Revista Brasileira de Paleontologia, 24(4):345–356, Outubro/Dezembro 2021
A Journal of the Brazilian Society of Paleontology

doi:10.4072/rbp.2024.4.05

CLIMATIC AND VEGETATIONAL DYNAMICS IN SOUTHERN BRAZIL BETWEEN 47.8 AND 7.4 CAL KA BP: A PALYNOLOGICAL ANALYSIS

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ABSTRACT – Vegetation and climate changes in southern Brazil are described based on the palynological analysis from marine core SIS 188, collected on the continental slope, which records the interval between 47.8 and 7.4 cal ka BP. The pollen record indicates that the grasslands dominated the landscape in southern Brazil throughout the studied period. During the last glacial period, the forests were reduced. Between 32.8 and 20.2 cal ka BP, there is an increase in grassland and reduction of arboreal palynomorphs, coinciding with colder and drier climatic conditions of the Last Glacial Maximum (LGM). From 30 to 25.2 cal ka BP, an increase in the sedimentation rate and concentration of most pollen indicators is observed. This change could be related to low sea level, which exposed the continental shelf to eolian erosion and fluvial inputs that transported sediments and palynomorphs to the ocean. A significant decrease in sedimentation rate is recorded between 19.5 and 12.6 cal ka BP, probably related to sea-level rise during deglaciation. During deglaciation and beginning of the Holocene, the increase in arboreal pollen indicates the expansion of forests, reflecting warmer and wetter climate. Heinrich event 1 is marked by a peak in the percentages of the arboreal vegetation at 15.9 cal ka BP. Around 8.5 cal ka BP, there seems to be another interval of higher moisture, indicated by the composition of the palynological association, formed by pteridophytes *Blechnum*, *Huperzia*, Polypodiaceae, Pteridaceae and Cyatheaceae. These results show that the palynological record from the SIS188 marine core is sensitive to global climatic changes and can provide a reliable paleovegetational reconstruction for the continental environment.

Keywords: Pelotas Basin, paleoclimate, palynomorphs, palynology, Quaternary.

RESUMO – As mudanças na vegetação e clima do Sul do Brasil foram estudadas a partir da análise de palinomorfos provenientes do testemunho marinho SIS 188, coletado no talude da Bacia de Pelotas, que documenta o intervalo de tempo entre 47,8 e 7,4 cal ka BP. O registro polínico indica que os campos dominaram a paisagem no Sul do Brasil ao longo do intervalo estudado. Durante o último período glacial, as florestas estavam reduzidas. Entre 32,8 e 20,2 cal ka BP, observa-se uma expansão dos campos e a retração dos palinomorfos arbóreos, coincidindo com as condições climáticas mais frias e secas durante o Último Máximo Glacial (UMG). De 30 a 25,2 cal ka BP, observa-se um aumento na taxa de sedimentação e da concentração da maioria dos indicadores polínicos. Essa mudança pode estar relacionada ao rebaixamento do nível do mar, que expôs a plataforma continental a erosão eólica e *inputs* fluviais que transportaram sedimentos e palinomorfos para o oceano. Há uma queda significativa na taxa de sedimentação entre 19,5 a 12,6 cal ka BP, provavelmente relacionada ao aumento do nível do mar durante a deglaciação. Durante a deglaciação e início do Holoceno, o aumento da concentração de pólen arbóreo indica a expansão das florestas, refletindo um clima mais quente e úmido. O Evento Heinrich 1 aparece marcado no registro por um pico na porcentagem do grupo “Árvores” em 15,9 cal ka BP. Ao redor de 8,5 cal ka BP parece haver outro intervalo de maior umidade, indicada pela composição da associação palinológica, composta pelas pteridófitas *Blechnum*, *Huperzia*, Polypodiaceae, Pteridaceae and Cyatheaceae. Estes resultados mostram que o registro palinológico do testemunho marinho SIS188 é sensível às mudanças climáticas globais e podem prover uma reconstrução paleovegetacional confiável para o ambiente continental.

Palavras-chave: Bacia de Pelotas, paleoclima, palinomorfos, palinologia, Quaternário.

INTRODUCTION

Studies of vegetation and its dynamics in response to past climate changes are important to understand how the flora responds to those changes. It is possible to deduce past changes through the analysis of proxies such as palynomorphs, which allow us to make inferences about vegetational and climatic changes that have occurred throughout the Quaternary (Salgado-Labouriau, 2001; Traverse, 2007; Cassino *et al*., 2017). The Quaternary Period is recognized as a time of marked climate change, characterized by alternate glaciations and deglaciations (Baker & Fritz, 2015), which influenced the development of vegetation. Those climate changes directly influenced the relative sea level (**RSL**), which varied widely throughout the Quaternary (Waelbroeck *et al*., 2002). Such changes directly controlled the evolution of coastal systems and their sedimentary dynamics in southern Brazil (Villwock & Tomazelli, 1995).

Palynological analyses using marine sedimentary cores are less frequent than studies on continental cores. Studies carried out in marine cores focus on the analysis of palynomorphs of widely different origins, which makes it difficult to accurately assess changes in vegetation. On the other hand, because they represent the vegetation of a larger area, possible local noise is minimized, and the signal interpreted represents the vegetation in a regional scale. In addition, marine cores often reach older ages than continental ones, which is useful as a research tool on RSL variations and in understanding the conditions and factors that influence the depositional paleoenvironment (González & Dupont, 2009; Dai *et al*., 2015; Li *et al*., 2017), as well as long distance transportation by winds and marine currents. In recent years, some palynological studies have been developed in Brazil, focusing on coastal and/or marine environments (Behling *et al*., 2002; Luz *et al*., 2011; Cancelli *et al*., 2012; Diniz & Medeanic, 2012; Freitas & Carvalho, 2012; Freitas *et al*., 2013; Gu *et al*., 2017, 2018; Ávila *et al*., 2020). This study aims to produce additional information on the paleoclimatic and paleovegetational history in southern Brazil in the period from 47.8 to 7.2 cal ka BP, based on samples obtained from a deep-sea core.

STUDY AREA

Coastal system and climate setting

The marine core SIS188 (-29.579046 S, -47.295608 W) was collected in the continental slope of the southern Brazilian continental margin, in an area corresponding to the northern Pelotas Basin, at a water depth of 1,514 m. The sampling site is currently located approximately 220 km off the present-day coastline (Figure 1).

Two rivers reach the coastline adjacent to the cored area, the Mampituba and Araranguá. Nowadays they are located about 262 and 225 km, respectively, to the core. The drainage basin of Mampituba River occupies an area of 1,200 km^2, it originates in the highlands of southern Brazil (South Brazilian Plateau) and discharges into the Atlantic Ocean, close to the Torres city at Rio Grande do Sul State, and has an average flow of 18.6 m^3.s^{-1} (D´Aquino *et al*., 2011). The drainage basin of the Araranguá River occupies an area of 3,020 km^2, with an average flow of 65 m^3.s^{-1} (Loitzembauer & Mendes, 2016).

The Patos Lagoon, another continental input south of the core area, has a surface of 10,360 km^2 and is considered the largest choked lagoon in the world (Kjerfve, 1986). It receives water from a drainage basin of 140,000 km^2, directly from tributaries or through the São Gonçalo Channel, which connects it with the Mirim Lagoon basin (Kjerfve, 1986). The Rio de la Plata is located farther south of the studied area and is the discharge of the Plata drainage basin. It is the second largest river system in South America, covering an area of approximately 3,200 x 106 km^2 (Acha *et al*., 2008).

The South Atlantic Subtropical High (**SASH**), a high-pressure system located around 30°S over the Atlantic Ocean, controls the atmospheric circulation in the studied area (Wainer & Taschetto, 2006). The SASH is responsible for the predominance of NE winds in the southwest region throughout the year, followed by SW winds during the passage of cold fronts, more common in winter.

The climate in southern Brazil is humid temperate-subtropical, with rainfall evenly distributed throughout the year, with relatively humid conditions and annual precipitation around 1,100 mm (Grimm & Tedeschi, 2009). The temperature varies between 15 and 25ºC throughout the year (Diaz *et al*., 1998). El Niño Southern Oscillation (**ENSO**) events influence annual rainfall, producing positive anomalies during El Niño years and negative anomalies during La Niña years (Grimm & Tedeschi, 2009).

Vegetation context

Several previous works have described the type of vegetation of southern Brazil and Uruguay (*e.g*. Klein, 1978; 1979; Boldrini, 2009) which is mainly influenced by topography and climate (Figure 1).

The Atlantic Forest dominates the northern portion of the southern Brazilian coastal plain. It contains families such as Moraceae and Myrtaceae, and the *Alchornea triplinervia* species, which are common in this vegetation formation. In the highlands of southern Brazil (South Brazilian Plateau), the landscape is composed of a mosaic of *Araucaria* Forest and grasslands, due to colder climatic conditions. *Araucaria angustifolia*, *Podocarpus lambertii*, *Mimosa scabrella* and *Ilex* spp. mainly dominate the *Araucaria* forests (Boldrini, 2009).

Grasslands occur mainly in the lowlands of Rio Grande do Sul and Uruguay and are dominated by the Poaceae, Cyperaceae, Asteraceae, Apiaceae and Fabaceae families, associated with colder and drier climate (Mourelle & Prieto, 2012). Gallery forests occur along the streams of this region, composed mainly by the *Salix chilensis*, *Sebastiania commmersoniana*, *Myrsine laetevirens* and Myrtaceae (Mourelle & Prieto, 2012). The coastal lagoons of southern Brazil and Uruguay are dominated by salt marshes composed of Cyperaceae, Chenopodiaceae and Amaranthaceae (Marangoni & Costa, 2009). The vegetation of the drainage basin of the Rio de la Plata is formed by a mix of grasslands, gallery forests, dry forests, and semi deciduous forests (Hueck, 1966).

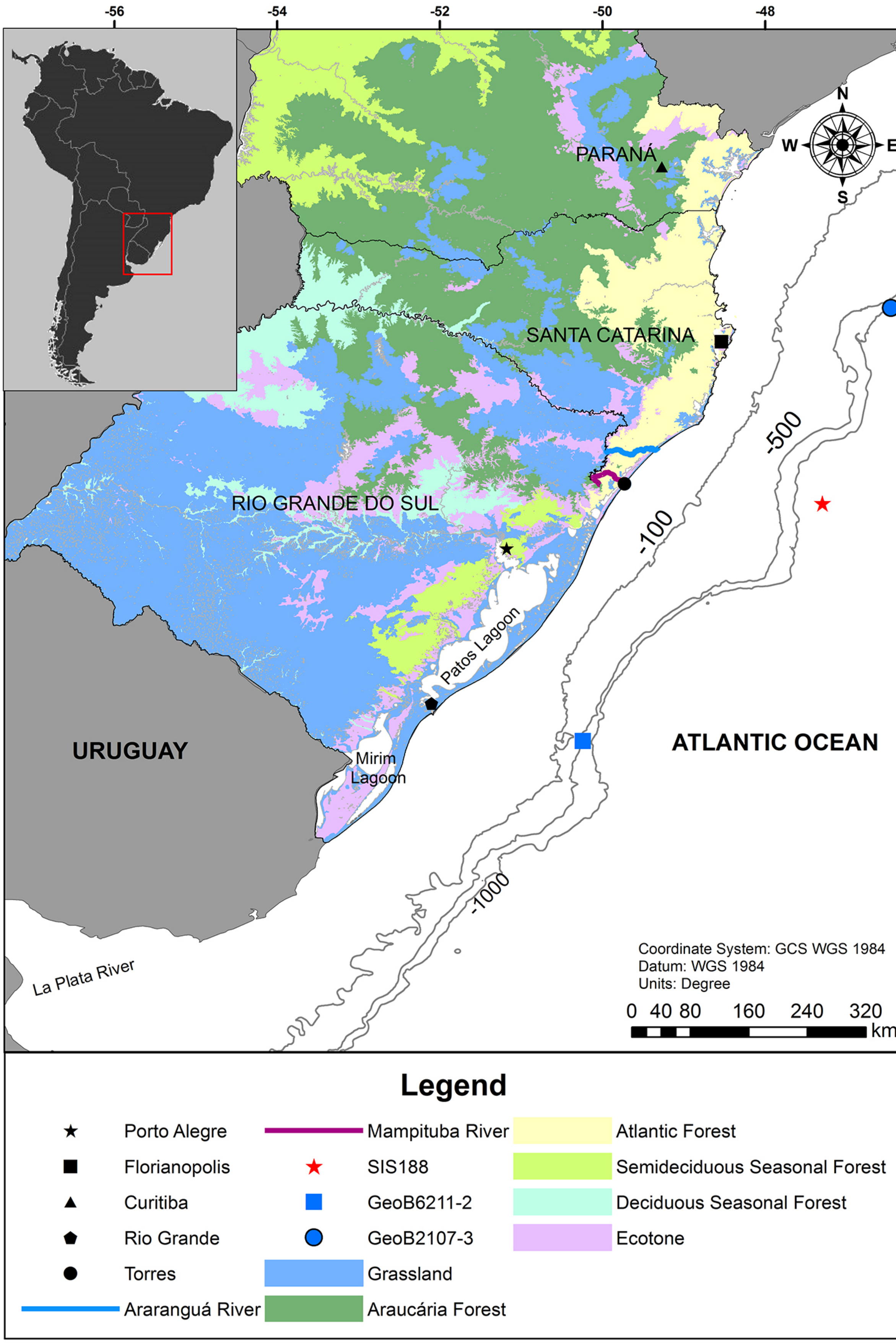

Figure 1. Location of SIS 188 core and the main vegetation formations (IBGE, 2004) in the adjacent continental area. The cores GeoB2107-3 (Gu *et al.*, 2017) and GeoB6211-2 (Gu *et al*., 2018), cited in the Discussion section, are indicated too.

METHODOLOGY

The core SIS188 was retrieved with a piston corer by Fugro company at the southern Brazilian continental slope (-29.579046 S; -47.295608 W, Figure 1), at 1,514 m water depth, recovering 338 cm of sediments. After the removal of about 20 cm from the top and middle portion of the core by the company, the remaining material was sent to the Geological Oceanography Center of the Federal University of Rio Grande (FURG), where it was stored in a refrigerated container. In order to perform the palynological analyses, 56 samples were collected along the core, at intervals of 6 cm between each of them.

Age model

The age model was built based on the correlation of the $\delta^{18}O$ isotope curve of planktonic foraminifera from the SIS188 core with the standard curve of Lisiecki & Stern (2016) (Figure 2). As control points, four AMS ^{14}C ages were obtained (Table 1). The age model was built using the AnalySeries software (Paillard *et al*., 1996) and was partially presented by Duque-Castaño *et al*. (2019).

The ^{14}C datings were performed on the planktonic foraminifera *Globigerinoides ruber* (fraction > 150 µm), using the accelerated mass spectrometry (**AMS**) method at the Radiocarbon Laboratory of the Fluminense Federal University (**LAC-UFF**). The ages obtained by ^{14}C were adjusted considering a Delta R from the Marine Reservoir Correction Database of 54.0 ± 42.0 (De Masi, 1999; Angulo *et al*., 2005; Alves *et al*., 2015) and calibrated according to the Marine13 curve (Reimer *et al*., 2013) using the Calib Radiocarbon Program (Stuiver & Reimer, 1993) (Table 1).

The analysis of $\delta^{18}O$ were also performed on *Globigerinoides ruber* (fraction > 150 µm), on a MAT-253 dual-inlet mass spectrometer with a Kiel IV carbonate device at the Stable Isotope Laboratory of the University of California, Santa Cruz. Isotope data are reported in permil relative to the Vienna Pee Dee Belemnite (V-PDB) standard (Figure 2).

Palynological processing and analysis

One tablet of *Lycopodium clavatum* exotic spores (lot number 1030, produced by the Department of Quaternary Geology at Lund University, and calibrated in Sweden with 20,848 ± 1,545 spores/tablet) was added to each sediment sample to calculate the pollen concentration (Stockmarr, 1971). The palynological processing followed the preparation technique proposed by Faegri & Iversen (1975), with the addition of 10% hydrochloric acid (HCl) for the removal of carbonates and 5% potassium hydroxide (KOH) for the removal of organic matter and humic acids. To concentrate the palynomorphs, a solution of zinc chloride ($ZnCl_2$), with a density between 1.8 to 1.9 g/cm^3, was used and at least five slides of each sample were assembled using glycerin gelatin. The slides were analyzed under an optical microscope at 400 or 1,000 x magnification and 300 pollen grains and spores were counted for each sample, when possible. Additionally, the diatoms present in the palynological slides were counted as well. Although these samples were not prepared for this purpose, these data were included as they provide interesting information when analyzed with the pollen assemblage. The identification was based on several bibliographic references (*e.g*. Leal & Lorscheitter, 2007; Leonhardt & Lorscheitter, 2007, 2008, 2010; Roth & Lorscheitter, 2013; Masetto & Lorscheitter, 2016) as well as on the palynological collection at the laboratory.

The Tilia 2.1.1 software (Grimm, 1993) was used for constructing the pollen diagrams as well as calculating the sedimentation rates (clastic material), concentration and percentage. The establishment of the palynozones (**PZs**) was carried out by CONISS and all data was compared with the sea level curve, derived from the database available at the National Oceanic and Atmosferic Administration (**NOAA**) website (Spratt & Lisiecki, 2016) applicable worldwide. The standard deviation of this curve changes through time and is higher between 8 and 22 cal ka BP, reaching >10 meters for some ages.

RESULTS

The core SIS 188 comprises the time interval between 47.8 and 7.4 cal ka BP, according to the age model (Table 1, Figure 2).

In 56 analyzed samples, 40 spores and 59 pollen grains were identified, besides other non-pollen palynomorphs. For paleoenvironmental interpretation purposes, the taxa were grouped into the following categories: Bryophytes, Pteridophytes, Herbs, Shrubs, Trees, Lianas, Varied Habits, Indeterminate (when the taxonomic identification of the pollen grain was not possible), Algae, and Diatoms. Despite not being considered palynomorphs, diatoms were also counted. Based on these groups, three palynozones (**PZ**) were defined as described below (Figures 3, 4 and 5).

PZ I (47.8–33.3 cal ka BP, 336–208.5 cm)

From a sedimentological point of view, this interval is composed of carbonate-rich hemipelagic mud. The sedimentation rates are rather constant throughout the PZ I, about 9 cm/kyr.

Concentration sum of continental palynomorphs is moderate in this PZ, in comparison with the subsequent palynozones. The groups "Bryophytes" and "Shrubs" reach their highest values in this PZ. The concentration of the freshwater diatom *Cyclotella meneghiniana* shows peaks at 43.5 cal ka BP and 36.5 cal ka BP (Figure 3).

Among the indicators, the "Herbs" group predominates in this PZ, with percentages that vary from 30.4 to 57.1%, exhibiting a mild general increasing trend along the palynozone. Cyperaceae and Poaceae are the dominant taxa within this group, with *Plantago* also standing out. The group "Varied Habits" exhibits a decreasing trend within the PZ, varying from 46.4 to 8%, with emphasis on Moraceae-Urticaceae. The "Pteridophytes" group, represented mainly by *Blechnum*-type, *Microgramma*-type and *Marattia laevis*,

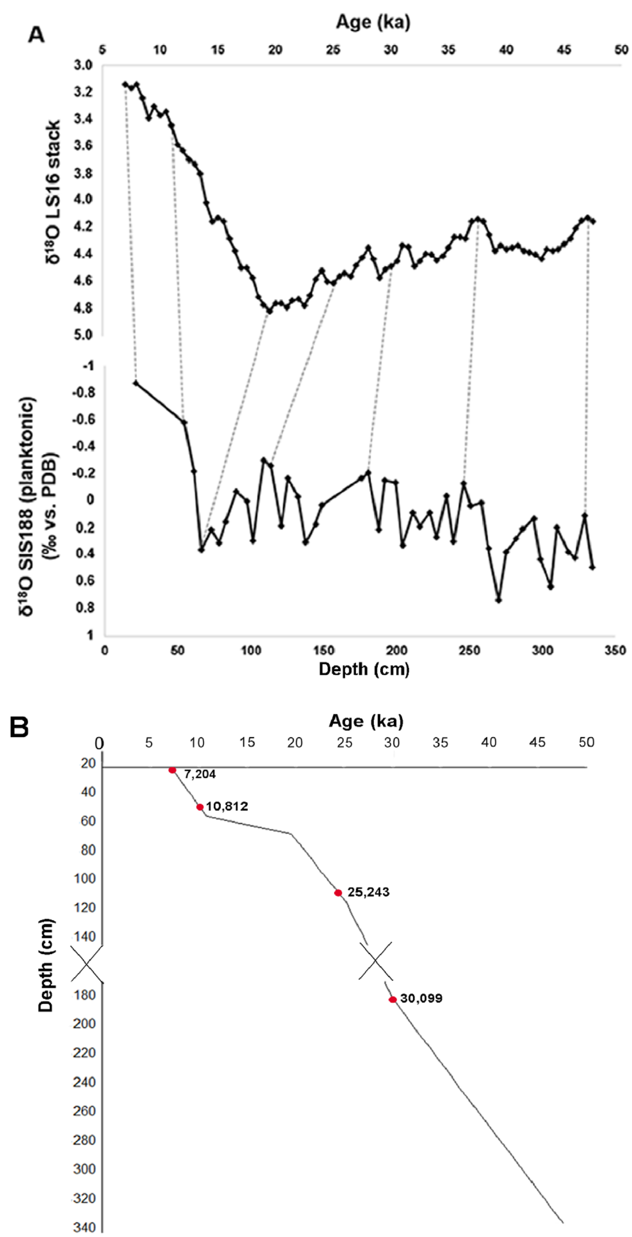

Figure 2. Age model. **A**, correlation between the Lisiecki & Stern (2016) Intermediate South Atlantic curve and the oxygen-isotope data from SIS 188. **B**, relationship between age and depth in SIS 188. The red points indicate the depths where radiocarbon ages were obtained.

varies from 1.9 to 17.4%. The group "Shrubs" has its highest percentages, varying from 0 to 5.7%, represented mainly by *Baccharis*-type and Melastomataceae. The "Trees" group varies between 0 and 5.5%, with *Podocarpus lambertii* and *Araucaria angustifolia* as the main representatives. The "Bryophytes" group, while not very abundant, shows higher percentages in this palynozone (up to 3.5%), represented mainly by *Phaeoceros laevis*. The "Lianas" group, represented by *Ephedra tweediana*, presents low percentages throughout the core, but reaches a peak (2.6%) at 43 cal ka BP. The "Indetermined" group has higher percentages in this PZ than in subsequent ones, with peaks between 43 and 41.9 cal ka BP and between 37.5 and 35.9 cal ka BP. The "Algae" group, with *Pseudoschizaea rubina* in particular presents low percentages (0–2.2%) (Figures 4 and 5).

The "Diatoms" group, represented by *Cyclotella meneghiniana* (Figure 5), exhibits its highest values in this PZ, ranging from 3.4 to 25.3%, with higher proportions between 38.6 and 34.3 cal ka BP.

PZ II (32.8–20.2 cal ka BP, 204–71.5 cm)

The sediments in this PZ are composed of carbonate-rich hemipelagic mud, with the presence of very thin layers of organic matter at depths of 75, 90, 100 and 105 cm. The sedimentation rate reaches the highest values in this palinozone, reaching 13.8 cm/ka between 30 and 25.2 cal ka BP and decreasing to 8.3 cm/ka from 24.9 to 19.7 cal ka BP.

The concentration of most palynomorphs increase between 29.8 and 27.3 cal ka BP and reach the highest values throughout the core, with greater expressiveness of "Herbs" and "Varied Habits" (Figure 4). However, the concentrations of "Bryophytes" and "Shrubs" groups are very low in this range. There is another concentration peak of "Pteridophytes", "Herbs", "Trees", "Lianas" and "Diatoms" groups (Figure 3) in this PZ at 22.9 cal ka BP.

The "Varied Habits" and "Herbs" groups continue to predominate in PZ II. The "Varied Habits" significantly increases its percentages in relation to the previous PZ, ranging from 21.2 to 60.6% (with emphasis on for Moraceae-Urticaceae). The "Herbs" group continues with high percentages (27.6 to 64%), with emphasis on Poaceae and Cyperaceae. Many indicators decrease their percentages in this PZ, such as the "Bryophytes", "Pteridophytes", "Shrubs", "Trees" and "Indetermined" groups. The percentages of the

Table 1. Radiocarbon ages used in the construction of the age model of the SIS 188 core.

Depth (cm)	Species	Age (14C years BP)	Error (years)	Calibrated age median probability (cal ka BP)	Lab ID
21	*G. ruber*	6725	± 31	7204 [age range at 2-sigma (95.4% probability): 7060–7318 cal BP]	170210
54	*G. ruber*	9921	± 34	10812 [age range at 2-sigma (95.4% probability): 10649–11015 cal BP]	170055
113.5	*G. ruber*	21360	± 59	25243 [age range at 2-sigma (95.4% probability): 25003–25497 cal BP]	170056
180.5	*G. ruber*	26325	± 77	30099 [age range at 2-sigma (95.4% probability): 29690–30498 cal BP]	170211

"Pteridophytes" group show a slight increase in the upper half of the PZ, ranging from 2.7 to 11%, with emphasis on the *Blechnum*-type, *Huperzia*, *Microgramma*-type and Cyatheaceae. Regardless of the fact that they are not very representative in the PZ II fossil assemblage, the "Trees" group show an increase in percentage, reaching 5.7% between 22.4–21.2 cal ka BP. Indicators from the "Lianas" and "Diatoms" groups remain with low representation in the fossil assemblage (Figures 4 and 5).

The "Diatoms" group (represented by *Cyclotella meneghiniana*) presents a great decrease in its percentages, varying from 2.3 to 12.4% (Figure 5).

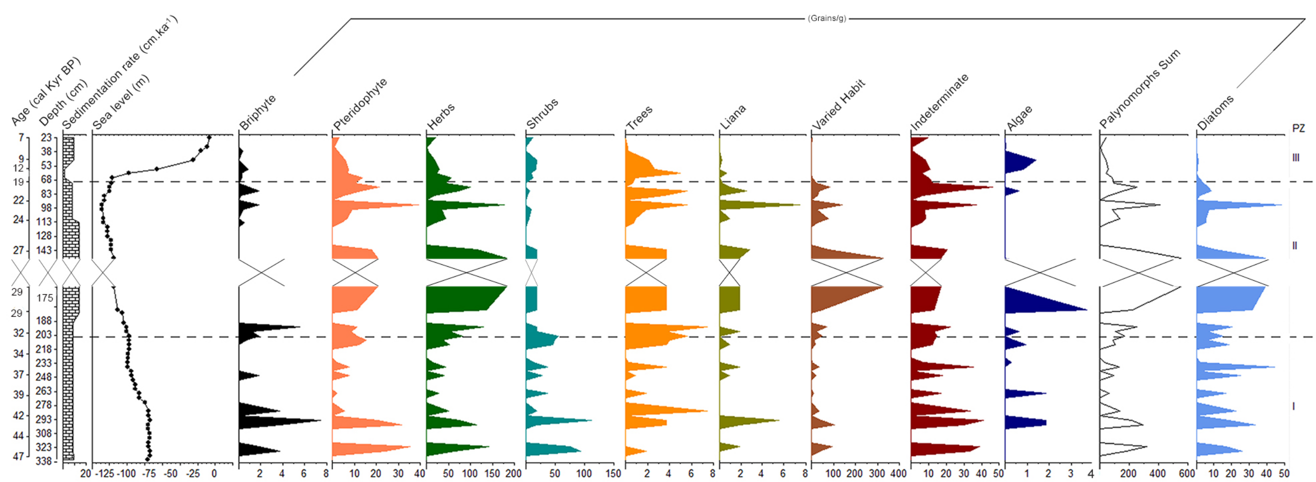

Figure 3. Pollen concentration summary diagram showing sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt & Lisiecki, 2016), vegetation groups, and palynozones (**PZ**) for SIS 188 core. For a better visualization of the values expressed in this graph, they were all divided by 10,000 (except sedimentation rate).

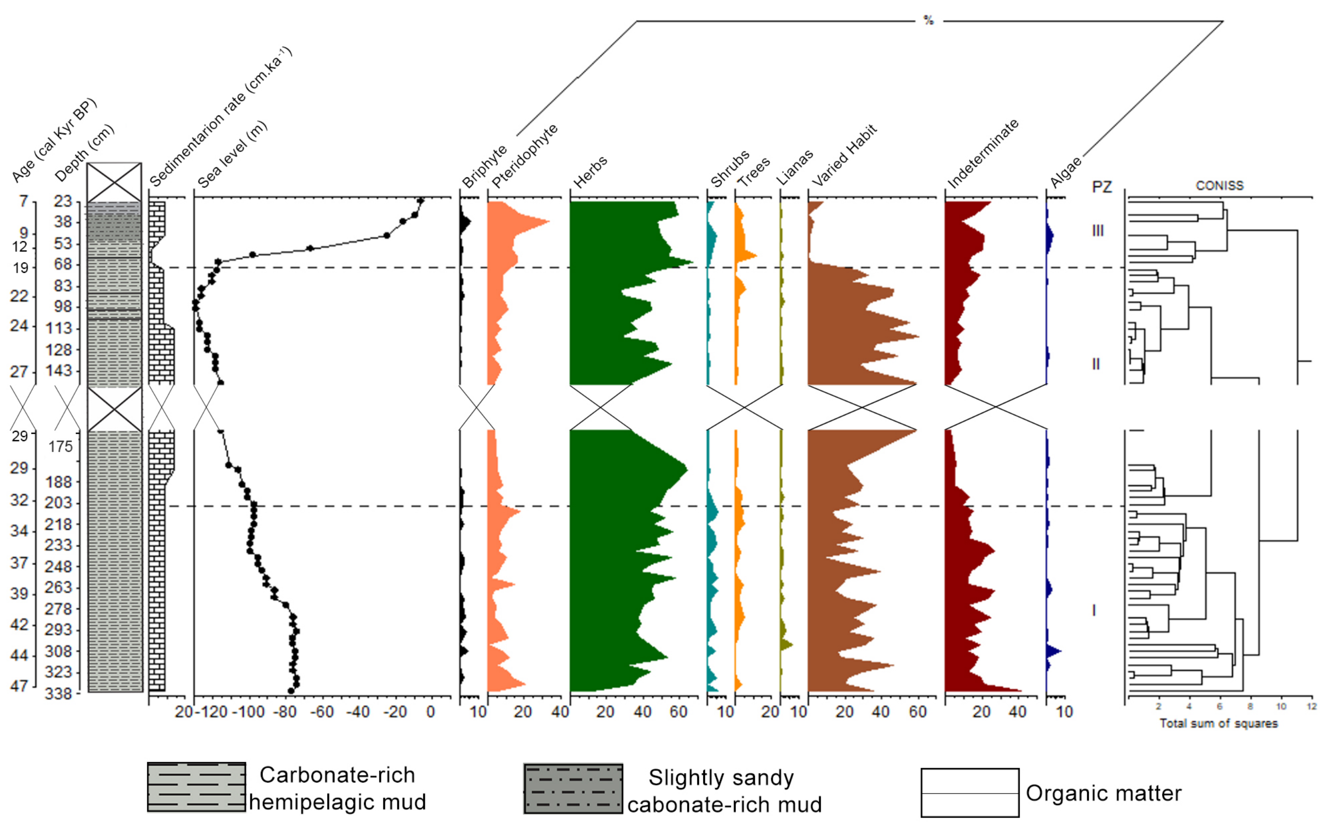

Figure 4. Pollen percentage summary diagram showing lithology, sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt & Lisiecki, 2016), vegetation groups, palynozones (**PZ**) and the CONISS dendrogram (based on individual taxa percentage values) for core SIS 188.

PZ III (19.5–7.4 cal ka BP, 66–23 cm)

In most of this PZ, the sediments consist of carbonate-rich hemipelagic mud, except at the 31–45 cm interval, which contains slightly sandy carbonate-rich mud. Sedimentation rates reach their lowest values (1.4 cm/ka) between 19.5 and 12.6 cal ka BP (66–56.5 cm) but rise to 9.1 cm/ka starting at 10.8 cal ka BP (54 cm).

Palynomorph concentrations are very low in this PZ. All groups show a decrease in their values, with the exception of "Trees", "Herbs" and "Pteridophytes". The two latter exhibit a peak around at 16.4 cal ka BP and "Trees" shows a peak at 15.9 cal ka BP (showing low concentrations from 9 cal ka BP onwards). The concentrations of the diatom *Cyclotella meneghiniana* are very low throughout this PZ (Figure 3).

The "Herbs" group predominates in PZ III (49.7–67.2%), with an expressive increase of Poaceae, as well as Liliaceae and Chenopodiaceae. Cyperaceae exhibits a decline, although it remains with significant percentages. The percentages of the "Varied Habits" group falls abruptly on PZ III, while those of "Bryophytes" and "Lianas" remain low. The percentages of "Pteridophytes", "Shrubs", "Trees", "Diatoms" and "Indetermined" groups increase in this PZ. "Trees" group reach 11.9% at 15.9 cal ka BP, mostly represented by *Araucaria angustifolia*, *Podocarpus lambertii* and *Celtis*. The percentages of "Algae" group are high between 12.6 and 10 cal ka BP, particularly *Pseudoschizaea rubina* and *Botryococcus*. "Shrubs" group reach 4.7% at 10 cal ka BP, with emphasis on *Baccharis* type and Asteraceae. The "Pteridophytes" group shows a peak of *Blechnum*, *Huperzia*, Polypodiaceae, Pteridaceae and Cyatheaceae (Figures 4 and 5) at 8.5 cal ka BP and their percentages range from 8.1 to 18.7%.

The "Diatoms" group, represented by *Cyclotella meneghiniana*, has the smallest percentages in this PZ, ranging from 0 to 2.8% (Figure 5).

DISCUSSION

Palynomorphs of continental origin are usually transported to coastal and oceanic areas by winds, rivers, and marine currents. The SIS188 core represents the latest part of the last glacial period, including the Last Glacial Maximum (LGM, 23–19 ka BP), and the Early–Middle Holocene interglacial. During this interval, the sea level varied widely, reaching up to -130 m during the LGM (Waelbroeck *et al.*, 2002), possibly displacing the Mampituba and Araranguá rivers mouth. Besides, changes in the eolian process intensity over the region during this period also occurred (Maher *et al.*, 2010; Vanneste *et al.*, 2015; Voigt *et al.*, 2015). These are the main transport mechanisms that may have brought the palynomorphs to the ocean, where they became available to transportation by marine currents.

Paleoenvironmental interpretations

PZ I (47.8–33.3 cal ka BP)

The high percentages of the "Herbs" group indicate that grasslands dominated the adjacent continental area during this interval. The predominance of grasslands during the last glacial period has been observed in several palynological records, such as in marine cores on the southeastern Brazilian coast (Behling *et al.*, 2002), on the South Brazilian Plateau (Behling *et al.*, 2004) and marine core GeoB2107-3 on the southern Brazilian continental slope (Gu *et al.*, 2017; Figure 1).

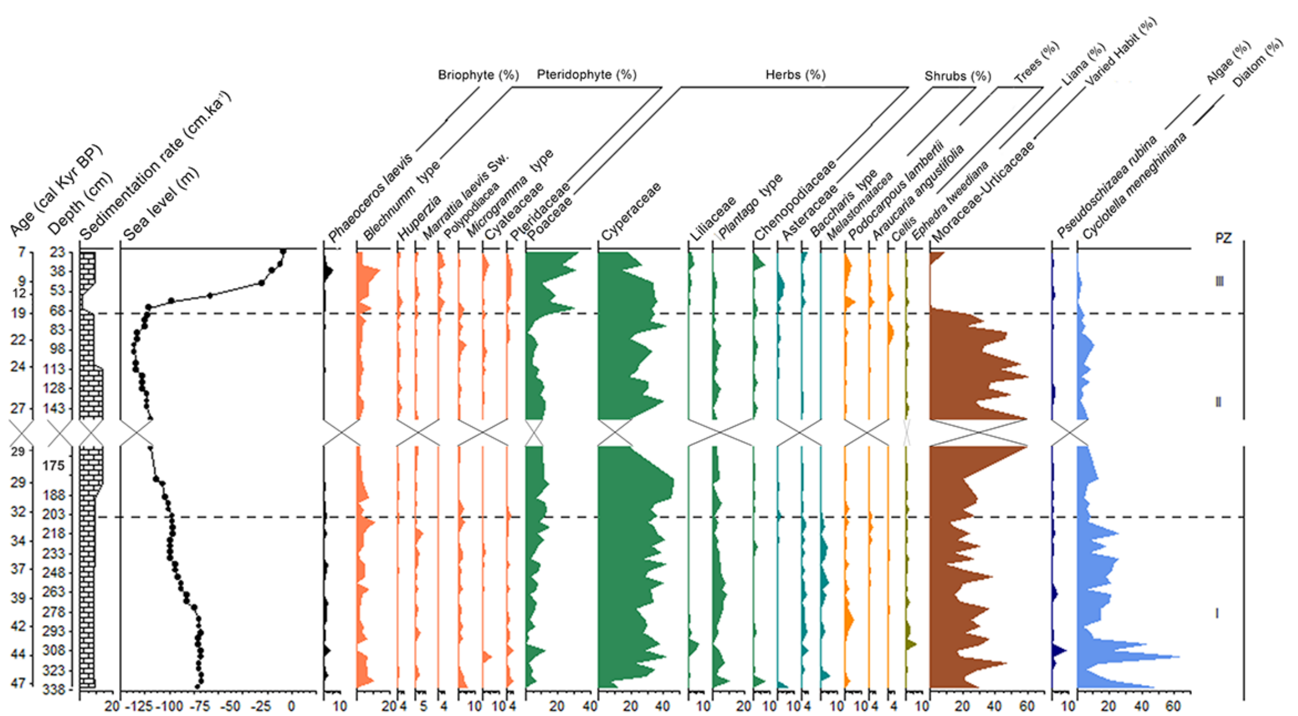

Figure 5. Pollen diagram of the main taxa found in core SIS 188, showing sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt & Lisiecki, 2016), and palynozones (**PZ**).

The predominance of Cyperaceae over Poaceae and the high percentages of *Blechnumm*-type and *Phaeoceros laevis* suggest that wetlands such as swamps (Menéndez, 1962; Tryon & Tryon, 1982) may have been common in the adjacent coastal plain at that time. In addition, the highest percentages of "Bryophytes" and "Pteridophytes" groups in this PZ indicate wetter environmental conditions in this period than during the LGM and at the beginning of deglaciation. There is also a peak of *Podocarpus lambertii* at this stage, consistent with an increase in moisture. Similar environmental conditions, at a comparable timeframe, were found by Behling *et al*. (2004) on the continent, between 42.8 and 26.9 cal ka BP, and by Gu *et al*. (2017) in GeoB2107-3 core (Figure 1), between 55.8 and 38.5 cal ka BP. The interval of PZ I corresponds to the interstadial MIS 3 (57–29 ka), an interval characterized by warmer and wetter climate than MIS 2 (29–14 ka, including the LGM), but colder than MIS 1 (14 ka to the present) (Lisiecki & Raymo, 2005). The environmental conditions, documented by the vegetation changes, partially follows this chronology, also marked by local characteristics. The same trend was observed in other places at the region, as in a core studied at Cambará do Sul (South Brazilian Plateau) (Behling *et al*., 2004).

Within the "Trees" group, the pollen grains of *Araucaria angustifolia* and *Podocarpus lambertii*, typical components of the *Araucaria* Forest and considered pioneers in the expansion over grasslands (Backes & Irgang, 2002), stand out. The pollen grains from the Moraceae-Urticaceae and Melastomataceae families, which occur in various environments, common in forests or on their margins, also stand out. The spores of the pteridophytes *Marattia laevis* and *Microgramma*-type, herbaceous or epiphyte species of both lowland and highland Atlantic rainforest and restinga (Santos & Sylvestre, 2001), are important in this palynozone, occurring in forest environments (Lorscheitter *et al*., 1998, 2005). This data suggest that the region had forest formations associated with the grasslands. Prieto & Quattrocchio (1993) and Freitas *et al*. (2015), also register the presence of these pteridophytes in Holocene sediments from Argentina, and in slope sediments from the Campos Basin (southeastern Brazil), respectively.

The largest percentages of the diatom *Cyclotella meneghiniana* are found in PZ I. This cosmopolite euryhaline planktonic species is found in many rivers and estuaries around the world (Finlay *et al*., 2002). Therefore, its largest percentages may indicate a period of greater humidity and consequently the formation of freshwater bodies along the continental shelf (Stoermer & Julius, 2003). The abundance of this diatom in PZ I also demonstrates the importance of aquatic transport for the occurrence of continental microfossils in deep marine cores.

PZ II (32.8–20.2 cal ka BP)

The sedimentation rate increases from 30 to 25.2 cal ka BP, possibly related to the lower velocity of the Intermediate Western Boundary Current (that flows to the south at the depth core) inferred for SIS188 (Gonçalves & Leonhardt, 2021), and the intensification of the eolian processes that occurred in MIS 2 (Maher *et al*., 2010; Vanneste *et al*., 2015). It is reflected in the concentration of most palynomorphs, which increases between 29.8 and 27 cal ka BP. In addition to the velocity changes in deep current and the intensification of the winds, the increase is possibly also related to the greater proximity of the mouth of the rivers Araranguá and Mampituba to the core, due to the lower RSL at that time.

The "Herbs" and "Varied habits" groups continue to dominate the pollen records, with an important increase of the latter, represented by Moraceae-Urticaceae. These are pioneer taxa that occur in forest edges and/or in its interior (Berrío *et al*., 2000). Their great abundance can indicate that intense paleoclimatic oscillations induced changes in the vegetational ecological structure. This zone is also characterized by a marked decrease in the percentages of *Cyclotella meneghiniana* that starts with the beginning of the sea level fall, when the environmental conditions get somewhat dryer. As a result, freshwater bodies along the continental shelf may have been reduced.

At the same time, the reduction of arboreal components such as *Araucaria angustifolia* and *Podocarpus lambertii*, and the decrease of "Bryophytes" and "Pteridophytes" groups in relation to PZ I indicates an expansion of the grasslands, due to a colder and drier climate at South of Brazil (Cruz Jr. *et al*., 2005). Behling *et al*. (2002) and Gu *et al*. (2017) also observed a reduction in forest indicators in the marine cores collected off the Brazilian coast.

The same pattern is observed when examining continental palynological records. In southern and southeastern Brazil, the landscape was dominated by grasslands during this period, even in places where forest formations predominate today (Behling, 2002). At the South Brazilian Plateau, the *Araucaria* Forest was much reduced at that time (Behling *et al*., 2004; Leonhardt & Lorscheitter, 2010; Scherer & Lorscheitter, 2014; Spalding & Lorscheitter, 2015). In general, this core and the other marine and continental cores from this region indicate dry environments. However, the relatively higher proportion of taxa that occur in swamp and woodland areas, such as the "Pteridophyte" group, mainly *Blechnumm*-type, *Huperzia*, *Microgramma* type and *Cyatheaceae* (Tryon & Tryon, 1982; Lorscheiter *et al*., 1998), indicates wetter conditions from ~27 ka BP onwards. This increase was also detected in a sedimentary core of the South Brazilian Plateau between 28 and 23.5 cal ka BP (Spalding & Lorscheitter, 2015).

Although the LGM was a cold and dry period, peaks in concentration of many of the pollen indicators were observed in the core SIS188. This increase can be related to an increased eolian transport (Kohfeld *et al*., 2013) and/or to the decrease of sea level (Waelbroeck *et al*., 2002). Mampituba and Araranguá rivers, carrying sediments and palynomorphs, could have crossed the exposed continental shelf, becoming closer to the site of deposition, and increasing the concentration of preserved palynomorphs. A similar increase in palynomorphs was reported by Gu *et al*. (2017; 2018) from two other cores on the southern Brazilian margin (see Figure 1).

PZ III (19.5–7.4 cal ka BP)

There is a significant reduction in the sedimentation rate between 19.5 and 12.6 cal ka BP, making this period poorly represented in the core. Gu *et al*. (2018), studying the GeoB6211-2 marine core collected on the upper slope off southern Brazil (Figure 1), also observed a decrease in the sedimentation rate in a partially overlapping period (14.8–8.7 cal ka BP). For GeoB6211-2, that reduction can be related to the sea level rise during the deglaciation, displacing the mouth of Rio de la Plata and Patos Lagoon estuary, which began to deposit its sediments on the newly submerged continental shelf (Lantzsch *et al*., 2014). The same pattern possibly occurred with the Mampituba and Araranguá rivers, closer to SIS188 core. The decrease in the concentration of most palynomorphs could be attributed to the sea level rise and/or to the weakening of eolian process over the region (Voigt *et al*., 2015).

The percentages of "Varied habits" group falls abruptly at the beginning of this PZ, possibly due to the climate change and landscape development related to sea level rise, which may have favored other plant formations. The pollen association shows that grasslands remained the dominant plant type, and indicate a significant contribution of eolian input, because the pollen from grassland plants, like Poaceae, is easily transported by winds. Nonetheless, "Trees", "Shrubs" and "Pteridophytes" groups are higher in this PZ, indicating a development of vegetation that accompanies the climate changes of the deglaciation and the beginning of the Holocene, with increased temperature and wettness. Several works in the region have detected similar vegetation and climate change at that time. Gu *et al*. (2017, 2018), studying the marine cores GeoB2107-3 and GeoB6211-2 (Figure 1), concluded that the Atlantic Forest expanded from approximately 14.5 cal ka BP. On the southeastern Brazilian coast, the percentage of coastal arboreal vegetation taxa increased after the LGM (Behling *et al*., 2002). In continental cores in southeastern Brazil, taxa of different forest formations began to expand from 17 cal ka BP (Behling, 2002), whereas in the south the forest expansion started approximately around 12 cal ka BP (Behling, 2002; Leonhardt & Lorscheitter, 2010; Scherer & Lorscheitter, 2014; Spalding & Lorscheitter, 2015).

The "Trees" group reach a peak of 11.9% at 15.9 cal ka BP, especially *Araucaria angustifolia*, *Podocarpus lambertii* and *Celtis*, all occurring in the *Araucaria* Forest. Some pteridophytes, such as *Huperzia* and Polypodiaceae, which also occur in these forests (Lorscheitter *et al*., 1998; 2005), follow this peak. The same vegetational change was observed in the GeoB6211-2 core (Gu *et al*., 2018), but was not detected in the GeoB2107-3 core (Gu *et al*., 2017) or in the continental cores studied in the region, perhaps due to their temporal resolution.

Studies carried out in speleothems of the Botuverá Cave, southern Brazil, show higher precipitation rates for the time period represented by PZ III, associated with the Heinrich event 1 (Wang *et al*., 2004; Cruz Jr. *et al*., 2005). Chiessi *et al*. (2015), studying the marine core GeoB6211-2 (Figure 1), documented a temperature increase related to this same event, with a peak around 15 cal ka BP. Both the increase in temperature and rainfall may have promoted the development of forest vegetation observed in the core SIS188. Between 12.6 and 10 cal ka BP, there is a small increase in freshwater taxa *Pseudoschizaea rubina*, typical of freshwater environments (Rossignol, 1962), and *Botryococcus*, which can also occur in brackish environments (Vuuren & Levanets, 2016), indicating the formation of water bodies along the coast.

Around 8.5 cal ka BP, there seems to be another increase in wettness, indicated by a peak in the percentages of the "Pteridophytes" group and the herbaceous taxon Chenopodiaceae. The percentage of pteridophytes increases especially with Polypodiaceae, Pteridaceae and Cyatheaceae, families that have many species associated with forest environments (Lorscheitter *et al*., 1999; 2001; 2005). The Chenopodiaceae family presents many ruderal or halophytic species that prefer coastal or xeric habitats, which are generally characterized by high levels of alkaline salts (Kün *et al*., 1993; Joly, 2002) and, together with large proportions of Cyperaceae, indicate the presence of salt marshes in the coastal region. The same pattern of vegetation was found in GeoB6211-2 core (Figure 1), from 8.7 cal ka BP (Gu *et al*., 2018) and also by Mourelle *et al*. (2015), which indicate a development of the vegetation of salt marshes around the estuary of the Rio de la Plata since 8 cal ka BP.

Although oscillations in wettness allowed some development of forests and lagoons, the grasslands continued to be the dominant vegetation during the Early and Middle Holocene. The record of the marine core SIS188 is comparable to those obtained in the highlands (Behling, 2002; Behling *et al*., 2004; Leonhardt & Lorscheitter, 2010; Scherer & Lorscheitter, 2014; Spalding & Lorscheitter, 2015) and the coastal plain of southern Brazil (Behling & Negrelle, 2001; Lorscheitter, 2003; Leal & Lorscheitter, 2007). The forest expansion was prevented by environmental disturbances caused by marine incursions at that time.

CONCLUSIONS

The results of the palynological analyses of marine core SIS188, covering the period from 47.8 to 7.4 cal ka BP, allowed to reconstruct vegetational and climate dynamics of the continental region adjacent to the core location. In southern Brazil, grasslands were the dominant vegetation during the entire studied period.

From 47.8 to 33.3 cal ka BP, wet environments such as swamps expanded, and forests were reduced. The environmental conditions were wetter during this period and at the beginning of the deglaciation than during the LGM. From 32.8 to 20.2 cal ka BP, an expansion of the grasslands and retraction of the forest indicators was observed, resulting from a colder and drier climate of the LGM. From 19.5 to 7.4 cal ka BP, the development of the forest followed the climate changes accompanying the deglaciation and the beginning of the Holocene, marked by an increase in temperature and wettness. The global climate event Heinrich 1 was detected in the studied area as an increase of precipitation and temperature, which favored the expansion of the arboreal component.

ACKNOWLEDGMENTS

The authors are grateful to CAPES (Brazilian Coordination of Higher Education Staff Improvement) for the financial support (process 88887.091729/2014-01). The first author is also grateful to CAPES for the PhD´s scholarship that enabled the execution of this work and to the Oceanology Graduate Program of FURG for the opportunity.

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Received in 15 January, *2021*; *accepted in 02 August*, *2021*.