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GEOSCIENCES

Benthic foraminifera diversity from the south Atlantic Ocean: Tierra del Fuego and surrounding waters (South America)

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Abstract: The present study provides a detailed record of foraminiferal fauna and their ecological implications from surface sediments from Atlantic shelf of Tierra del Fuego, Argentina. The foraminiferal assemblage is mostly composed by four main hyaline genera, such as *Cibicidoides*, *Cibicides*, *Globocassidulina* and *Buccella*, which allowed the identification of three environmental zones. Zone 1 (Z1, 37 to 90 m) encompasses the eastern Beagle Channel and San Sebastian Bay. The assemblage reflected well-oxygenated marine inner shelf habitat, adapted to cold temperate waters. Zone 2 (Z2, up to 98.4 m), is located around the southern tip of Tierra del Fuego. The assemblage suggested a deeper marine environment, well oxygenated and with higher energy, probably due to the effect of tides and mainly by the influence of Malvinas Current. Finally, Zone 3 (Z3, up to 195 m) is located furthest from the Atlantic coast and the assemblage suggested an environment characteristic of outer shelf, with well-oxygenated cold waters and high-energy environment, reflected by species adhered to the substrate and coarse sediments. The distribution and abundance of certain species showed the influence of the Malvinas Current, while others evidenced a contribution of the Cape Horn waters.

Key words: Benthic foraminifera, environmental features, ocean Currents, Patagonia Argentina.

INTRODUCTION

Some of the pioneering studies on foraminifera from the Austral Southwest Atlantic Ocean are those of d'Orbigny (1839) and Cushman & Parker (1931), who analyzed the recent foraminifera. Heron-Allen & Earland (1932) extended these studies by analyzing sediments from the Malvinas Islands (Falkland Islands) and adjacent zones. Subsequently, near the study area, benthic foraminiferal fauna from Ushuaia and its surrounding areas were described, determining the zoogeographic province to which this fauna belongs (Lena 1966). Moreover, Herb (1971) determined bathymetric zones based on the distribution of certain species of benthic foraminifera between the Malvinas Islands and the South Shetlands Islands. Later, Thompson (1978) described the living benthic foraminifera fauna around Staten Island and the southeastern margin of Tierra del Fuego. In recent studies, Bernasconi et al. (2022) analyzed the abundance and diversity of modern benthic foraminifera along the Beagle Channel, distinguishing three distinct environmental sectors. More recently, Korsun et al. (2023) examined the modern benthic foraminiferal fauna of the western Beagle Channel and its tributary fjords to interpret records of meltwater discharges. However, few studies have focused on foraminiferal assemblages in surface samples from the Southwest Atlantic Ocean and the eastern region of Tierra del Fuego. Therefore, this study aims to expand the knowledge of the diversity of benthic foraminiferal assemblages in surface samples from the western shelf of the Atlantic Ocean, encompassing the area between east of San Sebastián Bay, east mouth of Beagle Channel and north of the southern tip of Tierra del Fuego and Staten Island. This research is of significant importance as the knowledge of modern foraminifera composition could be used as analogues to be applied to the fossil record in paleoecological and paleoenvironmental reconstructions in the study area.

STUDY AREA

Tierra del Fuego is located between 52° and 56° S at the southernmost region of South America. It is surrounded by the Patagonian and the Fuegian Andes to the west and south, respectively, and is bordered by the Atlantic Ocean to the east and Pacific Ocean to the west (Fig. 1). The geographic configuration of this region includes Isla Grande de Tierra del Fuego, which occupies approximately 70% of the 66,000 km^2 of the entire archipelago. Besides, there are several scattered islands to the south, including Staten Island. The eastern border of Isla Grande de Tierra del Fuego is marked by the Atlantic coastline, which extends in general with a northwest-southeast direction for approximately 330 km. This area is characterized by a macrotidal range of up to 10 m, subject to high-energy wave action and powerful, forceful westerly winds (Bujalesky 2007). To the southeast, separated from the mainland by the Le Maire Strait, lies Staten Island with a mixed tidal regime with a predominance of semi-diurnal tides. The Beagle

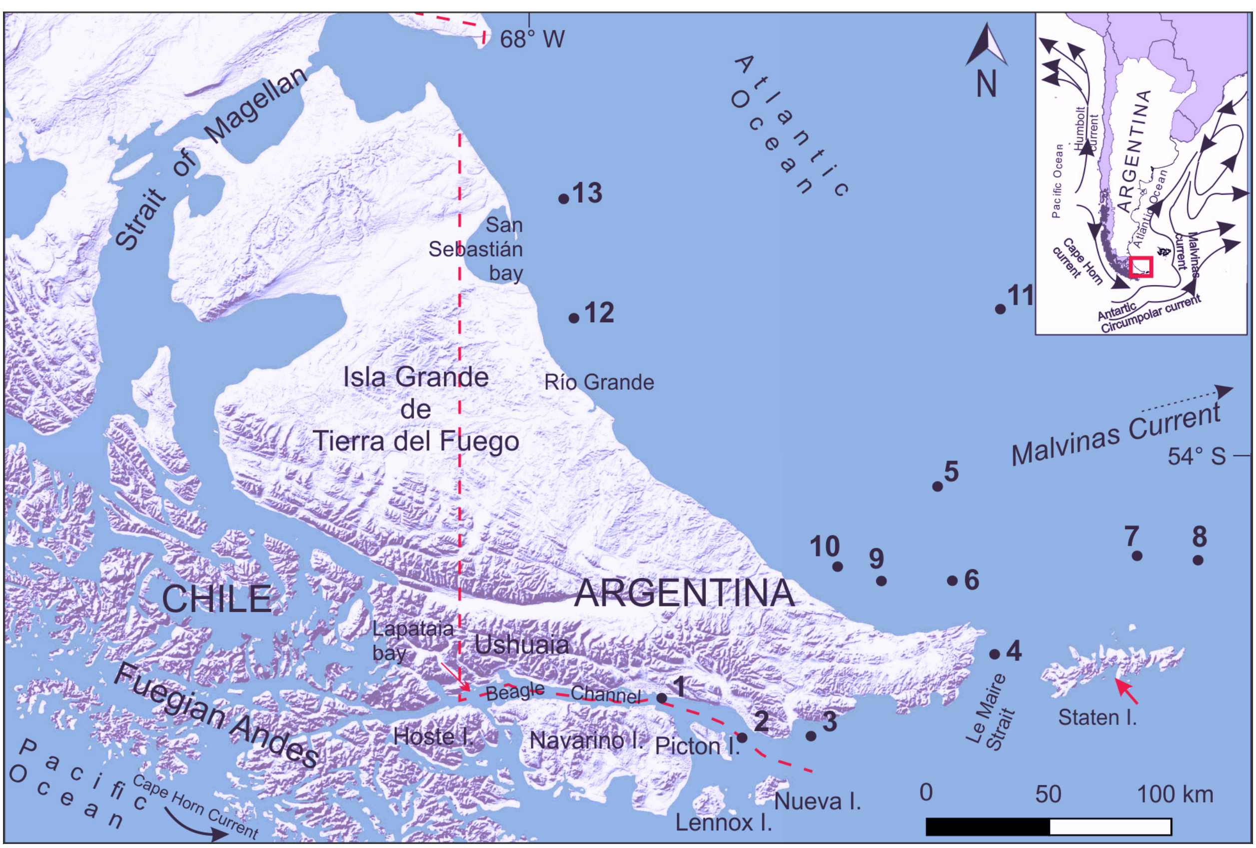

Figure 1. Study area and location of the surface samples from the east sector Tierra del Fuego with indication of the principal ocean currents.

Channel, stretching approximately 180 km in an east-west direction and located at the southern end of the archipelago, having an average width of 5 km and depths ranging between 100 and 450 m. This channel undergoes a microtidal range and a semidiurnal regime with diurnal inequalities (Bujalesky 2011).

The study area is located between 52°59’ and 55°02’ S and 67°52’ and 63°31’ W, encompassing the area from the northeast of San Sebastian Bay to the eastern mouth of the Beagle Channel, and extending to the northeast of the Staten Island. The oceanic sector surrounding the coast of Tierra del Fuego is characterized by intense mixing processes, resulting from vertical convective currents that occur between the Atlantic and Pacific oceanic waters. These waters develop in the Drake Passage, a region situated between the Malvinas Islands and the coast of Tierra del Fuego (Capurro 1981, Boltovskoy 1981, Bujalesky 2007). In this sector, the Cape Horn and Malvinas Currents play significant roles; the former is the northern extension of the Antarctic Circumpolar Current and is characterized by cold sub-Antarctic waters, with minimal influence from the warmer waters of the South Pacific. Moreover, after passing through the south of Tierra del Fuego, the Cape Horn Current migrates northward through the Le Maire Strait, where it mixes with the West Wind Drift waters and subsequently loses its identity. A branch of this current that extends northward and eastward along the Argentine shelf gives rise to the Malvinas Current (Boltovskoy et al. 1980). Geomorphologically, the study area is divided into two main sectors: the inner Patagonian Shelf with depths ranging between 37 to 98 m, and the Tierra del Fuego Shelf, where depths vary between 101.5 and 195 m (Violante et al. 2014).

From a biogeographical perspective, the study area is located within the Argentine Province, specifically within the Malvinas Subprovince based on benthic foraminifera determined by Boltovskoy (1976). This subprovince covers the southern part of the continental shelf of the South Atlantic. Towards the southwest, its boundary is poorly defined, approximately at 52° S, extending from the outer shelf zone to the bathyal depths (Boltovskoy et al. 1980). The characteristic species of the Malvinas Subprovince are *Angulogerina angulosa angulosa* (Williamson) (now renamed *Trifarina angulosa*), large specimens of *Buccella peruviana* (d’Orbigny), *Cassidulina crassa* (d’Orbigny) (now renamed *Globocassidulina crassa*), *Cassidulinoides parkerianus* (Brady), and *Ehrenbergina pupa* (d’Orbigny) (Boltovskoy 1976, 1981, Boltovskoy et al. 1980).

MATERIALS AND METHODS

The surface sediment samples were collected between the eastern mouth of the Beagle Channel, the north of Staten Island and the east of San Sebastian Bay in the continental shelf of Tierra del Fuego. Thirteen sediment samples (0 – 2 cm) were collected using a Shipek grab sampler aboard the oceanographic vessel Puerto Deseado during the “Patagonia Austral” campaign in 2012. The sample sediments were extracted from depths ranging between 37 to 195 m water depth. Upon retrieval, the upper 2 cm of the sediment were carefully subsampled to prevent sediment disturbance (Table I, Fig. 1). For the grain-size analysis, bulk subsamples were sieved to separate them into gravel (>2 mm), sand (2mm - 63 μm) and mud (<63 μm). For the foraminifera analysis, subsamples were washed over a 63 μm sieve (Tyler Screen System N° 230) and then air-dried. In order to assess the abundance of individuals in each sample, at least 300 individuals were extracted for examination under a stereomicroscope when it

Table I. Location, depth, abundance (Individuals/10gr dry sediment), species number, Shannon-Wiener and Fisher indeces for the samples taken in the south of Tierra del Fuego.

Sample	Code sample	Latitude (S)	Longitude (W)	Depth (m)	Abundance (A)	Species number (S)	Shannon-Wiener (H)	Fisher index
1	I1	54°54'27.7''	67° 14' 43.0"	37	8500	32	2.6	7.7
2	I2	55°2'35.5''	66° 43' 9.1"	90	11333	29	2.3	6.6
3	I3	55°06'0''	66° 15' 31.6"	52	2750	38	2.9	11.5
4	I15	54°45'17.2''	64° 54' 9.7"	98.4	1214	32	2.6	8.8
5	I22	54°7'39.7''	65° 19' 19.9"	101.5	1898	30	2.6	8.2
6	C18	54°30'19.8''	65° 14' 16.8"	86.5	1652	33	2.7	9.2
7	C17	54°22'51.6''	63° 57' 48.6"	115	1810	26	2.2	7.3
8	C16	54°23'18.6''	63° 32' 56.4"	195	1701	30	2.5	8.9
9	C19	54°31'7.3''	65° 43' 28.2"	63	50000	31	2.6	8.7
10	C20	54°28'22.0''	66° 1' 51.6"	46.7	37500	23	2.5	6.4
11	C25	53°24'46.8''	64° 57' 0.7"	130	498	25	2.1	6.8
12	C27	53°27'38.5''	67° 47' 7.8"	35.6	47	3	1.1	-
13	C29	53°1'0.48''	67° 52' 26.4"	37.1	854	25	2.2	6.9

was possible. The samples were standardized to 10 grams of bulk sediment per sample. Because the abundance of living specimens was very low (approximately 1%), the ecological indices and statistical analysis were applied to the total fauna (living + dead).

The diversity indices species richness (S), Shannon-Wiener (H) and Fisher's alpha index were calculated (Table I). The Fisher's alpha index was plotted using RStudio v. 4.1.1 (RStudio Team 2020).

The genera were systematically analyzed following the taxonomic references of Loeblich & Tappan (1992) and Sen Gupta (1999), while species were determined according to Herb (1971), Thompson (1978), Boltovskoy et al. (1980), and Bernasconi et al. (2022), among others. The most representative specimens were photographed using a scanning electron microscope (SEM Inspect 505) at Centro Atómico Bariloche (Argentina), and stored at the repository of Universidad Nacional del Comahue, Argentina, under numbers UNC-PMIC № 272 to 291.

An unconstrained cluster analysis based on the main species (relative abundance greater or equal to 5%) was conducted in order to identify different zones in the study area. The analysis and the distribution diagram were generated using Tilia software version 1.7.16 (Grimm 2012). Standardized Euclidian distance as the distance coefficient, and data transformation by standardization to mean 0 and typical deviation (SD) 1 were applied. Clusters were formed according to the sum of squared error hierarchical clustering method.

Benthic foraminifera genera were classified according to ecological preferences and their microhabitats (Corliss 1991, Jorissen et al. 1995, Kaiho 1999, Duleba et al. 1999, Murray 2006, Bernasconi et al. 2022). They were also classified according to their lifestyle: free (F), attached (A) or both (F-A); trophic strategy: herbivores (H), detritivores (D), and combined suspensiovores-herbivores (S-H) and herbivores-detritivores (H-D); microhabitat preference: epifaunal (E) or infaunal (I); and bottom water oxygen concentration (Kaiho 1994, 1999): oxic (O, >1.5 mL/L of dissolved oxygen) or dysoxic (Dy, <1.5 mL/L), (Table II). The ecological characteristics predominant in each sample were represented in different maps using the Qgis software (3.16 Hannover).

RESULTS

Foraminiferal diversity and ecology

The present study provides a detailed record of foraminiferal fauna from 13 surface samples sediments from the marine shelf of Tierra del Fuego, Argentina.

From the micropaleontology analysis, a total of 119,758 individuals and 99 species were identified, all of them distributed among 62 genera, 41 families, and 9 orders. The majority of specimens belong to the order Rotaliida (98.1%), followed by the orders Milliolida (1.3%), Polymorphinida (0.2%), Nodosariida (0.15%), Robertinida (0.14%), Lituolida (0.1%), Spirillinida (0.03%), Vaginulinida (0.03%) and Textulariida (0.03%) (See Supplementary Material – Data SI). The assemblage was predominantly represented by hyaline foraminifera forms (98.7%), mainly composed of the species *Cibicidoides dispars*, *Globocassidulina rossensis*, *Cibicides aknerianus*, *Cibicidoides variabilis*,

Table II. Ecological preferences for the most important species according to lifestyle, trophic strategies, microhabitat and Oxygen levels. Lifestyle: free (F), attached (A) and free-attached (F-A); trophic strategies: detritivores (D), herbivores (H), and suspensivore-herbivore (S-H) combination; microhabitat: epifaunal (E) and infaunal (I) and Oxygen levels: oxic (O) and dysoxic (Dy).

Most abundance species (> 5% of abundance)	Lifestyle	Microhabitat	Trophic strategy	Oxygen levels
Buccella peruviana	F	E	D	O
Globocassidulina crassa	F	I	D	O
Cassidulina laevigata	F	I	D	Dy
Cassidulinoides parkeriana	F	I	D	Dy
Cibicides aknerianus	A	E	S-H	O
Cibicides fletcheri	A	E	S-H	O
Cibicidoides dispars	A	E	S-H	O
Cibicidoides variabilis	A	E	S-H	O
Discanomalina vermiculata	F	E	D	O
Ehrenbergina pupa	F	E	D	O
Epistominella exigua	F	E	D	O
Globocassidulina rossensis	F	I	D	O
Globocassidulina subglobosa	F	I	D	O
Lobatula lobatula	A	E	S-H	O
Quinqueloculina seminulum	F-A	E	H	O
Rosalina williamsoni	A	E	H	O

and *Buccella peruviana* (Fig. 2). In addition, individuals with porcelaneous walls (1.3%) were mainly represented by *Quinqueloculina seminulum*, *Miliolinella subrotunda*, *Miliolinella lutea*, and *Triloculina baldai*. Agglutinated forms (0.05%) were mostly represented by *Lepidodeuterammina ochracea*, *Trochammina inflata*, *Trochammina plana* and *Trochammina squamata*, among others with minor relative abundance. The abundance of individuals varied from 47 (sample 12) to 50,000 (sample 9) per 10 gr of bulk sediment per sample. The number of species per sample ranged from 3 to 38. The Shannon-Wiener index (H) values ranged from 1 to 2.9, while Fisher's alpha (α) ranged from 0.8 to 11.5 (Table I, Fig. 3).

Regarding the ecological preferences of foraminifera, in terms of lifestyle, the A forms constituted 57.1%, F forms comprised 41.3% and the A-F lifestyle was 1.7%, depending on the stage in the life cycle. The main trophic strategies observed were a combination of S-H (50.1%), H (8.4%) and D (40.2%), and the combined H-D strategy in lower proportion. Moreover, the epifaunal habitat was predominant (74.6%), with the O condition being the most represented at 92.4% (Table II, Fig. 4).

The characteristic lithology comprised light to medium brown fine sands, mud with iron oxides and gravels. The lithology was primarily characterized as sandy sediments, although it was observed amounts of mud up to 61.4% (samples 1, 9, 10, 12, and 13) and gravel concentrations up to 80.0% (samples 4, 7, 8 and 13), Table I.

Foraminiferal assemblages

Based on the unconstrained cluster analysis, three environmental zones were recognized in the study area: Zone 1 (Z1), Zone 2 (Z2), and Zone 3 (Z3), (Table III, Figs. 5, 6).

The Z1 comprises four samples (1, 2, 12 and 13), located in the western sector of the study area, with depths ranging from 35.6 to 90 m. Samples 12 and 13, situated near San Sebastian Bay consist of sandy and gravel sediments with presence of mud deposited in a shallow environment (depths of 35.6 to 37.1 m) (Table I). To the south, near the mouth of the Beagle Channel, samples 1 and 2 are found at depths of 37 and 90 m, respectively, and consist mainly of sandy sediment. This zone exhibited intermediate values of abundance when compared to zones Z2 and Z3, with values ranging from 47 to 11,333 individuals. The assemblage was predominantly represented by *Cibicidoides dispars* with a mean relative abundance of 28.5%, followed by *Buccella peruviana* (17.7%), *Epistominella exigua* (6.8%), *Cibicides fletcheri* (4.8%), *Cibicides aknerianus* (6.1%) and *Globocassidulina rossensis* (3.1%) (Figs. 2, 5). The S values varied from 3 to 32, while the H index and Fisher's alpha values ranged from 1.0 to 2.6 and from 0.8 to 7.7, respectively (Table I, Fig. 3).

The Z2 is composed of samples 3, 4, 6, 9 and 10, located in the center-south region of the study area, with depths ranging from 46.7 to 98.4 m. The sediments were mainly composed by sandy sediments, with layers of gravel observed between depths of 52 and 86.5 m around the mouth of the Beagle Channel with predominance of gravel at 98 m of depth. The mud fraction was also recorded between depths of 46.5 and 63 m near the Le Maire Strait (Table I). This zone exhibited higher abundance values, ranging from 1,214 and 50,000 individuals. The assemblage was characterized by *Globocassidulina rossensis* (14.2%), *Cibicidoides dispars* (16.7%), *Cibicides fletcheri* (9%), *Cibicidoides variabilis* (4.7%), *Cibicides aknerianus* (12.3%), *Buccella peruviana* (3.7%), and *Discanomalina vermiculata* (2.3 %) (Figs. 2, 5). Species richness (S) varied from 23 to 38, the H index ranged between 2.6 and 2.9 and

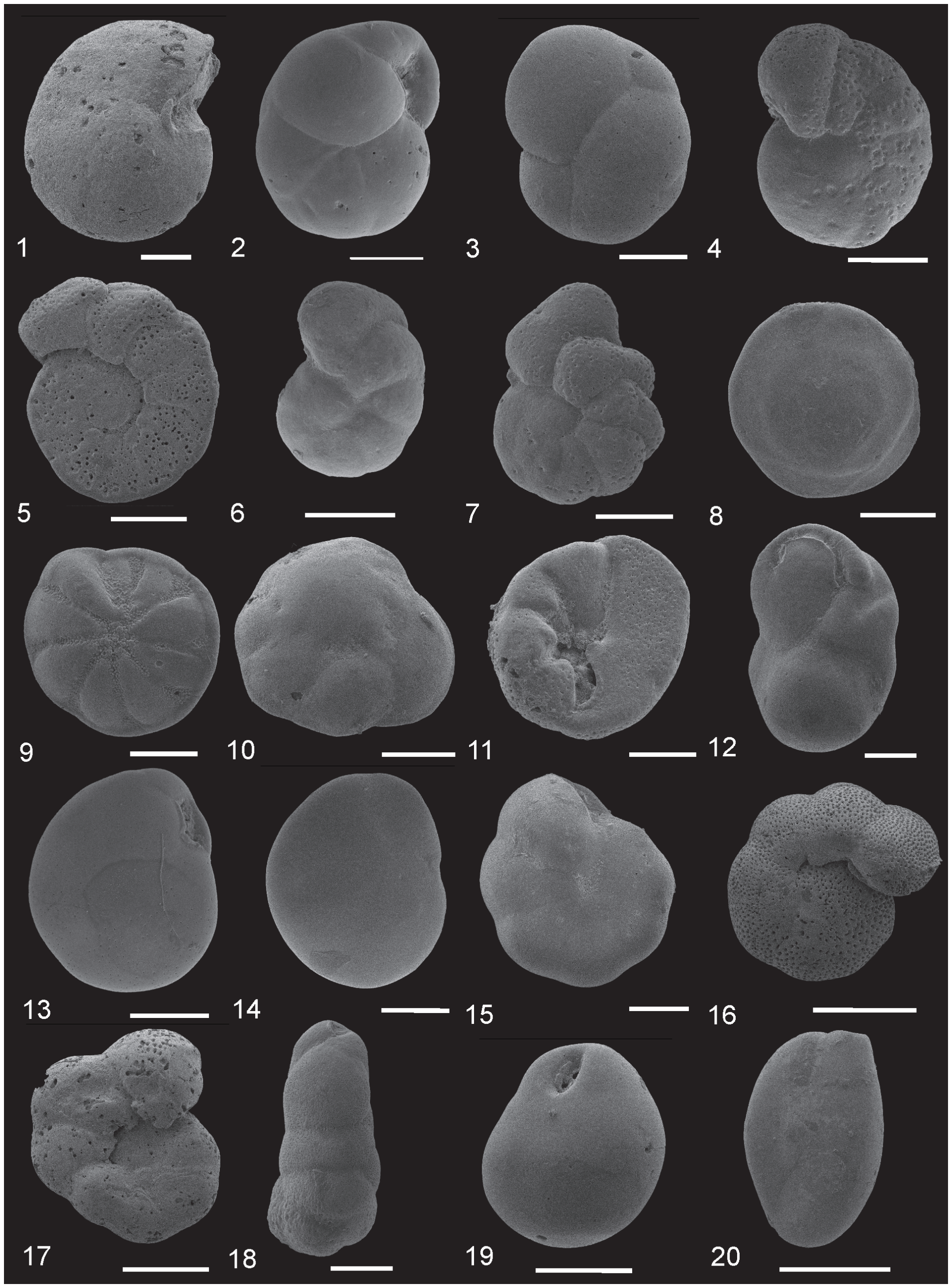

Figure 2. **Photomicrographs of the most important foraminiferal species identified in the surface samples, 1. *Cibicidoides dispars*, dorsal view, UCN-PMIC-272; 2. *Globocassidulina rossensis*, ventral view, UCN-PMIC-273; 3. *Globocassidulina rossensis*, dorsal view, UCN-PMIC-274; 4. *Cibicides fletcheri*, dorsal view, UCN-PMIC-275; 5. *Cibicides fletcheri*, ventral view, UCN-PMIC-276; 6. *Lobatula lobatula,* dorsal, UCN-PMIC-277; 7. *Cibicidoides variabilis*, dorsal view, UCN-PMIC-278; 8. *Buccella peruviana*, dorsal view, UCN-PMIC-279; 9. *Buccella peruviana*, ventral view, UCN-PMIC-280; 10. *Discorbis williamsoni*, dorsal view, UCN-PMIC-281; 11. *Discorbis williamsoni*, ventral view, UCN-PMIC-282; 12. *Ehrenbergina pupa*, ventral view, UCN-PMIC-283; 13. *Cassidulina laevigata*, ventral view, UCN-PMIC-284; 14. *Cassidulina laevigata*, dorsal view, UCN-PMIC-285; 15. *Epistominella exigua*, ventral view, UCN-PMIC-286; 16. *Discanomalina vermiculata*, dorsal view, UCN-PMIC-287; 17. *Discanomalina vermiculata*, ventral view, UCN-PMIC-288; 18. *Cassidulinoides parkeriana*, ventral view, UCN-PMIC-289; 19. *Globocassidulina crassa*, ventral view, UCN-PMIC-290; 20. *Quinqueloculina seminulum*, UCN-PMIC-291. Scale: 50 µm (1, 2, 3, 8, 9, 15), 100 µm (4, 5, 6, 7, 10, 11, 12, 13, 14, 18), 200 µm (19), 400 µm (20), 500 µm (17, 18).**

Fisher's index values were between 6.4 and 11.6 (Table I, Fig. 3).

The Z3 encompasses samples located in the center-north (5 and 11), and the east regions of the study area (7 and 8), at depths ranging from 86.5 to 195 m. The sediments are composed mainly by sand in the northwest and by -gravel accumulation in the north of Staten Island (Table I). This zone displayed the lowest abundance values among the zones, with counts ranging from 498 to 1,898 individuals. The assemblage was mostly composed of *Discanomalina vermiculata* (22.1%), *Globocassidulina crassa* (15.9%), *Ehrenbergina pupa* (13.3%), *Globocassidulina rossensis* (8.4%), *Quinqueloculina seminulum* (3.1%), *Cibicidoides dispars* (5.8%), *Cibicides aknerianus* (5.7%), and *Cibicides fletcheri* (2.1%) (Figs. 2, 5). The number of species ranged from 25 to 30, and the Shannon-Wiener index (H) values varied between 2.0 and 2.6 and the Fisher's index varied between 6.8 and 8.9, (Table I, Figs. 3).

DISCUSSION

The study area covers the southwest sector of the Atlantic Ocean, extending from the inner

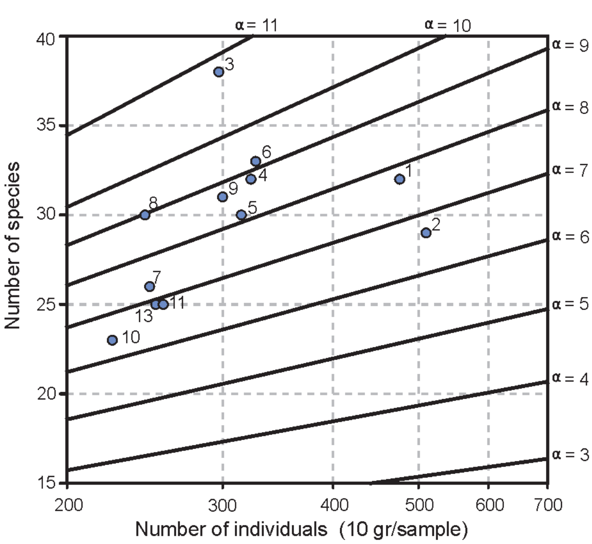

Figure 3. Plot of the Fisher's index values from the surface samples.

to the outer continental shelf of Tierra del Fuego, and includes coastal environments. This region is mostly characterized by sandy sediments. However, mud accumulations have been observed on the inner shelf near the coast (samples 9, 10 and 12). Furthermore, gravel accumulations have been reported near San Sebastian Bay (sample 13), in the Le Maire Strait (sample 4) and north of Staten Island (samples 7 and 8). These characteristics have been observed by Thompson (1978) in samples near to the study area, who identified the presence of silts and clay sediments in intertidal areas and bays protected from the direct influence of open ocean currents. Moreover, in intertidal areas exposed to the oceanic currents and waves, sand-sized sediments are common. In offshore areas that are directly influenced by the ocean currents, the predominant sediment types are coarse sand and gravel. This pattern is notably observed around Staten Island (Thompson 1978). Recently, Bernasconi et al. (2022) documented the presence of sandy sediments in the easternmost area of the Beagle Channel, noting high quantities of gravel in the area around of Gable Island. These characteristics were also observed in samples 1, 2 and 3 from this study.

The microfauna in our study area was predominantly composed of hyaline organisms, with a small percentage of porcelaneous forms and few agglutinated ones. Our findings are consistent with Herb (1971), who defined bathymetric zones for samples located north and south of the Drake Passage. Moreover, we observed that agglutinated forms had a low relative abundance near the study area. However, their distribution, both in the number of individuals and species, increased in Ushuaia Bay within Beagle Channel. This increase could be related to deeper waters, as suggested by Thompson (1978), Lena (1966) and Hromic (2007). Herb (1971) observed an increase in the number

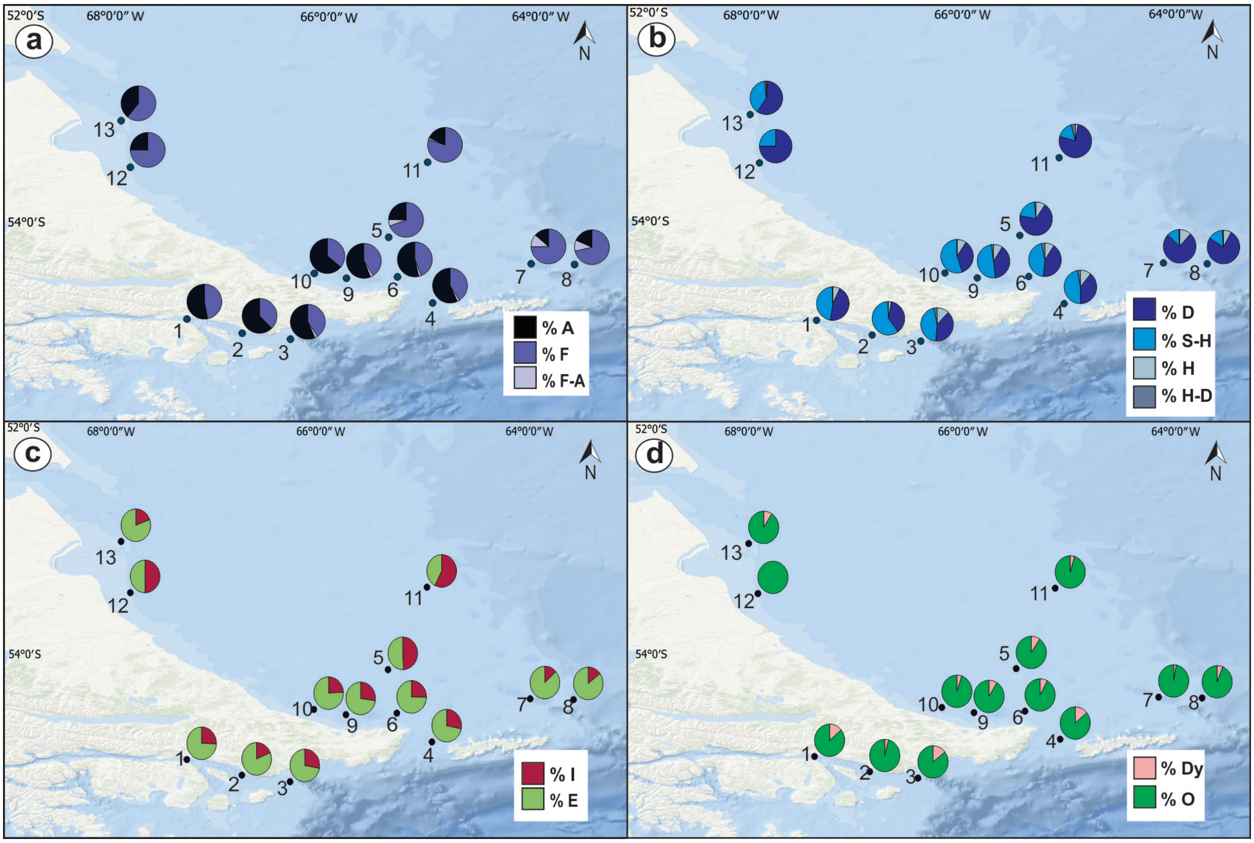

Figure 4. Maps showing the distribution of the ecological preferences for the total species according a) lifestyle: free (F), attached (A) and free-attached (F-A); b) trophic strategies: detritivores (D), herbivores (H), and herbivore-detritivore (H-D) or suspensivore-herbivore (S-H) combination, c) microhabitat: epifaunal (E) and infaunal (I), d) Oxygen levels: oxic (O) and dysoxic (Dy). See depth in Table I.

of agglutinated organisms with increasing depth to the south of the Antarctic Convergence, while to the north of this boundary, hyaline forms predominated, particularly around the southeastern margin of Tierra del Fuego. The occurrence of agglutinated species in channels and southern inland fjords, characterized by low rates of water renewal, has been noted. This distribution may be associated with low sedimentation rates and the limited availability of nutrients, with these organisms preferring deeper waters (Hromic & Zúñiga-Rival 2005). Therefore, the predominance of calcareous specimens found in the study area could be linked to the oceanographic conditions that align with a marine environment (Hromic 2007, Bernasconi et al. 2022).

The foraminifera assemblage of the study area was predominantly composed of individuals from four main hyaline genera *Cibicidoides*, *Cibicides*, *Globocassidulina* and *Buccella*. Notably, the genera *Cibicidoides* and *Cibicides* have been categorized as epifaunal organisms, which adhere to the substrate in well-oxygenated waters and high-energy marine environments, influenced by strong currents (Kaiho 1994, 1999, Ishman & Martínez 1995, Hromic 2002, 2006, Figueroa et al. 2005, Schönfeld et al. 2011, Bernasconi et al. 2018, 2022). Their ability to adhere to hard substrates and their planoconvex forms allow these genera to adapt to high-energy marine environments. This adaptability is due to their capability to easily reposition themselves after disturbances (Severin 1983, Nigam et al.

Table III. Summary of the three environmental zones; Zone 1 (Z1), Zone 2 (Z2) and Zone 3 (Z3).

Zones	Location	Depths	Samples	Location in the Continental Shelf	Foraminiferal assemblages
Z1	western sector, from east San Sebastián Bay to east Beagle Channel	35.6 - 90 m	1, 2, 12 and 13	Inner shelf	*Cibicidoides dispars*, *Buccella peruviana*, *Epistominella exigua*, *Cibicides fletcheri*, *Cibicides aknerianus* and *Globocassidulina rossensis*
Z2	center-south area	46.7 - 98.4 m	3, 4, 6, 9 and 10	Inner shelf	*Globocassidulina rossensis*, *Cibicidoides dispars*, *Cibicides fletcheri*, *C. variabilis*, *Cibicides aknerianus*, *Buccella peruviana* and *Discanomalina vermiculata*
Z3	from center-north to east: north Isla de los Estados	86.5 - 195 m	5, 7, 8 and 11	Outer shelf	*Discanomalina vermiculata*, *Globocassidulina crassa*, *Ehrenbergina pupa*, *Globocassidulina rossensis*, *Quinqueloculina seminulumn*, *Cibicidoides dispars*, *Cibicides aknerianus* and *Cibicides fletcheri*.

2000, Fernandes 2006, Alperin et al. 2011). These genera have been documented from shelf to bathyal zones and display characteristics of passive suspension feeders (Alexander & De Laca 1987, Ishman & Martínez 1995, Murray 2006, Hromic 2007, Alperin et al. 2011, Hromic & Montiel 2011). Furthermore, they are regarded as reliable indicators of high oxygen levels and a constant food supply (Kaiho 1999, Figueroa et al. 2005). The genus *Globocassidulina*, identified as an infaunal organism with a free lifestyle, exhibits characteristics of detritivore feeding, as noted by Murray (2006). This genus has been also associated with oxygen-rich marine environments with sandy sediments, and can be found in cold to temperate waters across a broad range of habitats, from inner shelf to bathyal environments, and as an open sea dweller among foraminifera species (Boltovskoy 1957, Boltovskoy et al. 1980, Murray 2006, Sousa et al. 2006, Alperin et al. 2008, Arellano et al. 2011, Mello et al. 2014, Bernasconi et al. 2018, 2019, Bernasconi & Cusminsky 2020, Bernasconi et al. 2022). Calcareous benthic foraminifera are among the most sensitive indicators of dissolved oxygen levels in the ocean, showing great differences in the characteristics of the foraminifera test formed under oxic and dysoxic conditions (Kaiho 1999). Thus, oxygen availability is a critical factor controlling species richness and food availability among species in oxic conditions (Hromic 2012). Furthermore, *Buccella* primarily found in the coastal zone, leads as a free lifestyle with a detritivore feeding strategy. It is widely distributed throughout the Argentine shelf, from restricted areas to the continental open shelf (Boltovskoy 1976, Cusminsky et al. 2006, Bernasconi & Cusminksy 2005, 2020, Alperin et al. 2011, Bernasconi et al. 2018). *Buccella* is halotolerant, capable of withstanding in salinity caused by freshwater influxes (Hromic & Zúñiga-Rival 2005, Bernasconi et al. 2022).

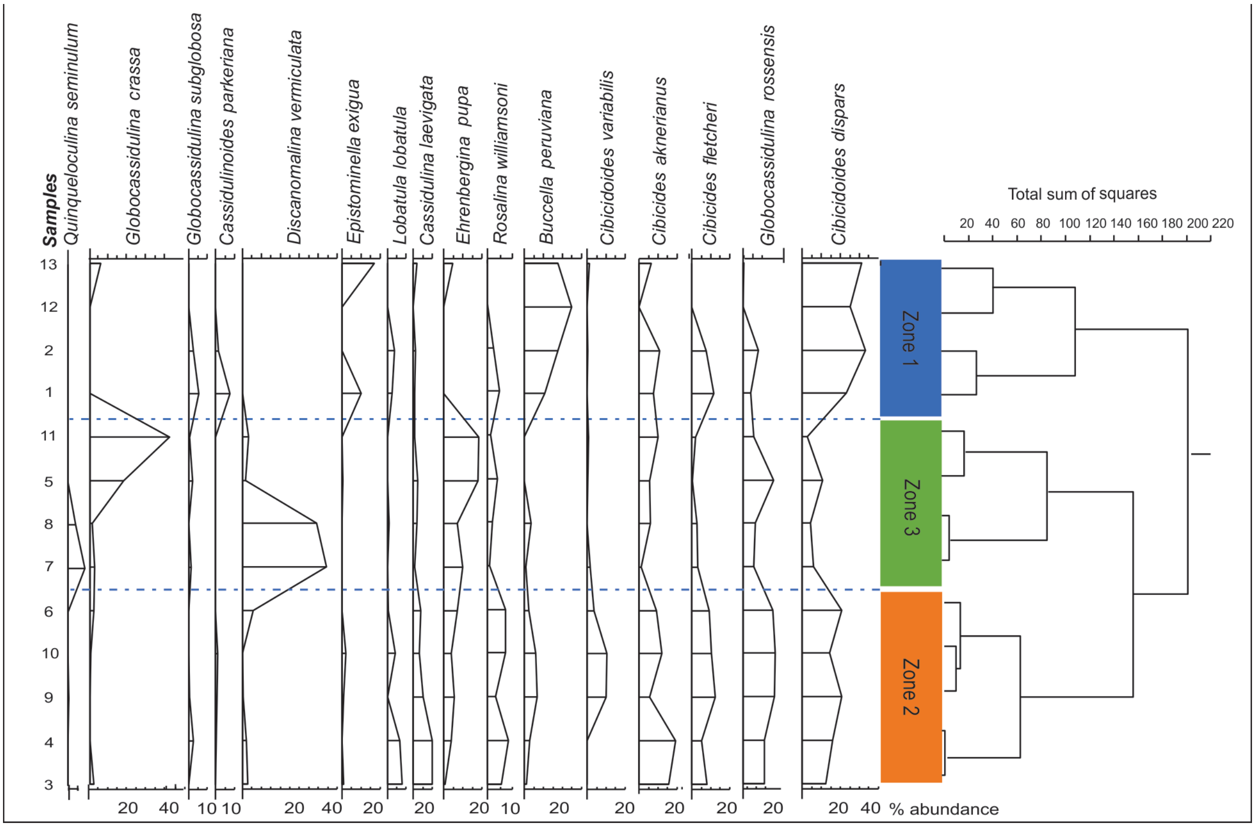

Figure 5. Dendrogram analysis of foraminiferal species with 5 % of relative abundance at least in one sample in the Beagle Channel and cluster analysis showing the samples grouping, Z1 (blue), Z2 (orange) and Z3 (green). The relative abundance is expressed in %.

Regarding the abundance and the diversity index, low values were observed in Z1, while Z2 exhibited the maximum values, suggesting an open sea environment with a salinity of approximately 35 PSU (Table I, Fig. 3). The samples from the three zones showed greater abundance and diversity than those previously reported for other sectors of the Argentine shelf (Bernasconi et al. 2018, Bernasconi 2020, Bernasconi & Cusminsky 2020). The Z1 was characterized by mean H and Fisher´s alpha values were between 0.6 and 2.7 and 3 and 19, respectively. According to Murray (2006), these values are indicative of marine inner shelf environments, with salinities ranging from 33 to 37 PSU and depths between 0 – 100 m. The assemblage was primarily represented by *Cibicidoides dispars*, *Buccella peruviana*, *Epistominella exigua*, and *Cibicides aknerianus*. The most abundant species, *Cibicidoides dispars*, was found in all four samples comprising the zone, achieving higher abundance at 90 m. These findings support the information for the area and its surroundings (Herb 1971, Thompson 1978, Bernasconi et al. 2022). This species has been identified in shallow areas of the inner shelf of Cape Horn, at depths no exceeding 42 m, and near Staten Island in both protected and exposed offshore zones at depths ranging from 75 and 118 m (Herb 1971, Thompson 1978). *Cibicidoides. dispars* has been recorded in the Strait of Magellan and in the Ushuaia Bay sector along the Beagle Channel (Lena 1966, Zapata & Alarcón 1988, Hromic 1996, Hromic et al. 2004, Bernasconi et al. 2022). *Cibicides aknerianus* was recorded only between depths of 37 and 90 m in

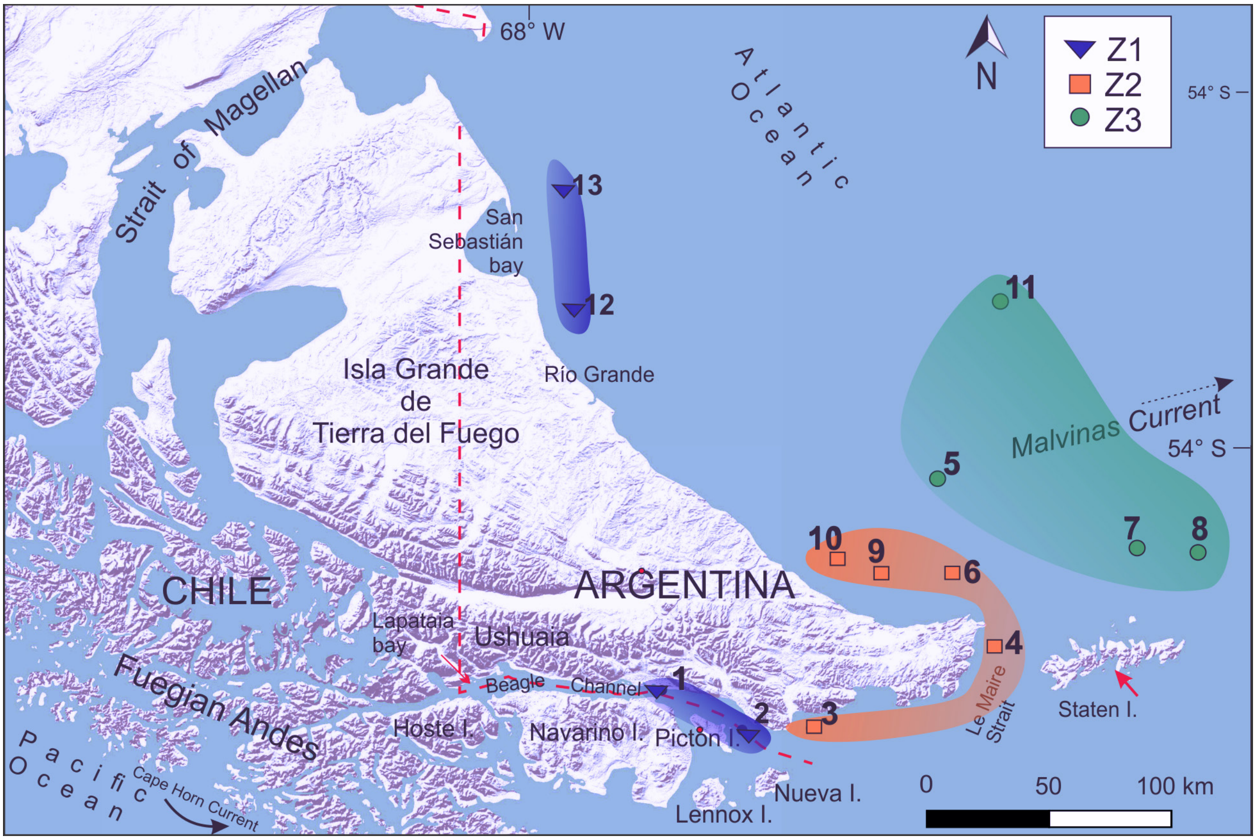

Figure 6. **Map showing the zones Z1 (blue triangle), Z2 (square orange) and Z3 (circle green) recognized in the south of Tierra del Fuego area.**

predominantly sandy sediments with a coarse grain size near San Sebastian Bay. This species has also been identified in southern Chile and south of the Strait of Magellan within a depth range of 50 and 100 m by Zapata et al. (1995) and Hromic (2009), respectively. Meanwhile, *Buccella* was recorded in all samples of this zone, exhibiting the highest abundance values at depths not exceeding 90 m. This species was identified as *Buccella peruviana* in Ushuaia Bay at depths not exceeding 9 m of depth (Lena 1966). Subsequently, its presence was recognized in sediments from the eastern mouth of the Strait of Magellan and south of Lennox Island, near San Sebastian Bay and to the east of the Beagle Channel in this study (Hromic 1996, 2009). More recently, *B. peruviana* was described as part of the recent benthic foraminiferal fauna of the Beagle Channel (Bernasconi et al. 2022). The genera *Cibicides*, *Cibicidoides*, *Globocassidulina*, and *Buccella*, indicate a coastal, cold-water, and high-energy biofacies (Hromic 2009). This assemblage, identified in samples from the Beagle Channel, is suggested to represent a marine environment characterized by coarse sediments and high oxygen levels (Bernasconi et al. 2022). Besides, the genus *Epistominella* is represented by the species *E. exigua*, described by Murray (2006) as ranging from epifaunal to semi-infaunal with a free-living lifestyle. This detritivorous species was found in temperate to cold marine environments, from the inner shelf to the bathyal zone (Murray 2006, Bernasconi et al. 2018) (Table II). *Epistominella exigua* showed a remarkable tolerance to variations in organic flux, and its relative abundance may indicate pulses of organic matter in the environment (Altenbach et al. 1999, Almeida et al. 2015). It was mentioned in high abundance for the Ushuaia sector, in sediments ranging from 1 to 9 m in depth (Lena 1966), it was also identified in South Georgia as the bathyal fauna, at depths between 370 to 1600 m (Echols 1971), and near the San Matías Gulf on both the inner and outer shelf (Alperin et al. 2008). The presence of this species indicated an inner shelf of marine environment with good oxygenation and cold, high-energy waters. These characteristics are typical of marine biofacies with coarse sediments and high oxygen levels. Furthermore, such environments suggest high productivity and organic matter input (Murray 2006, Hromic 2009, Bernasconi et al. 2022).

The Z2 was characterized by the highest abundance and diversity values, indicating a very favorable environment for the distribution and development of foraminifera (Jorissen et al. 1995) (Table I, Fig. 6). The mean values of the H and Fisher's alpha indices are within the values indicated to inner shelf environments (0-100 m), according to Murray (2006). In this zone, species such as *Cibicidoides dispars*, *Cibicidoides variabilis, Globocassidulina rossensis*, *Cibicides aknerianus*, and *Cibicides fletcheri* become more abundant, whereas there is a significant decrease in the abundance of *Buccella peruviana* and *Epistominella exigua*. The species *C. dispars* and *C. variabilis* were prominently present throughout Z2, showing the highest values at depths between 46.5 and 86.5 m in sandy sediments interspersed with mud and gravel, extending to the tip of Tierra del Fuego. *Cibicides aknerianus* and *C. fletcheri* were found across the zone, displaying an increase in abundance compared to Z1, predominantly in muddy-sandy sediments. Other species, including *Discanomalina vermiculata* and *Ehrenbergina pupa*, are also present in this zone. They had been documented down to depths of 641 m and were still found at 878 m in the Drake Passage, as well as on the upper slope between 200 to 2000 m of depth (Herb 1971, Murray 2006). The species *Discanomalina vermiculata* is found in lower proportions within this zone predominantly in coarse sediments down to a depth of 98.4 m. The genus *Ehrenbergina* displays a free-living lifestyle, occupying an epifaunal habitat with a detritivorous feeding strategy, and it is typical of marine environments that extend from the outer shelf to the bathyal zone in cold waters, as noted by Murray (2006) (Table II). *Ehrenbergina pupa* appeared in all samples collected from the zone spanning depths of 46.7 and 98.4 m. This species is identified as part of the Malvinas fauna, according to Heron-Allen & Earland (1932) and Kahn & Watanabe (1980). Notably, this species begins to emerge at a depth of 52 m within the zone, associated with sandy-gravel sediments, specifically in the westernmost sector. The assemblage observed in the Z2 was registered near this zone, especially regarding the presence and abundance of species such as *Globocassidulina rossensis*, *Cibicidoides dispars*, *Cibicides fletcheri*, and *Buccella peruviana* (Hromic 2007, Bernasconi et al. 2022). These species have been identified in the Beagle Channel, suggesting a marine environment with coarse sediments and high oxygen levels, as well as cold and coastal waters due to the presence of *Cibicides*, *Globocassidulina*, and *Buccella* (Lena 1966, Hromic 2009, Bernasconi et al. 2022). Conversely, *D. vermiculata* has been identified in the Cape Horn area, inhabiting depths ranging from 42 to 1000 m, with its greatest abundance at deeper levels (Herb 1971). This assemblage suggests a deeper, well-oxygenated environment with higher energy, likely influenced by tidal movements and predominantly by the Malvinas Current. Moreover, several elements from Cape Horn waters have been recognized, further supporting these environmental characteristics.

The Z3 exhibited intermediate values of abundance and diversity when compared to zones Z1 and Z2 (H between 2 and 2.6; Fisher´s alpha between 4.4 and 5.6). Murray (2006) indicated that, for outer shelf marine environments at depths of 100 to 200 m, typical H values range from 0.6 to 2.75 and alpha values from 5 to 19, with H values above 2 pointing out high diversity (Table I, Fig. 3). This zone showed a marked increase in the presence of *Discanomalina vermiculata*, *Ehrenbergina pupa*, *Globocassidulina crassa,* and *Quinqueloculina seminulum*. Notably, *Discanomalina vermiculata* and *Q. seminulum* are most abundant, reaching their higher concentrations north of Staten Island in sandy-gravel sediments at depths of 115 to 195 m. *Discanomalina vermiculata* was previously founded near the study area, noting its presence in the Strait of Magellan and southern chilean channels. The trochospiral structure of *D. vermiculata* species, suggests an affinity for adhering to substrates, which may indicate adaptation to turbulent environments (Hromic 2011). Moreover, this species has been identified in Staten Island and its surrounding regions, spanning broad bays and the open sea at depths from 10 to 903 m, with a noted higher concentration in deeper waters (Thompson 1978). Similar findings have been reported in Tierra del Fuego and South Georgia Island (Boltovskoy & Watanabe 1980). In addition, the species has been observed in the Strait of Magellan and southern chilean channels in earlier studies (Zapata & Alarcón 1988, Zapata et al. 1995, Hromic 2009, 2011) and more recently, albeit less abundantly, in the western Beagle Channel and adjacent fjords (Korsun et al. 2023). The species *Globocassidulina rossensis* and *G. crassa*, were notably present in this area at depths ranging from 101.5 to 195 m, within sandy sediments. The *G. rossensis* species has been observed in Cape Horn and in the South Shetland Islands, within the inner shelf area at depths of 40 and 73 m, respectively. Meanwhile, *G. crassa* was found at depths ranging from 104 m to 641 m and in the deep-sea basin of the Drake Passage, between depths of 2780 and 2826 m (Herb 1971). *Ehrenbergina pupa* exhibited its highest abundance at depths of 130 m. It has been documented within the bathymetric zone of the outer shelf of Cape Horn, spanning depths of 200 to 300 m, and between 100 and 150 m in the Strait of Magellan and the southern islands of Chile (Herb 1971, Hromic 1996, 2009, 2011). The porcelaneous species, notably represented by *Quinqueloculina seminulum*, were found north of Staten Island at depths ranging from 115 to 195 m. The genus *Quinqueloculina* is characterized by its epifaunal habitats, typically inhabit in the inner shelf and also in lagoons and marshes, with rare occurrence in the bathyal zone (Murray 2006). These microorganisms usually inhabit shallow environments, though certain species are found at greater depths (Loeblich & Tappan 1992). Thus, the assemblage related to Z3 indicated an outer shelf environment, characterized by well-oxygenated, cold waters and high-energy environment, as evidenced by the presence of adhered species and coarse sediments.

From a biogeographical standpoint, the distribution and abundance of species such as *G. crassa* and *E. pupa* suggest the influence of the Malvinas Current (Boltovskoy 1976, Boltovslkoy et al. 1980, Kahn & Watanabe 1980). The littoral foraminiferal fauna in Ushuaia and its vicinity is characteristic of subantarctic waters (Lena 1966). Also, *Discanomalina vermiculata* has been reported in the Malvinas Islands (Falkland Islands) and surrounding regions (Heron-Allen & Earland 1932). A boundary between the Malvinas Current and coastal waters was indicated at north of the parallel 52° S and to the west of the Malvinas Islands, in isobath 82 m of depth, where typical species of the coastal zone predominate, including the most numerous ones such as *Buccella peruviana*, *Globocassidulina crassa* and *Quinqueloculina seminulum* (Kahn & Watanabe 1980). Subsequently, the isobath of 80 m at the western limit of the Malvinas Current, approximately 39° S, was determined based on the presence of latter foraminifera species (Bernasconi & Cusminsky 2020). In this study, *B. peruviana* and *Q. seminulum* could be considered similar to the assemblages mentioned for the coastal zone, especially because the specimens of *B. peruviana* are small and very abundant in the areas closest to the coast.

Differences in the distribution of certain species were observed, which are thought to be related with the Malvinas Current. However, the geographical positioning of the different zones is consistent with the influence of a second current emanating from the southernmost region. Specifically, species identified as typical of the Cape Horn sector, such as *D. vermiculata*, *Discorbis williamsoni,* and albeit in very low abundance, *Mississippina concentrica* and *Pullenia subcarinata,* were discovered in the study area (Herb 1971, Thompson 1978). Consequently, Herb (1971) recognized the existence of two Subprovinces: Cape Horn and Malvinas, although Bolstovskoy et al. (1980) later suggested that the differences between these two areas were insignificant. In the present study, species identified as typical of the Malvinas Current were more prominently represented, indicating a significant influence of waters from Malvinas Current. It is important to highlight that *D. vermiculata* is not typically abundant in the Malvinas Current but rather in the Cape Horn region (Boltovskoy 1959). Therefore, the influence of the waters from the Cape Horn sector is particularly evident in Zone Z3, marked by a significant increase in the abundance of *Discanomalina vermiculata* and the presence of *Mississippina concentrica*, which has been noted as a species restricted to the Cape Horn area (Herb 1971). Furthermore, in the southwest sector of Tierra del Fuego (Chile), associated with glacial meltwater, the presence of this species has been observed, although in low proportions (Korsun et al. 2023). Within this framework, the Cape Horn Current originates from the Drake Passage and is diluted due to excessive rainfall in the southeast of the Pacific Ocean and continental discharge along the west coast of South America (Boltovskoy et al. 1980, Acha et al. 2004). This water mass, known as the Cape Horn Current, enters the continental shelf through the Le Maire Strait, contributing to the low salinity water south of the Strait of Magellan, potentially corresponding with zones Z1 and Z2 (Acha et al. 2004) (Fig. 6). Approximately at the latitude of 54°49’ S and moving eastward, the Argentine shelf-break front sector is identified, where subantarctic waters merge with the cooler and more saline waters of the Malvinas Current, generating a thermohaline front. This is consistent with the location of Z3 (Acha et al. 2004). Although, the positioning of these fronts varies and is subject to multiple influencing factors, the faunal association observed in the study area likely affected by the presence and mixing of elements from Malvinas and Cape Horn water masses.

CONCLUSIONS

The present study provides a detailed record of foraminiferal fauna from surface sediments of east ocean waters of Tierra del Fuego (Argentina) and their ecological implications. From the foraminifera species distribution, three environmental zones (Z1, Z2 and Z3) were identified in the study area. Zone I was characterized by a shallow marine environment close to the Tierra del Fuego coast with cold to temperate water, high energy environment, and an oxic inner shelf environment. Zone 2 was deeper than Z1 representing an inner to outer shelf environment with high oxygen levels. Lastly, Zone 3 represented the deepest area and is located farthest from the Tierra del Fuego coast, depicting the outer shelf characterized by well-oxygenated and cold waters influenced by the Malvinas Current. In Z3, the influence of waters from the Cape Horn was recognized through the presence of *Discanomalina vermiculata*.

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SUPPLEMENTARY MATERIAL

Data SI.

How to cite

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EMILIANA BERNASCONI: collected samples from the sea surface, carried out systematic, ecological and statistical analysis, interpreted the results, wrote drafts, and figures, changes, and gave final approval for publication. SILVINA R. PÉREZ: processed the samples and collected the foraminifera fauna, carried out systematic, ecological and statistical analysis, interpreted the results, wrote drafts, and figures, changes, and gave final approval for publication. MARÍA S. CANDEL: interpreted the results, wrote drafts, and figures; changes, and gave final approval for publication.