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Benthic foraminifera as indicators of river discharge in the Western South Atlantic continental shelf margin

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Abstract

The present work focuses on fresh water signatures at the sediment-water interface (1 cm) using foraminiferal species in both austral winter and summer in eleven longitudinal transects on the Western South Atlantic continental margin between 27° and 37°S, at water depths of 11.7 to 250 m. Here we show that depth, salinity, temperature, oxygen, grain size (mud and sand percentage), suspended matter, organic matter, SiO_4, NO_2, and NO_3 in this order of importance are responsible for the distribution of foraminiferal species and thecamoebians. The presence of these microfossils indicate freshwater influx in four sectors over the continental shelf: Itajaí-Açu River, Laguna estuarine system, Patos Lagoon and RdlP (Rio de la Plata) will be explored further in detail. Our findings on freshwater signature on the continental shelf sediments through benthic species indicator are comparable to other continental systems worldwide, and a paleo record study would be useful for three South American countries (Brazil, Argentina and Uruguay). A freshwater signature in the continental shelf indicates deposition sites probably linked to anthropogenic impact since most of the pollutants and contaminants are dumped into water bodies that eventually reach and accumulate in the ocean. Therefore, the freshwater-related species on the continental shelf reflects exactly where the depositional sediment sites are, and where anthropogenic impacts accumulate.

Foraminiferal microhabitat occupation within these zones is discussed in detail. And we conclude that together with the fauna, the abiotic parameters play an important role in determining the occurrence and degree of marine eutrophication induced by the input of polluted river waters, also showing possible anoxic environments on the shelf.

Keywords: Western South Atlantic continental margin; benthic Foraminifera; fresh water; nutrients, eutrophication, anoxic.

1. Introduction

The Western South Atlantic continental margin is influenced by freshwater input from the drainage basin of Rio de la Plata (RdlP). It is the second largest basin in South America and receives more than 75% of its discharge from Paraná River, Uruguay River (Depetris and Paolini, 1991), and other tributaries, in the southern coast of Brazil, such as the Patos-Mirim Lagoon, Estuarine complex of Laguna, and Itajaí Açu River.

The discharge from RdlP is of about 21,000 m^3s^{-1}, naturally slightly higher during late summer, and maximum discharge occurs where the historical maxima of river discharge during the year following the onset of during El Niño periods which triples relative to typical Mean River discharge (Berbery and Barros, 2002). In addition, the plume penetration of the RdlP along shore faces opposing summer northeasterly winds (Piola et al., 2005).

This hydrographic system extends from the subequatorial zone through the tropics, funneling its numerous tributaries into RdlP, which are discharged into the South Atlantic Ocean, and spread along the coasts of Argentina, Uruguay and Brazil (Figure 1). This coastal zone water mass (CW) outflow influences the near-shore ecosystem (Ciotti et al., 1995; Muelbert and Sinque, 1996; Sunyé and Servain, 1998) exporting carbon from the continent into the oceans (Degens et al., 1991).

The continental margin, between 27° and 37°S, is dominated by four main water masses: cold-fresh Sub Antarctic Shelf Water (SASW), warm-salty Subtropical Shelf

Water (STSW), cold upwelled South Atlantic Central Water (SACW), and the coastal Plata Plume Water (PPW) from RdlP.

Previous articles on the Western South Atlantic continental margin demonstrate the spatial distribution of benthic foraminifera is related to water mass dynamics (Burone *et al*., 2013, Eichler et al., 2014; 2016). Specifically Eichler et al. (2014) showed that *Bulimina marginata* is tolerant species to transitional zones and influenced by location of Subtropical Shelf Front (STSF), a complex regional extension of the Brazil/Malvinas Confluence Zone over the shelf defined by a thermohaline subsurface front between STSW and SASW described by Piola et al. (2008). Later on, Eichler et al. (2016) showed that spatial abundance of infaunal benthic foraminiferal species *Buccella peruviana, Globocassidulina subglobosa,* and *Uvigerina peregrina* are responding to the interaction of SASW, STSW and upwelling of SACW respectively.

Scott and Medioli (1980) showed that *Arenoparella mexicana* and *Trochammina inflata* occurred in all marshes from high to low salinity, and Murray (1991) suggested that *A. mexicana, Ammoastuta salsa, Haplophragmoides wilberti* and *Trochammina* sp. are species typical of coastal salt marshes and are more abundant where freshwater input is higher. Worldwide freshwater input (Murray, 2006, Debenay et al., 2006) is related to faunal response among other environmental variables. Thecamoebians are testate protists that occur in a variety of freshwater habitats and brackish environments and have been successfully used as proxies for a variety of environmental and climatic parameters in limnological and paleolimnological studies (Farooqui, et al., 2012). They are truly fresh water microorganisms.

Present studies consider details on the signature of freshwater on selected benthic microorganisms found in the sediment-water interface (1 cmbsf). We intend to investigate the influence of RdlP plume and other local river discharge including the Itajaí-Açu system, the Laguna estuarine system, and the Patos lagoon over the continental shelf. Specifically, we seek to examine whether flocculation influences foraminiferal dynamics, and how microhabitats of these organisms vary. This question has implications for the influence of river discharge on water mass dynamics in this area, and in turn, on the benthic species dynamics of marine bottom sediment on the continental shelf. Our findings are comparable to estuaries worldwide and can indicate potential polluted zones on the coastal marine sediments.

2. Material and Methods

2.1 Sample Collection

Sampling was done on a shelf region bound by the offshore Brazil/Malvinas current system and inshore by the freshwater source of RdlP up to water depths of 250 m. During two oceanographic cruises, 120 surface sediment samples were collected in both austral winter (August, 20th to September, 2nd 2003, 64 samples) and summer (February, 1st to 19th 2004, 56 samples).

A Van Veen Grab sampler was used in 11 transects in water depths of 10 and 250 m. These transects from south to north were named as follows: Mar del Plata, Punta Medanos, Plata River, Punta del Este, Punta del Diablo, Albardão, Rio Grande, Solidão, Torres, Santa Marta Cape, and Itajaí in water depths ranging from 10 to 250m (Figure 2).

2.2. Field and laboratory procedures for Foraminiferal study

After collection, the uppermost layer of the sediment sample (about 1cm) was scraped off and kept in ethanol. A solution of Rose Bengal in ethanol was used for staining live specimens for 48hs. A fixed volume of 10 cm^3 of sediment was washed through a 63 µm sieve and oven dried at 60°C. The samples were then floated using trichloroethylene (C_2HCl_3) to separate shells from sediment. Processed samples were split from 63 µm size fraction with a microsplitter to obtain at least 100 specimens of benthic foraminifera per sample (Fatela and Taborda, 2002). All foraminifera were picked from a split and included in the quantitative analysis of the assemblage counts. Unsplit samples from some stations did not contain 100 tests, but they were taken into account. Planktonic foraminifera were counted, however it was not considered in the analysis.

Data on total (dead plus living) benthic foraminifera are used here. The analysis of total assemblage of benthic foraminifera was chosen because dead and living foraminifera provide insight into different aspects of the environment. While dead benthic foraminiferal assemblages give a time-averaged record over a period of one to several years (Murray, 2001), the living foraminifera thriving at their optimum environmental conditions reproduce more often (Martins et al. 2015) giving us a snapshot of this current moment. By combining total benthic foraminiferal assemblages with environmental variables, we were able to track and average signature of the present bottom environmental and oceanographic conditions for the last year.

Identification and counting of specimens were done under a Stemi V6 Zeiss stereomicroscope, and taxonomy followed Ellis and Messina (1940). Scanning electron micrographs were taken to help with some problematic identifications. Absolute and relative abundances were computed for all specimens. All species have morphological characters easily observed and future studies will not face taxonomical ambiguity.

2.3. Water samples

Nutrient analysis data on water samples were taken from Braga et al. (2008) came from bottom or near-bottom water (less than 1 m) from most of the stations. Temperature (˚C) and salinity (PSU) were recorded at every station using the model 911 CTD from SeaBird Electronics.

Samples for dissolved oxygen and nutrients were collected in bottles mounted on a rosette. Data analysis from the entire water column is described in Braga et al. (2008), however in our work, we have exclusively used data for bottom water. Dissolved oxygen ($mL \cdot L^{-1}$) was first extracted and measured by the Winkler procedure using an automated titration method (Grasshoff et al., 1983).

The dissolved nutrients analyzed were silicate, nitrite, and nitrate (μM). The dissolved nutrients were filtered through Whatman GF/F membranes. The samples were frozen (-20 °C) and the analyses of nitrate and nitrite were performed using an automated

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system (AutoAnalyzer II – Bran-Luebbe), following the procedure in Grasshoff et al. (1983). The silicate analyses were done by a spectrophotometric method. The suspended particulate matter (SM) (mg·L^{-1}), and the organic matter (OM) (mg·L^{-1}) in the bottom water were analyzed gravimetrically (Strickland and Parsons, 1972). The OM were determined by the weight difference prior to dissolution with 1N HCl and 1N H_2O_2, respectively (Carver, 1971).

2.4. Granulometric analysis

Grain-size distributions for winter and summer were determined by sieving and pipette methods (Müller, 1967), and the data was treated and classified according to Folk and Ward´s (1957) statistical parameters and Shepard's (1954) triangular diagram, respectively.

2.4. Data analyses integration

Biological Resemblance matrices for winter and summer were constructed using the Bray-Curtis similarity measure with a log (x+1) transformation to normalize foraminiferal counts. Species-abundance data were calculated for foraminiferal samples (including taxa contributing <0.45% or occurring in more than 13 samples) and subjected to a Q-mode cluster analysis to define the foraminiferal assemblages. The Bray-Curtis distance was used to measure the proximity between the samples, and Ward's linkage method was used to arrange samples into a hierarchical dendrogram.

The foraminiferal data were analyzed using Non-metric Multidimensional Scaling (MDS; Clarke, 1993) to emphasize the geometrical aspects of similarity and to visualize complex data in a graphical environment. This approach recognizes patterns that might not be apparent in a cluster analysis and provides a map of samples in which the placement of samples, rather than simply representing their geographical location, reflects the similarity of their biological communities and environmental patterns. The MDS plots were created using PRIMER (Clarke & Warwick, 1994).

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Environmental resemblance matrices for winter and summer were constructed using the Euclidean distance with a log (x+1) transformation to normalize data. The Biota and Environment matching analysis (BIOENV) was performed between biological and environmental resemblance matrices with Spearman as the similarity rank correlation method in both seasons to identify which variables are responsible for the foraminiferal distribution.

Benthic foraminiferal relative abundance and environmental data on suspended matter (SM), organic matter (OM), silicate (SiO_4^{4-}), nitrite (NO_2) nitrate (NO_3^-), grain size (mud and sand percentage) were used to generate contour maps using Surfer 8 (Golden software) to illustrate data.

3. Results

The relative abundance of foraminiferal species in the 65 winter samples and 55 summer samples are in the supplementary data (Tables 1 and 2). Depth, salinity, temperature, dissolved oxygen (Figure 3), suspension matter (SM), organic matter (OM), silicate (SiO_4^{-4}), nitrite (NO_2^-) and nitrate (NO_3^-) of the bottom water (Figure 4), and the grain size of the sediments (Figure 5) in winter and in summer data are displayed in the supplementary data (Tables 3 and 4).

3.1 Environmental setting

Figure 3 shows the different water masses in our study sites: 1. Cold, fresh, well-oxygenated SASW, 2. Cold-upwelled SACW, 3. Warm-salty and less oxygenated STSW, and 4. Well oxygenated, cold, lower salinity CW which includes RdlP plume and other local river contribution with SASW.

Distribution of silicate and nitrate are similar to dissolved oxygen, salinity and temperature, and reflect both continental and marine input on the shelf, and upwelling with the presence of nutrient enriched austral waters and other processes of primary production (Figure 4, Tables 3 and 4) close to the mouth of the Patos Lagoon.

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In austral winter, CW is under direct influence of the lower salinity RdlP plume in shallower stations (less than 50 m). In summer, CW penetrates as far north as the Albardão, and towards the south, we observed a decrease of salinity in the CW. Salinity ranged from minimum 29.1UPS in summer, and 26.5UPS in winter, and 35.9UPS maximum in both seasons. Temperature ranged from minimum of 5.5°C in winter and 6.4°C in summer and maximum varied from 19.6°C in winter and 24.3°C in summer.

In winter, bottom water oxygenation shows a clear separation, with oxygenated waters (more than 5.4 $mL \cdot L^{-1}$) south of Rio Grande, and low oxygenated waters (less than 4.4 $mL \cdot L^{-1}$) north of Rio Grande especially in the deepest parts (Table 3). In summer, this pattern is less clear and oxygen concentration follows temperature patterns (Table 4).

Suspended matter (SM) in the winter is highest (107.6mg/L) in shallower stations at Punta del Diablo and in deeper stations at Rio Grande and Solidão (57.2mg/L); in summer, maximum concentrations occur in the deepest stations at Punta del Este (59.0mg/L). The organic matter distribution in summer (0 to 41.6mg/L) and in winter (0-28mg/L) follow the same pattern of SM. In summer, the maximum OM is also found at Punta del Este, and in coastal stations is indicative of freshwater discharge with high concentration of organic matter. Silicate, used here as a tracer of freshwater input is high in Punta Medanos, Punta del Este, Albardão, Torres and Santa Marta Cape in the winter ranging from 0 to 26.1mg/L; and in summer, maximum concentrations are observed in Albardão and Punta del Este ranging from 0.9 to 18.7mg/L. Winter maximum nitrite concentration is observed in Punta Medanos, Mar del Plata, and Albardão. In summer, maxima are seen at Punta del Diablo and Santa Marta. In winter, highest NO_2 concentrations occur mainly in the deepest stations at Mar del Plata and Punta del Este ranging from 0.5 to 1.5mg/L, and in summer, increase in nitrate is observed mainly in the deepest stations of Punta Medanos and Plata River ranging from14.2 and 19.6 mg/L.

Percentage of mud and sand for winter (Figure 5) shows that mud values are usually <2% closer to Patos Lagoon and higher values north of RdlP. On the other hand,

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percentage of sand is lower in specific points in the estuary of RdlP and south of Patos Lagoon, while the northern transects have less sand in deeper sites. Percentage of sand is higher (>80%) closer to the coast in the northern transects. In winter, percentage of gravel ranges from 0 to 46.7, sand ranges from 53.3 to 100%, and silt and clay totals are 12.1%.

3.2 Foraminiferal Data

The mixohaline (same as 'brackish', which describes the delicate balance of water that is neither fresh nor marine species) characteristic of freshwater occurs in shallow samples close to sources of continental water discharge. We have divided the mixohaline species based on the differences of their tests. Calcareous foraminiferal species consist of *Bolivina striatula, Buliminella elegantissima, Bulimina elongata, Elphidium excavatum, E. poeyanum,* and *Pseudononion atlanticum* (Figure 6) as indicative of mixing of marine saline water with cooler and fresher water, derived from continental runoff, and another fauna showing a less saline environment with marshes and mangroves origin, featuring the agglutinated *Ammobaculites exiguus, Arenoparrella mexicana, Gaudryina exilis, Textularia earlandi* and thecamoebians (truly freshwater, transported organisms) (Figure 7).

Bolivina striatula occurs in the shallowest stations between RdlP (35.8°S) and Rio Grande (31.5°S), in winter, abundance peaks reaches 16-40% occurs in Punta del Este at 34.8°S, Albardão at 32°S, and Rio Grande near 31.5°S. And in summer, the location of the 40% occurrence peak is concentrate to the RdlP. In winter, *Buliminella elegantissima* is dominant (35.3%) in Punta del Diablo (33°S) and in Albardão (33.7%; 32°S), and in summer Albardão (40%). In winter, 17.4% of *Bulimina elongata* is abundant in Punta del Este, and in summer, the population peak is found in the RdlP (30%). *Elphidium excavatum* is observed in the shallowest stations in the winter of Punta del Diablo (61%), RdlP (16.4%), and Rio Grande (27.6%).

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Elphidium poeyanum is seen in Albardão (44.4%) in winter and in the summer, and the abundance of this species occurs in in the shallowest stations Punta del Diablo (40.3%), Albardão (43.5%) and Rio Grande (49.1%) and it is indicator of Patos lagoon and Laguna freshwater discharge. In the winter, *Pseudononion atlanticum* is observed in Punta del Este (25.8%), Rio Grande (33.3 %), Torres (67.7 %), mainly in the shallowest stations (less than 50 m), and in summer, is concentrated in Rio Grande (40%), indicator of RdlP, Patos lagoon, and Laguna freshwater influence.

In winter, *Ammobaculites exiguus* occur in Punta del Este (10.2%) at 65 m water depth, while in summer, peak numbers (10.6%) are observed in the deepest region of RdlP at 95 m. *Arenoparrella mexicana* occurs at 12%, 9% and 10% abundance between 64 and 87 m in the transects of Mar del Plata, Punta Medanos and Punta del Este, respectively. In summer, this species is seen (11.1%) in Albardão at 92 m and 40 m at Punta del Este (14.6%) also indicating RdlP freshwater influence.

The frequency of *Gaudryina exilis* is 7.8% in winter at 37 m water depth in Albardão, and in the summer, their peak occurrence of 6.3% occurs at Punta Medanos at 80 m water depth, Punta del Este (28 m) and Albardão (64 m) is indicative of freshwater Patos lagoon influence.

Peak occurrence (50%) of *Textularia earlandi* is at Punta del Este at 22 m water depth in the winter, and in the summer (7.1%) in Punta Medanos at 23 m is indicative of RdlP and Laguna freshwater influence.

Thecamoebians tests have been observed mainly in the winter at depths of 64 m in Punta del Este. The influence of the fluvial discharge is observed as deep as 92 m in the Albardão region, indicating influence of freshwater discharge from Patos Lagoon over the shelf is even more intense in summer. These microorganisms are indicative of RdlP and Patos lagoon freshwater influence.

The main benthic Foraminifera species *Pseudononion atlanticum, Bolivina striatula, Buliminella elegantissima, Bulimina elongata, Elphidium excavatum*, *E.*

poeyanum, Ammobaculites exiguus, Arenoparrella mexicana, Gaudryina exilis, Textularia earlandi, and thecamoebians species found in this study are shown in Plate 1.

3.4 Data correlation

A cluster analysis based on the major total species (live + dead specimens) from winter reveal the existence of seven groups of stations containing similar foraminiferal composition (Fig. 8). The MDS analysis shows the foraminiferal indicator species (Fig. 9) for the seven groups. It was possible to observe that Group I has *Discorbis williamsoni* as the characteristic species of stations 4 and 16, and it is located on the inner shelf, south of RdlP. Group II has *Ammonia beccarii* as the characteristic species of the shallower stations closer to the inner shelf of RdlP (stations 0 and 32). Group III has *Buliminella elegantissima*, *Bolivina striatula*, and *Elphidium poyeanum* as indicator species in the shallower stations, indicating inner shelf environments influenced by Patos Lagoon input (stations 30, 50, 48, 49, 17, and 33). Group IV has *Buccella peruviana* as the indicator species of colder water in outer shelf stations of RdlP (stations 29, 11, 12, 27, 13, 31, 22, 28, 5, 3, 19, 21, 26, 2, 14, 1, 15, 34, 62, 20, 6, 18). Group V has *Cassidulina subglobosa* as its indicator species in only one station (68) in the inner shelf north of Patos Lagoon. Group VI is dominated by *B. striatula* and *Elphidium poyeanum* at stations 36, 37, 47, 69, 46, and 70 mostly indicating the influence of Patos Lagoon, Mirim Lagoon and Laguna Estuarine System river discharge in the inner and middle continental shelf. Group VII has stations from inner to outer shelf, in the northern part of our study area (stations 52, 64, 54, 79, 80, 81, 58, 59, 65, 60, 66, 71, 72, 74, 42, 73, 61, 83, 38, 45, 53, 43, 44, 82, 51 and 67), and the presence of *Hanzawaia boueana* and *Bulimina marginata* in those stations indicates the influence of warmer waters from STSW rather than freshwater influence from Laguna Estuarine System and Itajaí Açu River. Station 38 has the deepest and southernmost occurrence of *Hanzawaia boueana* and *Bulimina marginata* in the Mirim Lagoon.

A cluster analysis based on the major total living specimens from summer reveals the existence of five groups of stations (Fig. 10). The MDS analysis shows the foraminiferal indicator species (Fig. 11) for the five groups.

Group I has *Discorbis williamsoni* and *Ammonia beccarii* as characteristic species in shallow stations (stations 0 and 20) on the inner shelf at the RdlP. Group II has *Buccella peruviana* (cold-water tolerant), *Discorbis williamsoni*, *Buliminella elegantissima,* and *Elphidium poyeanum* in stations 4, 15, 33, 37, 14, 22, 21, 34, 19, 2, 13, 16, 24, 23, 31, 32, 1, and 17 from the inner to middle shelf, which indicate the presence of mixing river discharge of the RdlP, with the SASW cold water mass. Group III has also *Buliminella elegantissima* and *Elphidium poyeanum* in the northern part of the inner shelf at the RdlP, indicating the influence of the Patos Lagoon (stations 48, 49, 63, 64, 38 and 50). Group IV has *Bulimina marginata and Bolivina striatula* as indicator species, suggesting mixture of STSW and freshwater from both Mirim and Patos lagoons deeper on the shelf (stations 30, 40, 60, 51, 52, 53, 41 and 42). Group V records *Bolivina striatula*, *Hanzawaia boueana, Uvigerina peregrina, Buliminella elegantissima* and *Cassidulina subglobosa* as indicator species of inner to outer shelf, in the northern part of study site, with the limit of their occurrence being Patos Lagoon (66, 88, 79, 57, 87, 5, 12, 6, 73, 58, 59, 78, 39, 62, 90, 76, 65, 89, 61, 75, and 77). Only stations 5, 6, and 12 located on the outer shelf of the southernmost limit of our study site shows the penetration of STSW in the deeper parts of the RdlP in summer.

Figure 12 shows a summary of the interaction and mixing between warm (STSW) and cold (SASW) water masses for austral winter and summer and associated faunal changes. These changes primarily relate to the distribution of freshwater foraminiferal species. This finding confirms the BIOENV results that indicate depth, salinity, and temperature are the most important variables along the coast in controlling faunal assemblages. Freshwater runoff in this shelf environment plays an important role in the establishment of foraminiferal distribution from inner to outer shelf. The areas of water mass mixing in winter form an elongate freshwater plume in the inner shelf closer to the

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coast, indicating the presence of freshwater through flow from inner to the outer shelf. In the summer, plume is more concentrated south of Patos Lagoon, while shoreward of Mirim Lagoon it occurs in the middle and in the outer shelf.

4. Discussion

The results of our study demonstrate this portion of the shelf is a very dynamic area that experiences influence of freshwater from the RdlP and local discharge from other sectors, including the Itajaí Açu system, Laguna Estuarine System, and Patos Lagoon over the sediments of continental shelf. We also show that CW is a cool, marine, less saline water mass influenced by freshwater discharge and can be traced to water depths of 50 m agreeing with Burone *et al*., (2013) who through a multiproxy study between the RdlP and the adjacent Southwestern Atlantic inner shelf assessed the sediment footprint of river vs. marine influence.

The distribution of silicate and nitrate associated with dissolved oxygen, salinity and temperature as tracer of continental input reveals the strong fresh water from RdlP, and local continental contributions along the coast agreeing with the biological findings. Terrestrial and marine input on the shelf are regeneration processes from river inputs, flocculation, upwelling, and primary production close to the mouth of Patos Lagoon, but also recorded in other local smaller sources as Itajaí-Açú River, and Laguna Estuarine System.

In winter, high silicate values are associated with low salinity, confirming substantial influence of freshwater on the continental shelf, while the concentration of nitrogenous compounds is indicative of open marine influence. Nutrient, dissolved oxygen, and suspended matter distributions show fresh water discharges close to the coast and to RdlP estuary. Nutrient and dissolved oxygen concentrations of deep and bottom waters in the Guinea and Angola Basins have showed that silicate enrichment associated with oxygen deficiencies at about 4000m depth (van Benenkom, 1996; van Benekom and Berger, 1984) is due to the remineralization of terrestrial debris, mainly composed of clay and organic matter. On the other hand, close to the river mouth of the Rhône (Gulf of Lion, NW Mediterranean), the limited oxygen penetration in the sediment combined with hydro-sedimentary processes on a river-dominated shelf constitute stressful conditions for foraminiferal faunas and is dominated by opportunistic species (Goineau et al., 2011).

The general trends in paralic foraminiferal faunas around the world are decreasing in diversity and decreasing in calcareous forms passing to agglutinated species landward, in relation with decreasing pH and decreasing availability of calcium carbonate (review in Murray 1973, 1991; Debenay 1990; Hayward and Hollis 1994). Marine sediments show fauna transition on the mouths of the RdlP, Itajaí Açu system, Laguna Estuarine System, and Patos Lagoon, where calcareous benthic foraminiferal species: *Pseudononion atlanticum* (Cushman, 1936), *Bolivina striatula* (Cushman, 1922), *Buliminella elegantissima* (d'Orbigny, 1839), *Bulimina elongata* (d'Orbigny, 1826), *Elphidium excavatum* (Terquem, 1875), and *E. poeyanum* (d'Orbigny, 1826) are replaced by agglutinated *Ammobaculites exiguus* (Cushman & Brönnimann, 1948), *Arenoparrella mexicana* (Kornfeld, 1931), *Gaudryina exilis* (Cushman & Brönnimann, 1948), *Textularia earlandi* (Parker, 1952), and thecamoebians (genera *Difflugia* and *Centropyxs)* in more restricted environments. These species were established as either mixohaline, or freshwater species (Scott and Medioli, 1978). Their distribution are limited by water depth and continental water discharge (Eichler et al. 2012), shown in overview, however the present study would like to further discuss in detail the freshwater tolerant fauna that is showing opportunism traits on marine sediments along the shelf and its implication for the potential pollution that may accumulate.

Bolivina striatula is an opportunist characteristic of mangroves of Puerto Rico (Culver, 1990, Debenay et al., 1998), and *Buliminella elegantissima* mangroves of Columbia (Boltovskoy and Hincapié de Martinez, 1983; Otvos, 1978). Eutrophication has markedly changed the distribution of the opportunistic and tolerant species *Bulimina elongata* in Amvrakikos Gulf, in northwestern Greece (Naeher et al., 2012). These buliminids prevail in muds associated with low hydrodynamics, low oxygenation, and high organic matter on the Northern Gulf of Cadiz Continental Shelf (Mendes et al., 2012; Garcia-Gallardo et al., 2017). In our study, these species indicate the presence of low hydrodynamics with organic enrichment accumulation in at least four sites on the shelf. *Elphidium excavatum* is originally from the outer paralic system (Martin and Liddell, 1988) and is found in mangrove environments in Equator by Boltovskoy and Vidarte (1977), and in New Zealand (Gregory, 1973; Hayward et al., 1996, 1999). Goldstein (1976) also found *Elphidium poeyanum* in mangrove sediments of the Bahamas. The presence of this species in our continental shelf shows that there is mixohaline influence and flocculation process occurring. *Pseudononion atlanticum* is also an opportunist low oxygen-tolerant species (Blackwelder et al., 1996) and its distribution may indicate hypoxia in at least three areas over the studied continental shelf. Boltovskoy et al. (1980) describe *Bolivina striatula, Buliminella elegantissima, Elphidium excavatum, E. gunteri*, and *Elphidium* spp. as marine euryhaline, opportunists tolerant to less saline waters of the Patos Lagoon and RdlP. On the other hand, Eichler et al. (2007) found *Buliminella elegantissima, Elphidium excavatum*, and *E. poeyanum* in polyhaline (a salinity category term applied to water bodies with a salinity of between 18 and 30 PSU) water where sand-silt sediments of Bertioga estuarine channel are enriched with organic carbon and sulfur.

The agglutinated *Ammobaculites exiguus, Arenoparrella mexicana, Gaudryina exilis, Textularia earlandi* are inner paralic environments species (Martin and Liddell, 1988). Together with the presence of thecamoebians indicate input from freshwater runoff or ground water, which high numbers usually mark strong inflow from a river (Scott et al., 2001). Both the agglutinated and the thecamoebians species are characteristic of the estuary of the RdlP and Patos Lagoon and their occurrence in shelf sediments strongly suggests freshwater influence. *Ammobaculites exiguus* has been found in the mangroves of Florida and the Bahamas (Phleger, 1965*)*, New Zealand (Gregory, 1973; Hayward et al., 1996, 1999), and *Arenoparrella mexicana* in the mangroves of Brazil

(Zaninetti et al., 1977; 1979; Hiltermann et al., 1981; Scott et al., 1990) and Equator (Boltovskoy and Vidarte, 1977). *Bolivina* sp, and *Arenoparrella mexicana* are typical of the oligohaline and mesohaline mangrove-fringe environment (5–18 psu) of Bertioga Channel in SP, Brazil (Eichler et al., 2007). Their presence indicate very saline restricted environments in the inner shelf. *Textularia earlandi* is also found in mangrove sediments from Colombia (Boltovskoy and Hincapie de Martinez, 1983) but is not restricted to this environment. This species has been found in the inner shelf worldwide and its presence is thought to be more related to the higher grain sizes and high hydrodynamics than freshwater itself. *Gaudryina exilis* has been found in mangroves of Senegal (Debenay et al., 1989) and Puerto Rico (Culver, 1990) and thecamoebians in Ecuador (Boltovskoy and Vidarte, 1977), Trinidad and South Caribbean (Todd & Brönniman, 1957; Saunders, 1957, 1958; Drooger & Kaasschieter, 1958). Similar results have been recently documented in the Gulf of Guinea, Eastern South Atlantic, Nigeria (Fajemila and Langer, 2016) and in Gabon (Langer et al., 2016a and b) showing similarities across the Atlantic, specifically between the western coast of Brazil and the Gulf of Guinea states.

Data from BIOENV indicate that the responsible variables for the foraminiferal distribution are depth, salinity, temperature, oxygen, grain size, SM, OM, SiO_4, NO_2, and NO_3 in this order of importance. Most freshwater indicators were found on shallower sites, where salinity was lower, and percentage of mud suggests a depositional site rather than erosional regime at those sites. On the other hand, northern transects have less sand in deeper sites, and more sand closer to the coast. These indicate the presence of low hydrodynamics with organic enrichment accumulation in at least four sites on the shelf, which includes RdlP and other local input as Itajaí-Açú River, Laguna estuarine system and Patos Lagoon over the continental shelf.

The cluster and MDS analysis based on the major total species showed some similarities and differences from winter to summer. There is presence of *Discorbis williamsoni* and *Ammonia beccarii* on shallower stations of inner shelf, south of RdlP. In winter, *Buliminella elegantissima*, *Bolivina striatula*, and *Elphidium poyeanum* are

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indicators of shallower stations of inner shelf influenced by Patos Lagoon input. *Buccella peruviana* is indicator of colder water in outer shelf stations shelf of RdlP. In summer, however, *B. peruviana*, *Discorbis williamsoni*, *Buliminella elegantissima,* and *Elphidium poyeanum* in the inner to middle shelf, indicate the presence of mixing of river discharge of the RdlP and SASW, the cold water mass. *Buliminella elegantissima* and *Elphidium poyeanum* in the northern part of the inner shelf at the RdlP, indicate the influence of the Patos Lagoon. Environments dominated by *B. striatula* and *Elphidium poyeanum* indicate the influence of Patos Lagoon, Mirim Lagoon and Laguna Estuarine System river discharge in the inner and middle continental shelf. In the northern part of our study area, from inner to outer shelf, the presence of *Hanzawaia boueana* and *Bulimina marginata* in those stations indicates the influence of warmer waters from STSW rather than freshwater influence from Laguna Estuarine System and Itajaí Açu River. The presence of *Bulimina marginata and Bolivina striatula* suggest mixture of STSW and freshwater from Patos lagoon in deeper parts of the shelf. In summer, the limit of their occurrence is Patos Lagoon, which the southernmost limit of our study site shows the penetration of STSW in the deeper parts of the RdlP

5. Conclusions

Distribution of silicate and nitrate associated with dissolved oxygen, salinity and temperature show regeneration processes occurring due to the presence of river inputs, upwelling, and other process of primary production in four sites on the shelf: PPW and other local input as Itajaí-Açú River, Laguna Estuarine System and Patos Lagoon over the continental shelf.

The responsible variables for the foraminiferal distribution are depth, salinity, temperature, oxygen, grain size, SM, OM, SiO_4, NO_2, and NO_3 in this order of importance. Most freshwater indicators were found on shallower sites, where salinity was lower, and percentage of mud suggests a depositional site rather than erosional regime at those sites. These more restrict environments indicate more freshwater influence and

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the presence of agglutinated *Ammobaculites exiguus, Arenoparrella mexicana, Gaudryina exilis, Textularia earlandi*, and the thecamoebians, which are organisms of continental origin, estuaries and salt marshes, and are present are under more influence of anthropogenic activities from land. The abovementioned species are biological indicators of freshwater influence over the continental shelf.

Acknowledgements

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Figure 1: Water masses and fronts (STSW, STSW, STSF) (modified from Eichler et al., 2016).

Figure 2: Transects from south to north are as follows: (T1) Mar del Plata, (T2) Punta Medanos, (T3) Plata River, (T4) Punta del Este, (T5) Punta del Diablo, (T6) Albardão, (T7) Rio Grande, (T8) Solidão, (T9) Torres, (T10) Santa Marta, and (T11) Itajaí collected in winter and summer.

Figure 3: Bottom hydrographical data: salinity (PSU), temperature (°C), oxygen ($mL \cdot L^{-1}$) and Coastal zone water (CW), Subantartic Shelf Water (SASW), Subtropical Shelf Water (STSF) (modified from Eichler et al., 2008).

Figure 4: Distribution maps of the dissolved and particulate matter from bottom water: total suspension matter (SM), suspended organic matter (OM), silicate (SiO_4^{4-}), nitrite (NO_2^-) and nitrate (NO_3^-).

Figure 5: Percentage of mud and sand from the winter samples.

Figure 6: Relative abundance of *Bolivina striatula, Buliminella elegantissima, Bulimina elongata, Elphidium excavatum, Elphidium poeyanum, Pseudononion atlanticum* and the occurrence of freshwater influence (modified from Eichler et al., 2012).

Figure 7: Relative abundance of *Ammobaculites exiguus, Arenoparrella mexicana, Gaudryina exilis, Textularia earlandi* and thecamoebians species (modified from Eichler et al., 2012).

Figure 8: Cluster analysis based on the major total species (live + dead specimens) from winter.

Figure 9: MDS analysis and the foraminiferal indicator species from winter.

Figure 10: Cluster analysis based on the major total species from summer.

Figure 11: MDS analysis and the foraminiferal indicator species from summer.

Figure 12: Summary of the interaction and mixing between warm (STSW) and cold-water masses (SASW) for austral winter and summer.

Supplementary data

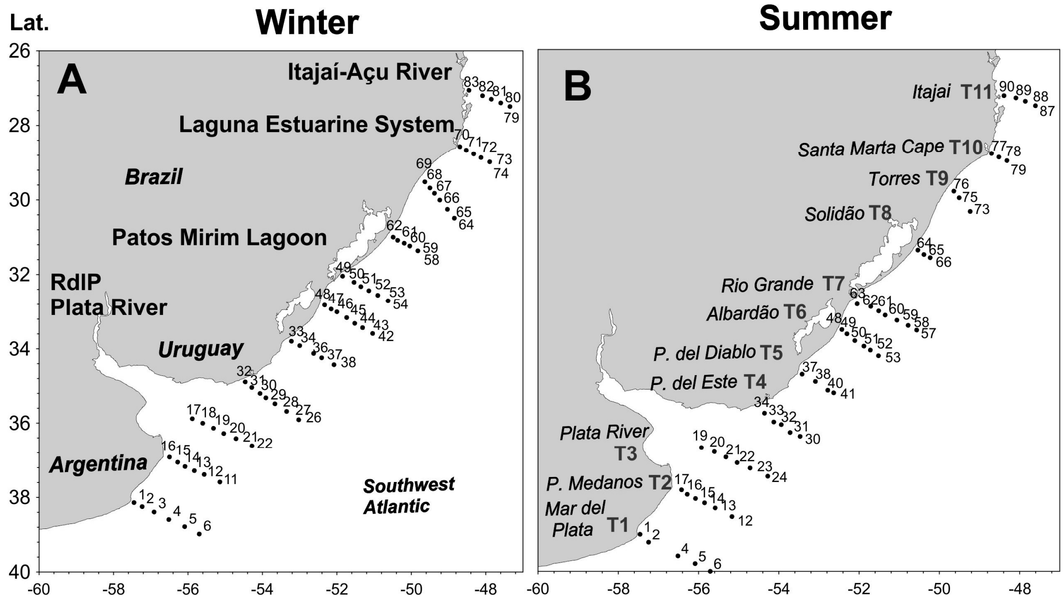
Table 1: Relative abundance of foraminiferal species and total number of individuals in winter 2003.

Table 2: Relative abundance of foraminiferal species and total number of individuals in summer 2004.

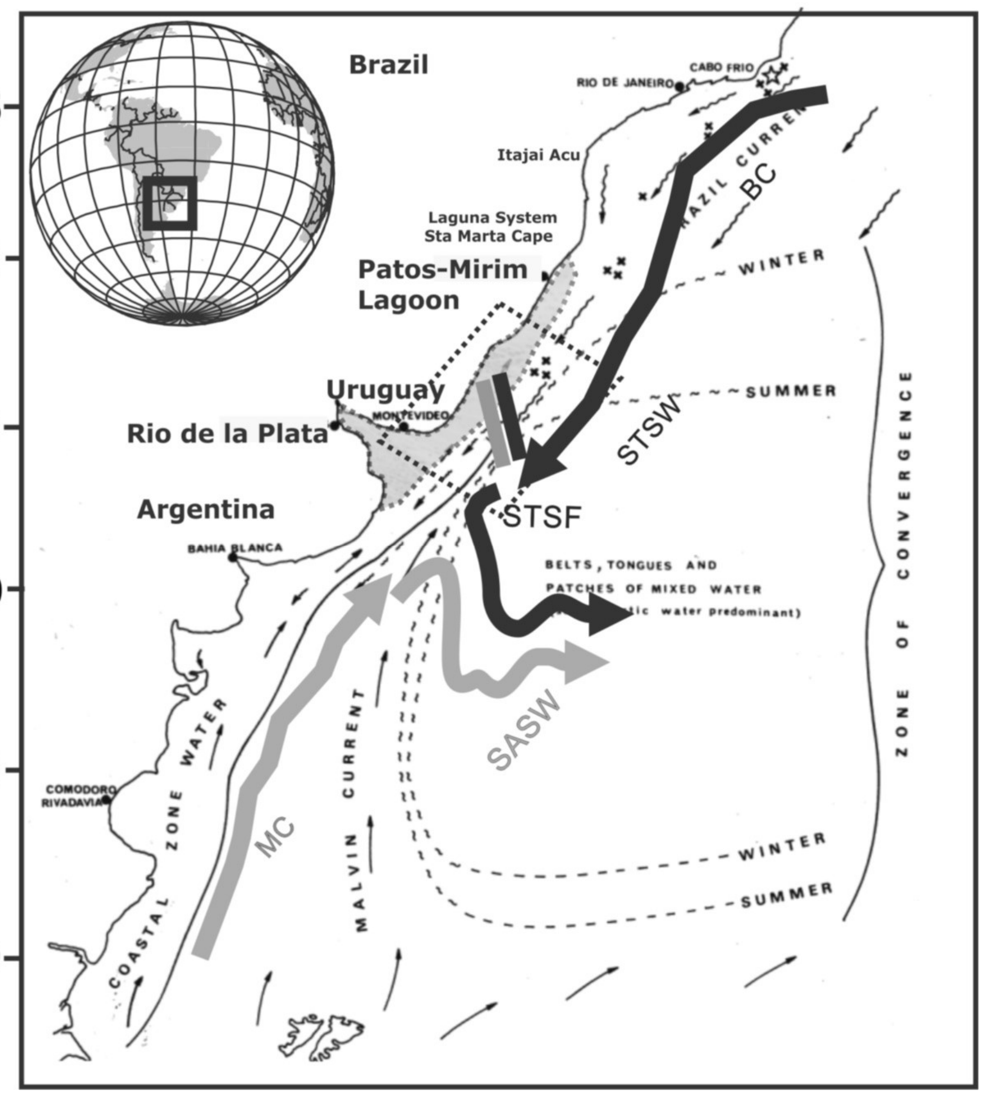
Table 3 (supplementary data): Information on geographical location, depth, salinity, temperature, oxygen, suspended matter (SM), organic matter (OM), SIO4, NO2, NO3 and percentage of gravel, sand, silt and clay for the austral winter.

Table 4 (supplementary data): Information on geographic location, depth, salinity, temperature, oxygen, suspended matter (SM), organic matter (OM), SIO_4^{4-}, NO_2^-, NO_3^- and percentage of gravel, sand, silt and clay for the austral summer.

Plate: 1. *Bolivina striatula, Buliminella elegantissima, Elphidium poeyanum, Pseudononion atlanticum, Elphidium excavatum, Ammobaculites exiguus, Gaudryina exilis, Arenoparrella mexicana, Textularia earlandi*, Thecamoebians.



Lat.
Winter
Summer
A
B
Itajaí-Açu River
Laguna Estuarine System
Brazil
Patos Mirim Lagoon
RdlP
Plata River
Uruguay
Argentina
Southwest
Atlantic
Itajai T11
Santa Marta Cape T10
Torres T9
Solidão T8
Rio Grande T7
Albardão T6
P. del Diablo T5
P. del Este T4
Plata River
T3
P. Medanos T2
Mar del
Plata T1



Brazil
RIO DE JANEIRO
CABO FRIO
Itajai Acu
BRAZIL CURRENT
BC
Laguna System
Sta Marta Cape
Patos-Mirim
Lagoon
WINTER
Uruguay
SUMMER
Rio de la Plata
MONTEVIDEO
STSW
Argentina
STSF
BAHIA BLANCA
BELTS, TONGUES AND
PATCHES OF MIXED WATER
SASW
COMODORO
RIVADAVIA
COASTAL ZONE WATER
MC
MALVIN CURRENT
ZONE OF CONVERGENCE
WINTER
SUMMER

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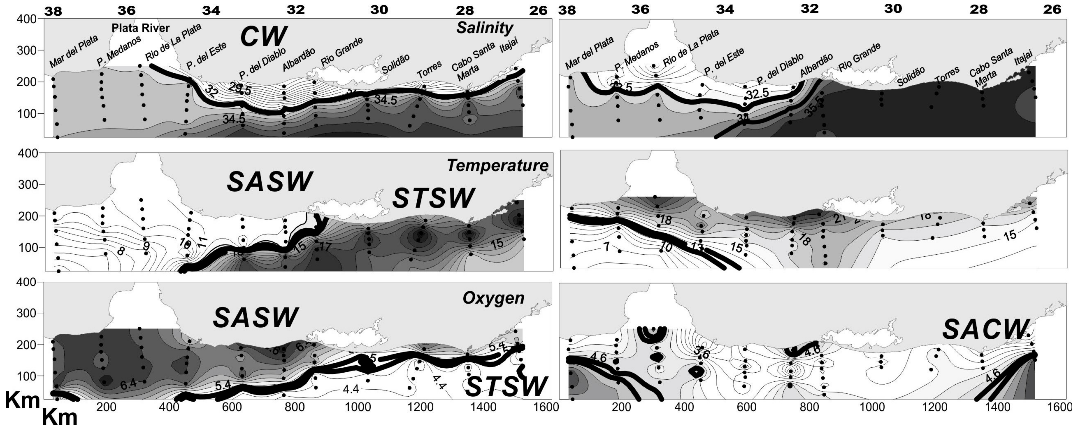

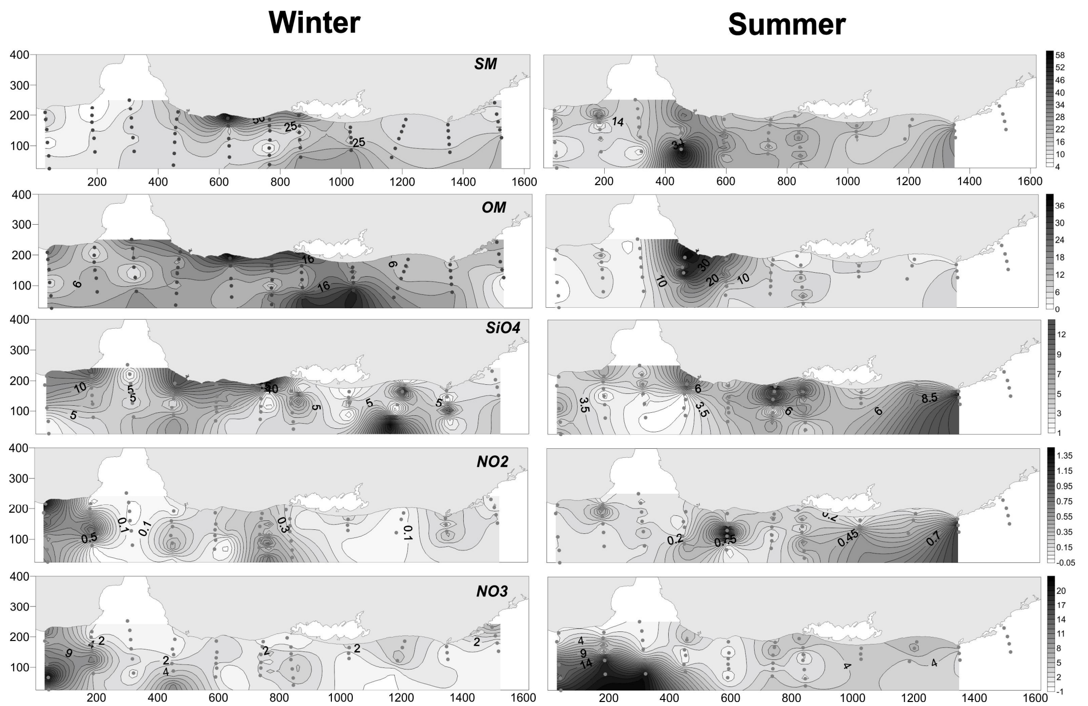

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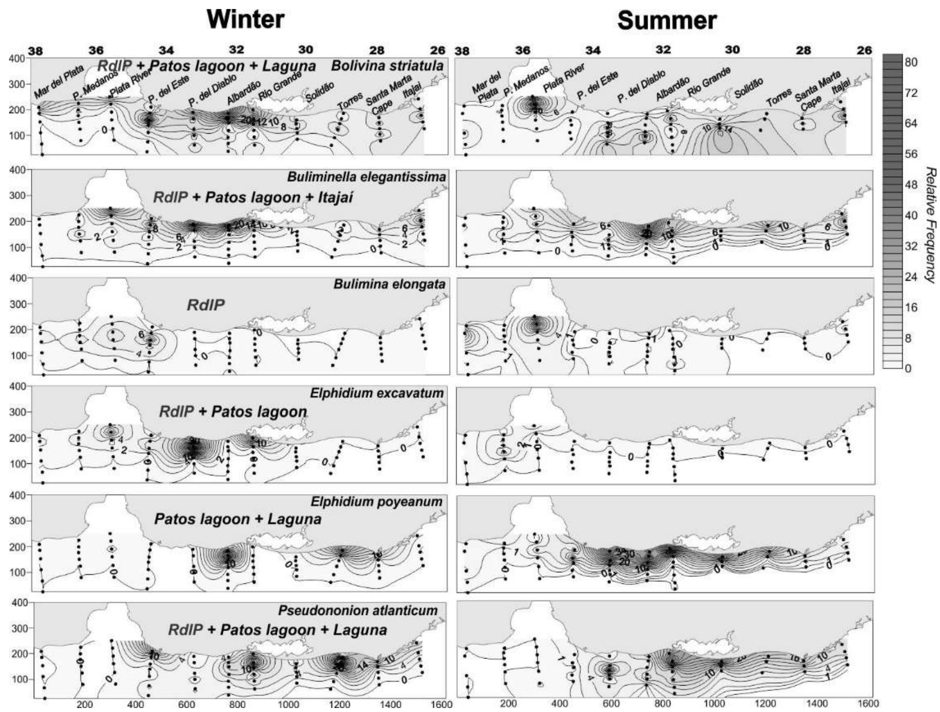

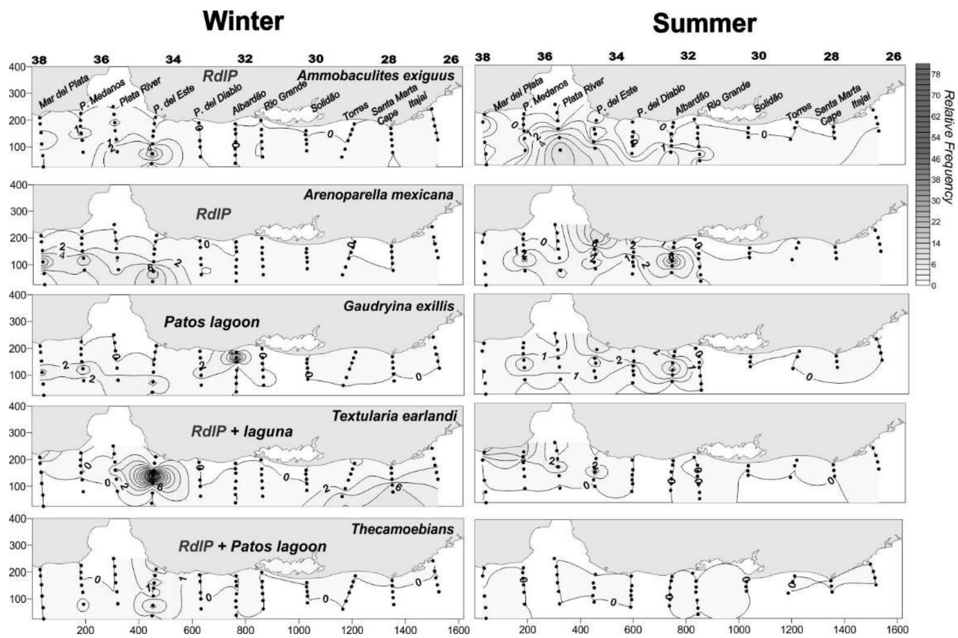

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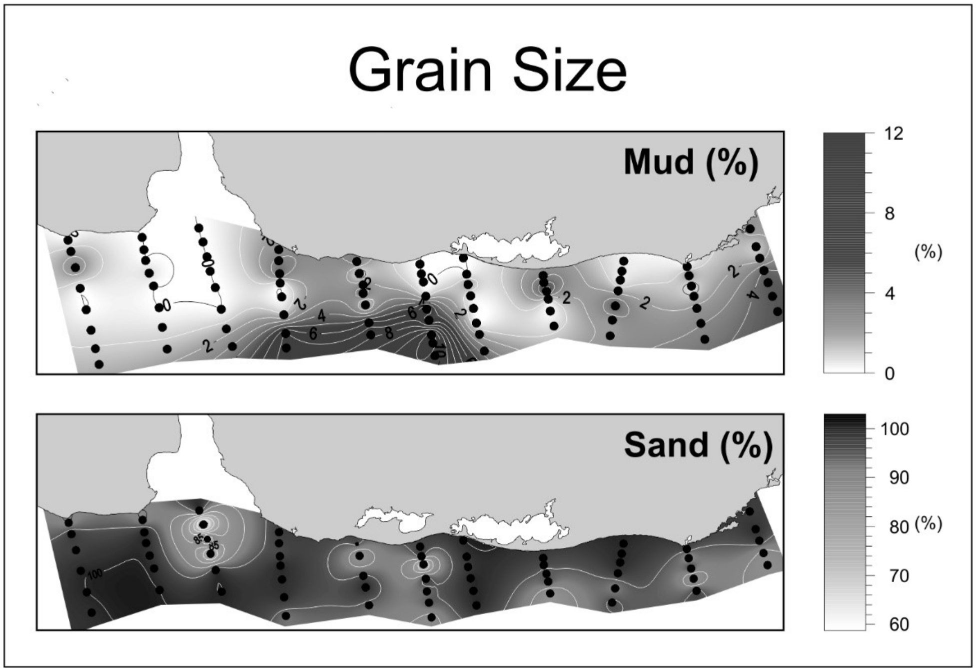

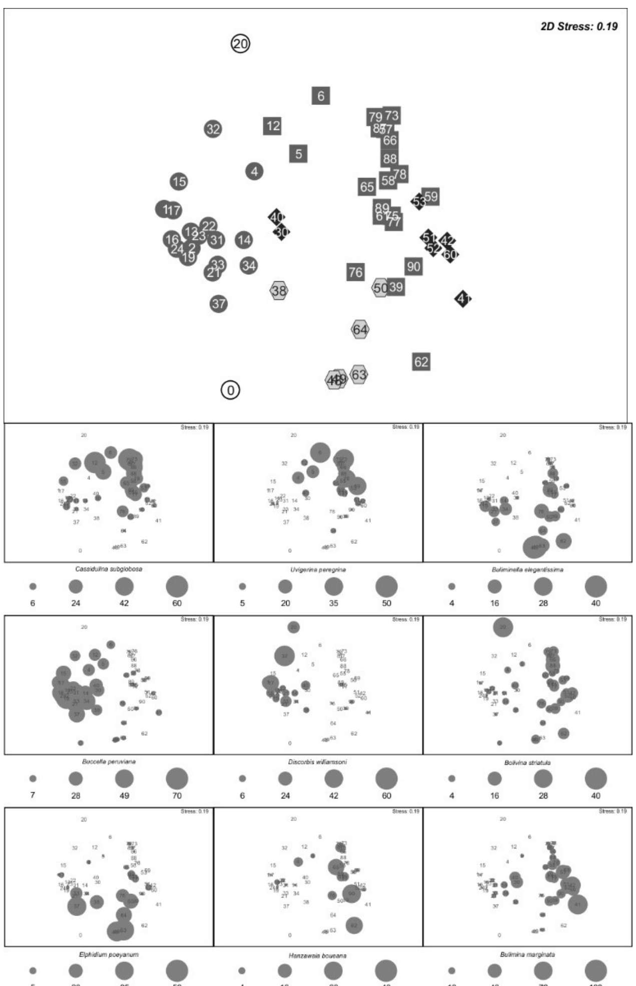

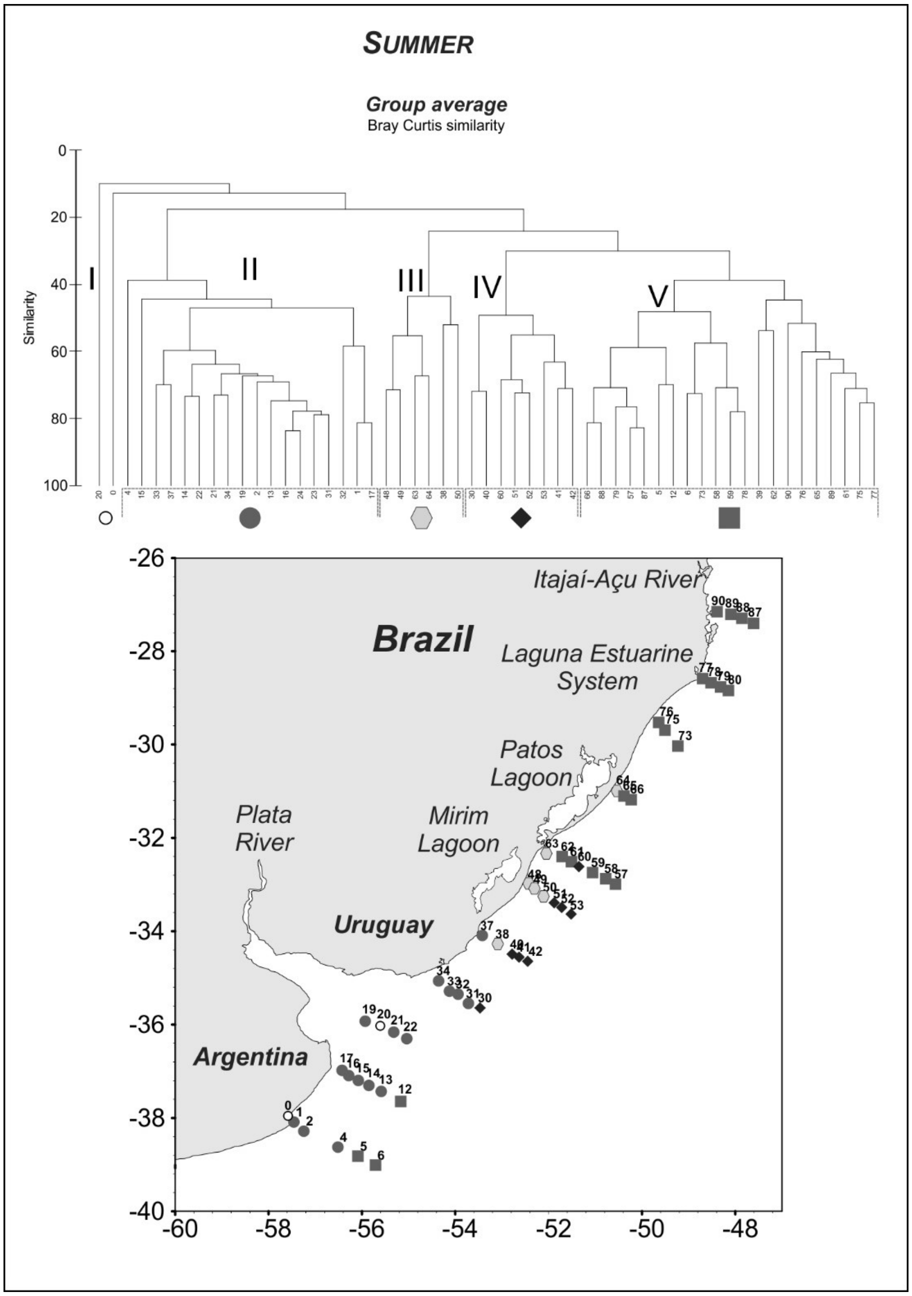
SUMMER
Group average
Bray Curtis similarity
Similarity
I
II
III
IV
V
Itajaí-Açu River
Brazil
Laguna Estuarine
System
Patos
Lagoon
Plata
River
Mirim
Lagoon
Uruguay
Argentina

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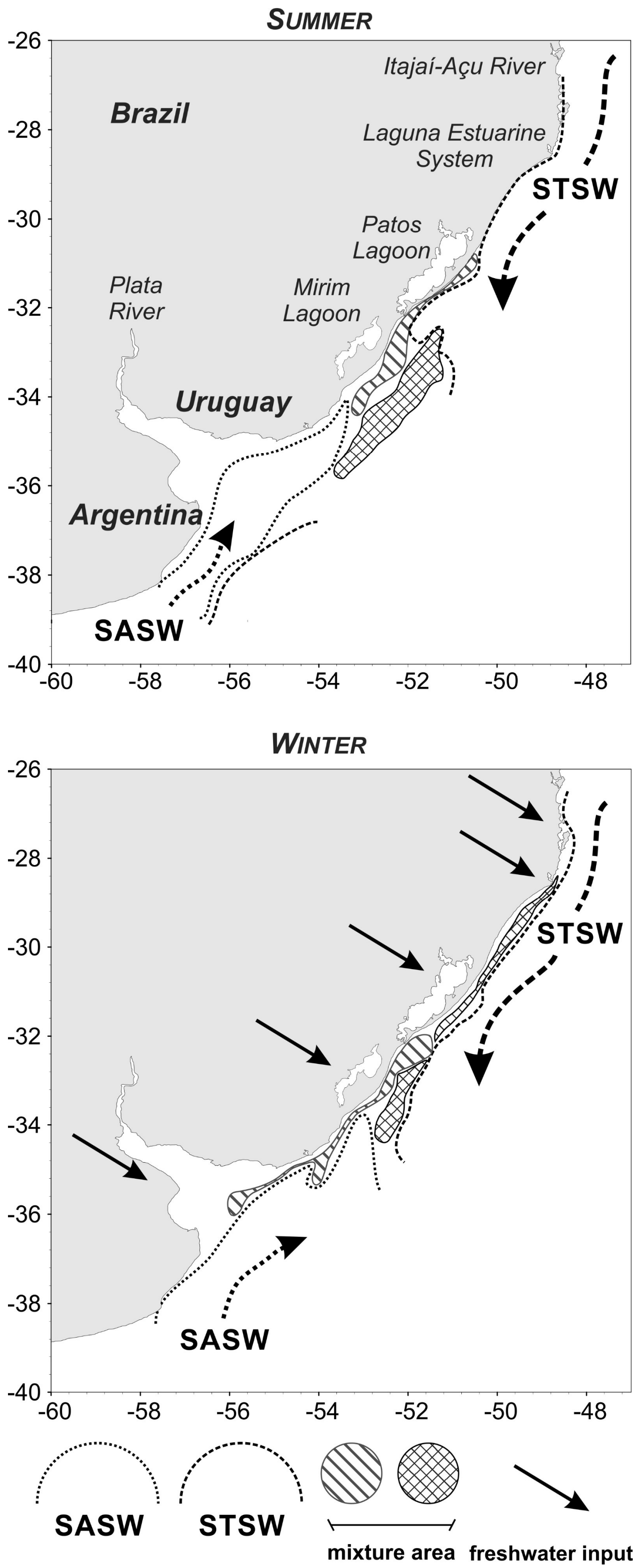

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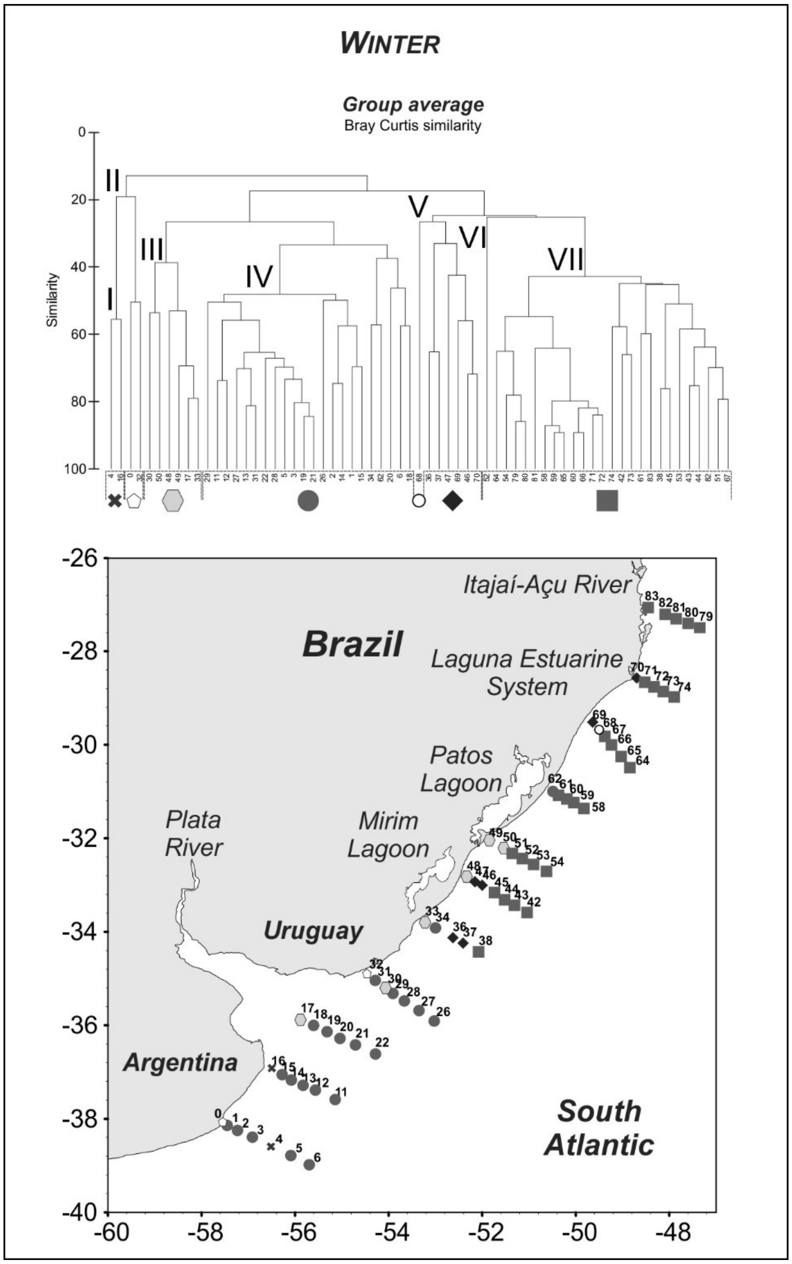

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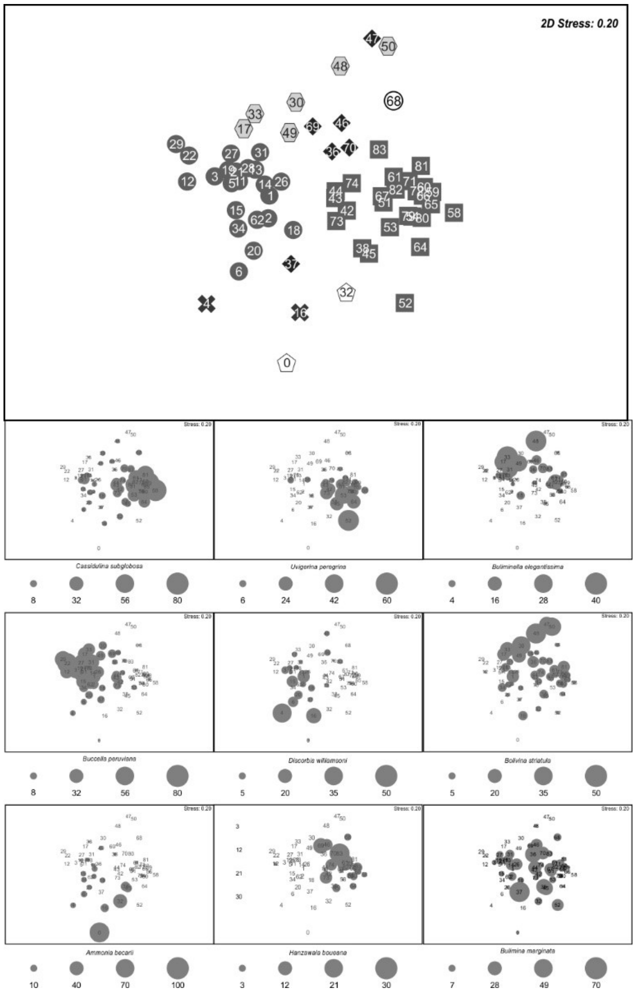

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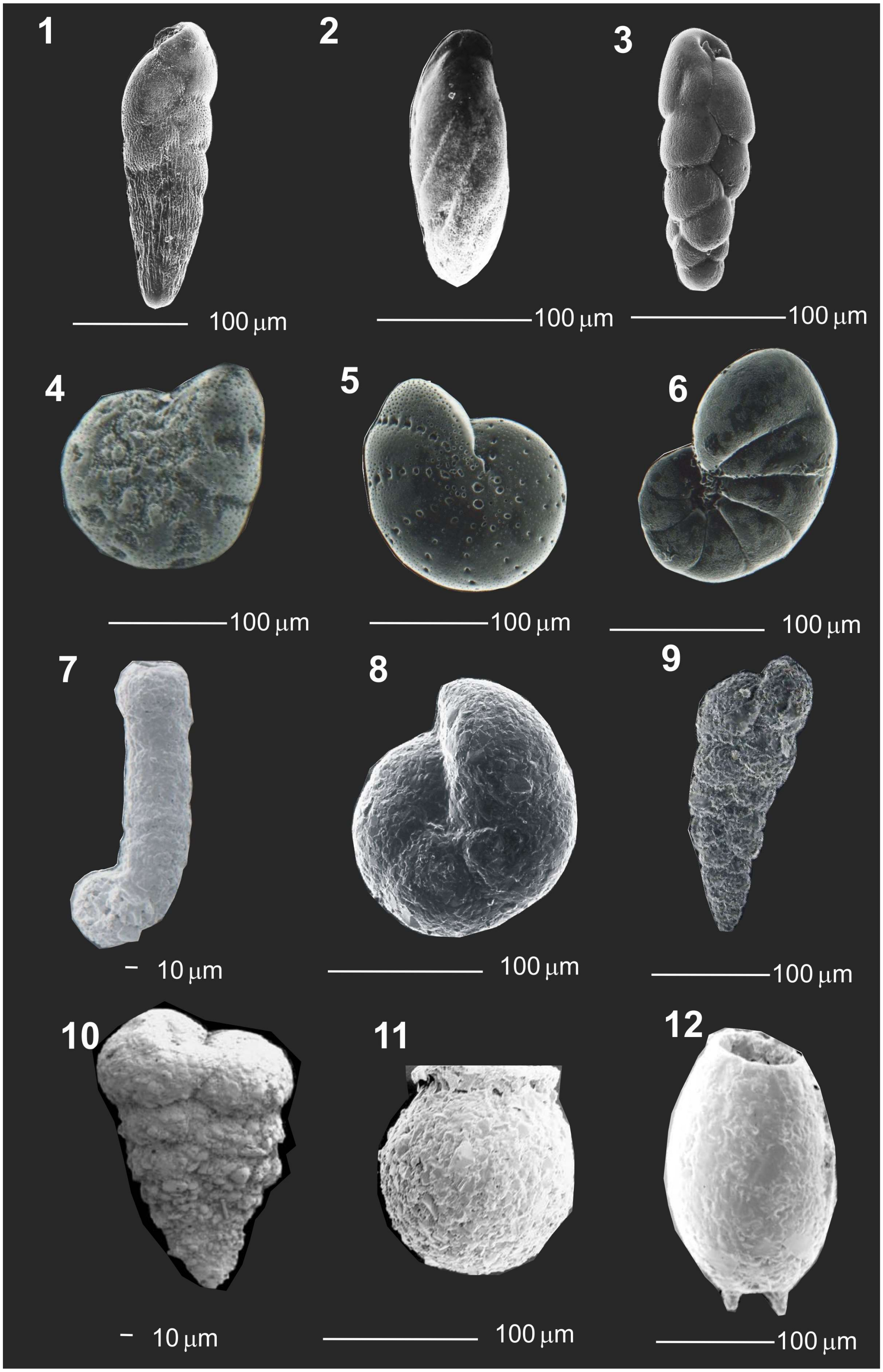

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