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Changes in water masses in the Late Quaternary recorded at Uruguayan Continental Slope (South Atlantic Ocean)

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Abstract

Planktonic foraminifera inhabit in the ocean waters and their spatial distribution is driven mainly by surface temperature. Thus, the tests remain deposited in the ocean sediment show different assemblages according to global climate zones. The main goal of this study was to assess the planktonic foraminifera found in the lowest continental slope of Uruguayan Continental Margin (UCM), and to identify the best criteria for future Late Quaternary biostratigraphic and paleoceanographic models and based on carbonate preservation to identify water masses changes. For this purpose, this work examines foraminifera within a sediment core (T-90, 372 cm recovery, 3273 m water depth) collected in the lowest slope of UCM using a gravity corer. Forty height samples were selected along the core for foraminifera presence/absence analysis, and 13 samples, in the core section between 20 and 100 cm for foraminiferal faunal census. The age model was based on three AMS ^{14}C dating. Foraminifera were absent in the core bottom, but were very abundant in its upper part. This variation of foraminifera was associated with fluctuations of lysocline in the glacial/interglacial transition, related to changes in geometry of bottom water masses. The most abundant species were *Globorotalia inflata*, *Neogloboquadrina incompta*, *Globigerina bulloides*, *Globorotalia crassaformis*, *Globigerinoides ruber* (white, *sensu stricto*) and *Neogloboquadrina pachyderma*. Principal component analysis (PCA) allowed to distinguished 3 groups of species in terms of climate zones: *G. inflata* (transicional), *N. incompta* (subpolar) and *N. pachyderma* (polar). Cluster analysis also identified three patterns of relative abundance among these three species, which can be related to oscillations in the latitude of Brazil-Malvinas Confluence zone during the last 15 ka. For future studies, it will be possible to check the relationship between these species as indicators of others paleoceanographic events in the study area.

Keywords: Foraminiferal faunal census counts. Planktonic foraminifera assemblages. Carbonate preservation. Pelotas Basin.

1. Introduction

The spatial distribution of planktonic foraminiferal is essentially regulated by temperature, following a latitudinal gradient, and secondarily by the salinity and the sea surface productivity. Thus, the global climate zones (i.e. tropical, subtropical, transitional, subpolar and polar) may be mapped by planktonic foraminifera assemblages (Bé, 1977; Vincent and Berger, 1981; Schiebel and Hemleben, 2017). Also, chemical composition of their tests (i.e. crystallinity of the wall, stable isotopes and element ratios) is used to reconstruct seawater changes. The greatest diversity values and larger tests size in planktonic foraminifera are found in the oligotrophic subtropical gyre, while the polar zones of both hemispheres are dominated by a single species of small size, *Neogloboquadrina pachyderma* (Kucera, 2007). Among the first studies of planktonic foraminifera distribution in the South Atlantic Ocean it can be highlighted Bé and

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Tolderlund (1971), Bé (1977), Boltovskoy (1981), Boltovskoy (1994), Vincent and Berger (1981), Boltovskoy et al. (1996, 2000) and Kemle-von Mücke and Hemleben (1999).

The use of planktonic foraminifera for Late Quaternary studies in the western South Atlantic has increased noticeably in the last two decades. These studies are mainly focused on biostratigraphy, paleoceanography and paleobiogeography aspects. Among them, can be cited studies in the Brazilian Continental Margin (e.g. Pivel et al., 2010, 2011, 2013; Portilho-Ramos et al., 2014; Petró et al., 2016; Gonzales et al., 2017; Santos et al., 2017) and in the Argentinian Continental Margin (e.g. Chapori et al., 2015; Voigt et al., 2015). Despite the importance of these organisms, there are still few studies registered in the Pelotas Basin (Uruguayan Continental Margin).

Planktonic foraminifera studies in Late Quaternary of Pelotas Basin are still scarce. Except the works of Boltovskoy (1994) and Boltovskoy et al. (1996, 2000) which identified planktonic foraminifera distribution in the sediment and water column, respectively, the other studies were mainly focused on geochemical approaches and paleoceanographic bias (e.g. Chiessi et al., 2007; Razik et al., 2013; Voigt et al., 2015; Campos et al., 2017) and not on the recognition of these organism assemblages.

The main goals of this study are to identify the planktonic foraminifera assemblages in the last 15 ka in the continental slope of the Uruguayan Continental Margin (UCM; Pelotas Basin), as well as identifying water masses changes based on carbonate preservation. This survey will support the next steps for broad research, improving the data interpretation and correlation with other paleoceanographic proxies.

1.2. Study Area

1.2.1 Oceanographic framework

The UCM is dominated by the confluence of currents with contrasting thermohaline properties, namely, the southward-flowing Brazil Current (BC), the northward-flowing Malvinas Current (MC), and the outflow of the Río de la Plata (RdlP), which discharges freshwater from the second largest hydrographic basin in South America (average value of 22,000 m^3/s; Framiñan and Brown, 1996). This confluence occurs in the Brazil–Malvinas Confluence zone (BMC) in the open ocean (Olson et al., 1988) and extends towards the Subtropical Shelf Front (STSF) on the continental shelf (Piola et al., 2008).

The Southwestern Atlantic Margin is characterized by its complex hydrography. It encompasses the BMC (the southward-flowing BC separates from the continental margin and collides with the northward-flowing MC), as well as the interaction of Antarctic water masses (Antarctic Intermediate Water, AAIW; Upper Circumpolar Deep Water, UCDW; Lower Circumpolar Deep Water, LCDW; Antarctic Bottom Water, AABW), with the Brazil Current, recirculated AAIW, and North Atlantic Deep Water (NADW) (Piola and Matano, 2001) at different depths. In addition, the BMC underwent latitudinal oscillations over time during the Quaternary (e.g. Laprida et al., 2011). The interface between AABW and NADW defines the lysocline, the depth where occurs an abrupt increase in the dissolution of $CaCO_3$ (Berger, 1968), still above the Carbonate Compensation Depth (CCD), where the dissolution is complete. According to Frenz et al. (2003), the lysocline is currently below 4000 m water depth in the Argentine Basin and below 4200 m water depth in the southern Brazil Basin. On the other hand, according to Stramma and England (1999), the present lysocline is at 3900 m deep in the tropics and at 3500 m deep in the subtropics.

1.2.2 Morphosedimentary context

The UCM comprises three physiographic domains: an extensive continental shelf that widens towards the Argentinian margin (c.a. 200 km; Urien and Ewing, 1974), a steep slope and an extensive continental rise (Ewing et al., 1963; Urien and Ewing, 1974; Violante et al., 2010). The continental shelf is dominated by a relict sand coverture which has been deposited in littoral, barrier and estuary environments and reworked during several Cenozoic transgressive-regressive events (Urien et al., 1980a, b).

On the continental slope, a well-developed Contourite Depositional System (CDS) exhibits both erosive (terrace and Channels) and depositional (drifts) feature associated with the action of different Antarctic water masses and their interfaces (Preu et al., 2013; Franco-Fraguas et al., 2014; Hernández-Molina et al., 2016). A Submarine Canyon Systems (SCSs) composed by seven canyons is incised on contourite deposits (Ewing et al., 1963; Lonardi and Ewing, 1971; Hernández-Molina et al., 2016). Hemipelagic sediments, mainly mixing pelagic carbonate with terrigenous sediments, coming from the Río de la Plata are dominant in the slope (Frenz et al., 2003).

2. Materials and Methods

The T-90 core was recovered from the slope of UCM (51°52'02.533"W, 36°18'43.599"S), at 3273 meters of water column depth (Fig. 1) during studies carried out by the oil and gas company Total S.A. A gravity corer was used and a sedimentary column of 372 cm was recovered. Following opening, the core was subsampled in the laboratory at 2 cm intervals, for sedimentological and geochemical analyses (not included in this paper). Subsamples were immediately frozen and subsequently freeze-dried, and for microfaunal analyses subsamples were oven dried (T <60°C).

Organic matter was used for radiocarbon dating owing to the lack of suitable carbonate material such as mono-specific foraminifera or well-preserved mollusks. Approximately 7 g of bulk sediment were sampled at 2.5, 82.0 and 101.0 cm

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down cores, and subsequently separated for AMS radiocarbon dating at Beta Analytics Inc. (Miami/USA). Calibration of radiocarbon ages was performed using BetaCal3.21, method SHCal13 (Hogg et al., 2013).

A total of 48 sub-samples were selected, with an average sampling resolution of 10 cm intervals. The samples were prepared according to the standard procedure for the recovery of calcareous microfossils, and the planktonic foraminifera was picked from the >125 µm grain size fraction. Firstly, the occurrence of planktonic foraminifera was checked in all 48 samples. In a second stage, 13 samples with more than 300 specimens were selected (between 20 and 100 cm) for planktonic foraminiferal census counts.

Foraminifera species were classified according to Bé (1967, 1977), Bolli and Saunders (1989), Hemleben et al. (1989) and Schiebel and Hemleben (2017). A Principal Components Analysis (PCA) was performed with the matrix samples units versus foraminifera assemblages. Then, a cluster analysis was performed with PCA axes versus samples units, with Euclidean similarity index, to identify similar samples. Both statistical analyses were carried out with the Past 3 program (Hammer et al., 2001).

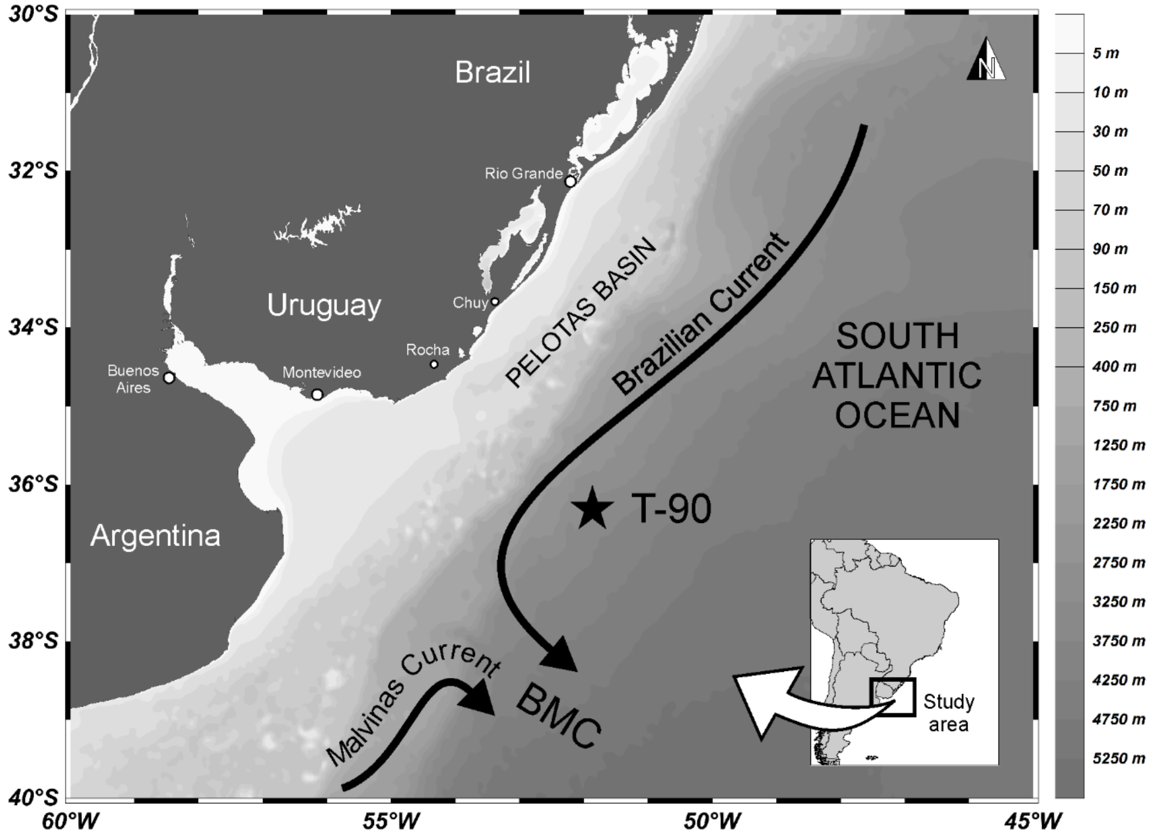

Fig. 1. Map of the location of the studied core T-90. Scheme of the regional circulation, BMC: Brazil-Malvinas confluence.

3. Results and Discussion

The three AMS ^{14}C dating showed ages of 2.69 (±0.3) ka in 2.5 cm, 7.64 (±0.4) ka in 82.0 cm and 14.24 (±0.4) ka in 101.0 cm (Fig. 2A). This data indicates an increase of the sedimentation rate between 101 cm and the core top. The base of the core cannot have an estimated age due to the lack of dating and to the absence of foraminifera that would allow to identify a biostratigraphic datum of known age.

3.1. Preservation of planktonic foraminifera

The core base (372 to 180 cm) is marked by the absence of planktonic foraminifera (Interval I). Between 180 and 100 cm (Interval II), low density foraminifera tests occur, less than 300 tests per sample, which is the minimum amount for a reliable analysis (Dennison and Hay, 1967). Between 100 and 15 cm (Interval III), planktonic foraminifera tests show higher densities, always with more than 300 specimens per sample. Between 15 cm and the core top (Interval IV), the occurrence of planktonic foraminifera shows low density again (values lower than 300) (Fig. 2A). In this sense, the absence of foraminifera was associated with $CaCO_3$ dissolution, a common process at this depth (3273 m). The balance between dissolution and non-dissolution of $CaCO_3$ is related to several factors, mainly the presence of CO_2 in ocean water. Also, it may be identified by the carbonate ion concentration ($\Delta[CO_3^{2-}]$), where in sub-saturated environments, a dissolution of the carbonate tends to occur (Broecker and Takahashi, 1978).

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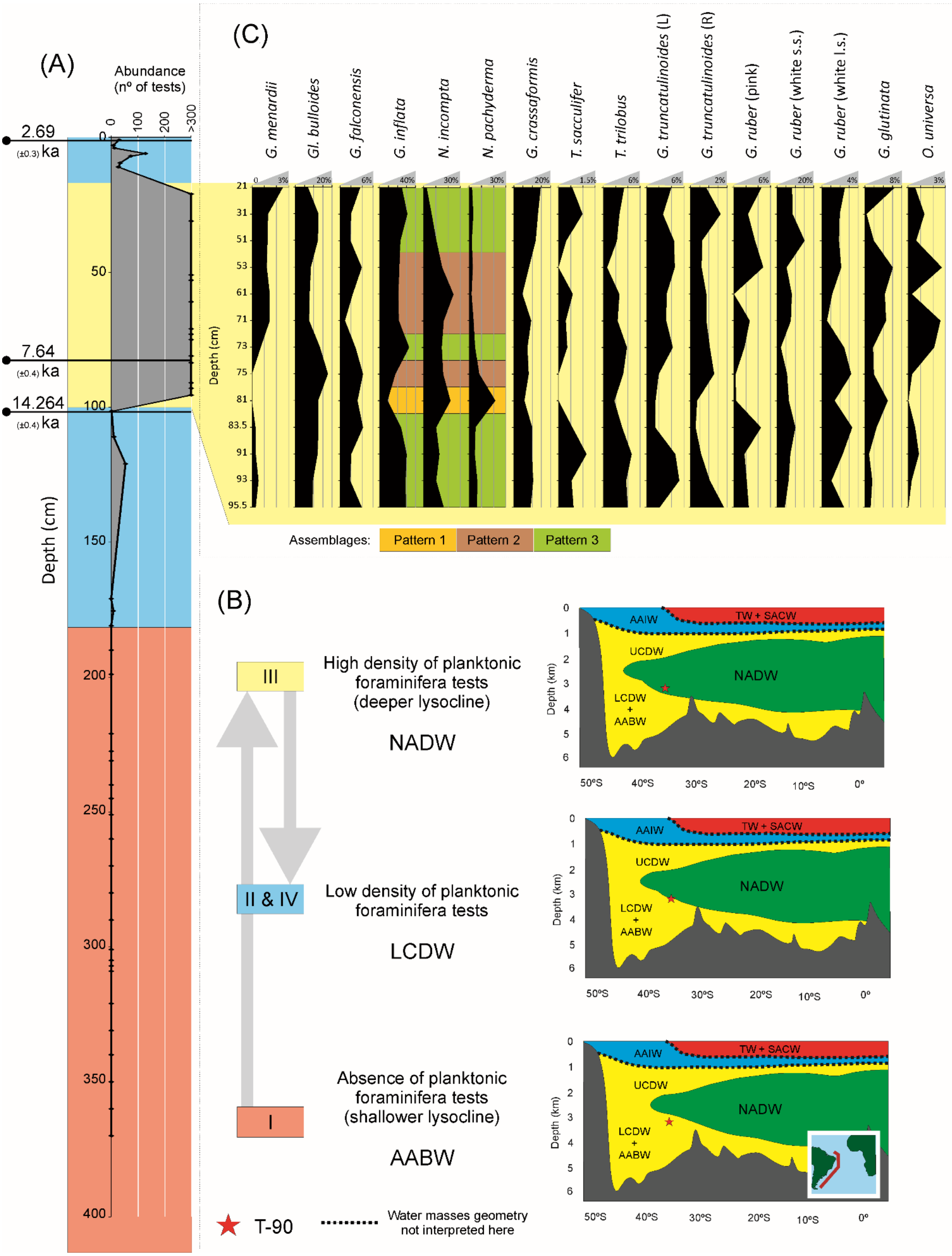

Fig. 2. Schematic diagram of core T-90 and data correlation: (A) Profile with the density of planktonic foraminifera along the core and the AMS 14C dating. (B) Changes in water masses geometry as a function of carbonate presence/absence. (C) Relative abundances of planktonic foraminifera between 100 and 20 cm.

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This difference of concentration ($\Delta[CO_3^{2-}]$) is observed between the water masses from the south (AABW and CDW) and from the north (NADW), being NADW more saturated that AABW and CDW. The interface between these water masses generates an abrupt increase in dissolution rates (lysocline; Berger, 1968). In this sense, the base of the corer (between 372 and 100 cm) may be attributed to a more superficial position of the lysocline than in the Holocene. Thus, it can be concluded that the lysocline position was shallower than 3273 m in this portion of the UCM slope during an earlier period to at least 15 ka, due to the influence of Antarctic Bottom Water (AABW), related to a glacial period context. On the other hand, where the carbonate begins to have a good preservation, it could be related to an interglacial period, where AABW retreats as the NADW advances, with the lysocline position deeper than 3273 m (Fig. 2B). The carbonate preservation in the core top agree with the lysocline depth at present time, which can vary from 3900 m deep in the tropics and 3500 m deep in the subtropics (Stramma and England, 1999) or below 4000 m water depth in the Argentinian Basin and below 4200 m water depth in the southern Brazilian Basin (Frenz et al., 2003).

According to Hernández-Molina et al. (2016), in the area where T-90 is located, occurs a contourite terrace feature (T4). The T4 terrace is presently under the influence of the LCDW, but coincides with the proposed depth range of the LCDW–AABW interface during past glacial eras (Preu et al., 2013; Hernández-Molina et al., 2016). However, this terrace is at present under the influence of LCDW. This can explain the low density of foraminifera tests on the core top. Thus, both the low density of foraminifera tests in the intervals II (180 to 100 cm) and IV (15 cm to the top) can be related to LCDW, relatively more corrosive waters than NADW. The results related to presence/absence agree with Petró et al. (2018a), who finds the lysocline position and (calcite compensation depth (CCD) fluctuations in the Pelotas Basin slope (Brazilian margin), as a function of climate and water masses geometry changes. Nevertheless, in the study region it is not possible to identify the CCD fluctuations due to the absence of analysis of presence of coccolith (carbonatic nannofossils), more resistant to dissolution than foraminifera (Hay, 1970; Hsü and Andrews, 1970; Stoll et al., 2001). Also, the calcium carbonate dissolution process may be related to marine gas hydrates (Dickens and Forswall, 2009), whose occurrence in the Pelotas Basin is reported by Tomasini et al. (2011). The bottom of core T-90 was described by the second author and Michel Mahiques (personal communication), who identified sedimentary features associated with gas hydrates. Future multiproxy analyses should prove or discard this hypothesis.

3.2. Faunal census counts

The base of the interval III, where planktonic foraminifera are present, was dated in 14.240 (±0.4) ka, so the samples studied for foraminifera classification comprise approximately the last 15 ka of the Late Quaternary. A total of 31 taxa, represented by 28 species and its phenotypic variations were identified (Fig. 3). The most abundant species were *Globorotalia inflata*, which showed the highest average abundance (24.1%), and *Neogloboquadrina incompta*, ranked in second with an average abundance of 13.7%. In the third place, *Globigerina bulloides* presented an average abundance of 10.9%, which is the dominant species in one sample. Among all the taxa identified, 14 of these occur in all samples (Fig. 3). The predominant species characterized the transitional zone, mainly by the presence of *G. inflata* and *G. bulloides*. The species *N. incompta*, subpolar zone indicator, determines cold waters influence in the studied area.

Among the species from the menardiiform group, which includes *Globorotalia menardii*, *Globorotalia fimbriata*, *Globorotalia tumida* and *Globorotalia flexuosa*, basically occurs *G. menardii* (0.9% of average abundance, present in 11 samples), with rare *G. tumida* (one sample) and *G. fimbriata* (two samples). These species (the menardiiform group) are considered very important indicators; the classical biostratigraphic models used for the basins of the Brazilian east margin are based on the presence and absence of species from this group (Ericson and Wollin, 1968; Vicalvi, 1997, 1999; Sanjinés, 2006; Sanjinés et al., 2007). This zonation is applicable in much of the Atlantic Ocean due to an increase in the occurrence of these species in interglacial periods and a drastic reduction in glacial periods (Ericson and Wollin, 1968), since these species reseeding from the Indian Ocean through the Agulhas leakage, which is enhanced during interglacial periods (Berger and Vincent, 1986; Peeters et al., 2004). However, models based on menardiiform species there is not yet been satisfactory applied in Pelotas Basin slope, and our data also did not demonstrate a good applicability.

Among the rare species, it is possible to highlight the presence of *Turborotalita quinqueloba*, species corresponding to the subpolar zone, generally with low abundance in warmer regions (Schiebel and Hemleben, 2017). It is also highlighted the occurrence of *Orbulina universa*, presented in 11 of the total samples. These species may have relation with the good preservation of the carbonate, related to the dissolution processes (Petró et al., 2018b).

3.3. Foraminiferal assemblages changes

The analyses in foraminiferal assemblages were applied only in the interval III of the analyzed core. The PCA created 12 axes. The two axes with the greater eigenvalues were used to generate the scatter plot, crossing axes 1 (53.1% of variance) and 2 (18.0% of variance) (Fig. 4). The distribution of the species in the diagram shows the different behavior of the three main climate zones indicator species (*G. inflata*, *N. incompta* and *N. pachyderma*). However, the transitional species *G. bulloides* did not demonstrate a recognizable pattern, being limited to the origin of the graph. *G. bulloides* has a strong

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relationship with paleoproductivity (Conan et al., 2002), and may be influenced by local factors, which may explain the low correlation with regional distribution patterns. Although the PCA does not emphasize *G. bulloides*, this species is always abundant, with a minimum of 6.8% (Fig. 3). Its great occurrence may be a result of the high productivity in the UCM due to the nutrient input from Patos lagoon and Río de la Plata plume (Gonzalez-Silveira et al., 2006).

The cluster analysis identified the most similar samples, where three sample patterns were recognized (Fig. 4). These patterns basically reflected three parameters: the abundance of *G. inflata* and *N. pachyderma* and the proportion between *G. inflata* and *N. incompta* (Gi/Ni= [% *G. inflata*]/ [% *N. incompta*]).

The first pattern, formed by a single sample (81 cm), showed the highest abundance of *N. pachyderma* (21.2%) and the lowest abundance of *G. inflata* (8.8%) among the entire range studied, being dominated by *N. incompta* (21.9%) and the Gi/Ni ratio = 0.4. The second pattern (samples 53, 61, 71 and 75 cm) presented *G. inflata* abundances between 17.4 and 21.9%, generally more abundant than *N. incompta*, always similar proportions between these species (Gi/Ni ratio between 0.8 and 1.4), and low abundance of *N. pachyderma*. Finally, the third pattern (samples 21, 31, 51, 73, 83.5, 91, 93 and 95.5 cm) was defined by the *G. inflata* abundances always greater than 21.9%, with a high Gi/Ni ratio (2.2 to 9.8), and low abundance of *N. pachyderma*.

The three patterns showed a predominance of transitional planktonic foraminifera assemblages at the beginning and the end of the interval, highlighted by an influence of subpolar to polar species in the intermediate portion (Fig. 2C). This record can be related to minor oscillations in the BMC, due to seasonal alternations or due to changes over time (Hernández-Molina et al., 2016)

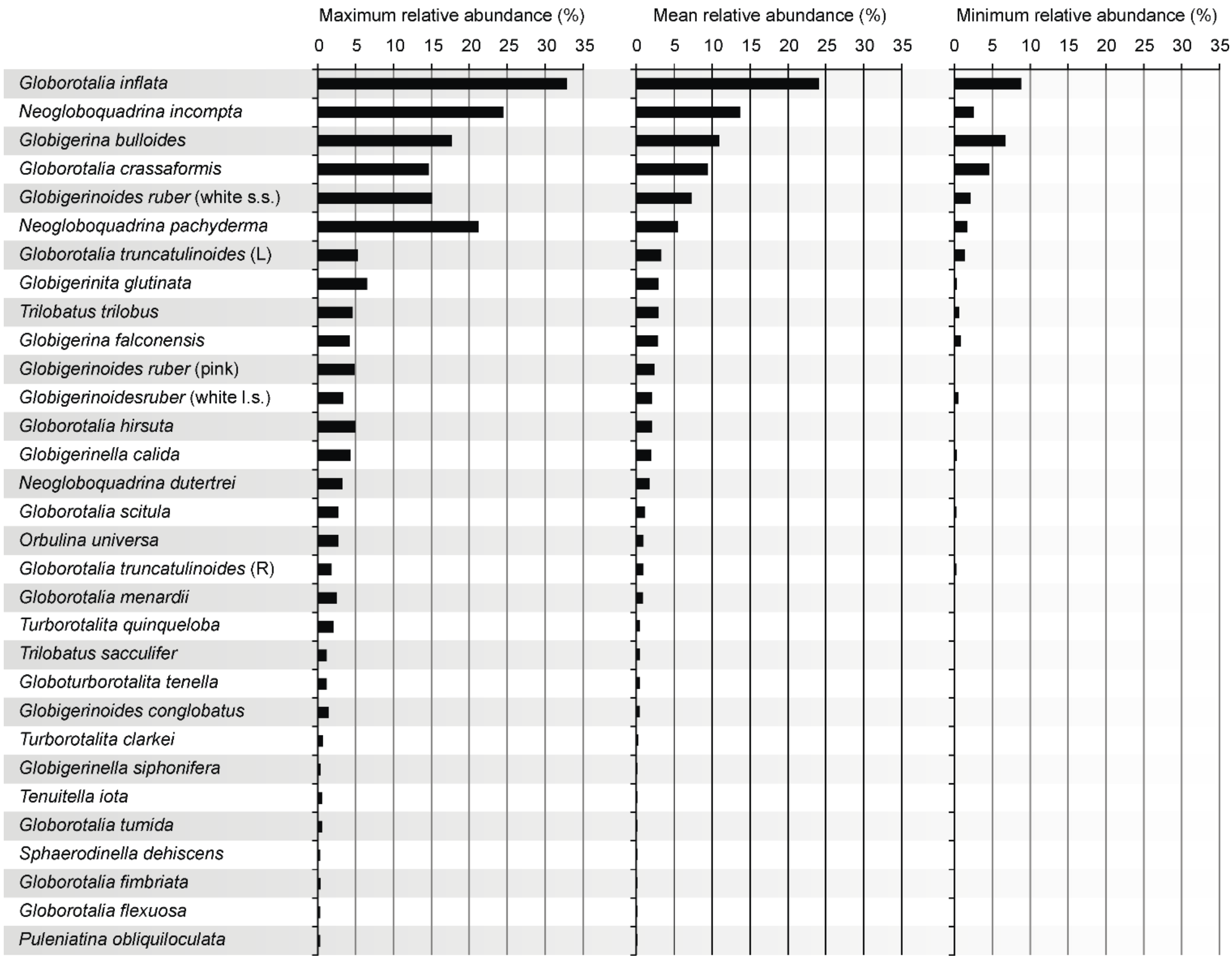

Fig. 3. Maximum, average, and minimum abundances of identified species.

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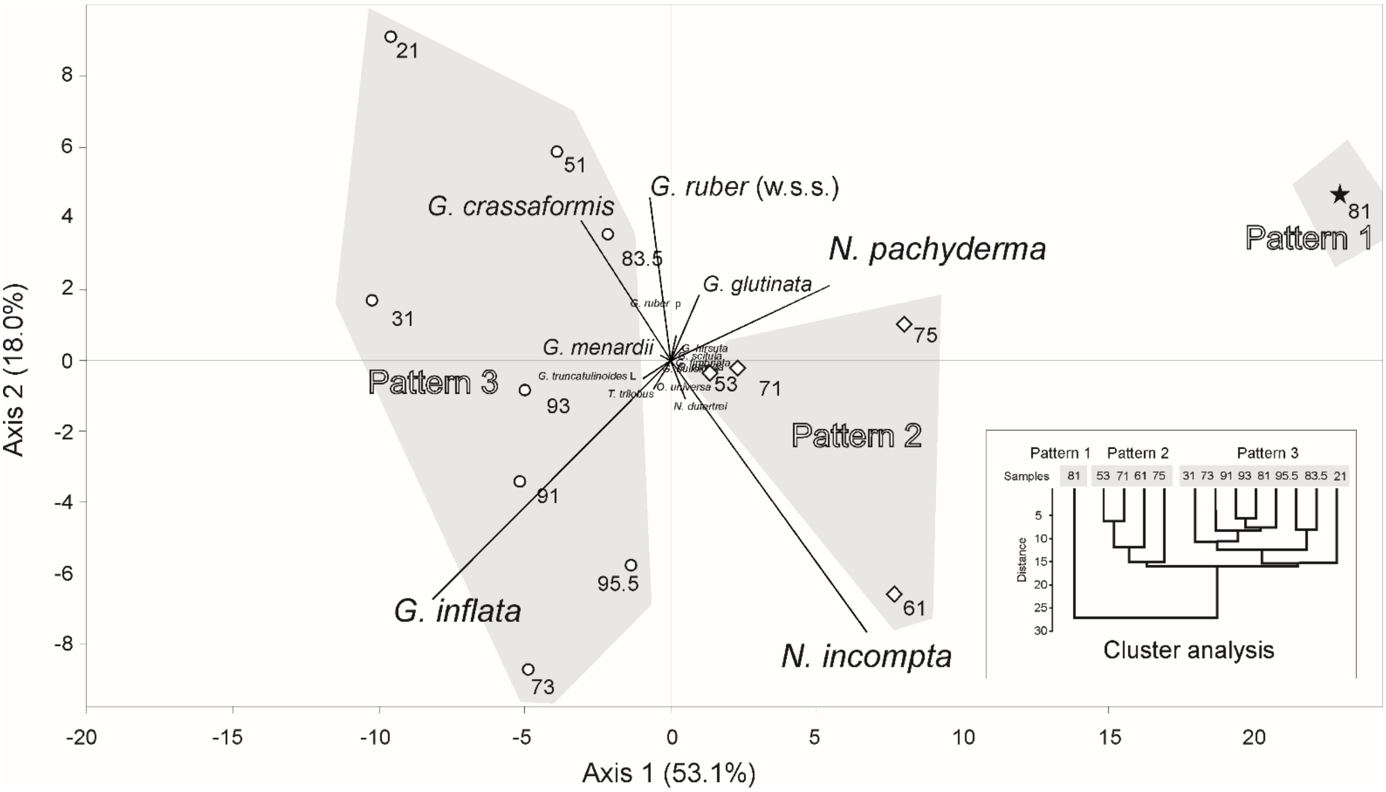

Fig. 4. Diagram of Principal Component Analysis (PCA) performed with the relative abundances of the species. The most notable species are *Globorotalia inflata* (transitional), *Neogloboquadrina incompta* (subpolar) and *Neogloboquadrina pachyderma* (polar). In detail, the cluster analysis performed with the values of the PCA axes, which defined the three patterns of samples.

Tropical and subtropical species such as *Globigerinoides ruber* (white and pink), *Trilobatus sacculifer* and *Trilobatus trilobus* did not show much influence on the pattern of samples distribution. The observed three sample patterns may show three distinct oceanographic moments, determined by the species ratio of the transitional, subpolar and polar zones. Therefore, the difference of the planktonic foraminifera distribution in this region is more associated to the surface waters of the transitional zone influenced by periods of cold-water incursion. The absence of influence of tropical and subtropical species agrees with the interpretation of Preu et al. (2013), that BMC in modern times is located close to its southernmost position in the Quaternary. Likewise, the layers where occur the presence of subpolar and polar species (*N. incompta* and *N. pachyderma*, respectively) may register the influence of BMC northward. Thus, the change of planktonic foraminifera assemblages is related to surface configuration of ocean currents in an interglacial period.

4. Conclusion

In transitional waters a mixture of cold and warm planktonic foraminifera species occurred over time due to millennial climate variations. On the other hand, bottom conditions may be related to deep water masses changes, which may be linked to planktonic foraminifera tests preservation or dissolution. The oscillations in the geometry of the water masses modified the lysocline depth position during the Late Quaternary, modifying the degree of carbonatic preservation of the pelagic material. The absence of foraminifera at the base of the core was associated with high carbonate dissolution, when the lysocline position was shallower than at the present, while the carbonatic preservation is associated with a deeper lysocline position, in the last 15 ka. At present, the study area is under influence of LCDW, which agree with low foraminifera density in the interval IV (between 15 cm and the core top). Changes of the relative abundance of *G. inflata* (transicional), *N. incompta* (subpolar) and *N. pachyderma* (polar) suggest oscillations in the latitude of Brazil-Malvinas Confluence zone during the last 15 ka.

The characterization of the principal planktonic foraminiferal species will be useful to define strategies of new studies on paleoceanography and biostratigraphy in the Late Quaternary from the UCM. In this sense, it is important to identify differences and similarities with the adjacent basins and to determine some datum, as levels of change of the dominant planktonic foraminifera species. Therefore, the oscillations between transitional, subpolar, and polar planktonic foraminifera assemblages, especially between the species *G. inflata* and *N. incompta*, may be tested in future studies in the continental slope of Pelotas Basin, and correlated with oceanographic changes on a regional scale

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(South Atlantic margin). For future studies, multiproxy approaches are needed in order to improve the understanding paleoceanographic changes.

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