Universidade Federal do Rio Grande – FURG
Instituto de Oceanografia

Programa de Pós-Graduação em Oceanologia

Dinâmica vegetacional, influência continental sobre a produtividade oceânica e as mudanças climáticas no sul do Brasil no Quaternário tardio

Silvia Regina Bottezini

Tese apresentada ao Programa de Pós-Graduação em Oceanologia, como parte dos requisitos para a obtenção do Título de Doutor.

Orientadora: *Profª. Drª.* Adriana Leonhardt

Universidade Federal do Rio Grande (FURG), Brasil.

Rio Grande, RS, Brasil

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ATA ESPECIAL DE DEFESA DE TESE DE DOUTORADO – 05/2021

Às 13h e 30min. do dia 06 de setembro do ano de dois mil e vinte e um, por videoconferência, reuniu-se a Comissão Examinadora da Tese de **DOUTORADO** intitulada **" Dinâmica vegetacional, influência continental sobre a produtividade oceânica e as mudanças climáticas no sul do Brasil no Quaternário tardio"**, da **Acad. Silvia Regina Bottezini.** A Comissão Examinadora foi composta pelos seguintes membros: Profa. Dra. Adriana Leonhardt – Orientadora - (IO/FURG), Profa. Dra. Paula Dentzien Dias Francischini - (IO/FURG), Profa. Dra. Ingrid Horák-Terra – (UFVJM) e Profa. Dra. Maria Alejandra Gómez Pivel – (UFRGS). Dando início à reunião, a Orientadora e Presidente da sessão, Profa. Dra. Adriana Leonhardt, agradeceu a presença de todos e fez a apresentação da Comissão Examinadora. Logo após esclareceu que a Candidata teria um tempo de 45 a 60 min para explanação do tema, e cada membro da Comissão Examinadora, um tempo máximo de 30 min para perguntas. A seguir, passou à palavra a Candidata que apresentou o tema e respondeu às perguntas formuladas. Após ampla explanação, a Comissão Examinadora reuniu-se em reservado para discussão do conceito a ser atribuído a Candidata. Foi estabelecido que as sugestões de todos os membros da Comissão Examinadora, que seguem em pareceres em anexo, foram aceitas pelo Orientador/Candidata para incorporação na versão final da Tese. Finalmente, a Comissão Examinadora considerou a candidata **APROVADA,** por unanimidade. Nada mais havendo a tratar, foi lavrada a presente ATA que após lida e aprovada, será assinada pela Comissão Examinadora, pela Candidata e pelo Coordenador do Programa de Pós-Graduação em Oceanologia.

Profa. Dra. Adriana Leonhardt
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Profa. Dra. Maria Alejandra Gómez Pivel

Acad. Silvia Regina Bottezini

Prof. Dr. Rodrigo Kerr
Coordenador PPGO

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A

ACAS **– Água Central do Atlântico Sul**

AIA **– Água Intermediária**

Antártica

ANP **– Agência Nacional do Petróleo**

AP **– Antes do Presente**

ASAS **– Alta Subtropical do Atlântico Sul**

B

BP **–** ***Before Present*** **(Antes do Presente)**

C

CB **– Corrente do Brasil**

CBM **– Confluência Brasil Malvinas**

CCB **– Corrente Costeira Brasileira**

CM **– Corrente das Malvinas**

CNB **– Corrente Norte do Brasil**

CSE **– Corrente Sul Equatorial**

E

EIM **– Estágios Isotópicos Marinhos**

ENOS **– El Niño Oscilação Sul**

I

IBGE **– Instituto Brasileiro de Geografia e Estatística**

L

LGM **–** ***Last Glacial Maximum*** **(Último Máximo Glacial)**

M

MIS **–** ***Marine Isotope Stage*** **(Estágio Isotópico Marinho)**

N

NE **– Nordeste**

NMM **– Nível Médio do Mar**

NOAA **–** ***National Oceanic and Atmospheferic Administration*** **(Administração Oceânica e Atmosférica Nacional)**

P

PR **– Paraná**

PRP **– Pluma do Rio da Prata**

PZ **– Palinozona**

R

RSL **–** ***Relative Sea Level*** **(Nível Médio do Mar)**

S

SASH **–** ***South Atlantic Subtropical High*** **(Alta Subtropical do Atlântico Sul)**

SC **– Santa Catarina**

T

TW **– *Tropical Water* (Água Tropical)**

U

UMG **– Último Máximo Glacial**

Z

ZCIT **– Zona de Convergência Intertropical**

Resumo

A partir da análise de palinomorfos continentais e marinhos e da comparação destes com *proxies* de paleoprodutividade recuperados do testemunho SIS 188, coletado no talude da Bacia de Pelotas, o presente estudo teve como objetivos entender a dinâmica da vegetação continental e compreender o papel da influência continental sobre a produtividade oceânica ao longo do Quaternário Tardio. O registro documenta o intervalo de tempo entre 47,8 e 7,4 cal ka BP e inclui os Estágios Isotópicos Marinhos (EIM) 3, 2 e 1 (parcialmente). A assembleia polínica indica que os campos dominaram a paisagem no Sul do Brasil ao longo do intervalo estudado, refletindo a flora típica do Planalto Leste do Estado do RS, localizado na mesma latitude do testemunho. Desta forma, a poeira carregada pelos ventos e as descargas dos rios Mampituba e Araranguá, seriam as principais fontes dos palinomorfos, ao invés da Corrente Costeira Brasileira (CCB). Entre 47,8 e 33,3 cal ka BP, ambientes úmidos, como pântanos, se expandiram e as florestas foram reduzidas. Durante o Último Máximo Glacial (UMG), houve uma expansão dos campos e a redução dos indicadores florestais, refletindo um clima mais frio e seco. De 19,5 a 7,4 cal ka AP, as mudanças ambientais do início do Holoceno e do degelo propiciaram o desenvolvimento das florestas, refletindo um clima mais quente e úmido. O pico na porcentagem do grupo “Árvores” em 15,9 cal ka BP é atribuído ao Evento Heinrich 1. As análises dos *proxies* de paleoprodutividade indicaram que durante os intervalos glaciais (EIMs 3 e 2), a produtividade esteve atrelada à intensificação dos processos de ressurgência e ao transporte de poeira. Ao final do EIM 2, houve uma queda nas concentrações polínicas, que foi intensificada no EIM 1, atribuída à subida do nível do mar e ao enfraquecimento dos ventos de sudoeste. Neste intervalo a produtividade foi alta, embora as concentrações de palinomorfos de origem continental tenham diminuído muito. Ademais, a correlação entre a Razão N e a concentração polínica só é significativa quando se excluem as amostras deste EIM, indicando que o aumento do nível do mar interfere na fertilização pelo aporte continental das águas marinhas distantes da costa.

Palavras-chave: Palinomorfos; Vegetação; Paleoprodutividade; Bacia de Pelotas.

Abstract

Based on the analysis of continental and marine palynomorphs and their comparison with paleoproductivity proxies, recovered from the SIS 188 core collected on the slope of the Pelotas Basin, this study aimed to understand the continental vegetational dynamics and the role of continental influence on ocean productivity throughout the Late Quaternary. The record documents the time interval between 47.8 and 7.4 cal ka BP and includes Marine Isotopic Stages (MIS) 3, 2 and partially 1. The palynological assemblage indicates that the grasslands dominated the landscape in southern Brazil throughout the studied period, reflecting the typical flora of the East Plateau of the Rio Grande do Sul State, located at the same latitude as the core. Therefore, the dust carried by the winds and discharges from the Mampituba and Araranguá rivers would be the main sources of palynomorphs, instead of the Brazilian Coastal Current (BCC). Between 47.8 and 33.3 cal ka BP, wet environments such as swamps expanded and forests were reduced. During the Last Glacial Maximum (LGM), there was an expansion of grasslands and a reduction in forest indicators, reflecting a colder and drier climate. From 19.5 to 7.4 cal ka BP, the environmental changes of the beginning of the Holocene and of the deglaciation propitiated the development of forests, reflecting warmer and wetter climate. The Heinrich Event 1 is marked by a peak in the percentage of the "Trees" group at 15.9 cal ka BP. Analyses of paleoproductivity proxies indicated that during glacial intervals (MIS 3 and 2), productivity was linked to the intensification of upwelling processes and dust transport. At the end of MIS 2, there was a decrease in pollen concentrations, which was intensified in MIS 1, attributed to rising sea level and the weakening of southwesterly winds. In this interval, productivity was high, although the concentrations of palynomorphs of continental origin have decreased sharply. Furthermore, the correlation between the N Ratio and pollen concentration is only significant when samples from MIS 1 are excluded, indicating that the rise in sea level interferes in the fertilization by the continental input of marine waters far from the coast.

Keywords: Palynomorphs; Vegetation; Paleoproductivity; Pelotas Basin.

Capítulo I: Introdução

1.1 O período Quaternário

O período Quaternário, que teve início há aproximadamente 2,6 milhões de anos antes do presente (AP) e se estende até os dias de hoje, caracteriza-se pelo desenvolvimento de extensas e generalizadas glaciações nas altas latitudes do Hemisfério Norte e profundas mudanças climáticas no sistema Terra [Head *et al*. 2008]. O clima global foi marcado por uma sucessão contínua de períodos glaciais e interglaciais, sendo os glaciais marcadamente mais frios e secos com expansão dos mantos de gelo, quando comparados com os interglaciais [Rahmstorf 2002, Clark *et al*. 2009].

A alternância entre períodos quentes e frios é expressa na quantidade do isótopo de ^{18}O contidos nos testemunhos de gelo da Groenlândia e da Antártica, bem como na variação deste nas carapaças de foraminíferos e outros organismos marinhos calcificantes preservados em testemunhos marinhos (Figura 1) [Rabassa & Ponce 2016]. A proporção entre ^{16}O e ^{18}O ($\delta^{18}O$) na água do mar se modifica ao longo do tempo, caracterizando os chamados “Estágios

Isotópicos Marinhos" (EIM), correspondendo a momentos com diferentes condições de clima e temperatura [Rabassa & Ponce 2016].

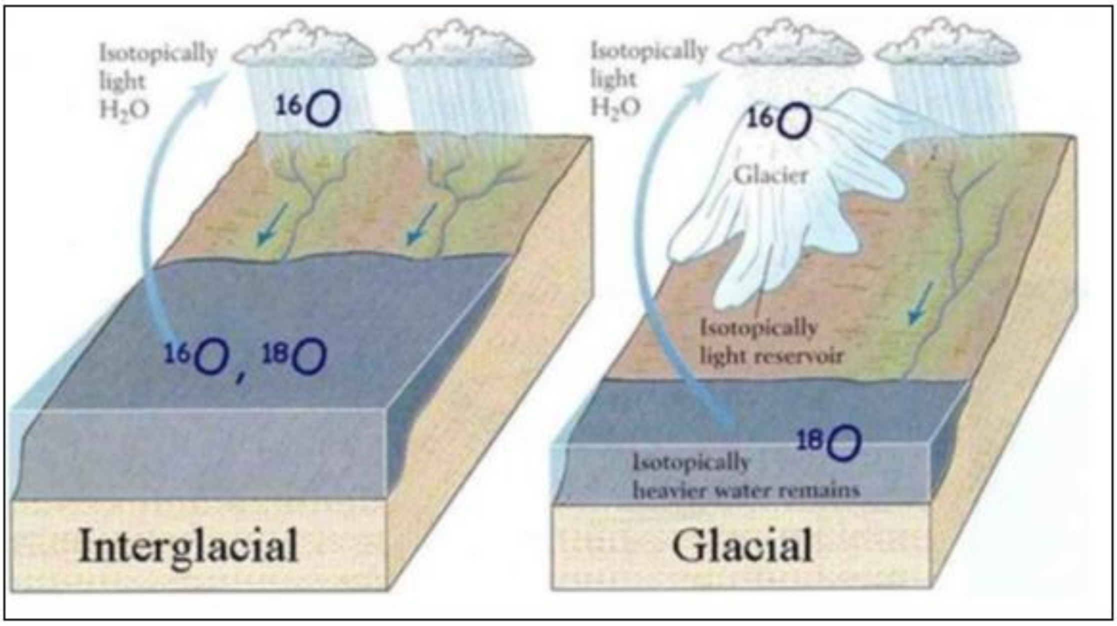

Figura 1: Assinatura isotópica em períodos glaciais e interglaciais. [EM: Analysis of Vostok Ice Core Data. Acessado em 10/08/2021].

1.2 Paleopalinologia

A Paleopalinologia é o ramo da Palinologia que se ocupa do estudo dos mais diversos microfósseis de parede orgânica, entre eles: grãos de pólen e esporos (indicadores exclusivamente terrestres), cistos de dinoflagelados, palinoforaminíferos (indicadores exclusivamente marinhos), escolecodontes, acritarcos, fungos e algas. A Paleopalinologia é uma importante ferramenta para ajudar a compreender as variações climáticas e ambientais pretéritas, pois permitem reconstituir com grande autenticidade os tipos de paleovegetação e paleopaisagem, uma vez que seu desenvolvimento está intimamente ligado às mudanças nos padrões climáticos [Salgado-Labouriau 2007, Traverse 2007, Ybert *et al*. 2012].

Uma das vantagens apresentadas pelos palinomorfos é que podem ser encontrados em todos os ambientes deposicionais, desde o continental até o oceano profundo, variando apenas de acordo com sua abundância relativa (abundantes a raros), dependendo do grupo em questão e do ambiente deposicional. Um outro aspecto positivo no emprego dos palinomorfos está relacionado à sua evolução, que é considerada rápida dentro da escala geológica, fazendo com que as características morfológicas estejam atreladas a curtos períodos de tempo, tornando-os úteis nos estudos paleogeográficos, estratigráficos e paleoambientais [Salgado-Labouriau 2007, Traverse 2007].

1.3 Palinologia marinha

Por se tratar de uma ciência interdisciplinar, a palinologia é frequentemente utilizada nos estudos de reconstituição paleoambientais. Análises quantitativas de pólen foram aplicadas com sucesso na reconstituição da vegetação, clima e impactos humanos no passado utilizando testemunhos terrestres [e. g.: Behling, 2004]. Quando comparada com a palinologia terrestre, a palinologia marinha ainda é um campo de pesquisa jovem que vem ganhando mais espaço e visibilidade por sua importância para as pesquisas sobre as mudanças climáticas globais.

Testemunhos sedimentares marinhos podem fornecer longos e contínuos registros sobre mudanças ambientais no continente e também no oceano, permitindo uma comparação direta de *proxies* de origem terrestre como grãos de pólen, esporos, algas de água doce e de *proxies* marinhos como dinocistos e algas marinhas para a reconstituição dos ambientes pretéritos. Desta forma, as interações terra-oceano podem ser investigadas na mesma escala de tempo. Em testemunhos sedimentares marinhos, a dinâmica da vegetação e do ecossistema, da mesma forma que as mudanças climáticas, podem ficar registradas em escala mais regionalizada do que em testemunhos terrestres [Hooghiemstra *et al*. 2006; González *et al*. 2008]. Os palinomorfos de origem marinha, como dinocistos por exemplo, refletem as condições da superfície do mar, como salinidade, temperatura, condições eutróficas e fornecem informações sobre mudanças nas correntes marinhas. Portanto, testemunhos marinhos podem contribuir para uma compreensão mais abrangente e profunda das mudanças ambientais passadas e atuais, permitindo ainda fazer previsões mais precisas sobre mudanças ambientais futuras.

1.4 Estudos palinológicos em regiões costeiras e oceânicas no Brasil

Ao longo das últimas décadas, vários trabalhos palinológicos vêm sendo desenvolvidos no Brasil com ênfase em ambientes costeiros e/ou marinhos, com o objetivo de compreender melhor a evolução paleoclimática e paleoambiental da região [Behling *et al.* 2000, Behling *et al.* 2002, Medeanic *et al.* 2007, Gu *et al.* 2017, 2018a, 2018b, 2020; Ávila *et al*. 2020]. Behling *et al.* [2000] identificaram períodos de maior precipitação no Nordeste brasileiro através do aumento na concentração de palinomorfos continentais, especialmente samambaias. A duração e amplitude destes eventos são compatíveis com os ciclos Dansgaard-Oeschger e eventos Heinrich, que são bem conhecidos no Atlântico Norte, indicando que há uma forte conexão inter-hemisférios do sistema climático. As análises de dois testemunhos marinhos na costa Sudeste do Brasil por Behling *et al.* [2002], indicaram que os campos dominaram a paisagem durante o último período glacial, enquanto a Mata Atlântica e a floresta semidecidual reduziram significativamente, voltando a aumentar em direção ao final do UMG, resultado de condições climáticas mais quentes e úmidas.

Gu *et al.* [2017, 2018a], estudando testemunhos marinhos coletados na costa sul do Brasil, apontaram para uma expansão dos campos durante o UMG e a retração dos componentes de matas. Os resultados também apontam para a influência das águas transportadas pela Corrente do Brasil (CB) ao longo do período estudado e também da Corrente Costeira Brasileira (CCB) na área de estudo, indicado pelas assembleias de dinoflagelados. Ávila *et al*. [2020], estudaram um testemunho coletado próximo ao Cone do Rio Grande e atribuíram as mudanças nos *taxa* de dinoflagelados à influência da Água de Plataforma Subantártica, que trouxe águas frias e ricas em nutrientes para a área.

Trabalhos desenvolvidos na planície costeira sul brasileira demonstram a relação entre o desenvolvimento da vegetação e eventos transgressivos-regressivos marinhos ao longo do Quaternário. Evidências da última transgressão marinha, em 5 ka BP, foram encontradas na parte norte da planície costeira do Rio Grande do Sul [Cordeiro & Lorscheitter 1994, Lorscheitter & Dillenburg 1998, Medeanic *et al.* 2001, Werneck & Lorscheitter 2001] e um aumento de pluviosidade, também em 5 ka BP [Medeanic *et al.* 2003].

1.5 Influência continental e Paleoprodutividade

A plataforma continental sul-brasileira está sob a influência de grandes aportes fluviais. O mais importante deles é oriundo do Rio da Prata, que aporta na região oceânica adjacente, aproximadamente 23.000 m³/s de água doce. Em condições favoráveis de ventos de sudoeste, durante o inverno austral, a Pluma do Rio da Prata (PRP) pode atingir até 26° S, e ficando mais restrita à desembocadura durante o verão [Piola *et al.* 2000]. Outro importante aporte continental vem da Lagoa dos Patos [Vaz *et al.* 2006], cuja drenagem pretérita se dava através de paleo-canais que cortavam a plataforma continental em períodos de nível do mar mais baixos [Calliari 1984, Abreu & Calliari 2005].

Embora ocupem apenas uma pequena fração dos oceanos, as margens continentais são regiões de alta produtividade e armazenamento de carbono a longo prazo em função do alto fluxo de nutrientes (seja por aportes continentais e/ou por processos de ressurgência) [Wang *et al*. 2015]. Neste contexto, a margem continental sul-brasileira se apresenta como uma das mais produtivas da margem ocidental do Atlântico Sul, em função do sistema de ressurgência do Atlântico Sul, que teria sido ainda maior no passado [Lessa *et al*. 2017] e pela fertilização através da Pluma do Rio da Prata, que são importantes fatores para o aporte de nutrientes para as águas superficiais desta região [Gonzalez-Silveira *et al*. 2006]. Sabe-se que as plumas dos rios são regiões de intensas interações rio-mar-terra e são caracterizadas por um complexo transporte de materiais e processos biogeoquímicos. Diversos trabalhos têm sido desenvolvidos ao longo da margem sul-sudeste do Brasil que reportam a influência da pluma do Rio da Prata ao longo do Quaternário, tanto na produtividade quanto no transporte de sedimentos [e. g.: Mahiques *et al*. 2009, Pivel *et al*. 2011, Mathias *et al*. 2014, Almeida *et al*. 2015, Mathias *et al*. 2020].

O estudo das variações na paleoprodutividade configura um dos pontos-chave na paleoceanografia, fornecendo informações sobre as alterações oceanográficas e atmosféricas pretéritas. Deste modo, os cocolitoforídeos (algas unicelulares) se destacam como excelentes *proxies* das condições da superfície do mar [Flores *et al*. 2000, Andruleit *et al*. 2008, Grelaud *et al*. 2009], uma vez que sua distribuição é controlada por fatores como latitude, correntes oceânicas, disponibilidade de nutrientes, temperatura, salinidade e luminosidade. Vários trabalhos têm sido desenvolvidos na costa sul-sudeste brasileira para se entender a dinâmica da produtividade ao longo do tempo utilizando-se cocolitoforídeos para tal [e. g.: Baumann & Kinkel 1999, Baumann *et al*. 2004, Leonhardt *et al*. 2013, Gonçalves & Leonhardt 2016, Gonçalves & Leonhardt 2021].

Capítulo II: Hipótese

Mudanças climáticas do Quaternário influenciaram o padrão da vegetação na área continental adjacente ao local de coleta.

Mudanças climáticas do Quaternário alteraram os mecanismos de fertilização das águas marinhas no Atlântico Sudoeste.

Capítulo III: Objetivos

O objetivo geral deste trabalho foi verificar a influência das mudanças climáticas sobre os padrões de vegetação na área continental adjacente ao local de coleta e os mecanismos que atuaram sobre a fertilização das águas marinhas na Margem Continental Sul-Brasileira ao longo do Quaternário Tardio.

Objetivos específicos:

- relacionar as mudanças climáticas com as mudanças na composição da vegetação no Sul do Brasil;

- analisar o papel da influência continental na fertilização e paleoprodutividade das águas marinhas na Margem Continental Sul-Brasileira.

Capítulo IV: Área de Estudo

4.1 Contexto Geológico

O testemunho SIS 188 foi recuperado do talude da Bacia de Pelotas, que está localizada no sul da América do Sul, estendendo-se desde o estado Santa Catarina, Sul do Brasil, até o Uruguai (Figura 2). Em território brasileiro, a bacia se estende desde o Alto de Florianópolis, ao Norte, limite geológico com a Bacia de Santos, até a fronteira geográfica com o Uruguai, ao Sul. No país vizinho, a bacia prossegue até o Alto de Polônio, que a separa geologicamente da Bacia de Punta Del Este. Sua porção submersa se estende por uma área de 346.873 km^2, até o limite de 200 milhas náuticas, já a área emersa ocupa aproximadamente 40.900 km^2 [Morelato & Fabianovicz 2015].

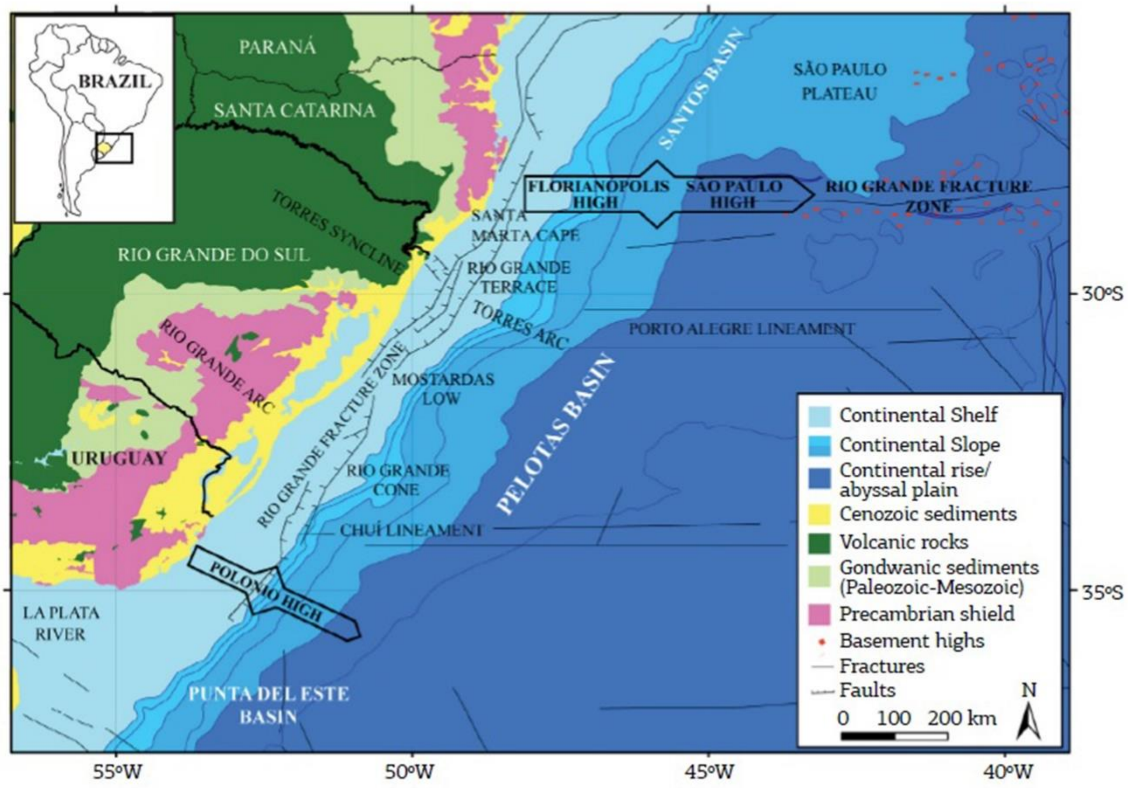

Figura 2. Mapa de localização da Bacia de Pelotas e suas principais feições estruturais [Rosa *et al*. 2017].

A origem da Bacia de Pelotas se deu a partir do rifteamento ocorrido quando da ruptura do Gondwana, que marcou a abertura do Oceano Atlântico Sul a partir do Jurássico, ela é definida como uma bacia marginal subsidente preenchida por sequências clásticas continentais e transicionais [Asmus & Porto 1972]. A tendência transgressiva encontrada nas sequências segue até o Oligoceno e, desde o Mioceno até o presente, as sequências demonstram uma regressão marinha [Morelato & Fabianovicz 2015].

Segundo Villwoc & Tomazelli [1995], a seção quaternária da bacia é formada por depósitos de leques aluviais e por quatro sistemas laguna-barreira, que foram depositados ao longo dos últimos 400.000 anos, como decorrência de eventos transgressivos glacio-eustáticos. A Bacia de Pelotas é preenchida por depósitos sedimentares com idades que variam desde o Cretáceo Inferior

(Neocomiano) ao Holoceno, sendo que na porção emersa os depósitos mais antigos são do Eomioceno [Gomide 1989; Anjos- Zerfass *et al*. 2008].

A plataforma continental sul brasileira é bastante extensa e se caracteriza pelo relevo suave e baixa declividade, possuindo uma largura média de 125 km [Dias *et al.* 1994]. Outra feição bastante característica da plataforma é a presença de diversos bancos arenosos e vales, oriundos da paleodrenagem, como por exemplo, o paleo-canal do Rio da Prata (Figura 3) [Calliari 1964; Lantzsch *et al.* 2014].

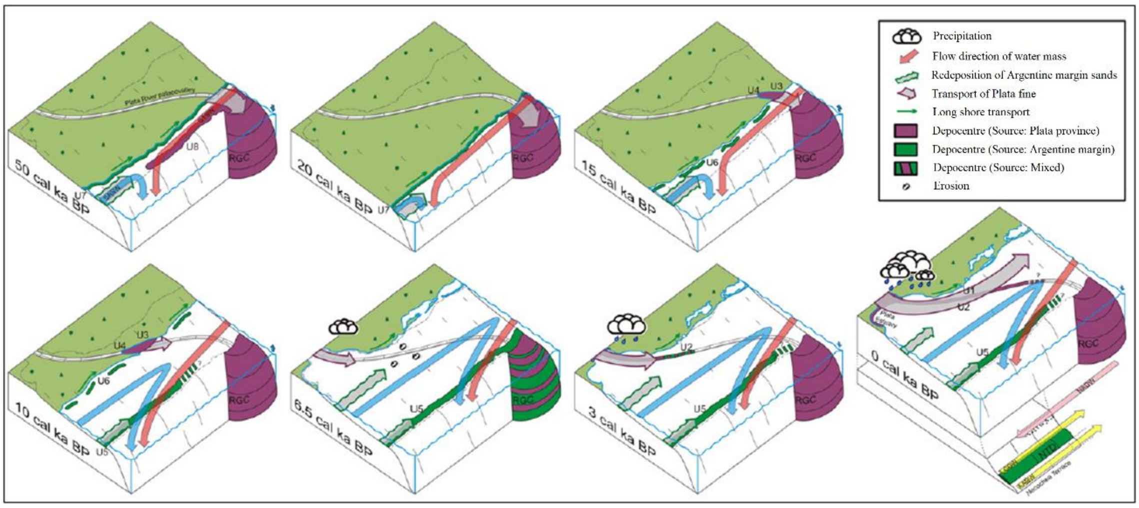

Figura 3. Bloco diagrama com detalhamento do posicionamento e local de deposição dos sedimentos oriundos da drenagem do Rio da Prata de 50 kyr BP até o presente [Lantzsch *et al.* 2014].

O talude continental se estende a profundidades que vão de 2600 a 3000 m, sendo comuns vales e cânions submarinos em toda a sua extensão. A largura considerável do talude (mais de 250 km próximo ao cabo de Santa Marta) e a declividade suave até profundidades de 3000 m, sugerem a dominância de processos deposicionais durante a sua formação [Calliari 1998]. Na parte mais ao norte da bacia, a característica mais pronunciada é o Terraço do Rio Grande, com batimetria que varia de 250 a 500m e ocupa considerável área de declive, estimada em torno de 500 km^2 [Basseto *et al*. 2000]. Na porção central do talude da Bacia de Pelotas, este remete à forma de um cone, que se estende desde a plataforma externa até profundidades de 4000 m. No flanco sul do Cone do Rio Grande, desenvolve-se o Vale do Rio Grande, o mais importante vale do setor, estendendo-se da plataforma externa até o sopé continental [Dias *et al*. 1994].

4.2 Contexto oceanográfico e climático

A Corrente do Brasil (CB) domina a coluna d´água na área de estudo em sua porção superior (Figura 4). A CB é a corrente de contorno oeste que fecha o giro subtropical do Atlântico Sul, sendo responsável pelo transporte de calor e água salgada da região tropical para latitudes maiores do Atlântico Sudoeste [Peterson & Stramma 1991]. Ela tem origem em aproximadamente 10°S e compreende o ramo sul da Corrente Sul Equatorial (CSE), que se bifurca ao chegar na costa do Brasil, dando origem também à Corrente Norte do Brasil (CNB). A CB flui em direção sul contornando a América do Sul se afastando da plataforma continental entre 33 e 38º, quando encontra a Corrente das Malvinas (CM), que transporta águas mais frias e ricas em nutrientes, formando a Confluência Brasil-Malvinas (CBM) [Peterson & Stramma 1991].

Nos 100 m superiores a CB transporta a Água Tropical (AT), com temperaturas maiores que 20° C e salinidade acima de 36 [Peterson & Stramma 1991; Stramma & England 1999]. De 100 a 600 m de profundidade, a coluna d´água é dominada pela Água Central do Atlântico Sul (ACAS), com temperaturas que variam entre 6 e 20° C e salinidade entre 34,6 e 36. Abaixo dela está a Água Intermediária Antártica (AIA), mais fria e menos salina (2–6° C e salinidade 33,8-34,8). Enquanto a ACAS possui um conteúdo de oxigênio relativamente baixo, a AIA é uma massa de água rica em oxigênio [Garcia *et al*. 2014].

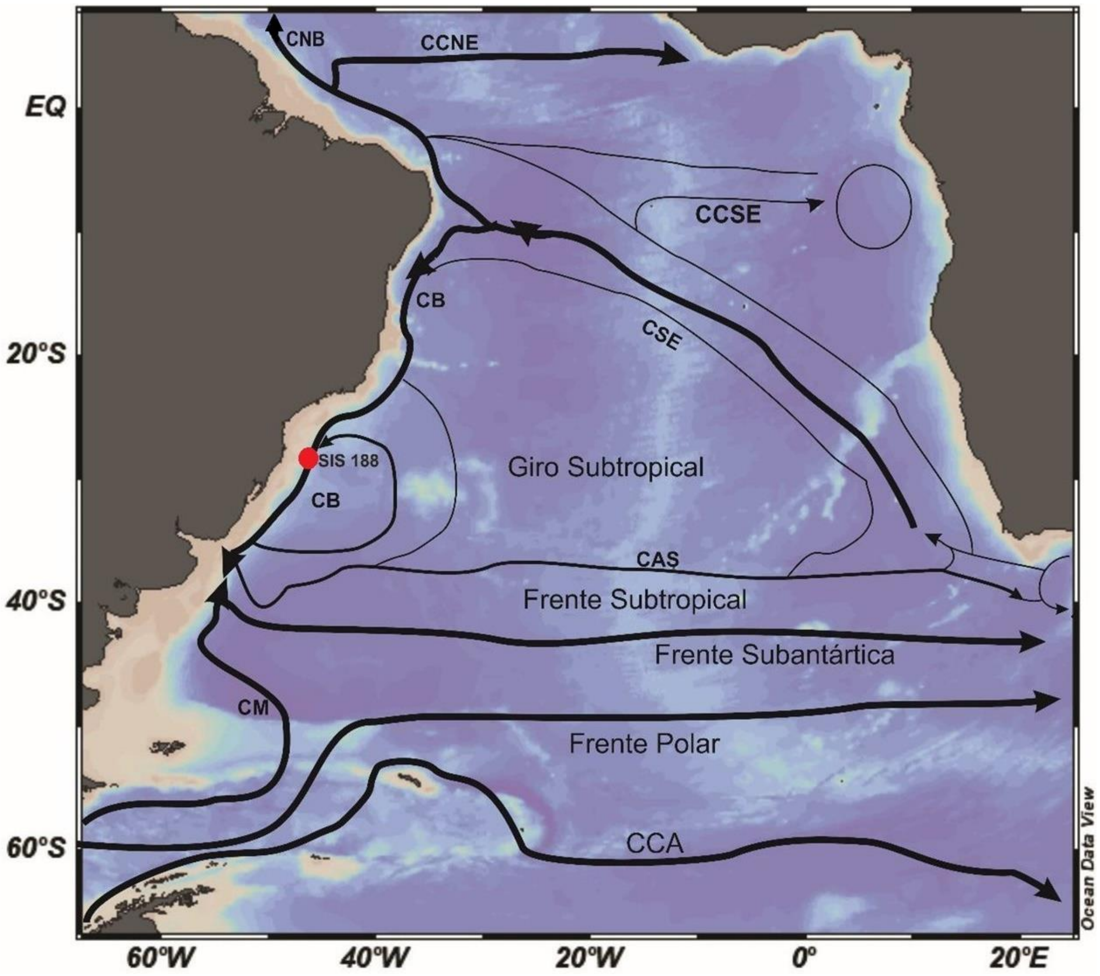

Figura 4. Mapa da circulação superficial do Atlântico Sul indicando a localização do testemunho SIS 188 (ponto vermelho). CNB= Corrente Norte do Brasil, CCNE= Contracorrente Norte Equatorial, CCSE= Contracorrente Sul Equatorial, CSE= Corrente Sul Equatorial, CB= Corrente do Brasil, CAS= Corrente do Atlântico Sul, CM= Corrente das Malvinas e CCA= Corrente Circumpolar Antártica. Figura adaptada de Peterson & Stramma [1991].

Na área de estudo há também a influência da Corrente Costeira Brasileira (CCB), formada pela descarga do Rio da Prata e da Lagoa dos Patos. A CCB flui para o norte carregando águas de baixa temperatura e baixa salinidade, além de material continental oriundo das bacias de drenagem desses dois corpos d'água [Souza & Robinson 2004; Piola *et al*. 2005; Razik *et al*. 2015]. A CCB pode carregar também, material sedimentar oriundo da descarga dos rios Mampituba e Araranguá, dois rios menores que desembocam próximo à área de coleta. O Rio Mampituba possui uma área de drenagem de 1.200 km^2, nasce na Serra

Geral e deságua no Oceano Atlântico, próximo à cidade de Torres no estado do Rio Grande do Sul, e tem vazão média de 18,6 $m^3.s^{-1}$ [D´Aquino *et al*. 2011]. Já a bacia hidrográfica do Rio Araranguá possui área de 3.020 km^2, com vazão média de 65 $m^3.s^{-1}$ [Loitzembauer & Mendes 2016].

Mais ao sul do local de coleta, há a influência da descarga da Lagoa dos Patos e do Rio da Prata. A Lagoa dos Patos possui uma superfície de 10.360 km^2, sendo considerada a maior lagoa obstruída do mundo, ela recebe água de uma bacia de drenagem de 140.000 km^2, diretamente dos afluentes ou pelo Canal de São Gonçalo, que a conecta com a bacia da Lagoa Mirim [Kjerfve 1986]. Já o Rio da Prata recebe a descarga da bacia de drenagem do Prata, é considerado o segundo maior sistema fluvial da América do Sul, cobrindo uma área de aproximadamente 3,2 x 106 km^2 [Acha *et al*. 2008].

A circulação atmosférica na área de estudo é controlada pelo centro de alta pressão do anticiclone do Atlântico Sul. A Alta Subtropical do Atlântico Sul (ASAS) é um sistema de alta pressão, localizada a cerca de 30 ° S de latitude sobre o Oceano Atlântico e está associado à circulação média meridional da atmosfera pela célula de Hadley [Wainer & Taschetto 2006; Moura *et al*. 2018]. As variações na intensidade e na posição da ASAS afetam diretamente o clima na América do Sul, em especial, no Brasil. Este sistema é responsável pela predominância dos ventos de NE na região sudoeste ao longo do ano e de SW durante a passagem de frentes frias, que são mais comuns no inverno. A variabilidade anual da ASAS é responsável pela migração sazonal da CCB, que é deslocada para o norte durante o inverno austral e fica mais restrita ao sul durante o verão [Bastos & Ferreira 2000].

A Zona de Convergência Intertropical (ZCIT) é outro sistema de grande importância para a circulação atmosférica na área de estudo (Figura 5). A ZCIT é um sistema sinótico que ocorre na região do Equador, localizado no ramo ascendente da célula de Hadley e atua transferindo calor e umidade dos níveis inferiores da atmosfera das regiões tropicais para os níveis superiores da troposfera e para as médias e altas latitudes [Asnani 1993; Ferreira 1996]. Sua posição média fica em torno dos 6° ao norte do Equador, sofrendo uma grande variação sazonal latitudinalmente, migrando entre 9°N no verão boreal e 2°N no inverno boreal sobre o oceano Atlântico, com exceções como nos casos de El Niño [Schneider *et al*. 2014]. A ZCIT também está envolvida na manutenção do balanço térmico global, além da sua influência nas regiões tropicais.

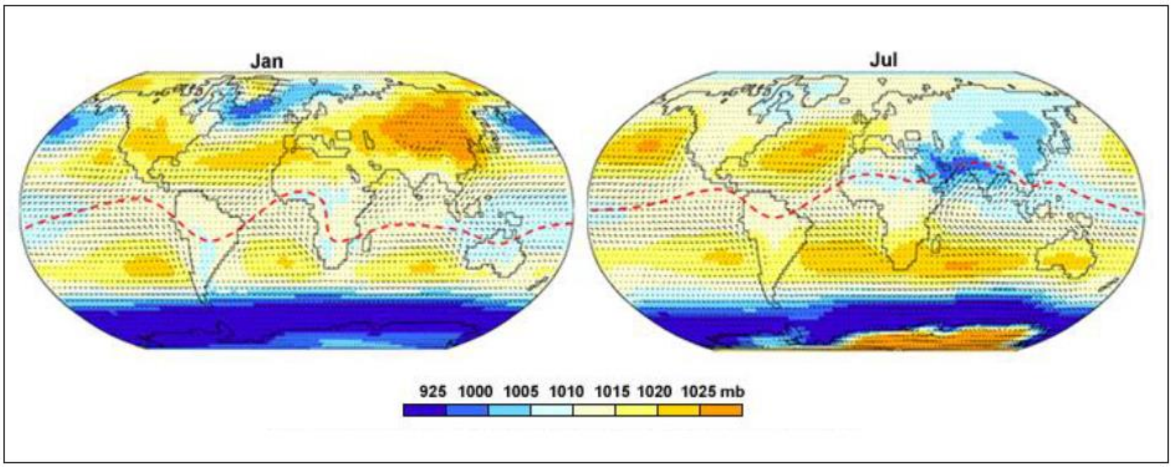

Figura 5. Mudança sazonal da localização da ZCIT. A linha pontilhada em vermelho marca a posição média da ZCIT em janeiro (à esquerda) e julho (à direita). A escala de cores representa a pressão ao nível do mar. Fonte: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies, Departamento de Geografia da Universidade do Oregon, EUA.

No sul do Brasil, o clima é úmido temperado-subtropical, com chuvas distribuídas uniformemente ao longo do ano, com condições relativamente úmidas e a precipitação anual fica em torno de 1100 mm [Diaz *et al*. 1998]. Eventos El Niño Oscilação Sul (ENOS) influenciam a precipitação anual, apresentando anomalias positivas durante os anos de El Niño e anomalias negativas durante os anos de La Niña [Grimm & Tedeschi 2009]. A temperatura ao longo do ano varia entre 15 e 25ºC [Diaz *et al*. 1998].

4.3 Contexto vegetacional no continente adjacente

A vegetação na área continental adjacente inclui ecossistemas de alta diversidade, com a Mata Atlântica, Floresta de Araucárias, Campos e Pampa, que foram descritos em vários trabalhos anteriores [e. g. Klein 1978, 1979; Boldrini 2009; Oliveira-Filho *et al*. 2015] (Figura 6). O clima e a topografia são os principais fatores que controlam a distribuição da cobertura vegetal na região.

A parte norte do sul do Brasil e a planície costeira são dominadas pela Mata Atlântica sendo considerada um dos *hot-spots* de biodiversidade do planeta [Galindo-Leal & Câmara 2003]. A vegetação subtropical ocorre nas terras altas, é formada por um mosaico de florestas de Araucária e campos, fruto das condições climáticas mais frias. As matas de Araucária são encontradas nas regiões mais elevadas, entre as latitudes 24° e 30°S entre 1000 e 1400 m de altitude [Hueck 1966] e são compostas principalmente por *Araucaria angustifolia*, *Podocarpus lambertii*, *Mimosa scabrella* e *Ilex* spp [Boldrini 2009].

A região sul do Brasil possui também vastas áreas de campos, que dentro do território brasileiro, estão inseridos em dois biomas de acordo com a classificação do IBGE (2004): no bioma Pampa, que corresponde à metade sul do Rio Grande do Sul, e no bioma Mata Atlântica. Este último, inclui áreas de campos de Planalto Sul-Brasileiro formando um mosaico com as florestas da metade norte do RS, e nos estados de Santa Catarina (SC) e Paraná (PR). Nas terras baixas, principalmente do Rio Grande do Sul e Uruguai, os campos dominados pelas famílias Poaceae, Cyperaceae, Asteraceae, Apiaceae e Fabaceae, que estão associadas a climas mais frios e secos [Mourelle & Prieto 2012]. Ao longo dos rios e riachos da região, ocorrem as matas ciliares, compostas principalmente pelas espécies *Salix chilensis*, *Sebastiania commmersoniana*, *Myrsine laetevirens* e por espécies pertencentes à família Myrtaceae [Mourelle & Prieto 2012].

Ao longo da costa do Rio Grande do Sul e Uruguai, ocorrem lagoas costeiras, dominadas por marismas compostos principlamente palas famílias Cyperaceae, Chenopodiaceae e Amaranthaceae [Marangoni & Costa 2009]. A bacia de drenagem do Rio da Prata possui uma vegetação formada por um *mix* de pastagens, matas de galeria, matas secas e matas semideciduais [Hueck 1966]. A distribuição e composição da vegetação moderna, está condicionada às condições climáticas e também são fortemente influenciados pelas atividades antrópicas.

Figura 6. Distribuição da vegetação moderna na América do Sul [Adaptada de Schmithüsen 1976 e Hueck 1960].

Capítulo V: Material e Métodos

5.1 Testemunho sedimentar

O testemunho sedimentar marinho SIS 188 foi recuperado ao norte do talude da Bacia de Pelotas pela Agência Nacional do Petróleo (ANP), em parceria com a FUGRO – Serviços Submarinos e Levantamentos LTDA. A coleta foi realizada com um testemunhador a pistão do tipo *Piston Corer* a uma profundidade de lâmina d´água de 1514 m, sob as coordenadas -29,22° S -47,28° W e foram recuperados 338 cm de sedimentos. Após a retirada de cerca de 20 cm do topo e do meio, foi encaminhado para o Núcleo de Oceanografia Geológica da Universidade Federal do Rio Grande (FURG), onde ficou armazenado em container refrigerado.

5.2 Modelo de idade

O modelo de idade foi construído com base na correlação da curva isotópica $\delta^{18}O$ dos foraminíferos planctônicos do testemunho SIS 188 com a curva padrão de Lisiecki & Stern [2016]. Como pontos de controle, quatro datações AMS ^{14}C foram obtidas. O modelo de idade foi construído usando o software AnalySeries [Paillard *et al*. 1996].

As datações ^{14}C foram realizadas em carapaças do foraminífero planctônico *Globigerinoides ruber* (fração >150 μm), no Laboratório de Radiocarbono da Universidade Federal Fluminense (LAC-UFF). As idades obtidas por ^{14}C foram ajustadas considerando um Delta R do Marine Reservoir Correction Database de 54,0 ± 42,0 (Nadal De Masi 1999; Angulo *et al*. 2005; Alves *et al*. 2015) e calibrado de acordo com a curva Marine13 (Reimer *et al*. 2013) usando o programa de calibração Radiocarbono Calib (Stuiver & Reimer 1993).

As análises de $\delta^{18}O$ também foram realizadas em *G. ruber* (fração >150 μm), em um espectrômetro de massa de entrada dupla MAT-253 com dispositivo de carbonato Kiel IV no Laboratório de Isótopos Estáveis da Universidade da Califórnia, Santa Cruz. Os dados do isótopo são relatados em permil em relação ao padrão Vienna PeeDee Belemnite (V-PDB).

5.3 Processamento químico palinológico

Para a realização das análises palinológicas, foram coletadas 56 amostras ao longo do testemunho, com intervalos de 6 cm entre cada uma delas.

Previamente ao início do processamento químico das amostras, foi adicionado um tablete do esporo exótico *Lycopodium clavatum* em cada amostra de sedimento seco, para a realização do cálculo de concentração (grãos de polen e esporos/g) [Stockmarr 1971].

As amostras foram então submetidas ao processamento químico padrão proposto por Faegri & Iversen [1975], com a retirada do conteúdo indesejado para as análises palinológicas. Inicialmente, as amostras foram submetidas a uma solução de Ácido clorídrico (HCl) a 10% por 2h, para a remoção dos materiais carbonáticos. Em seguida, foram lavadas com água destilada até atingirem pH neutro. Posteriormente, foi adicionada uma solução de Hidróxido de potássio (KOH) a 5% às amostras, em banho-maria a 100° C por 8 minutos, para a remoção da matéria orgânica e dos ácidos húmicos. As amostras foram então novamente lavadas com água destilada até a completa clarificação do sobrenadante. Após esta lavagem, Cloreto de zinco ($ZnCl_2$), com densidade entre 1,8 e 1,9 g/cm^3 foi adicionado às amostras para a separação dos palinomorfos do sedimento.

Para hidratar os palinomorfos, uma solução de glicerina a 50% foi adicionada às amostras por pelo menos 30 minutos e posteriormente, foram confeccionadas as lâminas palinológicas. Estas foram montadas sobre uma placa aquecedora a 60°C usando como meio de montagem gelatina glicerinada.

5.4 Análise palinológica

As lâminas palinológicas foram analisadas em microscopia ótica, em aumento de 400x e/ou 1000x e, sempre que possível, foram contados 300 grãos de pólen e esporos de origem terrestre por amostra. A identificação dos palinomorfos foi feita com base nas seguintes bibliografias de descrição palinológica: Leal & Lorscheitter, 2007; Leonhardt & Lorscheitter, 2007, 2008, 2010; Roth & Lorscheitter, 2013; Masetto & Lorscheitter, 2016, além de consultas à palinoteca de referência do laboratório.

Os resultados obtidos a partir das análises foram processados no software Tilia 2.0, onde foram realizados os cálculos de concentração e porcentagem [Grimm, 1993]. A concentração de palinomorfos (C) é calculada através dos dados de palinomorfos totais contados na amostra (PC), concentração total de

Lycopodium clavatum adicionados (CL), *L. clavatum* contados na amostra (LC) divididos pelo peso seco da amostra (PscA) (Equação 1).

$$C = \frac{[(CL.PC)]}{LC}$$

Equação 1: Cálculo de concentração de palinomorfos para cada amostra.

Para os cálculos de porcentagem, os palinomorfos foram divididos de acordo com o ambiente de origem:

- Indicadores continentais: Briófitas, Pteridófitas, Ervas, Arbustos, Árvores, Lianas, Hábitos Variados, Indeterminados (quando a identificação taxonômica do grão de pólen não foi possível), algas de água doce e diatomáceas. Apesar de não serem consideradas palinomorfos, as diatomáceas também foram contabilizadas.
- Indicadores marinhos: Cistos de dinoflagelados, escolecodontes e palinoforaminíferos.

A metodologia utilizada não é a usual para a recuperação de diatomáceas e dinoflagelados, no entanto estes foram contabilizados nas amostras como um dado adicional.

Os diagramas apresentados foram plotados utilizando a extensão TiliaGraph do software Tilia 2.0 [Grimm 1993]. Os valores de porcentagens dos palinomorfos continentais compuseram uma matriz de dados utilizada para uma análise de agrupamento entre as unidades amostrais. Empregou-se como método de ligação dos grupos a técnica de variância mínima (método de Ward) (programa CONISS) [Grimm 1987], com a dissimilaridade entre amostras medida por distância euclidiana.

Capítulo VI: Artigos Científicos

Para a obtenção do título de Doutor pelo Programa de Pós-Graduação em Oceanologia, é requerido que o discente realize a submissão de pelo menos dois artigos científicos como primeiro autor em periódico com corpo indexado. Desse modo, os resultados da pesquisa desenvolvida durante o período de doutorado e a discussão dos resultados serão apresentados em forma de artigos neste Capítulo. O primeiro manuscrito, de autoria de Silvia Regina Bottezini, Adriana Leonhardt, Débora Diniz e Andréia Souza Pereira de Ávila é intitulado *"Climatic, vegetational and coastal system dynamics in southern Brazil between 47.8 and 7.4 cal ka BP: a palynological analysis*" e foi aceito para publicação no periódico *"**Revista Brasileira de Paleontologia**"*. O segundo manuscrito, de autoria de Silvia Regina Bottezini, Adriana Leonhardt, Débora Diniz e Andréia Ávila é intitulado ***"**Continental Influence on the Fertilization of Marine Waters during the Late Quaternary in the South of the Brazilian Continental Margin*" e está submetido para publicação no periódico ***"Ocean and Coastal Research"***.

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 estiveram 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 ndica 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; Gu *et al*., 2018; Ávila *et al*., 2020). This study aims to produce additional information on the palaeoclimatic 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).

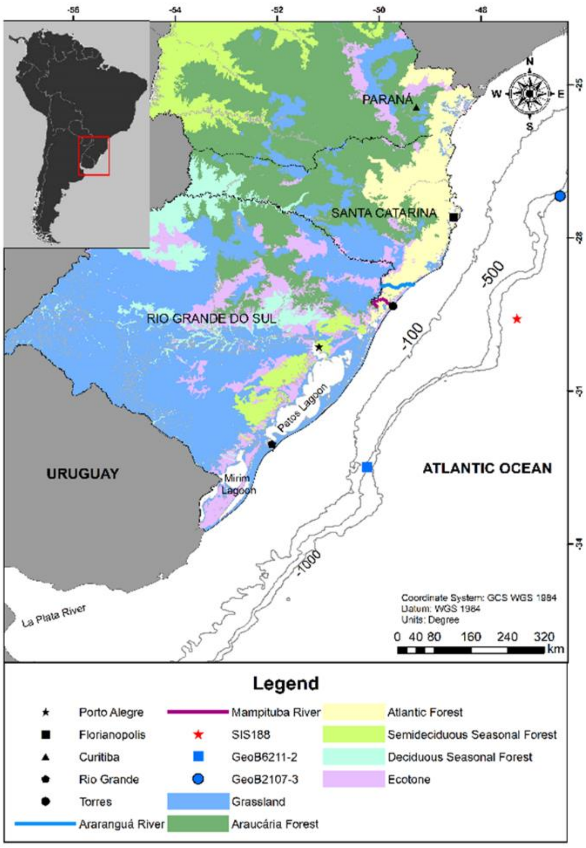

Figura 7 (tese) Figure 1. Location of SIS 188 core and the main vegetation formations (IBGE, 2004) in the adjacent continental area. The cores GeoB2107-3 (Gu *et al*., 2017) and GeoB6211-2 (Gu *et al*., 2018), cited in the Discussion section, are indicated too.

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 sampling site. The drainage basin of Mampituba River occupies an area of 1,200 km^2, 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 cored 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 it 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).

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 Calibration Program (Stuiver & Reimer, 1993) (Table 1).

The analysis of $\delta^{18}O$ were also performed on *G. 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).

Tabela 1 (Tese) Table 1. Radiocarbon ages used in the construction of the age model of the SIS 188 core.

Depth (cm)	Species	Age (^{14}C 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

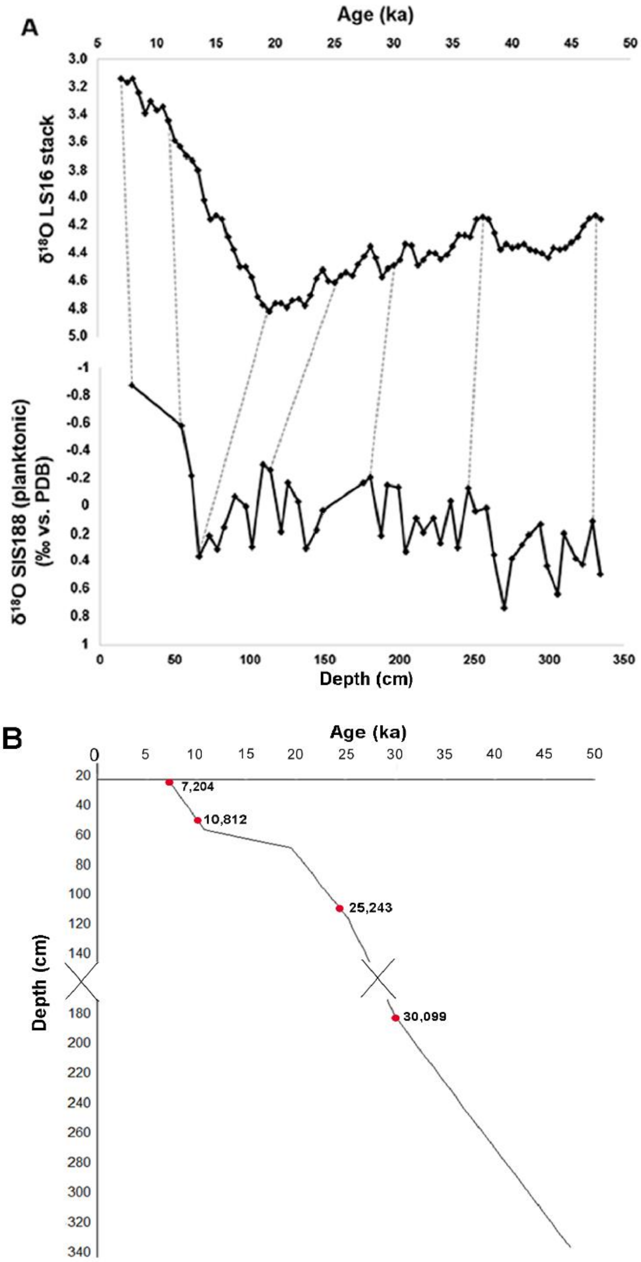

Figura 8 (Tese) Figure 2. Age model. (A) Correlation between the Lisiecki & Stern (2016) Intermediate South Atlantic curve and the oxygen-isotope data from SIS 188. (B) Relationship between age and depth in SIS 188. The red points indicate the depths where radiocarbon ages were obtained.

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 (47.8–33.3cal ka BP, 336–208.5cm)

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).

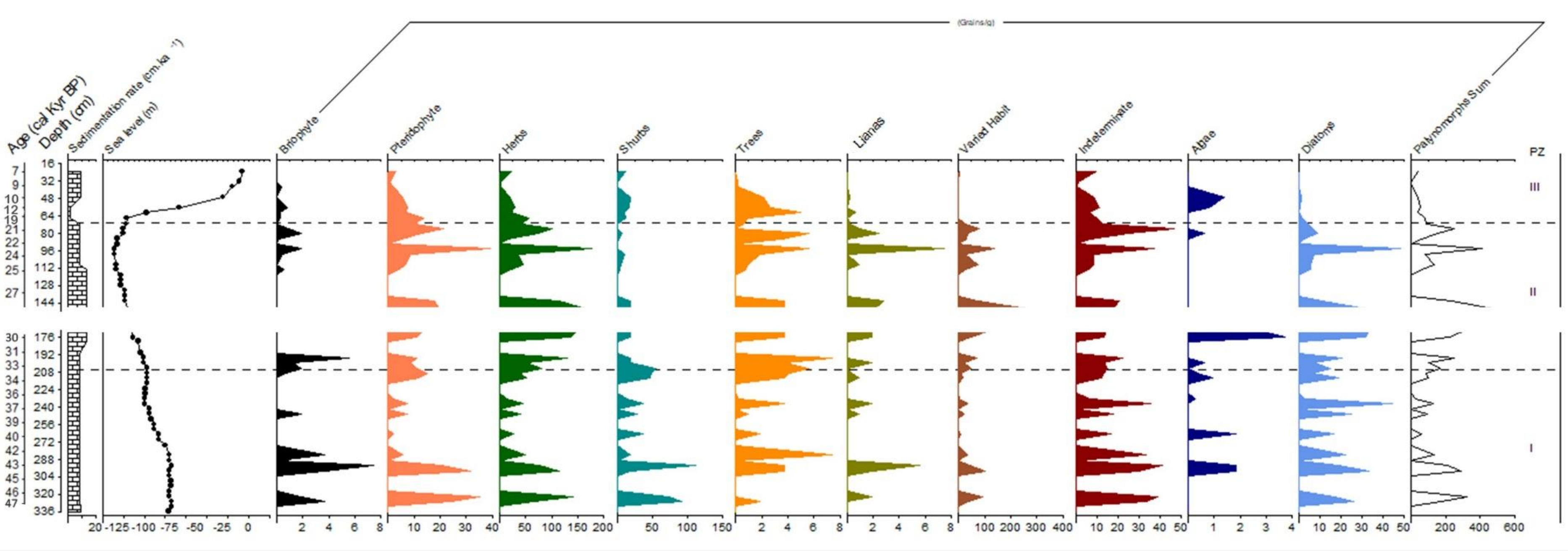

Figura 9 (Tese) Figure 3. Pollen concentration summary diagram showing sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt & Lisiecki, 2016), vegetation groups, and palynozones (PZs) for SIS 188 core. To better visualize of the values expressed in this graph, they were all divided by 10,000 (except sedimentation rate).

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*, 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 (32.8–20.2cal 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 PZII. 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 "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 PZII 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).

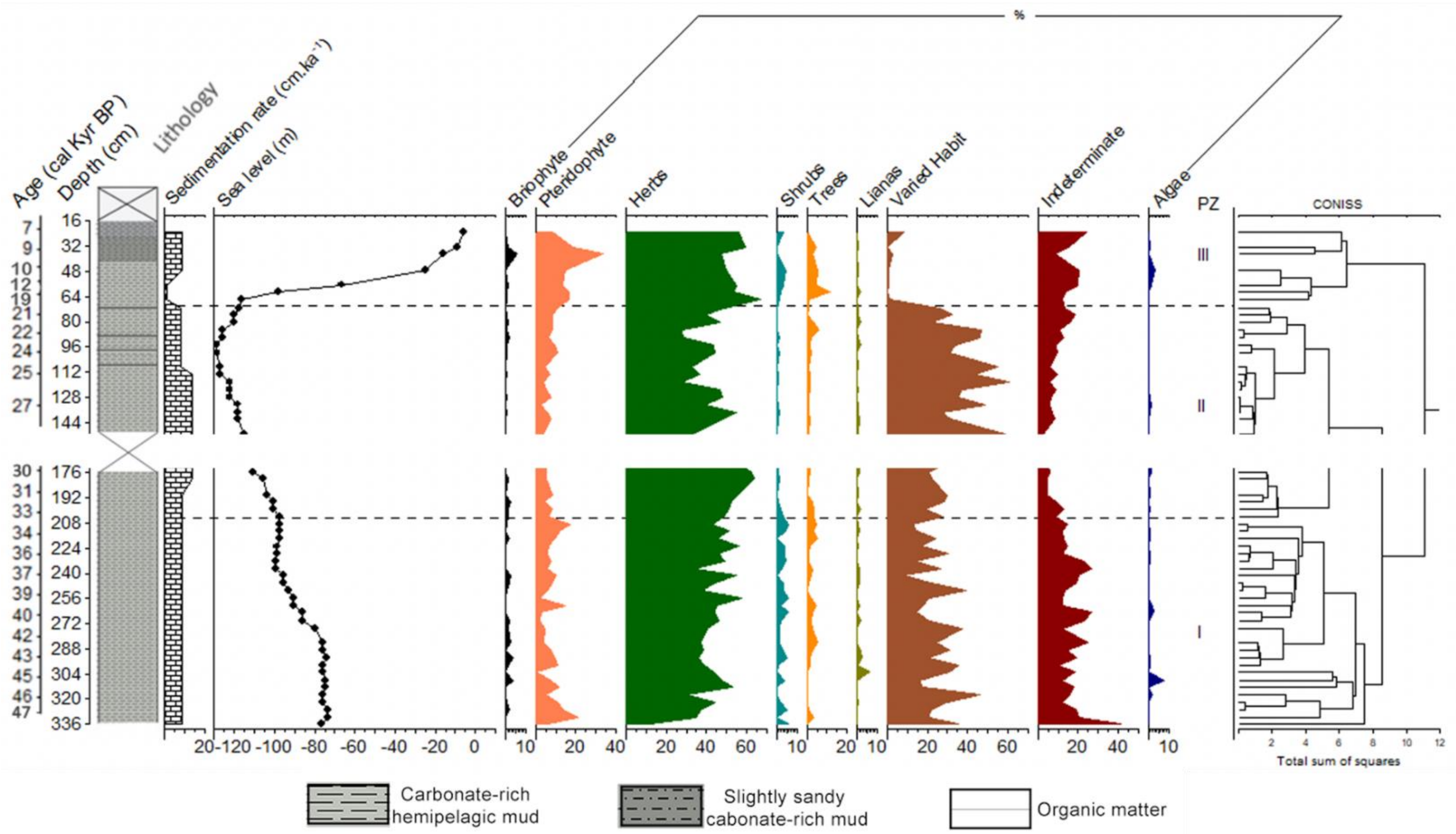

Figura 10 (Tese) Figure 4. Pollen percentage summary diagram showing lithology, sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt & Lisiecki, 2016), vegetation groups, palynozones (PZ) and the CONISS dendrogram (based on individual taxa percentage values) for core SIS 188.

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

PZ III (19.5–7.4cal ka BP, 66–23cm)

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 PZIII (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 fall abruptly on PZIII, while those of "Bryophytes" and "Lianas" remain low. The percentages of "Pteridophytes", "Shrubs", "Trees","Diatoms" and "Indetermined" groups increase in this PZ. "Trees" group reache 11.9% at 15.9 cal ka BP, mostly represented by *A. angustifolia*, *P. 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 reache 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

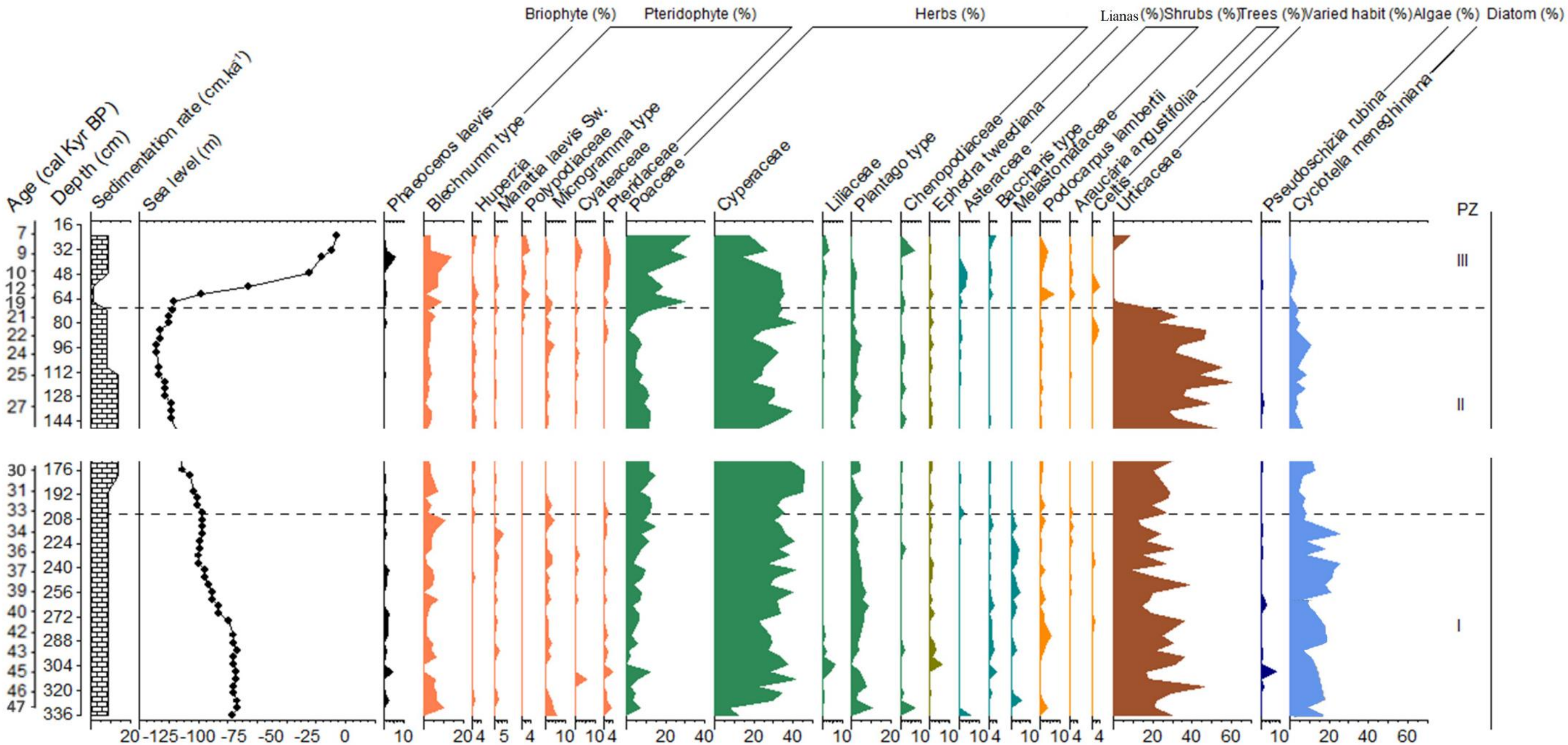

Figura 11 (Tese) Figure 5. Pollen diagram of the main taxa found in core SIS 188, showing sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt & Lisiecki, 2016), and palynozones (PZs)

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 occured (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 become 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).

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 *P. 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 PZI 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 *A. angustifolia* and *P. 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; Lorscheitter *et al*., 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 *C. meneghiniana* are found in PZI. 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 PZI 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 core depth) 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 *C. 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 *A. angustifolia* and *P. lambertii*, and the decrease of "Bryophytes" and "Pteridophytes" groups in relation to PZI indicates an expansion of the grasslands, due to a colder and drier climate at South of Brazil (Cruz *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 were 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, it´s 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 *A. angustifolia*, *P. 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 PZIII, 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 core GeoB6211-2 (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 wetness 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

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Continental Influence on the Fertilization of Marine Waters during the Late Quaternary in the South of the Brazilian Continental Margin

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ABSTRACT

Based on the comparison between continental palynomorphs and paleoproductivity proxies from the marine sediment core SIS188, this study aimed to understand the role of continental influence on ocean productivity along the late Quaternary. Retrieved from the slope of the Pelotas Basin at a depth of 1,514 m, the core documents the time interval between 47.8 and 7.4 cal ka BP, including the Marine Isotope Stages (MIS) 3, 2 and 1. The palynological content found in the core SIS188 indicates a typical flora of the East Plateau of RS, which is at the same latitude as the core. Thus, continental input sources such as eolian dust and discharges from the Mampituba and Araranguá rivers would be more likely source areas for the palynological content found than the Brazilian Coastal Current (BCC). During the glacial intervals (MIS 3 and MIS 2), paleoproductivity was linked to the intensification of upwelling and the transport of eolian dust; this last mechanism may have transported the pollen grains to the core region. There is a decrease in the concentrations of continental palynomorphs at the end of MIS 2, which is accentuated in MIS 1 when the sea level is higher, and winds are weaker. Paleoproductivity was high during MIS 1 especially from the Holocene onwards, although the concentration of continental-derived palynomorphs decrease sharply. Furthermore, the correlation between the N Ratio (paleoproductivity proxy) and the pollen concentration in the sediments only becomes significant when samples from this MIS are excluded, highlighting that the rise in sea level is a factor that interferes with the fertilization of marine waters far from the coast by continental input.

KEYWORDS: PALYNOMORPHS, PALEOPRODUCTIVITY, CONTINENTAL INFLUENCE, PELOTAS BASIN

INTRODUCTION

To reconstruct past environmental changes, especially in the ocean, an understanding of land-ocean interactions is vital. Over the past few years, some palynological studies have been developed on the Brazilian coast correlating indicators of continental (pollen grains and spores) and marine (dinoflagellate cysts) origin

(e. g. Behling et al., 2000; Behling, 2002; Jennerjahn et al., 2004; Dupont et al., 2010; Gu et al. 2018a; Gu et al. 2018b; Gu et al. 2020; Ávila et al., 2020).

Palynological analyses in marine sedimentary cores off the coast of southern Brazil showed relatively synchronous changes between the factors that influenced the vegetation composition and the associations of dinoflagellates, indicating a relationship between continental and oceanographic environmental changes (Gu et al. 2017, 2018a; Ávila et al., 2020). One advantage that marine cores offer is the temporal resolution, which is a useful tool in research on mean sea level (MSL) variations and in understanding the conditions and factors that influence the depositional paleoenvironment (McCarthy et al., 2003; González and Dupont, 2009; Dai et al., 2015; Li et al., 2017), as well as long-distance wind and marine transport.

Studies in marine sedimentary cores collected along the south-southeast coast of Brazil contribute to the understanding of terrestrial nutrient inputs for offshore areas. Gu et al. (2017), in a study conducted in a core recovered close to the core object of this work, suggest that during the end of MIS 3 and MIS 2 the study area was under the strongest influence of the Brazilian Coastal Current (BCC) due to the lower sea level. Also, the presence of *Nothofagus* pollen, probably transported first by the Malvinas Current (MC) and then by the BCC, would be related to the increase in the discharge of the South American rivers that drain the Andes or to the strengthening of west winds.

Within paleoceanography, studies on paleoproductivity are of great importance as they provide clues about past atmospheric and oceanographic systems variations. In paleoceanographic research, coccolithophorids (unicellular algae) stand out as excellent proxies of sea surface conditions (Flores et al., 2000; Andruleit et al., 2008; Grelaud et al., 2009), since their distribution is controlled by factors such as latitude, ocean currents, nutrient availability, temperature, salinity, and luminosity. On the south-southeast coast of Brazil, several works have been developed to understand the dynamics of productivity over time using coccolithophorids (e.g., Baumann et al., 2004; Leonhardt et al., 2013; Costa et al., 2016).

Continental margins are regions of high productivity due to high nutrient input (due to continental influence and/or upwelling processes) (Wang et al., 2015). The southern Brazilian margin is among the most productive areas on the western margin of the South Atlantic, due to the South Atlantic upwelling system, which in the past would have been even greater (Lessa et al., 2017), and due to fertilization through La Plata River plume and continental drainage, which represent important factors for the supply of nutrients to surface waters (Gonzalez-Silveira et al., 2006). Currently, the BCC which transports the waters of the plume reaches latitudes of about 28°S (Piola et al., 2005), and its course to the north is mainly controlled as a function of wind stress (Piola et al., 2008). Several works developed along the south-southeast Brazilian margin report the influence of BCC along the Quaternary in both productivity and sediment transport (e.g.: Mahiques et al., 2009; Pivel et al., 2011; Mathias et al., 2014; Almeida et al., 2015; Mathias et al., 2020).

The objective of this work is to analyze the role of continental influence on oceanic paleoproductivity in the Pelotas Basin in Late Quaternary, from the comparison between palynomorphs of continental origin and marine proxies indicators of productivity.

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STUDY AREA

The marine sediment core SIS188 was collected on the northern continental slope of the Pelotas Basin, at a depth of 1,514 m. The sampling site is located approximately 206 km from the current coastline (Figure 1).

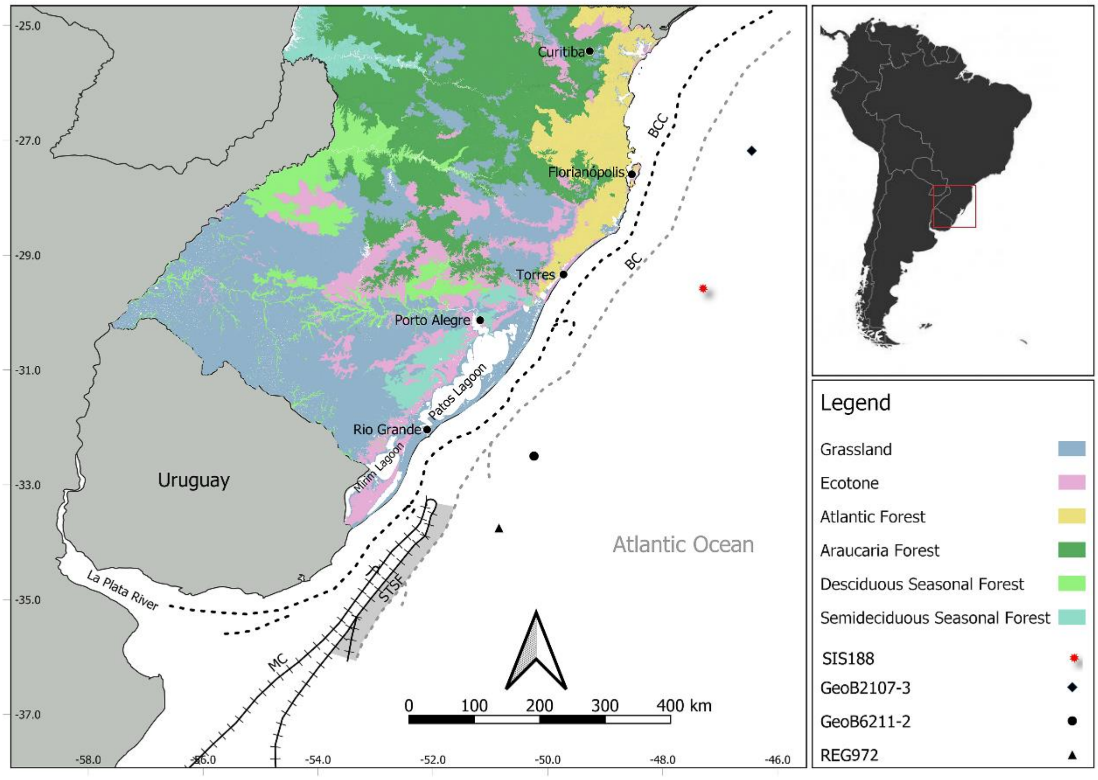

Figura 12 (Tese) Figure 1. Location of SIS 188 core showing the main vegetation formations (IBGE, 2004) in the adjacent continental area and the oceanographic currents wich influence the study area are indicated on the map (BC: Brazilian Current, BCC: Brazilian Coastal Current, MC: Malvinas Current). The cores GeoB2107-3 (Gu et al., 2017), GeoB6211-2 (Gu et al., 2018a) and REG 972 (Ávila et al., 2020), cited in the Discussion section, are indicated too.

The Brazil Current (BC) dominates the surface portion of the water column in the study area. The BC is the boundary in the South Atlantic subtropical gyre, and it is responsible for heat and saltwater transport from the tropical region to higher latitudes in the Southwest Atlantic (Peterson and Stramma, 1991). It originates at approximately 10°S from the southern branch of the South Equatorial Current (SEC), which bifurcates when reaching the Brazilian margin into the BC and North Brazil Current (NBC). The BC flows in a southerly direction, until reaching the region of the Brazil-Malvinas Confluence (Stramma and England, 1999). In the upper 100 m, the BC transports Tropical Water (TW), with temperatures above 20°C, salinity > 36 and low nutrient concentrations (Peterson and Stramma, 1991; Stramma and England, 1999). From 100 to 600 m water depth, the water column is dominated by South Atlantic Central Water (SACW), which is rich in nutrients and has temperatures ranging between 6–20°C and salinities between 34.6–36 (Braga and Niencheski, 2006).

The study area is also influenced by the Brazilian Coastal Current (BCC). The BCC is a branch of the BC that flows northward along the coast and the inner shelf, carrying nutrient-rich, low-temperature and low-salinity waters as well as continental material from the La Plata River and the Patos Lagoon drainage basins (Souza and Robinson, 2004; Piola et al., 2005; Razik et al., 2015). The BCC can also carry sedimentary material from the discharge of the Mampituba and Araranguá rivers, two smaller rivers that flow close to the sampling area. The Mampituba River has a drainage area of 1,200 km^2 and an average flow of 18.6 m^3 s^{-1} (D'Aquino et al., 2011). It begins in Serra Geral and flows into the Atlantic Ocean near the city of Torres, in the state of Rio Grande do Sul. The watershed of the Araranguá River has an area of 3,020 km^2, with an average flow of 65 m^3 s^{-1} (Loitzembauer and Mendes, 2016).

However, the main continental inputs to the Southwest Atlantic, the Patos Lagoon and the La Plata River, are located south of the sampling site. The Patos Lagoon has a surface area of 10,360 km^2, being considered the largest choked lake 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 La Plata River receives discharge from the La Plata drainage basin, and it is considered the second largest river system in South America, covering an area of approximately 3.2 x 10^6 km^2, and extending along the coast for up to 1,300 km (Piola et al., 2005; Acha et al., 2008).

Atmospheric circulation in the study area is controlled by the high-pressure center of the South Atlantic anticyclone. The South Atlantic Subtropical High (SASH) is a high-pressure system located at about 30°S latitude over the Atlantic Ocean and it is associated with the southern mean meridional circulation of the atmosphere through the Hadley cell (Wainer and Taschetto, 2006; Moura et al., 2018). Variations in the intensity and position of SASH directly affect the climate in South America, especially in Brazil. This system is responsible for the predominance of NE winds in the southwest region throughout the year and SW winds during the passage of cold fronts, which are more common in winter. The annual variability of the SASH is responsible for the seasonal migration of the BCC, which reaches its northward limit during the austral winter and is more restricted to the south during the summer (Bastos and Ferreira, 2000).

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

Several previous works describe the different types of vegetation present in southern Brazil and Uruguay (e.g., Klein, 1978, 1979; Boldrini, 2009; Oliveira-Filho et al., 2015), mainly influenced by the climate and topography of the region (Figure 1). The Atlantic Forest occupies the northern part of the southern region and the coastal plain. Coastal lagoons also occur along the coasts of Rio Grande do Sul state and Uruguay, dominated by marshlands composed mainly of the Cyperaceae, Chenopodiaceae, and Amaranthaceae families (Marangoni and Costa, 2009). In the higher portions, there is a mosaic of forest with Araucaria and grasslands. The Araucaria forests are found between 24° and 30°S, between 1,000 and 1,400 m of altitude (Hueck, 1966), mostly represented by *Araucaria angustifolia*, *Podocarpus lambertii*, *Mimosa scabrella*, *Ilex* spp., and *Dicksonia sellowiana* (Boldrini, 2009). The grasslands, which occupy vast areas of southern Brazil, are mainly dominated by the Poaceae, Cyperaceae, Asteraceae, Apiaceae, and Fabaceae families, which are associated with cooler and drier climates (Mourelle and Prieto, 2012). Along the rivers and streams of the region, there are riparian forests composed by the species *Salix chilensis*, *Sebastiania commmersoniana*, *Myrsine laetevirens*, and other species from the Myrtaceae family (Mourelle and Prieto, 2012).

METHODS

The marine sediment core SIS188 (-29.579046º S; -47.295608º W) was collected by the Fugro company on the northern continental slope of the Pelotas Basin at a water depth of 1,514 m, using a piston corer. A total of 338 cm of sediment was recovered. The company removed about 20 cm from the upper and middle part of the core, and the rest of the material was sent to the Núcleo de Oceanografia Geológica of the Universidade Federal do Rio Grande (FURG), where it was stored in a refrigerated container.

Age model

The age model was built based on the correlation of the $\delta^{18}O$ isotopic curve of the planktonic foraminifera of the SIS188 core with the standard curve of Lisiecki and Stern (2016) (Figure 2). As control points, four AMS ^{14}C ages were obtained (Table 1). The age model was constructed using the AnalySeries software (Paillard et al., 1996), and was partially presented by Duque-Castaño et al. (2019). Radiocarbon dating was performed on the planktonic foraminifera *Globigerinoides ruber* (fraction > 150 µm), using the accelerated mass spectrometry (AMS) method at the Laboratório de Radiocarbono of the Universidade Federal Fluminense (LAC-UFF). 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 and Reimer, 1993) (Table 1). Analyses of $\delta^{18}O$ were also performed on *G. ruber* (fraction > 150 µm) in a MAT-253 dual input mass spectrometer with a Kiel IV carbonate device at the Laboratory of Stable Isotopes at the University of California, Santa Cruz. Isotope data are reported in permil relative to the Vienna Pee Dee Belemnite (V-PDB) standard (Figure 2).

Processing and palynological analysis

For palynological analyses, 56 samples were collected along the core with intervals of 6 cm between them. Prior to processing, a tablet of the exotic spore *Lycopodium clavatum* (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 concentration of pollen (Stockmarr, 1971). The palynological processing followed the preparation technique proposed by Faegri and Iversen (1975), with the addition of 10% hydrochloric acid (HCl) to remove carbonates and 5% potassium hydroxide (KOH) to remove organic matter and humic acids. To concentrate the palynomorphs, a solution of zinc chloride ($ZnCl_2$), with a density between 1.8-1.9 g cm^{-3} was used, and at least five slides of each sample were assembled in glycerinated gelatin. The slides were analysed under an optical microscope at 400x or 1,000x magnification, and 300 pollen grains and spores were counted for each sample when possible. Identification was based on several bibliographic references (e.g., Leal and Lorscheitter, 2007; Leonhardt and Lorscheitter, 2007, 2008, 2010; Roth and Lorscheitter, 2013; Masetto and Lorscheitter, 2016), as well as on the palynological collection in the laboratory.

In addition, diatoms and dinoflagellates present on the palynological slides were also counted. Although these samples were not prepared for this purpose, these data were included as they provide interesting information when analysed together with the pollen assemblage.

Statistical analysis

Percentages of continental palynomorphs (Bryophytes, Pteridophytes, Herbs, Shrubs, Trees, Lianas, Varied Habits, Indeterminate and Algae) were calculated using the total sum of the occurrence of these groups. The percentages of marine palynomorphs (Palynophoraminifera, Scolecodonts, Acritarchs and Dinoflagellates) were calculated from the sum of their occurrence with the total occurrence of continental palynomorphs. The percentages of diatoms were calculated from the sum of their occurrence with the total of continental and marine palynomorphs. The Tilia 2.1.1 software (Grimm, 1993) was used to construct pollen diagrams as well as to calculate sedimentation rates (clastic material), concentration and percentage. All data were compared with the sea level curve, derived from the database available on the National Oceanic and Atmospheric Administration (NOAA) website (Spratt and Lisiecki, 2016) applicable worldwide. The standard deviation of this curve changes with time and is greater between 8 and 22 cal ka BP, reaching > 10 meters at some ages.

The correlation between the paleoproductivity proxy N Ratio (Flores et al, 2000) obtained by Gonçalves and Leonhardt (2021) and the pollen concentration in the samples was calculated. The significance of the correlation was assessed by auto-resampling, with 10,000 iterations, α=0.1. Analyses were performed using MULTIV statistical analysis software (Pillar, 1997).

RESULTS

The marine sediment core SIS188 comprises the time interval between 47.8 and 7.4 cal ka BP (Table 1, Figure 2).

Tabela 2 (Tese) Table 1. Radiocarbon ages used in the construction of the marine core SIS188 age model**.**

Depth (cm)	Species	Age (^{14}C years BP)	Error (years)	Calibrated age (cal ka BP)	Lab ID
21	*G. ruber*	6725	±31	7204	170210
54	*G. ruber*	9921	±34	10812	170055
113.5	*G. ruber*	21360	±59	25243	170056
180.8	*G. ruber*	26325	±77	30099	170211

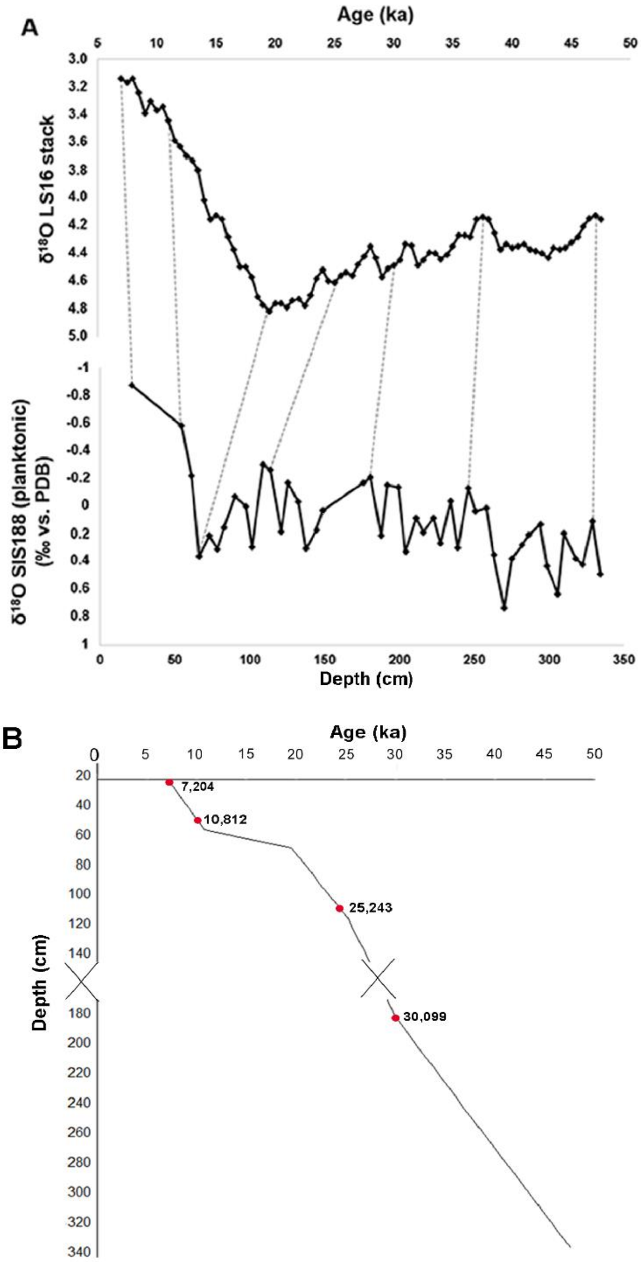

Figura 13 (Tese) Figure 2. Age model. (A) Correlation between Lisiecki and Stern (2016) South Atlantic intermediate standard curve and the oxygen isotope data from the marine core SIS188. (B) Relationship between age and depth in the marine core SIS188. The red dots are the depths where radiocarbon dating was done.

A total of 40 spores and 59 pollen grains were identified in 56 analyzed samples, in addition to other non-pollinic palynomorphs. For paleoenvironmental interpretation purposes, taxa were grouped into the following categories: continental palynomorphs - Bryophytes, Pteridophytes, Herbs, Shrubs, Trees, Lianas, Varied Habits, Indeterminate (when the taxonomic identification of the pollen grain was not possible) and Algae; marine palynomorphs - Palinoforaminifera, Scolecodonts, Acritarchs and Dinoflagellates; and Diatoms (Figures 3 and 4).

The results were divided according to the Marine Isotope Stages (MIS) that are documented in the marine core SIS188, for paleoenvironmental interpretation purposes. A detailed description of the fluctuations of the main taxa of the continental palynomorph groups can be obtained from Bottezini et al. (in press). Data on paleoproductivity obtained for the SIS188 core are also presented, as described in Gonçalves and Leonhardt (2021).

The correlation between the N Ratio and the pollen concentration in the sediments was not significant (0.24; α=0.15). However, removing the samples corresponding to EIM 1, the correlation increases and becomes significant (0.33; α=0.07).

MIS 3 (47.7- 29 cal ka BP; 336 - 176 cm)

This core interval is composed by carbonate-rich mud. Sedimentation rates are close to 9 cm/kyr, from 47.8 cal ka BP to around 30 cal ka BP. Thereafter, they reach 13.8 cm/kyr (the highest values within the core) until the end of MIS 3 (Figure 3). Continental palynomorph concentrations are moderate in this interval untill 29.8 cal ka BP, showing an increase trend towards the end of MIS 3 and a peak at 28 cal ka BP (Figure 4).

Among the continental indicators, "Herbs" predominate in MIS 3, followed by the group "Varied Habits". The groups "Bryophytes" and "Shrubs" present the highest percentages along the core in this interval. The "Trees" group shows a decrease towards the end of the period. The "Lianas" show low percentages throughout the core, but they have a slight increase in 43 cal ka BP. The "Indeterminate" group presents higher percentages within this range than in the subsequent ones, with peaks between 43 and 41.9 cal ka BP and between 37.5 and 35.9 cal ka BP. The group "Algae" has low percentages, while the diatom *Cyclotella meneghiniana* has highest values in this interval, with higher proportions between 38.6-34.3 cal ka BP (Figure 3).

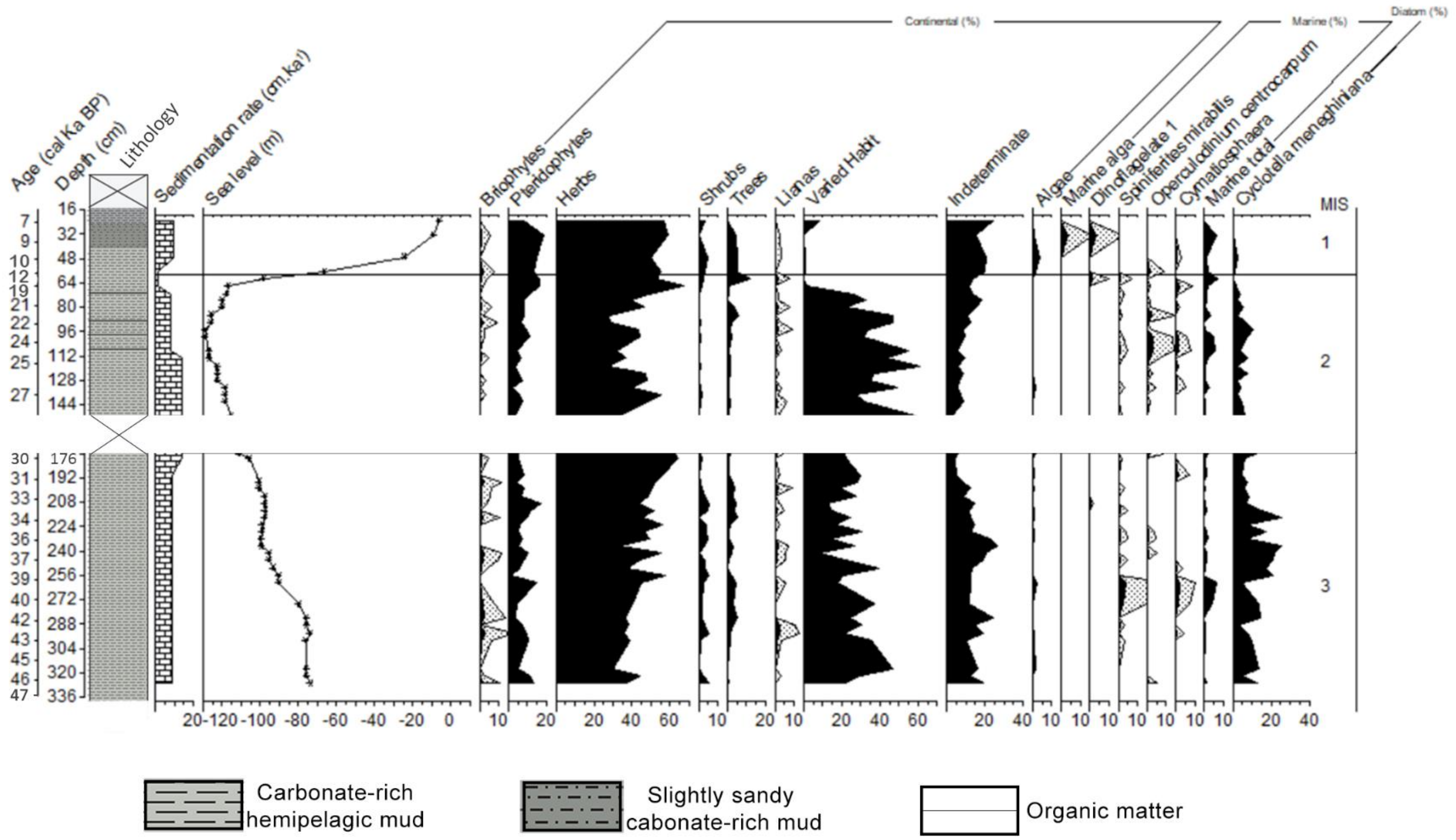

Figura 14 (Tese) Figure 3. Pollen percentage summary diagram showing lithology, sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt and Lisiecki, 2016), continental, marine and diatom palynomorph groups and the Marine Isotope Stages (MIS). To better visualization in the graph, Briophytes, Lianas, Marine alga, Dinoflagellate, *S. mirabilis*, *O. centrocarpum* and *Cymatiosphaera* were exaggerated.

The concentrations of the "Marine" group are low throughout the MIS 3 (Figure 4). The same trend is followed by the percentages which, however, show a peak between 40.8 and 39.2 cal ka BP (reaching 6.3%), represented mainly by the dinoflagellate *Operculodinium centrocarpum* and the algae *Cymatiosphaera* (Figure 3).

According to Gonçalves and Leonhardt (2021), the curve of coccoliths per gram of sediment presents low values in almost the entire MIS 3, increasing from 30.1 ka. Likewise, the TOC (Total Organic Carbon) curve presents the lowest values recorded in the core. Unlike previous proxies, the N Ratio curve does not show particularly low values throughout MIS 3. There are some intervals of increased N Ratio, such as between 47.5 - 41.7 cal ka BP and between 33.3 - 29.9 cal ka BP (Gonçalves and Leonhardt, 2021) (Figure 4).

MIS 2 (29 - 14 cal ka BP; 176 - 59 cm)

In this interval, the sediments are composed of carbonate-rich mud, with thin layers of organic matter at depths of 75, 90, 100 and 105 cm. Sedimentation rates at the beginning of MIS 2 are high (13.8 cm/kyr) up to 24.9 cal ka BP, when they drop to 8.3 cm/kyr. At 19.5 cal ka BP, sedimentation rates are even lower, reaching the lowest values in the studied interval (1.4 cm/kyr) (Figure 3).

The concentrations of most palynomorphs of continental origin are high in MIS 2. However, the concentrations of "Bryophytes" and "Shrubs" are very low. There is a concentration peak at 22.9 cal ka BP (with emphasis on the groups "Pteridophytes", "Herbs", "Trees", "Lianas" and "Diatoms") (Figure 3).

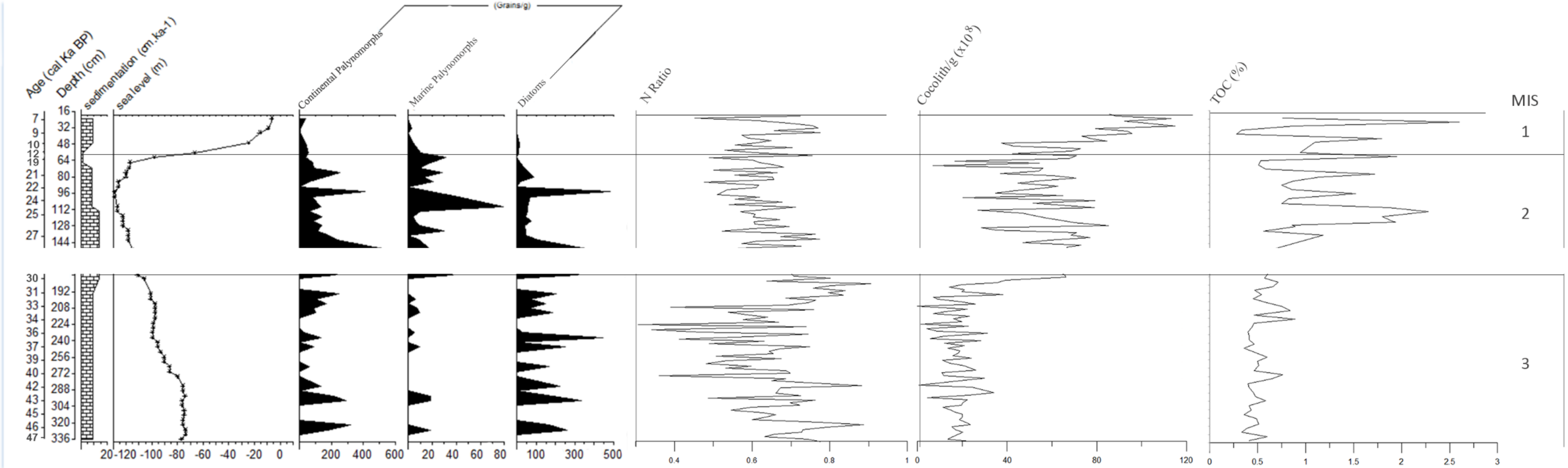

Figura 15 (Tese) Figure 4. Diagram showing sedimentation rate (in centimeters per thousand years), sea level (in meters; Spratt and Lisiecki, 2016), concentration of continental indicators and paleoproductivity proxies (Gonçalves and Leonhardt, 2021) (for a better visualization of the values of the continental and marine indicators, they were all divided by 10,000).

Among continental indicators, the groups "Varied Habits" and "Herbs" continue to prevail in the record, with the former predominating. However, at the end of MIS 2, the percentages of "Varied Habits" drop abruptly and "Herbs" return to dominate the pollen association. The percentages of "Pteridophytes" tend to increase from 27.3 cal ka BP, especially between 19.5 and 15.9 cal ka BP. The "Trees" group shows an increase in their percentages between 22.4 - 21.2 cal ka BP and a peak at 15.9 cal ka. The groups "Bryophytes", "Lianas" and "Shrubs" continue with low percentages. "Indeterminate" presents lower percentages than in MIS 3, with tending to increase towards the end of MIS 2. The "Algae" group presents lower percentages than in MIS 3. The percentages of *C. meneghiniana* fall when compared to MIS 3 (Figure 3).

The "Marine" group reaches its highest concentrations in MIS 2, with peaks at 29.8, 26.6, 24.7 and 15.9 cal ka BP (Figure 4). The percentages range from 0 to 6.9%, with peaks between 24.7 and 23.6 cal ka BP and at 15.9 cal ka BP, with emphasis on *O. centrocarpum* and *Cymatiosphaera* (Figure 3).

According to Gonçalves and Leonhardt (2021), the curve of coccoliths per gram of sediment shows a slight decrease from the beginning of MIS 2 to the end of LGM, increasing later. TOC clearly increases compared to MIS 3 values, but with greater fluctuations: it reaches the highest levels between 25.9 and 24.8 cal ka BP (1.8 to 2.28%) and the lowest between 20.3 and 18.3 cal ka BP (0.51 to 0.58%). The N Ratio shows a decreasing trend over MIS 2 (Gonçalves and Leonhardt, 2021) (Figure 4).

MIS 1 (14 - 7.4 cal ka BP; 59 - 22 cm)

Over most of this interval, the sediments are composed of carbonate-rich hemipelagic mud, except between 31 and 45 cm which contains a lightly sandy carbonate-rich mud. Sedimentation rates rise from 1.4 cm/kyr to 9.1 cm/kyr from 10.8 cal ka BP (54 cm) (Figure 3).

The concentrations of palynomorphs of continental origin are very low during MIS 1 (Figure 4). The "Herbs" group dominates the pollen association, but the groups "Pteridophytes", "Trees" and "Shrubs" are also relevant. The percentages of the groups "Varied habits", "Bryophytes" and "Lianas" remain low. The "Indetermined" group has high percentages in this range. "Algae" percentages are slightly higher between 12.6 and 10 cal ka BP. The diatom *C. meneghiniana* presents its lowest percentages in MIS 1 (Figure 3).

The concentrations of the "Marine" group also drop at the beginning of MIS 1 (Figure 4), although their percentages peak at 6.8% at 8.5 cal kyr BP. The specimens *O. centrocarpum* and *Cymatiosphaera* do not stand out at MIS 1 (Figure 3).

According to Gonçalves and Leonhardt (2021), the highest content of coccoliths per gram of sediment are found in MIS 1, during the Holocene, reaching 115 x 10^8 coccoliths/gram at 8.5 cal ka BP. TOC presents its highest and lowest levels in the Holocene, ranging from 0.28% (9.1 cal ka BP) to 2.6% (7.9 cal ka BP). The N Ratio curve increases in the Holocene, especially between 9 and 7.9 cal ka BP (Gonçalves and Leonhardt, 2021) (Figure 4).

DISCUSSION

The primary productivity of the Southwest Atlantic region can be increased by several local factors such as a greater influence of the La Plata River plume (transported by the BCC), the strengthening of upwelling systems, and the intensification of the westerlies that carry continental dust to the ocean. Recently, several studies have pointed out the BCC as one of the main contributing agents of terrigenous sediments and fertilization of marine waters in the region, in the continental shelf or even in the open ocean (Mahiques et al., 2009; Pivel et al., 2011; Mathias et al., 2014; Gu et al., 2017; Gu et al., 2018a; Mathias et al., 2020). The BCC, although currently a coastal current, would influence the slope region at intervals where the relative sea level was lower. However, a study on paleoproductivity carried out in the core SIS188 (Gonçalves and Leonhardt, in press) found a clearer relationship of this parameter with the insolation of the study area (and with the associated atmospheric processes).

Insolation drives atmospheric processes and can play an important role in enhancing or weakening the upwelling systems. Currently, the SASH is shifted south between January and March, causing northeasterly winds to predominate in the southern and southeastern regions of Brazil during the Southern Hemisphere summer, intensifying upwelling (Palma and Matano, 2009), and causing the plume of the La Plata River to be contained to the south. During winter, there is a predominance of southwest winds in the region, which drive the plume to the latitude of the study region (Piola et al., 2005).

The same mechanism may have occurred over time in the region's recent past. The correlation between different paleoproductivity proxies (N-Ratio, number of coccoliths and TOC content in sediments) from the core SIS188 with the monthly insolation over time, demonstrated by Gonçalves and Leonhardt (in press), show a pattern similar to the current one for the time interval studied, with positive correlation during spring and early summer, and negative correlation during late summer and early autumn. Therefore, the increase in productivity in the study area increases at intervals of higher insolation, with a predominance of northeasterly winds, which intensify upwelling. No significant correlations were found for the intervals of lower insolation (Southern Hemisphere winter), when the BCC could reach the latitude of the study area driven by southwest winds (Gonçalves and Leonhardt, in press).

Furthermore, the palynological content found in the core SIS188 points to the presence of several elements of the Araucaria Forest (Bottezini et al., in press), a typical vegetation of the East Plateau of RS, which is at the same latitude as the core. The presence of exotic pollen grains *Alnus* and *Nothofagus* is very scarce in the core SIS188, being indicative of long-distance transport. Both are typical of Andean vegetation (Cabrera, 1994) and could have reached the study area by wind transport since these grains are also found in bogs on the South Brazilian Plateau (Leonhardt and Lorscheitter, 2009). Besides wind-borne dust, other source of continental input to the ocean are the discharges from the Mampituba and Araranguá rivers, which would be a more likely source for the palynological content found. The correlation analysis between the pollen concentration in the sediments and the N-Ratio found in the core SIS188 indicates that there is some influence of the continental input on the fertilization of the marine environment in the studied area. However, this correlation (of 0.33) is only significant when samples belonging to MIS 1 are excluded from the analysis, indicating that the rise in sea level hinders the arrival of these elements in the open sea.

MIS 3 (47.7- 29 cal ka BP, 336 - 137.5 cm)

The climate in this interval was predominantly cold (with a predominance of grassland vegetation, indicated by the high percentages of the "Herbs" group). Climatic conditions were wet enough to allow the development of lakes and swamps on the coastal plain (indicated by the high percentages of the groups "Bryophytes", "Pteridophytes", and the diatom *C. meneghiniana*) and of forest formations probably in refuges (Bottezini et al., in press).

During MIS 3, paleoproductivity was increased between 47.5 - 41.7 ka BP and between 33.3 - 29.9 ka BP in the core SIS188 (Gonçalves and Leonhardt, in press). These intervals coincide in part with the increase in the influx of dust followed by the increase in productivity found in the core SIS249 (Lopes et al., 2021), which is very close to SIS188. The authors attribute this increase in dust influx to the expansion of the southwest wind belt generated by the South Pacific anticyclone to north in glacial intervals (Pichat et al., 2014; Jacobel et al., 2017), reaching the Pelotas Basin. These intervals contain the samples that reach the highest pollen concentrations of MIS 3 (Figure 4), indicating that these palynomorphs probably reached the region from wind transport and that this continental input had some influence on marine paleoproductivity.

The positive correlation between pollen concentration in sediments and the N-Ratio also point to this explanation. The same pattern was not found for the other paleoproductivity proxies (coccolith abundance and TOC content in sediments) due to the chemical properties of the deep water masses and the deep current velocity (Gonçalves and Leonhardt, 2021).

MIS 2 (29 - 14 cal ka BP, 137.5 - 59 cm)

During MIS 2, climatic fluctuations induced changes in the ecological structure of the vegetation (increase of the "Varied Habits" group), with environmental conditions starting to become drier and cooler (decrease in the percentages of *C. meneghiniana* and the groups "Trees", "Bryophytes", and "Pteridophytes"). This climatic trend becomes more evident around 19.5 cal ka BP, in the Last Glacial Maximum (LGM), being interrupted by the Heinrich Event 1 (15.9 cal ka BP), related to greater precipitation and/or temperature increase (Bottezini et al., in press).

The increase in productivicty inferred by proxies such as coccolith per gram of sediment and TOC content is quite accentuated and remains high throughout MIS 2, demonstrating the increase in paleoproductivity at this stage, related to the intensification of upwelling in the region (Pereira et al., 2018; Gonçalves and Leonhardt, in press). Although palynomorph concentrations show a large peak at the start of MIS 2, they do not remain as high throughout the stage, although they are on average higher than in MIS 3 and MIS 1 (Figure 4). This increase in the concentration of palynomorphs may be related to the greater proximity of the mouths of the Araranguá and Mampituba rivers in relation to the core due to the sea-level lowering and/or wind intensification during MIS 2, especially during the LGM (Kohfeld et al., 2013; Bottezini et al., in press).

The decrease in sea level typical of MIS 2 is also reflected in the record of marine palynomorphs, which reach their highest concentrations in this interval mainly related to the occurrence of *O. centrocarpum* and *Cymatiosphaera*. *Operculodinium centrocarpum* is a cosmopolitan dinoflagellate that can occur in environments with high salinity and low levels of nutrients, being associated with the coastal-ocean transition (Dale, 1996; Zonneveld et al., 2013). This species is commonly found in sediments under warm water bodies such as the Tropical Water, which is transported by the BC (Santos et al., 2017). The algae *Cymatiosphaera* is pointed as an indicator of neritic environments (Grill and Quatrocchio, 1996), showing greater proportions in the core SIS188 when the sea level was lower.

At the end of MIS 2 and beginning of MIS 1 (between 19.5 and 12.6 cal ka BP) there is a significant reduction in the sedimentation rate, which is possibly related to deglaciation and to an increase in the relative sea level, displacing the mouth of the Mampituba and Araranguá rivers, which start to deposit their sediments in shallower waters. The decrease in the concentration of most palynomorphs (which extends to the end of the record) may be related to this process and/or the decrease in wind intensity (Voigt et al., 2015; Bottezini et al., in press).

MIS 1 (14 - 7.4 cal ka BP; 59 - 22 cm)

With the climatic changes of deglaciation and the beginning of the Holocene, a small development of forests and lakes is observed on the continent, while grasslands remain the dominant plant formation (Bottezini et al., in press).

The decrease in concentrations of continental palynomorphs observed since the end of MIS 2 is accentuated in MIS 1, when the sea level is higher and there is a weakening of the southwest winds during the Holocene (Voigt et al., 2015), decreasing the wind transport of palynomorphs to the study area.

According to the paleoproductivity proxies measured in the core SIS188 (Figure 4), paleoproductivity was high during MIS 1, especially in the Holocene, which would be the result of the geochemical dynamics caused by marine regression during the LGM (Gonçalves and Leonhardt, in press), since the upwelling system seems to be weakened in this interval (Chiessi et al., 2015; Pereira et al., 2018; Duque-Castaño et al., 2019; Gonçalves and Leonhardt, in press). At the same time, the concentration of palynomorphs of continental origin decreases significantly in this interval, demonstrating a decoupling between the continental input (whether wind or fluvial) and marine productivity. The correlation between the N-Ratio and the pollen concentration in the sediments only becomes significant when the samples of this MIS are excluded, also pointing to the rise in sea level as a factor that interferes with the fertilization of marine waters far from the coast by continental input.

Although several studies point to an influence of the BCC on the slope of the Brazilian Continental Margin (between 24.9º and 38ºS) in glacial intervals, few use proxies linked to the plume of the La Plata River. One of these works is that of Mathias et al. (2021), which characterized the sediments of the core GL-1090 collected in the Santos Basin (24º 92´ S; 42º 51´ W; at 2,225 m of water column). From paleomagnetic, geochemical and grain size data, they obtained a characterization compatible with the sediments of the La

Plata River plume. The authors concluded that the presence of these sediments on the slope was due to transport by the BCC in glacial intervals with the lowest sea level. However, it is also possible that these sediments were deposited at shallower depths and redistributed by undercurrents that also undergo changes with the decrease in relative sea level.

Other works that infer the presence of the BCC in the open sea in the southern Brazilian Continental Margin present paleoproductivity proxies (Pivel et al., 2011 - planktonic foraminifera; Almeida et al., 2015 - benthic foraminifera; Gu et al., 2017; Gu et al., 2018a; Gu et al., 2018b – marine dinoflagellates) that could be responding to other fertilization mechanisms. On the other hand, Ávila et al. (2020), when studying palynomorphs and organic matter content in the sediments of the core REG972 (33.75ºS, 50.85ºW, 1,025 m of water column), attributed the increases in paleoproductivity in the Rio Grande Cone region, to a greater influence of Subantarctic Shelf Water in periods of lower sea level, not to the influence of the BCC.

CONCLUSION

The studied core covered the time interval between 47.8 and 7.4 cal ka BP, recording part of MIS 3, MIS 2, and part of MIS 1. The palynological association found over time in the core does not provide clear evidence of influence of the BCC on the continental input for the study area, as the vegetation interpreted from this record is more related to the local flora. Comparison of continental palynomorphs with paleoproductivity proxies in the core SIS188 indicates that during this period the BCC did not have a clear influence on the fertilization of marine waters. The continental input from wind transport seems to have had some influence on this process, leading to an increase in paleoproductivity during the glacial interval (MIS 3 and MIS 2).

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Capítulo VII: Síntese da Discussão e Conclusões

Os resultados das análises palinológicas indicaram que, de modo geral, a área continental adjacente foi dominada por campos durante o intervalo de tempo estudado, compatíveis com resultados de trabalhos anteriores realizados no planalto sul-brasileiro e na costa sul e sudeste [Behling *et al*. 2002, 2004, Gu *et al*. 2017, 2018a]. No intervalo de tempo entre 47.8–33.3 cal ka BP (PZ I), áreas úmidas como pântanos podem ter sido comuns na plataforma continental, refletindo condições ambientais mais úmidas do que durante o UMG e início do degelo, indicado pelas maiores porcentagens dos grupos "Briófitas" e "Pteridófitas". O intervalo de tempo da PZI corresponde à parte do EIM 3, que se caracteriza por um clima mais quente e úmido do que o EIM 2, embora se trate de um período glacial [Lisiecki & Raymo 2005].

No contexto oceanográfico, durante o EIM 3 os *proxies* de paleoprodutividade indicam um intervalo de maior produtividade entre 47,5- 41,7 ka BP e entre 33,3- 29,9 ka BP [Gonçalves & Leonhardt, aceito], coincidindo, em parte, com o aumento no influxo de poeira que acompanha o aumento na produtividade no testemunho SIS249 [Lopes *et al*. 2021]. Estes intervalos contém as amostras que atingem as maiores concentrações polínicas do EIM 3, indicando que os palinomorfos alcançaram a região através do transporte eólico e que este teve influência sobre a produtividade marinha. A correlação positiva entre a concentração polínica nos sedimentos e a Razão N também apontam para esta explicação.

Durante o EIM 2 (parte da PZII), as oscilações climáticas características deste período induziram mudanças significativas da vegetação (aumento do grupo “Hábitos variados”), com as condições ambientais começando a se tornar mais secas e mais frias (diminuição das porcentagens de *C. meneghiniana* e dos grupos “Árvores”, “Briófitos” e “Pteridófitos”). Esta tendência climática se torna mais marcante em torno dos 19,5 cal ka BP, no Último Máximo Glacial (UMG), sendo interrompida pelo Evento Heinrich 1 (15,9 cal ka BP), relacionado a maior precipitação e/ou aumento de temperatura [Bottezini *et al*., aceito]. Neste intervalo (EIM 2) é observado um aumento na paleoprodutividade, relacionado à intensificação da ressurgência na região [Pereira *et al*. 2018 Gonçalves & Leonhardt, aceito]. O aumento nas concentrações polínicas observado no início deste estágio pode estar relacionado à maior proximidade da foz dos rios Mampituba e Araranguá em função do rebaixamento do nível do mar e/ou à intensificação dos ventos, especialmente durante o UMG [Kohfeld *et al*. 2013, Bottezini *et al*. aceito]. A diminuição do nível do mar também é observada nas concentrações dos palinomorfos marinhos, que são as maiores ao longo do registro, representados principalmente por *O. centrocarpum* e *Cymatiosphaera*. O dinoflagelado *O. centrocarpum* é encontrado em sedimentos sob massas de água quentes, como a AT, que é transportada pela CB [Santos *et al*. 2017]; já a alga *Cymatiosphaera* é indicadora de ambientes neríticos [Grill & Quatrocchio, 1996] e suas maiores proporções são encontradas no testemunho SIS 188 quando o nível do mar estava mais baixo.

No final do EIM 2 e início do EIM 1 (entre 19,5 e 12,6 cal ka BP) a taxa de sedimentação cai significativamente, possivelmente relacionada à deglaciação e ao aumento do nível relativo do mar, deslocando a foz dos rios Mampituba e Araranguá, que passam a depositar seus sedimentos na plataforma recém submersa. A diminuição na concentração da maioria dos palinomorfos (que segue até o final do registro) pode estar relacionada a este processo e/ou à diminuição da intensidade dos ventos [Voigt *et al*. 2015; Bottezini *et al*. aceito].

No EIM 1 (parte da PZIII), a queda nas concentrações dos palinomorfos continentais que é observada desde o fim do EIM 2, se acentua neste intervalo, quando o nível do mar está mais alto e ocorre um enfraquecimento dos ventos de sudoeste durante o Holoceno [Voigt *et al*. 2015], diminuindo o transporte eólico de palinomorfos para a área de estudo. Há um pequeno desenvolvimento de florestas e lagos no continente, como consequência das mudanças climáticas da deglaciação e do início do Holoceno. No entanto, os campos continuam sendo a formação vegetal dominante [Bottezini *et al*. aceito].

Durante o EIM 1, a paleoprodutividade foi alta, especialmente a partir do Holoceno. Isto se deve à dinâmica geoquímica provocada pela regressão marinha durante o UMG [Gonçalves & Leonhardt aceito], visto que os processos de ressurgência estavam enfraquecidos neste intervalo [Chiessi *et al.* 2015, Pereira *et al*. 2018, Duque-Castaño *et al*. 2019, Gonçalves & Leonhardt aceito]. A concentração dos palinomorfos continentais cai abruptamente, indicando que há um desacoplamento entre o aporte continental (seja fluvial ou eólico) e a paleoprodutividade. A correlação entre Razão N e concentração polínica só é significativa quando as amostras do EIM 1 são excluídas, apontando que o aumento do NMM é um fator que interfere na fertilização das águas marinhas pelo *input* continental.

Vários trabalhos apontam a influência da CCB no talude da Margem Continental Brasileira (entre 24,9º a 38ºS) durante intervalos glaciais, no entanto poucos utilizam *proxies* ligados à PRP. Mathias *et al*. [2021] caracterizaram os sedimentos do testemunho GL-1090 coletado na Bacia de Santos utilizando dados paleomagnéticos, geoquímicos e tamanho de grão, sendo compatíveis com sedimentos da PRP. Os autores concluíram que estes sedimentos foram transportados pela CCB em intervalos glaciais, com NMM mais baixo. Outra possiblidade é que tenham sido depositados em profundidades mais rasas e posteriormente redistribuídos pelas correntes de fundo, que também sofreram alterações com o rebaixamento do NMM. A presença da CCB em mar aberto também foi inferida por *proxies* de paleoprodutividade [Pivel *et al*. 2011, Almeida *et al*. 2015, Gu *et al*. 2017, Gu *et al*. 2018a, Gu *et al*. 2018b] que poderiam estar relacionados à outros mecanismos de fertilização. Na região do Cone do Rio Grande, Ávila *et al*. [2020] atribuíram o aumento de produtividade à maior influência da Água Subantártica de Plataforma, e não a influência da CCB.

A reconstituição da vegetação pretérita, da dinâmica do clima no Sul do Brasil e da paleoprodutividade oceânica do Atlântico Sul ocidental são muito importantes na contribuição do entendimento aprofundado das mudanças ambientais no sudoeste da América do Sul desde o final do Quaternário. Os resultados apresentados neste estudo contribuem ainda mais para a compreensão das interações terra-oceano. No entanto ainda são necessários mais estudos de alta resolução temporal em testemunhos marinhos para o Atlântico Sudoeste a fim de compreender melhor o papel da influência continental sobre a paleoprodutividade marinha ao longo do tempo.

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