, but some results from the Arctic (*e.g.* Korsun and Hald 2000) show that they may give intriguing results reflecting significant, seasonal, environmental changes.

In the northern part of Admiralty Bay, sediment fill is up to ~70 m thick (Griffith and Anderson 1989), and most likely preserves a paleoenvironmental record since the Last Glacial Maximum as in nearby Maxwell Bay (Milliken *et al.* 2009). A core was drilled in Maxwell Bay in 2005 and yielded the highest resolution Holocene sediment record ever obtained from the Antarctic Peninsula. For that reason, efforts to recover another long core from Admiralty Bay are not likely to be taken any time soon. However, shorter records may also improve our knowledge of local environmental changes, especially as some terrestrial data already exist (*e.g.* Emslie *et al.* 2003; Tatur *et al.* 2004). Analyzing foraminiferal assemblages in such marine cores are highly likely to provide fine support for any paleoclimatic interpretation.

One intriguing question brought up by the discovery of *Cribrorhynchium webbi* in Admiralty Bay (Majewski and Tatur 2009) is why are there so few elphidiids present in the Antarctic, while they are so widely distributed throughout the Arctic? Some members of this family are present as far south as New Zealand, Australia, and nearby sub-Antarctic islands, as well as in Chilean fiords (Hayward *et al.* 1999, 2007; Hromic *et al.* 2006). Possibly, the isolation of Antarctica, with the lack of typical open shelf areas, estuaries, and oceanographic pathways for cross-frontal exchange as the North Atlantic Current, is so severe that it prevented more widespread dispersal of these foraminifera. If an ancestor of *C. webbi* reached the Antarctic shelf during just a single event, molecular studies on living specimens could unravel not only its closest relative north of the Antarctic Circumpolar Current, but possibly also the timing of such divergence. Such an event could potentially take place during some significant happenings in oceanographic history. Unfortunately, up to date, no truly living specimens of this species have been collected.

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Appendix 1

Full list of benthic foraminifera from Admiralty Bay

(* Majewski 2005, # Majewski *et al.* 2007, + this study)

Monothalamous organic-walled and agglutinated foraminifera

- Allogramia cf. crystallifera*. Fig. 2.1[#]
Ammodiscus incertus (d'Orbigny, 1839). Fig. 11.10*
Ammodiscus incertus discoideus Cushman, 1917. Fig. 11.11*
Ammovertellina sp. Fig. 22.3*
Armorella cf. spherica Heron-Allen *et* Earland, 1929. Fig. 9.14–15*, Fig. 3.2[#]
Armorella-like. Figs 3.5[#], 7.3[#]
Astrammina rara Rhumbler, 1931. Fig. 9.10*, Fig. 3.1[#]
Astrammina triangularis. Fig. 7.2[#]
Astrorhiza sp. Fig. 7.1[#]
Bathysiphon cf. argenteus. Fig. 2.8[#]
Bathysiphon cf. flexilis. Figs 2.9[#], 7.5[#].
Bowseria arctowskii Sinniger, Lecroq, Majewski *et* Pawlowski, 2008 (= Sausage-like undetermined allogromiid). Fig. 4.6–7[#], Figs 2–3 (Sinniger *et al.* 2008)
Crithionina cf. granum. Fig. 10.8*, Fig. 2.16[#]
Crithionina sp. Fig. 2.17[#]
Gloioigullmia sp. 1. Fig. 2.10[#]
Gloioigullmia sp. 2. Fig. 2.11[#]
Gloioigullmia-like. Fig. 2.13[#]
Glomospira gordialis (Jones *et* Parker, 1860). Fig. 12.4*
 ?*Glomospira* sp. Fig. 12.5*
Hemisphaerammina bradyi (Loeblich *et* Tappan, 1957). Fig. 10.1–5*
Hippocrepina cf. crassa. Fig. 4.4–5[#]
Hippocrepinella alba. Fig. 2.14[#]
Hippocrepinella hirudinea (Heron-Allen *et* Earland, 1932). Fig. 9.6–7*, Fig. 4.1–2[#].
Lagenammina spp. Fig. 3.6–7[#], including *Lagenammina arenulata* (Skinner, 1961). Figs 9.8–9, 9.12*
Micrometula sp. Fig. 2.7[#].
 Mudballs Fig. 3.10–13[#]
Nemogullmia sp. Fig. 2.5–6[#]
Pelosina didera. Fig. 3.8[#]
Pelosina aff. *sphaerilocolum*. Fig. 3.9[#]
Pelosina sp. Fig. 9.1*
Phainogullmia cf. aurata. Fig. 4.3[#]
Protonina decorata Earland, 1933. Fig. 10.10*
Psammophaga sp. Fig. 2.2–3[#]
Psammospaera fusca Schulze, 1875. Fig. 9.13*, Fig. 3.3–4[#].
Psammospaera rustica Heron-Allen *et* Earland, 1912. Fig. 9.11*
 ?*Psammospaera* sp. Fig. 10.9*
Rhabdammina sp. Fig. 9.3–5*
Saccorhiza sp. Fig. 11.9*
Tholosina centroforata Rhumbler, 1935. Fig. 10.6–7*
Thurammina corrugata Earland, 1934. Figs 11.1–2, 11.4*
Thurammina cf. corrugata. Fig. 11.3*
Tinogullmia sp. Fig. 2.4[#].
Tolypammina vagans (Brady, 1879). Fig. 12.1–2*
Vanhoefenella gaussi Rhumbler, 1905. Fig. 9.2*, Fig. 2.15[#]

- Webbinella limosai* Earland, 1933. Fig. 11.5–6*
Webbinella cf. *limosai* Earland, 1933. Fig. 11.7–8*
 Egg-shaped, ovoid saccamminid. Fig. 4.10–11#
 Undetermined, yellow ovoid allogromiid. Fig. 4.8#
 Undetermined attached 1. Fig. 2.18#
 Undetermined allogromiid. Fig. 4.12–14#
 Undetermined dark fusiform saccamminid. Figs 4.5#, 7.4#
 Undetermined elongate saccamminid. Fig. 4.16#
 Undetermined, white, spherical allogromiid. Fig. 4.9#

Multi-chamber agglutinated foraminifera

- Adercotryma glomerata* (Brady, 1878). Fig. 14.1*
Ammopemphix quadrupla (Wiesner, 1931). Fig. 10.11*
Atlantinella atlantica (Parker, 1952). Fig. 16.1–4*
eggerella minuta (Wiesner 1931). Fig. 2.4+, possibly (= ?*Rhumblerella* sp.) Fig. 14.6*
Hormosinella ovicula gracilis (Earland, 1933). Fig. 13.1*
Hormosinella sp. Fig. 13.2–3*
Labrospira jeffreysii (Williamson, 1858). Fig. 13.14*
Labrospira wiesneri Parr, 1950. Fig. 13.13*
Leptohalysis scottii (Chaster, 1892), Fig. 2.1+
Miliammina arenacea (Chapman, 1916). Fig. 12.6–7*
Miliammina lata Heron-Allen *et* Earland, 1930. Fig. 12.8*
Nodulina dentaliniformis (Brady, 1884). Fig. 13.4–5*
Nodulina kerguelensis (Parr, 1950). Fig. 13.8*
Nodulina subdentaliniformis (Parr, 1950). Fig. 13.6–7*
Paratrochammina (Lepidoparatrochammina) bartrami (Hedley, Hurdle *et* Burdett, 1967). Fig. 14.7–8*
Paratrochammina (Lepidoparatrochammina) lepida Brönnimann *et* Whittaker, 1988. Fig. 14.9–10*
Portatrochammina antarctica (Parr, 1950). Fig. 15.1–4*
Portatrochammina bipolaris (Brönnimann *et* Whittaker, 1980). Fig. 15.7–8*
Portatrochammina cf. *bipolaris*. Fig. 15.5–6*
Recurvoides contortus Earland, 1934. Fig. 14.2*
Reophax pilulifer Brady, 1884. Fig. 13.11–12*
Reophax scorpiurus de Montfort, 1808. Fig. 13.10*
Reophax sp. Fig. 13.9*
Sorosphaera sp. Fig. 16.5*
Spiroplectammina biformis (Parker *et* Jones, 1865). Fig. 14.3–5*
Textularia antarctica (Wiesner, 1931). Fig. 2.3+
Textularia tenuissima Earland, 1933, Fig. 2.2+

Calcareous foraminifera

- Angulogerina earlandi* Parr, 1950. Fig. 22.8–9*
Astrononion antarcticum Parr, 1950. Fig. 25.8*
Astrononion echolsi Kennett, 1967. Fig. 25.6–7*
Bolivina pseudopunctata Höglund, 1947. Fig. 22.6–7*
Cassidulinoides parkerianus (Brady, 1881). Fig. 23.1–2*
Cassidulinoides porrectus (Heron-Allen *et* Earland, 1932). Fig. 23.3*
Cibicides lobatulus (Walker *et* Jacob, 1798). Fig. 24.7–8
Cibicides cf. *lobatulus* (Walker *et* Jacob, 1798). Fig. 24.5–6*
Cibicides refulgens de Montfort, 1808. Fig. 25.1*
Cornuspira involvens (Reuss, 1850). Fig. 16.8*

- Cornuspira* sp. Fig. 16.7*
- Criboelphidium webbi* Majewski 2009. (= *Criboelphidium* sp.) Fig. 26.3–4*, Figs 5–6 (Majewski and Tatur 2009)
- Dentalina communis* (d'Orbigny, 1826). Fig. 20.2–3*
- Epistominella exigua* (Brady, 1884). Fig. 2.7⁺
- Fissurina crebra* (Matthes, 1939). Fig. 21.8*
- Fissurina* cf. *trigonomarginata* (Parker et Jones, 1865). Fig. 21.4*
- Fissurina* sp. 1. Fig. 21.5*
- Fissurina* sp. 2. Fig. 21.6*
- Fursenkoina fusiformis* (Williamson, 1858). Fig. 23.9–12*
- Glandulina antarctica* Parr, 1950. Fig. 22.3*
- Globocassidulina biora* (Crespin, 1960). Fig. 23.4–8*, Fig. 3 (Majewski and Pawlowski in press)
- ?*Globofissurella* sp. Fig. 21.7*
- Gordiospira fragilis* (Heron-Allen et Earland, 1932). Fig. 16.9–10*
- Hyalinonetrion gracillima* (Seguenza, 1862). Fig. 20.7*
- Lagena* cf. *heronalleni*. Fig. 20.9–10*
- Lagena squamososulcata* Heron-Allen et Earland, 1922. Fig. 20.11*
- Lagena subacuticosta* Parr, 1950. Fig. 20.8*
- Laryngosigma hyalascidia* Loeblich et Tappan, 1953. Fig. 22.4*
- Lenticulina* sp. Fig. 20.4*
- Neoeponides* sp. Fig. 2.6⁺
- Nonionella bradii* (Chapman, 1916). Fig. 25.4–5*
- Nonionella iridea* Herron-Allen et Earland, 1932. Fig. 25.2–3*
- Oolina felsinea* (Fornasini, 1894). Fig. 21.3*
- Oolina globosa caudigera* (Wiesner, 1931). Fig. 21.2*
- Oolina lineata* (Williamson, 1848). Fig. 21.1*
- Parafissurina fusiformis* (Wiesner, 1931). Fig. 22.1–2*
- Patellina corrugata* Williamson, 1858. Fig. 16.6*
- Planispirinoides* sp. Fig. 17.1*
- Procerolagena gracilis* (Williamson, 1848). Fig. 20.5–6*
- Pseudobulimina chapmani* (Heron-Allen et Earland, 1922). Fig. 22.5*
- Pseudofissurina mccullochae* Jones, 1984. Fig. 21.9–10*
- Pullenia subcarinata* (d'Orbigny, 1839). Fig. 26.1*
- Pullenia* cf. *subcarinata*. Fig. 26.2*
- Pyrgo bulloides* (d'Orbigny, 1826). Fig. 19.1*
- Pyrgo depressa* (d'Orbigny, 1826). Fig. 19.4–5*
- Pyrgo elongata* (d'Orbigny, 1826). Fig. 19.2*
- Pyrgo* sp. Fig. 19.3*
- Quinqueloculina* cf. *seminulum*. Fig. 17.3*
- Quinqueloculina weaveri* Rau, 1948. Fig. 17.4*
- Quinqueloculina* sp. 1, Fig. 18.1–3*
- Quinqueloculina* sp. 2, Fig. 18.4*
- Quinqueloculina* sp. 3, Fig. 18.5–6*
- Quinqueloculina* sp. 4, Fig. 17.2*
- ?*Quinqueloculina* sp. Fig. 17.5*
- Rosalina globularis* d'Orbigny, 1826. Fig. 24.1–4*
- ?*Sigmoilina* sp. Fig. 19.6*
- Stainforthia* cf. *concava* (Höglund 1947), Fig. 2.5⁺
- Triloculinella antarctica* (Kennett 1967). Fig. 20.1*