Mid-Late Pleistocene benthic foraminifera from Southwestern South Atlantic: driven by primary productivity or water mass properties?

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ABSTRACT: In the Atlantic sector of the Southern Ocean up to 35°S, Neogene benthic foraminiferal faunal changes have been interpreted, alternatively, as changes in deep water-masses distribution and organic matter availability. In surface, the Southwestern South Atlantic presents a highly dynamic frontal zone and exhibits large spatial and temporal variability in primary productivity that influences the export of organic carbon from the euphotic zone. However, below ~1000 meters depth, it is characterized by the interaction of several water masses. For this reason, the western sector of the South Atlantic is a natural laboratory to test the benthic foraminifera's response to changes in both, the deep water-masses distribution and the exported productivity. In order to define which was the main factor controlling the benthic foraminiferal assemblages structure during a glacial Mid-Late Pleistocene event, abundance analysis of organic matter content, oxygen availability and water masses marker species, and Q-mode factor analysis were carried out on core SP1251 (3400m; ~38°S - 54°W). Our results indicate that the benthic foraminiferal assemblages are mainly composed of high organic matter and oxygen availability-associated species revealing that productivity has been the main factor in determining the structure of the assemblages' composition. These results also reflect that surface productivity regime would have not been uniform as a result of variations in the shelfbreak upwelling of Patagonia as a consequence of variations in the Antarctic upwelling.

Key words: Benthic Foraminifera, Mid-Late Pleistocene, South Atlantic Ocean, Paleoceanography, Primary productivity

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INTRODUCTION

Benthic foraminifera are one of the most important constituents of marine fauna and occur in all oceanic environments. They are widely distributed and dominate meiobenthic communities, showing wide ecological adaptability. They are easily preserved in marine sediments that are deposited above the calcium carbonate compensation depth, and for this reason, they have been extensively used to reconstruct deep ocean environments. The environmental factors that influence their distribution and abundance include depth, grain size, calcium carbonate saturation, and mainly temperature, salinity, oxygenation and food availability and quality (Gooday 1993; Smart et al. 1994). As some of these parameters vary across different water masses, several studies have identified the abyssal benthic foraminifera that characterize the water masses of the principal basins of the Atlantic Ocean (e.g., Lohmann 1978; Schnitker 1980 and references therein; Mackensen et al. 1993). This allowed the use of several "index species" or "specific combinations of benthic foraminiferal species", in some cases rather subjectively and in others by using statistical methods, as proxies of past water masses vertical distribution in deep-sea environments of the Southwestern South Atlantic (SWSA) (Johnson

1983; Hodell, Kennett and Leonard 1983). However, the existent cross-correlation between the water masses physicochemical characteristics is one of the major problems to link them with the foraminifers distribution. This makes very difficult to determine exactly which physicochemical parameter controls the distribution of the foraminiferal assemblages (Jorissen, Fontanier and Thomas 2007). Against this backdrop, researches conducted since the 1990s indicate that the oxygenation of the bottom and interstitial waters, and the source, quantity and quality of food are the primary factors controlling the distribution of deep-sea benthic foraminifera (Gooday 1993, 2003; Thomas et al. 1995; Jorissen, Fontanier and Thomas 2007). In fact, several authors argue that the use of faunal composition to reconstruct the Quaternary history of bottom water circulation has no basis because faunal changes in sedimentary records exclusively reflect changes in surface productivity (Herguera and Berger 1991; Berger and Herguera 1992; Loubere 1994, 1999; Jorissen, Fontanier and Thomas 2007). In spite of recent important advances in the understanding of surface ocean productivity and the role of organic carbon flux in structuring benthic foraminiferal assemblages (Smart et al. 1994; Jorissen, Stigter and Widmark 1995; Jorissen, Fontanier
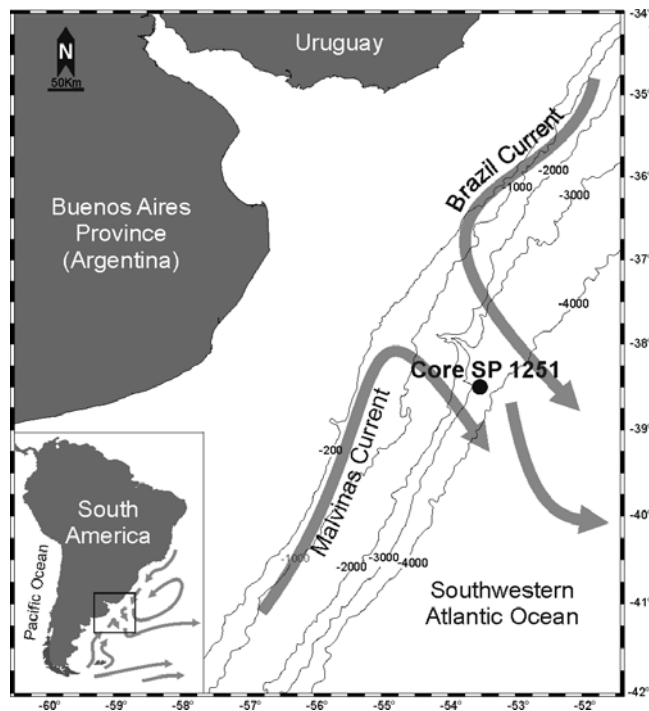
TEXT-FIGURE 1
Location map of core SP1251 (black circle). Main regional surface currents (Brazil and Malvinas Currents) are shown in grey.

TABLE 1
Water masses, organic matter source and oxygen availability-associated taxa.

	Water masses	Organic matter source	Oxygen availability
N. umbonifera	AABW		
U. peregrina	UCDW	High and continuous fluxes of organic matter	Oxygen depleted environments
G. subglobosa	UCDW	Phytodetritus pulses	Well oxygenated environments
E. exigua	NADW	Phytodetritus pulses	
O. umbonatus	NADW		
A. weddellensis		Phytodetritus pulses	
Stainforthia spp.		Phytodetritus pulses	Well oxygenated environments
Melonis spp.		High levels of organic matter	Oxygen depleted environments
Uvigerina spp.		High and continuous levels of organic matter	Oxygen depleted environments
Globobulimina spp.		High levels of organic matter	Oxygen depleted environments
Bolivina spp.		High levels of organic matter	Oxygen depleted environments
Bulimina spp.		High levels of organic matter	Oxygen depleted environments
Cassidulina spp.		High levels of organic matter	Oxygen depleted environments
Chilostomella spp.			Oxygen depleted environments
Nonionella spp.			Oxygen depleted environments

and Thomas 2007), the influence of water masses on meiobenthic community structure remains undefined and derived paleoceanographic reconstructions dubious.

The SWSA presents a highly dynamic hydrographic structure defined by the presence of contrasting deep water masses such as North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). Considering that thermohaline circulation and surface primary production have changed dramatically between glacial and interglacial periods (Duplessy et al. 1988; 1991; Sarnthein et al. 1994; 1995), we assess whether the hydrographic changes that occurred during the Late Quaternary in the SWSA controlled the benthic foraminiferal species composition, or if the "water mass signal" was overprinted by a "primary productivity signal". In order to address this question we analyzed benthic foraminiferal assemblages data from a sediment core obtained from the northern sector of the Argentine Continental Margin. Core SP1251 (SWSA, 3400m water depth; text-figure 1) lies between water masses of northern and southern origin. During glacial times, the depth of the boundary between the water masses changed as a consequence of a major influence of cold bottom waters of Antarctic origin in the SWSA (Duplessy et al. 1988; Sarnthein et al. 1994; Berger and Wefer 1996b; Curry and Oppo 2005; Mulitza et al. 2006). As primary productivity in the Southern Ocean is also known to have changed during glacial times (Mollenhauer et al. 2004; Loubere 1994, 1999), the location and depth of core SP1251 render it a natural laboratory to distinguish whether "water masses" or "productivity" was the most relevant factor in determining the composition of the benthic foraminiferal assemblages in the SWSA.

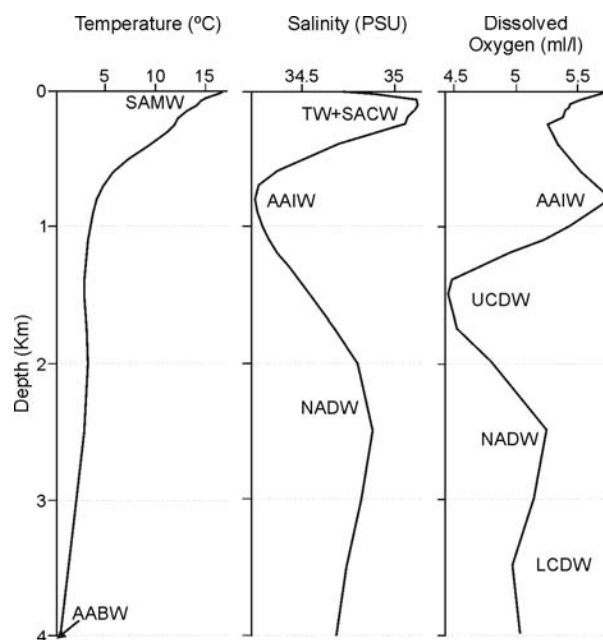**MODERN HYDROGRAPHIC STRUCTURE OF THE SWSA**

The South Atlantic Ocean is a key area in the global climate system. As a consequence of the development of thermohaline circulation during the Neogene, the South Atlantic has become a crucial passage for the Atlantic Meridional Overturning Circulation (AMOC) that moves warm water into the North Atlantic and cold water out (Berger and Wefer 1996a). Particularly, the SWSA plays an important role in this heat transport as it is filled by waters from the North Atlantic Ocean, from the Pacific Ocean and from the Weddell Sea (Reid, Nowlin and Patzert 1977). For this reason, its hydrographic structure has been the aim of many different works (e.g. Lohmann 1978; Schnitker 1980; Boltovskoy 1981; Boltovskoy et al. 1996; Gordon 1981; Hodell, Kennett and Leonard 1983; Peterson and Stramma 1991; Stramma and England 1999; Piola and Matano 2001; Henrich et al. 2003; Chiessi et al. 2007).

The SWSA presents a highly dynamic frontal zone at the surface: the Brazil-Malvinas Confluence zone (~38°S) which is bounded by two energetic western boundary currents, the warm Brazil Current to the north and the cold Malvinas Current to the south (text-figure 1; Reid Nowlin and Patzert 1977; Gordon 1981; Peterson and Stramma 1991; Stramma and England 1999; Piola and Matano 2001). Depths up to 500m are dominated by the southward flow of Tropical Water (TW) and South Atlantic Central Water (SACW), and by the northward flow of Subantarctic Mode Water (SAMW; text-figure 2). Meanwhile, the northward flow of high-oxygen and low-nutrient Antarctic Intermediate Water (AAIW) dominates between 500 and

1200m depth (text-figure 2; Piola and Matano 2001). North of the Confluence, water depths between ~1700 and 3000m are bathed by the southward flowing NADW, while to the south this water mass encounters and interacts with the Circumpolar Deep Water (CDW). This splits the CDW in two branches: the Upper Circumpolar Deep Water (UCDW; between ~1000-2000m depth) and the Lower Circumpolar Deep Water (LCDW; between ~3000-3700m depth; Reid Nowlin and Patzert 1977; Saunders and King 1995; Piola and Matano 2001; Arhan, Mecier and Park 2003; Arhan et al. 2002; Henrich et al. 2003; Preu et al. 2013). AAIW, UCDW and NADW boundaries can be distinguished by oxygen and nutrient content. NADW is an oxygen-rich and nutrient-poor water mass, characterized by relatively homogeneous nitrate, phosphate and oxygen profiles compared to the overlying UCDW and the underlying LCDW (Reid Nowlin and Patzert 1977). The CDW, by comparison, is an oxygen-poor and nutrient-rich water mass with an upper branch characterized by higher phosphate, nitrate and silicate values between 900m (tropical ocean) to 1500m (subtropical ocean) (Stramma and England 1999). This structure reflects that within the South Atlantic, the oxygen minimum comes from the Antarctic Circumpolar Current (text-figure 2; Reid Nowlin and Patzert 1977). Below ~3700-4000m depth, the northward flowing, corrosive Antarctic Bottom Water (AABW) fills the Argentine basin (Arhan, Mecier and Park 2003; Arhan et al. 2002; Frenz et al. 2003). It is formed in the Weddell Sea and is characterized by low temperature, salinity and nutrients, but high oxygen values (text-figure 2; Reid Nowlin and Patzert 1977; Alleman et al. 2001). The boundary between the LCDW and the AABW determines the depth of the calcite lysocline (Reid Nowlin and Patzert 1977; Frenz et al. 2003).

TEXT-FIGURE 2

Potential Temperature (°C), Salinity (PSU) and Dissolve Oxygen (µmol kg^{-1}) from the core site. Hydrographic data were obtained from WOA 2009. **TW**: Tropical Water; **SACW**: South Atlantic Central Water; **SAMW**: South Atlantic Mode Water; **AAIW**: Antarctic Intermediate Water; **UCPW**: Upper Circumpolar Water; **NADW**: North Atlantic Deep Water; **LCPW**: Lower Circumpolar Water; **AABW**: Antarctic Bottom Water.

DEEP-SEA FORAMINIFERA AS WATER MASS INDICATORS

As in many basins of the world ocean, SWSA deep-sea foraminiferal assemblages have been related to specific water masses (i.e., Lohmann 1978; Schnitker 1980; Boltovskoy 1981; Boltovskoy and Totah 1987; 1988; Boltovskoy et al. 1980; Hodell, Kennett and Leonard 1983; Johnson 1983; Harloff and Mackensen 1996). Such is the case of *Nuttallides umbonifera* (Cushman 1933), whose dominance below ~3700-4000m depth enabled its use as an indicator of the AABW in the SWSA (Table 1). The preference of this species for the AABW has been proposed not only in the SWSA, but also in the North Atlantic and Pacific oceans (i.e., Lohmann 1978; Schnitker 1980; Boltovskoy 1981; Boltovskoy and Totah 1987; 1988; Boltovskoy et al. 1980; Hodell, Kennett and Leonard 1983; Johnson 1983; Harloff and Mackensen 1996). The combined dominance of *Globocassidulina subglobosa* (Brady 1881) and *Uvigerina peregrina* (Cushman 1923) has been considered indicative of the UCDW above 2000m (Schnitker 1980; Hodell, Kennett and Leonard 1983; Johnson 1983) or poor oxygen conditions above 4000m (Lohmann 1978), while the combined dominance of *Epistominella exigua* (Brady 1884) and *Oridorsalis umbonatus* (Reuss 1851) has been considered indicative of the NADW (Table 1; Lohmann 1978; Schnitker 1980; Hodell, Kennett and Leonard 1983; Johnson 1983). *E. exigua* presents a significant potential for use in paleoceanographic reconstructions due to its wide geographic distribution and presence throughout much of the Cenozoic (Sun et al. 2006). It is found throughout the modern oceans, widespread in North and South Atlantic sediments, usually at abyssal depths, constituting 30-50% of the total foraminiferal assemblage (Gooday 1993). As a matter of fact,

north of 48°S Mackensen et al. (1993) found assemblages dominated by *E. exigua* and called them "the northern component deep water fauna" due to its distributional coincidence with the area bathed by the core of the NADW. Subsequently, and in spite of the extensive use of these species as markers for the aforementioned water masses, Boltovskoy and Totah (1987; 1988) found that dominant taxa varied slightly between the South Atlantic and South Pacific, and suggested that benthic assemblages probably reflected other ecological parameters as well as physico-chemical properties of the water masses.

PRODUCTIVITY IN THE SWSA

The South Atlantic presents an extremely variable pattern of surface productivity due to the variability in the availability of light and nutrients. This is reflected in the biodiversity of the benthic environment (Corliss et al. 2006). In particular, the SWSA is part of a large marine ecosystem that involves a rich and highly diverse community of species associated with high phytoplankton concentrations (Romero et al. 2006). High biological production is usually related to the occurrence of shelf fronts (Simpson 1981). Consequently, the presence of the Brazil-Malvinas Confluence determines the advection of nutrient-rich subantarctic waters through the Drake Passage into the western Argentine basin up to 38°S, due to the northward flow of the Malvinas Current along the eastern margin of the continental outer shelf. The chlorophyll blooms observed along this current are symptomatic of the upwelling of nutrient-rich waters to the surface of the Patagonian shelf (Matano, Palma and Piola 2010). The tidal mixing in the shelfbreak drives this upwelling, even when the winds in this region are not upwelling-favorable.

TABLE 2
Distribution and percentages of marker and most representative species identified in this study. Bottom line represents the mean percentage of each species along the core.

Core depth (cm)	Uvigerina peregrina (%)	Islandiella inflata (%)	Alabaminella weddellensis (%)	Epistominella exigua (%)	Globobulimina ovula (%)	Trifarina angulosa (%)	Gyroidina lamarckiana (%)	Ioanella tumidula (%)	Fursenkoina complanata (%)	Globocassidulina subglobosa (%)	Nuttallides umbonifera (%)	Oridorsalis umbonatus (%)
0	7.9	9.7	18.5	8.2	0.7	9.2	2.1	4.3	0.9	3.1	0.7	0.1
5	17.9	16	1.9	9.3	1.3	9	5.8	1.6	4.8	1.6	0	0
16	16.2	8.5	13.1	7.2	1	6.3	1.8	4.4	1.3	2.1	0.2	0.1
20	26.9	10.4	0	7.5	0.5	4.5	3.5	2.5	3	1.5	5.5	0
44	25	19.4	8.6	7.1	1.4	4.9	3.7	3.1	1.7	0.6	0	0
60	52	4.3	2.7	2.7	1.9	1.2	1.6	0.7	1	0.3	0.1	0.3
74	15	8.5	12.7	7.2	1.7	1.7	0.8	5.1	2.1	0	1.7	2.1
90	10	16.7	13.6	2.9	7.2	4.3	2.5	4.3	3.2	1.1	0.5	0.9
96	12	17.7	7.1	3.2	20.7	1.9	0	2.6	6.3	1.3	0	4.4
137	16	10.9	5.5	7.3	14.5	5.5	3.6	1.8	1.8	3.6	3.6	0
156	14	11.1	8.3	16.7	0	2.8	13.9	2.8	2.8	0	0	0
Mean (%)	19.5	12.1	8.4	7.2	4.6	4.6	3.6	3	2.6	1.4	1.1	0.7

Its impact appears to extend beyond to the north following the 200m isobath (Romero et al. 2006). Matano, Palma and Piola (2010) punctuated that in the Patagonian shelf, a persistent chlorophyll maximum can be recognized, making the Patagonian shelf a Class I marine ecosystem with a productivity rate larger than 300 g C m^{-2} yr^{-1} (Csirke 1997; Brandhorst and Castello 1971; Lutz and Carreto 1991; Sabatini, Reta and Matano 2004) and spring blooms of 25– 30 mg m^{-3}, an order of magnitude larger than those observed in typical offshore locations (e.g., Acha et al. 2004; Romero et al. 2006; García et al. 2008; Signorini et al. 2009). The "Patagonia High Chlorophyll Band" of Romero et al. (2006) terminates near the Brazil-Malvinas Confluence where the Malvinas Current veers offshore (Reid Nowlin and Patzert 1977). As a consequence, the subpolar portion of the SWSA results the most productive portion of the entire Southern Ocean (Matano, Palma and Piola 2010).

DEEP-SEA FORAMINIFERA AS PRODUCTIVITY INDICATORS

Exported organic matter flux resulting from phytoplankton blooms produces a slight layer of labile (phytodetritic) organic matter that is easily hydrosoluble and facilitates the development of opportunistic epifaunal species of benthic foraminifera (Gooday 1993; 2003; Jorissen 1998; Jorissen, Stigter and Widmark 1995; Smart et al. 1994; Sun et al. 2006). However, when high and continuous fluxes of exported primary productivity govern, the benthic assemblages are dominated by low oxygen-tolerant infaunal species. This usually occurs in areas of high input of labile organic matter, such as in upwelling regions, at oceanic fronts and near river discharge (Smart 2002; Loubere and Fariduddin 1999; Jorissen, Fontanier and Thomas 2007). On the contrary, vertical and lateral transport of refractory organic matter usually originating in nepheloid layers, turbidity currents and/or submarine canyon-associated currents has been observed in most of the continental margins (Gooday 2003). These areas present eutrophic environments where organic matter decay decreases the oxygen availability (Smart 2002).

Many researchers consider exported productivity to be the main factor structuring assemblages (i.e., Lutze and Coulbourn 1984; Smart 2002), even when other factors such as bottom current speed and grain size can affect their structure (Jorissen, Fontanier and Thomas 2007). Seasonal fluxes of organic matter generated by large primary productivity serve as food for the benthic organisms (Loubere and Fariduddin 1999; Sun et al. 2006) allowing a group of opportunistic epifaunal taxa to reproduce quickly, and causing a strong dominance of epifaunal species (Gooday 1993; 2003; Smart 2002; 2008; Smart et al. 1994; Thomas et al. 1995; Loubere 1994, 1999). Considering this criteria, species composition and overall abundance of benthic foraminifera are used to provide an estimate of paleoproductivity regimes (Herguera and Berger 1991).

Many studies have suggested that the abundance of *Alabaminella weddellensis* (Earland 1936), *E. exigua*, *G. subglobosa* and *Fursenkoina* spp. (=*Stainforthia* spp. – Hofker, 1956) can be used to recognize seasonal pulses of phytodetritus originating from surface primary productivity in eutrophic areas (Table 1; Gooday 2003; Smart et al. 1994; Smart 2008; Thomas et al. 1995; Thomas and Gooday 1996). However, *A. weddellensis* was found to be associated with phytodetritic deposits exclusively along with *E. exigua*, not alone (Sun et al. 2006). *G. subglobosa* has been associated not solely with phytodetritic deposits, but also with well-oxygenated environments and strong bottom currents (Thomas et al. 1995; Schmiedl, Mackensen and Miiller 1997; Sousa et al. 2006; Smart 2008). Along the continental margins, where oganic matter is high and oxygen availability is low but not null, infaunal species such as *U. peregrina* usually are the dominant components of the assemblages. Uvigerinids commonly occur in areas with high, continuous fluxes of organic matter, and are often associated with reduced bottom oxygen concentrations, such as in upwelling areas (Table 1; Jorissen, Fontanier and Thomas 2007; Smart 2008). Other taxa such as *Melonis barleeanus* (Williamson 1858), *Globobulimina* spp. (Cushman 1927), *Bolivina* spp. (d'Orbigny 1843), *Bulimina* spp. (d'Orbigny 1826), and *Cassidulina* spp. (d'Orbigny 1826) have also been documented associated to high levels of organic matter (Table 1; Lutze and Coulbourn 1984; Corliss, Martinson and Keffer 1986; Mackensen et al. 1993; Schmiedl and Mackensen 1997; Schmiedl, Mackensen and Miiller 1997; Smart 2002; 2008; Gooday 2003; Loubere and Fariduddin 1999; Jorissen, Fontanier and Thomas 2007). Eutrophic environments produce low levels of available oxygen that only a few species can tolerate. Despite that, there are no species that live in anoxic environments. *Melonis* spp. (Montfort 1808), *Globobulimina* spp., *Bolivina* spp., *Bulimina* spp., *Cassidulina* spp., *Chilostomella* spp. (Reuss 1849), *Uvigerina* spp. and *Nonionella spp.* (Rhumbler 1949) are usually related with environments with oxygen depletion (Table 1; Smart, 2002).

TABLE 3
Scaled varimax Factor scores for each of the 126 taxa recorded in this study. The Factor scores indicate the relative contribution of each of the benthic foraminiferal taxa to the three Factor assemblages.

Species	Factor 1	Factor 2	Factor 3
Alabaminella weddellensis	6.906565072	0.153881722	-0.56267418
Astrononion spp.	0.005176272	-0.007992226	-0.017121029
Bolivina ordinaria	-0.00574119	-0.001449787	-0.000372253
Bolivina malovensis	0.184788447	0.003963093	-0.079856766
Bolivina silvestrina	0.682494357	-0.099418373	0.47956323
Bolivina subspinescens	0.008895086	0.002218731	-0.005019958
Bolivina spp.	0.040944046	-0.001691832	-0.033629533
Bulimina aculeata	0.033552455	-0.014739513	-0.02327467
Bulimina inflata	0.087207724	0.004072263	-0.031968385
Bulimina rostrata	0.057585658	-0.006007725	0.008924363
Cassidulina laevigata	1.16186068	0.067063224	-0.518342837
Cassidulina minuta	0.059792136	-0.023074071	0.011235
Cassidulina spp.	0.183457743	0.066571836	0.107818179
Cassidulinoides parkerianus	0.002208015	-0.010460211	-0.016192766
Chilostomella czizeki	-0.017223569	-0.004349361	-0.001116759
Cibicides ex gr. aknerianus	-0.294536385	-0.187640229	0.396537986
Cibicides bradyi	0.567688107	-0.062248127	0.007256348
Cibicides dispars	0.446046422	0.018239347	-0.126454693
Cibicides mckannai	0.027344379	-0.00919715	-0.013749691
Cibicides pseudoungerianus	0.017700138	0.002542437	-0.006545304
Cibicides robertsonianus	0.010111127	-0.018731737	-0.017101619
Cibicides wuellerstorfi	0.257463204	-0.070582515	-0.123076159
Cibicides spp.	0.012048982	0.002987675	-0.01041217
Clavulina communis	0.021272018	-0.001346377	0.008790464
Dentalina advena	0.017700138	0.002542437	-0.006545304
Discorbis peruvianus	-0.069435429	-0.018125604	0.046984926
Discorbis subvilardeboanus	0.042094605	0.002920815	-0.02804248
Discorbis sp. (williamsoni?)	0.068633636	0.003837479	-0.030322671
Eggerella bradyi	0.31064539	0.000920159	-0.036250976
Ehrenbergina carinata	0.200317617	0.017249289	-0.115430058
Elphidium gunteri	-0.069435429	-0.018125604	0.046984926
Epistominella exigua	4.014825735	-0.213697315	-0.893657792
Epistominella obtusa	1.470855327	-0.01498973	-0.745721849
Epistominella spp.	0.201067848	0.067219249	0.104767489
Eponides polius	0.38378291	-0.076704872	-0.234707474
Eponides spp.	0.099429979	-0.009427262	-0.04121235
Fissurina ampullacea	0.035400276	0.005084875	-0.013090608
Fissurina annectens variocarinata	0.017700138	0.002542437	-0.006545304
Fissurina carinata	0.008895086	0.002218731	-0.005019958
Fissurina compressa	0.009114793	-0.003065717	-0.00458323
Fissurina fimbriata	0.009114793	-0.003065717	-0.00458323

Species	Factor 1	Factor 2	Factor 3
Fissurina furcillifera	-0.004158229	0.000357938	-0.012974527
Fissurina globosa	0.033143326	-0.003142421	-0.01373745
Fissurina laevigata, f. labiata	0.018009879	-0.000846986	-0.009603189
Fissurina laevigata, f. typica	0.043427911	0.021271729	0.157278832
Fissurina marginata	0.009114793	-0.003065717	-0.00458323
Fissurina cf. F. modesta	0.017700138	0.002542437	-0.006545304
Fissurina obtusa	0.008895086	0.002218731	-0.005019958
Fissurina orbignyana	0.006966748	-0.008066939	0.081803547
Fissurina cf. F. sacculus	0.046687893	-0.01458068	0.173151244
Fissurina cf. F. schwageriana	0.006146537	-0.005533702	-0.003654967
Fissurina toddae, f. typica	0.03549031	0.006979899	-0.016585221
Fissurina toddae, f. virgulata	0.033143326	-0.003142421	-0.01373745
Fissurina spp.	0.017113789	-0.000988439	-0.004174882
Fursenkoina complanata	0.543689349	-0.060339609	0.703205585
Fursenkoina pontoni	0.014291065	-0.011057942	-0.021704259
Fursenkoina rigii	0.072711139	-0.0018204	0.021378974
Fursenkoina schreibersiana	0.069139259	0.002068414	0.006034026
Globobulimina ovula	0.672108446	-0.003515967	9.496470752
Globocassidulina subglobosa	0.895959608	4.632703852	0.258524131
Gyroidina globosa	0.377608851	-0.098337079	-0.259698317
Gyroidina lamarckiana	1.824742461	-0.268301134	-0.60688407
Gyroidina medicea	-0.022964758	-0.005799148	-0.001489012
Gyroidina soldanii	-0.030264858	-0.003363646	-0.028883663
Gyroidina umbonata	0.541293696	0.053608222	-0.239487745
Gyroidina spp.	-0.00574119	-0.001449787	-0.000372253
Hoeglundina elegans	0.173966823	-0.07054656	-0.276906332
Ioanella tumidula	2.059932442	-0.015940188	-0.156231231
Islandiella inflata	5.531771557	-0.429646966	1.641714961
Karreriella bradyi	0.038123813	-0.019851455	0.246527399
Karreriella siphonella	0.021272018	-0.001346377	0.008799644
Karreriella spp.	0.09527175	-0.009069323	-0.054186876
Lagena distoma	0.021272018	-0.001346377	0.008799644
Lagena elongata	0.033230966	-0.000253727	0.001882087
Lagena nebulosa	0.007372095	-0.015050428	0.077776327
Lagena raricosta	0.065149396	0.010614987	-0.030048081
Lagena stelligera	0.017700138	0.002542437	-0.006545304
Lagena substriata	0.012707938	-0.006617152	0.0821758
Lagena vulgaris	0.021272018	-0.001346377	0.008799644
Lagena wiesneri	0.009114793	-0.003065717	-0.00458323
Lagenosolenia favosiformis proba	-0.013053315	-0.001860792	-0.007954568
Martinottiella antarctica	0.521391686	0.024597877	0.381523062
Melonis affine	0.421609272	-0.023709659	0.221152324

Species	Factor 1	Factor 2	Factor 3
Nonionella auricula	1.019493345	-0.054201605	0.104961406
Nuttalides umbonifera	0.19755349	0.058520799	0.179884751
Oolina globosa globosa	0.006217759	-0.000357137	-0.00728981
Oolina globosa annulata	0.008895086	0.002218731	-0.005019958
Oolina lineata	0.017790172	0.004437462	-0.010039917
Oolina melo	0.054804273	-0.009184415	-0.028219406
Oolina squamosa	0.033143326	-0.003142421	-0.01373745
Oolina spp.	0.006146537	-0.005533702	-0.003654967
Oridorsalis umbonatus	0.35487311	-0.065556077	0.529432157
Parafissurina admiralis	0.008895086	0.002218731	-0.005019958
Parafissurina aperta	0.015861834	-0.005848208	0.076783588
Parafissurina dorbignyana	0.017700138	0.002542437	-0.006545304
Parafissurina lateralis, f. crassa	0.008895086	0.002218731	-0.005019958
Parafissurina lateralis, f. typica	0.084219721	-0.001838498	-0.039826376
Parafissurina spp.	0.033143326	-0.003142421	-0.01373745
Pullenia bulloides	0.039612902	-0.005245406	0.067552652
Pullenia osloensis	0.164579375	0.001187725	-0.071260431
Pullenia quadriloba	0.03549031	0.006979899	-0.016585221
Pullenia quinqueloba	0.017790172	0.004437462	-0.010039917
Pullenia salisburyi	0.261716428	-0.001210108	-0.046474024
Pullenia subcarinata	-0.00574119	-0.001449787	-0.000372253
Pyrgo depressa	-0.933380254	-0.021984718	5.354520125
Pyrgo denticulata	0.006146537	-0.005533702	-0.003654967
Pyrgo murrhina	0.105576112	-0.017705409	-0.039298444
Pyrgo nasuta	-0.09004434	-0.023826807	-0.037933929
Pyrgo patagonica	-0.069435429	-0.018125604	0.046984926
Pyrgo subsphaerica	-0.069435429	-0.018125604	0.046984926
Pytine spp.	-0.006906778	-0.007394495	-0.011609535
Quinqueloculina cf. Q. lamarckiana	0.003153896	0.000768944	-0.005392211
Quinqueloculina milletti	-0.208306288	-0.054376812	0.140954778
Quinqueloculina patagonica	-0.251146493	-0.067741247	0.176374442
Robulus spp.	0.017700138	0.002542437	-0.006545304
Sphaeroidina bulloides	0.006307792	0.001537888	-0.010784423
Siphuvigerina hispida	-0.14791765	4.432678451	-0.042703945
Siphuvigerina proboscidea	0.01210832	9.175577536	-0.022195993
Textularia spp.	-0.00574119	-0.001449787	-0.000372253
Trifarina angulosa	2.865201565	0.115826105	-0.281123189
Triloculina tricarinata	0.048752246	-0.023330271	-0.025642856
Triloculina trigonula	0.25644069	0.019490434	-0.053235478
Triloculina trilocularis	0.054415344	-0.004488797	-0.004937806
Trochammina spp.	0.027554403	-0.019666823	-0.015548132
Uvigerina bifurcata	2.404744137	-0.484801232	0.028714245
Uvigerina peregrina			
Accumulated variance (%)	**63,76203**	**74,73593**	**84,78097**

METHODS

Site location

Sediment core SP1251 (877cm total core length) was collected from the Argentine Continental Margin at 38°29.7'S, 53°40.7'W in a water depth of 3400m (text-figure 1). Core location is suitable to understand late Quaternary changes in deep water circulation and surface productivity conditions. In the modern ocean, the water-sediment interface at this site lies at the water mass boundary between NADW and LCDW. Therefore, if intermediate and deep water masses changed their relative positions due to a significant suppression of NADW contributed to the South Atlantic during glacial times (Berger and Wefer 1996b), even small changes should be detected based on appropriate proxies.

Chronology

The age of core SP1251 was determined by biostratigraphy based on planktic foraminifera from the >63μm sediment size fraction (full count). The zonal scheme of Berggren et al. (1995) with slight modifications by Kennett and Srinivisan (1983) and Pujol and Duprat (1983), as well as the first occurrence of *Globorotalia truncatulinoides* at 300 kyrs in the South Atlantic (Pharr and Williams 1987) were considered for age estimation. The core contained fauna of the PT1b Zone (Berggren et al. 1995) or *G. truncatulinoides* Partial Range Subzone (Srinivasan and Kenneth 1981). Taking into account the planktic species distribution and range, the age of productive samples is probably between 300 kyrs and 120 kyrs. Moreover, reconstruction of sea surface temperatures in Laprida et al (2011) would indicate that the sequence corresponds to a glacial time that could be assigned to the final phase of the MIS 6, probably between 160 ka BP and 140 ka BP (García Chapori 2013). The absence of Holocene sediments in the topmost samples was supported by the complete absence of *Globorotalia menardii* and the high proportion of subantarctic species (Ericson and Wollin 1968; Boltovskoy 1973) (for more details see Laprida et al. 2011).

Lithology and Faunal analysis

The whole section recovered by core SP1251 consists of olive gray (5Y 3/2) to light olive gray (5Y 5/2) silty clay sediments with no relevant changes in lithology or color. Thus, the sampling interval was determined based on minimal lithological changes.

Samples were washed through a 63μm sieve, dried in an oven at ≤50°C and weighted. All benthic foraminifera from the >63 μm size fraction were picked under a binocular microscope to insure that even the smaller sized specimens were included in the analysis, some of them being paleoecologically important like *A. weddellensis* and *E. exigua* (e.g., Gooday 1993; Thomas et al. 1995). Only the uppermost 156cm of sediment contained abundant benthic and planktic foraminifera. Below that level, foraminifers were present in insufficient amounts for statistical treatment or were completely absent. Therefore, quantitative counts were made on the uppermost 11 samples.

Taxa were identified according to Ellis and Messina (1940 and later), Boltovskoy et al. (1980), Saito, Thompson and Breger (1981), Kennett and Srinivasan (1983), Loeblich and Tappan (1988) and Kemle-Von Mücke and Hemleben (1999) criteria. In order to recognize taphonomic biases and the dissolution effect caused by corrosive Antarctic waters, the planktic to benthic foraminifer ratio was analyzed. Total foraminiferal abundance,
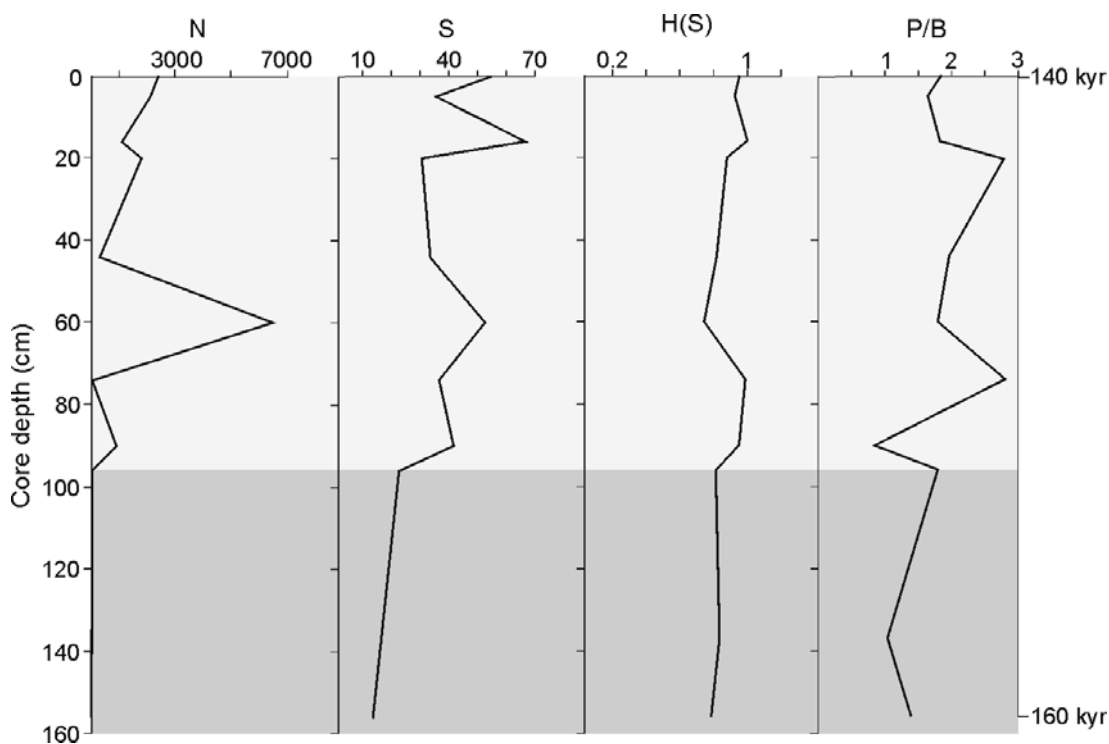
TEXT-FIGURE 3
Total foraminferal abundance (N), species richness (S), Shannon-Weaver diversity index (H(S)) and planktic/benthic ratio (P/B) of the fertile portion of the core. Shaded in grey are the two sections recognized base on these analyses.

species richness, Shannon Weaver diversity index and the relative abundance of marker species were analyzed. Therefore, we analyzed the relative abundance of *E. exigua, A. weddellensis, G. subglobosa, U. peregrina* as a markers of quantity and quality of organic matter; the relative abundance of *Globobulimina ovula* (d'Orbigny 1826) as marker of oxygen availability and the relative abundance of planktic foraminifera *Globigerina bulloides* (d'Orbigny 1826)*,* as a surface productivity marker (Thomas et al. 1995; Zaric et al. 2005; Fraile et. al. 2007 and references therein). In order to discern whether the water mass signal or the productivity signal was the most important in determining the benthic foraminiferal assemblages, Q-mode factor analysis was performed on the data set using the C2 software (Juggins 2007) and the relative abundance of *E. exigua, O. umbonatus, U. peregrina, G. subglobosa* and *N. umbonifera* was simultaneously analyzed as water masses associations. Finally, benthic faunal results were compared with quantitative and semi-quantitative estimations of sea surface temperatures (SST) obtained by Laprida et al. (2011) for the same core based on the Modern Analog Technique, the proportion of *Neogloboquadrina pachyderma* (Ehrenberg 1861) (*sinistra*) relative to *N. pachyderma* (*sinistra + dextra*), and the relative abundance of subantarctic [*G. bulloides, Globigerinita uvula* (Ehrenberg 1861), *Globorotalia scitula* (Brady 1882), *Globorotalia truncatulinoides* (d'Orbigny 1839), *N. pachyderma* (sinistral and dextral) and *Turborotalia quinqueloba* (Natland 1938)], transitional [*Globigerinita glutinata* (Egger 1893) and *Globorotalia inflata* (d'Orbigny 1839)] and subtropical [*Globigerina falconensis* (Blow 1959), *Globigerina rubescens* (Hofker 1956), *Globigerinella siphonifera* (d'Orbigny 1839), *Globigerinoides conglobatus* (Brady 1879), *Globigerinoides*

ruber (d'Orbigny 1839), *Globorotalia menardii* (Parker, Jones and Brady 1865), *Neogloboquadrina dutertrei* (d'Orbigny 1839) and *Orbulina universa* (d'Orbigny 1839)] species according to Boltovskoy et al. (1996).

RESULTS

The number of benthic foraminifera ranged from 2 to 6511 individuals/g, with a mean of 895 individuals/g (text-figure 3). A total of 127 taxonomic units were recognized with a proportion of unidentified individuals lower than 10% per sample. Assemblages were diverse in terms of number of species, ranging from 15 to 68 species per sample (text-figure 3). Only a few species were frequent and well represented, however, as samples usually contained a large proportion of rare species (relative abundance <2% each).

U. peregrina was the dominant species of the benthic assemblage with a mean relative abundance of 19.5%, though in some samples it represented over than 25% (20cm, 44cm and 60cm). It was followed by *Islandiella inflata* (Le Roy 1944) (12.1%), *A. weddellensis* (8.4%), *E. exigua* (7.2%), *Globobulimina ovula* (4.6%) and *Trifarina angulosa* (Williamson 1858) (4.6%). Species with mean relative abundances over 2% like *Gyroidina lamarckiana* (d´Orbigny 1839), *Ioanella tumidula* (Brady 1884) and *Fursenkoina complanata* (Egger 1893) were considered also relatively common. The most representative species are listed in Table 2, while the additional 90 species identified (Appendix 1) are too rare to determine distributional patterns and were not considered in this analysis.
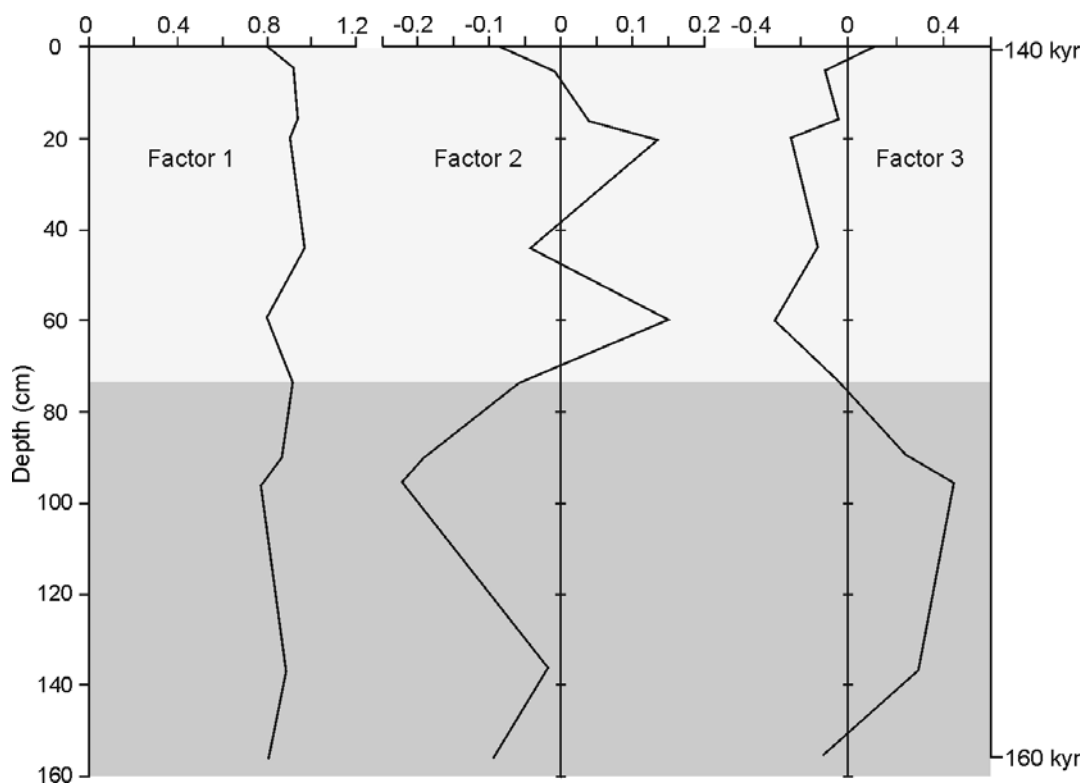
TEXT-FIGURE 4
Relative importance of the three most significant Factors versus core depth. **Factor 1**: *A. weddellensis - I. inflata - E. exigua - T. angulosa - U. peregrina - I. tumidula* assemblage; **Factor 2**: *S. proboscidea - G. subglobosa – S. hispida* assemblage; **Factor 3**: *G. ovula – P. depressa* assemblage. Shaded in grey are the two sections recognized along the core.

Factor analysis revealed three distinct benthic foraminiferal assemblages, which account for ~85% of the total variance (Table 3). Factor 1, dominated by multiple species such as *A. weddellensis, I. inflata, E. exigua, T. angulosa, U. peregrina* and *I. tumidula* (high organic matter assemblage); Factor 2 consists of *Siphouvigerina proboscidea* (Schwager 1866) - *G. subglobosa - Siphouvigerina hispida* (Schwager 1866) (high oxygen assemblage); and Factor 3, composed of *G. ovula - Pyrgo depressa* (d'Orbigny 1826) (low oxygen assemblage). Based on the dominance of these benthic foraminiferal assemblages, two sections were recognized along the fertile portion of our core (text-figure 4). From 156 to 74cm, high organic matter (Factor 1) and high oxygen (Factor 3) assemblages dominated. At 74cm, Factor 3 was replaced by Factor 2 and thus, the upper section of the core between 74-0cm resulted to be dominated by high organic matter and low oxygen (Factor 2) assemblages.

Total foraminiferal abundance, species richness, diversity index values and marker species abundances also evidenced two sections not consistent with those obtained by the factor analysis (text-figures 3 and 5). The lower section (156 to 96cm) is characterized by very low values of total foraminiferal abundance (<20 individuals/g) and species richness (<25 species/sample), whereas the diversity index values oscillated around 0.8. Richness and diversity showed a slightly positive tendency (text-figure 3). Along this interval, *U. peregrina* abundance varied between 12% and 16% while *G. bulloides* presented abundances lower than 10%, and *G. subglobosa* never exceeded 4% (text-figure 5). For its part, *E. exigua* abundance varied between

3% and 17% while *A. weddellensis* presented abundances lower than 9% and *O. umbonatus* only attained ~4% at 96 cm. In this section, *G. ovula* represented ~20% of the total benthic foraminiferal fauna and *N. umbonifera* never exceeded 5% (text-figure 5).

The upper section (96 to 0cm) reflected an important change in the benthic assemblage structure, with a conspicuous increase in total foraminiferal abundance reaching >6000 individuals/g at 60cm, and showing a positive tendency of the species richness toward the top, although diversity index is fairly constant (text-figure 3). Along this interval the abundance of *G. ovula* abruptly decreased and *U. peregrina* presented a peak at 60cm to decrease abruptly between 44cm and the top. *G. bulloides* showed almost the same pattern as *U. peregrina*, whereas *G. subglobosa* and *O. umbonatus* never exceed 2%. *E. exigua* and *A. weddellensis* showed similar patterns, opposite to the pattern of *U. peregrina*, becoming slightly more relevant between 44cm and the top of the core (text-figure 5).

DISCUSSION

Mid-Late Pleistocene glacial event and dissolution potential

Core SP1251 was deposited during a Mid-Late Pleistocene cold period between 160 and 140 kyrs (García Chapori 2013). SST reconstructions performed by Laprida et al. (2011) reflect temperatures 4 to 6°C colder than modern in the study area (text-figure 6). These SST, along with the high proportion of *N. pachyderma* (sinistral) and the dominance of subantarctic spe-
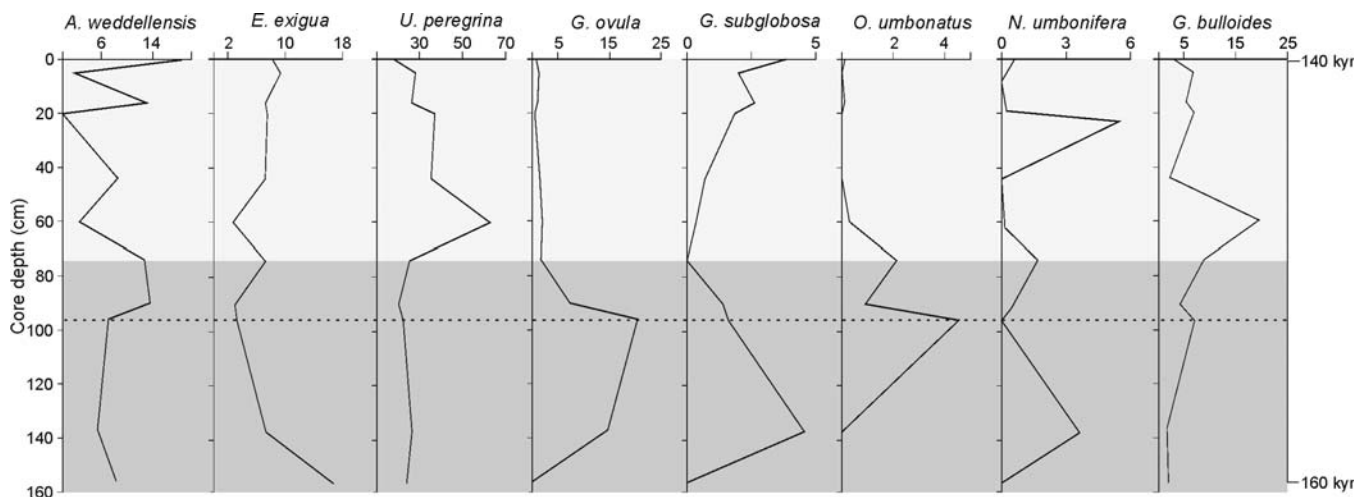
TEXT-FIGURE 5
Percentages of productivity-associated species (*A. weddellensis, G. ovula, G. bulloides*), water masses-associated species (*O. umbonatus, N. umbonifera*) and species associated to both (*E. exigua, U. peregrina, G. subglobosa*). Shaded in grey are the two sections recognized along the core. Dotted line represents the beginning of the transition between sections.

cies, indicate a clear dominance of surface waters of polar origin in the studied area (text-figure 6). The fertile portion of the core (the topmost 156cm) presents benthic foraminiferal assemblages characteristic of the SWSA continental slope (Boltovskoy 1976; 1979). Diversity, species richness and the P/B ratio present values within limited ranges (text-figure 3), indicating that conditions in the taphonomic active zone would have been rather constant, and hence taphonomic process have not affected the assemblages. As a general consensus, southern-source corrosive deep water masses would have expanded to shallower depths in the western Atlantic basins during glacial periods (e.g., Duplessy et al. 1988; Sarnthein et al. 1994; Berger and Wefer 1996b; Curry and Oppo 2005; Mulitza et al. 2006).This is particularly important since the Argentine basin is characterized by strong dissolution processes related to the dominance of the AABW at ~4000m depth (Piola and Matano 2001; Arhan, Mecier and Park 2003; Arhan et al. 2002; Frenz et al. 2003). Very low abundances of *N. umbonifera* in the fertile levels of the core would indicate a minor influence of the AABW and hence of corrosive waters (Gooday 2003) at this depth, corroborating that dissolution would not have substantially affected the assemblages. Below 156cm, the core is barren of calcareous fauna. This barren zone may correspond to a colder (stadial) phase of the glacial interval, when the AABW and the lysocline shoaled and dissolution related to corrosive bottom waters of Antarctic origin was intense (Laprida et al. 2011).

Water-mass signal in SWSA

The distribution of deep-sea benthic foraminifera in the SWSA was initially suggested to be controlled by physio-chemical properties of deep water masses (Lohmann 1978; Schnitker 1980). This faunal-water mass relationship was used in the reconstruction of deep-water circulation patterns during the Neogene (e.g., Johnson 1983; Hodell, Kennett and Leonard 1983; Mackensen et al. 1993 and references therein).

Compilations of deep water $\delta^{13}C$ and Cd_W for the Late Glacial Maximum indicate that the main core of glacial NADW was at least 1000 meters shallower than today, while in the Western Atlantic, depths below ~2km were filled with the Southern Ocean Water, the glacial version of AABW/CPDW (Curry and Oppo 2005; Marchitto and Broecker 2006; Oppo and Curry 2012). This water mass distribution suggests that cold deep waters from Antarctic origin (CDW, AABW or both) would have been displaced to shallower depths in the SWSA during glacial periods. For Pleistocene glacial events, Vergnaud Grazzini et al. (1984) also proposed that NADW was colder than today, probably related to more intense mixing between NADW and CDW and suggested intensification in the production of the AABW.

Late Neogene benthic foraminifera were grouped into three assemblages indicative of specific water masses (Hodell, Kennett and Leonard 1983): *N. umbonifera* assemblage (associated with AABW), *G. subglobosa-U. peregrina* assemblage (associated with CDW) and *O. umbonatus-E. exigua* assemblage (associated with NADW). As both the AABW and the CDW would have been displaced to shallower depths in the SWSA during glacial periods, we would expect that benthic foraminiferal assemblages of core SP1251 (3400m water depth) would reflect a dominance of water masses of Antarctic origin. The dominance of *U. peregrina* could lead to the hypothesis of CDW dominance over NADW and AABW. However, *G. subglobosa*, the other species related with the CDW, presents almost the opposite pattern to *U. peregrina* (text-figure 5). On the other hand, if during the cold period represented in core SP1251 the CDW would have been displaced to shallower depths due to an intensification of the AABW as Vergnaud Grazzini et al. (1984) pro-
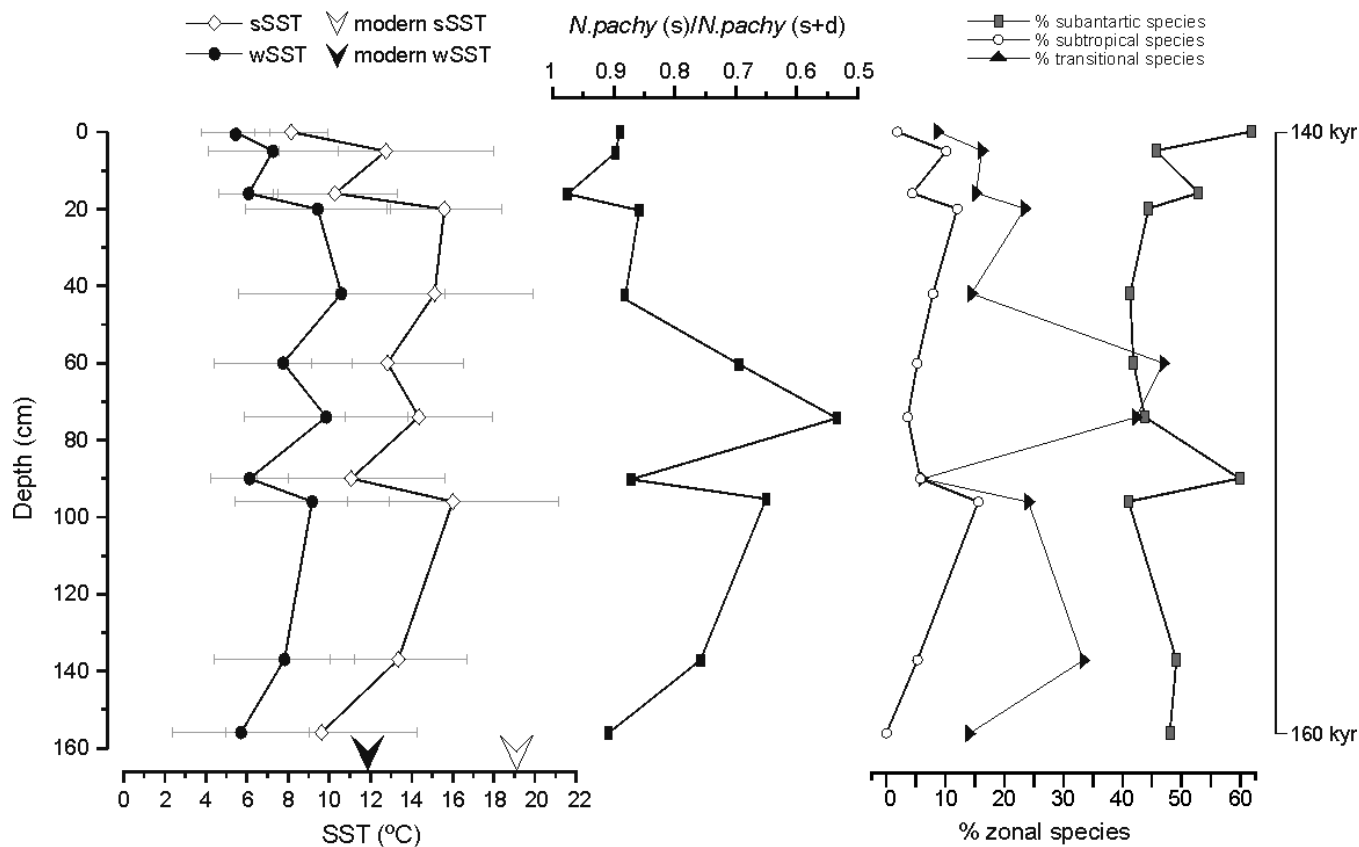
TEXT-FIGURE 6
Summer and winter reconstructed SSTs. Modern winter and summer sea surface temperature (SST) values are indicated by rows in the SSTs axis. Trends in *N. pachyderma* (sinistral) proportion. Trends in relative abundance of zonal species considering subatarctic, transitional and subtropical species after Boltovskoy et al. (1996). Modified from Laprida et al. (2011).

posed, we should have found higher abundances of *N. umbonifera*.

Based on both factor and compositional analyses, we found no evidence that water mass determined the structure of benthic foraminiferal assemblages of core SP1251. Even when the assemblage represented by Factor 1 includes *U. peregrina* (considered as indicative of the UCDW) as one of the most relevant species, it does not include *G. subglobosa*, precluding the association of this assemblage with any particular water mass as Hodell, Kennett and Leonard (1983) did. For example, between 156cm and 96cm, species considered as markers of water masses are scarce. Above 96cm, even when the abundance of *E. exigua* increases slightly, *O. umbonatus* abundance decreases (text-figure 5). This inconsistency makes it difficult to assign this increase/decrease to a major/minor influence of the NADW. In conclusion, it is not possible to recognize the dominance of any of the water mass marker in our record. We conclude that the structure of assemblages has not been controlled by deep water mass structure during the cold period spanned by the core.

Productivity signal in SWSA

In the Atlantic sector of the Southern Ocean up to 35°S, Mackensen et al. (1993) proposed that the distribution of ben-

thic foraminifera was determined by both bottom water mass properties and organic matter flux from the surface. In areas of uniform bottom water mass distribution, the benthic assemblage composition mainly depends on ocean surface processes that govern the food supply, whereas in areas of high primary productivity, the water mass signal recorded by the benthic foraminiferal fauna is overprinted by a productivity signal. According to factor analysis performed in core SP1251, this seems to be the case in the SWSA. The two more relevant assemblages, summarized in Factors 1 and 2, are composed of species associated to high organic matter availability and well-oxygenated environments. The third assemblage (Factor 3) is composed by low oxygen-associated species, indicating that the sum of the three factors reflects quality and quantity of food supply. Therefore, the productivity signal would have been the main factor in determining the structure of benthic communities in the SWSA during the time spanned by the core.

During glacial periods, the flux of carbon to the sea floor was generally enhanced. In core SP1251, the clear dominance of the high organic matter assemblage all along the core corroborates this statement. However, the stratigraphic distribution of the two other assemblages allow the identification of two distinct sections: the lower section (156cm and 74cm) where the low-oxygen assemblage dominates together with Factor 1; and

the upper section (between 74cm and the top of the core), where the high-oxygen assemblage leads instead. According to several authors, *Globobulimina* (main contributor to Factor 3) is a typical component of assemblages from depleted oxygen slope environments where it is able to exploit refractory organic matter (Fontanier et al. 2002; Gooday 2003; Alve 2010), while *G. subglobosa* (main contributor to Factor 2) has been associated with well-oxygenated environments (Thomas et al. 1995; Schmiedl, Mackensen and Miiller 1997; Sousa et al. 2006; Smart 2008). Changes in the oxygenation of the bottom water suggest a change in the trophic state and source of the organic matter, from refractory to phytodetritic, on which the benthic assemblages nourish. This could be related to variations in the shelfbreak upwelling of Patagonia (Matano and Palma 2008) during the Mid-Late Quaternary as a consequence of variations in the Antarctic upwelling, which seems to have played a fundamental role in the surface nutrient availability of the Southern Ocean (Thomas et al. 1995; Sigman and Boyle 2000; Mackensen, Rudolph and Kuhn 2001; Toggweiler, Russell and Carson 2006; Anderson et al. 2009; Hendry et al. 2012). Currently, the Malvinas Current drags large amounts of nutrients along the Argentine Continental Margin, making it a highly productive region (Saraceno, Provost and Piola 2005; Romero et al. 2006; Matano and Palma 2008; Matano, Palma and Piola 2010). If the high productivity conditions of the Patagonian Margin changes, surface productivity of the remaining whole margin also must change. The upwelling of nutrient and CO_2 rich bottom waters South of the Polar Front would have decreased during cold periods as a result of the northern displacement of the westerly wind belt (Toggweiler, Russell and Carson 2006; Rojas et al. 2008), resulting in a major formation of AAIW in detriment of the SAMW (text-figure 7; Sigman and Boyle 2000; Sigman, Hain and Haug 2010). The development of a stable, fresh, frequently ice-covered surface layer around Antarctica reduced deep-ocean ventilation and caused SST negative anomalies in the SWSA (Kwok and Comiso 2002; Barreira and Compagnucci 2005) as SST reconstruction reflects (text-figures 6 and 7). This could have led to an upwelling of nutrient-depleted waters along the Patagonian shelf and, consequently, to a lowering in surface productivity of the whole Argentine Continental Margin. In this low productive margin, the main source of organic matter would have been the South America continent itself. According to Bozzano, Violante and Cerredo (2011), northern Patagonia and the southern Pampa are the principal sources of sediment deposited by along-slope processes. High quantity of dust produced in Patagonia and Argentinean Pampas is transported eastward by the westerly winds before settling into the South Atlantic (Prospero et al. 2002). Increased wind speeds, and colder sea-surface and atmospheric temperatures increased the deposition of atmospheric dust during glacial times, especially close to arid and semi-arid areas such as Patagonia, suggesting that these areas were the main dust source regions. This included large quantities of refractory organic matter of continental origin that could have been laterally advected by the extensive submarine canyon systems that dissected the Argentine slope (Violante et al. 2010). Submarine canyons transport large amounts of sediment to the deep sea through gravity-driven sediment flow events. The Mar del Plata Submarine Canyon is developed between 500 and 3700m water depth, ~60km to the north of the core position. This canyon may have acted as a funnel for the refractory organic matter transported eastward from the continent and exposed shelf, especially during glacial periods when the sea-level fell, the front shifted offshore, and flocculation occurred at deeper locations enabling the clays from the Rio de la Plata to reach the slope (Bozzano, Violante and Cerredo 2011).

Therefore, reworked terrestrial and/or marine refractory organic matter transported through the canyon system could have been one of the main sources of food for benthic communities in this particular area during relatively low productivity moments such as the one reflected by the lower section of the core. The combination in the lower part of the core of high organic matter and low-oxygen assemblage reflects conditions of high organic matter availability and depleted oxygen, typical of meso-eutrophic environments.

The dominance of high organic matter and high-oxygen assemblages in the uppermost section marks a change in the primary productivity pattern suggesting that surface primary productivity would have been the main source of food of the benthic communities instead of refractory organic matter. However, the decrease of *G. ovula* at 96cm and the progressive increase of total foraminiferal abundance, species richness and P/B ratio evidence a gradual change in the environmental trophic conditions missed out by the factor analysis.

The onset of high productivity conditions at the Patagonian Margin could explain the pattern obtained in the upper section of the core, where phytodetritic and surface productivity-associated species show relatively high abundances indicating less influence of lateral advection processes of organic matter (Figure 5). The Antarctic upwelling and the SAMW formation increased due to a poleward shift of the westerly winds (Figure 7; Sigman and Boyle 2000; Toggweiler, Russell and Carson 2006; Rojas et al. 2008) as a consequence of climatic amelioration during the final phase of the MIS 6 and before MIS 5e interglacial. Termination II starts after ~140 kyrs when Antarctic temperature increased from low glacial values (Masson-Delmotte et al. 2010) in coincidence with the age estimated for the upper part of the core. Thus, nutrient availability at the surface led to an increase in surface productivity in the whole SWSA (Toggweiler, Russell and Carson 2006; Anderson et al. 2009), including the Patagonian Margin during the final phase of the glacial cycle. The contribution of phytodetritic species and high-oxygen assemblage indicate a strong seasonal (bloom forming) cycle of the primary productivity, and the establishment of an oligo-mesotrophic environment, typically found at high latitudes.

The individual analysis of marker species reveals different productivity regime within the upper section. The strong seasonal cycle of the primary productivity is punctuated by a weakly seasonal (non-bloom) high flux regime at 60cm, where the conspicuous increase in *U. peregrina* marks a short-term change in trophic conditions. In the SWSA, *U. peregrina* has been reported to show notable fluctuations in its abundance, being strongly dominant during glacial periods (Corliss, Martinson and Keffer 1986), when the abundances of *E. exigua* and *A. weddellensis* were very low (Thomas et al. 1995). This has been interpreted as an increase in the amount of organic carbon to the sea floor that resulted from an increase in surface productivity (Corliss, Martinson and Keffer 1986; Gooday 2003), indicating high and steady (weakly seasonal) organic carbon flux to the sea floor. These environments are usually characterized by high species richness and low diversity assemblages (Schmiedl and Mackensen 1997). Changes in the seasonal amplitude of primary productivity are likely to be driven by changes in the seasonal amplitude of drivers such as nutrient supply (Henson et al. 2013). Thus, this level would correspond to an intensification of the Antarctic upwelling and related increasing nutrient availability in the Patagonia Margin.
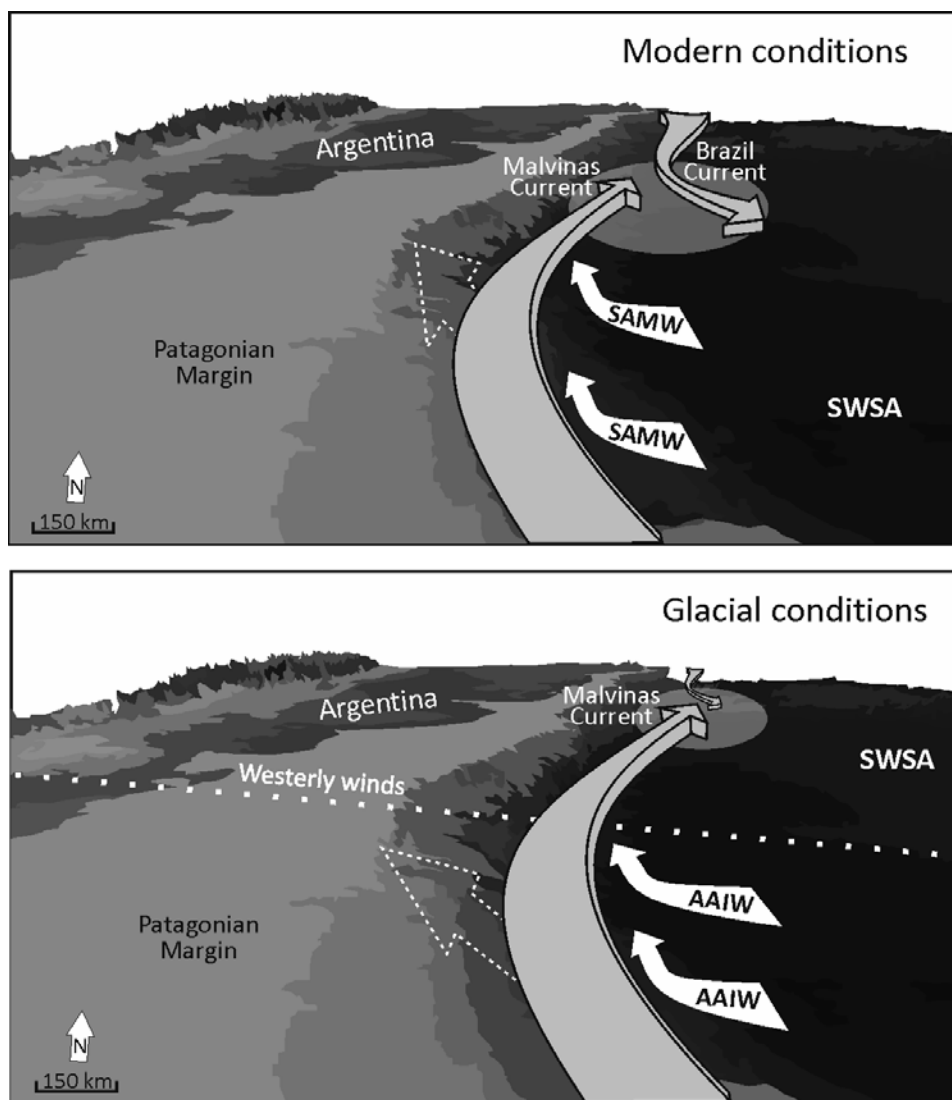
TEXT-FIGURE 7
Schemes of the Patagonian shelfbreak upwelling for the modern and glacial Southwestern South Atlantic (SWSA). **SAMW**: Subantarctic Mode Water; **AAIW**: Antarctic Intermediate Water. Filled arrows represent the main regional surface currents and the dotted arrow represent the Patagonian shelfbreak upwelling. Dotted line represents the northern limit of the Westerly winds during the cold period spanned by the core.

CONCLUSIONS

Benthic foraminifera have traditionally been used as tracers of deep water masses in the Southwestern South Atlantic since the Pliocene. However, according to our results, the Mid-Late Pleistocene assemblages of core SP1251 (Argentine Continental Margin, 38°S-53°W, 3500m depth) do not indicate the dominance of any specific deep-water mass despite its strategic location.

The more relevant assemblages obtained from factor analysis were composed of high organic matter and oxygen availability-associated species revealing that the productivity signal has been the main factor in determining the structure of the benthic communities. The analysis results reflected a change from low to high productivity, characterized by a strong seasonal regime, and evidenced that during low productive moments refractory organic matter from continental origin fed the meiobenthic communities. Conversely, during high productive moments, productivity-related marker species revealed changes in the productivity regime, showing short-term changes from seasonal blooms to weakly seasonal (non-bloom) primary productivity regimes. Variations in the exported productivity would be related to changes in the shelfbreak upwelling of Patagonia during the final phase of the MIS 6 as a consequence of changes in the Antarctic upwelling, which played a fundamental role in the surface nutrient availability of the Southern Ocean during glacial times.

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APPENDIX 1
Distribution of the additional 90 benthic foraminiferal species identified along the core but not considered in the analysis.

Prof(cm)	Bolivina ordinaria	Bolivina maloviensis	Bolivina silvestrina	Bolivina subspinescens	Bulimina aculeata	Bulimina inflata	Bulimina truncana	Islandiella inflata	Cassidulina laevigata	Globocassidulina minuta	Cassidulinoides parkerianus	Chilostomella czizeki	Cibicides ex. gr. aknerianus	Cibicides bradyi	Cibicides dispars	Cibicides mckannai	Cibicides pseudoungerianus	Cibicides robertsonianus	Cibicides wuellerstorfi	Clavulina communis	Dentalina advena	Discorbis subvilardeboanus	Eggerella bradyi	Ehrenbergina carinata	Epistominella obtusa	Gyroidina polia	Fissurina ampullacea	Fissurina annectens	Fissurina carinata	Fissurina compressa	Fissurina fimbriata	Fissurina furcillifera	Fissurina globosa	Fissurina laevigata	Fissurina marginata	Fissurina obtusa	Fissurina orbignyana	Fissurina toddae	Fissurina cf. F. modesta	Fissurina cf. F. sacculus	Fissurina cf. F. schwageriana	Fursenkoina pontoni	Fursenkoina rigii	Fursenkoina schreibersiana
0	0,00	0,61	0,61	0,00	0,12	0,37	0,00	9,66	3,30	0,00	0,00	0,37	0,98	0,61	0,00	0,12	0,00	0,00	0,00	0,12	0,49	0,37	0,73	3,79	0,24	0,24	0,12	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,12	0,12	0,00	0,00	0,00	0,00	0,00	0,12
5	0,00	1,28	3,85	0,00	0,00	0,32	0,00	16,03	1,28	0,00	0,32	0,00	0,00	3,21	0,00	0,96	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,24	0,00	0,00	0,00	0,00	0,32	0,32	0,00	0,00	0,96	0,32	0,00	0,00	0,00	0,00	0,00	0,00	0,96	0,00	0,00	0,00
16	0,00	0,33	0,22	0,11	0,11	0,33	0,11	8,52	3,43	0,00	0,00	0,33	1,88	1,33	0,00	0,00	0,11	0,00	0,00	0,00	0,22	1,22	4,31	0,00	0,00	0,00	0,11	0,00	0,00	0,11	0,00	0,11	0,00	0,11	0,00	0,22	0,00	0,00	0,00	0,00	0,00	0,11	0,11	
20	0,00	0,00	0,00	0,00	0,00	0,00	0,00	10,45	2,99	1,00	0,50	0,00	0,00	3,48	0,00	0,00	0,00	0,00	0,00	0,00	0,50	0,00	1,00	1,00	0,00	0,00	0,00	0,00	0,00	0,50	0,00	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,50	0,00	0,00		
44	0,00	0,00	0,57	0,00	0,86	0,00	0,29	19,43	0,29	0,57	0,29	0,00	0,29	0,86	0,00	0,00	0,86	0,29	0,00	0,00	0,00	0,00	1,71	0,00	0,00	0,00	0,00	0,00	0,00	0,29	0,00	0,00	0,00	0,29	0,00	0,00								
60	0,15	0,00	0,89	0,00	0,30	0,59	0,00	4,29	0,15	0,30	0,00	0,44	2,96	2,81	0,00	0,00	0,00	0,44	0,89	0,00	0,74	0,89	1,04	1,04	0,89	0,00	0,00	0,00	0,00	0,00	0,15	0,00	0,00	0,00	0,00	0,00								
74	0,00	0,42	0,00	0,00	0,00	0,00	0,00	8,40	4,62	0,00	0,00	0,84	0,00	2,10	0,00	0,00	0,00	0,42	0,00	0,00	0,00	2,94	0,00	1,26	2,52	0,00	0,00	0,00	0,00	0,00	0,42	0,00	0,00	0,00	0,42	0,00	0,00							
90	0,00	0,00	4,52	0,00	0,00	0,23	0,45	16,74	0,90	0,90	0,00	0,00	0,00	1,36	0,90	0,00	0,00	0,68	0,23	0,00	0,00	0,45	0,00	0,68	0,23	0,00	0,00	0,00	0,00	0,00	0,00	0,23	0,00	0,00	0,00	0,00	0,23	0,00	0,00	0,68	0,45			
96	0,00	3,16	0,00	0,00	0,00	0,00	0,00	17,72	0,00	0,00	0,00	0,00	0,63	1,27	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,63	0,00	0,00	0,00	0,63	0,00	0,00	1,27	0,00	0,00	0,00	0,00			
137	0,00	0,00	0,00	0,00	0,00	0,00	0,00	10,91	0,00	0,00	0,00	0,00	0,00	1,82	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,82	0,00	0,00	0,00	0,00	0,00					
156	0,00	0,00	0,00	0,00	0,00	0,00	0,00	11,11	0,00	0,00	0,00	0,00	2,78	0,00	0,00	0,00	0,00	2,78	0,00	0,00	0,00	0,00	0,00	5,56	2,78	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00					

Prof(cm)	Gyroidina globosa	Gyroidina medicea	Gyroidina soldanii	Gyroidina umbonata	Hoeglundina elegans	Karreriella bradyi	Karreriella siphonella	Lagena distoma	Lagena elongata	Lagena nebulosa	Lagena raricosta	Lagena stelligera	Lagena substriata	Lagena vulgaris	Lagena wiesneri	Lagenosolenia favosiformis	Martinottiella antartica	Melonis affine	Nonionella auricula	Oolina globosa	Oolina lineata	Oolina melo	Oolina squamosa	Parafissurina admiralis	Parafissurina aperta	Parafissurina orbignyana	Parafissurina lateralis	Pullenia bulloides	Pullenia osloensis	Pullenia quadriloba	Pullenia quinqueloba	Pullenia salisburyi	Pullenia subcarinata	Pyrgo depressa	Pyrgo denticulata	Pyrgo murrhina	Pyrgo nasuta	Quinqueloculina lamarckiana	Quinqueloculina patagonica	Sphaeroidina bulloides	Triloculina tricarinata	Triloculina trigonula	Triloculina trilocularis	Uvigerina bifurcata	Uvigerina hispida	Uvigerina proboscidea
0	0,00	0,00	0,00	1,59	0,49	0,00	0,00	0,00	0,12	0,00	0,00	0,37	0,12	0,00	0,00	0,00	0,12	0,00	0,00	1,10	0,12	0,00	0,00	0,00	0,00	0,00	0,12	0,24	0,00	0,37	0,12	0,00	0,37	0,00	0,00	0,00	0,00	0,12	0,00	0,00	0,00	0,00	0,86	0,00	0,00	1,71
5	0,00	0,00	0,00	2,88	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,32	0,00	0,32	0,00	0,00	2,56	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,32	0,00	0,00	0,00	0,00	0,00	0,32	0,32	0,00	0,00	0,00	0,00	0,00	1,28	0,00	0,32	0,00	1,28		
16	0,00	0,00	0,11	1,88	2,10	0,00	0,00	0,00	0,00	0,00	0,22	0,00	0,00	0,00	0,00	0,33	0,66	1,22	0,11	0,22	0,00	0,00	0,11	0,11	0,00	0,00	0,33	0,11	0,11	0,11	0,22	0,11	0,00	0,44	0,00	0,22	3,21									
20	0,00	0,00	1,49	0,00	4,48	0,00	0,00	0,00	0,00	0,00	0,00	0,50	0,00	0,00	0,00	0,00	0,00	0,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,49	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,99									
44	0,00	0,00	0,00	2,86	0,00	0,00	0,00	0,00	0,29	0,00	0,00	0,00	0,00	0,00	1,43	0,00	0,86	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,29	0,00	0,00	0,00	0,00	0,00	0,00	0,29	1,14	0,00	0,00	0,00	0,00	0,57	0,00	0,86	0,00	0,00		
60	0,00	0,59	0,00	0,15	2,37	0,00	0,00	0,00	0,15	0,30	0,15	0,00	0,00	0,00	0,00	0,00	0,44	0,00	0,00	0,30	0,00	0,30	0,00	0,30	0,15	0,74	0,00	0,30	0,15	0,74	0,00	0,30	1,78	0,15	0,00	0,30	0,00	0,00	0,00	0,00	0,00	0,00	2,51			
74	0,00	0,00	0,00	2,10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,84	0,84	2,52	0,00	0,00	0,84	0,42	0,00	0,00	0,00	1,26	0,00	0,00	1,26	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,42	0,00	0,00	1,26								
90	0,00	0,00	0,00	0,00	0,00	0,00	0,23	0,23	0,23	0,00	0,00	0,00	0,00	0,23	0,00	0,00	1,36	2,94	4,75	0,00	0,00	0,00	0,00	0,00	0,45	0,00	0,00	0,90	0,00	0,00	0,23	0,00	0,00	0,00	0,00	0,00	0,68	0,00	0,00	0,45						
96	0,00	0,00	0,00	1,90	0,00	0,00	0,00	0,63	0,00	0,00	0,63	0,00	0,00	0,00	0,00	0,00	1,27	1,27	0,00	0,63	0,00	0,00	0,63	0,00	0,00	0,00	0,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00						
137	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	5,45	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	3,64						
156	5,56	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,78	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00						