

**UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL  
INSTITUTO DE GEOCIÊNCIAS  
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS**

**ANÁLISE BIOESTRATIGRÁFICA E PALEOCEANOGRÁFICA  
COM FORAMINÍFEROS PLANCTÔNICOS DO  
QUATERNÁRIO TARDIO NO ATLÂNTICO SUL OCIDENTAL**

**JAIME YESID SUÁREZ IBARRA**

**ORIENTADORA – Profa. Dra. María Alejandra Gómez Pivel**

**Porto Alegre – 2020**

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## RESUMO

Os foraminíferos planctônicos são excelentes ferramentas utilizadas em estudos bioestratigráficos e paleoceanográficos do Cenozoico devido à sua abundância, altas taxas de evolução, distribuição ampla e boa preservação. Além disso, suas carapaças carbonáticas se precipitam em equilíbrio isotópico com a água do mar, registrando as condições paleoceanográficas dos ambientes onde habitaram. Por tais razões, utilizaram-se as associações de foraminíferos planctônicos do testemunho SAT-048A, recuperado do talude médio da porção norte da Bacia de Pelotas para: i) avaliar o potencial de aplicação dos bioecozoneamentos desenvolvidos para as bacias de Santos e Campos, ii) reconstruir as condições oceanográficas de superfície e fundo e, iii) propor um modelo teórico para melhor avaliar os efeitos da dissolução na fragmentação dos foraminíferos planctônicos. Para isto, esta dissertação se baseia em dados inéditos de cunho paleomicrontológico, geoquímico e sedimentológico do testemunho SAT-048A, e dados não publicados do testemunho SIS-188. O artigo i) demonstra a aplicabilidade das bioecozonas da parte mais tardia do Quaternário, porém, se reconhece que antigos limites considerados síncronos, responderam realmente de forma “temporal-progressiva” devido às mudanças no contexto do Oceano Atlântico. O artigo ii) reconstrói as variações na paleoprodutividade e paleotemperaturas da superfície, assim como os fluxos de matéria orgânica ao fundo e seus possíveis efeitos na dissolução das testas dos foraminíferos planctônicos. Além de variações de cunho glacial-interglacial, a influência da insolação foi reconhecida nas bacias de Pelotas e Santos. O artigo iii), baseado na subjetividade que existe em relação à avaliação da fragmentação das testas, explora um novo método que relaciona a área e o perímetro dos restos de testas não completas. É proposta a medida “Intensidade da Fragmentação” e a mesma é avaliada com respeito aos outros indicadores de dissolução. Estudos futuros deverão i) estudar a aplicabilidade e, eventualmente, calibrar os bioecozoneamentos mais profundos no tempo, ii) avaliar a influência das massas d’água do fundo na dissolução das testas dos foraminíferos planctônicos e, iii) testar a efetividade da “Intensidade da Fragmentação” com amostras recentes e fósseis em diversas áreas e contextos sedimentológicos.

**Palavras-chave:** Bioecozoneamento, Paleoprodutividade, Paleotemperatura, Dissolução, Fragmentação.

## ABSTRACT

Planktonic Foraminifera are excellent tools used in Cenozoic biostratigraphic and paleoceanographic studies due to their abundance, high rates of evolution, wide distribution, and good preservation. In addition, their carbonate shells are precipitated in isotopic equilibrium with the sea water, registering the paleoceanographic conditions of the environments where they lived. For these reasons, the planktonic Foraminifera associations of the SAT-048A core were used, recovered from the continental slope of the northern portion of the Pelotas Basin, to: i) evaluate the application potential of the bioecozonations developed for the Santos and Campos basins, ii) reconstruct the oceanographic surface and bottom conditions and, iii) propose a theoretical model to better evaluate the effects of dissolution on the planktonic Foraminifera fragmentation. To accomplish these objectives, this dissertation is based on unpublished paleomicrotological, geochemical and sedimentological data from the core SAT-048A, and unpublished data from the core SIS-188. Article i) demonstrates the applicability of the bioecozones of the latest Quaternary, however, it is recognized that old limits considered synchronous, really responded in a “temporal-progressive” way due to changes in the context of the Atlantic Ocean. Article ii) reconstructs the variations in surface paleoproductivity and paleo-temperatures, as well as the sea floor organic matter fluxes and their possible effects on the dissolution of planktonic Foraminifera tests. In addition to glacial-interglacial variations, the insolation influence was recognized in the Pelotas and Santos basins. Article iii), based on the subjectivity that exists in relation to the tests fragmentation assessment, explores a new method that relates the area and perimeter of the planktonic Foraminifera fragmentation remains. The “Fragmentation Intensity” index is proposed and it is evaluated with respect to the other dissolution indicators. Future studies should i) study the applicability and, eventually, calibrate the bioecozonations deeper in time, ii) evaluate the influence of the bottom water masses in the planktonic Foraminifera tests dissolution, and iii) test the effectiveness of the “Fragmentation Intensity” with recent and fossil samples in different areas and sedimentological contexts.

**Keywords:** Bioecozonation, Paleoproductivity, Paleotemperature, Dissolution, Fragmentation.

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## Capítulo 1.

### Introdução

Os foraminíferos planctônicos são um grupo de protistas unicelulares que teve uma rápida taxa de eventos evolutivos durante o Cenozoico (Thunell, 1984), o que os tornou um dos melhores fósseis-guia. No entanto, essa taxa é relativamente lenta quanto utilizada no Quaternário Tardio, e apenas alguns desses eventos podem ser observados. Apesar disso, eles representam uma ferramenta muito importante para estudos paleontológicos de sedimentos de poucos milhares de anos devido à sua distribuição espacial ser altamente dependente da temperatura da superfície do mar (Arnold & Parker, 2003). Assim, mudanças paleoclimáticas deixam assinaturas nas associações desses microfósseis (Portilho-Ramos et al., 2014). Nesse sentido, estudos bioestratigráficos no Quaternário Tardio baseiam-se em variações reversíveis das abundâncias relativas de espécies de foraminíferos planctônicos, em função das flutuações ambientais (Vicalvi, 1999).

Variações nas abundâncias do plexo *Globorotalia menardii* e *Pulleniatina obliquiloculata* mostraram ser bons marcadores de condições ambientais passadas além de servirem para estudos bioestratigráficos (Ericson & Wollin, 1968; Kennett & Huddleston, 1972; Bé et al., 1976; Prell & Damuth, 1978; Vicalvi, 1999; Sanjinés, 2006; Ferreira et al., 2012). Contudo, devido à extensão diferente das mudanças paleoclimáticas, esses eventos devem ser calibrados com precisão para as diferentes regiões onde se estendem, a fim de evitar erros em falsas correlações de tempo/bioeventos (Costa et al., 2018).

Vários bioecozoneamentos foram desenvolvidos para as bacias de Santos (e.g., Portilho-Ramos et al., 2006; Ferreira et al., 2012) e Campos (e.g. Vicalvi, 1999; Sanjinés, 2006; Vicalvi, 2013; Portilho-Ramos et al., 2014; Duarte et al., 2017), para sedimentos do Quaternário tardio, mas nenhum específico para a Bacia de Pelotas. As primeiras abordagens bioestratigráficas no Quaternário tardio da Bacia de Pelotas estão restritas à plataforma e ao talude continental superior (Vicalvi, 1977; Carvalho, 1980). Como esses estudos foram realizados em águas rasas, apenas uma variação no nível do mar foi identificada pela ausência (na base) e presença (no topo) de foraminíferos planctônicos (Carvalho, 1980), sem um modelo de idade robusto. Vicalvi (1977) e Rodrigues & Carvalho (1980) determinaram o limite Pleistoceno/Holoceno pela simples relação de espécies de água quente e fria. Estudos mais recentes em bacias próximas, ao norte, mostram que o limite Pleistoceno/Holoceno é



mais complexo e que existe um diacronismo temporal entre os bioeventos registrados nestas bacias (Costa et al., 2018). Além disso, este limite cronoestratigráfico não é necessariamente correlacionado com o limite das bioecozonas estabelecidas por Ericson & Wollin (1968), como evidenciado por Pivel et al. (2013), Broecker & Pena (2014) e Petró et al. (2016).

### **1.1. Problema**

Como observado no parágrafo anterior, a Bacia de Pelotas carece de um esquema bioestratigráfico para o Quaternário tardio, possivelmente por haver um menor interesse econômico. Além disso, o desenvolvimento de um esquema bioestratigráfico robusto pode ser mais complicado devido a: i) sua localização mais ao sul, onde a diferença latitudinal com as bacias de Campos e Santos resulta em temperaturas médias anuais mais baixas; ii) a alternância sazonal (capítulo 2, seção 2, Fig. 2); e iii) a possível influência de um complexo sistema de sedimentação envolvendo correntes de contorno e o Cone do Rio Grande.

Dado que o principal fator ambiental (a temperatura) que controla a distribuição espacial dos foraminíferos planctônicos varia na Bacia de Pelotas, os bioecozoneamentos das bacias de Campos e Santos podem não ser aplicados nesta bacia. Para testar esta hipótese, este estudo avalia o potencial de aplicabilidade dos bioecozoneamentos desenvolvidos para as bacias imediatamente a norte (Vicalvi, 2013) no testemunho SAT-048A coletado do talude continental no norte da Bacia de Pelotas.

### **1.2. Objetivo do estudo**

Avaliar, na Bacia de Pelotas, a aplicabilidade dos bioecozoneamentos estabelecidos para as bacias de Campos e Santos, por meio de uma análise bioestratigráfica e paleoceanográfica no Quaternário tardio.

Objetivos específicos

✚ Comparar os bioecozoneamentos (da parte mais tardia do Quaternário) das bacias de Campos e Santos com as abundâncias relativas de foraminíferos planctônicos dos testemunhos SAT-048A e SIS-188.

✚ Reconstruir as variações nas condições oceanográficas superficiais (temperaturas, produtividade) na área de estudo, a partir de análises composicionais e isotópicas de foraminíferos planctônicos.

✚ Identificar os processos que modularam as condições de fundo (disponibilidade de matéria orgânica, dissolução) no talude médio da porção norte da Bacia de Pelotas.

### 1.3. Motivação

Para a indústria dos hidrocarbonetos, os bioecozoneamentos do Quaternário Tardio são cruciais para a análise de estabilidade do fundo do mar, auxiliando a geotecnia na perfurar os poços. Nesse sentido, o presente estudo auxilia na análise de estratégias de perfuração e contribui para a segurança em atividades de exploração *offshore*. Além disso, arcabouços bioestratigráficos robustos permitem definir modelos de idade de testemunhos sem a necessidade de análises dispendiosas como as de isótopos e datações radiométricas.

Como as mudanças climáticas não são sincrônicas nem geograficamente homogêneas, as espécies de foraminíferos planctônicos respondem diferentemente em termos espaço-temporais a estas flutuações, levando mais ou menos tempo para ocupar ou abandonar certos ambientes. Observando que os bioecozoneamentos de foraminíferos planctônicos do Quaternário tardio são baseados em variações de abundâncias relativas de espécies chave, que refletem mudanças paleoambientais (e não envolvem eventos de evolução), é importante ter um alto controle cronológico para a aplicação destes “zoneamentos paleoclimáticos e bioestratigráficos” nas diferentes regiões geográficas.

Além disso, para um melhor entendimento do clima e modelagem de seu comportamento futuro, é necessário reconstruir as flutuações e mecanismos associados no passado. Assim, este estudo não apenas trata sobre bioestratigrafia, mas também fornece informações sobre variações paleoceanográficas no Quaternário tardio da porção norte da Bacia de Pelotas.

### 1.4. Sobre a estrutura desta dissertação

A presente dissertação foi organizada em capítulos em formato de artigos científicos. No primeiro deles (Capítulo 2) é avaliado o potencial de aplicação dos bioecozoneamentos desenvolvidos para as bacias de Santos e Campos. Tal artigo foi submetido ao periódico *Marine Micropaleontology* (Qualis A2), atendendo à norma do Programa de Pós-Graduação em Geociências. O segundo artigo (Capítulo 3) visa reconstruir as condições paleoceanográficas de superfície e fundo, assim como entender os mecanismos que as desencadearam. No terceiro artigo (Capítulo 4) é proposto um modelo teórico para melhor

avaliar os efeitos da dissolução na fragmentação dos foraminíferos planctônicos. Finalmente, no capítulo 5 são apresentadas as considerações finais e perspectivas.

Todos os dados referentes às publicações serão disponibilizados em repositórios digitais de livre acesso.

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## Capítulo 2

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## Time-spatial boundaries of bioecozonations (planktonic Foraminifera) in the latest Quaternary: a case study from the western South Atlantic

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### Highlights:

- ✓ The last *G. menardii* complex delayed reappearance was recorded for the study area.
- ✓ We proposed the last disappearance of *P. obliquiloculata* as a diachronic event.
- ✓ New biostratigraphic markers for the Pleistocene-Holocene transition are proposed.

### Abstract

Planktonic Foraminifera assemblages registered the climate fluctuations that occurred during the Quaternary. These assemblage variations (frequently abundance reversals) are widely used to establish bioecozones. Since climate variations are neither synchronic nor spatially homogenous, this paper assesses the applicability of the southeastern Brazilian continental margin bioecozonations to the understudied southern Brazilian continental margin (SBCM). To accomplish this purpose, census counts were made on two cores retrieved from the continental slope of the SBCM. According to the age models, the sediment core SAT-048A registered the last 43 kyr, while the analyzed section of core SIS-188 registered the last 35 kyr. Relative abundances of the *Globorotalia menardii* complex and *Pulleniatina obliquiloculata* allowed us to recognize and calibrate the biochronology of the limits Y2/Y1, Y1B/Y1A and Y/Z for the SEBCM and SBCM. The last *G. menardii* complex reappearance was dated for the first time in the Pelotas Basin agreeing with a delayed return. The time progressive disappearance of *P. obliquiloculata*, reported for the Caribbean and Equatorial Atlantic, is also proposed for the western South Atlantic, despite previous studies. The Pleistocene-Holocene transition is not concomitant with the last reappearance of the *G. menardii* complex. Instead, the transition can be recognized based on the Last Abundance Peak of the *Globorotalia truncatulinoides* dextral morphotype (*GtdLAP*), also recognized in other cores of the SEBCM, which in turn means that surface waters were less stratified. Finally, the ratio of the species *Globigerinella calida* and *Neogloboquadrina incompta* also helped to characterize the Holocene-Pleistocene transition and the tropical-subtropical/subpolar water influence.

**Keywords:** Biostratigraphy, Biochronology, Paleobiogeography, Pleistocene-Holocene transition, Micropaleontology.

## 1. Introduction

Planktonic Foraminifera are marine single-celled protists with a very quick rate of evolutionary events during the Cenozoic (Thunell, 1984; Wade et al., 2010), which makes them one of the best index-fossils. However, this rate is relatively slow for the Late Quaternary where only a few of these events can be observed. Although for this time range planktonic Foraminifera display a scarce number of speciation or extinction events, they represent an important tool for biostratigraphic and paleoceanographic researches of the last few thousand years due to one fact: their spatial distribution is highly dependent on the sea surface temperature (Bé, 1977; Arnold & Parker, 2003; Kucera, 2007) and paleoclimatic changes imprint their signatures on the foraminiferal assemblages (Portilho-Ramos et al., 2014b). In this sense, biostratigraphical studies of the Late Quaternary are based on reversible variations of relative abundances of planktonic Foraminifera species as a function of environmental fluctuations, and in this way they are applied around the globe (*e.g.* Capotondi et al., 1999; Pérez-Folgado et al., 2004; Wilson, 2012; Drinia et al., 2016; Ducassou et al., 2018).

Changes in the *Globorotalia menardii* complex (*Globorotalia menardii*, *Globorotalia menardii* var. *fimbriata*, *Globorotalia tumida* and *Globorotalia flexuosa*) and *Pulleniatina obliquiloculata* abundances have shown to be good markers of past paleoceanographic events, and thus - with some caution - useful for biostratigraphical purposes (Ericson & Wollin, 1968; Kennett & Huddlestun, 1972; Bé et al., 1976; Prell & Damuth, 1978; Vicalvi, 1999; Sanjinés, 2006; Ferreira et al., 2012). Nevertheless, due to the different extension and intensity of the paleoclimatic changes, these events must be calibrated with precision for the different regions where they extend, in order to avoid mistakes in false time/bio-event correlations (Costa et al., 2018).

Several bioecozonation schemes for Late Quaternary sediments were developed for the southeastern Brazilian continental margin (SEBCM) (*e.g.* Vicalvi, 1999, 2013; Portilho-Ramos et al., 2006; Sanjinés, 2006; Ferreira et al., 2012; Portilho-Ramos et al., 2014b; Duarte et al., 2017), but none specific for the southernmost Brazilian margin, the Pelotas Basin, where oceanographic conditions are different. The first Late Quaternary biostratigraphic approaches for this basin are restricted to the shelf and upper continental slope (Vicalvi, 1977; Carvalho, 1980). Since these studies were performed in shallow waters, only relative sea level changes and the possible Pleistocene/Holocene



boundary were identified by the absence (at the base) and the presence (at the top) of planktonic Foraminifera (Carvalho, 1980), without a robust age model. Vicalvi (1977) and Rodrigues & Carvalho (1980) indicated the Pleistocene/Holocene boundary by the warm and cool-water species ratio.

Still, the Pelotas Basin lacks a specific Late Quaternary biostratigraphic framework, probably due to its lower economic potential. Furthermore, the development of a robust bioecozonation can be difficult due to: i) its southern location where the latitudinal difference results in cooler mean annual temperatures respect to the SEBCM basins; ii) the seasonal alternation between saltier and fresher water; iii) the closer presence of large nutrients sources (the Río de la Plata Estuary, RPE, and the Patos-Mirim lagoon system, PMLS; Gonzalez-Silvera et al., 2006) (see section 2); and iv) the possible influence of a complex sedimentation system involving contour currents and the Rio Grande Cone (Viana, 2001; Duarte & Viana, 2007; Hernández-Molina et al., 2016).

Since the mean environmental factors (temperature, salinity) that control the spatial distribution of planktonic Foraminifera strongly varies within the Pelotas Basin (see Section 2), bioecozonations from the SEBCM should be carefully revised when applied to this basin. Thus, the goal of this study is to evaluate the application potential of bioecozonations developed for the immediately northward basins (Vicalvi, 2013) in the Pelotas Basin. For this purpose, we present a study case of the latest Quaternary, based on the record from cores SAT-048A and SIS-188, retrieved from the continental slope of the Pelotas Basin.

### 1.1 Why “bioecozones” and not “biozones”?

Biostratigraphy deals with the fossil content of the sedimentary record. Its basic unit is the **biozone**, delimited by appearances, disappearances, and variations in the abundance of guide fossils. These events are always related to the appearance or extinction of species, within a unidirectional evolutionary process (Hedberg, 1976; Pearson, 1998). Therefore, the no repetition of fossils in rocks can provide a relative notion of age. The grouping of those phenomena can define range, interval, lineage, or assemblage biozones of a determined taxon or taxa. Nevertheless, there is a biozone delimited not by first or last occurrences but by a significant greater abundance: the abundance (or “acme”) biozone, which can be locally limited by paleoecological or

taphonomical controls. Other kind of biozones have a “*carte blanche*”, as new problems or solutions are faced (Easton et al., 2005).

The biozones mentioned in the former paragraph are here called “classic biozones”, since they are related to the evolution of the organisms and the no repetition of the events. In order to avoid confusion, another term concerning the reversible fluctuations caused by spatial migrations, associated with paleoclimatic changes is explored.

Poag & Valentine (1976) defined the **ecozone** as a body of strata characterized by a paleoenvironment distinguishable from the paleoenvironment of adjacent strata and added two variants: **bioecozone** and **lithoecozone**. The bioecozone was defined as a body of strata characterized by a paleoenvironment inferred by the fossil content, distinguishable from the paleoenvironments of the adjacent strata. On the other hand, the lithoecozone is a body characterized by a paleoenvironment inferred from sedimentological features (*e.g.* ripple marks, mud cracks) distinguishable from the paleoenvironments of the adjacent strata. Different paleoenvironments should be understood as changes in environmental factors (*e.g.* temperature, salinity, oxygenation) when fossils were alive, modifying the composition of the biocoenoses, and not as changes in the sedimentary environment after their death (*e.g.* transport, dissolution).

Thus, considering the interaction between (or the impact of) the environment and (in the) organisms, the term “bioecozone” (Poag & Valentine, 1976) is used in this study, since the classic biozones refers to evolutionary changes, less present in relatively short time intervals such as the Late Quaternary.

## 2. Study area

Located in the meridional border of the Brazilian continental margin (*i.e.* the SBCM, Fig. 1), the Pelotas Basin is limited from the Santos Basin to the north by the Florianópolis High and from the Punta del Este Basin to the south by the Polonio High. The surface oceanographic setting, in the offshore portion, is made up by tropical and oligotrophic waters carried southward by the Brazil Current (BC) (Peterson & Stramma, 1991). Around 38°S, the BC collides with the Malvinas Current (MC), which transports cool and eutrophic waters northwards forming the Brazil/Malvinas Confluence (BMC), a very dynamic region seasonally displaced following the wind stress: southward in the

austral summer and northward during the winter (Piola & Matano, 2019). Due to their latitudinal extension, the SBCM and SEBCM basins experiment a temperature gradient, warmer to the north and cooler to the south. (Fig. 1). Two major continental sources of nutrients and freshwater reach the area, benefiting primary productivity: the RPE and the PMLS (Gonzalez-Silvera et al., 2006) (Fig. 2).

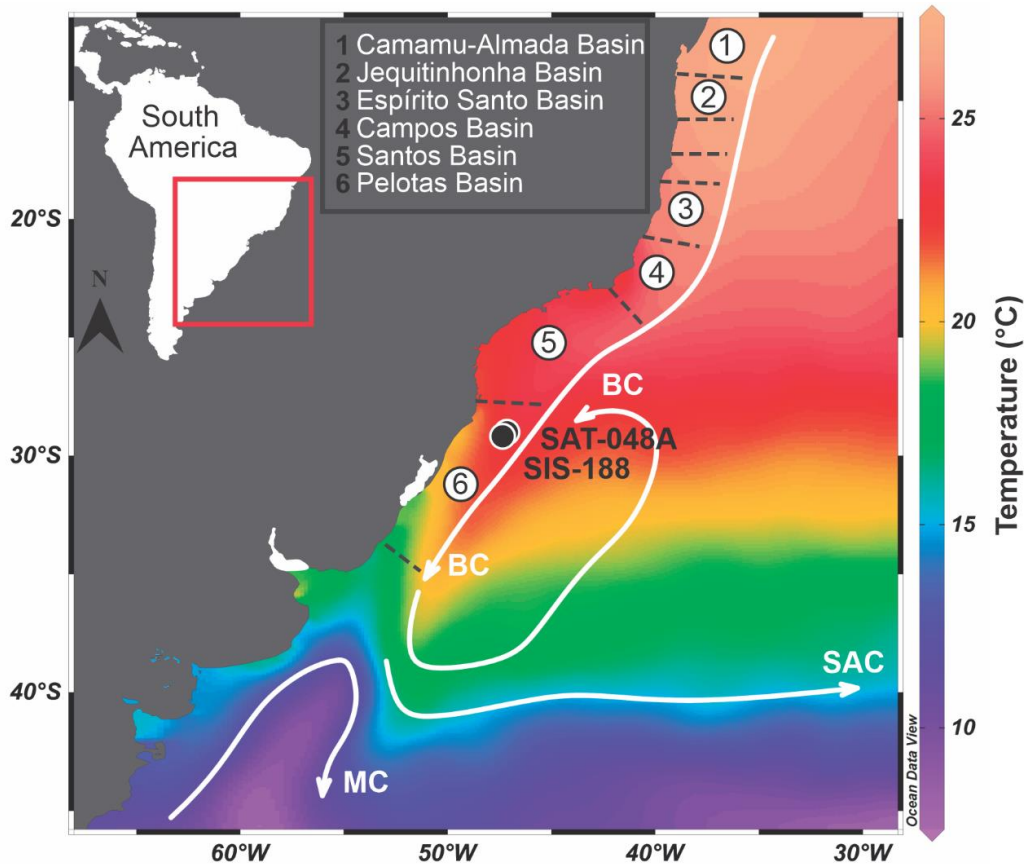


Fig. 1. Mean annual sea surface temperature ( $^{\circ}\text{C}$ ) according to the World Ocean Atlas 2013 (WOA13, Locarnini et al., 2013). At surface, the Brazil Current (BC) transports the warm and oligotrophic Tropical Water and the Malvinas Current (MC) transports the cool and eutrophic Sub-Antarctic Water. The BC and the South Atlantic Current (SAC) comprise the southwestern portion of the South Atlantic subtropical gyre (Peterson & Stramma, 1991). The map shows, from south to north, the Pelotas (6), Santos (5) and Campos (4) basins in the SBCM and SEBCM, respectively. Black dots represent the location of cores SAT-048A and SIS-188.

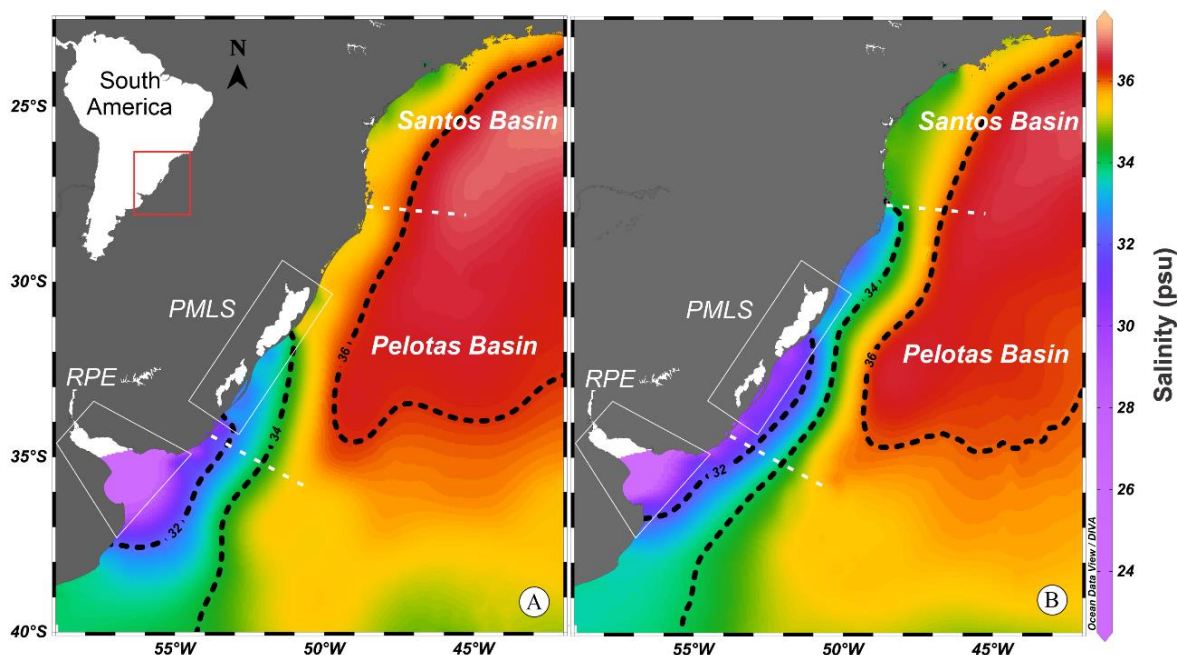


Fig. 2. Seasonal variation of sea surface salinity (psu) according to the World Ocean Atlas 2013 (WOA13, Zweng et al., 2013): climatologic average for the January – March months (a) and for the July – September months (b). These figures illustrate how the Pelotas Basin experiences cooler temperatures than the Santos Basin and significant seasonal changes. Dashed black lines in (a) and (b) correspond to 32, 34, and 36 psu isohalines, evidencing the intrusion of fresher waters from the south during July – September. The Río de la Plata Estuary (RPE) and the Patos-Mirim lagoon system (PMLS) are the two largest sources of nutrients and freshwater.

### 2.1. Bioecozonations for the latest Quaternary from the Brazilian continental margin

A general updated scheme, summarizing previous relevant studies, is shown in Fig. 3. Ericson & Wollin (1968) defined ten Quaternary bioecozones, based on the presence and absence of the *Globorotalia menardii* complex from ten cores of the Caribbean Sea and the Equatorial and South Atlantic Ocean (between 17°N – 29°S). The bioecozones were named from Q (oldest) to Z (most recent), and the Y/Z limit was related to the Pleistocene/Holocene boundary.

Vicalvi (1999) subdivided Ericson & Wollin's (1968) bioecozones X, Y and Z into 18 sub-bioecozones for the Upper Quaternary sediments from the Campos Basin and São Paulo Plateau, using the relative abundance of the *Globorotalia menardii* complex and the *Pulleniatina obliquiloculata* species. The bioecozone Y was split in five (Y5 – Y1). Based on eight cores retrieved from Campos Basin, Kowsmann &

Vicalvi (2003, as cited in Sanjinés, 2006), divided the sub-bioecozone Y1 (Vicalvi, 1999) into Y1B and Y1A, with the last reappearance of *P. obliquiloculata* (YP.4, Sanjinés, 2006; Last Reappearance Datum – LRD – of *P. obliquiloculata*, Vicalvi, 2013) at 15 ka.

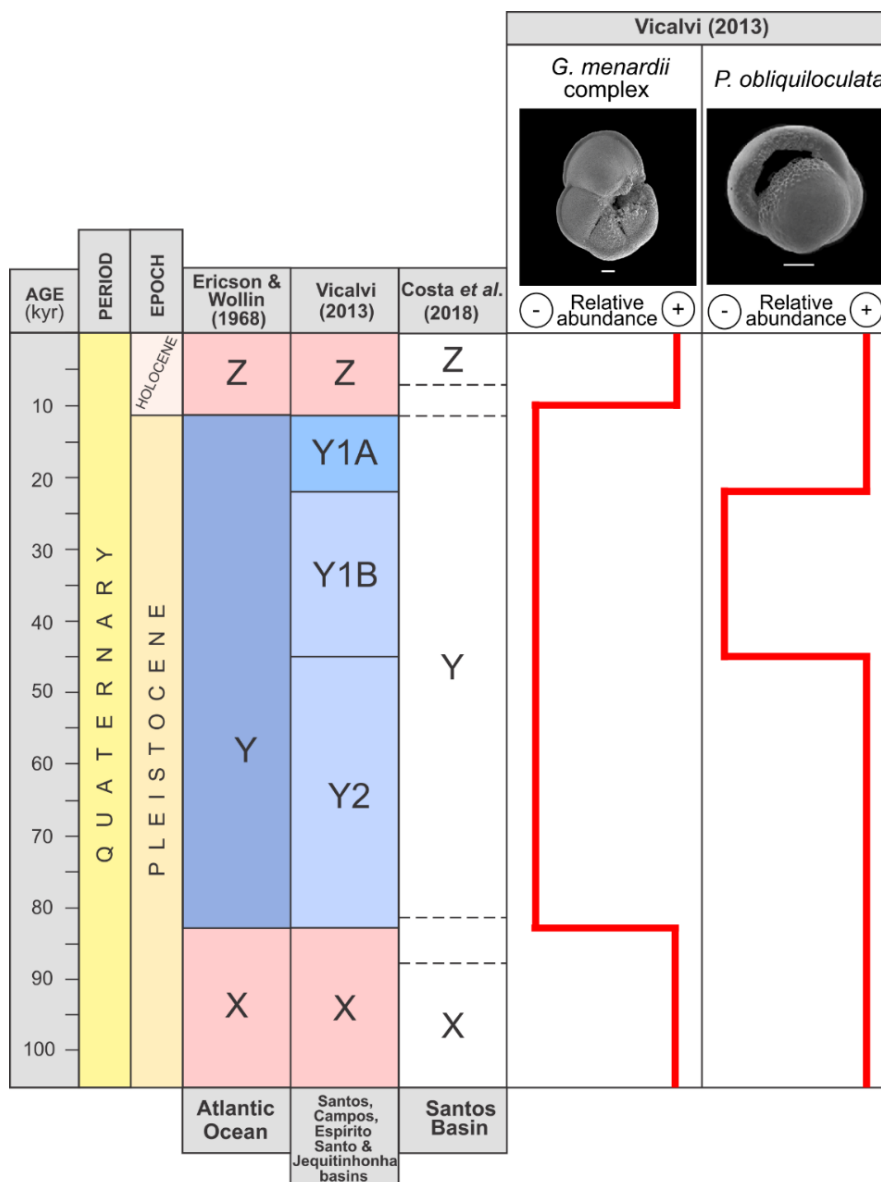


Fig. 3. General updated and calibrated scheme of bioecozonations proposed for the Late Quaternary that embrace the SEBCM basins. Scale bars for the planktonic Foraminifera SEM images are 100  $\mu$ m.

Portilho-Ramos et al. (2006) recognized the bioecozones X, Y and Z (Ericson & Wollin, 1968) in the Santos Basin, as well as the subdivisions proposed by Vicalvi

(1999): X1 and Y5 – Y1. The same authors also suggested a sampling refinement for the upper core part in order to identify sub-bioecozones Z2 and Z1 and the last reappearance of *P. obliquiloculata*. Vicalvi (2013) reassessed the Y bioecozone division, defining only two sub-bioecozones: Y2 and Y1, where Y2 embraced all former sub-bioecozones from Y5 to Y2 and Y1 stayed the same. This new subdivision was better suited for cores with lower sedimentation rates.

Ferreira et al. (2012) established a bioecozonation in the Santos Basin for the last 620 kyr, based on the *G. menardii* complex and *P. obliquiloculata*, recognizing seven bioecozones from Ericson & Wollin (1968), T to Z, and 14 sub-bioecozones from Vicalvi (1999). Vicalvi (2013), used cores from the SEBCM (Santos, Campos, Espírito Santo basins) as well as from the northeast Brazilian continental margin (NEBCM; Jequitinhonha basin), and established a quantitative bioecozonation using relative abundances. This new scheme could enable the biostratigraphic recognition of an isolated sample. For example, a random sample with a high relative abundance of the *G. menardii* complex, and without the control of the whole record downcore, could belong to all of the so called “interglacial” bioecozones” (e.g. Z, X...), but when the relative abundances of the other index species proposed in Vicalvi (2013) are compared, it could be possible to assign an age.

Toledo et al. (2016) built a biochronological frame of the Western South Atlantic (Santos Basin) for the last 772 kyr, registering new biostratigraphic events calibrated with the stable oxygen isotope record. Regarding planktonic Foraminifera in the latest Quaternary, there is the “disappearance event (D1)” of the *G. menardii* complex ( $\leq 1\%$ ) at 84 ka for two cores, which marks the X/Y limit, and the “reappearance event (R1)” registered at 12 ka, when *G. menardii* complex rises from  $\geq 1\%$ . The authors also proposed the biostratigraphic markers “lowest and highest common occurrences of *Globorotalia hirsuta*”. A significant increase and continuous record (lowest common occurrence, LCO, of *G. hirsuta*) occurred at ~120 ka and the highest common occurrence (HCO) of *G. hirsuta* at 33.5 ka. Toledo et al. (2016) dated the first occurrence of *Globorotalia menardii* var. *fimbriata*, sub-biozone *G. m. fimbriata* (Bolli & Saunders, 1989), at 10 – 12 ka.

The analysis of six cores from the continental slope of the Santos Basin led Costa et al. (2018) to assess the reliability of the appearances/disappearances of the *Globorotalia menardii* complex from the middle Pleistocene to Holocene as a

biostratigraphical tool, and found that the age limits of the bio-events marked by this taxa are not synchronous in the basin. Costa et al. (2018) also recommended not to use the relative abundance of the *G. menardii* complex to indicate paleoclimatic conditions. An example of this can be seen in Portilho-Ramos et al. (2015) in the Campos Basin, where a high relative abundance of the *G. menardii* complex coincides with an also high relative abundance of *Globigerina bulloides* and cooler sea surface temperature reconstructions during the bioecozone X.

### 3. Material and methods

The cores SAT-048A and SIS-188 (Fig. 1) were retrieved from the Pelotas Basin slope (29°11'S; 47°15'W; 1542 mbsl & 29°22'S; 47°28'W; 1514 mbsl) by *FUGRO Brasil – Serviços Submarinos e Levantamentos Ltda* for the *Agência Nacional do Petróleo* (Brazilian National Agency of Petroleum, Natural Gas and Biofuels). The sediments date from Pleistocene/Holocene and correspond to the Imbé Formation (Bueno et al., 2007). The core SAT-048A was analyzed in Frozza et al. (2020) and for this paper, the Foraminifera shells were reassessed in order to distinguish the planktonic Foraminifera morphospecies. Also new samples were added, totalizing 54 samples for the of 3.13 m retrieved, at intervals of 6 cm. For the core SIS-188, 21 samples were chosen from the upper 2.08 m. Each sample was washed through a 0.063 mm sieve and oven dried at maximum temperatures of 60°C. Only material larger than 0.150 mm was used for the planktonic Foraminifera assemblage analyses, where a minimum of 300 specimens (Patterson, 1989) per sample were classified up to the species level using a stereomicroscope. Taxonomic criteria followed Bé (1967), Bé et al. (1977), Bolli & Saunders (1989), Hemleben (1989), Kemle von Mücke & Hemleben (1999), Schiebel & Hemleben (2017) and Anjos-Zerfass (2019).

Grain sizes were determined (for bulk samples and calcium carbonate-free samples; Fig. S1) for both cores (SAT-048A and SIS-188) using a laser diffraction particle size analyzer Horiba Partica-LA-950. Calcium carbonate-free samples were analyzed after reaction with hydrochloric acid (HCl), 10%, at the *Centro de Geologia Costeira e Oceânica* (CECO) of the *Universidade Federal do Rio Grande do Sul* (UFRGS).

Age models were already published for both cores (Table S1). The core SIS-188 age model, published by Duque-Castaño et al. (2019), was based on the correlation of oxygen isotopes record (*Globigerinoides ruber* white), the standard reference curve for the Intermediate South Atlantic waters (Lisiecki & Stern, 2016; ISA-LS16) and four Accelerator Mass Spectrometry (AMS)  $^{14}\text{C}$  ages as control points, using the software Analyseries (Paillard et al., 1996). For the core SAT-048A, it was used a reviewed version of the Frozza et al. (2020) age model, carried out by Savian et al. (submitted), based on rbacon package (Blaauw & Christen, 2011; version 2.4.2) and the Laschamp geomagnetic excursion as a control point besides the radiocarbon dates.

#### 4. Results

Assemblage results for cores SAT-048A and SIS-188 are available at the supplementary material. In the SAT-048A core, the *G. menardii* complex are virtually absent during the 43 – 12 ka BP and reached maximum values of almost 8%, at 7.0 ka BP (Fig. 4L). *Pulleniatina obliquiloculata* reached maximum values of 0.8% and remained virtually absent during the 26 – 16 ka BP (Fig. 4K). The *Globigerinella calida* and *Neogloboquadrina incompta* ratio ( $G.calida:N.incompta = \%G. calida / \%G. calida + \%N. incompta$ ) remained low until the Holocene/Pleistocene boundary, when values close to one were reached, remaining high up to the top (Fig. 4J). *Globorotalia hirsuta* (Fig. 4I) and *Globoconella inflata* (Fig. 4H) experienced a similar trending, increasing for the 43 – 26 ka BP and decreasing afterwards, with the maximum abundance of *G. hirsuta* during the Holocene. The *Globorotalia truncatulinoides* species showed three peaks of maximum abundances at 35, 25 and 12 ka BP (Fig. 4G).

In the SIS-188 core (Fig. 4), the *G. menardii* complex remained virtually absent during the 32 – 12 ka BP and reached maximum values of almost 4% at 7.44 ka BP (Fig. 4F). The *P. obliquiloculata* reached maximum values of 0.8%, between 30.3 – 26.3 ka BP and remained virtually absent during the 24 – 10 ka BP (Fig. 4E). The *G.calida:N.incompta* ratio remained low until the Early Holocene (Fig. 4D). *Globorotalia hirsuta* did not show clear trends (Fig. 4C). *Globoconella inflata* experienced a similar trending to core SAT-048A, reaching minimum values during the Holocene (Fig. 4B). The *Globorotalia truncatulinoides* species showed a very varied pattern for the whole section (Fig. 4A).



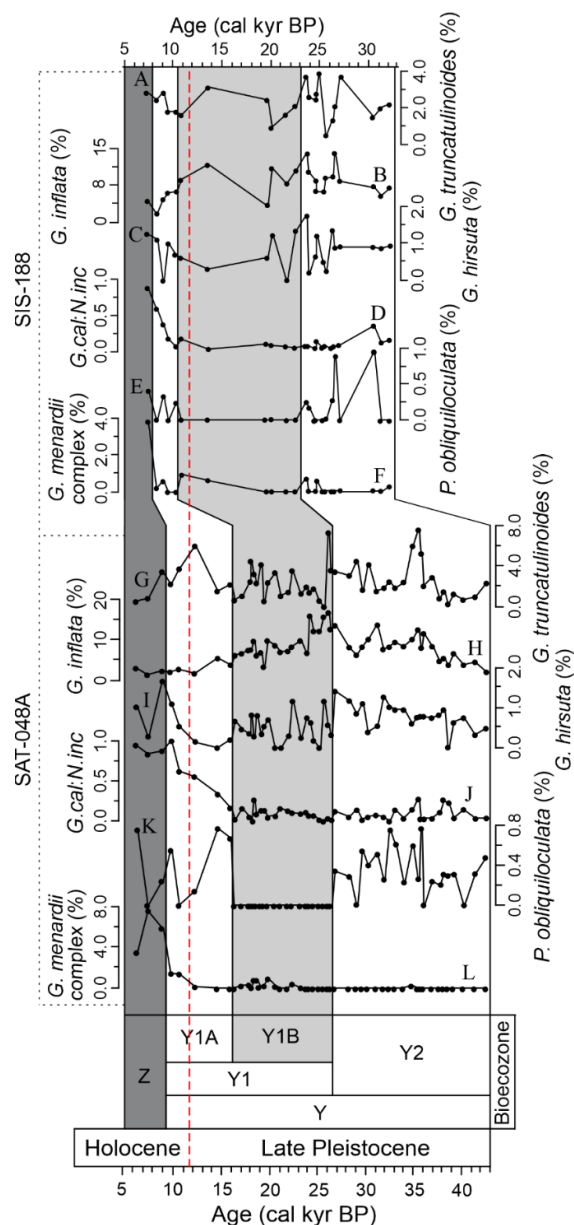


Fig. 4. Relative abundances of the planktonic Foraminifera species used in the biostratigraphic analysis of SIS-188 and SAT-048A cores through time. In the SIS-188 core are represented (A) *Globorotalia truncatulinoides*, (B) *Globoconella inflata*, (C) *Globorotalia hirsuta*, (D) the *Globigerinella calida*:*Neogloboquadrina incompta* ratio, (E) *Pulleniatina obliquiloculata*, and (F) *Globorotalia menardii* complex. In the SAT-048A core are represented (G) *Globorotalia truncatulinoides*, (H) *Globoconella inflata*, (I) *Globorotalia hirsuta*, (J) the *Globigerinella calida*:*Neogloboquadrina incompta* ratio, (K) *Pulleniatina obliquiloculata*, and (L) *Globorotalia menardii* complex. All axes are in %, except (C) and (J). At the base, bioecozones according to Ericson & Wollin (1968) and Vicalvi (2013). Red dashed line represents the Holocene/Pleistocene boundary. Note that the bioecozone Z starts after the Holocene onset.

## 5. Discussion

### 5.1 Age models

The four AMS  $^{14}\text{C}$  ages for the core SIS-188 showed a normal deposition with no disturbance sedimentary processes. However, for the Y1B sub-bioecozone (Fig. 4A–F) a larger temporal distance between samples can be noted, possibly related to a lower sedimentation rate or to the age model construction, since sample spacing was almost regular. Nevertheless, the occurrences of reversals in planktonic Foraminifera radiocarbon dates in this region are not rare (*e.g.* Sortor & Lund, 2011; Hoffman & Lund, 2012; Portilho-Ramos et al., 2019; Rodrigues et al., 2020). The AMS  $^{14}\text{C}$  ages of the core SAT-048A indicate two intervals where samples with older ages occur overlapping younger ages (table S1). Reversals can be related to morphological features of the sea bottom that create instability or to sedimentological processes, such as turbidity or contour currents, that remobilize the sediments. Alternatively, changes in the radiocarbon ages can be product of other processes than physical/sedimentological, such as chemical interactions that affect the radiocarbon concentration (Rodrigues et al., 2020).

The first reversal in the SAT-048A core, occurs at 183.5 cm (dated as 34.6 ka), between 217 and 149 cm, an interval constituted by hemipelagic mud rich in carbonate, with ages of 27.9 and 22.9 ka BP, respectively (Savian et al., *subm.*). The second one (85 cm, dated as 19.5 ka), between 113 and 65 cm, presents hemipelagic mud with organic matter and ages of 19 and 15.4 ka BP respectively. Both reversals occur between the ages 28 – 15 kyr BP, where relative sea level was about 100 and 120 m below present level (Waelbroeck et al., 2010). In these periods' instability, features of geologic risk could be formed (Kowsmann et al., 2014). Nevertheless, despite some remarkable peaks on the grain size record (supplementary material), reversals of AMS  $^{14}\text{C}$  planktonic Foraminifera dates are not associated to them. Changes in grain sizes of  $\text{CaCO}_3$  free samples, which represent terrigenous/authigenic/not calcareous sediments, are not expressive and indicate that no abrupt sedimentary processes modified the record. As no abrupt textural changes were associated to those reversals, other kind of sedimentary process can be considered. The action of contour currents in the proximities of the study area (Viana, 2001; Duarte & Viana, 2007; Hernández-Molina et al., 2016) could, gradually, remobilize older biogenic particles from one place and

redeposit them with recent formed material in another one, masking or modifying the foraminiferal record and increasing the temporal mixing.

Moreover, Rodrigues et al. (2020) reported the upward migration of  $^{14}\text{C}$ -depleted methane fluids from gas chimneys for the Rio Grande Cone, south portion of the Pelotas Basin, likely affecting AMS  $^{14}\text{C}$  ages of organic matter. Post-depositional diagenetic incorporation in shell interstitial pores (Wycech et al., 2016) of fossil carbon could have produced an alteration in the radiocarbon dates, yielding older ages.

## 5.2 Biostratigraphic analysis

### *Globorotalia menardii* complex and *Pulleniatina obliquiloculata* species

As detailed in section 1.2, Ericson & Wollin (1968) used the presence (absence) of the planktonic menardellids to identify interglacial (glacial) periods for the Caribbean Sea and the Atlantic Ocean, defining ten bioecozones for the Quaternary, from Q (oldest) to Z (recent). For the Late Quaternary, X and Z correspond to interglacial episodes, while W and Y represent glacial episodes. A couple of decades later, Vicalvi (1999) established a minimum of 3% of relative abundance of the planktonic menardiiforms to indicate the beginning of bioecozone Z, emphasizing this bio-event as synchronous with the Pleistocene/Holocene boundary.

In the core SAT-048A, the relative abundance of the planktonic menardiiforms exceeds 3% from 8.4 ka BP onwards, while in the core SIS-188 only at 7.4 ka BP, after the Holocene onset for both cores. This marked the limit of the bioecozones Y and Z approximately 3 – 4 kyr after the chronological beginning of the Holocene (11.7 ka BP), as already observed by Pivel et al. (2013) (8.2 ka BP in the Santos Basin), and by Petró et al. (2016) (right after 10.6 ka BP in the Campos Basin). Broecker & Pena (2014) also reported this reappearance, at 7.15 ka BP for the Equatorial Atlantic. This reentering in the Atlantic Ocean from the Indian Ocean would likely reflect a change in the configuration of the global circulation (e.g., Peeters et al., 2004), not necessarily local temperature variations.

Bolli & Saunders (1989) defined the sub-bioecozone “*Globorotalia menardii fimbriata*” (Bolli & Premoli-Silva, 1973) as a taxon range zone, corresponding to the warm postglacial period, associated to the Holocene, although the same authors suggested – questionably – it could also be found in the Late Pleistocene. For the Santos

Basin, Toledo et al. (2016) dated the event of appearance of the *Globorotalia menardii* var. *fimbriata* (sub-biozone *G. fimbriata* of Bolli & Saunders, 1989) between 12 – 10 ka BP. Also, for the Santos Basin, Santarosa (2010) found this appearance at about 5 ka, with a very low relative abundance (average of 0.2%). In the SAT-048A core, no specimens of *G. menardii* var. *fimbriata* were identified in the 300 subsamples counting. However, when looked at the whole sample, a few specimens of *G. menardii* var. *fimbriata* appeared since 8.4 ka BP. The very low abundance can be related to its distribution possibly being restricted to higher temperatures in lower latitudes.

Vicalvi (1999, 2013) defined the limit Y2/Y1 between 45 – 42 ka BP for the Campos Basin in the bio-horizon of the last disappearance of *P. obliquiloculata* (YP.3, Vicalvi, 1999; Last Disappearance Datum – LDD – Vicalvi 2013). Portilho-Ramos et al. (2014a) found the same age proposed by Vicalvi (1999) (45 – 42 ka BP) for the Santos Basin, and Portilho-Ramos et al. (2014b) established this limit as synchronic for the SEBCM (Santos and Campos) basins. On the other hand, the data used by Ferreira et al. (2014) shows the LDD of *P. obliquiloculata* at 30.5 and 32.2 ka BP in two cores further to the north of the Santos Basin, therefore more than 10 kyr later than the age found in Portilho-Ramos (2014a, b). For cores SIS-188 and SAT-048A, in the north of the Pelotas Basin, *P. obliquiloculata* is characterized by an extremely low relative abundance, presenting maximum values of almost 1%. However, it was possible to identify the LDD of *P. obliquiloculata* when the relative abundance dropped to zero, at 26.5 and 23.5 ka BP, for SAT-048A and SIS-188, respectively. There is a delay of around 20 kyr when compared to the ages obtained for Campos Basin (Vicalvi, 1999, 2013; Petró et al., 2016), but closer to the Santos Basin ages (Ferreira et al., 2014), which indicates that *P. obliquiloculata* suffered a gradual disappearance, early in the north and later southward.

The asynchrony of this bio-event was documented by Prell & Damuth (1978) as a “time transgressive disappearance” for the Equatorial Atlantic and Caribbean Sea. These authors found ages of 60 – 50 ka BP for the Gulf of Mexico and 35 ka BP for the Equatorial Atlantic, suggesting a progressive increase in surface salinities because of the expansion of continental glaciers associated to the disappearance of *P. obliquiloculata*. This model proposed by Prell & Damuth (1978) explains very well such delay found by this study in the Pelotas Basin. Fig. 5 clearly shows the relation between the disappearance ages of *P. obliquiloculata* and the salinity concentrations: older when the

cores are closer to higher salinity concentrations and younger where salinity concentrations decrease, extending not only for the SBCM, but also for the Equatorial Atlantic. So, while the ice sheets expanded “slowly” and salt started to accumulate in the oceans, relatively fresher waters from the south (although cooler) would be able to hold more suitable conditions to host *P. obliquiloculata* (Xu et al., 2005). During the Last Glacial Maximum, the oceans became saltier and the *P. obliquiloculata* species “disappeared”. The time-progressive character of this bio-event hinders its accuracy as a biostratigraphic tool for interbasin comparisons and highlights the importance of calibration studies for better constrained ages in the different regions. The LDD of *P. obliquiloculata* ages of different cores from the equatorial and western South Atlantic are shown in Table 1.

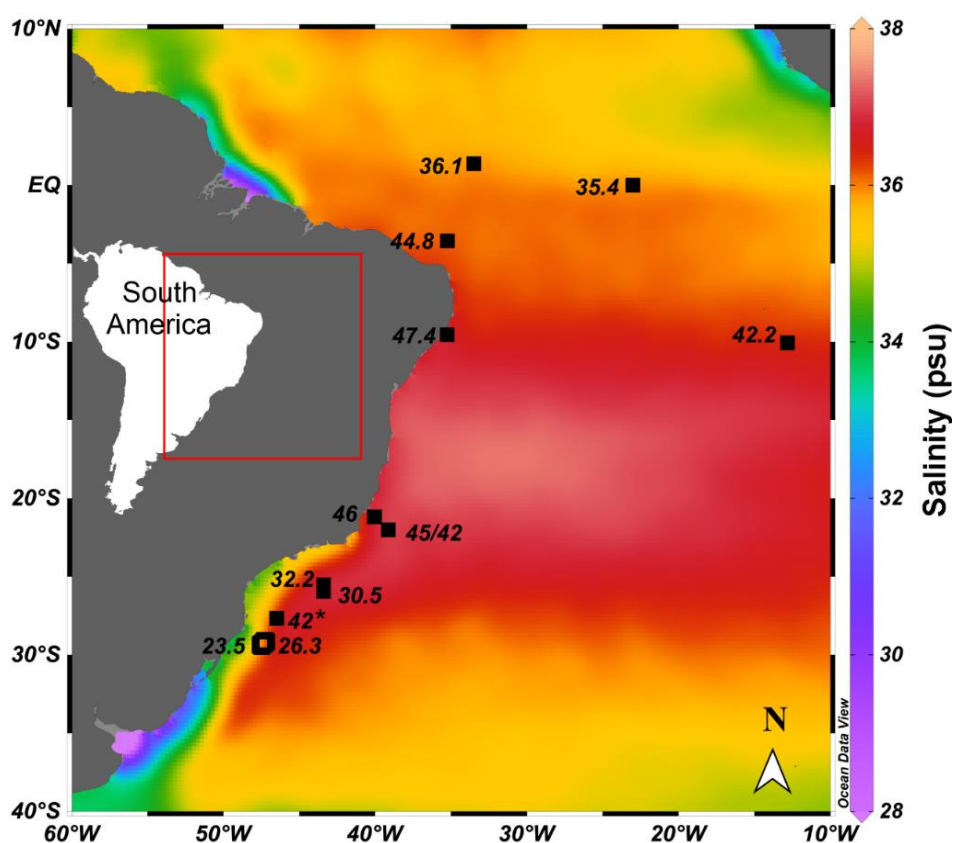


Fig. 5. The ages for the *P. obliquiloculata* last disappearance datum (LDD, Vicalvi, 2013) are shown for the different core studies listed in Table 1. The older ages correspond to higher salinity regions, and the correlation shows a progressive character of *P. obliquiloculata* disappearance for the Equatorial and South Atlantic. Data is available in Supplemental Material IV. Mean Annual Salinity from the World Ocean Atlas 2013 (WOA13, Zweng et al., 2013).

Portilho-Ramos et al. (2019) refined the JPC-17 age model with more AMS  $^{14}\text{C}$  and  $\delta^{18}\text{O}$  correlation points. This new model showed some age inversions, including one point previously used by Portilho-Ramos (2014a, b). But, after the Portilho-Ramos et al. (2019) reassessment, the JPC-17 continued with only one AMS  $^{14}\text{C}$  date near the Y2/Y1 limit. So, the need for a better calibrated and constrained age model for the deeper part of the core JPC-17 makes the use of the LDD of *P. obliquiloculata* age (42 ka BP)\* in the Santos Basin as uncertain, when analyzed in the Central-South Atlantic context of time-progressive disappearance of the *P. obliquiloculata*.

Kowsmann & Vicalvi (2003, as cited in Sanjinés, 2006) used the LRD of *P. obliquiloculata* (Vicalvi, 2013), around 15 ka BP, to divide the sub-bioecozone Y1 into Y1B (early) and Y1A (late). According to the variation of *P. obliquiloculata* this subdivision happened in the SAT-048A at 15.6 ka BP and at 10.2 ka BP for SIS-188. The better constrained age for the core SAT-048A could be due to the higher resolution sampling for radiocarbon analyses compared to core SIS-188. Contrary to the time-progressive character of the LDD of *P. obliquiloculata* (Vicalvi, 2013), there is a less asynchrony in this biostratigraphic limit (see Y1B/Y1A boundary in Fig. 6). This bio-event is related to the global and relatively fast sea level rising at the end of the Marine Isotope Stage 2 (Waelbroeck et al., 2010). A biostratigraphic framework for the SBCM, with the bioecozonations proposed and calibrated ages for their limits, is shown in Fig. 6.

Table 1. *Publication, estimated age, coordinates, and core of the different studies where the LDD of P. obliquiloculata was also documented.*

Author	age (ka BP)	Longitude	Latitude	Core
Prell & Damuth (1978)	35.4	23°00'W	0°0'N	A180-73
Prell & Damuth (1978)	36.1	33°29'W	1°22'N	V25.59
Prell & Damuth (1978)	42.2	12°49'W	10°4'S	V22-174
Prell & Damuth (1978)	44.8	35°14'W	3°33'S	V25-56
Prell & Damuth (1978)	47.4	35°15'W	9°33'S	V22-38
Petró et al. (2016)	46	40°2'W	21°12'S	GL-77
Vicalvi (1999)	45 – 42	39°W	22°S	-
Ferreira et al. (2014)	30.5	43°24'W	25°57'S	BS-D
Ferreira et al. (2014)	32.2	43°24'W	25°32'S	BS-A

Portilho-Ramos et al. (2014a, b)	42*	46°29'W	27°41'S	JPC-17
This study	26.3	47°15'W	29°11'S	SAT-048A
This study	23.5	47°28'W	29°22'S	SIS-188

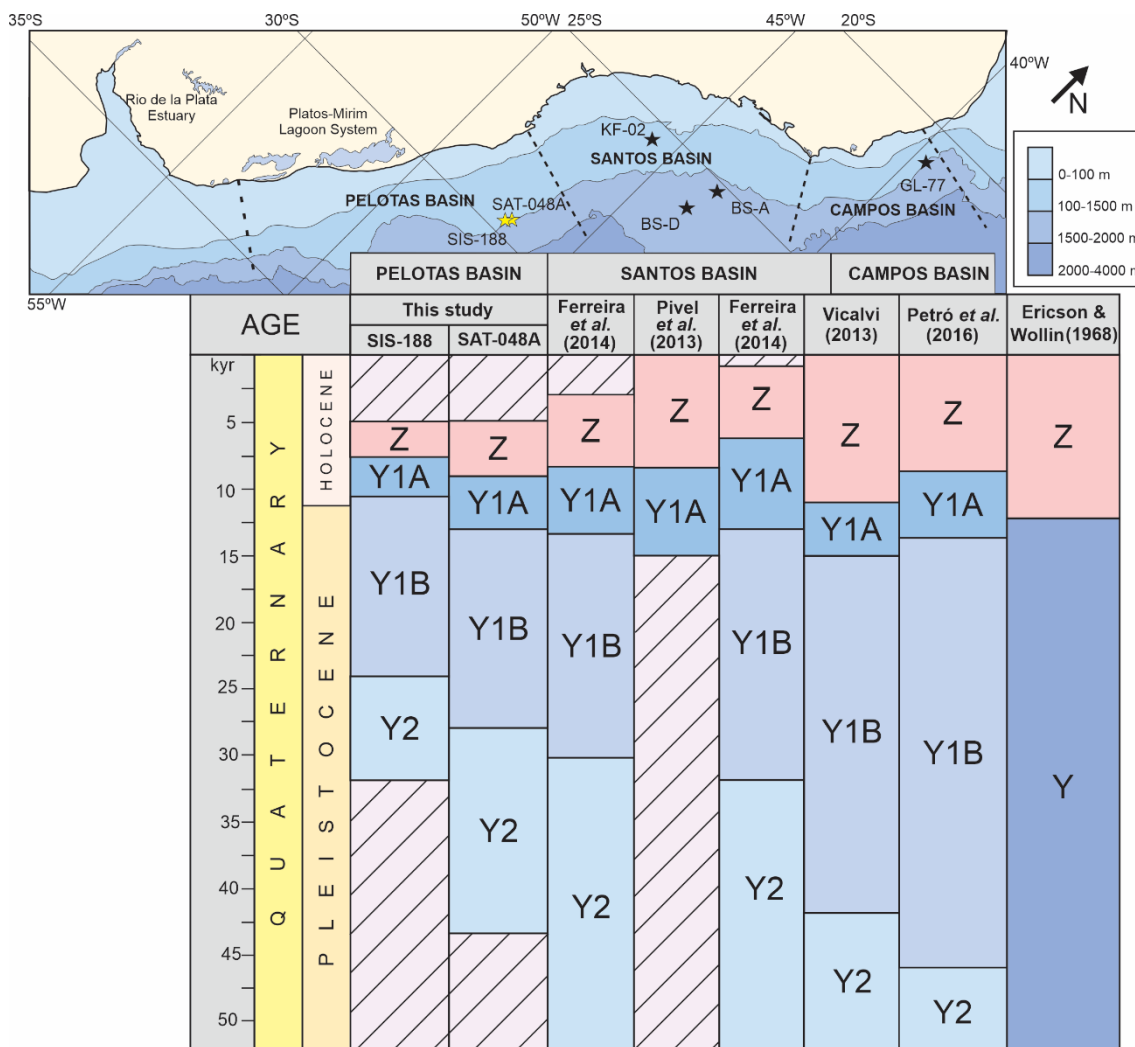


Fig. 6. Biostratigraphic framework of the latest Quaternary for the SEBCM (KF-02 (Pivel et al., 2013); BS-A, BS-D (Ferreira et al., 2014); GL-77 (Petró et al., 2016)), and the SBCM (SIS-188, SAT-048A; this study). A notable diachronism between the limits can be seen. Note: (i) the limit Y/Z is not synchronous with the Pleistocene/Holocene boundary (Broecker & Pena, 2014), (ii) the diachronism of the Y/Z limit in the SEBCM basins (Costa et al., 2018), (iii) the “time progressive disappearance” (LDD) of *P. obliquiloculata* that marks the Y2/Y1 limit (Prell & Damuth, 1978) range ages from 46 to 23 ka BP, and (iv) the last reappearance (LRD) of *P. obliquiloculata* (Y1B/Y1A) seems to have less scattered ages. Hatched areas indicate unavailable data.

### *Globorotalia hirsuta*

Toledo et al. (2016) proposed, for the Santos Basin, the LCO (lowest common occurrence) and HCO (highest common occurrence) of *G. hirsuta* at ~120 ka and 33.5 ka BP respectively. When analyzing the relative abundance of *G. hirsuta*, in the record of the cores SAT-048A and SIS-188, no pattern of decreasing at (or about) 33.5 ka BP was observed (Fig. 4C,I).

### *Globorotalia truncatulinoides* and *Globoconella inflata*

Vicalvi (1999) characterizes the species *G. truncatulinoides* (both coiling directions) and *G. inflata* in the Y2 and Y1 sub-bioecozones, with an increase in their relative abundances after the Y2/Y1 limit. As the relative abundances of these species do not have a stable tendency in our cores during the bioecozone Y, no similarities were found. At the beginning of bioecozone Z, Vicalvi (1999) recorded a decrease in the species *G. inflata* and higher percentages for *G. truncatulinoides* close to the Pleistocene/Holocene boundary. In our data, the abundances of *G. inflata* show a decrease in this boundary, following a decreasing trend since 25 ka BP for both cores. Although *G. truncatulinoides* shows a maximum in its relative abundance in the age sample 11.7 ka BP for the core SAT-048A, it is not the only maximum of this species during the last 43 kyr, two more peaks of maximum abundance (over 6%) are reached at around 35 and 25.7 ka BP, making it difficult to use it as an index species of the Pleistocene/Holocene boundary. For the core SIS-188, higher values of *G. truncatulinoides* are reached at 25 ka BP.

As mentioned earlier, the *Globorotalia menardii* complex reappearance does not mark the beginning of the Holocene, leaving a gap in the biostratigraphic analyses for the identification of the Pleistocene/Holocene boundary. Nonetheless, the relative abundance of the *G. truncatulinoides* dextral morphotype only, could help to identify the Pleistocene-Holocene transition. In the core SAT-048A, two peaks of the dextral morphotype were found, the first one at 35.4 ka BP, and the second peak, which results more interesting, was at 11.7 ka BP. The core SIS-188 shows a not so outstanding peak during the Early Holocene.

The peak of *G. truncatulinoides* dextral morphotype during the Pleistocene-Holocene transition is also registered in another six cores of the SEBCM and NEBCM basins (Table 2, Fig. 7). Since the extent of this bio-event goes beyond local areas and



proves to be chronologically precise, the *Globorotalia truncatulinoides* dextral, henceforth called *Globorotalia truncatulinoides* dextral Last Abundance Peak (*GtdLAP*) can help to biostratigraphically identify the Pleistocene/Holocene boundary. The mean age for the beginning of the *GtdLAP* is 12.8 ka BP. Additionally, high dextral *G. truncatulinoides* relative abundances indicate less stratified surface waters (Mullitz et al., 1997, Schiebel & Hemleben, 2017).

Table 3. *Publications and locations where the GtdLAP was also registered in cores of the SBCM SEBCM and NEBCM basins.*

Authors	Year of publication	Core	Basin
Toledo et al.	2007	CMU-14	Camamu
Toledo et al.	2007	ESP-O8	Espírito Santo
Petró et al.	2016	GL-77	Campos
Toledo et al.	2007	SAN-76	Santos
Pivel et al.	2013	KF02	Santos
Ferreira et al.	2014	BS D	Santos
This study		SAT-048A	Pelotas
This study		SIS-188	Pelotas

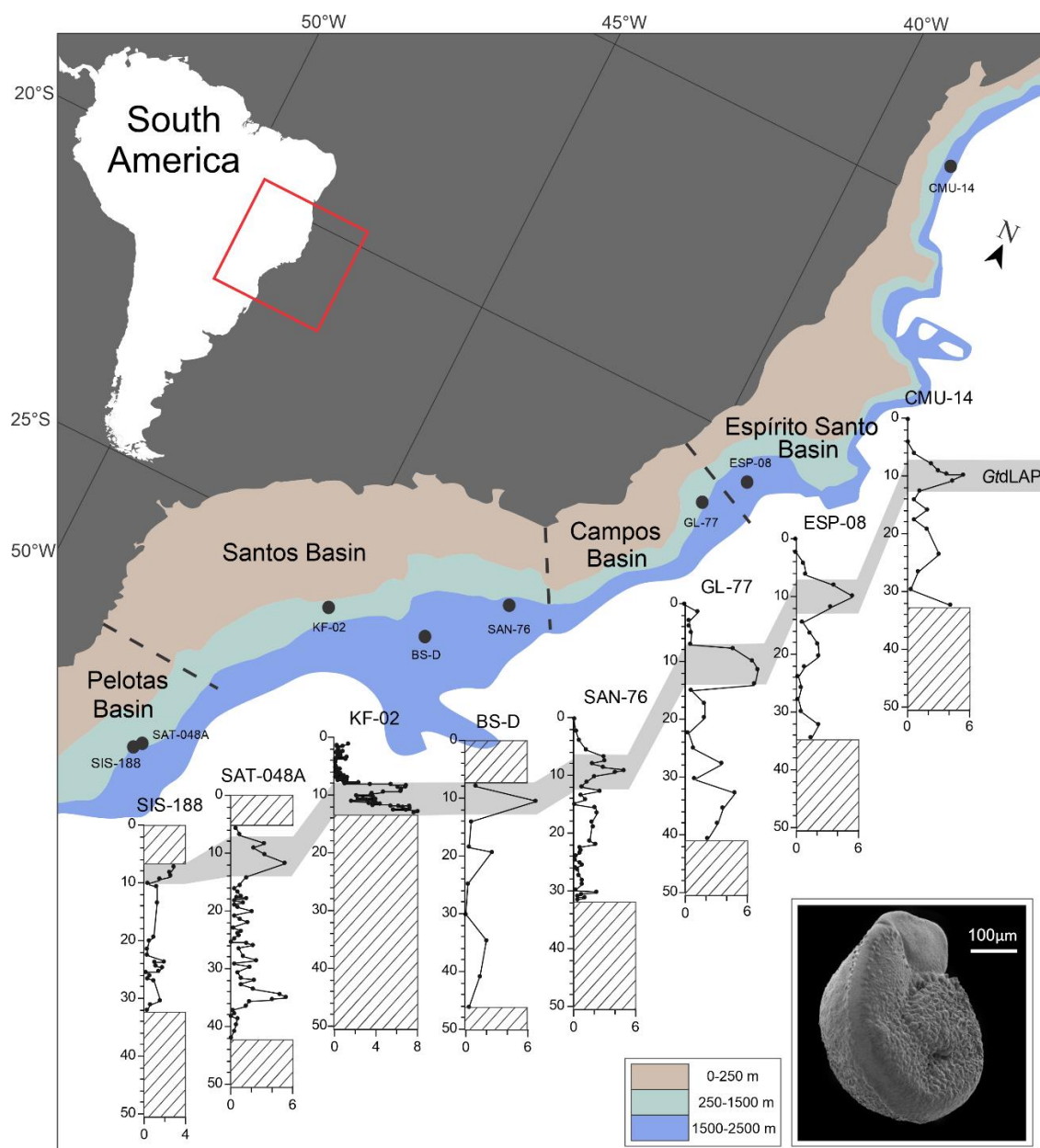


Fig. 7. The peak of *G. truncatulinoides* dextral morphotype in the cores retrieved from the SBCM and SEBCM basins (listed in Table 3). The dashed lines represent the limits between basins. Dots indicate the location of cores SIS-188 and SAT-048A (this study), KF-02 (Pivel et al., 2013), BS-D (Ferreira et al., 2014), SAN-76, ESP-08 and CMU-14 (Toledo et al., 2007) and GL-77 (Petró et al., 2016). Profiles below the map show the age (ka BP) (Y axis) vs. relative abundances (%) of *Globorotalia truncatulinoides* dextral morphotype (X axis). Gray band corresponds to the *Globorotalia truncatulinoides* dextral Last Abundance Peak (*GtdLAP*).

Beside the peaks, the coiling directions of *G. truncatulinoides* have been successfully applied for biostratigraphic and paleoceanographic analyses (e.g. Ericson

& Wollin, 1968; Feldmeijer et al., 2015; Ducassou et al., 2018). However, the relatively low abundances in our cores prevent us from doing a robust reconstruction of the changing proportions between coiling morphotypes through time.

*Globigerinella calida vs. Neogloboquadrina incompta*

Relative abundances of opposite ecological species have been applied in the Mediterranean Sea (Capotondi et al., 1999; Sbaffi et al., 2001; Pérez-Folgado et al., 2003) and the South Atlantic (Vicalvi, 1977; Rodrigues & Carvalho, 1980). Following this idea we explore the relative abundances of *G. calida* vs. *N. incompta* as a Holocene-Pleistocene transition marker (Fig. 4D,J).

The species *G. calida* presents low abundances during the Pleistocene portion registered in our cores, when cooler conditions are expected, while *N. incompta* displays higher percentages. When the Holocene started, the proportions were alternated, decreasing *N. incompta* and increasing *G. calida*. The excluding ecological preference (Fig. 8) of these species, *G. calida* typical of tropical and subtropical water, *N. incompta* typical of subpolar water (Kucera, 2007), also could allow us to differentiate the Pleistocene/Holocene boundary in the Pelotas basin.

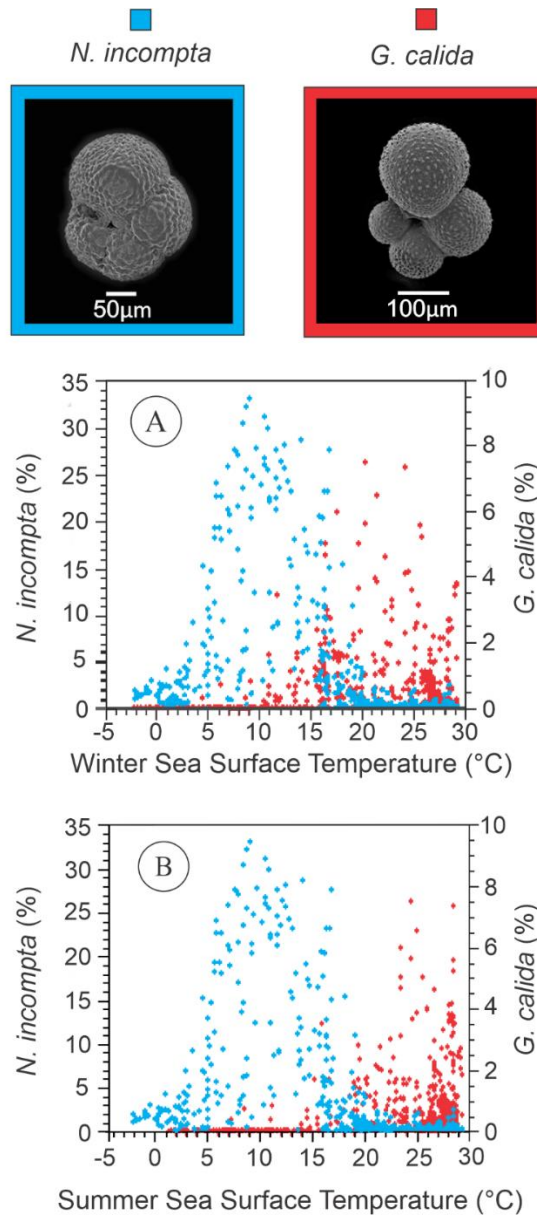


Fig. 8. Relative abundances of the species *Neogloboquadrina incompta* and *Globigerinella calida* versus (a) Winter Sea Surface Temperature (°C), and (b) Summer Sea Surface Temperature (°C), modified from Hilbrecht (1996). From the image it is possible to see the clear the excluding ecological niche character of both species, which correspond to the subpolar and sub/tropical bio-provinces, respectively (Kucera, 2007), and make them useful for identifying the Pleistocene-Holocene transition recognition in the SBCM.

## 6. Conclusions

The analysis of planktonic Foraminifera biostratigraphic taxa through time allowed the assessment of the applicability of the bioecozonations established for the SEBCM in the SBCM, with the partial recognition of the bioecozones Y and Z and the chronologic bio-events calibration. The age model of the core SAT-048A spans the last 43 kyr, while the core SIS-188 the last 33 kyr, both lacking the Late Holocene. The diachronism of the limit Y/Z with the Pleistocene/Holocene boundary, already documented in the SEBCM, is here documented for the first time in the Pelotas Basin at 8.4 and 7.4 ka BP. The limit Y2/Y1 in the Pelotas Basin was found at 26.5 and 23.5 ka BP, a delay of 20 kyr according to previous reports in the SEBCM, agreeing with the time progressive disappearance “model” proposed for the Atlantic Ocean. The age limit Y1B/Y1A was found at 15.6 and 10.2 ka BP. The southern position and cooler conditions of the Pelotas Basin influenced the lower relative abundances of the *G. menardii* complex and *P. obliquiloculata* for our cores. The increase of the *G. truncatulinooides* dextral (*GtdLAP*) and the *G. cal:N.inc* ratio show up to better document, in the cores of the SBCM and SEBCM basins, the Pleistocene-Holocene transition. Thus, the reversal changes of planktonic Foraminifera relative abundances in the latest Quaternary are shown as useful tools (when properly calibrated), despite the diachronous boundaries already documented for the whole Atlantic.

The AMS  $^{14}\text{C}$  inversions, recurrent in this region, seem to show an unstable and active slope, but the faciology does not show variations. Therefore, it is suggested to study how contour currents could rework planktonic Foraminifera and how this could affect the microfossil record. Future studies, integrating paleomicroontology, geochemistry and seismic stratigraphy, are necessary to understand the possible relationship of age inversions with ocean floor stability, selective transport of planktonic Foraminifera shells or geochemical diagenetic alterations.

Finally, assessing the applicability of SEBCM bioecozonations in the cores SAT-048A and SIS-188 represents only “the tip of the iceberg”. Their short register and location showed the applicability, of some synchronic and many asynchronous bioecozone limits. But more studies are required, especially for the southern portion of the Pelotas Basin which experiments a stronger alternation between warm and cool foraminiferal bioprovinces, in order to find new key species. In order to assess the real

potential of the biostratigraphic limits, studies with higher resolution cores, as well as longer temporal records, and strong age models, are crucial to avoid mistakes of false time-limits correlation. For now, due to the offsets of the bioecozonations limits in the marginal South Brazilian sedimentary basins, better calibrated age models are mandatory for core comparisons, meanwhile, their spatial-temporal boundaries are better known.

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## Supplementary material

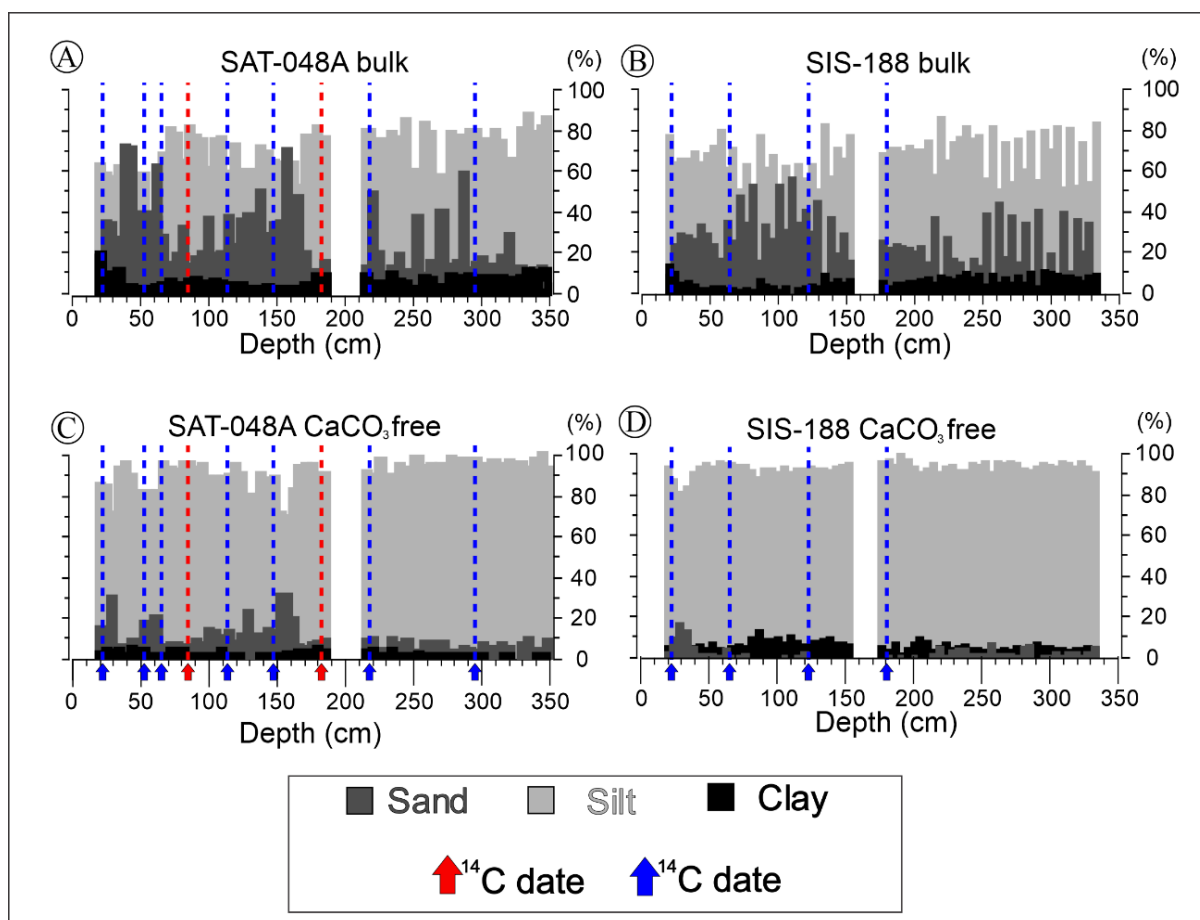
The AMS  $^{14}\text{C}_{G. rub}$  results of cores SIS-188 and SAT-048A are shown in Table S1. The  $^{14}\text{C}$  ages were corrected for reservoir effect using the Marine Reservoir Correction Database (Delta R=54.0+/-42.0) based on ages from Angulo et al. (2005), and Alves et al. (2015). Calibrated ages were obtained according to the calibration curve Marine13 (Reimer et al., 2013).

Table S1. SIS-188 (Duque-Castaño et al., 2019) and SAT-048A (Frozza et al., 2020) AMS  $^{14}\text{C}_{G. rub}$  ages and calibrated ages (corrected by global and local reservoir effects).

Core	Sample		Species	Age $^{14}\text{C}$ (ka BP)	Error (ka)	Calibrated $^{14}\text{C}$ age (ka BP)
	depth (cm)	LAC-UFF sample code				
SIS-188	21	170210	<i>G. ruber</i>	6.725	0.031	7204
	54	170055	<i>G. ruber</i>	9.921	0.034	10812
	113.5	170056	<i>G. ruber</i>	21.360	0.059	25243
	180.5	170211	<i>G. ruber</i>	26.325	0.077	30099
SAT-048A	23	170209	<i>G. ruber</i>	5.471	0.032	5.791
	54	180167	<i>G. ruber</i>	10.594	0.117	11.756
	65	190321	<i>G. ruber</i>	13.548	0.038	15.700
	85	180168	<i>G. ruber</i>	16.599	0.212	19.470*
	113	180169	<i>G. ruber</i>	15.531	0.185	18.309
	149	190704	<i>G. ruber</i>	19.536	0.104	22.973
	183.5	190323	<i>G. ruber</i>	31.174	0.271	34.643*
	217	180170	<i>G. ruber</i>	22.997	0.451	26.797
295	190540	<i>G. ruber</i>	38.997	0.260	42.560	

\*AMS  $^{14}\text{C}$  dates samples with reversals along the core.

The results of the grain sizes (%) vs. depth (cm) are shown in Fig. S1.



*Fig. S1.* Results of grain sizes (bulk and CaCO<sub>3</sub> free) for cores SIS-188 and SAT-048A: sand (% , dark gray bars), silt (% , light gray bars) and clay (% , black bars). Red arrows and lines indicate the AMS  $^{14}\text{C}$  reversals. The grain size record does not reveal abrupt shifts that could be related to sudden sedimentological processes. Bulk samples with sand have low sand content in CaCO<sub>3</sub> free, which means that sand particles mostly correspond to calcareous microfossils.

## Capítulo 3

### **Paleoceanographic fluctuations and planktonic Foraminifera dissolution during the last glacial-interglacial interval at the western South Atlantic**

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#### **Highlights:**

- ✓ High (low) productivity was found during glacial (postglacial) times.
- ✓ Precessional-related changes were observed in microfossil and geochemical proxies.
- ✓ Paleoproductivity fluctuations were evidenced in the bottom organic matter flux.
- ✓ Enhanced productivity increased the planktonic Foraminifera tests dissolution.

#### **Abstract**

Paleoceanographic studies reconstructing surface paleoproductivity and benthic conditions are important because they allow us to measure the biological pump effectiveness. In order to assess the effect of productivity changes, a multiproxy paleoceanographic reconstruction (planktonic Foraminifera assemblages, geochemical and sedimentological analyses) were conducted on the core SAT-048A, recovered from the continental slope of the southern Brazilian margin. The reconstruction enabled us to recognize changes related to glacial-interglacial and precessional cycles. From the benthic-pelagic data fluctuations, four intervals were established. In general, the glacial (postglacial) corresponds to high (low) surface productivity, high (low) organic matter (OM) fluxes to the seafloor and high (low) dissolution rates of the planktonic Foraminifera tests. Within the glacial, similar patterns were observed for higher insolation values (even more enhanced productivity). Nevertheless, the impact of bottom water dynamics should be better assessed, since changes in the Atlantic Meridional Overturning circulation and the reorganization of water masses, may change the CO<sub>3</sub><sup>2-</sup> saturation levels, this influencing carbonate preservation.

**Keywords:** Late Quaternary, Micropaleontology, Stable Isotopes, Paleotemperature, Paleoproductivity, Fragmentation, Carbonate preservation

#### **1. Introduction**

The Late Quaternary climate is characterized by orbit-related glacial-interglacial fluctuations (EPICA Community Members, 2004; Jouzel et al., 2007) associated to CO<sub>2</sub> ppm



variations (Petit et al., 1999; Shakun et al., 2012). Nevertheless, orbital cycles changes are not enough to induce such temperature changes, and thus, feedbacks in the Earth's climate system are expected to amplify (or reduce) the primary signal (Lorius et al., 1990; Shackleton, 2000). An intensified biologic pump in the oceans, and therefore an increase of exported biogenic carbon -along with biogenic carbonate- burial in the sediments (Brummer & van Eijden, 1992), is expected during glacial times as a mechanism to remove atmospheric CO<sub>2</sub>. Since planktonic Foraminifera are important contributors of pelagic calcium carbonate flux (Milliman et al., 1999; Schiebel, 2002; Kučera, 2007) they represent an important piece in the global climate system to be studied, due to their capacity to remove CO<sub>2</sub> and contribute to its storage in the marine sediments.

Furthermore, high biological surface productivity can: i) boost the benthic communities (Cronin et al., 1999), leading to the remineralization of higher percentages of organic matter (OM) and, decreasing the biologic carbon burial; ii) free more CO<sub>2</sub> (*e.g.* due to respiration processes; Hales, 2003) and dissolve larger quantities of biogenic carbonate, (*e.g.* planktonic Foraminifera tests; Schiebel, 2002). Therefore, biologic pump can have a contrary effect (Zamelczyk et al., 2012; Naik et al., 2014).

Since the study area (Fig. 1) was affected by a high glacial productivity (Gu et al., 2017; Pereira et al., 2018; Portilho-Ramos et al., 2019), it is a good opportunity to study the effects of this higher OM fluxes to the seafloor. Therefore, this chapter intends to reconstruct the past sea surface and bottom oceanographic characteristics, using a multiproxy analysis (paleomicrotological, geochemical and sedimentological), in order to better understand the benthic-pelagic dynamic during the last glacial-interglacial interval in the western South Atlantic.

## **2. Regional setting**

The studied core comprises sediments from the Pelotas Basin, located off Santa Marta Cape (Fig. 1), in the western South Atlantic. The proximal portion of the continental shelf of the Pelotas Basin represents a submerged coastal plain (Martins, 1984) that was exposed during the last Pleistocenic regression (Marine Isotope Stage 2) and dissected by drainage networks from fluvial systems (Weschenfelder et al., 2014), contributing with larger inputs of terrestrial nutrients compared to the Holocene.

Surface circulation in the shelf portion of the study area is dominated by the northward Brazilian Coastal Current, which carries the Coastal Water (CW), a mixture of oceanic and continental drainage waters. Offshore, the Brazil Current (BC) transports southward the warm (temperature,  $T > 20^\circ\text{C}$ ) and salty (salinity,  $S > 36$  psu) Tropical Water (TW) at the surface layer. The BC flows along the South American margin slope until it converges with the Malvinas Current (MC), a northward surface current carrying cold ( $T < 15^\circ\text{C}$ ) and fresher ( $S < 34.2$  psu) Subantarctic Water, forming the Brazil/Malvinas Confluence (BMC) close to  $38^\circ\text{S}$  (Gordon & Greengrove, 1986). The BMC forms a large meander which separates southward from the continental margin (Peterson & Stramma, 1991; Piola & Matano, 2017), and varies seasonal and interannually, moving to the North in austral autumn and winter, and to the South in spring and summer, influencing the nutrient distribution along the continental shelf of the Argentinian, Uruguayan and southern Brazilian coasts (Gonzalez-Silvera et al., 2006). Presently, two main continental sources of nutrients and freshwater for the area are the Río de la Plata Estuary and the Patos-Mirim lagoon system. Although the configuration of continental drainage certainly changed under the varying sea-level conditions of the late Quaternary, they both represent sources of continental drainage, and thus, nutrients to the study area.

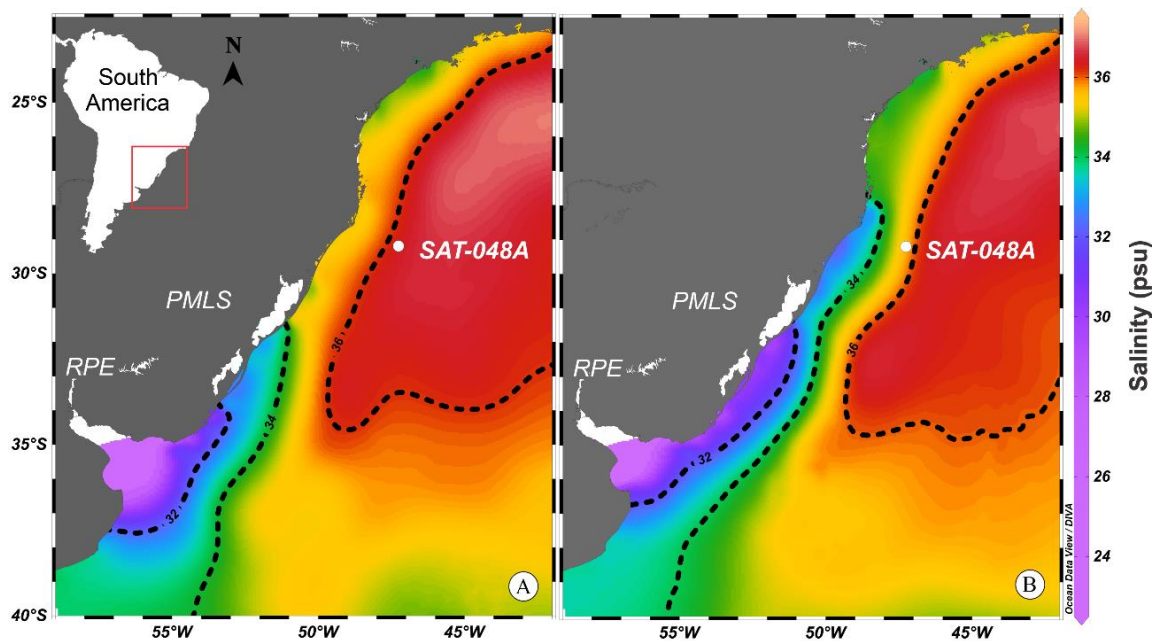


Fig. 1. Location of the core SAT-048A and seasonal variation of average sea surface salinity in the study area for the months of (A) January-March (B) and July-September, according to the World Ocean Atlas 2013 (WOA13, Zweng et al., 2013). The isohalines 32, 34 and 36 psu (dashed lines) highlight the less saline water intrusion from the south during the austral winter

according to the wind regime. Present Río de la Plata Estuary (RPE) and Patos-Mirim Lagoon System (PMLS) represent important continental nutrients sources to the study area.

The water masses that circulate in subsurface (Fig. 2) immediately below the TW are divided into: South Atlantic Central Water (SACW), Antarctic Intermediate Water (AAIW), Upper Circumpolar Deep Water (UCDW), North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) (Reid et al., 1976; Campos et al., 1995; Hogg et al., 1996; Stramma & England, 1999). The NADW represents warmer and saltier water bodies when compared to AAIW, UCDW and AABW. In addition, the NADW also promotes the preservation of carbonate, due to the oversaturation of the carbonate ion ( $\text{CO}_3^{2-}$ ), in relation to the overlying UCDW and the underlying AABW, which are both undersaturated with respect to  $\text{CO}_3^{2-}$  and, therefore, may lead to the dissolution of carbonate (Frenz et al., 2003). Indeed, the interface between the NADW and the AABW defines the depth of the lysocline (Frenz & Henrich, 2007), through which occurs a great change in the dissolution indexes.

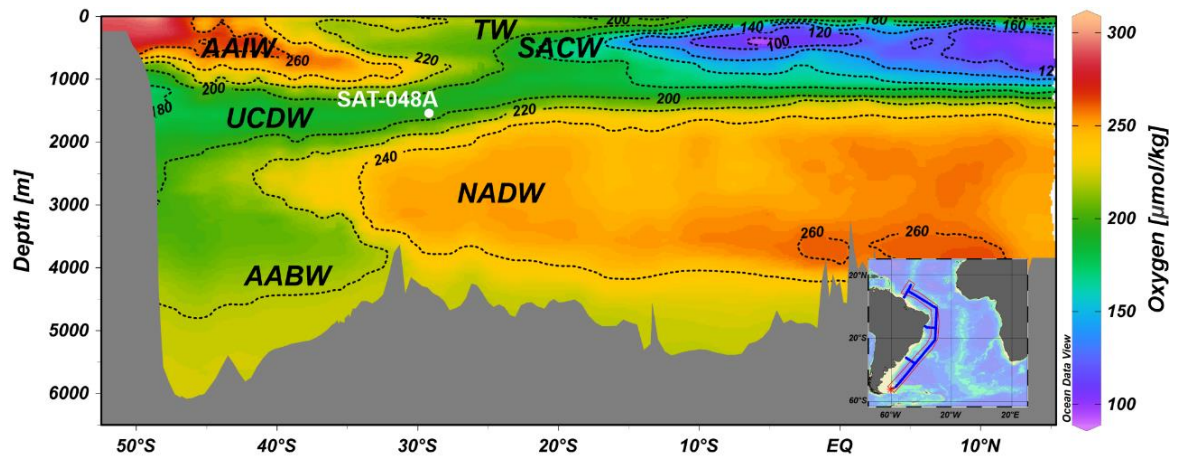


Fig. 2. Isolines (dotted curves) of dissolved Oxygen concentrations ( $\mu\text{mol/kg}$ ) from a section of the South American Continental Margin, showing the South Atlantic water masses that circulate in the region: Tropical Water (TW), South Atlantic Central Water (SACW), Antarctic Intermediate Water (AAIW), Upper Circumpolar Deep Water (UCDW), North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW).

### 3. Material and methods

The piston core SAT-048A, with a total recovery of 315 cm, was collected by FUGRO Brasil – Serviços Submarinos e Levantamentos Ltda for the Agência Nacional do Petróleo

(Brazilian National Agency of Petroleum, Natural Gas and Biofuels) at 29°11'S, 47°15'W, 1542 m water depth (Fig. 1). The core was sampled at intervals of about six cm, totalizing 54 samples, already studied by Suárez-Ibarra et al. (submitted, chapter 2). Each sample was washed over a 0.063 mm sieve and oven dried under temperature below 60°C. The taxonomical identification of the planktonic Foraminifera species, from subsamples of at least 300 specimens larger than 0.15 mm, followed Bé (1967), Bé et al. (1977), Bolli & Saunders (1989), Hemleben et al. (1989), Kemle von Mücke & Hemleben (1999), Schiebel & Hemleben (2017) and Anjos-Zerfass (2019).

For the age model, it was used a revised version of the Frozza et al. (2020) age model, carried out by Savian et al. (submitted), based on rbacon package (Blaauw & Christen, 2011; version 2.4.2; R Core Team, 2019) considering the Laschamp geomagnetic excursion as a control point besides the ten AMS radiocarbon dates.

Past Sea Surface Temperatures (SST) were estimated using the Modern Analogue Technique (MAT, Hutson, 1980) tool from the software PAST (version 3.2; Hammer et al., 2001) considering two depths: 0–75 m (mean value for the 75 m depth range) and 100 m (single depth). The SST were calibrated with a dataset composed as follows: i) relative abundances of planktonic Foraminifera of surface sediments from the South Atlantic Ocean extracted from the ForCenS database (Siccha & Kucera, 2017) coupled to ii) modern mean annual temperature estimates obtained from the World Ocean Atlas 2013 (Locarnini et al., 2013) extracted with the software Ocean Data View (Schlitzer, 2020).

Paleoproductivity was assessed from the relative abundances of the species *Globigerinita glutinata* (Conan et al., 2000; Souto et al., 2011), the ratio between *Globigerina bulloides* and *Globigerinoides ruber* (*G.bull*:*G.rub*, Conan et al., 2002; Toledo et al., 2008), the benthic:planktonic Foraminifera ratio (Berger & Diester-Haass, 1988; Loubere, 1991, Gooday, 2002), called B:P hereafter, the ostracod abundance (number of valves in the >0,150 mm fraction per gram of sediment), and the  $\delta^{13}\text{C}$  record of *Uvigerina* spp. (Mackensen, 2008). Part of these data were already published by Frozza et al., (2020). As a sea surface fertilization index, the  $\delta^{13}\text{C}$  record of *G. ruber* pink morphotype was analyzed (Wefer et al., 1999). For oxygen and carbon stable isotope analyses, approximately seven specimens of the benthic genus *Uvigerina* spp. ( $\delta^{18}\text{O}_{Uvi}$ ,  $\delta^{13}\text{C}_{Uvi}$ ; Frozza et al., 2020) and 12–15 specimens the planktonic species *G. ruber* (pink morphotype) ( $\delta^{18}\text{O}_{G.rub}$ ,  $\delta^{13}\text{C}_{G.rub}$ ) were selected from the > 0.250 mm fraction.

The dissolution effect was estimated based on the planktonic Foraminifera fragmentation (Berger, 1970), bulk sand fraction (%), Berger et al., 1982; Gonzales et al.,

2017; data from chapter two), volume of Planktonic Foraminifera (PF/g, Le & Shackleton, 1992) and CaCO<sub>3</sub> (%). The Berger (1970)'s method includes two analyses: i) the broken (from 90 to 50% of the tests) and ii) fragment (smaller than 50% but larger than 150 µm) remains counting. Bulk sand contents were determined using a laser diffraction particle size analyzer Horiba Partica-LA-950. The calcium carbonate content for the samples was determined by weight loss after reaction with 10% hydrochloric acid (HCl) at the Calcareous Microfossils Laboratory of the *Universidade Federal do Rio Grande do Sul* (UFRGS).

#### 4. Results

The core SAT-048A sediments correspond to hemipelagic muds rich in carbonate. The average grain size of the samples is slightly sandy mud, ranging from slightly clayey mud to muddy sand in some cases. The core corresponds to the Latest Pleistocene and Early/Middle Holocene muds of the Imbé formation. The age model (Savian et al, submitted) revealed a sediment recovery ranging from 43 to 5 ka BP, with sedimentation rates varying between 3 to 10 cm/kyr (Fig. 3).

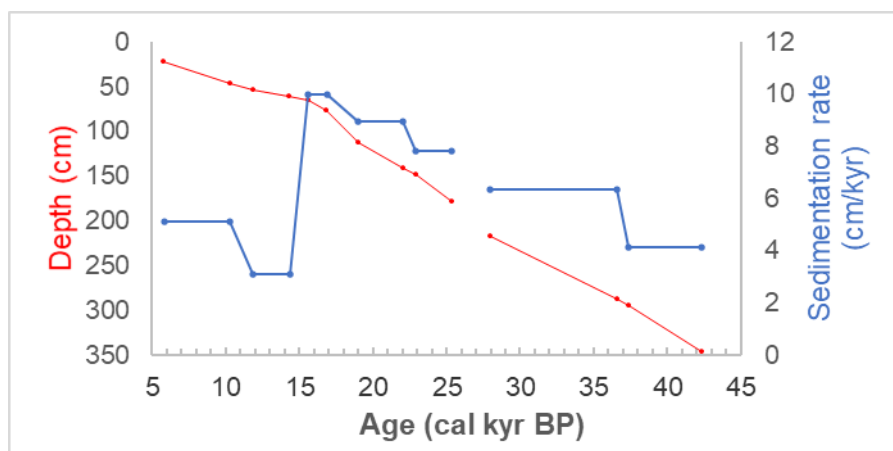


Fig. 3. The sedimentation rate (cm/kyr) through the time-span recorded by core SAT-048A shows a progressive increase from 43 to 15 ka BP, when it decreases to a minima between 14 and 11 kyr BP and remains low until 5 ka BP. Data gap interval corresponds to unavailable samples.

#### Planktonic Foraminifera

Some planktonic Foraminifera species display two contrasting temporal distribution patterns: i) species with higher abundance values during the late Pleistocene (*G. glutinata*, *G. bulloides*, *G. inflata* and *N. incompta*) that decreased towards the Holocene (Fig. 4) and ii)

species with lower abundance values during the late Pleistocene (such as *G. ruber* white and pink, *Trilobatus trilobus*, *G. menardii*, *G. calida*, *O. universa*, *G. tumida* and *G. conglobatus*) and higher abundances in the Holocene (Fig. 5). These two groups correspond respectively to cool and warm water species.

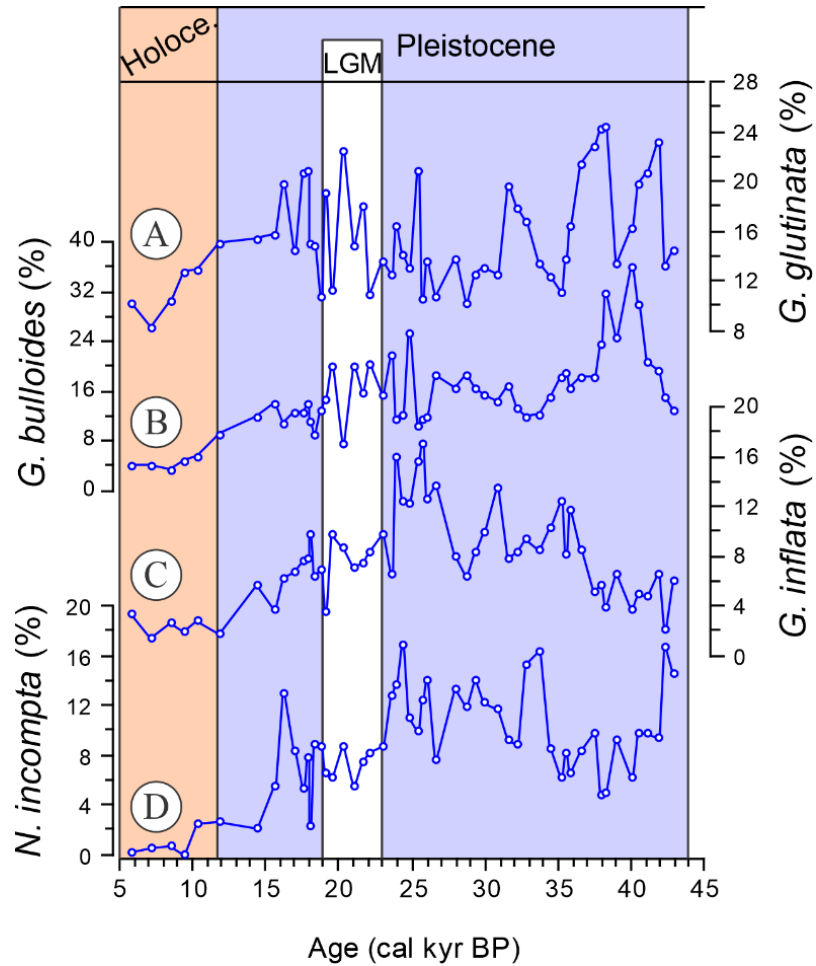


Fig. 4. Relative abundances (%) of cool water species (Kucera, 2007) along the core SAT-048A reveal a decrease pattern from the latest Pleistocene to Recent. (A) *G. glutinata*, (B) *G. bulloides*, (C) *G. inflata* and (D) *N. incompta*.

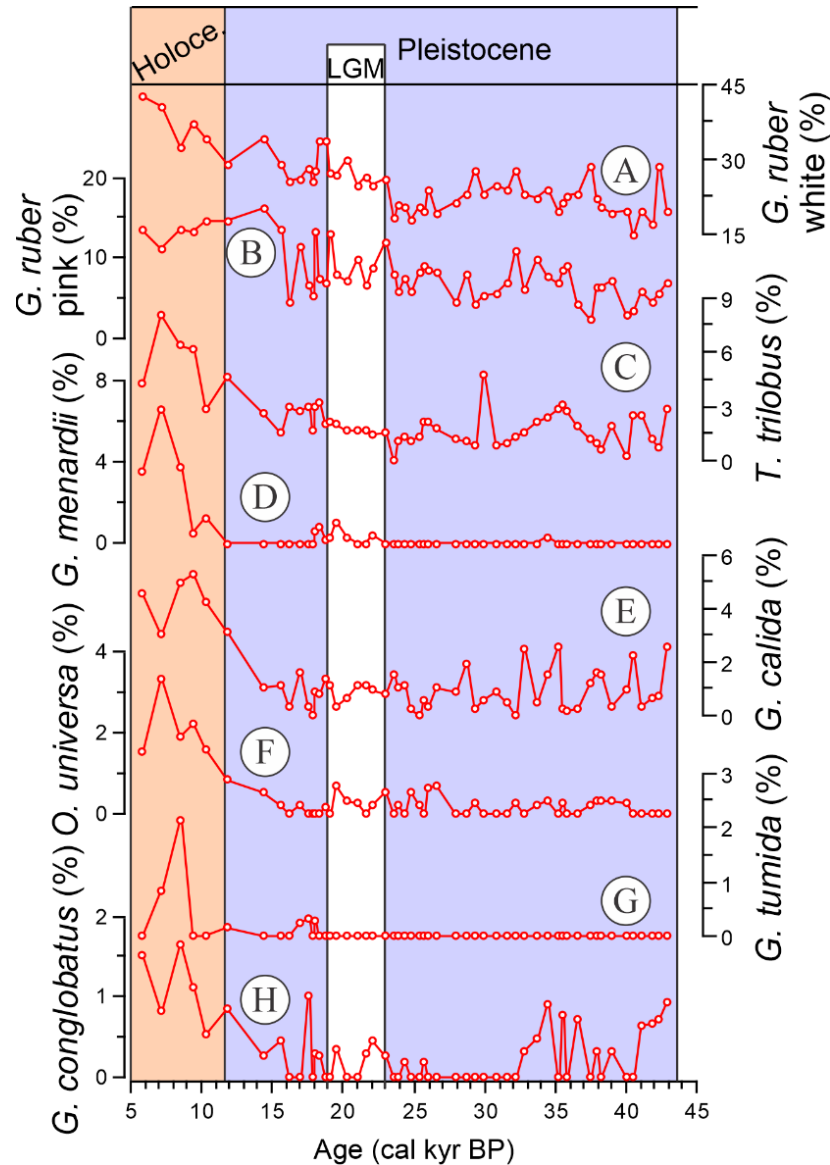


Fig. 5. Relative abundances (%) of warm water species (Kucera, 2007) along the core SAT-048A displaying an increase pattern from the Holocene onset to Recent. (A) *G. ruber* white, (B) *G. ruber* pink, (C) *T. trilobus*, (D) *G. menardii*, (E) *G. calida*, (F) *O. universa*, (G) *G. tumida* and (H) *G. conglobatus*. Nevertheless, *G. ruber* white (A) started to increase right before the Last Glacial Maximum (LGM) and *G. ruber* pink (B) between the LGM end the Holocene.

#### Sea Surface Temperatures (SST) estimates

The annual mean temperature estimates for the upper 75 meters showed a high variability from 43 ka BP until 16 ka BP (Fig. 6). From then, the values remained comparatively more stable, although the lower sedimentation rate (Fig. 3) starting at around 16 ka BP results in a lower temporal resolution, given the constant sampling interval. The trend of strongly variable but overall cooler temperatures changes at around the Last Glacial



Maximum (LGM), when a warming trend was established, extending until the Holocene. No cooling was observed during the LGM. In contrast, the subsurface paleotemperatures at 100 m showed less variable values for the 43 – 25 ka BP period, but preserved the same warming trend observed for the upper 75 m from the LGM onwards.

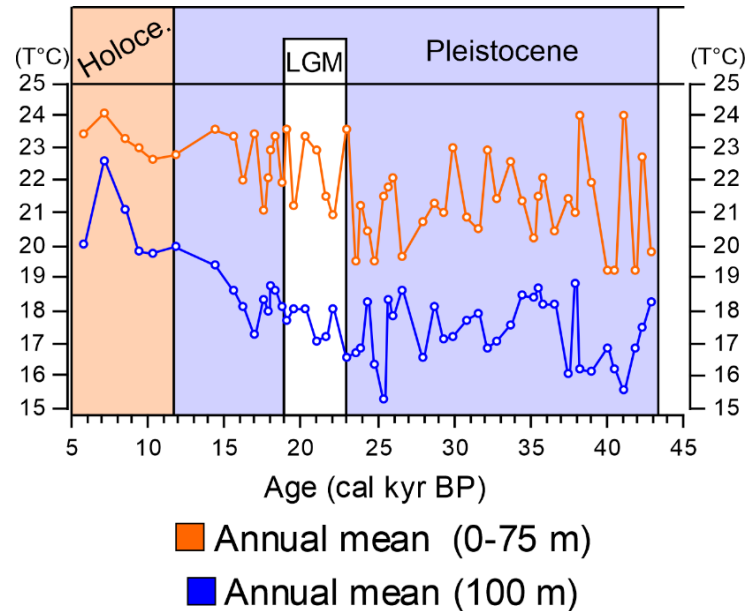


Fig. 6. Modern Analogue Technique (MAT) annual mean paleotemperature estimates for the upper 75 m (orange curve) and for 100 m depth (blue curve) at the study site. Besides their different temperature ranges, both curves agree on a clear tendency to warmer surface and subsurface waters since the Last Glacial Maximum (LGM).

#### Paleoproductivity

For the 43 – 35 ka BP portion, the highest values for four (Fig. 7A–D) of the paleoproductivity tracers are observed. Continuing with a decreasing trend, the 35 – 25 ka BP interval is characterized by lower values, except by the ostracods' abundance (Fig. 7F), which shows a small increment. Subsequently, from 25 to 13 ka BP, all the indicators except the *G.bull*:*G.rub* ratio, exhibited relatively higher values, although generally smaller than those from the 43 – 35 ka BP interval. The *G.bull*:*G.rub* ratio started a decreasing trend around 25 ka BP. From 13 ka BP onwards, a progressive decreasing trend is established until 5 ka BP, registering the lowest values of the record.



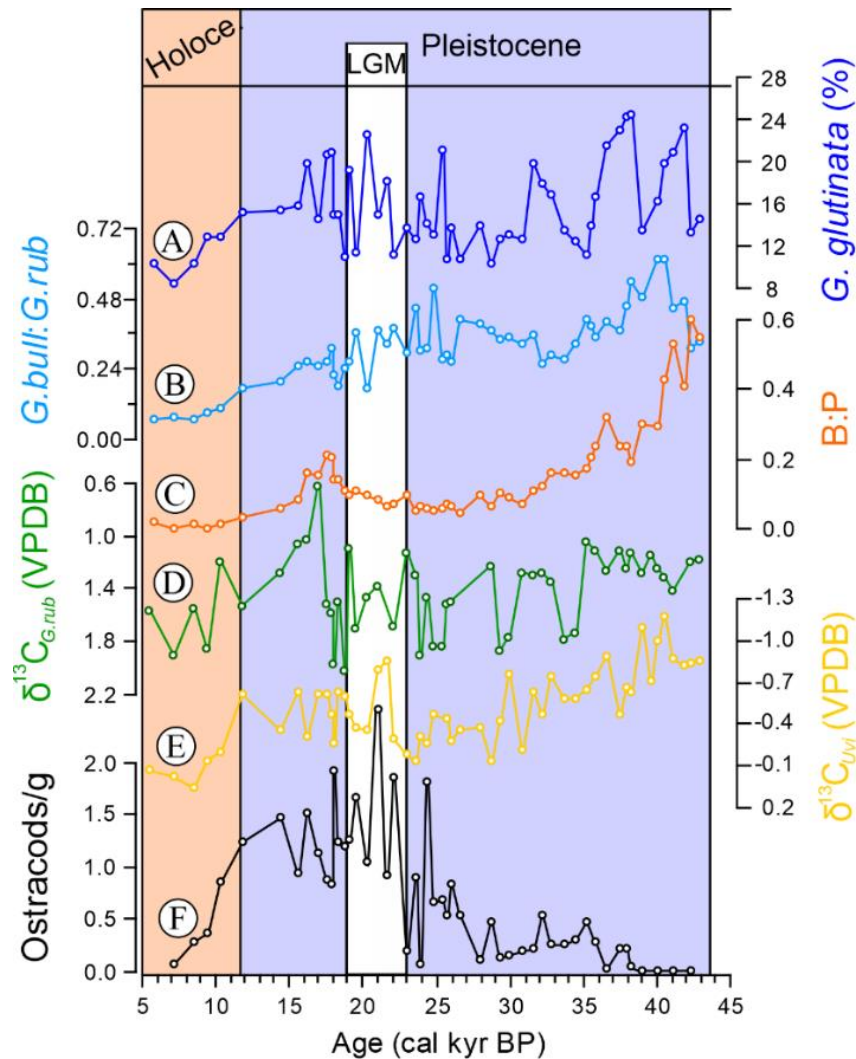


Fig. 7. Paleoproductivity and paleofertility estimates for the core SAT-048A based on relative abundances (%) of (A) *G. glutinata*, (B) *G.bull:G.rub* ratio, (C) Benthic:Planktonic Foraminifera proportion, (D)  $\delta^{13}\text{C}_{G.rub}$ , (E)  $\delta^{13}\text{C}_{Uvi}$  and (F) ostracod abundance (number of valves/g).

#### Dissolution indicators

The broken index (Fig. 8A) showed low values since 43 ka BP until 25 ka BP, and increased during the LGM. Since the end of the LGM until the Pleistocene/Holocene transition a decreasing trend was established remaining low until 5 ka BP. The fragment index (Fig. 8B) displays a decrease since the base of the record up to 25 ka BP, where values remained variable until 16 ka BP, as the lowest values are obtained during the Pleistocene/Holocene transition, and increased at 10 ka BP. In general terms, the  $\text{CaCO}_3$  content, the PF/g and bulk sand content (Fig. 8C–E) show a stable increasing trend towards better preservation conditions from 43 to 24 ka BP. From 24 to 15 ka BP the trend is inverted

and reached better preservation conditions before the Holocene onset, after which there is another increase in dissolution.

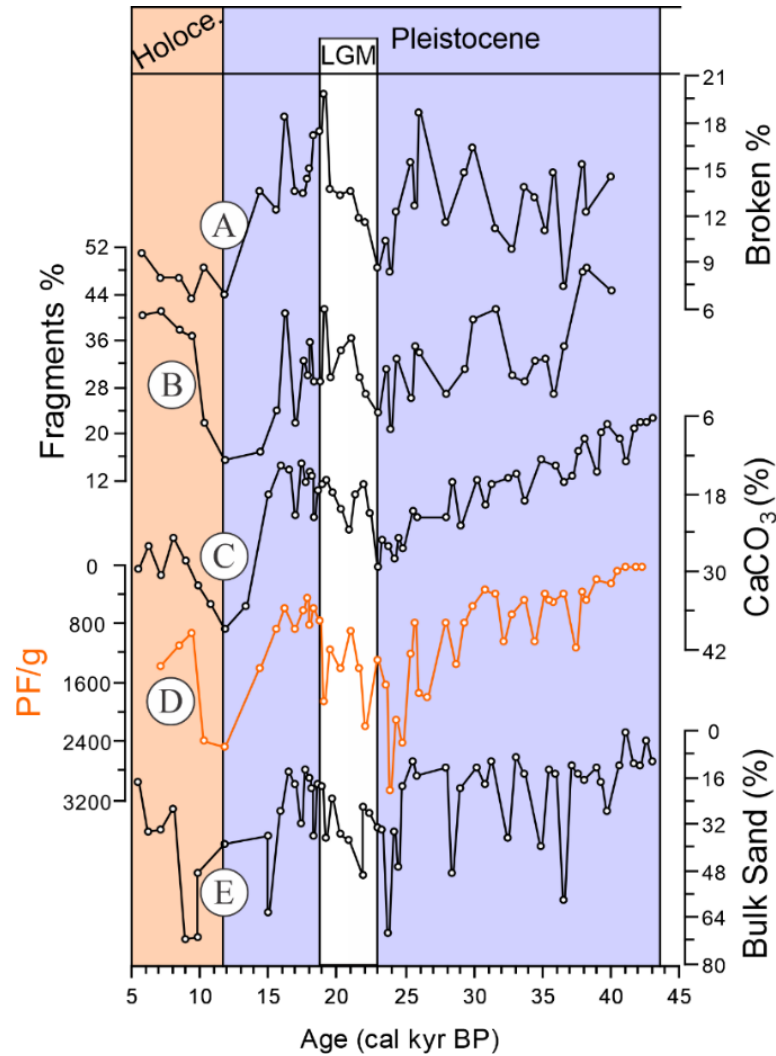


Fig. 8. Dissolution indicators applied to the core SAT-048A: relative abundances of (A) broken foraminifera (%), and (B) fragments (%), (C)  $\text{CaCO}_3$  content (%), (D) Planktonic Foraminifera (tests per gram) and I proportion of sand in bulk samples (%). Inverted axes in C–E to aid visualization.

## 5. Discussion

The estimated sedimentation rate for core SAT-048A varies according to relative sea level fluctuations (Fig. 9), reaching the highest values during the lowest relative sea levels, pattern already found for lower latitudes of the South Brazilian Continental Margin (SBCM) (Mahiques et al., 2007 Kowsmann et al., 2014).

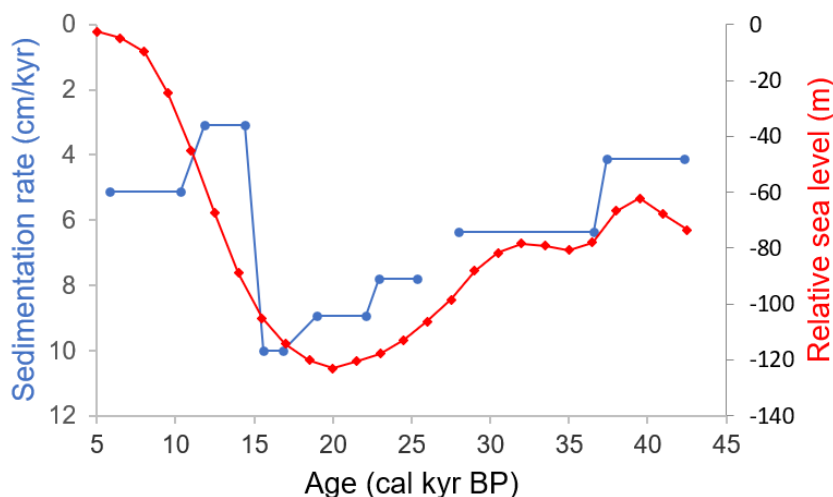


Fig. 9. Sedimentation rates (blue) of core SAT-048A for the last 43 – 5 ka BP, varying according to the mean eustatic or ice-volume equivalent sea level fluctuation (red) (Waelbroeck et al., 2002).

#### Long term fluctuations

#### Paleoproductivity

Portilho-Ramos et al. (2019) explained the high productivity during the last glacial by two mechanisms: i) prolonged winter conditions and ii) short austral summer upwellings. The first implies prevalent southwesterly (SW) winds year-round carrying discharges from the Río de La Plata (Pimenta et al., 2005; Piola et al., 2005) and continental outflow from sources that presently converge at the Patos-Mirim lagoon system closer to the study area (Piola et al., 2000; Nagai et al., 2014). Strengthened SW winds would also displace the BMC closer to the area (Gonzalez-Silvera et al., 2006). The high relative abundance of *G. inflata* and *N. incompta* (Fig. 4C,D) can be interpreted as a closer BMC, due to the enhanced SW winds during the late last glacial. The second mechanism involves the northeast (NE) winds flowing along the shore and pushing surface waters offshore due to the Ekman transport, allowing the summer upwelling (Chen et al., 2019). The temperatures cooler than 20°C at 100 m depth (Campos et al., 2000; Silveira et al., 2000; Castelão et al., 2004), along with *G.bull*:*G.rub* ratio values higher than 0.25 (Lessa et al., 2014), can be interpreted as a constant presence of the SACW in the subsurface during the short austral upwelling of the late glacial (Fig. 10).

Additionally, Mahiques et al. (2007) proposed that, during low sea levels (glacial), the offshore position of the BC favored the input of nutrients and terrigenous particles. Higher terrigenous input is also expected under lower relative sea levels due to the exposure of part of the continental shelf. Moreover, the Río de la Plata (Lantsch et al., 2014) and Jacuí and

Camaquã paleo-discharges (Weschenfelder et al., 2014) were closer to the study area during this interval. Higher Fe/Ca values (Heil, 2006), higher proportion of eutrophic dinocysts (Gu et al., 2017) and high terrestrial palynomorphs proportions (Bottezini et al., 2019), are all evidence of the greater influence of continental outflow in the study areas under lower relative sea levels of the late last glacial.

In contrast, for the Holocene, the onshore displacement of the BC, along with higher relative sea levels and no SACW intrusions, inhibited the photic zone fertilization, leading to oligotrophic conditions.

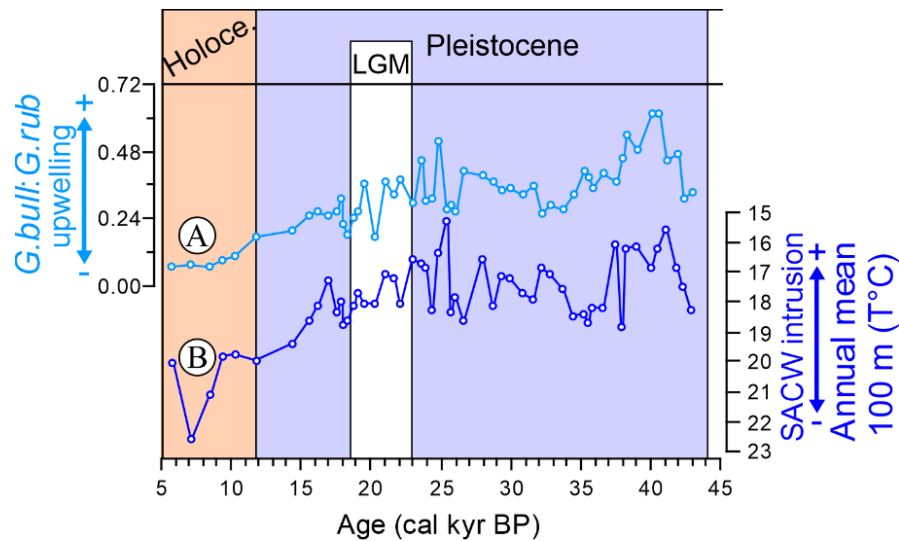


Fig. 10. (A) *G.bull:G.rub* ratios and (B) annual mean 100 m temperatures for the core SAT-048A. Intervals with higher *G.bull:G.rub* ratios and temperatures cooler than 20°C are interpreted as presence of the SACW in the subsurface, as a result of late glacial enhanced upwelling.

#### Paleotemperatures

The SAT-048A SST reconstructions showed variable cooler temperatures until 25 ka BP along with a warming and relatively stable trend afterwards, with the coolest temperatures being registered prior to the LGM. Besides, the surface (0-75 m) annual mean temperature increased faster than the subsurface estimates (Fig. 6), which showed a more gradual warming during the LGM. Warming trends during the LGM were also recorded by Pereira et al. (2018) and Portilho-Ramos et al. (2019). This occurs in a context of gradual Atlantic Meridional Overturning Circulation (AMOC) weakening, leading to uninterrupted heat accumulation in the subtropical South Atlantic gyre and, therefore, a high glacial maxima out-of-phase (Santos et al., 2017). Luz et al. (2020) showed that this cool or warm water presence during the LGM is associated to the water masses that interplay at the surface near the continent: the offshore

and warm TW brought by the BC and the onshore and cooler CW brought by the Brazil Coastal Current (BCC) (Luz et al., 2020, and references therein). The authors found that the alkenone-derived SST estimates differed according to the BC/BCC (TW/CW) influence: the shallower and closer to the coast core (RJ-1501) registered a late deglacial warming, while in the deeper and more offshore core (RJ-1502), the early deglacial warming trend (Santos et al., 2017) was recognized.

#### Short term fluctuations

##### Surface paleoproductivity

Four intervals for the last 43 kyr can be defined according to the fluctuations in productivity indicators: IV (43 – 35 ka BP), III (35 – 24 ka BP), II (24 – 13 ka BP) and I (13 – 5 ka BP) (Fig. 11). The intervals IV, III and II were characterized by higher productivity than interval I. But more interesting are the fluctuations during the late glacial, with intervals IV and II, characterized by a higher summer insolation (Fig. 11F), which led to stronger NE winds and, therefore, to enhanced summer upwelling-fertilization. This was registered by the increased relative abundance of *G. glutinata* (Fig. 11C,D; Conan et al., 2000; Souto et al., 2011) while the relative increase of *Turborotalita quinqueloba* (Fig. 11A) is associated with intrusions of cooler SACW in the photic zone (Souto, et al., 2011; Lessa et al., 2014; Lessa et al., 2016). Although quite variable from 35 – 18 ka BP, the  $\delta^{13}\text{C}_{G.rub}$  decreased values (Fig. 11E) also corroborate the SACW intrusions (Venancio et al., 2014, 2016) and, therefore, higher fertilization in the area (Prell & Curry, 1981; Curry et al., 1992). The higher relative abundance of *Globigerina falconensis* (Fig. 11B) during Intervals IV and II agree with Sousa et al. (2014), who associated this species with eutrophic conditions in the southeastern South Brazilian Margin.

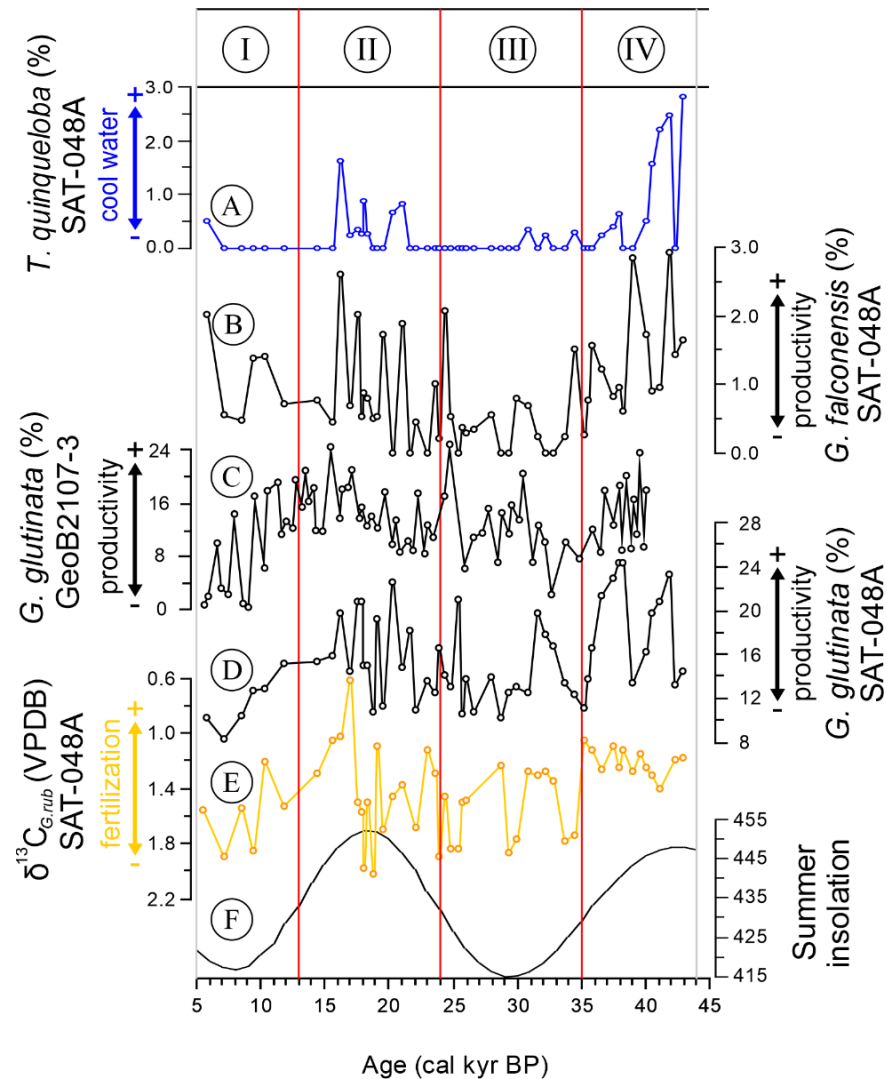


Fig. 11. Fluctuations in temperature, productivity, and fertilization indicators as a response to summer insolation variations at the study site. Relative abundances (%) of (A) *T. quinqueloba* (SAT-048A), (B) *G. falconensis* (SAT-048A), (C) *G. glutinata* (GeoB2107-3, see core location in Fig. 12, Pereira et al., 2018), and (D) *G. glutinata* (SAT-048A), (E)  $\delta^{13}\text{C}_{G.rub}$  on core SAT-048A (SAT-048A) and (F) summer insolation (Laskar et al., 2004). Intervals IV and II are characterized by very high productivity, III by high productivity and I by more oligotrophic conditions. Inverted axes in E to aid visualization.

The orbital forcing linked to the precessional cycle was able to – in a minor contribution – modulate the paleoproductivity fluctuations, in accordance with previous studies showing orbit-related changes (*G. bulloides* – Lessa et al., 2017, 2019; eutrophic environmental dinocysts – Gu et al., 2017; Portilho-Ramos et al., 2019). Along with the orbital forcing, is the “silicic acid leakage hypothesis”, brought by Portilho-Ramos et al. (2019) to explain the glacial high productivity. According to this hypothesis, glacial SACW enriched in dissolved

$\text{Si(OH)}_4$  intruded the subsurface water during the short summer conditions, enhancing diatom blooming. Species of planktonic Foraminifera that feed on diatom like *G. bulloides* or *G. glutinata* can be favored (Schiebel and Hemleben, 2017) under these conditions. Higher diatom record of Bottezini et al. (2019) and *G. glutinata* from SAT-048A for the late glacial support this hypothesis.

The *G.bull:G.rub* ratio and sea subsurface temperatures (Fig. 10) showed a decrease in upwelling and cool water intrusions, respectively, from interval IV (43 – 35 ka BP) to III (35 – 24 ka BP). But no increase (decrease) of *G.bull:G.rub* ratio (sea subsurface temperatures) is registered for section II (24 – 13 ka BP), where higher upwelling would be expected because of the higher summer insolation and stronger NE winds. The absence of an increase can be associated to the record of the heat accumulation in the South Atlantic subtropical Gyre (Santos et al., 2017; Luz et al., 2020), which was observed at 25 ka BP for the SAT-048A core, coinciding with the beginning of interval II, and hampering upwelling. Another factor proposed as a fertilization control in the SBCM are the relative sea level variations (Gu et al., 2017; Pereira et al., 2018, Portilho-Ramos et al., 2019). Since during the interval II the eustatic level was lower (Waelbroeck et al., 2002) than during interval IV, a higher (terrigenous-related) fertilization was expected. However, paleoproductivity estimates for interval II are lower respect to interval IV (Fig. 11), suggesting a small role for the continental terrigenous fertilization for deeper cores. Finally, during interval I, NE winds were not strong enough to effectively pump SACW (which would also be poorer in silicic acid) to the photic zone (as shown by warmer subsurface water SST, low *G.bull:G.rub* ratio, and low relative abundance of *G. glutinata*). Furthermore, the onshore displacement of the BC, along with higher relative sea level, and rivers discharging farther away, inhibited the terrigenous input, leading to oligotrophic conditions. A schematic surface paleoceanographic reconstruction is presented in Fig. 12.

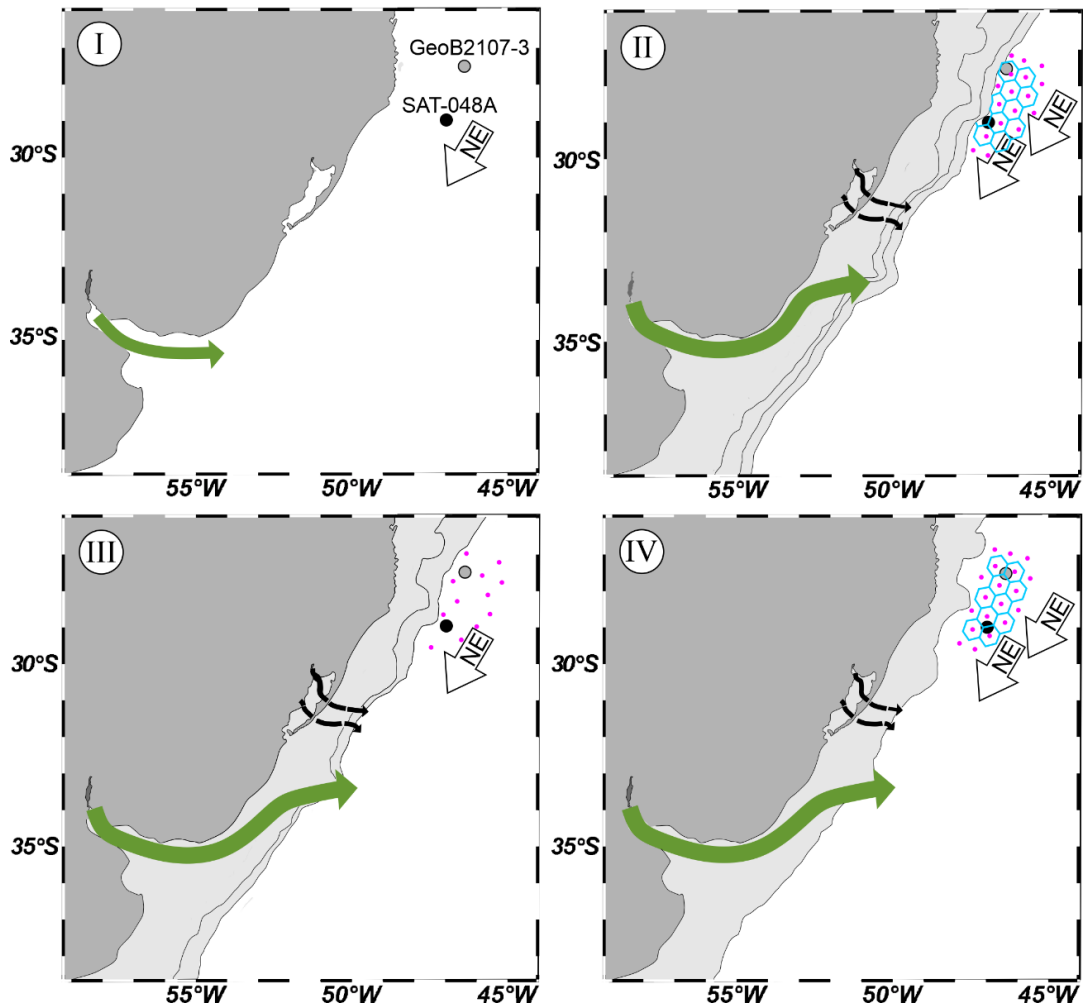


Fig. 12. Schematic sea surface reconstruction for the study area next to the cores SAT-048A and GeoB2107-3 (Pereira et al., 2018). Paleo-relative sea levels according to Waelbroeck et al. (2002). During intervals IV, III and II, the terrigenous nutrients input into the coastal surface waters by de la Plata (green, Lantsch et al., 2014), Jacuı and Camaquı paleo-rivers (black, Weschenfelder et al., 2014) discharges is closer than during interval I. In intervals IV and II, enhanced northeast (NE) winds triggered subsurface water pumping (blue honeycomb), as a mechanism of surface water fertilization. Pink dots represent intrusions in subsurface water rich in dissolved  $\text{Si}(\text{OH})_4$  (Portilho-Ramos et al., 2019). Intervals: IV (43 – 35 ka BP), III (35 – 24 ka BP), II (24 – 13 ka BP) and I (13 – 5 ka BP).

#### Organic matter (OM) bottom flux

Orbital to suborbital climate cycles can influence the abundance shifts of deep-sea benthic communities (Cronin et al., 1999). Since abundance fluctuations of benthic Foraminifera and ostracods are related to variations in particulate organic carbon fluxes to the seafloor (Smith et al., 1997; Rex et al., 2006; Rex and Etter, 2010), their use as surface paleoproductivity indicators is widespread (Nees et al., 1999; Herguera, 2000; Rasmussen et



al., 2002; Gooday, 2003; Yasuhara et al., 2012). The surface productivity fluctuations, indicated by *G. glutinata* (Fig. 13A), are similar to those of the organic matter (OM) flux recorded by the B:P (Fig. 13C). This effective OM exportation (from the surface to the sea floor) revealed a high benthic-pelagic coupling (Toledo et al., 2007). Intervals II and IV show higher values than I and III, with minimum rates registered during the Holocene, when oligotrophic conditions occur. The B:P changes are also accompanied by similar  $\delta^{13}\text{C}_{Uvi}$  trends (Fig. 13B), which are expected to decrease when higher OM fluxes (rich in  $^{12}\text{C}$  due to the preferential incorporation of the light isotope during photosynthesis (Wefer et al., 1999)) reach the seabed (Ravello and Hillaire-Marcel, 2007). The B:P ratio showed a positive linear relationship with productivity, whereas ostracod abundance showed a hump-shaped relation with productivity (Yasuhara et al., 2012), increasing under enhanced – but still moderate – supply of OM and declining under very high productive conditions. Additionally, abundance oscillations of deep-sea benthic organisms can also be related to paleobathymetry variations, decreasing exponentially with depth increase (Rex et al., 2006; Rex and Etter, 2010). While the ostracods record showed a negative relation (Fig. 13J,K), the B:P ratio did not follow the same fluctuations than the relative sea level.

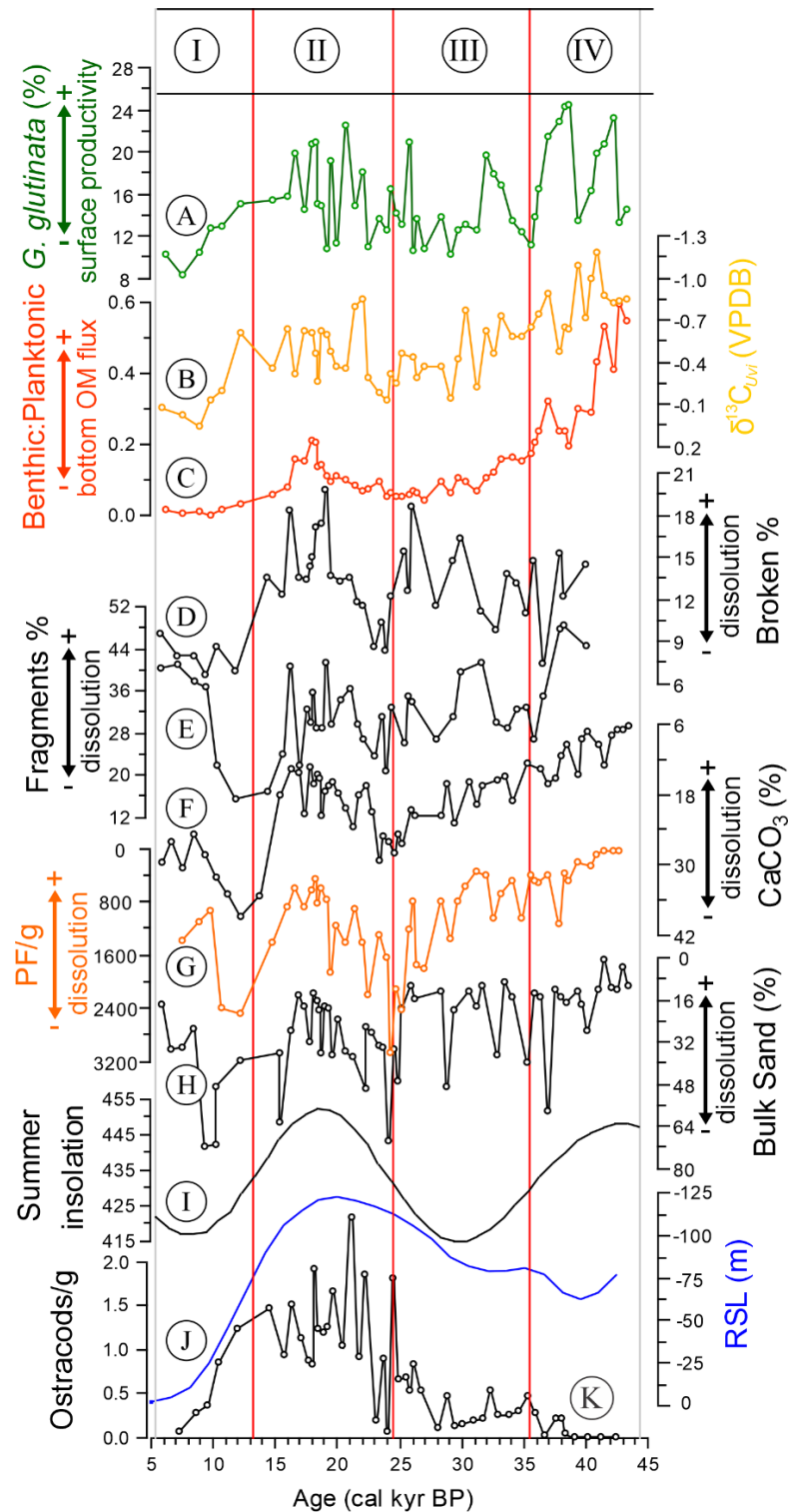


Fig. 13. Proxies associated to organic matter (OM) flux and carbonate dissolution along the core SAT-048A in the four intervals (VI – I). (A) *G. glutinata*, (B)  $\delta^{13}C_{Uvi}$ , (C) Benthic:Planktonic ratio, (D) broken planktonic Foraminifera tests and (E) fragments, (F)  $CaCO_3$  content, (G) volume of planktonic Foraminifera (tests/g), (H) sand content, (I) summer insolation (Laskar et al., 2004), (J) relative sea level (Waelbroeck et al., 2002), and (K) volume of ostracods (valves/g). Inverted axes in B, F-H and J to aid visualization.

Dissolution indicators showed higher values during interval IV (Fig.13D-H), and their fluctuations fit very well respect to the OM flux. Enhanced dissolution could be triggered by two different (and not mutually exclusive) processes: i) high CO<sup>2</sup> concentrations (decreasing pH) due to the remineralization of the OM fluxes into the sea floor (Jahnke et al., 1997; Schiebel, 2002) (Fig. 14) or ii) reorganization of water masses related to AMOC dynamics (Fig. 15). Although the benthic and planktonic foraminifera proportions are also used as a dissolution indicator (Berger & Diester-Haass, 1988, Conan, 2002), Kucera (2007) states it is only applied for abyssal depths. Additionally, Petró et al., (2018) sustain that it should not be applied as a dissolution proxy, since the high solubility of the carbonate tests is associated with the high magnesium content in the calcite structure, which is often higher in benthic foraminifera, generating an opposite effect to that expected in B:P ratio. So, the B:P changes in the core SAT-048A (depth 1542 mbsl) are likely controlled by OM flux and food availability.

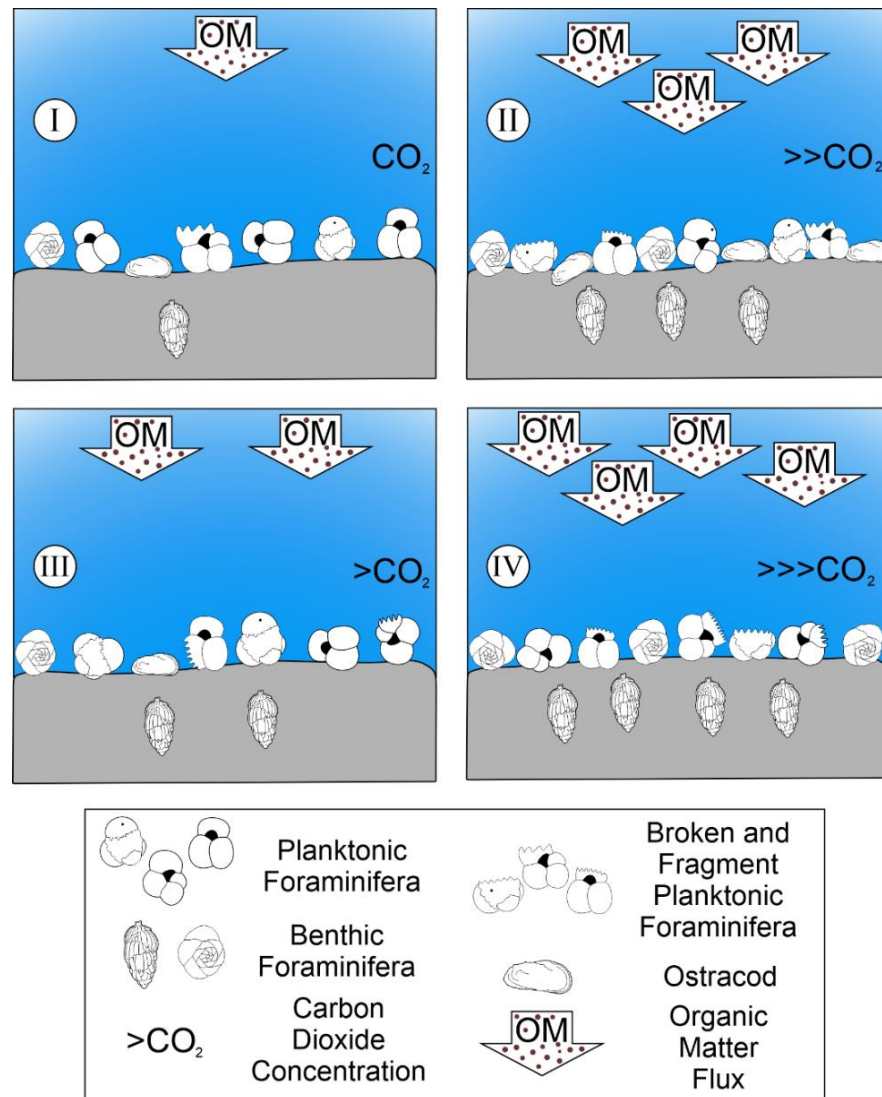


Fig. 14. Schematic representation of the dissolution effects on our deep-water assemblages triggered by paleoceanographic changes at the surface (paleoproductivity, Fig) and at the sea floor (organic matter inputs, OM). Higher inputs of OM can lead to an increase of CO<sub>2</sub> concentrations, decreasing pH and affecting the planktonic Foraminifera tests. Intervals: IV (43 – 35 ka BP), III (35 – 24 ka BP), II (24 – 13 ka BP) and I (13 – 5 ka BP).

In the SBCM basins, the  $\delta^{13}\text{C}_{Uvi}$  values have been used to infer oscillations of OM inputs (Toledo et al., 2007; Rodrigues et al., 2018; Dias et al., 2018; Frozza et al., 2020). Nevertheless,  $\delta^{13}\text{C}_{Uvi}$  values involves several controlling factors, such as accumulation rates of organic carbon, regional changes in/of water masses global carbon cycle, photosynthesis-respiration processes, temperature, and pH (Zahn, 1986; Ravelo & Hillaire-Marcel, 2007; Hesse et al., 2014). Lund et al. (2015) and Howe et al. (2016) suggested that glacial decreased benthic  $\delta^{13}\text{C}$  values are associated to a weak AMOC. The pre-deglacial BC warming trend (45 ka BP; Santos et al., 2017) revealed the accumulation of heat in the South Atlantic subtropical

gyre, due to the less heat and salt exportation to the North Atlantic by the North Brazil Current, and the Glacial-NADW shallowing due to smaller density values, being restricted to the upper 2.5 km during the LGM (Lynch-Stieglitz et al., 2006). The more positive  $\delta^{13}\text{C}_{Uvi}$  values since 43 to 24 ka BP can reveal the gradual higher presence of the NADW (Fig. 15), in the interhemispheric Atlantic seesaw dynamic (Barker et al., 2009). The higher presence of the Glacial-NAIW, with a better carbonate preservation potential (Frenz et al., 2003), could be the responsible of the  $\text{CaCO}_3$  anomaly in the late glacial record of the core SAT-048A, accumulated during the LGM (Fig. 13E), an extremely low relative sea level period, where terrigenous input was higher and the carbonate content dilution was expected. Anyhow, the carbonate preservation and  $\delta^{13}\text{C}_{Uvi}$  values fluctuations can be the result of the interplay between the OM flux and water masses changes.

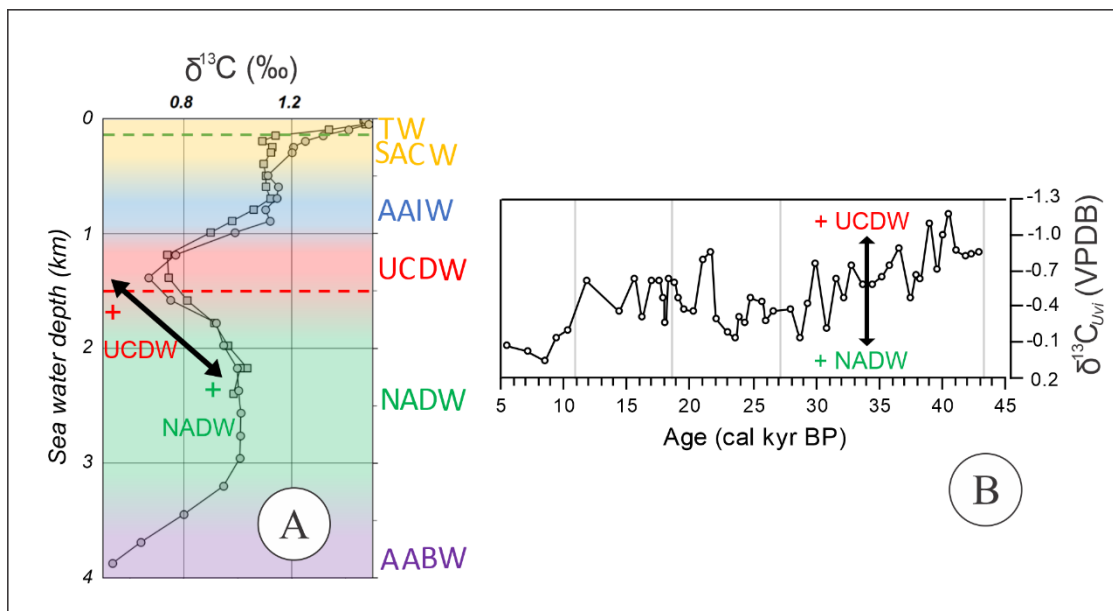


Fig. 15. (A) profile for the study area of the  $\delta^{13}\text{C}$  variations according to depth (GLODAPv2, Olsen et al., 2016, 2019) and (B)  $\delta^{13}\text{C}_{Uvi}$  results along the core SAT-048A. Red dotted line in (A) represents the SAT-048A. From (A) it is possible to infer on (B) a higher NADW influence when  $\delta^{13}\text{C}_{Uvi}$  values are more positive, which meant that  $\text{CaCO}_3$  was better preserved than during the UCDW presence (Frenz et al., 2003). TW: Tropical Water, SACW: South Atlantic Central Water, AAIW: Antarctic Intermediate Water, UCDW: Upper Circumpolar Deep Water, NADW: North Atlantic Deep Water, and AABW: Antarctic Bottom Water.

## 6. Conclusions

Planktonic Foraminifera compositional assemblages recovered from the core SAT-048A, from the western South Atlantic, along with geochemical analyses and sedimentological data, enabled us to reconstruct the surface and bottom paleoceanographic fluctuations that occurred -in phase- during the last 43 kyr. In long term changes, the Pleistocene-Holocene transition witnessed a shift of glacial eutrophic environment to more oligotrophic post-glacial conditions, as suggested by the *G.bull*:*G.rub* ratio, and the subsurface temperatures, where SACW-intrusions were inhibited and de la Plata and local river discharges were placed further away from the core.

In short term changes, the orbital-scale fluctuations of the upwelling dynamics (indicated by *G. glutinata*, *T. quinqueloba* and  $\delta^{13}\text{C}_{G.rub}$ ) influenced directly in the bottom OM flux (as showed by the B:P and  $\delta^{13}\text{C}_{Uvi}$ ). Imposed to already known mechanisms behind the high glacial productivity, stronger NE winds, generated by higher insolation values, enhanced the intrusions of cooler and nutrient richer waters in subsurface for 43 – 35 and 24 – 13 ka BP, fertilizing the photic zone. The enhanced upwellings conditions were also registered in the sea floor, where – likely – the bacterial decomposition of OM increased the  $\text{CO}_2$  concentration, creating more acidic conditions that caused different levels of planktonic Foraminifera tests dissolution. Nevertheless, the reorganization of deep waters could cause the alternation of two water masses in contact with the seabed: i) the NADW, linked to preservation of  $\text{CaCO}_3$  and, ii) the UCDW, related to  $\text{CaCO}_3$  dissolution, due to its  $\text{CO}_3^{2-}$  undersaturated condition. Additionally, the continental influence (*i.e.* terrigenous input) must be better assessed, since no increased productivity was registered during the lowest relative sea levels (Last Glacial Maximum). In order to quantify the impact and interplay of these two possible dissolution causes, new isotopic provenance analyses are required.

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## Supplementary material

From the 54 samples, a total of 21,962 specimens of planktonic Foraminifera were classified into 28 morphospecies (supplemental material). A total of 4878 specimens of benthic Foraminifera were counted. Table S1 lists the morphospecies, total relative abundance and total absolute abundance in descending order. The dominant species in the associations were *Globigerinoides ruber* (white), with a maximum relative abundance of 25.32%, followed by *Globigerinita glutinata* (15.56%) and *Globigerina bulloides* (15.56%). Other representative but less abundant species are *Neogloboquadrina incompta* (8.57%), *Globigerinoides ruber* (pink, 8.22%) and *Globoconella inflata* (7.69%).

Other species, with total relative abundances between 5 and 1% are (in decreasing order): *Trilobatus trilobus*, *Globoturborotalita tenellus*, *Neogloboquadrina dutertrei*, *Globorotalia scitula*, *Globoturborotalita rubescens*, *Globigerinella calida*, *Globorotalia truncatulinoides* (R), *Globorotalia crassaformis* and *Globorotalia truncatulinoides* (L).

Finally, species with extremely low total absolute abundance (> 1%) are *Candeina nitida*, *Globigerina falconensis*, *Globigerinella siphonifera*, *Globigerinoides conglobatus*, *Globorotalia hirsuta*, *Globorotalia menardii*, *Globorotalia tumida*, *Neogloboquadrina pachyderma*, *Orbulina universa*, *Pulleniatina obliquiloculata*, *Trilobatus sacculifer*, *Turborotalita humilis* and *Turborotalita quinqueloba*.



Table S1. List of the species/morphospecies identified and their total relative and absolute abundances.

Species/ morphospecies	Total relative abundance (%)	Total absolute abundance
<i>Globigerinoides ruber</i> (white)	25.32	5573
<i>Globigerinita glutinata</i>	15.56	3391
<i>Globigerina bulloides</i>	15.56	3355
<i>Neogloboquadrina incompta</i>	8.57	1892
<i>Globigerinoides ruber</i> (pink)	8.22	1828
<i>Globoconella inflata</i>	7.69	1701
<i>Trilobatus trilobus</i> (wo. sac.)	2.22	492
<i>Globoturborotalita tenellus</i>	2.22	480
<i>Neogloboquadrina dutertrei</i>	1.64	371
<i>Globorotalia scitula</i>	1.50	322
<i>Globoturborotalita rubescens</i>	1.46	314
<i>Globigerinella calida</i>	1.29	292
<i>Globorotalia truncatulinoides</i> (R)	1.28	295
<i>Globorotalia crassaformis</i>	1.28	289
<i>Globorotalia truncatulinoides</i> (L)	1.16	258
<i>Triolobatus sacculifer</i> (w. sac.)	0.93	212
<i>Globigerina falconensis</i>	0.89	193
<i>Globorotalia hirsuta</i>	0.62	135
<i>Globigerinella siphonifera</i>	0.41	93
<i>Globorotalia menardii</i>	0.37	77
<i>Orbulina universa</i>	0.36	79
<i>Turborotalita quinqueloba</i>	0.32	67
<i>Globigerinoides conglobatus</i>	0.32	70
<i>Neogloboquadrina pachyderma</i>	0.24	54
<i>Pulleniatina obliquiloculata</i>	0.21	44
<i>Globorotalia tumida</i>	0.07	16
<i>Turborotalita humilis</i>	0.04	9
<i>Candeina nitida</i>	0.04	8

## Capítulo 4

### Fragment or broken? Improving the planktonic Foraminifera fragmentation assessment

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#### Highlights:

- ✓ Due to subjectivity in test fragmentation, a new standardized method is explored.
- ✓ Fragmentation Intensity showed the best correlation values with carbonate content.
- ✓ Broken and fragment indexes, despite their wide use, showed less sensitivity assessment.

#### Abstract

Since dissolution can deeply alter planktonic Foraminifera assemblages, it is imperative to correctly quantify its effect on the samples. The fragmentation index has been widely used to measure how preserved planktonic Foraminifera tests are. Nevertheless, the lack of a standardized and less subjective method can lead to wrong interpretations. Here we explore an improved method, called Fragmentation Intensity, to better assess the planktonic Foraminifera fragmentation through image software analysis.

**Keywords:** Dissolution, Calcareous microfossils, Taphonomy, Preservation, Methodology.

#### 1. Introduction

The fragmentation index (Berger, 1970; Keigwin, 1976; Kimoto et al., 2003) is considered a robust and reliable tool to assess the dissolution effect on the planktonic Foraminifera tests (e.g., Dittert et al., 1999; Kucera, 2007). This effect involves partial damage and loss of the test wall, which can be easily identified by the number of broken tests and fragments. Since Berger (1970) proposed the ‘broken’ (i.e., tests with holes) and ‘fragments’ (representing < 50% of the test) indexes, they have been widely used in the literature (e.g., Thunell, 1976; Rottman, 1979; Conan et al., 2002; Hayward et al., 2004;

Petrizzo et al., 2008), although in most studies only one index is analyzed (e.g., Bordiga et al., 2013; Zamelczyk et al., 2013; Gonzales et al., 2017). Additionally, ‘broken’ and ‘fragment’ are often used indistinctly (e.g., Zhang et al., 2007; Petrizzo et al., 2008; Toledo et al., 2008), mixing two variables which are actually different (Fig. 1).

Attempts have been made to improve Berger (1970)’s indexes. One of them was proposed by Le & Shackleton (1992), where the authors -arbitrarily- assumed that one whole planktonic Foraminifera test can break into eight fragments. This method was then reassessed by Pfuhl & Shackleton (2004), where the fragment-divisor used was three, to represent a more linear increase in dissolution. Furthermore, both, Le & Shackleton (1992) and Pfuhl & Shackleton (2004), did not discuss about the broken tests and established the fragments identification as those tests that were not whole -or essentially whole-. Once again, the lack of a standardized method is evidenced, which ends in subjectiveness and increased error.

Moreover, low values of the broken fragmentation index can be related to two opposite circumstances: i) low dissolution, where better preservation conditions result in a reduced number of broken tests and, ii) high dissolution, where the broken tests turn into fragments, giving as a result a reduced number of broken tests (Fig. 1). Besides, the definition of what can be a broken test or a fragment is quite subjective, and the indexes can vary between the authors accuracies/definitions.

Given the above, there is clearly room for method improvement, especially in terms of standardization. Thus, our goal is to explore an improved and standardized method for the planktonic Foraminifera fragmentation assessment.

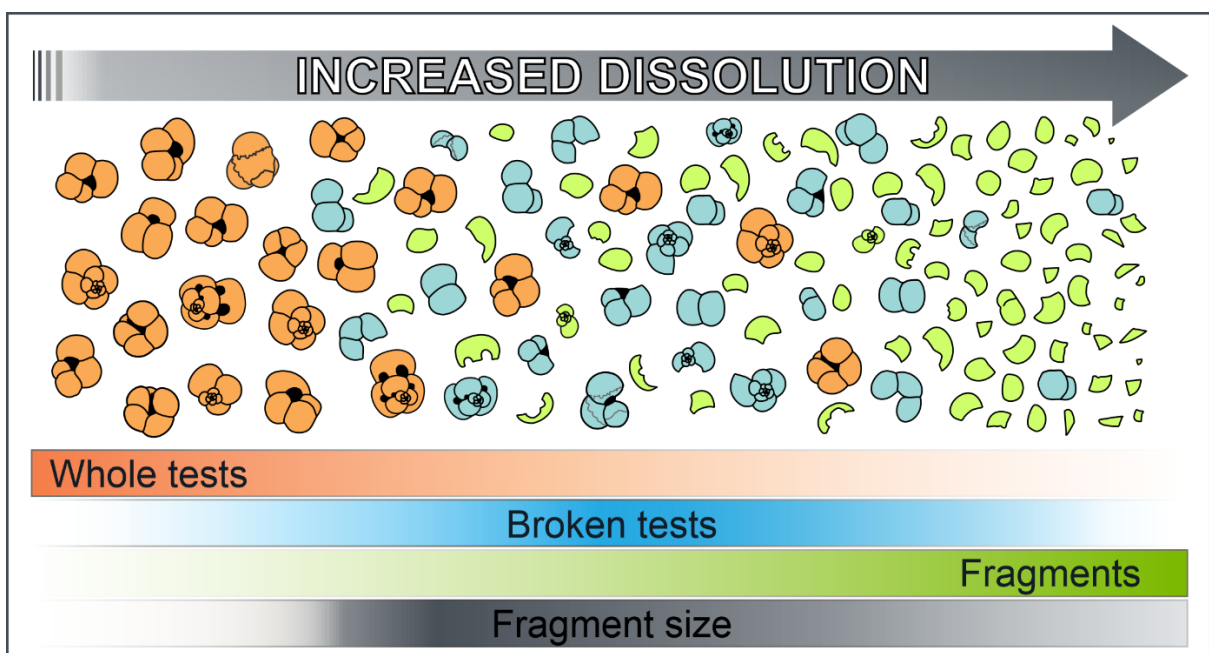


Fig. 1. Schematic representation of the transformation of whole tests into broken tests and fragments. When fragmentation starts, it frequently causes the loss of the less calcified last chambers. In a simple model, this would turn a whole test into one broken test and a fragment. As dissolution increases, each broken test could potentially provide several fragments (as long as they are not completely dissolved) and the remaining test itself would become a fragment, too. Also, fragments decrease their size through time.

## 2. The Method

In this new method we aim to reduce subjectiveness first by considering both broken and fragments together. Thus, the investigator does not have to decide whether the observed remains correspond to more or less than half a test. However, we are aware that the relative abundances of broken tests and fragments do not display the same behavior relative to dissolution (Fig. 1). We overcome this problem, by also considering the ratio between the area and perimeter of the remains, though we do not measure the real surface but instead, an approximation based on the projection of a view taken from the Foraminifera remains. Depending on the orientation of broken tests and fragments in the pictures, the overall measurements could vary. However, if broken tests and fragments are not glued but instead, simply distributed on the picking tray they will tend to show their largest ‘plan view’ area. And, since these measurements are made automatically using scaled photographs and an image processing program, we further reduce subjectiveness.

The premise is schematized in Fig. 2. Under intense dissolution, a broken shell can divide into new fragments. While the total area can remain similar (in gray), the total perimeter is increased due to the addition of the new (red line) perimeter to the old (blue line) perimeter. Since the area/perimeter ratio is inversely proportional to the dissolution effect ( $>$  dissolution,  $<$ area/perimeter), the fragmentation remains (broken and fragments) are divided by this ratio (equation 1).

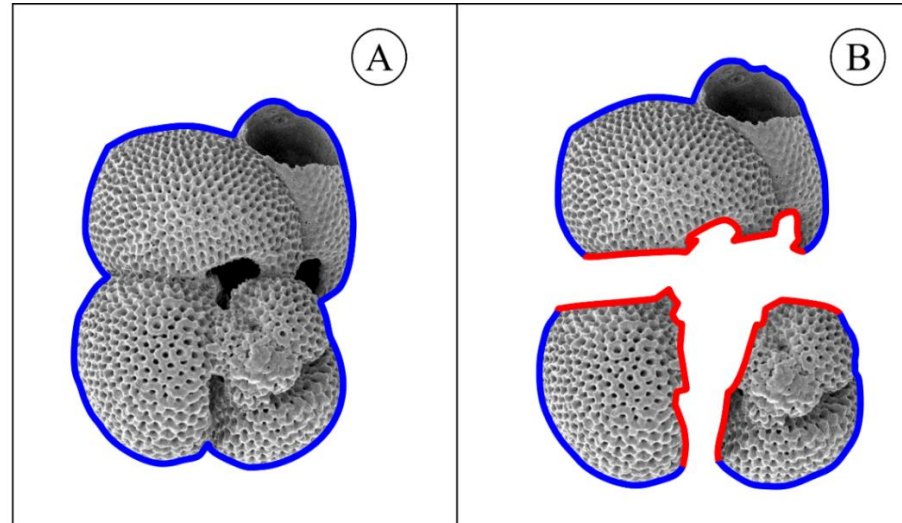


Fig. 2. Schematic representation of the dissolution effect on a broken planktonic Foraminifera, *Trilobatus sacculifer* resulting in new fragments, to better understand the relation between area (gray) and perimeter (blue and red lines).

Thus, we define the Fragmentation Intensity as:

$$FI = \frac{\left( \frac{fb}{fb + PF} \right)}{\left( \frac{area}{perimeter} \right)} \quad (\text{equation 1})$$

where *fb* corresponds to the amount of broken tests and fragments, *PF* is the amount of whole planktonic Foraminifera tests, and *area* and *perimeter* are the averages for the remains (broken and fragments specimens) per sample. Values closer to zero indicate better preserved tests, while values closer to one correspond to tests more affected by dissolution.

For the counting and area/perimeter measurements, all planktonic Foraminifera remains (i.e., broken tests and fragments) need to be disposed on a dark background (Fig. 3A,C) for subsequent photographing and scaling. When possible, the remains position should be standardized to avoid bias in the measurements. Here we disposed the broken tests in spiral or umbilical view, and fragments with convexity downwards, for better resolution of the edges during the image processing. Care must be taken to not overlay fragments.

In our case an Axiocam105 camera attached to a Discovery.V8 Zeiss stereomicroscope was used. The open source image analysis software ImageJ2 (Rueden et al., 2017) was used for counting the broken tests and fragments (Fig. 3) and calculate their average area ( $\mu\text{m}^2$ ) and

perimeter ( $\mu\text{m}$ ). Priorly, images were converted to an 8-bit grayscale for pixel threshold, dividing it into two layers: the dark background and the white remains (Fig. 3A,C). Then, through the pixel contrasting intensity range, the software was able to measure and count the particles (Fig. 3B,D).

Given that our census counts were performed on the  $>150\mu\text{m}$  size fraction, all fragments smaller than that were automatically selected and removed from calculations using the Analyze Particles tool (Fig. 3D).

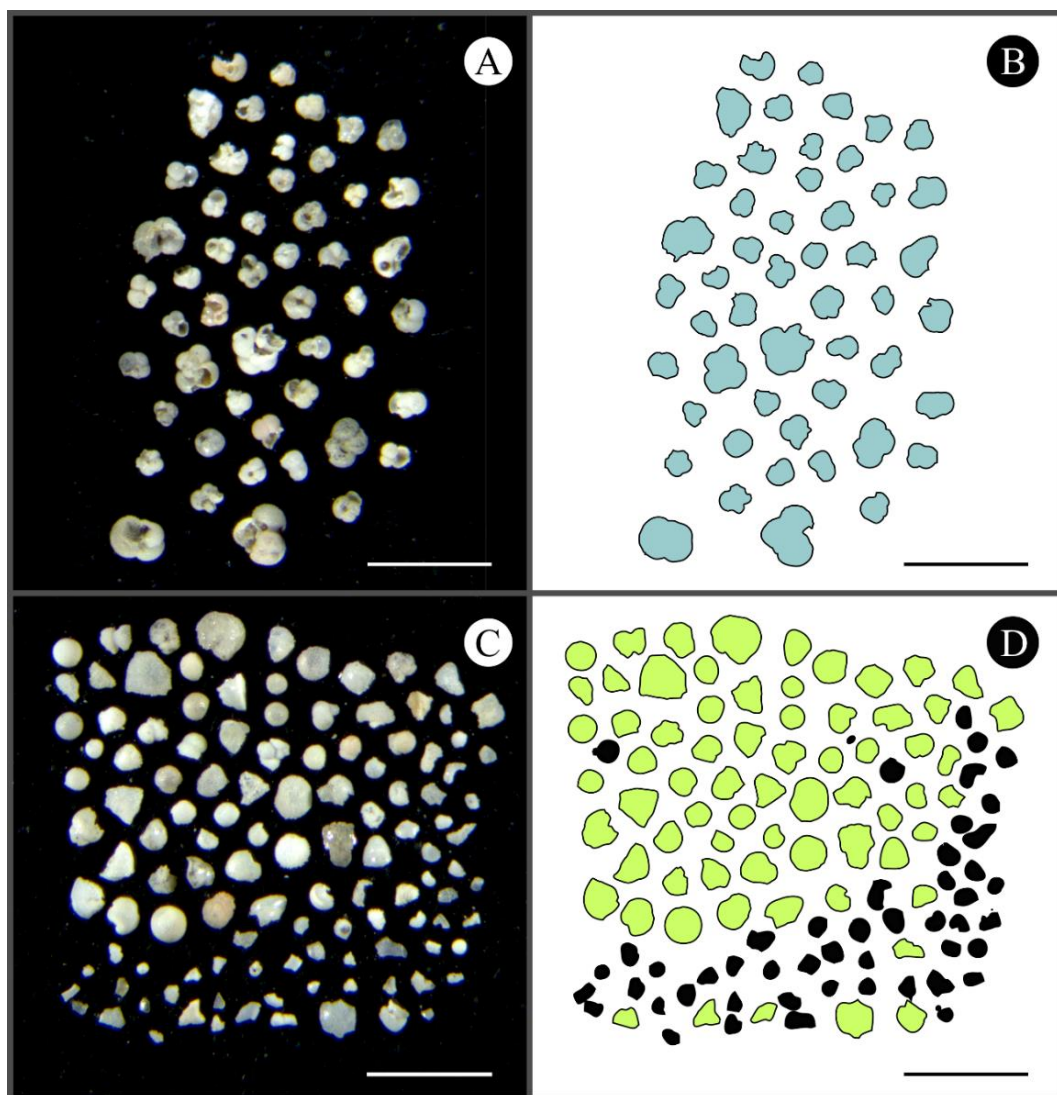


Fig. 3. Disposition of the planktonic Foraminifera fragmentation remains for the counting and measuring on the ImageJ2 software. ((A) represents the broken planktonic Foraminifera and (C) the fragments. In this case broken tests and fragments were displayed separately to compare Fragmentation Intensity results with Berger (1970)'s indexes. After the software image processing, (B)

blue shapes represent the measured area and the black lines represent the perimeter of the broken tests; (D) green shapes represent the measured area and perimeter of the fragments, and black shapes correspond to fragments smaller than the mesh size area ( $22500 \mu\text{m}^2$ ) which were therefore excluded from measurements. Scale bar:  $1000 \mu\text{m}$ .

### 3. Method evaluation

In order to evaluate the Fragmentation Intensity, we applied it to a sediment core together with other traditionally used dissolution indexes, namely the planktonic Foraminifera broken and fragment indexes (Berger, 1970), the bulk sand fraction (%) (e.g., Berger et al., 1982; Gonzales et al., 2017), the volume of Planktonic Foraminifera (Le & Shackleton, 1992) and the  $\text{CaCO}_3$  content (%). The Berger (1970)'s method includes two analyses: i) the broken (from 90 to 50% of the tests) and ii) fragment (less than 50% but larger than  $150 \mu\text{m}$ ) remains counting.

For the analysis, 41 samples from the SAT048A piston core (collected on the continental slope of the southern Brazilian continental margin,  $29^\circ 11' 52.110''\text{S}$ ,  $47^\circ 15' 10.219''\text{W}$ ; 1542 m.b.s.l., recovery of 315 cm) were used. Even retrieved well above the lysocline, changes in planktonic Foraminifera fragmentation,  $\text{CaCO}_3$  content and bulk sand content can be related to dissolution processes either related to enhanced productivity or to the influence of the more corrosive Upper Circumpolar Deep Water (Petró et al., submitted; Suárez-Ibarra et al., submitted). The core is composed mainly by hemipelagic mud rich in carbonates interlaced with thin layers rich in organic matter. Planktonic foraminifera census counts (performed on subsamples of at least 300 specimens), and the age model are detailed in Frozza et al. (2020).

Bulk sand contents were determined using a laser diffraction particle size analyzer Horiba Partica-LA-950. The calcium carbonate content for the samples was determined by weight loss after reaction with 10% hydrochloric acid (HCl) at the Calcareous Microfossils Laboratory of the Federal University of Rio Grande do Sul (UFRGS). Given that carbonate content measurements were not performed for the same exact samples analyzed for the remaining indexes,  $\text{CaCO}_3$  and bulk sand values were linearly interpolated. Considering that the calcium carbonate curve fluctuates smoothly (see Results section), we assume this does not introduce a significant error.

## 4. Results

The dissolution indexes results for core SAT048A are plotted in Fig. 4. Overall, the carbonate content, the planktonic Foraminifera (whole tests)/gram and the bulk sand content follow a similar trend, although values fluctuate smoothly for calcium carbonate and more variably for the bulk sand proportion. All three variables indicate a decrease in dissolution from high values around 43 ka BP to low values (better preservation) at around 25 ka BP, followed by an increase for 25 to 17 ka BP, a faster decrease from 17 to 12 ka BP and relatively higher values during the Holocene. Better preservation conditions seem to have occurred around 25 ka BP and at the late deglacial to early Holocene.

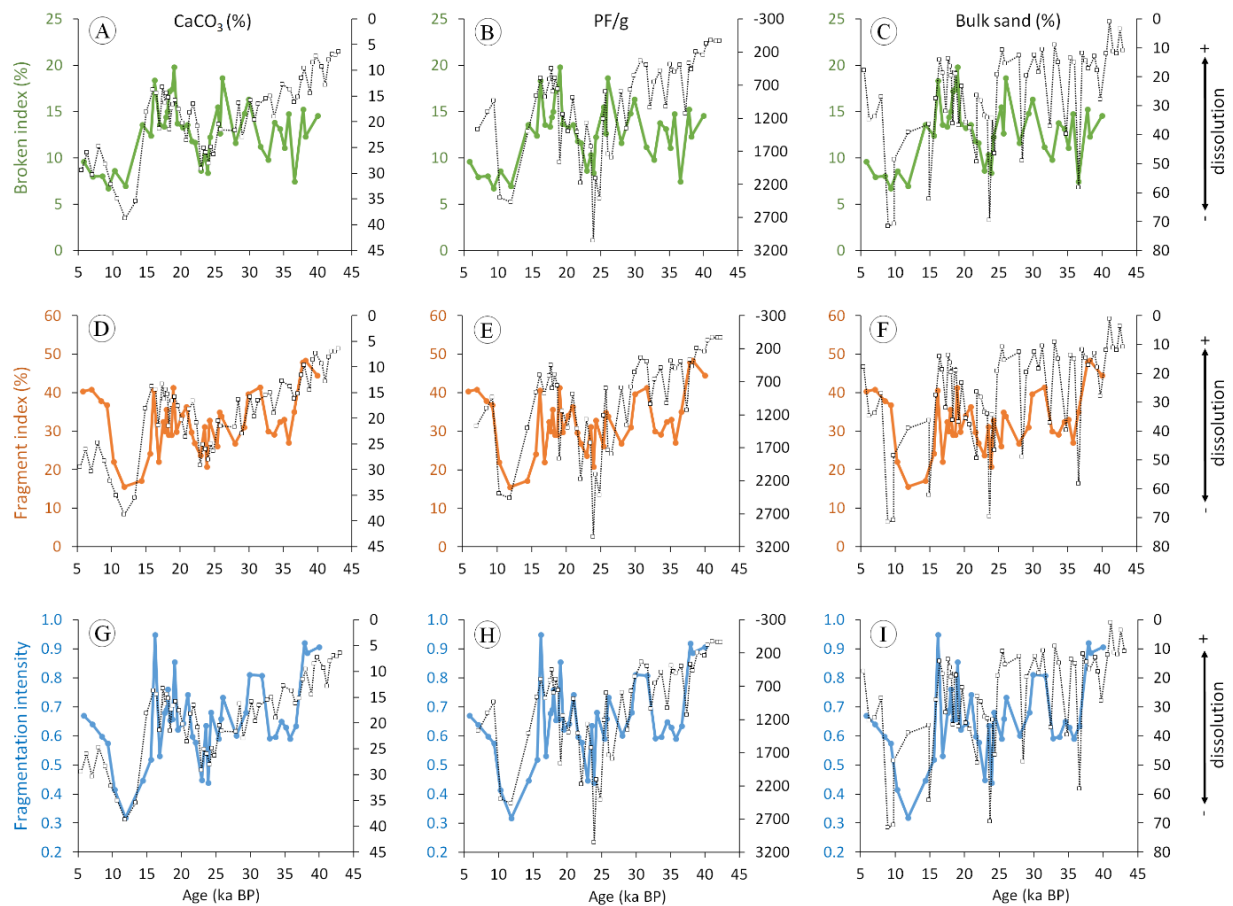


Fig. 4. Comparison of different dissolution indexes obtained for core SAT048A. From top to bottom, rows correspond to Berger's (1970) broken index (% in green) and fragment index (% in orange), and our Fragmentation Intensity (in blue). Each column, from left to right correspond to three commonly used dissolution indexes: carbonate content (%), whole planktonic Foraminifera/gram (PF/g) and bulk sand content (%). Both ordinates, from rows and columns variables, are plotted against age (ka BP), abscissa.



The fragment index (Fig.4, middle row) displays roughly the same trending than the CaCO<sub>3</sub> content, the PF/g, and the bulk sand content for the 43 – 25 ka BP interval. Nevertheless, the dissolution increase trend registered by the other indexes for the 25 – 17 ka BP is only gently observed by the fragment index. For the 17 – 12 ka BP interval a decreased trend for the dissolution effect is inferred by all indexes, but for the Holocene record the fragment index indicates higher dissolution than at 18 ka BP, which is not shown by the CaCO<sub>3</sub> content, the PF/g, and the bulk sand content.

If the fragment index showed some deviations from the other dissolution effect indexes, the broken index (Fig. 4, upper row) is not better fitted, showing similar trends to the CaCO<sub>3</sub> content, the PF/g and the bulk sand content only for the 25-12 ka BP interval. In contrast, the Fragmentation Intensity (Fig. 4, lower row) seems to better capture the overall trends indicated all indexes, throughout the record.

From the R-squared values (Fig. 5) for broken index, fragment index and Fragmentation Intensity *vs.* carbonate content, planktonic Foraminifera tests/g and bulk sand content, the Fragmentation Intensity *vs.* CaCO<sub>3</sub> (%) (Fig. 5G) indicate the best fit values. Broken index *vs.* carbonate and bulk sand content showed relatively good correlations. Nevertheless, broken index *vs.* and PF/g shows no significant correlation. Fragment index *vs.* carbonate content, PF/g and bulk sand content showed the lower correlation values. In contrast, Fragmentation Intensity *vs.* carbonate content, planktonic Foraminifera tests/g and bulk sand content showed two of the highest correlations. Only no significant ( $p>0.05$ ) correlation was obtained for the broken index and PF/g (Fig. 5B).

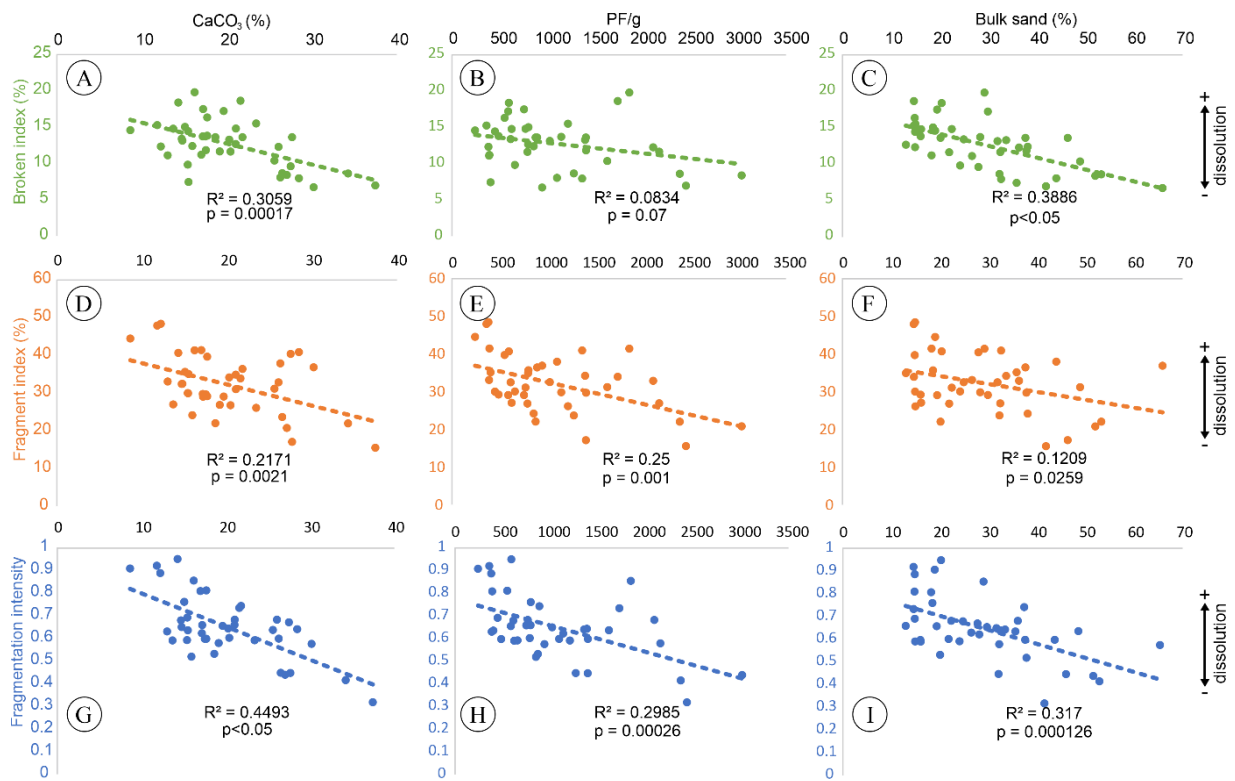


Fig. 5. Scatterplots of the values obtained for Berger's (1970) 'broken' and 'fragment' indexes and the Fragmentation Intensity *versus* the carbonate content (%), the planktonic Foraminifera (whole tests)/gram and the bulk sand (%). Linear regression models (R<sup>2</sup>) are given for each plot. The significance level adopted was  $p < 0.05$ . Rows correspond to broken index, fragment index and Fragmentation Intensity, while columns correspond to carbonate content, planktonic Foraminifera tests/g and bulk sand content.

## 5. Discussion

Comparing the CaCO<sub>3</sub> content, the PF/g and the bulk sand content with Berger (1970)'s broken index, it appears that the latter underestimates dissolution for the older samples (from ~45 – 35 ka BP) and probably for the youngest samples as well, likely because dissolution was high enough to more efficiently convert broken tests into fragments. On the other hand, Berger's (1970) fragment index seems to overestimate dissolution for the latest part of the record, with Holocene values as high as glacial values. Although the Fragmentation Intensity seems to better capture the dissolution trend throughout the record (Fig. 4), a more accurate evaluation, is given in Fig. 5 where Berger (1970)'s indexes and the Fragmentation Intensity index are compared to the carbonate content, the planktonic Foraminifera (whole tests)/gram and the bulk sand, yielding, overall, the best correlations.

As shown by Le & Shackleton (1992), dissolution quantification is hampered when fragments are compared as equal to the well preserved planktonic Foraminifera tests, and despite their proposal of dividing by eight improving Berger (1970)'s indexes, their index is not efficient for very dissolved remains. Besides providing a better fit, the Fragmentation Intensity has the advantage of counting together as remains both broken tests and fragments, therefore, the error induced by their differentiation is avoided.

A potential caveat with the proposed method is related to changing Foraminifera assemblage composition through time, which could change test sizes and given the well-known selective dissolution of species (Berger, 1968; Vincent & Berger 1981; Thunell & Honjo, 1981, Petró et al., 2018), it could potentially yield differing fragmentation patterns. This effect would only be quantifiable through experimentation.

## 6. Final remarks

Our new planktonic Foraminifera fragmentation assessment index, called Fragmentation Intensity, seems better suited to identify dissolution effects on foraminiferal samples than the classical fragmentation indexes (Berger, 1970; Le & Shackleton, 1992; Pfuhl & Shackleton, 2004). Our method is not free from subjectivity, but it contributes to diminish it by lumping broken tests and fragments together, and by using an image software for taking measurements. Indeed, the easy use of imaging software for extracting counts and measurements allows us to propose an improved method which would have been unfeasible decades ago.

We are aware that the proposed method is based on a theoretical model which, applied to real samples, provided consistent results. However, further testing would provide more confidence to the method, and potentially, good calibration studies following a depth-transect approach or *in situ* experiments could eventually adapt the index into a proxy of calcium carbonate undersaturation.

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## Capítulo 5

### Considerações finais

O testemunho SAT-048A não só permitiu testar a aplicação dos bioecozoneamentos desenvolvidos para as bacias de Campos e Santos na Bacia de Pelotas, como também permitiu a calibração das idades dos bio-eventos ocorridos na parte mais tardia do Quaternário, apesar de algumas inversões de  $^{14}\text{C}$ . A idade tardia registrada para o Último *Datum* de Desaparecimento (UDD) da *Pulleniatina obliquiloculata*, permitiu rever antigas propostas sobre a sincronia deste bio-evento na Margem Continental Sul-Brasileira (MCSB) e, também, posicionar o processo que o desencadeia no contexto do Oceano Atlântico. O Último *Datum* de Reaparecimento (UDR) da espécie *P. obliquiloculata* e do complexo *Globorotalia menardii*, permitiram assignar as devidas bioecozonas ao testemunho e, ao mesmo tempo, estender espacialmente o alcance destas espécies à bacia mais sul da margem continental sul-brasileira. A proposta de novas espécies para a identificação do limite Pleistoceno/Holoceno deve funcionar como incentivo para estudos de associações completas de foraminíferos planctônicos, com o intuito de descobrir novos bio-eventos que sirvam de base para a bioestratigrafia do Quaternário tardio.

A relação entre a produtividade superficial e os fluxos de matéria orgânica ao fundo do mar foi identificada pelos indicadores micropaleontológicos (*Globigerinita glutinata*, razão de foraminíferos bentônicos e planctônicos) e isotópicos ( $\delta^{13}\text{C}$  em *Globigerinoides ruber* e *Uvigerina* spp.). Análises micropaleontológicas (fragmentação de foraminíferos planctônicos), geoquímicas (teor de  $\text{CaCO}_3$ ) e sedimentológicas (tamanho de grão areia, %), revelaram uma menor preservação do  $\text{CaCO}_3$  no intervalo glacial, com o valor maior para este intervalo registrado durante o Último Máximo Glacial. Contudo, o processo causante da variação permanece em aberto, sendo direcionado ou pelo aporte de matéria orgânica ao fundo ou por variações nas massas d'água de fundo.

A análise do efeito da dissolução sobre as testas dos foraminíferos planctônicos através do processo de imagens permitiu entender melhor seu efeito. A partir desta análise, criou-se um modelo teórico para refinar e estandarizar antigos índices de fragmentação, comparando-o com indicadores independentes já estabelecidos.

### **Perspectivas**

A aplicação dos bioecozoneamentos das bacias de Campos e Santos deve ser testada em testemunhos com maior recuperação temporal e/ou localizados mais ao sul.

As inversões da  $^{14}\text{C}$  em carapaças de foraminíferos planctônicos, recorrentes na MCSB, devem ser melhor estudadas, dado que são elementos chave na calibração das idades associadas aos eventos bioestratigráficos.

A influência das variações nas massas d'água de fundo na dissolução deve ser melhor estudada através de futuros estudos isotópicos nos próprios foraminíferos, tais como  $\epsilon\text{Nd}$ .

O índice de fragmentação deve ser testado em associações de foraminíferos de distintos ambientes, com o fim de corroborar a sua eficácia, e possível calibração como proxy de subsaturação de carbonato de cálcio das massas d'água.



<b>ANEXO I</b>	
Título da Dissertação/Tese:	
<b>“ANÁLISE BIOESTRATIGRÁFICA E PALEOCEANOGRÁFICA COM FORAMINÍFEROS PLANCTÔNICOS DO QUATERNÁRIO TARDIO NO ATLÂNTICO SUL OCIDENTAL”</b>	
Área de Concentração: Paleontologia	
Autor: <b>Jaime Yesid Suárez Ibarra</b>	
Orientadora: Profa. Dra. María Alejandra Gómez Pivel	
Examinadora: Dra. Geise de Santana dos Anjos Zerfass	
Data: 08/09/2020	
Conceito: A	
<b>PARECER:</b>	
<p>A dissertação apresenta um trabalho original o qual oferece uma significativa contribuição ao conhecimento. O tema tratado é relevante e o candidato apresenta os dados de forma coerente e clara.</p> <p>O candidato demonstra conhecimento do tema ao desenvolver argumentos sólidos com base nos dados adquiridos e em dados prévios compilados da literatura. Além de tecer considerações bem embasadas, o candidato propõe uma inovação metodológica com excelentes perspectivas de aplicações futuras tendo em vista a robustez do método e a utilização de tecnologia que contribui para a redução do tempo de análise e uniformização dos resultados.</p> <p>Em relação à estrutura da dissertação, destaco o encadeamento de ideias com os parágrafos, os tópicos e os capítulos dispostos em uma sequência lógica. Vale também ressaltar a excelente qualidade das figuras.</p> <p>Em relação ao título, sugiro mencionar a Bacia de Pelotas, uma vez que os testemunhos estudados estão localizados em uma área da bacia e, embora as interpretações possam ser extrapoladas para o Atlântico Sudoeste, os dados estão restritos à área da bacia. Assim, sugiro que o título seja modificado para “Análise Bioestratigráfica e Paleoecológica com base em Foraminíferos Planctônicos do Quaternário Tardio na Bacia de Pelotas, Atlântico Sul Ocidental”.</p> <p>O texto é bem escrito e apenas pontualmente apresenta problemas de clareza devido ao uso de personalização de seres inanimados ou de processos, o que deve ser evitado para não suscitar dúvidas ou ambiguidades. Recomendo também evitar o uso de adjetivos e qualificativos imprecisos como, por exemplo, “bastante”. Sugiro sintetizar as argumentações e evitar a repetição de ideias.</p> <p>Por fim, o candidato realizou uma abrangente revisão bibliográfica, contemplando tanto trabalhos clássicos quanto bibliografia atualizada sobre o tema.</p>	
Assinatura	Data: 08/09/2020


*Geise de Santana dos Anjos Zerfass*



Ciente do Orientador:

Ciente do Aluno:



<b>ANEXO I</b>	
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Área de Concentração: Paleontologia	
Autor: <b>Jaime Yesid Suárez Ibarra</b>	
Orientadora: Profa. Dra. María Alejandra Gómez Pivel	
Examinador: Dr. Igor Martins Venâncio	
Data: 20/08/2020	
Conceito: A	
<b>PARECER:</b>	
<p>A dissertação de mestrado de Jaime Yesid Suárez Ibarra está muito bem escrita e organizada. O texto foi subdividido em capítulos. Os capítulos 2, 3 e 4 foram apresentados na forma de manuscritos submetidos ou em preparação pelo autor. O capítulo 2 é um manuscrito submetido recentemente para a revista internacional Marine Micropaleontology. Nesse capítulo são abordadas questões relativas ao estabelecimento de biozoneamentos para a porção sul da margem continental brasileira. No texto, o autor poderia fornecer informações mais detalhadas sobre os modelos de idades dos testemunhos estudados. As explicações ambientais de alguns bioeventos também poderiam ser melhor exploradas e com uso de referências bibliográficas mais atuais. No capítulo 3, o autor teve como objetivo reconstruir as condições paleoceanográficas dos últimos 45 ka na mesma área de estudo. Neste capítulo seria importante mostrar alguns gráficos que avaliem a performance da Técnica do Análogo Moderno (MAT em inglês) que foi utilizada para reconstruir paleotemperaturas. Além disso, as interpretações relacionadas as variações orbitais (precessão), e também aos fatores que controlam o sinal dos isótopos de carbono em foraminíferos bentônicos podem ser aprimoradas. No capítulo 4, o autor visou propor um novo método para avaliar a dissolução e a fragmentação em foraminíferos. A proposta metodológica é interessante, mas ainda necessita de mais análises e experimentos para futura aplicação. De forma geral, a dissertação é bem escrita e apresenta importantes contribuições científicas para os campos da Bioestratigrafia e da Paleoceanografia. Portanto, julgo que o trabalho deve ser aprovado com conceito máximo.</p>	
Assinatura: 	Data: 20/08/2020
Ciente do Orientador:	
Ciente do Aluno:	

<b>ANEXO I</b>
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Área de Concentração: Paleontologia
Autor: <b>Jaime Yesid Suárez Ibarra</b>
Orientadora: Profa. Dra. María Alejandra Gómez Pivel
Examinador: Prof. Dr. João Carlos Coimbra
Data: 30 de agosto de 2020.
Conceito: A (Excelente)
<b>PARECER:</b>
<p>A dissertação trás uma valiosa contribuição ao conhecimento da aplicação dos foraminíferos planctônicos à bioestratigrafia, correlação, paleoceanografia e paleoclimatologia do Quaternário tardio nas bacias do sudeste e sul do Brasil. O documento está bem redigido e organizado, sendo que as sugestões/correções de forma foram marcadas no arquivo pdf que o presente examinador entregará para apreciação do autor. A revisão bibliográfica é atualizada e pertinente, havendo apenas duas sugestões de leitura que farei mais abaixo. Os objetivos estão claros, contudo, faltou listar nos "objetivos específicos" a construção de um modelo matemático para medir a intensidade de fragmentação das testas de foraminíferos, sendo este um importante produto da dissertação devido às suas aplicações à paleoceanografia em nível mundial. Dividida em cinco capítulos, a dissertação tem como núcleo principal os capítulos 2, 3 e 4, cada qual referente a um artigo científico. O capítulo 2 é o de maior importância, pois discute diferentes metodologias aplicadas à bioestratigrafia e correlação das bacias de Campos, Santos e Pelotas, no Quaternário tardio. O autor evidencia diacronismos até então pouco conhecidos, e propõe novos marcos estratigráficos para o limite Pleistoceno-Holoceno. O capítulo 3 trás um estudo multiproxy, incluindo tanto diferentes grupos de microfósseis quanto análises sedimentológicas e químicas, contribuindo para o melhor entendimento da flutuação dos fatores abióticos e da paleoprodutividade na região e tempo em tela. O capítulo 4 apresenta um modelo matemático para melhor avaliar o estado de preservação de testas de foraminíferos planctônicos, muitas vezes recuperadas quebradas ou reduzidas a fragmentos de diferentes dimensões, fenômeno que de uma forma ou de outra se reflete na composição final das assembléias. Este tema está também relacionado à dissolução e, conseqüentemente, afeta a análise paleoceanográfica em maior ou menor grau. Na sua forma atual o artigo é qualificado e de interesse internacional, contudo, este examinador gostaria de sugerir que o autor inclua na sua discussão o trabalho de Malmgren (1983), o qual foi publicado no periódico Marine Micropaleontology, 8:183-191. Indico, ainda, a tese de Bornmalm (1997),</p>

publicada na íntegra numa revista monográfica relativamente pouco conhecida, como segue: Fossil & Strata, 41: 1-100 (+ Appendix).

Assinatura: João Carlos Coimbra

Data: 30/08/2020

Ciente do Orientador:

Ciente do Aluno: