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

INFERÊNCIAS PALEOAMBIENTAIS E PALEOCLIMÁTICAS PARA O QUATERNÁRIO CONTINENTAL DO SUL DO BRASIL BASEADAS EM ANÁLISES DE PALINOFÁCIES E DE GEOQUÍMICA ORGÂNICA DE AMBIENTES INFLUENCIADOS POR DIFERENTES REGIMES HIDROLÓGICOS

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O essencial é invisível aos olhos

Antoine de Saint-Exupéry

RESUMO

A presente pesquisa está centrada na interpretação das análises de palinofácies e de geoquímica orgânica realizadas em três perfis sedimentares (T1, T2 e T3) de zonas úmidas continentais influenciadas por diferentes regimes hidrológicos na faixa climática subtropical durante o Quaternário no sul do Brasil (Estado do Rio Grande do Sul) com o principal objetivo de demonstrar a utilidade dessas análises para a obtenção de dados paleoclimáticos e paleoambientais. A análise de palinofácies realizada nos testemunhos T1-Mina do Museu (7.963 anos antes do presente - AP) e T2-Mina Modelo (9.542 anos AP), provenientes de Ametista do Sul, e no testemunho T3-Iraí (10.586 anos BP), proveniente de Iraí, revelou um amplo domínio do Grupo Fitoclasto. Os Palinomorfos são o segundo grupo dominante e o Grupo Produto Amorfo é o menos abundante. Esse tipo de análise foi particularmente eficaz para as interpretações dos eventos de precipitação e de sucessão vegetacional em Ametista do Sul, porque o isolamento hidrológico desses alagados efêmeros de altitude torna-os muito sensíveis aos efeitos climáticos. As flutuações na profundidade da água foram inferidas a partir das concentrações dos elementos autóctones (*especialmente Botryoccocus* e outras algas), que predominam nos intervalos basais e tendem a diminuir progressivamente em direção ao topo. *Pseudoschizaea*, por sua vez, parece atuar como um marcador biológico de intervalos de transição. O aumento da frequência e da variedade dos esporomorfos terrestres nas camadas mais superficiais indica um aumento da diversidade vegetal e está relacionado ao processo de evolução sucessional da área. Para Ametista do Sul, os resultados permitiram determinar que as oscilações nos padrões de umidade resultaram em um padrão intermitente do nível de água dos alagados, o qual pode representar um reflexo de mudanças climáticas regionais ou, talvez, de mudanças em escala global relacionadas com os “eventos Bond”. Em Iraí, a fração orgânica melhor representada é constituída por elementos derivados de plantas terrestres, uma característica típica da matéria orgânica preservada em turfeiras Esse tipo de ambiente úmido nunca chegou a secar completamente, uma vez que os teores de umidade eram subsidiados por diferentes fatores, tais como o nível do lençol freático, as inundações do Rio Uruguai e a água da chuva. A ocorrência muito baixa de algas, contudo, indica que a profundidade da água não era suficientemente espessa para o desenvolvimento da biomassa algálica, embora o ambiente anóxico e redutor também possa ter limitado a expansão deste grupo. Os parâmetros organogeoquímicos foram particularmente úteis para interpretações de eventos de anoxia e de mudanças nos regimes hidrológicos dos sedimentos turfosos. Os teores de carbono orgânico total (COT) e enxofre total (ST) são mais altos na porção basal do perfil, diminuindo em direção ao topo, e podem estar relacionados ao regime hidrológico ou à interferência antrópica na dinâmica da paisagem. O teor anômalo de enxofre observado em uma das amostras de Iraí pode ser devido a uma fonte externa e talvez relacionado com a presença de fontes termais na região. A presente pesquisa tem potencial como uma referência moderna capaz de ser aplicada na reconstrução de paleoambientes continentais análogos associados a regiões alagadas em cinturões subtropicais.

PALAVRAS-CHAVE – *matéria orgânica (MO); carbono orgânico total (COT); enxofre total (ST); ambiente continental; mudanças paleoclimáticas; influência pluviométrica; lençol freático; transbordamento fluvial; alagados efêmeros; sedimentos turfosos.*

ABSTRACT

The present research focuses on the interpretation of the palynofacies and organic geochemistry analyses performed on three sedimentary cores (T1, T2 and T3) from continental wetlands influenced by different hydrological regimes in the sub-tropical climatic belt during the Quaternary in southern Brazil (Rio Grande do Sul State), with the main goal of demonstrating the usefulness of these analyses for obtaining paleoclimatic and palaeoenvironmental data. Palynofacies analysis was performed for the cores T1-Mina do Museu (7963 years before present - BP) and T2-Mina Modelo (9542 years BP) from Ametista do Sul, and for the T3-Iraí core (10586 years BP) from Iraí and revealed a high dominance of the Phytoclast Group. The Palynomorph is the second most dominant group and the Amorphous Product is the least abundant group. This kind of analysis was particularly effective in the interpretations of rainfall events and vegetation succession in Ametista do Sul, because the hydrological isolation renders the ephemeral ponds at high altitude highly sensitive to climatic effects. The fluctuations in the water depth are inferred from the concentration of the autochthonous elements (especially *Botryoccocus* and other algae), which predominate in the basal intervals and tend to decrease progressively towards the top. *Pseudoschizaea*, in its turn, appears to act as a biological marker for transitional intervals. The increasing frequency and variety of the terrestrial sporomorphs in the topmost interval indicate an increased vegetal diversity and is most likely related to the process of successional evolution of the area. For Ametista do Sul, the results allowed to determine that the oscillations in the moisture pattern resulted in the intermittent feature of pond water level and this may reflect the regional climate changes or perhaps the global scale changes related to the Bond events. In Iraí, the better represented organic fraction consists of elements derived from terrestrial plants, a characteristic typical of organic matter preserved in peat bogs. This kind of wetland never dried completely, since the moisture content was subsidized by different factors, such as the groundwater, the flood events of the Uruguay River and the rainfall water. The very low occurrence of algae, however, indicates that the water was not deep enough for the development of algalic biomass, although the anoxic, reducing environment may also have limited the expansion of this group. The organic geochemistry parameters were particularly useful for interpretation of anoxia events and changes of hydrological regimes in the peaty sediment. The total organic carbon (TOC) and the total sulfur (TS) contents are higher in the basal portion of the profile, decreasing towards the top and could be linked to hydrologic regimes or to anthropogenic interference in the landscape dynamics. The anomalous TS content observed in one of the samples from Iraí might be due to an external source and perhaps related to the presence of thermal springs in the region. The present research has potential as a modern reference that can be applied in the reconstruction of past analogous continental paleoenvironments associated to wetland areas in subtropical belts.

KEY-WORDS - *organic matter (OM); total organic carbon (TOC); total sulfur (TS); continental environment; paleoclimatic changes; rainfall influence; water table; river overflow; ephemeral ponds; peaty sediments.*

LISTA DE ABREVIATURAS E SIGLAS

AMOC -	*Atlantic Meridional Overturning Circulation*
AMS -	*Accelerator Mass Spectrometry*
AP -	antes do presente
ASTER -	*Advanced Spacebone Thermal Emission and Reflection Radiometer*
BP -	before present
cal anos -	idade calibrada
cal yr -	*calibrated years*
COT -	carbono orgânico total
GRIP -	*Greenland Ice Core Project*
HSG -	*hematite stained grain*
IRD -	*ice-rafted debris*
ITCZ -	*Intertropical Convergence Zone*
ka -	mil anos
Ma -	milhões de anos
MO -	matéria orgânica
MOA -	matéria orgânica amorfa
MOP -	matéria orgânica particulada
NAD -	*North Atlantic Deep Water*
NGRIP -	*North Greenland Ice Core Project*
PA -	produto amorfo
pMC -	percentagem de carbono moderna
RI -	resíduo insolúvel
SASM -	*South American Summer Monsoon*
SST -	*Sea Surface Temperature*
ST -	enxofre total
T1 -	Testemunho 1 - Mina do Museu (Ametista do Sul)
T2 -	Testemunho 2 - Mina Modelo (Ametista do Sul)
T3 -	Testemunho 3 - Iraí
THC -	Thermohaline Circulation

SUMÁRIO

PARTE I

PARTE II

PARTE III

APRESENTAÇÃO

Esta tese de doutorado, intitulada **INFERÊNCIAS PALEOAMBIENTAIS E PALEOCLIMÁTICAS PARA O QUATERNÁRIO CONTINENTAL DO SUL DO BRASIL BASEADAS EM ANÁLISES DE PALINOFÁCIES E DE GEOQUÍMICA ORGÂNICA DE AMBIENTES INFLUENCIADOS POR DIFERENTES REGIMES HIDROLÓGICOS**, foi desenvolvida entre março de 2009 e março de 2013 junto ao Programa de Pós Graduação em Geociências do Instituto de Geociências da Universidade Federal do Rio Grande do Sul (IG/UFRGS), em colaboração com o Laboratório de Palinofáceis e Fácies Orgânica do Instituto de Geociências da Universidade Federal do Rio de Janeiro (LAFO/IG/UFRJ).

A presente tese foi estruturada em torno de artigos submetidos a periódicos. Conseqüentemente, sua organização compreende as seguintes partes principais:

- **Parte I -** Introdução do tema e descrição do objeto da pesquisa, onde estão sumarizados os objetivos, as hipóteses e justificativas da pesquisa, bem como o estado da arte e metodologia aplicada.

- **Parte II -** Artigos submetidos em língua inglesa a periódicos internacionais com conceito Qualis Capes B1, com corpo editorial permanente e revisores independentes.

ARTIGO 1: “Holocene environmental climatic changes based on palynofacies and organic geochemical analyses from an inland pond at high altitude in southern Brazil”
Periódico: GEOBIOS (Qualis capes B1)

ARTIGO 2: “Relation between sedimentary organic record and climatic fluctuations in the Holocene attested by palynofacies and organic geochemical analyses from an inland pond of highlands in southern Brazil”
Periódico: GEOLOGICA ACTA (Qualis Capes B1)

ARTIGO 3: “Palynofacies and organic geochemistry studies of organic matter from a wetland system of Southern Brazil influenced by different hydrological regimes in the Quaternary”
Periódico: JOURNAL OF SOUTH AMERICAN EARTH SCIENCES (Qualis Capes B1)

- **Parte III -** Considerações finais, nas quais os dados constantes dos três artigos são compilados em um texto integrador com conclusões gerais e sugestões para trabalhos futuros.

- **Referências** – apenas as citadas no texto da tese.

PARTE I

1 INTRODUÇÃO

Em rochas sedimentares, a matéria orgânica representa a menor porção da fração sedimentar e deriva direta ou indiretamente da parte orgânica dos organismos (TISSOT & WELTE, 1984). A presença de compostos orgânicos no sedimento se deve a uma série de fatores de natureza biológica, física, química e geológica atuando, de forma inter-relacionada, na produção, acumulação e preservação da matéria orgânica e faz parte do Ciclo do Carbono Orgânico. Esses fatores, de acordo com Traverse (1994), resultam em uma complexa associação entre a origem, o transporte e a deposição de partículas orgânicas. Cada partícula orgânica individual comporta-se como uma partícula sedimentar e, por isso, as análises palinofaciológicas baseiam-se na abundância relativa de tais partículas (Menezes ***et al***., 2008). Dessa forma, a tendência de distribuição de cada grupo ou subgrupo da matéria orgânica particulada está condicionada à sua origem biológica e aos processos sedimentares que atuam pré- e pós-soterramento, através de uma série contínua de processos físico-químicos envolvidos no ciclo do carbono e que causam mudanças progressivas e irreversíveis na composição da matéria orgânica ao longo do tempo (TISSOT & WELTE, 1984).

Todo estudo envolvendo a matéria orgânica sedimentar é baseado em conceitos que envolvem a interação da biosfera com a geosfera, o lhe que confere um caráter multidisciplinar que integra ferramentas distintas de investigação e permite a interação de diferentes ciências (MENDONÇA-FILHO ***et al***., 2010).

A análise de palinofácies compreende a caracterização qualitativa e quantitativa da matéria orgânica particulada contida nos sedimentos e rochas sedimentares (TYSON, 1995) e fornece relevantes dados paleoambientais, paleoecológicos e paleoclimáticos que auxiliam na compreensão da evolução das áreas investigadas. Esses resultados, por sua vez, servem como subsídio para modelos preditivos da evolução ambiental, ecológica e climática em escalas mais amplas. A vantagem da aplicação da técnica de palinofácies, segundo Tyson (1995), reside no fato de que ela fornece informações diretas sobre a origem e as características da matéria orgânica, permitindo uma análise mais detalhada e sutil das variações no ambiente sedimentar. A análise palinofaciológica pode ser correlacionada com estudos geoquímicos que complementam a pesquisa, entre os quais se destaca a análise de carbono orgânico total (COT), que fornece dados sobre a quantidade e o estado de preservação da matéria orgânica presente no sistema, constituindo-se num parâmetro importante para determinar o conteúdo orgânico em rochas sedimentares.

Embora a caracterização dos parâmetros palinofaciológicos seja amplamente aplicada em depósitos de origem marinha, deltaica, estuarina ou epicontinental, são escassos os estudos envolvendo depósitos predominantemente continentais sem potencial petrolífero, uma vez que a técnica de palinofácies foi especialmente desenvolvida para a indústria do petróleo com a finalidade de predizer o potencial de rochas geradoras de hidrocarbonetos.

O presente trabalho utiliza a análise de palinofácies e de geoquímica orgânica em sedimentos continentais que nunca estiveram sob influência marinha. Os dados gerados foram complementados por análise sedimentológica e datação radiocarbônica a fim promover o refinamento dos resultados. A integração de tais métodos de investigação permitiu tecer inferências paleoambientais, paleoecológicas e paleoclimáticas baseadas em dados de alta resolução e confiabilidade.

A presença de pequenos banhados naturais associados a ***gossan*** (estruturas no topo dos morros) em Ametista do Sul, bem como a ambientes de turfeira em Iraí, oferecem uma oportunidade ímpar de investigação, pois fornecem dados paleoambientais, paleoclimáticos e paleoecológicos inéditos sobre o Quaternário da Região do Alto Uruguai no Estado do Rio Grande do Sul.

A caracterização quantitativa e qualitativa da matéria orgânica sedimentar nessas áreas úmidas e frequentemente saturadas de água do planalto noroeste do RS contribui para a identificação dos processos físicos, biológicos, químicos e antrópicos atuantes na evolução dos ambientes estudados, bem como de paleoambientes afins do passado geológico, oferecendo subsídios importantes ao estabelecimento de modelos.

Para os sedimentos turfosos de Iraí, os dados acessados com a datação radiocarbônica e demais métodos de investigação permitiram tecer inferências sobre os processos sedimentares associados à gênese e evolução de tais depósitos, além de fornecer informações sobre a composição orgânica e organogeoquímica dos sedimentos, aos quais são popularmente atribuídas propriedades medicinais, não comprovadas cientificamente. A extensão da influência pluvial e fluvial, bem como da interferência antrópica, que atuam ou atuaram diretamente sobre esta área, puderam ser estimadas, além da constatação de influxos possivelmente externos ao ambiente de deposição.

Para o Distrito Mineiro de Ametista do Sul, a datação radiocarbônica realizada desde a base dos testemunhos (onde o sedimento encontra a rocha no topo das jazidas), aliada ao estudo da sucessão ecológica das áreas alagadas associadas a ***gossan*** (estruturas associadas à banhados ou clareiras e localizadas no topo dos morros contendo jazidas de ametista) permitiram conhecer temporalmente os fatores que condicionaram a evolução ambiental da área subsequente à gênese do geodos. O contexto de ambiente isolado e sujeito predominantemente ao regime hidrológico pluvial tornou esse tipo de depósito sedimentar altamente sensível à precipitação e permitiu estimar as variações pluviométricas desde o Holoceno inferior até o Recente para aquela região, além de possibilitar correlações em escalas mais amplas.

Esta tese constitui-se no primeiro estudo envolvendo análise palinofaciológica, organogeoquímica, sedimentar e radiocarbônica de sedimentos quaternários estritamente continentais provenientes da região do planalto noroeste do RS. A correlação entre os resultados obtidos para essa região e mudanças climáticas de escala global que ocorreram durante o Holoceno é também uma tentativa inédita dessa natureza para o Estado do RS.

Na expectativa de que esta investigação ultrapasse os limites acadêmicos e contribua de alguma forma para o desenvolvimento regional, aspira-se que a divulgação dos resultados obtidos permita a elaboração de modelos de predição ambiental que possam servir ao monitoramento dos ecossistemas locais continuamente impactados pelas atividades humanas, contribuindo assim com o planejamento ambiental sustentável de médio e longo prazo para aquela região.

2 HIPÓTESES E JUSTIFICATIVAS

Em virtude da ausência de estudos paleoambientais, paleoclimáticos e paleoecológicos na região do Alto Uruguai, noroeste do planalto sul-rio-grandense, a presente pesquisa procura elucidar a evolução ambiental, climática e ecológica ao longo do Holoceno em ambientes úmidos com características e regimes hidrológicos distintos, localizados nos municípios de Iraí e Ametista do Sul.

O isolamento hidrológico dos alagados de altitude em Ametista do Sul torna este tipo de ambiente sedimentar muito sensível às mudanças climáticas, porque a entrada de água no sistema é subsidiada exclusivamente pela precipitação de chuva, o que pode permitir inferências bastante precisas sobre os índices pluviométricos daquela região ao longo do Holoceno. Por outro lado, em Iraí, o sistema deposicional com características de turfeira sofre influência da pluviosidade, das cheias do Rio Uruguai e do nível do lençol freático. Essa característica de ambiente sedimentar aberto pode dificultar as interpretações paleoclimáticas envolvendo os índices pluviométricos regionais. Logo, uma das principais questões que esta tese procura elucidar envolve as vantagens e restrições que cada ambiente oferece às interpretações de caráter paleoclimático relacionadas às estimativas de pluviosidade.

Em Ametista do Sul, a vegetação circundante ao alagado também deve ter evoluído de forma isolada. A posição da área, isolada no topo de morros, sugere que essa deve ter sido inicialmente inóspita, em termos edáficos e hidrológicos, ao desenvolvimento da vegetação arbórea atualmente observada no local. Em Iraí, por sua vez, a mata ciliar predominante pôde se desenvolver em um ambiente mais favorável do ponto de vista edáfico e hidrológico, em virtude de sua localização em uma área de relevo mais baixo e próxima ao rio. Por conseguinte, outra questão a ser elucidada envolve a evolução sucessional da vegetação ao longo do Holoceno em cada uma das áreas estudadas e como as características do ambiente deposicional e a interferência antrópica influenciaram o registro sedimentar.

Ambos os sistemas deposicionais contêm o registro da evolução ambiental e climática daquela região durante o Holoceno. Em virtude das características distintas dos dois ambientes, a resolução dos dados obtidos poderá se expressar de maneira diversa nesses distintos ambientes sedimentares. Em virtude disso, uma das questões que esta tese busca elucidar é qualificar o potencial que cada um dos ambientes deposicionais tem para fornecer informações refinadas de caráter paleoambiental, paleoclimático e paleoecológico.

O uso de ferramentas de investigação, como as análises palinofaciológicas e organogeoquímicas, em ambientes estritamente continentais, que não sofrem influência direta das variações eustáticas nem têm potencial como rocha geradora, também será testado. Portanto, outra questão a ser averiguada é como os paleoambientes analisados respondem a tais ferramentas e qual o potencial das mesmas no levantamento de dados de caráter paleoambiental, paleoclimático e paleoecológico para tais ambientes.

Uma vez elucidadas as questões de caráter local e regional, o presente trabalho procurará verificar se os resultados de caráter regional têm correlação com registros paleoclimáticos de escala global referidos para o Holoceno e consagrados na literatura, como os eventos Bond e o evento 8.2 ka (abrangido pelos eventos Bond). Logo, uma importante questão a ser respondida diz respeito ao alcance dos dados levantados pelas análises palinofaciológicas e organogeoquímicas nos ambientes investigados. A questão talvez mais interessante a ser elucidada, ou levantada, por este estudo, diz respeito à possibilidade de uma região tão remota no noroeste do Rio Grande do Sul ter guardado em seu registro sedimentar dados que correspondem a acontecimentos de proporções extrarregionais e até mesmo de escala global.

3 OBJETIVOS

- Analisar quantitativa e qualitativamente a matéria orgânica particulada em sedimentos do Quaternário através da integração de dados palinofaciológicos, organogeoquímicos e granulométricos;
- Alocar temporalmente os sedimentos estudados, determinando a idade absoluta de diferentes níveis do pacote sedimentar através de datação radiocarbônica;
- Investigar os processos físicos, biológicos, químicos e antrópicos atuantes na gênese e evolução dos ambientes estudados;
- Acessar dados paleoambientais, paleoclimáticos e paleoecológicos inéditos, avaliando a extensão da influência dos regimes hidrológicos sobre os ambientes estudados e fornecendo subsídios para correlações em escalas mais amplas;
- Comparar os resultados obtidos em banhados naturais associados a ***gossan*** com aqueles resultantes de sedimentos turfosos, estabelecendo tanto parâmetros comuns quanto conjuntos de variáveis importantes ao estabelecimento de modelos preditivos em paleoambientes afins do passado geológico.

4 SÍNTESE DO CONHECIMENTO

4.1 Localização Geográfica e Síntese do Contexto Geológico

Os municípios de Ametista do Sul e Iraí estão localizados na porção noroeste do planalto sul-rio-grandense, região do Alto Uruguai. Essa região, por sua vez, está localizada no sul do Brasil, próxima à divisa entre os estados do Rio Grande do Sul e Santa Catarina (FIG. 1 e 2), sendo constituída por rochas basálticas da Formação Serra Geral e mundialmente conhecida por suas riquezas minerais, tais como os geodos contendo ametista (em Ametista do Sul) e as fontes termais contendo água mineral (em Iraí).

O município de Ametista do Sul (27º21'39"S; 53º10'55"W) tem área total de 93.490 km², altitude média de 505 metros e faz limite ao norte com Iraí; ao sul, com os municípios de Rodeio Bonito e Cristal do Sul; a oeste, com o município de Frederico Westphalen e a leste, com o município de Planalto (FIG. 2 e 3).

O município de Iraí (27º11'37"S; 53º15'02"W) tem área total de 182.185 km², altitude média de 235 metros e faz limite ao norte com o Estado de Santa Catarina; ao sul, com os municípios de Ametista do Sul e Planalto; a oeste, com os municípios de Frederico Westphalen e Vicente Dutra e a leste, com o município de Alpestre (FIG. 2 e 4).

Embora Ametista do Sul e Iraí sejam municípios vizinhos e estejam a uma distância de apenas dezenas de quilômetros um do outro, ocorrem diferenças nos regimes hidrológicos dessas áreas (FIG. 5). Em Iraí, a área de estudo é frequentemente inundada pelas cheias do Rio Uruguai, enquanto que em Ametista o mesmo não acontece, pois o local de estudo está no topo de morros e não sofre influência de outros corpos d’água adjacentes. Enquanto a lâmina d’água do primeiro sofre influência do lençol freático e do nível do rio, o segundo sofre apenas influência do regime de chuvas.

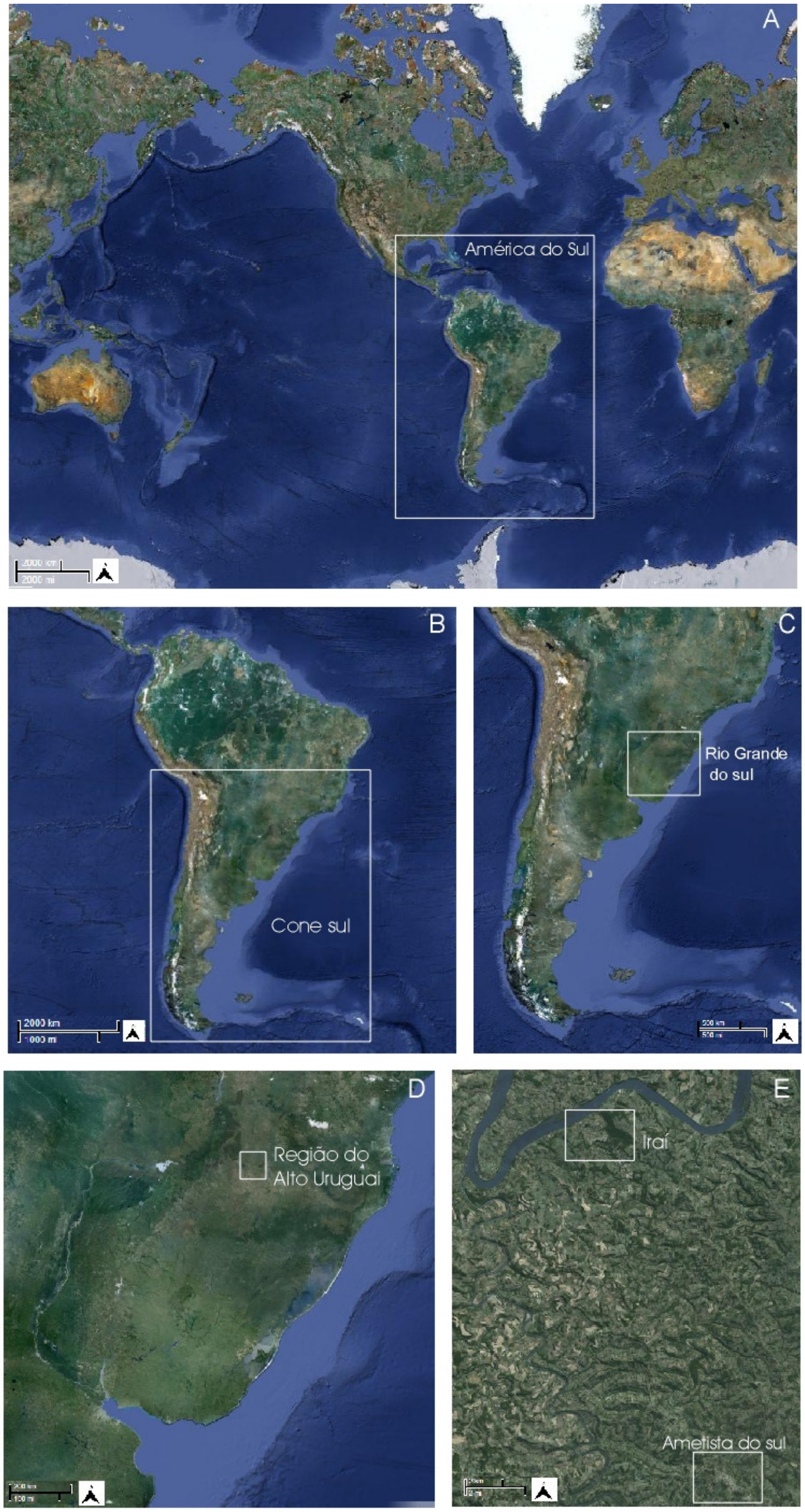


FIGURA 1 - Imagens de satélite obtidas do *Google Earth*. A) América do Sul no contexto global. B) O cone sul da América do Sul. C) O Rio Grande do Sul e sua localização no Cone Sul. D) Localização da Região do Alto Uruguai. E) Localização dos municípios de Ametista do Sul e Iraí.

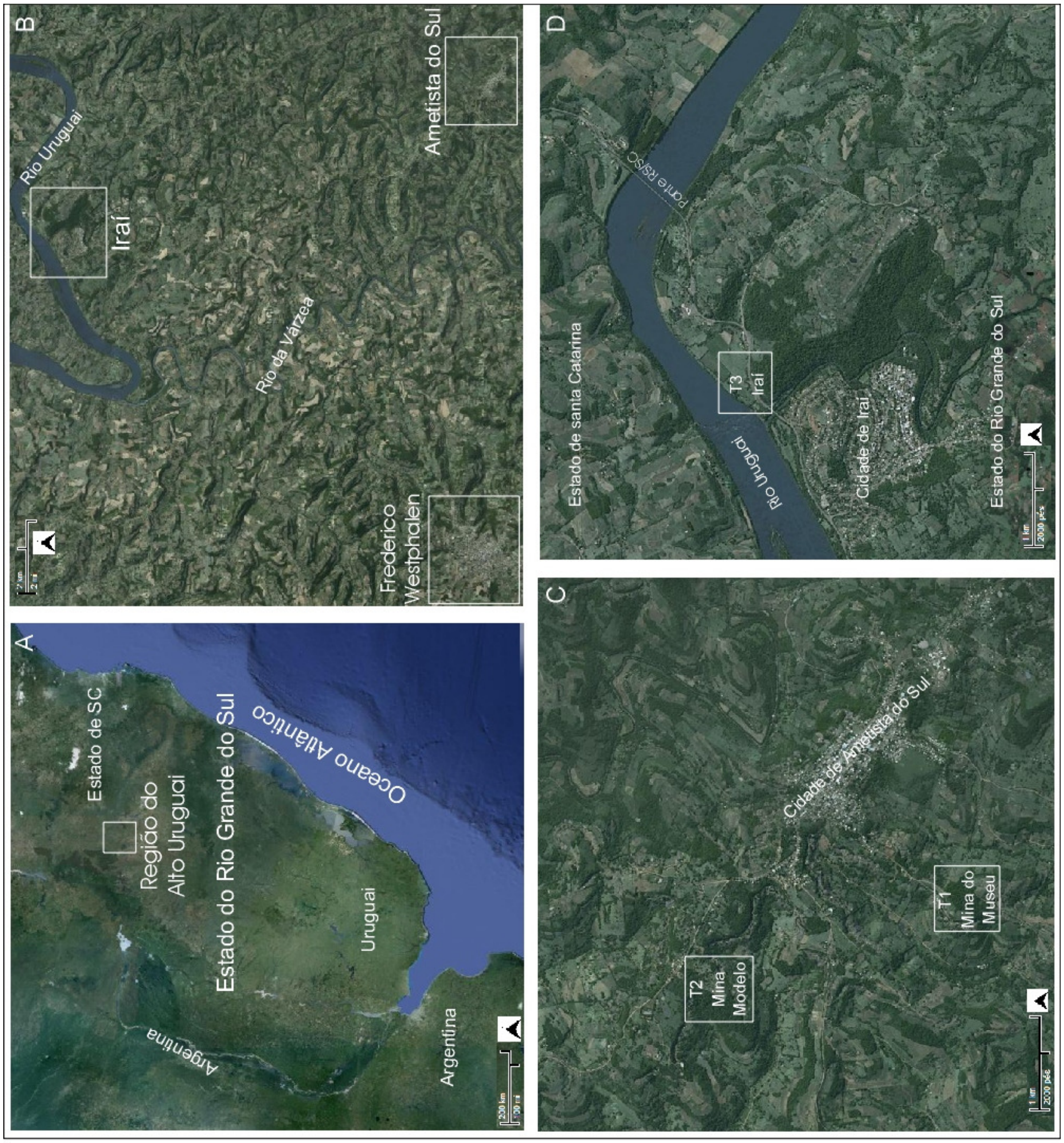


FIGURA 2 - Imagens de satélite obtidas do *Google Earth*. A) Estado do Rio Grande do Sul com a localização da Região do Alto Uruguai, na qual estão inseridas as áreas de estudo. B) Localização dos municípios de Ametista do Sul, Iraí e Frederico Westphalen no contexto da região do Alto Uruguai. C e D) Imagens do município de Ametista do Sul (C) e do município de Iraí (D), com a localização das áreas de estudo.

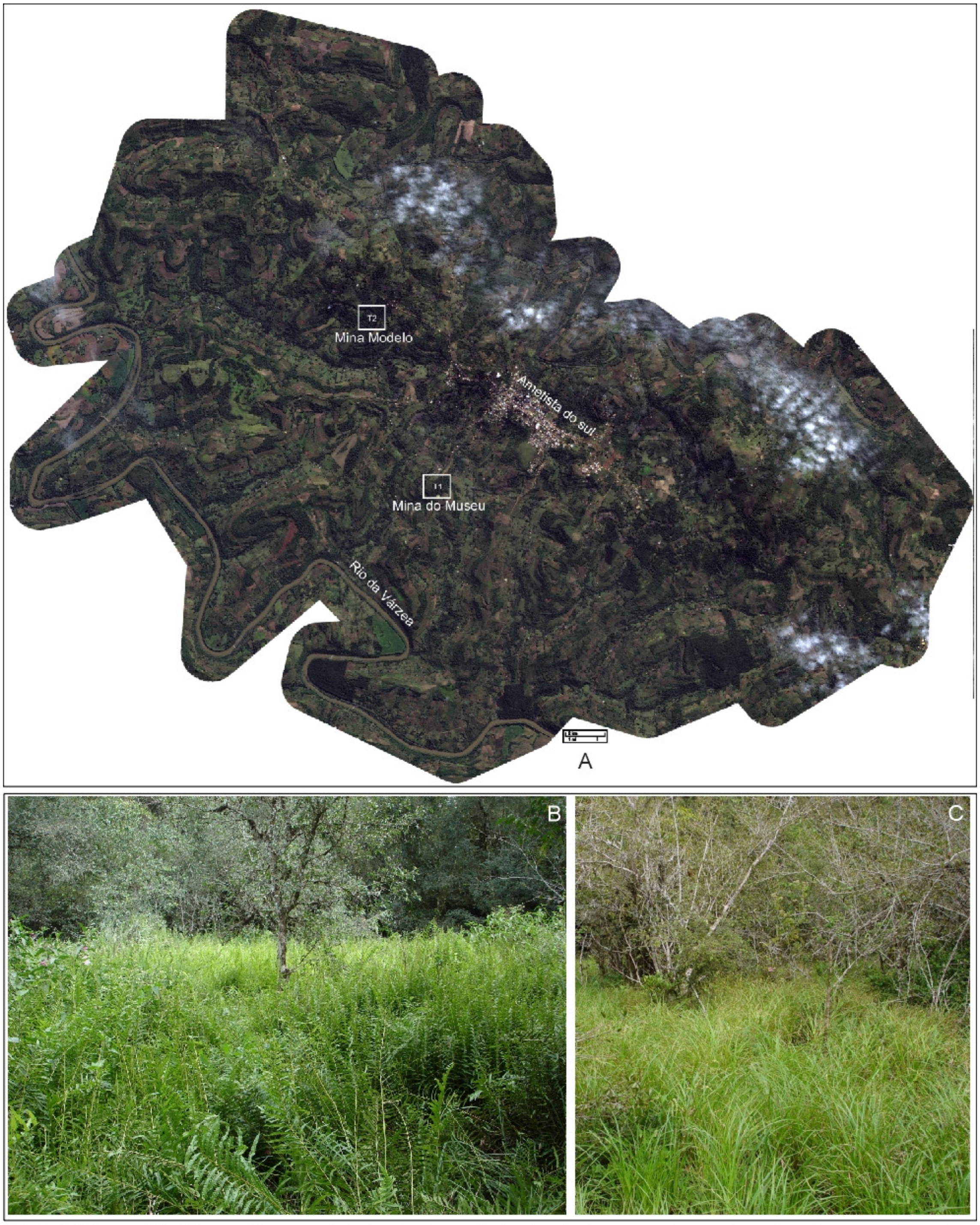


FIGURA 3 - A) Mapa do município de Ametista do Sul com a localização dos pontos de coleta dos testemunhos T1 - Mina do Museu e T2 - Mina Modelo. B) Aspecto Geral da vegetação no entorno do *gossan* da Mina do Museu. C) Aspecto geral da vegetação no entorno do *gossan* da Mina Modelo.

FIGURA 4 - Área de coleta em Iraí. A) Poço de onde é retirada a "lama medicinal". B) Área próxima ao poço com indicação da localização do Rio Uruguai. C) Aspecto da "lama medicinal" que aflora na superfície. D) Imagem mostrando que a "lama medicinal" ocorre em um nível mais baixo do terreno. E) Imagem geral da área onde aflora a "lama".

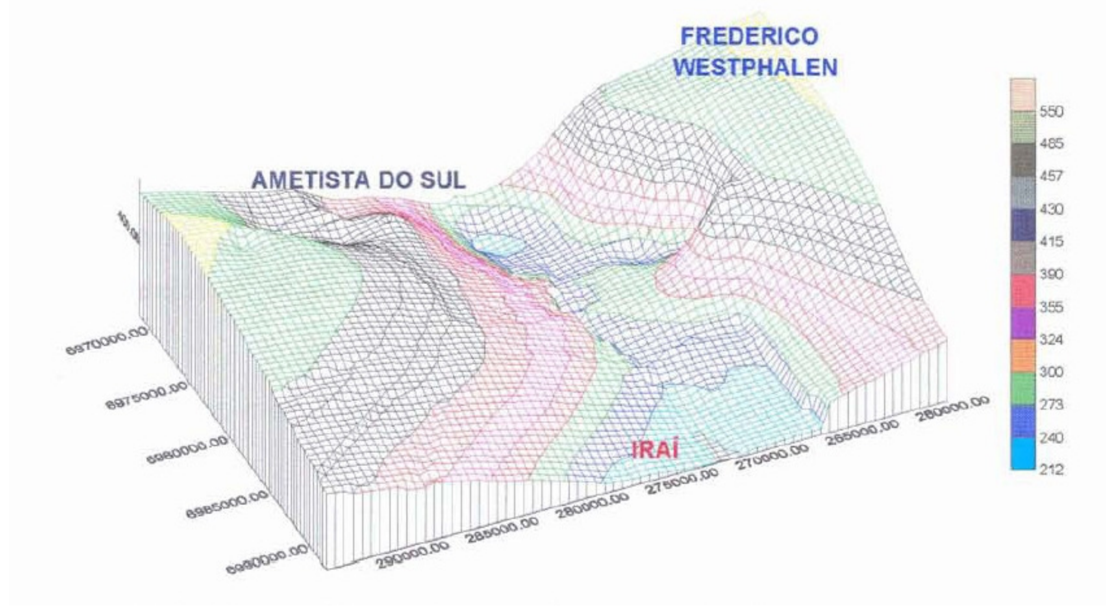


FIGURA 5 – Mapa geológico em 3D, mostrando o relevo que caracteriza o conjunto de derrames, salientando as diferenças de espessura entre eles. As diferentes cores, limitadas por traços horizontais, representam os 12 derrames que ocorrem na região (adaptado de GOMES, 1996, p.23)

Os mais importantes depósitos contendo ametista, em contexto global, são hospedados pelas rochas vulcânicas da Formação Arapey no Uruguai (Artigas) e da Formação Serra Geral no Brasil (Ametista do Sul), dois nomes para a mesma formação que ocorre no topo da Bacia vulcano-sedimentar do Paraná, no sul da América do Sul (DUARTE ***et al***., 2009). A área total, recoberta por rochas vulcânicas, tem cerca de 1.200.000 km^2 e o volume é acima dos 800.000 km^3 com espessura de poucos metros a partir da borda da Bacia do Paraná até mais de 1.700 m no depocentro (ZALÁN ***et al***., 1990; WILDNER ***et al***., 2006), o qual está localizado 300 km ao norte de Ametista do Sul (DUARTE ***et al***., 2009). A maior extensão da Bacia concentra-se no Brasil (1,1 x 10^6 km^2), ocorrendo também na Argentina, Uruguai e Paraguai (Duarte ***et al***., 2009). A província magmática do Paraná é uma das maiores províncias vulcânicas do mundo e consiste principalmente de basalto e andesito basáltico (> 95 vol. %), mas apresenta também cerca de 4 vol. % de riodacito, dacito e riolito (BELLIENI ***et al***., 1994). As lavas foram extrudidas durante o vulcanismo do derrame continental do Cretáceo Inferior, entre 137 e 127 milhões de anos (Ma) atrás (TURNER ***et al***., 1994). Uma datação de zircão proveniente de uma amostra de dacito do topo da pilha estratigráfica resultou em 135 ± 2 Ma (SHRIMP U-Pb, WILDNER ***et al***., 2006). Esse evento magmático de grande magnitude ocorreu em resposta à abertura do Oceano Atlântico Sul pela influência termal da pluma mantélica de Tristão da Cunha. Uma explicação alternativa para o grande derramamento de lava é o aquecimento do manto abaixo do Supercontinente Gondwana (COLTICE ***et al***., 2007). O forte controle tectônico foi produzido em duas principais direções de falhas subverticais: N45º - 65º O e N50º - 70ºS (ZALÁN ***et al***., 1990).

Uma espessa seção de rochas sedimentares, conhecida por Formação Botucatu no Brasil, estende-se logo abaixo da pilha vulcânica e inclui arenitos eólicos do Cretáceo Inferior (SCHERER, 2000), os quais estão em contato direto com os basaltos e constituem, juntamente com outras unidades areníticas, o sistema “Aquífero Guarani”, o maior reservatório de água subterrânea do mundo (ARAÚJO ***et al***., 1999). A espessura total da Bacia vulcano-sedimentar do Paraná é de cerca de 7.500 m no seu depocentro (ZALÁN ***et al***., 1990). A sedimentação na Bacia do Paraná começou no Triássico, seguida por um extenso evento vulcânico no Cretáceo Inferior (DUARTE ***et al***., 2009).

De acordo com o modelo proposto por Duarte ***et al***. (2009), a formação epigenética dos geodos de ametista ocorreu sob baixas temperaturas (<150ºC), seguindo um evento explosivo causado pela circulação ascendente de fluido hidrotermal a partir das rochas sedimentares da Bacia do Paraná. Esse modelo reconhece as condições frágeis do basalto durante a primeira fase de percolação de fluidos e considera importante a argilização do mesmo por ascensão da água quente sob alta pressão. As condições frágeis no basalto estão representadas por fendas hidrotermais e fraturas subhorizontais e subverticais presentes na base de muitos geodos e na zona mineralizada.

Segundo o referido modelo, a alteração hidrotermal do basalto foi causada pelos fluidos provenientes dos arenitos da Formação Botucatu. Uma vez aquecidos pelo calor residual do vulcanismo, esses fluidos ascenderam através de fraturas verticais nos basaltos levando areia em suspensão e depositando sílica nas porções mineralizadas das rochas, formando os geodos e cristalizando os minerais dentro deles (HARTMANN, 2008).

Como resultado desse processo, aqueles locais sem o acréscimo de sílica formaram os vales, enquanto aqueles enriquecidos por sílica formaram os morros de Ametista do Sul (FIG. 6). Dois fatores tornaram os morros mais resistentes do que os vales, são eles: a presença de arenitos agatizados próximos do minério e a injeção de veios de quartzo no basalto, ao redor da jazida. O intemperismo foi mais intenso nas porções do basalto que não tinham injeção de minerais de sílica e, por isso, a erosão não atingiu os morros tão intensamente quanto os vales (HARTMANN, 2008).

Outro registro da atuação dos fluidos hidrotermais é a presença de lagos ou banhados nos locais em que esses alteraram os basaltos e formaram as argilas (basaltos argilizados). Essas estruturas, denominadas ***gossan***, são o registro da passagem de água quente sob alta pressão através das fraturas após formar os geodos de Ametista dentro dos morros. Na vertical, essa porção alterada do basalto tem a forma de uma “chaminé” e o ***gossan*** corresponde, portanto, ao corte horizontal dessa “chaminé” (FIG. 6). Em projeção horizontal, a estrutura tem 100-200 m de largura e localiza-se no topo dos morros mineralizados, podendo ser observada por imagens de satélite (HARTMANN, 2008).

Os ***gossans*** (FIG. 6) têm formas hexagonais, poligonais ou irregulares e não apresentam a vegetação exuberante da região. Há dois tipos principais de ***gossans*** na região de Ametista do Sul, ambos com jazidas de ametista abaixo. O primeiro tipo não consegue sustentar a rica vegetação nativa da região de Ametista do Sul por permanecer longo tempo saturado em água nas épocas chuvosas. O segundo, é rico em argilas do tipo esmectita e é recoberto por banhados perenes. Abaixo desses banhados encontram-se jazidas de geodos de ametista de maior valor comercial. Portanto, essas estruturas (associadas à banhados ou clareiras) no topo do morro assinalam a posição dos geodos com cristais no interior do morro (HARTMANN, 2008).

No presente estudo foram selecionados dois banhados efêmeros, que correspondem ao primeiro tipo de ***gossan*** descrito por Hartmann (2008). Esses banhados são circundados por vegetação nativa e permanecem saturados em água durante os períodos chuvosos, mas secam em épocas de estiagem prolongada. Ambos os corpos d’água estão localizados no topo dos morros e logo abaixo deles existem duas minas de extração de Ametista, denominadas Mina do Museu e Mina Modelo.

Em virtude da proximidade geográfica, os municípios de Ametista do Sul e Irai estão ambos localizados sobre as rochas vulcânicas da Formação Serra Geral. Essa unidade litoestratigráfica também abriga o principal aquífero da região (conhecido como aquífero fraturado), o qual é explotado para consumo humano, agrícola e industrial, além de possuir importância turística pelo registro de vários balneários hidrotermais (FREITAS ***et al***., 2011), especialmente nos municípios de Iraí e Vicente Dutra. As fontes termais naturais presentes na região são provenientes de surgências localizadas em fraturas presentes nas rochas basálticas em vales cuja altitude encontra-se geralmente abaixo de 230 m (FREITAS ***et al***., 2011).

O Sistema Aquífero Guarani, hospedado pelos arenitos porosos da Formação Botucatu, encontra-se sotoposto às rochas vulcânicas da Formação Serra Geral. De acordo com Freitas ***et al***. (2011), as águas termais existentes na região do Alto Uruguai são provenientes da interconexão hidráulica entre o aquífero fraturado da Formação Serra Geral e o Sistema Aquífero Guarani, através de falhamentos de grande magnitude que propiciam a conexão entre esses dois sistemas, resultando em uma mistura de águas e surgências sob a forma de fontes termais. Os tipos hidrogeoquímicos das águas minerais provenientes dessas fontes apresentam altos teores de Cl e SO_4 e, segundo Freitas ***et al***. (2011), sugerem que aquíferos mais profundos, pré-Sistema Guarani, possam estar conectados hidraulicamente com o aquífero fraturado, causando a mistura de águas.

As fontes termais contendo água mineral permitiram a instalação de estações hidrominerais em Iraí, as quais se constituem numa alternativa turística e econômica para a região. De acordo com Freitas ***et al***. (2011), os dados isotópicos de ^{14}C obtidos pelo Consórcio Guarani (OEA/GEF, 2009) determinaram a idade de 8.860 anos antes do presente (AP) para a fonte do Balneário Osvaldo Cruz de Iraí, localizado no centro da cidade. As águas provenientes dessa fonte têm cerca de 33,3ºC, pH de 8,45 e tipo geoquímico caracterizado por águas mistas ($ClSO_4Na$) sulfatadas e cloretadas sódicas.

Além da água mineral, a popular “lama medicinal” é também um dos atrativos dos balneários, sendo frequentemente utilizada em associação aos banhos nas estações termais (HOFF ***et al***., 2005). A “lama medicinal” que ocorre no município de Iraí e região trata-se de um sedimento escuro, de odor característico e rico em matéria orgânica, o qual é extraído de uma área de charco em campo aberto, frequentemente saturada de água por influência do lençol freático e do transbordamento do Rio Uruguai. A lama, utilizada com fins terapêuticos junto aos balneários do município, ainda não teve suas propriedades medicinais comprovadas cientificamente, mas é explorada economicamente, sendo extraída de um poço aberto com finalidade comerciais. Contudo, toda a área circundante ao poço apresenta o mesmo tipo de sedimento, o qual se estende por alguns metros dentro de uma área de aproximadamente um hectare localizada dentro de uma propriedade privada. Essa lama de características peculiares ocorre na superfície dos basaltos, em áreas de relevo mais baixo, sendo possivelmente oriunda da intemperização dos mesmos, e acumula-se em vales onde os sedimentos se misturam aos fragmentos vegetais.

Dados sobre a geologia do local, envolvendo a origem dos sedimentos turfosos, são ainda escassos. Estudos realizados por Hoff ***et al***. (2005) utilizaram dados de espectrorradiometria e processamento digital de imagens ASTER na definição das áreas de ocorrência de argilas (lama medicinal) relacionadas às estações hidrominerais abrangidas no Mapeamento Geológico da Folha de Iraí/Frederico Westphalen, realizado pelo CPRM. As análises foram feitas na localidade de Boa Esperança, Município de Vicente Dutra (vizinho ao Município de Iraí), onde é também comum a ocorrência de tais “lamas medicinais” e indicaram a presença de minerais como montmorilonita, mordenita (grupo da zeolita) e ilita (grupo da sericita).

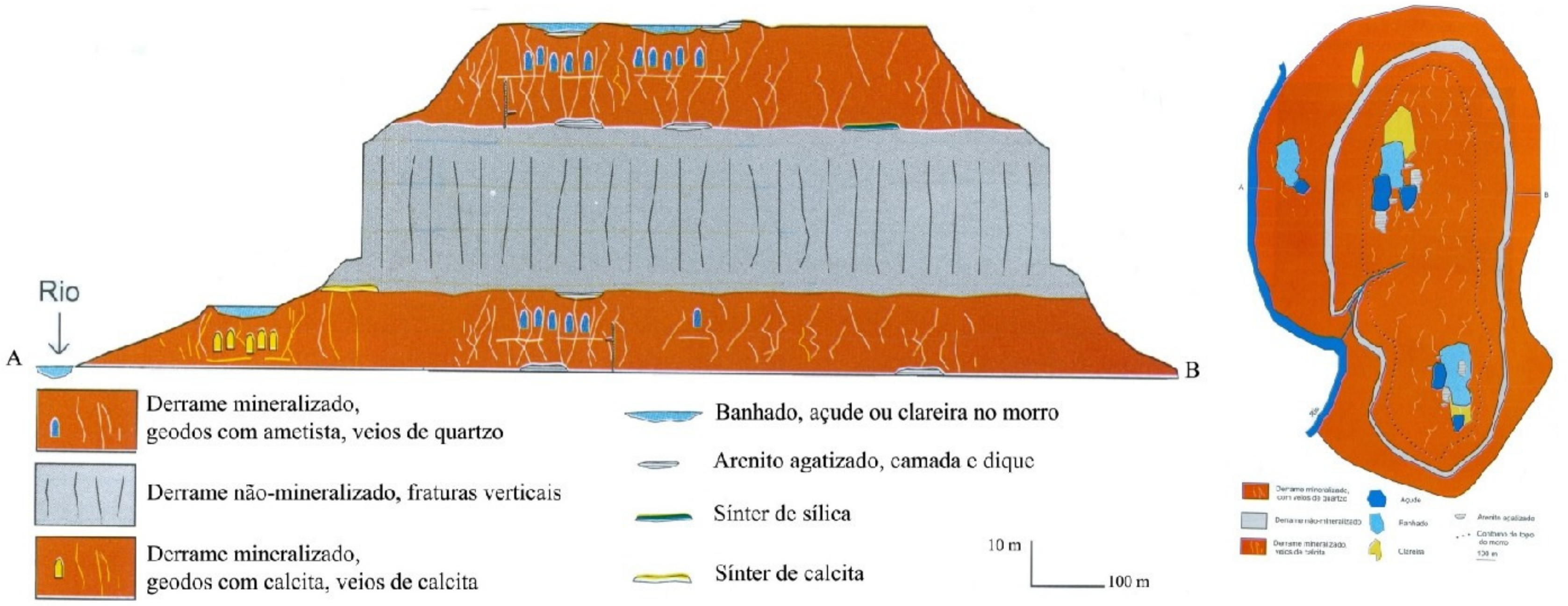


FIGURA 6 - Modelo de um morro mineralizado (visão lateral e apical) contendo geodos de ametista e de calcita, no distrito mineiro de Ametista do Sul (adaptado de Hartmann, 2008, p. 12)

4.2 Palinofácies: conceito e aplicações

O termo “palinofácies” foi introduzido por Combaz (1964) e, posteriormente, outros autores passaram a se referir ao mesmo, acrescentando novas considerações à sua denominação, conceituação e aplicabilidade (BATTEN, 1982a,b; HABIB, 1982; TRAVERSE, 1994), além da proposição de novos termos com significado equivalente como “fácies palinológicas” (HUGHES & MOODY-STUART, 1967) e “palinolitofácies” (Traverse, 1994). Termos estreitamente relacionados com a análise de palinofácies, mas com ênfase organogeoquímica, também foram propostos, como “organopalinologia”, “organopalinofácies” (QUADROS, 1975), e “organofácies” (CORNFORD ***et al***., 1975), esse último voltado à Petrografia Orgânica. Os trabalhos de Tyson (1993, 1995) e Batten (1996) foram especialmente importantes na divulgação do conceito e da aplicabilidade da análise palinofaciológica, tendo sido Tyson (1995) quem introduziu o conceito moderno do termo “palinofácies” (Quadro 1).

Mendonça-Filho (1999) foi pioneiro no Brasil na aplicação e divulgação dos conceitos baseados nos trabalhos de Tyson (1993, 1995), utilizando a análise de palinofácies associada à Geoquímica Orgânica no estudo de rochas sedimentares do Paleozoico Superior da Bacia do Paraná. Posteriormente, estudos baseados em análises palinofaciológicas e organogeoquímicas da matéria orgânica foram amplamente aplicados na investigação de depósitos de origem marinha e epicontinental no Brasil (CARVALHO, 2001, 2005, 2006a, b; MENEZES, 2002; MENDONÇA-FILHO ***et al***., 2002, 2003; MENEZES & MENDONÇA-FILHO, 2004; MEYER ***et al***., 2005, 2006; ARAI ***et al***., 2005; KERN ***et al***., 2005; MENEZES ***et al***., 2005, 2008; SOUZA, 2007; CHAGAS ***et al***., 2009; MEDEANIC & SILVA, 2010), sendo ainda poucos os estudos envolvendo áreas estritamente continentais e que tenham evoluído sem influência de variações eustáticas (MEYER ***et al***., 2010; SILVA ***et al***., 2010).

AUTOR	TERMO	CONCEITO
COMBAZ (1964)	“Palinofácies”	Estudo palinológico da assembleia total de constituintes da matéria orgânica contida em um sedimento após a remoção da matriz sedimentar (mineral) pela acidificação com ácido clorídrico (HCl) e fluorídrico (HF).
HUGHES & MOODY-STUART (1967)	“Fácies Palinológicas”	Todos os constituintes orgânicos após a remoção da matriz mineral. A partir da identificação do querogênio, direcionaram os estudos palinológicos para estudos de paleobotânica.
QUADROS (1975)	“Organopalinologia” “Organopalinofácies”	Implantou as técnicas de microscopia na Petrobrás para investigação da matéria orgânica em rochas sedimentares voltadas para a geoquímica orgânica.
CORNFORD ***et al***. (1975)	“Organofácies”	Sintetizaram o termo como o conjunto de parâmetros organopetrográficos e geoquímicos que caracterizam uma dada associação de sedimentos.
BATTEN (1981; 1982 a, b)	“Palinofácies”	Aplicou o termo não só para estudos paleoambientais e bioestratigráficos, mas também para avaliar as respostas do potencial gerador e maturação térmica em rochas sedimentares.
TRAVERSE (1994)	“Palinofácies”	Utilizava o termo para se referir à concentração local de certos palinomorfos particulares indicativos de um tipo de biofácies.
TRAVERSE (1994)	“Palinolitofacies”	Considerou este termo mais apropriado nos casos em que a pesquisa de palinofácies é voltada a estudos geológicos sobre o paleoambiente de deposição de uma determinada rocha.
HABIB (1982)	“Fácies orgânica definida palinologicamente”	Considerou a palinofácies como um aspecto particular do estudo de fácies orgânica, ou seja, aquela que pode ser determinada pelo estudo palinológico da matéria orgânica.
TYSON (1995)	“Palinofácies”	“Um corpo de sedimento contendo uma assembleia distinta de matéria orgânica palinológica idealizada para refletir um grupo específico de condições ambientais, ou para ser associada com um nível característico do potencial de geração de hidrocarbonetos”.

Quadro 1 – Relação dos autores, termos e conceitos relacionados com a análise de palinofácies.

4.2.1 Matéria Orgânica Particulada

A análise de palinofácies compreende o estudo da fração particulada da matéria orgânica sedimentar, comumente dividida em duas frações - querogênio e betume - o primeiro correspondendo à fração da matéria orgânica que é insolúvel em solventes orgânicos e o segundo, à fração solúvel. Assim sendo, “querogênio” tem sido o termo mais frequentemente utilizado para se referir à matéria orgânica particulada contida em rochas sedimentares. Alguns pesquisadores, contudo, preferem utilizar termos como “matéria orgânica particulada” ou “palinológica”, com significado equivalente ao do querogênio, (MENDONÇA-FILHO ***et al***., 2010).

O termo “matéria orgânica particulada” (MOP) será utilizado neste trabalho em substituição ao termo “querogênio” por tratar-se de material de idade recente (Holoceno), proveniente de sedimentos inconsolidados e cujo grau de maturação não corresponde àquele comumente atribuído ao querogênio proveniente de rochas geradoras mais antigas e com potencial na geração de hidrocarbonetos.

4.2.2 Classificação da Matéria Orgânica Particulada

O objetivo principal da análise palinofaciológica consiste em integrar aspectos da associação de partículas orgânicas, através da identificação dos componentes orgânicos individuais e da classificação dos grupos e subgrupos do querogênio (MENDONÇA-FILHO ***et al***., 2010).

Dependendo do tipo de análise (palinofaciológica, petrográfica, palinológica) diferentes classificações e terminologias são propostas para os grupos e subgrupos da matéria orgânica particulada (MOP). De acordo com Tyson (1993; 1995), uma análise palinofaciológica detalhada da matéria orgânica deve considerar variáveis como origem biológica das partículas, agrupamentos ecologicamente significantes, estado de preservação das partículas (coloração e intensidade da fluorescência), variações morfológicas significantes que podem influenciar seu comportamento hidrodinâmico e caráter geoquímico dos componentes.

A análise palinofaciológica convencional reconhece três grupos principais de MOP - fitoclastos, palinomorfos e matéria orgânica amorfa (MOA) - e baseia-se, fundamentalmente, nos trabalhos de Tyson (1995), Mendonça-Filho (1999) e Mendonça-Filho ***et al***. (2002, 2010).

Mendonça-Filho ***et al.*** (2010) salientam a importância de se utilizar um sistema de classificação dos grupos e subgrupos da MOP capaz de fornecer o máximo de informações sobre as variáveis envolvidas. O sistema de classificação deve também evidenciar os fatores que são mais relevantes para os objetivos do estudo em particular, o que significa fazer uma minuciosa subdivisão de categorias a fim de identificar qualquer variação quantitativa que possa ter relação com os principais controles na distribuição da matéria orgânica, utilizando-os na determinação do significado paleoambiental.

4.2.2.1 Grupo Fitoclasto

O termo “fitoclasto” foi introduzido por Bostick (1971) para descrever todas as partículas de tamanho argila ou areia fina que formam o querogênio derivado de vegetais superiores. Os fitoclastos são partículas facilmente identificáveis em lâminas organopalinológicas e podem exibir autofluorescência, dependendo da constituição química do tecido do qual derivam (MENDONÇA-FILHO ***et al***., 2010). As três grandes divisões ou grupos de fitoclastos (opacos, não-opacos e tecidos cuticulares) distribuem-se em subgrupos com características próprias, os quais, por sua vez, são também subdivididos em categorias diferenciadas (Quadro 2), com a finalidade de refinar ainda mais os dados da análise palinofaciológica.

De acordo com Tyson (1995), a maioria dos fitoclastos é derivada de tecidos ligno-celulósicos de macrófitas terrestres e, muito provavelmente, representam fragmentos de resistência mecânica e tecidos vasculares do xilema secundário (lenho) das gimnospermas e angiospermas arborescentes (mais os tecidos análogos em fetos arbóreos e em plantas vasculares extintas que apresentam crescimento secundário). A preservação desse material é reforçada pela natureza altamente estável, resistente e hidrofóbica da lignina, substância altamente resistente à decomposição, sendo que as estruturas lignificadas mais conspícuas vistas nas preparações organopalinológicas são fragmentos de elementos do xilema, constituído por traqueídes e vasos (TYSON, 1995).

Particularmente no presente trabalho, as hifas de fungo não foram alocadas no grupo dos fitoclastos, mas contadas à parte e posteriormente somadas à matéria orgânica particulada total. Isso é devido a dois motivos principais: primeiro, porque as hifas de fungo, diferentemente dos fitoclastos, não são partículas vegetais e segundo, porque a presença desse tipo de partícula em sedimentos inconsolidados do Quaternário pode corresponder a material recente, originado em fase posterior à deposição dos sedimentos.

Uma nova categoria de classificação foi atribuída ao subgrupo das cutículas durante o desenvolvimento da presente pesquisa, em virtude da ocorrência de um número expressivo dessas partículas com restos subcuticulares anexados. Assim sendo, a categoria das “cutículas associadas” foi incorporada à classificação geral para se referir àquelas cutículas associadas aos fragmentos de epiderme ou de mesófilo foliar. A presença de tais elementos associados indica boa preservação, uma vez que os processos de degradação e decomposição não foram eficientes o suficiente para desagregar todos os elementos foliares.

Com relação aos demais elementos do grupo fitoclasto, a classificação geral segue aquela convencionalmente adotada por Mendonça-Filho ***et al***. (2010).

4.2.2.2 Grupo Palinomorfo

O termo palinomorfo refere-se a todo componente de parede orgânica (esporopolenina, quintina, dinosporina) resistente ao ataque com ácido clorídrico e fluorídrico, subdividindo-se em esporomorfos terrestres, microplâncton de parede orgânica e zoomorfos (MENDONÇA-FILHO ***et al***., 2010).

Os esporomorfos terrestres são estruturas reprodutivas muito resistentes à degradação devido à inércia química da sua parede externa (exina), a qual é formada por esporopolenina (PLÁ JÚNIOR ***et al***., 2006). Esse subgrupo está representado pelos esporos de briófitas e pelos grãos de pólen de gimnospermas e angiospermas (Quadro 3).

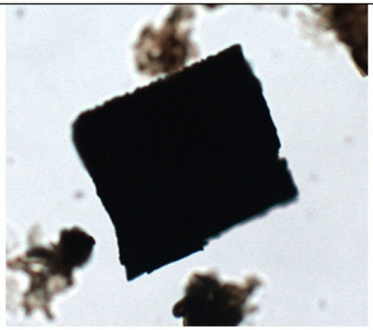
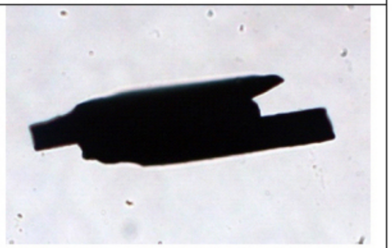
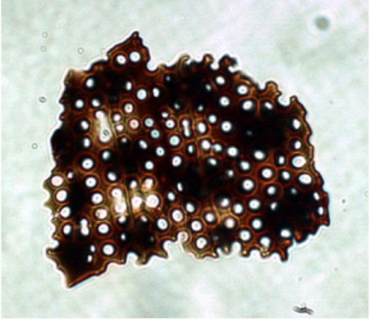
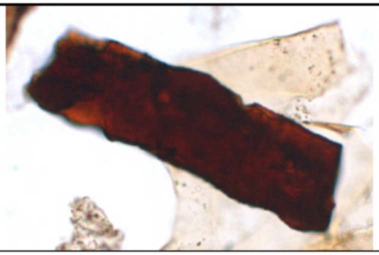
O subgrupo microplâncton está representado por algas unicelulares e esporos de algas com parede orgânica (esporomorfos algálicos). Os elementos algálicos são bons indicadores de salinidade, profundidade, pH e estado trófico tanto de ambientes aquáticos como de ambientes subjacentes à lâmina d’água ou submetidos a alagamentos periódicos. Em análises palinofaciológicas convencionais, envolvendo seções marinhas, a presença de prasinófitas, acritarcos e dinoflagelados é baseada em uma série de parâmetros bem conhecidos e que permitem interpretações bastante apuradas. No presente trabalho, contudo, apenas o microplâncton dulciaquícola está presente, uma vez que os sedimentos têm origem exclusivamente continental, motivo pelo qual são abordados apenas os grupos de algas mais freqüentes nesse tipo de ambiente.

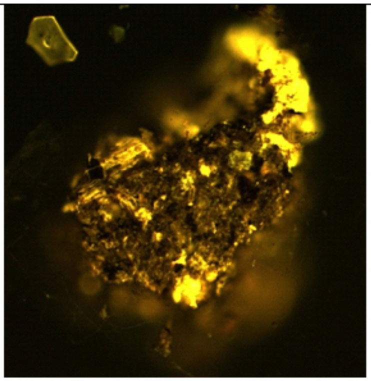
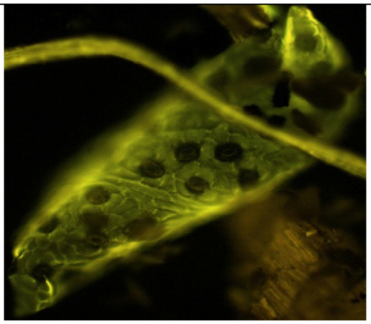
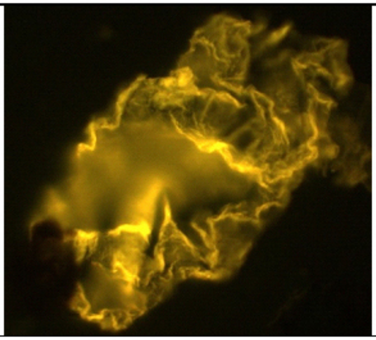
O subgrupo zoomorfo compreende palinoforaminíferos, escolecodontes e quitinozoários, organismos predominantemente marinhos, presentes em depósitos sedimentares antigos, motivo pelo qual não será dado maior detalhamento ao mesmo no presente trabalho, que investiga sedimentos continentais do Quaternário.

4.2.2.3 Grupo Produto Amorfo (PA)

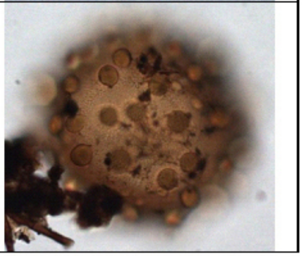
De acordo com Mendonça-Filho ***et al***. (2011, p 43), "o grupo amorfo consiste de todos os componentes de partículas orgânicas que aparecem sem estrutura na escala de microscopia de luz; incluindo matéria orgânica amorfa fitoplanctônica (tradicionalmente referido como "MOA"), bactérias derivadas de matéria orgânica amorfa (também tradicionalmente designadas por "MOA"), resinas de plantas superiores, e os produtos amorfos da diagênese dos tecidos de macrófitas".

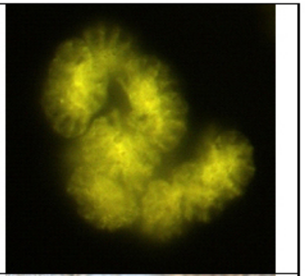
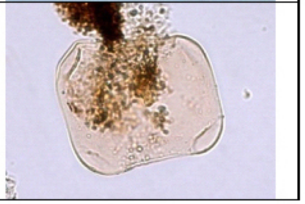
No presente trabalho, toda MO sem forma e sem arestas, sem contornos angulares ou qualquer tipo de característica que permita a sua classificação em qualquer outro grupo de MOP foi classificada como produto amorfo (PA). Tais partículas são mais provavelmente derivadas de algas ou de restos de plantas terrestres em um estado avançado de degradação, o que pode ser resultado tanto de ação microbiana como de outros processos de transformação da MOP atuantes nos ambientes deposicionais estudados, ou de ambos os processos simultaneamente (Quadro 4). O "produto amorfo" foi escolhido por causa da origem exclusivamente continental dos sedimentos analisados para evitar conflitos com a matéria orgânica amorfa (MOA), comumente relacionada a ambientes marinhos ou sistemas deposicionais que sofrem a influência das variações eustáticas.

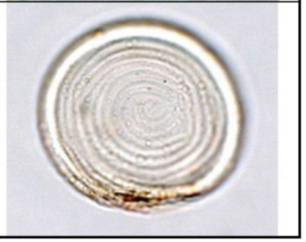
	CARACTERÍSTICAS	SUBD.	DESCRIÇÃO GERAL	IMAGEM	ORIGEM
FITOCLASTOS OPACOS	Partículas de coloração preta, inteiramente opacas, inclusive em suas porções marginais (sob em luz branca transmitida). Não exibem autofluorescência	Equidimensional	Forma quadrática. Margens angulares a subangulares. Contornos nítidos. Razão comprimento/largura da partícula < 2. Sem bioestrutura interna.		Fragmentos de lenho derivados de processos de maturação térmica, oxidação, ou pirólise (neste caso, denomina-se *Charcoal*).
		Alongado	Forma alongada. Margens angulares a subangulares. Contornos nítidos. Razão comprimento/largura da partícula >2. Podem ocasionalmente apresentar bioestrutura interna, como perfurações.		
FITOCLASTOS NÃO-OPACOS (NO)	Partículas translúcidas, de coloração variando do amarelo claro ao marrom escuro (sob luz branca transmitida). Podem exibir autofluorescência.	Bioestruturado	Coloração varia de marrom claro a escuro. Forma equidimensional a retangular. De acordo com a estrutura botânica interna que apresentam, podem ser divididos em: estriados, listrados, bandados e perfurados.		Fragmentos de xilema primário ou secundário de macrófitas terrestres, com estrutura botânica característica (geralmente células traqueídicas em vista radial ou tangencial)
		Não-bioestruturado	Coloração varia de marrom-claro a escuro. Forma variável. Não apresentam estrutura botânica interna. De acordo com o grau de preservação, podem ser divididos em degradados e não-degradados.		Fragmentos de tecidos lenhosos ou subcuticulares de macrófitas terrestres, sem estrutura botânica característica.

		Amorfizado		Coloração marrom claro a escuro. Forma irregular, com aparência de MOA. Exibem fluorescência e podem apresentar inclusões.		Derivado de tecidos vegetais em decomposição.
		Tecidos cuticulares	Cutícula	Coloração amarelo pálido a marrom claro. Forma de lâminas delgadas, com contornos nítidos. Podem apresentar estruturas celulares conspícuas, refletindo a epiderme original. Ocasionalmente, podem ocorrer associadas com restos subcuticulares anexados.		Camada mais externa da folha vegetal. Também presente na parte aérea da epiderme em plantas que não apresentam crescimento secundário.
			Membrana	Coloração amarelo pálido, com aparência "desbotada" e transparente. Delgadas. Forma irregular. Aspecto "amarrotado".		Origem possivelmente cuticular.

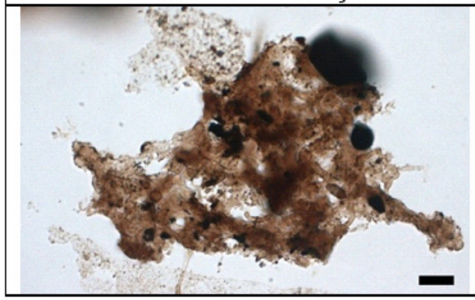
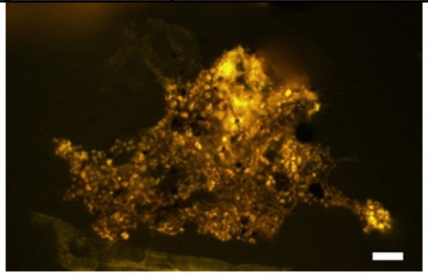
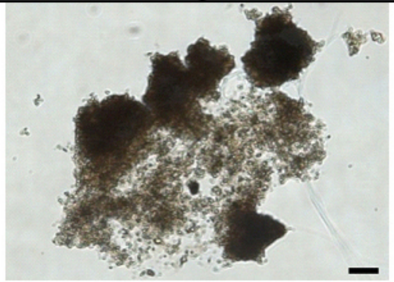
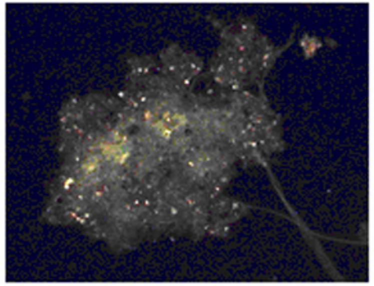
Quadro 2 – Características, descrição e origem dos subgrupos do Grupo Fitoclasto.

GRUPO	SUBG.	DESCRIÇÃO	DIVISÃO	SUBDIVISÃO	IMAGEM
PALINOMORFOS	Esporomorfos	Termo coletivo utilizado para todos os esporomorfos derivados de macrófitas terrestres.	Esporos de briófitas e pteridófitas	Simples	
				Ornamentados	
			Grãos de pólen de gimnospermas e angiospermas	Simples	
				Ornamentados	

	Microplâncton de parede orgânica	Termo coletivo utilizado para todos os esporomorfos derivados de algas.	Divisão Chlorophyta	*Botryococcus*	Não apresenta subdivisão	
				Zignematáceas	*Spirogyra*	
					Debaria	
					Mougeotia	

					Zignema	
				Desmidiáceas	*Desmidia*	
	Incertae sedis		*Pseudoschizaea*		Não apresenta subdivisão	

QUADRO 3 – Classificação e descrição do Grupo Palinomorfo.

PRODUTO AMORFO (PA)			
MO sem forma e sem arestas, sem contornos angulares, derivadas de algas ou de restos de plantas terrestres em um estado avançado de degradação e proveniente de sedimentos de origem exclusivamente continental			
			

QUADRO 4 – Descrição e imagem do Grupo Produto Amorfo.

4.3 Contexto Paleoclimático

Ao longo do desenvolvimento desta tese, novos conhecimentos foram sendo obtidos e relacionados com os dados levantados, acrescentando novas discussões às interpretações inicialmente geradas pelas análises palinofaciológicas e organogeoquímicas, motivo pelo qual este capítulo sobre paleoclima é inserido aqui.

O Holoceno afigura-se como o período interglacial quente mais estável de todos os demais períodos anteriores do ciclo glacial do Quaternário e não há dúvida de que as condições uniformes desse período promoveram o rápido crescimento da agricultura e da civilização que se seguiu ao final da última idade do gelo (PRESS *et al*., 2006). Embora o clima do Holoceno (11.500 anos AP até o Recente) tenha sustentado o crescimento e desenvolvimento da sociedade moderna, há surpreendentemente pouco conhecimento sistemático sobre a variabilidade do clima durante esse período (MAYEWSKY *et al*., 2004).

Diferentes autores têm caracterizado alguns fatores como definitivos na caracterização climática do Holoceno, os quais encontram-se estreitamente relacionados com variações de escala global, envolvendo os mecanismos de circulação atmosférica e oceânica da Terra (KOBASHI *et al*., 2007; THOMAS *et al*., 2007), e de escala astronômica, envolvendo variações na atividade solar (BOND *et al*., 2001).

Conhecer essas variações e compreender quais mecanismos atuam sobre as mesmas, determinar os principais eventos de escala global e sua periodicidade, bem como analisar a maneira como a interação de fatores distintos se manifesta climaticamente em diferentes partes do globo tem sido um dos maiores desafios dos quaternaristas dedicados ao Holoceno.

É sabido que vastas regiões da Terra experimentaram mudanças quase síncronas das temperaturas glaciais para interglaciais durante curtos intervalos de tempo e que a circulação atmosférica pode se reorganizar de modo muito rápido, invertendo o sistema do clima de um estado para outro num intervalo menor que o tempo de vida de uma pessoa (PRESS *et al*., 2006). Isso aumenta a expectativa de que as mudanças climáticas globais em curso, induzidas ou não pela ação humana, possam envolver inversões abruptas para um novo e desconhecido estado climático, para o qual nossa civilização está mal preparada.

Para avaliar o potencial das mudanças globais induzidas por variações no mecanismo oceano/atmosfera, e também pela ação humana, precisamos conhecer como o sistema clima funciona e o quanto ele varia enquanto resultado de um processo natural.

4.3.1 Mecanismo oceano/atmosfera de resfriamento e aquecimento climático dos períodos glaciais e interglaciais

Parte da energia solar recebida nos trópicos é transportada para os polos pelas correntes oceânicas através de um mecanismo conhecido por circulação termohalina (*Thermohaline Circulation* - THC). Esse movimento é causado pelas diferenças de temperatura e salinidade das águas oceânicas superficiais e profundas e forma uma espécie de “esteira transportadora” que distribui o calor entre as regiões tropicais e polares. A corrente do Golfo, por exemplo, transporta a água quente do oceano Oceano Atlântico tropical para o Atlântico Norte. À medida que as águas tropicais dirigem-se para o norte, vão perdendo calor e tornando-se mais frias e densas. Quando isso acontece, a densidade da água força o seu mergulho para o fundo do oceano e o mecanismo da esteira se estabelece, arrastando as águas tropicais para o norte e retornando as águas mais frias para o equador (fenômeno também conhecido como *Atlantic Meridional Overturning Circulation* - AMOC). Se o mergulho dessa água for impedido, o abastecimento de calor para o norte acaba sendo interrompido e as temperaturas do planeta diminuem bruscamente. Quando a camada de gelo que cobria o Atlântico Norte derreteu, uma quantidade enorme de água doce foi liberada no mar, o que provocou a diluição da salinidade e consequente redução da densidade da água, resultando na interrupção do mecanismo da esteira transportadora e no resfriamento do clima. Juntamente com essas imensas descargas de água doce, os *icebergs* resultantes do degelo descarregaram enormes quantidades de detritos glaciais (mais bem conhecidos como *ice-rafted debris* - IRD) na sedimentação marinha profunda. Após o degelo, o mecanismo voltaria a funcionar, levando novamente ao aquecimento daquelas regiões mais frias (ARAGÃO, 2009). Esses eventos de resfriamento e aquecimento promoveram, respectivamente, a expansão e retração das calotas polares durante os últimos ciclos glaciais, quando a Terra esteve submetida a fortes variações abruptas do clima em escala milenar relacionadas ao acoplamento dos sistemas oceano/atmosfera.

O fenômeno de redução ou desativamento da esteira transportadora tem extrema significância climática, pois resulta no colapso da AMOC, e isso afeta toda a distribuição de calor no Atlântico, resultando em flutuações na temperatura superfícial marinha (*Sea Surface Temperature* - SST) com consequente aumento do gradiente térmico entre os trópicos e as zonas de altas latitudes, sobretudo do Hemisfério Norte (HEMMING, 2004; RAHMSTORF, 2002; RUDIMANN, 2008). A quebra do gradiente de densidade, causado pela liberação de água doce, diminui a formação das águas profundas no Atlântico Norte (*North Atlantic Deep Water* - NAD) responsáveis pelo transporte das águas frias do norte para o sul (HEMMING, 2004). Em consequência disso, ocorre o resfriamento do Atlântico Norte e o aquecimento do Atlântico Sul, produzindo um efeito “gangorra” inter-hemisférico da SST, mais comumente conhecido na literatura pelo termo em inglês *see-saw effect* (BARKER *et al*., 2009; BROECKER, 1998; TIMMERMAN *et al*., 2007; CHIESSI *et al*., 2008; McMANUS *et al*., 2004; VELLINGA & WOOD, 2002). Esse padrão foi observado em diversos registros paleoclimáticos, tanto na comparação entre os testemunhos de gelo da Groenlândia (NGRIP - *North Greenland Ice Core Project* e GRIP - *Greenland Ice Core Project*) com os da Antártica (Vostok e Byrd) como nas comparações entre as SST do Atlântico Sul e Norte (BOND *et al*., 1995; BLUNIER & BROOK, 2001; JAESCHKE *et al*., 2007; CHIESSI *et al*., 2008) e em diversos modelos computacionais de circulação oceânica-atmosférica (CLAUSSEN *et al*., 2003). O resfriamento das águas do Atlântico Norte inevitavelmente se propaga para a atmosfera e resulta no deslocamento da zona de convergência intertropical (*Intertropical Convergence Zone* - ITCZ) para o sul, onde o oceano estaria mais quente (CHIANG & KOUTAVAS, 2004). O posicionamento mais ao sul da ITCZ condiciona o aumento da convergência de umidade dos oceanos para o continente, resultando no aumento da precipitação monçônica de verão (*South American Summer Monsoon* - SASM) nos trópicos do Hemisfério Sul (CRUZ *et al*., 2005a, 2009a; WANG *et al*., 2004, 2007). Durante os eventos milenares abruptos frios, o aumento das precipitações de monções é pervasivo em todo o território sul-americano ao sul da linha do Equador, enquanto tem-se forte decréscimo de precipitação no hemisfério oposto (HAUG *et al*., 2001; FLEITMANN *et al*., 2003; WANG *et al*., 2004; 2006; CRUZ *et al*., 2005).

4.3.2 O evento 8.2 ka

Na região da Baía de Hudson, no extremo leste da América do Norte, havia dois grandes lagos glaciais sustentados por uma barragem natural (BARBER *et al*., 1999; LEVERINGTON *et al*., 2002), que teria se rompido cerca de 8.200 anos atrás. Esse evento acabou liberando uma enorme quantidade de água doce no oceano, dando origem a uma anomalia de salinidade no Atlântico Norte que transformou a circulação termohalina e teve um impacto significativo sobre o clima global; esse período veio a ser conhecido como o “evento 8.2 ka” (KOBASHI *et al*., 2007; THOMAS *et al*., 2007).

O evento 8.2 ka (ka = mil anos) foi reconhecido pela primeira vez em testemunhos de gelo da Groenlândia (NGRIP, 2004), nos quais foram encontradas evidências de temperaturas baixas e extensa acumulação de neve (ALLEY *et al*., 1997; KOBASHI *et al*., 2007; THOMAS *et al*., 2007).

Existem evidências de que o evento 8.2 ka teria causado uma queda de temperatura de cerca de 2ºC na Europa (WICK & TINNER, 1997), um pronunciado resfriamento climático entre 8.9-8.3 ka nos EUA (HU *et al*., 1999), alterações significativas no nível do mar na Noruega (KLITGAARD-KRISTENSEN *et al*., 1998), condições extremamente secas na borda sudeste do Saara (GASSE & VAN CAMPO, 1994), avanços glaciais nos alpes do sul da Nova Zelândia (SALINGER & McGLONE, 1990) e um aumento da precipitação e/ou uma diminuição da temperatura na América do Sul e no Atlântico Sul central (DOUGLASS *et al*., 2005; LJUNG *et al*., 2008), bem como o abandono dos locais de habitação e migrações de seres humanos que viviam em parte da Europa e do Oriente Médio (GONZALEZ-SAMPERIZ *et al*., 2009).

Testemunhos da Groenlândia (ALLEY *et al*., 1997) e África (THOMPSON *et al*., 2002) sugerem que o evento 8.2 ka foi global em extensão. Apesar de esse evento estar bem definido, os seus efeitos no Brasil ainda não são bem conhecidos, porque os registros paleoclimáticos regionais em escala de centenas de anos são ainda escassos e associados quase que exclusivamente ao estudo de espeleotemas (CHENG *et al*., 2009; STRÍKES *et al*., 2011). Outros dados *proxy* para o mesmo período de tempo existem (CORDEIRO *et al*., 2008; SALGADO-LABOURIAU *et al*., 1998; BEHLING, 1998; BARBERI *et al*., 2000; CRUZ *et al*., 2005), mas não foram correlacionados com o evento 8.2 ka, possivelmente devido às pequenas diferenças nas idades obtidas através de datações de ^{14}C, calibradas e não-calibradas, ou através de interpolações de idades.

Recentemente, Sallum *et al*. (2012), a partir de uma análise *multi-proxy* envolvendo composição granulométrica, mineralógica, geoquímica e istópica dos sedimentos provenientes de uma paleolagoa no sudeste do Brasil, encontraram uma relação com o evento 8.2 ka e as elevadas taxas de sedimentação (10 cm/ano) registradas no período entre 8.385 e 8.375 anos AP, as quais seriam consequência do aumento da precipitação. Outras oscilações anormais de escala decadal teriam ocorrido nos sedimentos entre 9.400 e 7.500 anos AP e foram correlacionadas a eventos naturais de longo e curto prazo. De acordo com Sallum *et al*. (2012), as condições mais frias associadas ao evento 8.2 ka parecem ter afetado o equilíbrio ambiental na América do Sul e intensificado a monção de verão sul-americana (SASM), afetando significativamente as condições ambientais na zona costeira no sudeste brasileiro.

4.3.3 Os eventos Bond

A partir de registros da temperatura superficial marinha (SST) do Atlântico Norte baseados em indicadores paleoambientais *multi-proxy*, tais como variações IRD (detritos glaciais) e variações de $\delta^{18}O$ e $\delta^{13}C$ em testas de foraminíferos bentônicos e planctônicos, Bond *et al*. (1997) foram capazes de estimar eventos de resfriamento abrupto no Atlântico Norte durante o Holoceno, a exemplo dos eventos Heinrich do Pleistoceno (HEINRICH, 1988), porém de amplitude e duração menores. Dentre os indicadores paleoclimáticos e paleoambientais utilizados, o que se mostrou mais eficaz na determinação e na delimitação dos eventos foi o índice de IRD, cujos picos de concentração foram determinantes na delimitação dos períodos de resfriamento abrupto que mais tarde vieram a ser referidos na literatura como “eventos Bond”.

De maneira geral, os eventos Bond apresentam uma periodicidade média de 1500 anos (BOND *et al*., 1997; BOND *et al*., 2001) comumente observada em registros de SST de zonas tropicais e subtropicais do Pacífico e Atlântico Norte (ISONO *et al*., 2009). Bond *et al*. (2001) também argumentam que a maior parte das oscilações de temperatura na superfície do mar no Atlântico Norte estão provavelmente ligadas à atividade solar. Por isso, a maioria dos eventos Bond (9,4, 8,2, 7,4, 5,4, 2,7 e 2,3 ka AP) coincidem com períodos de baixa atividade solar. Bond *et al*. (2001) chegaram a esta constatação ao compararem a curva de HSG (*hematite stained grain*), obtida através das análises de IRD, com a curva de variabilidade solar, estimada pela variação de $\delta^{14}C$ em anéis de crescimento de árvores, e relacionarem esses dados com existência de um acoplamento entre as flutuações de SST do Atlântico Norte e os períodos de redução da atividade solar.

Os eventos Bond têm sido utilizados para correlacionar as alterações na intensidade da circulação termohalina atlântica com as flutuações na temperatura da superfície do mar e com as anomalias de precipitação registradas na Ásia e na América do Sul (FLEITMANN *et al*., 2003; WANG *et al*., 2005; HAUG *et al*., 2001; BAKER *et al*., 2001, 2005; CRUZ *et al*., 2005).

Da mesma forma que o evento 8.2 ka, as correlações de anomalias climáticas no Brasil com os eventos Bond ainda são tímidas e, na maior parte das vezes, restritas aos registros de isótopos de oxigênio obtidos de espeleotemas. Isso se deve provavelmente a pequenos desalinhamentos temporais entre os registros radiométricos que podem ser atribuídos a incertezas geradas pelos dados geocronológicos onde a resolução é menor e definida por poucas datações de ^{14}C.

Recentemente, Stríkes (2011) e Stríkes *et al*. (2011), baseados no estudo de isótopos de oxigênio obtidos de espeleotemas mineiros (1.3-10.2 ka AP), demonstraram que as quedas bruscas nos valores de $\delta^{18}O$ estão associadas com o aumento da precipitação no centro-leste do Brasil e correspondem a períodos anormalmente frios no Atlântico Norte durante os eventos Bond. A partir da comparação entre os registros isotópicos do norte de Minas Gerais com os demais registros paleoclimáticos relacionados a variações de disponibilidade hídrica nos trópicos da América do Sul, Stríkes *et al*. (2011) afirmam ser possível verificar uma forte relação positiva entre as anomalias de precipitação e os eventos Bond, uma vez que os episódios de resfriamento registrados nas zonas de altas latitudes do Hemisfério Norte promoveram significativas alterações na circulação monçônica da América do Sul. Em resumo, o aquecimento do Atlântico tropical sul em relação ao Atlântico tropical norte e o consequente deslocamento para sul da zona de convergência intertropical aumenta a convergência de umidade do Atlântico tropical para o interior da bacia Amazônica, o que intensifica as chuvas das monções de verão (SASM) em boa parte do continente sul-americano (STRÍKES, 2011; STRÍKES *et al*., 2011). O acoplamento da temperatura superficial marinha (SST) do Atlântico tropical na costa do nordeste brasileiro sugere que as variações da circulação termohalina seriam um dos fatores responsáveis pela geração da variabilidade climática nos trópicos (STRÍKES *et al*., 2011).

Stríkes *et al.* (2011) também observam que, no decorrer do Holoceno, o tempo de duração dos eventos abruptos de pluviosidade é mais longo durante o Holoceno inferior e médio e mais curto durante o Holoceno superior. Essa relação sugere, de acordo com Carlson *et al*. (2008), mudanças das condições de contorno do clima no transcorrer do Holoceno possivelmente relacionadas à diminuição da cobertura de gelo no Hemisfério Norte a partir de sete mil anos, levando à desativação da circulação termohalina que caracteriza os eventos Bond no Hemisfério Norte.

A possível expressão global dos eventos Bond motiva estudos paleoclimáticos de alta resolução baseados em indicadores paleoclimáticos e paleoambientais que estão direta ou indiretamente relacionados às variações da paleopluviosidade nas zonas tropicais e subtropicais (STRÍKES, 2011).

5 MATERIAIS E MÉTODOS

5.1 Etapas de campo

A fase de seleção e reconhecimento dos pontos de coleta foi concluída no segundo semestre de 2009. Em Ametista do Sul, os pontos de coleta foram selecionados inicialmente com o auxílio de mapas gerados por satélite (e.g. *Google Earth*) e com base no isolamento em relação à vegetação arbórea nativa circundante. A entrevista com moradores locais foi imprescindível para a confirmação da natureza espontânea da vegetação circundante e das áreas de clareira selecionadas (correspondentes a *gossan*). As expedições de campo contaram com o apoio da Cooperativa de Garimpeiros do Médio Alto Uruguai (COGAMAI) e da Prefeitura Municipal de Ametista do Sul. Para a coleta dos testemunhos de sondagem foram utilizados tubos de PVC de 7 cm de diâmetro e de 1,5 a 2 metros de comprimento (FIG. 7, A, C, D). Os testemunhos de sondagem foram identificados como T1 - Mina do Museu (27º22.373'S x 53º11.901'W) e T2 - Mina Modelo (27º19.536'S x 53º13.579'W). Em Iraí, o ponto de coleta está localizado nas proximidades do poço de onde é retirada a "lama medicinal" (FIG. 7, B). As expedições de campo contaram com o apoio da Prefeitura Municipal de Iraí. Para a coleta dos testemunhos de sondagem foram utilizados tubos de alumínio de 10 cm de diâmetro e de até 2 m de comprimento. O testemunho de sondagem foi identificado como T3 - Iraí (27°10'822" S x 53°14'980" W).

FIGURA 7 - Atividades de coleta realizadas em Ametista do Sul e em Iraí. A) Utilização de retroescavadeira para abertura das trincheiras em Ametista do Sul. B) Coleta utilizando tubo de alumínio e batente em Iraí. C) Delimitação das paredes de uma trincheira aberta pela retroescavadeira em Ametista do Sul. D) Coleta utilizando tubos de PVC cortados ao meio em Ametista do Sul.

5.2 Etapas de laboratório

5.2.1 Análise granulométrica

As análises granulométricas foram realizadas no Laboratório de Sedimentologia do Centro de Estudos de Geologia Costeira e Oceânica (CECO) do Instituto de Geociências da UFRGS e serviram ao refinamento das interpretações sobre o regime deposicional.

De acordo com o método proposto por Folk e Ward (1957), as análises granulométricas embasaram-se na técnica de peneiramento e pipetagem com intervalos de classe de 1 e ¼ de φ (*phi*) respectivamente, da escala de Wentworth (1922). Ao final dessa mesma rotina obtém-se a classificação das amostras segundo o diagrama de Shepard (1954).

5.2.2 Datação radiocarbônica

A datação radiocarbônica foi realizada pelo *Beta Analytic Radiocarbon Dating Laboratory* (Miami, Florida, EU), que utiliza a técnica radiométrica AMS (Accelerator Mass Spectrometry). A Idade Radiocarbônica Convencional é o resultado alcançado após a aplicação de correções para explicar as diferenças de fracionamento isotópico entre a amostra e a percentagem de carbono moderna (pMC). A Idade Radiocarbônica Convencional é citada como “BP” (Before Present), sendo que a palavra “Presente” refere-se ao ano 1950 da Era Cristã para efeitos de datação radiocarbônica. Os resultados são relatados como “pMC” quando a amostra analisada contém mais ^{14}C do que a referência padrão moderna (AD 1950), indicando que o material absorveu carbono “extra” da atmosfera após o advento dos testes com armas termo-nucleares na década de 1950. Nos casos em que a amostra datada tenha idade ligeiramente inferior ao advento nuclear, há alguma probabilidade da mesma reportar aos séculos XVIII, XIX ou XX da Era Cristã. Todas as idades citadas para os testemunhos T1, T2 e T3 estão calibradas.

5.2.3 Carbono orgânico total

A preparação do material para análise de carbono orgânico total (COT) seguiu as normas de referência da ASTM D 4239 (AMERICAN SOCIETY FOR TESTING AND MATERIALS - ASTM, 2008) e NCEA-C-1282 (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY - U.S. EPA, 2002) e foi realizada no Laboratório de Palinofácies e Fácies Orgânica (LAFO) do Instituto de Geociências da Universidade Federal do Rio de Janeiro. O equipamento utilizado para a determinação de COT é o analisador SC 144DR da LECO, que quantifica, simultaneamente, o conteúdo de carbono e enxofre através de um detector de infravermelho. Os resultados de COT expressam a quantidade de matéria orgânica presente no sedimento, enquanto o resíduo insolúvel (RI) corresponde à fração residual que não foi eliminada pelo tratamento ácido.

5.2.4 Preparação das amostras

O resgate de amostras para a preparação das lâminas foi realizado no Departamento de Estratigrafia e Paleontologia da UFRGS. As porções de sedimento selecionadas para análise foram acondicionadas em sacos plásticos, devidamente identificados, e enviadas para o Laboratório de Palinofácies e Fácies Orgânica (LAFO) do Instituto de Geociências da Universidade Federal do Rio de Janeiro, onde se procedeu ao processamento das amostras e confecção das lâminas.

O processamento químico das amostras (isolamento da matéria orgânica) para preparação das lâminas organopalinológicas é efetuado de acordo com os procedimentos palinológicos não-oxidativos descritos por Tyson (1995), Mendonça-Filho (1999) e Mendonça-Filho *et al*. (2010). Neste processo, são coletadas de 20 a 40 gramas das amostras de sedimento para a obtenção de um concentrado de matéria orgânica. A primeira etapa do processamento químico consiste na eliminação da fração carbonática através da acidificação com ácido clorídrico (HCl 37%). A segunda etapa consiste na eliminação da fração silicosa utilizando ácido fluorídrico (HF 40%). Na terceira etapa, a amostra sofre novo processo de acidificação (HCl 10%) para eliminação de fluorsilicatos que possam ter sido formados durante as etapas anteriores. A etapa seguinte consiste na utilização de líquido denso, ou cloreto de zinco ($ZnCl_2$), para separar, por flotação, a fração orgânica da fração inorgânica residual. Após esse processamento, o resíduo orgânico isolado é transferido para um frasco devidamente identificado, estando pronto para a preparação das lâminas organopalinológicas.

As lâminas organopalinológicas utilizadas no presente estudo encontram-se depositadas na Palinoteca do Laboratório de Palinologia do Instituto de Geociências da Universidade Federal do Rio Grande do Sul, sob a seguinte numeração:

Testemunho T1 – Mina do Museu (Ametista do Sul): MP-P 7119, MP-P 7120, MP-P 7121, MP-P 7122, MP-P 7123, MP-P 7124, MP-P 7125, MP-P 7126, MP-P 7127 e MP-P 7128, MP-P 7481, MP-P 7482, MP-P 7483 e MP-P 7484.

Testemunho T2 – Mina Modelo (Ametista do Sul): MP-P 7139, MP-P 7140, MP-P 7141, MP-P 7142, MP-P 7143, MP-P 7144, MP-P 7145, MP-P 7146, MP-P 7147, MP-P 7148, MP-P 7149, MP-P 7150, MP-P 7151, MP-P 7152, MP-P 7485, MP-P 7486, MP-P 7487 e MP-P 7488.

Testemunho T3 – Iraí: MP-P 7167, MP-P 7168, MP-P 7169, MP-P 7170, MP-P 7171, MP-P 7172, MP-P 7173, MP-P 7174, MP-P 7175, MP-P 7176, MP-P 7177, MP-P 7178, MP-P 7179, MP-P 7180, MP-P 7181, MP-P 7182, MP-P 7183, MP-P 7184, MP-P 7185, MP-P 7186, MP-P 7187, MP-P 7188, MP-P 7489, MP-P 7490 e MP-P 7491.

As lâminas palinológicas encontram-se depositadas na mesma Palinoteca, sob a seguinte numeração:

Testemunho T1 – Mina do Museu (Ametista do Sul): MP-P 7129, MP-P7130, MP-P 7131, MP-P 7132, MP-P 7133, MP-P 7134, MP-P 7135, MP-P 7136, MP-P 7137 e MP-P 7138.

Testemunho T2 – Mina Modelo (Ametista do Sul): MP-P7153, MP-P 7154, MP-P 7155, MP-P 7156, MP-P 7157, MP-P 7158, MP-P 7159, MP-P 7160, MP-P 7161, MP-P 7162, MP-P 7163, MP-P 7164, MP-P 7165 e MP-P 7166.

Testemunho T3 – Iraí: MP-P 7189, MP-P 7190, MP-P 7191, MP-P 7192, MP-P 7193, MP-P 7194, MP-P 7195, MP-P 7196, MP-P 7197, MP-P 7198, MP-P 7199, MP-P 7200, MP-P 7201, MP-P 7202, MP-P 7203, MP-P 7204, MP-P 7205, MP-P 7206, MP-P 7207, MP-P 7208, MP-P 7209, MP-P 7210, MP-P 7211, MP-P 7212, MP-P 7213, MP-P 7214, MP-P 7215, MP-P 7216 e MP-P 7217.

5.2.4.1 Contagem e classificação da matéria orgânica particulada

A contagem e a classificação da matéria orgânica particulada baseiam-se no sistema de classificação proposto por Tyson (1995), Mendonça-Filho (1999) e Mendonça-Filho *et al*. (2002, 2010), sendo realizada em microscopia de luz branca transmitida e luz azul ultravioleta incidente (fluorescência) HBO 100 W.

A contagem considera toda a matéria orgânica entre 300 a 500 partículas e os dados são registrados manualmente em folhas devidamente elaboradas para esta finalidade. A cobertura da lâmina é realizada através de seções transversais verticais utilizando um retículo cruzado graduado em oculares de 10X e objetivas de 20 e 40X de aumento, sendo registradas somente aquelas partículas que passam diretamente sob o retículo. Todas as partículas são contadas, exceto aquelas com tamanho inferior a 10 µm (retículo graduado) e qualquer contaminante (reconhecido pela cor, relevo ou forma). Contudo, alguns palinomorfos têm tamanho inferior a 10 µm (acritarcas e esporos pequenos). Nesse caso, tais partículas são consideradas equivalentes àquelas com tamanho igual ou superior a 10 µm e, por isso, contadas juntamente com as demais. Por outro lado, os fragmentos de palinomorfos com menos da metade do tamanho original são ignorados. Depois de realizada a contagem na lâmina, essa é novamente examinada sistematicamente para a identificação de qualquer indicador paleoecológico raro que possa não ter sido reconhecido durante o processo de contagem.

5.2.5 Tratamento estatístico dos dados

O tratamento estatístico dos dados palinofaciológicos foi realizado a partir da análise quantitativa das partículas orgânicas. Após a contagem dos componentes orgânicos particulados, os valores absolutos foram convertidos em valores percentuais e normalizados a 100% (utilizando o programa *Microsoft Excel Starter 2010*) para serem submetidos à análise de agrupamento de *cluster* (utilizando o programa *Statistica 7*) e gerar análises de agrupamento hierárquico *modo-Q* e *modo-R* entre os grupos e subgrupos da matéria orgânica particulada. Os resultados foram representados por dendrogramas, que podem ser definidos como um diagrama ramificado (árvore) que contêm entidades reunidas segundo algum critério. Para gerar o dendrograma *modo-Q*, foi escolhido o método de Ward com distância euclidiana. Para gerar o dendrograma *modo-R* foi escolhido o método de Ward com distância 1-Pearson r. A análise *modo-Q* permite observar o grau de similaridade entre as amostras para a determinação de associações e intervalos, enquanto a análise *modo-R* é realizada para verificar similaridades entre as partículas orgânicas e determinar as palinofácies. Os diagramas de dispersão foram gerados através do programa *C2 Data Analysis* (versão 1.7.2) após os valores absolutos terem sido convertidos em dados percentuais. Os dados percentuais e médios das associações da matéria orgânica particulada (parâmetros obtidos para os grupos fitoclasto, produto amorfo e palinomorfo) para o conjunto total de amostras analisadas são também apresentados sob a forma de diagramas ternários (gerados através do programa *Statistica 7)*, quadros e tabelas.

PARTE II

6 CORPO PRINCIPAL DA TESE

O corpo principal desta tese é composto de três artigos submetidos em língua inglesa aos periódicos internacionais Geobios, Geologica Acta e Journal of South American Earth Sciences.

O formato dos artigos está de acordo com aquele exigido pelos periódicos aos quais foram submetidos e a numeração das páginas é contínua a partir do número 1 (um) em cada um dos artigos.

6.1 Artigo 1

“Holocene environmental climatic changes based on palynofacies and organic geochemical analyses from an inland pond at high altitude in southern Brazil”
Periódico: GEOBIOS

CARTA DE RECEBIMENTO

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Geobios
Ms. Ref. No.: GEOBIO-D-13-00010
Title: Holocene environmental climatic changes based on palynofacies and organic geochemical analyses from an inland pond at high altitude in southern Brazil

Dear Gabrielli,

Your submission entitled "Holocene environmental climatic changes based on palynofacies and organic geochemical analyses from an inland pond at high altitude in southern Brazil" will be handled by Editor in Chief / Redacteur en Chef Gilles Escarguel, Ph.D., H.D.R.

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Instituto de Geociências
Programa de Pós-Graduação em Geociências

Porto Alegre, January 28, 2013.

Dear editor of Geobios

We are pleased to send you the manuscript “**Holocene environmental climatic changes based on palynofacies and organic geochemical analyses from an inland pond at high altitude in southern Brazil**” which allows to document paleoclimatic and paleoenvironmental evolution during the Holocece based on palynofacies and geochemistry organic data from southernmost Brazilian lacustrine sediments.

The manuscript is part of the PhD Thesis of the first author at the Geosciences Post-Graduate Course (UFRGS), under coordination of Prof. Dra. Margot Guerra Sommer (Brazil), including Prof. Dr. João Graciano Mendonça-Filho as collaborator. The data were not yet publishied and constitute an original contribution.

Certainly Geobios constitutes one of the most important journal to divulgue our data, besides its tradition and world scientific qualification.

Sincerely,

Gabrielli Teresa Gadens Marcon

Programa de Pós Graduação em Geociências

Profa. Dra. Margot Guerra Sommer

Advisor

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Manuscript Draft

Manuscript Number: GEOBIO-D-13-00010

Title: Holocene environmental climatic changes based on palynofacies and organic geochemical analyses from an inland pond at high altitude in southern Brazil

Article Type: Original article / Article original

Keywords: continental environment; pond; organic matter (OM); palynofacies analysis, total organic carbon (TOC); total sulfur (TS)

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Abstract: Analyses of palynofacies and organic geochemistry were carried out on a particular type of Holocene inland ephemeral pond at high altitude filled primarily by precipitation located in the sub-tropical climatic belt of southernmost Brazil (Mina do Museu, Ametista do Sul). The main goals of the study were to determine whether the particulate organic matter record is climatically sensitive and whether the changes in the organic matter of the lacustrine record reflect local or regional climatic changes or perhaps even events on a global scale. The predominance of phytoclasts indicates that this group controls the organic carbon content of the sediments in almost all intervals. The palynomorphs are the second most dominant group and the amorphous product is the least abundant group. Fluctuations in water depth are inferred from the frequency of Botryococcus and other algae species that tend to decrease progressively toward the top surface, when the autochthonous elements are replaced by parautochthonous (spores) and allochthonous (pollen grains). Pseudoschizaea appears to be relatively more resistant to dry periods than other algalic elements and seems to act as a biological marker of the transitional intervals related to seasonal drying. An increased rainfall event detected at approximately 8000 years BP, which was responsible for the beginning of the water accumulation process in the gossan and the sedimentation of the pond can be related to the "Bond Events". The saturation level of the pond remained in relative equilibrium from 7963 to 5584 years BP, when changes in the pattern of moisture created a drier environment and resulted in an intermittent pattern in the water depth that currently exists at the site

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Holocene environmental climatic changes based on palynofacies and organic geochemical analyses from an inland pond at high altitude in southern Brazil

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ABSTRACT

Analyses of palynofacies and organic geochemistry were carried out on a particular type of Holocene inland ephemeral pond at high altitude filled primarily by precipitation located in the sub-tropical climatic belt of southernmost Brazil (Mina do Museu, Ametista do Sul). The main goals of the study were to determine whether the particulate organic matter record is climatically sensitive and whether the changes in the organic matter of the lacustrine record reflect local or regional climatic changes or perhaps even events on a global scale. The predominance of phytoclasts indicates that this group controls the organic carbon content of the sediments in almost all intervals. The palynomorphs are the second most dominant group and the amorphous product is the least abundant group. Fluctuations in water depth are inferred from the frequency of *Botryococcus* and other algae species that tend to decrease progressively toward the top surface, when the autochthonous elements are replaced by parautochthonous (spores) and allochthonous (pollen grains). *Pseudoschizaea* appears to be relatively more resistant to dry periods than other algalic elements and seems to act as a biological marker of the transitional intervals related to seasonal drying. An increased rainfall event detected at approximately 8000 years BP, which was responsible for the beginning of the water accumulation process in the gossan and the sedimentation of the pond can be related to the “Bond Events”. The saturation level of the pond remained in relative equilibrium from 7963 to 5584 years BP, when changes in the pattern of moisture created a drier environment and resulted in an intermittent pattern in the water depth that currently exists at the site.

Keywords:
Continental environment
Pond
Organic matter (OM)
Palynofacies analysis
Total organic carbon (TOC)
Total sulfur (TS)

1. Introduction

Lakes can be viewed as dynamic response systems that integrate environmental, climatic and tectonic forces into a continuous and high-resolution archive of the local and regional changes (Gierlowski-Kordesch and Kelts, 2000). Organic matter (OM) constitutes an important fraction of the lake sediments, providing important information for the interpretation of lacustrine paleo-environments, the histories of climate change and the effects of regional and local anthropogenic actions. However, lake systems are diverse, and the sources of and alterations in OM are geographically and temporally variable, covering a broad spectrum from predominantly algal in certain locations to largely land derived in others (Meyers & Lallier-Verges, 1999). Consequently, OM accumulation and preservation in lakes with different geo-morphological and climatic regimes is directly influenced by both local and regional as well as global climatic conditions. Organic matter analyses obtained from bulk OM parameters (total organic carbon, Rock Eval pyrolisis, C/N determination, organic petrography, radiocarbon dating) have proven their utility for paleo-climatic and paleo-environmental reconstructions in the Holocene Brazilian lacustrine sedimentary records (e.g., Sifedine et al., 2001, 2003; Ledru et al., 2001; 2002; Tturcq et al., 2002; Jacob et al., 2004, 2005; Boussafir et al, 2012).

Meaningful reconstructions of the paleo-environmental and climatic history of lacustrine deposits have been achieved in the last twenty years via palynofacies analyses combined with other methods of investigation of the tropical and temperate sedimentary records in different regions of the world (Siffedine et al., 1994, 1995, 1996, 1998; Noel et al., 2001). However, in Brazil, only a few papers have added to the knowledge of environmental changes in the continental areas through palynofacies analyses of peatlands (Medeanic & Silva, 2010) or inland lacustrine deposits (Meyer et al., 2010 and Silva et al., 2010) from Quaternary deposits. In contrast, studies based on palynofacies and organic geochemistry analyses of OM have been widely applied in the investigation of Brazilian deposits of marine origin and epicontinental samples from Paleozoic (Mendonça-Filho, 1999), Mezosoic (Carvalho et al., 2006 a,b; Iemini et al.; 2007) and Cenozoic rocks (Del Papa et al., 2002; Menezes & Mendonça-Filho, 2004; Menezes et al., 2005; Meyer et al., 2005, 2006; Chagas et al., 2009; Mendonça-Filho et al., 2010a).

The concept of palynofacies as defined by Tyson (1995) corresponds to “a body of sediment containing a distinctive assemblage of palynological organic matter thought to reflect a specific set of environmental conditions or to be associated with a characteristic range of hydrocarbon-generating potential”. According to this author, the advantage of applying a palynofacies technique lies in the fact that it provides direct information with respect to the origin and characteristics of the particulate organic matter (POM), thus allowing a more detailed analysis of subtle variations in the sedimentary environment.

Many of the interpretive models available in the scientific literature that address organic geochemical and palynofacies analyses were designed for use in marine and epicontinental sections because these studies had the main objective of exploration of hydrocarbon source rocks. More recently, these analyses have been applied to different depositional systems, resulting in a powerful research tool. However, the study of Sebag et al. (2006) provides evidence that the palynofacies method offers a valuable contribution for connecting particulate OM to the depositional environments in Holocene deposits; this work also includes a review of the main approaches performed for the POM characterization from Quaternary deposits in recent terrestrial environments and is based on applied examples in surface deposits, soil profiles, wetlands, lacustrine ecosystems and within catchments.

The present study was carried out using palynofacies and organic geochemical analyses of a particular type of Holocene inland ephemeral pond (Keddy, 2010) located in the sub-tropical climatic belt in southernmost Brazil. This type of pond dries up periodically and is filled primarily by precipitation that depends directly of the pluviometric regime. The hydrological isolation renders this pond highly sensitive to climatic changes. According to Hartmann (2008), pools displaying similar morphologies are common in the studied area and might be originate from the claying of Cretaceous basalts by the action of hydrothermal fluids.

The Southern Hemisphere climate changes during the Holocene period have received considerable research attention in recent years, particularly with respect to the timing and correlation of climate events in the history of the northern hemisphere climate (Markgraf, 1998). The Bond events (Bond et al., 1997), registered in the North Atlantic sediment cores have been related to precipitation with anomalies over regions affected by the monsoons in Oman (Fleitmann et al., 2003), Asia (Wang et al., 2005), South America (Haug et al., 2001; Baker et al., 2001, 2005) and Brazil (Cruz et al., 2005). Recently, Stríkes et al. (2011) observed that the records of Brazilian speleothems are synchronous with those obtained by Bond et al. (1997), evidencing strong events of increased precipitation centered at 9.2, 8.2, 7.4, 7.0, 6.6, 5.2, 4.0, 3.2, 2.7, 2.3, 2.2, and 1.9 kyr BP. Based on Quaternary sediments from a paleo-lagoon in Southeastern Brazil, Sallum et al. (2012) found a relationship with the 8.2 ka event, which is also associated with the Bond events.

A key goal of paleo-limnology is to develop continental paleo-records of global change comparable to those available from the oceans or ice cores. Lacustrine records can potentially match these records and yield substantially greater temporal and spatial resolution. Based on these considerations, a specific location was selected as a site with favorable conditions for registering changes over time periods of thousands of years, and a pioneering investigation of the paleo-environmental and paleo-climate evolution in the highlands of southern Brazil was subsequently established.

In light of the above considerations, the main goals of the present study are: (i) to present the results obtained from palynofacies analyses carried out on a sedimentary profile covering approximately 8000 years of sedimentation from a Holocene subtropical ephemeral pool; (ii) to consider the paleo-environmental significance of the palynofacies analyses; (III) to determine if the POM record was affected by paleo-climatic change, i.e., if it is climatically sensitive and, (iv) to investigate whether these changes in the OM record reflect local or regional climatic changes or even events on a global scale.

2. Geological background and site description

The present investigation was focused on the sedimentary record recovered from a Holocene inland high-altitude pond, which is observed to dry up periodically (Keddy, 2010). The pond is located at the edge of a hill in the Ametista do Sul mining district in Rio Grande do Sul state in southern Brazil at an altitude of 500 m above sea level (FIG. 1) (Hartmann, 2008). Favorable aspects for the study include: (i) the hydrodynamics of the alluvial plains, that have a strong influence upon adjacent systems appear to have no influence in this area; (ii) the pond area is partly filled with sediments and (iii) the pond is directly subordinated to the regional pluviometric regime.

The local present-day climate is included in the subtropical climatic zone framed by the climatic type Cfa (subtropical-humid) of Köppen (1948), and the modern-day vegetation is dominated by semi-deciduous forests that belong to the Mata Atlantica. The bedrocks (basalts and rhyodacites) from the Cretaceous (135 Ma) Paraná volcanic province are included in the Serra Geral Group. These units cover an area of 917.000 km^2 in southeastern South America. The volcanic province is located near the top of the sedimentary Paraná Basin, which contains the notably large Guarani aquifer situated directly below the lavas (Araújo et al. 1999). This aquifer consists mostly of sandstones of the Botucatu and Guará

Formations (Scherer 2000). According to Hartmann et al. (2010), heating by volcanism provided a widespread and nearly infinite volume of hot water and vapor for basalt alteration and the related processes of cavity formation and filling.

The formation of amethyst geodes is explained by Hartmann (2008), Duarte et al. (2009) and Rosenstengel and Hartmann (2012) via the ascent of hot water and its vapor and the consequent alteration of the overlying basalts. This process also led to the formation of ponds identified as “gossans” (Hartmann, 2008), which have been considered as important guides for mineral prospecting (Pertille et al. 2012) due to their consistent relationship to the underground amethyst mines. Pools showing similar morphology are common in the studied area, and according to Hartmann et al. (2010; 2012), have the same origin; that is, the formation of gossans is due to supergenic processes in wich weathering is superimposed on the hydrothermal systems, constituting an anomaly coincident with the mineralization of amethyst geodes. According to Hartmann et al. (2012), the formation of smectite in the altered and mineralized rocks leads to the concentration of similar minerals in the overlying soil and a decrease in mass, and consequently, to the long-term residence of water in the depression or pond.

3. Material and Methods

3.1 Sampling

The sampling point (27º22.373’S x 53º11.901’W) is known as “Mina do Museu” because it is located immediately above an amethyst extraction mine. The site was originally selected with the aid of maps generated by satellite (e.g., *Google-Earth*) due to its isolation in the surrounding native woods. Interviews with local residents were essential to confirm the spontaneous nature of the surrounding vegetation of the pond.

At the time of sampling in autumn of 2009 (April), the pool area was not flooded, and its surface was dry and semi-consolidated due to a long drought in the region. Samples for different analyses were recovered from a 95 cm-long sediment core collected manually from the center area of the pool. The sampling was performed with the assistance of a tractor backhoe that opened a trench of approximately 1.0 m depth from the surface sedimentary level to the boundary with the underlying basalt. The corer consisted of a piece of PVC tube with a length of 1.0 m and a diameter of 7.0 cm that was, previously cut into two halves. For sample collection, the convex side of the semi-split corer was pressed against the wall of the trench. When filled with sediment, the corer was sealed with a plastic film on both sides to prevent loss of moisture. The core was split into subsamples in the laboratory for sedimentary, geochemical and palynofacies analyses.

3.2 Granulometric analyses

Granulometric analysis was performed in the “Laboratório de Sedimentologia, Centro de Estudos Costeiros e Oceânicos, Instituto de Geociências, Universidade Federal do Rio Grande do Sul (UFRGS)”. Sieving and pipetting were carried out with class intervals of 1 e ¼ de *phi* respectively, according to the method proposed by Folk and Ward (1957).

3.3 Dating

Samples for carbon isotopic dating were collected at the lithological boundaries to create a consistent age-depth model. Three radiocarbon datings were performed, on the lower boundary (65 cm depth), at the central part (40 cm depth) and at the upper boundary (20 cm depth) of the clay-silty mud of Interval B. Acceleration Mass Spectrometry (AMS) at the *Beta Analytic Radiocarbon Dating Laboratory* (Miami, Florida, USA) was used for the analysis. The interpolated ages were calculated using the intercept of the mean conventional age interval in the calibration curve of ^{14}C (CALIB version 4.3; Stuiver et al. 1998). The unconsolidated surface sediment (0-15 cm) was not sampled due to ambient or anthropic factors that could alter the results.

3.4 Geochemistry

The accumulation of OM in the sediments was estimated using total organic carbon (TOC) analyses. According to Tyson (1995), TOC analysis is a convenient method for determining the relative abundance of OM in sediments. The accumulation of OM is controlled by such major factors as primary productivity, water depth, and sediment grain size. The TOC is always controlled by three main variables: the input of OM, the preservation of the supplied OM, and the dilution of the OM by sediment accumulation (Tyson, 1995). The values of the TOC in marine rocks range from approximately 0.1% (deep-sea pelagic deposits) to 94% (coals) (Tyson, 1995).

The total organic carbon (TOC) and total sulfur (TS) analyses was carried out according to standards of ASTM D 4239 (American Society Testing and Materials, ASTM, 2008) and NCEA-C-1282 (United States Environmental Protection Agency, U.S.EPA, 2002). Following acidification to remove the carbonates, the TOC and ST analyses were made all samples with a LECO SC 144 device at the Laboratory of Palynofacies and Organic Facies (LAFO).

3.5 Sample preparation

The material preparation for the palynofacies analyses was carried out using the standard non-oxidative palynological procedures described by Tyson (1995), Mendonça Filho (1999) and Mendonça Filho et al. (2002, 2010). For the OM concentrate preparation procedure, the studied samples were ground to a size of approximately 2 mm. The samples were treated successively to remove carbonates (HCl 37% for 18 h), silicates (HF 40% for 24 h), and neoformed fluorides (HCl 37% for 3 h). Between steps, the samples were washed with distilled water until the wash water was neutral. After this procedure, $ZnCl_2$ (density=1.9 to 2 g/cm^3) was added and stirred, and the samples were centrifuged to separate the sulfides. The floated material was similarly washed and drops of HCl (10%) +distilled water were added to eliminate the heavy liquid. The isolated MO was sieved at 20 µm. After this procedure, strew slides were prepared with the organic residue.

The strew slides analyzed in this paper are stored in the "Laboratório de Palinologia, Instituto de Geociências, UFRGS" under the numbers MP-P 7119 to 7128 and MP-P 7481 to 7484.

3.6 Palynofacies analyses

The palynofacies analyses involved the quantitative (counted from 300 to 500 particles) and qualitative (organic particle component identification) examinations of the OM component groups and subgroups. These examinations were achieved by means of microscopy techniques under transmitted white light and blue/ultraviolet incident light (fluorescence). The counts followed the OM groups and subgroups classifications proposed by Tyson (1995), Mendonça Filho (1999), and Mendonça Filho et al. (2002, 2010; 2011). In this classification, the particulate organic matter is organized into three main groups according to their optical properties: phytoclasts, amorphous product and palynomorphs.

In the present paper, all OM without form and lacking sharp edges, angular contours or any type of feature permitting its classification in any other group of POM was classified as amorphous product (AP). Such particles most are likely derived from algae or plant debris in an advanced state of degradation, which may have resulted from microbial action as in other transformation processes of POM that are active in the depositional environment in study or from both processes concurrently. The term “amorphous product” was chosen because of the exclusively continental origin of sediment analyzed to avoid conflicts with the Amorphous Organic Matter (AOM), commonly related to marine environments or depositional systems that suffer the influence of eustatic variations.

According to Mendonça-Filho et al. (2011, p. 43), “the Amorphous Group consists of all particulate organic components that appear structureless at the scale of light microscopy; including phytoplankton derived amorphous organic matter (traditionally referred to as “AOM”), bacterially derived amorphous organic matter (also traditionally referred to as “AOM”), higher plant resins, and amorphous products of the diagenesis of macrophyte tissues”.

The classification of the subgroups of palynomorphs was established based on the peculiarities of the studied environment in which only freshwater algae are present and are associated with spores and pollen grains of exclusively continental origin (FIG. 2).

3.7 Statistical Treatment

Based on the quantitative analysis of the organic particulate components, a statistical treatment of the data was carried out. The data were recalculated for percentage values and submitted to multivariate statistical analyses (cluster analysis) for the OM groups and subgroups (correlation coefficient R-Mode) and for the similarities of observation between samples (Q-Mode) using the Statistic Basic program, version 6.0 (Valentin, 2000).

4. Results

4.1 Profile description

Visual observations associated with the granulometric analyses allowed the identification of three sedimentary intervals from the base level (95 cm) to the surface unconsolidated level:

Interval A. Corresponds to the lower portion of the core (65-95 cm) and shows a predominance of fragmented basalts with yellowish-gray color occurring as coarse gravel mixed with sand and clay-silty mud; this latter material most likely originated in superjacent levels and percolated through the basalt.

Interval B. Corresponds to the middle and more representative section of the core (65-15 cm) where a significant discordance is observed from the finer grained texture, granulometry and color patterns relative to the interval A. This material is composed of a grayish and semi-compact mud that is texturally homogeneous, showing a few thin vegetal remains. Due to the great homogeneity of the sediment in the interval B, only three samples were selected for granulometric analyzes, named Base (65 cm), Midst (40 cm) and Top (20 cm) (Table 1). The granulometric analysis allowed classification of the sediment as a degraded clay-silty mud with a predominance of the clay fraction along the entire profile (average of 56.8%,). In addition, the fine grain size indicates a low energy depositional setting and the absence of any sedimentary structures suggests that the sediments were deposited under quiet lacustrine conditions.

Interval C. Represents the surface sediments of the core (0-15 cm) and corresponds to a brownish-gray soil showing thin rootlets and bioturbation.

Only the B and C intervals were selected for geochemistry and palynofacies study because they consist of sediments with a greater potential for preservation of organic matter.

4.2 Radiocarbon dating

A chronological framework for the B interval sedimentary sequence was provided by the radiocarbon date (FIG. 3). A gradual low mass accumulation rate in the pond can be inferred based on the relationship of the long time interval with the short interval of sedimentation (65 cm). Additionally, the age of 8050 to 7950 years BP obtained from a 65 cm depth represents important information because it represents the beginning of the pond sedimentation just overlying the basalt package which corresponds to the roof of the underlying amethyst mine and should represent the age of the pond.

4.3 Geochemical Organic Analysis

The concentration of TOC is a fundamental parameter for describing the abundance of OM in sediments. The TOC concentrations are influenced by both the initial biomass production and the subsequent degree of degradation such that they integrate the different origins, delivery routes, depositional processes and consequent degrees of preservation of OM (Tenzer et al. 1997).

Throughout the T1 core the TOC values are relatively low, less than 1% in most intervals and gradually increase toward the top, where they reach the maximum value of 8.93% (Table 1). Thus, the higher values of the TOC at the top of the interval may be a reflection of the vegetational evolution of the area or may be associated with the lower degradation suffered by the OM in the more recent levels. A similar evolution is observed for the total sulfur (TS) values, ranging from 0.01 to 0.09% towards the base-top of the core (Table 1).

Low concentrations of the TOC and TS have been related to oxic phases; however, these values can vary independently under certain conditions (Tyson, 2001). The low values of the ST indicate that sulfate-reducing processes, which are typical of anoxic environments, were not significant along the sedimentary deposition. This evidence confirms the relatively oxic conditions of the depositional environment. According to Tyson (1995), the continental aquatic environments contain a notably low concentration of dissolved sulfate compared with marine environments in which the sulfate-reducing processes occurred exclusively under anoxic conditions involving the activity of anaerobic bacteria. The ratio between the concentrations of the TOC and ST is high (> 15) and typical of a freshwater environment, according to the model proposed by Berner and Raiswell (1984), despite the observation that the percentage of the TOC does not reach 1% in certain basal intervals.

Considering that finer sized sediments typically carry higher concentrations of OM, the low concentration of the TOC observed in the basal intervals of the studied core could be related to the slow rate of sediment accumulation, thereby causing longer exposure of the OM to processes of oxic degradation. This evidence is confirmed by the relationship of the long time interval with the short sedimentary interval observed in the 20 to 60 cm depth of the core.

Alternatively, the low levels of the TOC could be related to the lower input of terrigenous OM in the depositional system due to the low productivity of the environment. Thus, it can be inferred that at the start of the gossan sedimentation, the process of ecological succession from the surrounding area gradually evolved without sufficient vegetation to sustain a high productivity of OM in the initial portions of the interval. The least hypothesis is ratified by the high concentrations of TOC and TS occurring in Interval C, compared with the clay silty mud levels sampled in Interval B.

4.4 Palynofacies Analysis

The predominance of the phytoclast group (52.6%) was observed in the studied succession, whereas the palynomorph group was the second most dominant (39%) and the AP was last, with percentages lower than 8.4% (FIG. 4). The TOC concentrations of the sediments are regulated by the most abundant group, or in this case, the phytoclasts.

Possibly due to the recent nature of the sediment layers analyzed, the fluorescence intensity of the particles is rather intense in general, varying from yellow to greenish-yellow (*Botryococcu*s and other algae, FIG. 5) and from orange-yellow to orange-brown (phytoclasts and AP, FIG. 6).

4.4.1 Hierarchical cluster analysis, R-mode

According to the statistical R-Mode and using the Ward’s method with 1-Pearson distance, the samples were classified into four main clusters of the particles, denoted as Palynofacies A, B, C and D (FIG. 7 and 11).

The Palynofacies A corresponds to the exclusively autochthonous components of lacustrine origin. The Palynofacies B is represented by non-woody allochthonous elements of plant origin and by *Pseudoschizaea*, *incertae sedis* group associated with autochthonous freshwater algae (Christopher, 1976). The Palynofacies C corresponds to spores, parautochthonous elements, and amorphous components that are originally allochthonous. The Palynofacies D, in turn, is composed of woody phytoclasts and elements of terrestrial plant origin that are exclusively allochthonous.

The palynofacies show the distinctive stages of the analyzed depositional environment (corroborated by other statistical analyses that will be discussed below), beginning with a notably wet phase, wherein predominate algalic and autochthonous elements, progressed through transitional phases of relative moisture (evidenced by the presence of autochthonous and parautochthonous elements) with a gradual increase of terrigenous influence until the establishment of a dry phase with predominance of elements of terrestrial origin. The A and B palynofacies were divided because the frequency of *Botryococcus* and Cuticles are inversely proportional in some basal intervals and produce different curves on the scatterplot (FIG. 10).

4.4.2 Hierarchical cluster analysis Q-mode

According to the statistical Q-mode and using the Ward's method with Euclidian distance, five main associations of the samples were observed and denominated as Association I, II, III, IV and V (FIG. 8 and 11), that are related to the palynofacies defined by the cluster R-mode (FIG.7).

The Association I is represented by samples of 40, 45, 50 and 60 cm (FIG. 8). The particles that reach the peak frequency in this association are the PTS, pollen grains, *Botryococcus* and other algae (FIG. 9), which are related to Palynofacies A (*Botryococcus* and other algae) and Palynofacies D (PTS and pollen) (FIG. 7). Phytoclasts predominate in most samples (average of 48.83%), except for the 60 cm sample in which the palynomorphs are the dominant group (55.58%), given the increased concentration of *Botryococcu*s and other algae (FIG. 9). The average value of the palynomorphs (44.89%) is higher in this association compared with the others (FIG. 9). The high frequency of algalic elements also constitutes a remarkable feature of this association which exceeds the frequency of the sporomorphs of terrestrial origin in all samples (FIG. 9). The frequency of AP is low (average of 6.28%) and reaches the lowest concentration (3.06%) in this association (sample of 40 cm, FIG. 9). The pollen grains, although they achieve their peak concentration in this association (sample of 40 cm), do not predominate over the algae at any time. The peak frequency of the PTS, in turn, influences the prevalence of phytoclasts over palynomorphs in the samples of 45 and 50 cm (FIG. 9). Broadly speaking, the change in the dominance of one group by another between the sample of 60 cm and the others that are components of this association occurs due to an increased in the input of terrestrial elements in the system from samples of 50-40 cm (FIG. 9).

This observation is attested by the increase in frequency of both components, the phytoclasts and the pollen grains. This input of allochthonous elements inside the pond may have contributed to the dilution of the autochthonous elements and was not necessarily related to significant fluctuations in water depth, because certain algalic elements (*Pseudoschizae*a and other algae) increase in concentration precisely in such samples (40 and 45 cm, FIG. 9).

The Association II is represented by samples of 55 and 65 cm (FIG. 8). The particles that reach the peak frequency of this association are cuticles and membranes (FIG. 9), which are related to the Palynofacies B (FIG. 7). This association is characterized by the strong predominance of phytoclasts (average 62.55%), reaching a peak frequency (62.70%) in the sample of 65 cm (FIG. 9). The averages of the palynomorphs (32.54%) and the AP (4.91%) are the lowest compared with other associations (FIG. 9). Among the palynomorphs, the algalic elements (particularly *Botryococcus* and other algae) predominate over sporomorphs of terrestrial origin, particularly in the sample of 55 cm, in which the frequency of spores decreases significantly (FIG. 9). *Pseudoschizaea*, however, is absent or shows a notably low frequency in this association (FIG. 9).

The Association III is represented by samples of 20, 25, 30 and 35 cm (FIG. 8). *Pseudoschizaea* is the only particle that reaches peak frequency in this Association (FIG. 9) and is related to the Palynofacies B (FIG. 7). The phytoclasts group is predominant (average of 54.39%), followed by the palynomorphs (average of 39.25%) and the AP (average of 6.36%) (FIG. 9). Among the sporomorphs, algae are the dominant forms. *Botryococcus* predominates over the land esporomorfos in samples of 25, 30 and 35 cm, achieving a high frequency (56.29%) in the sample of 30 cm (FIG. 9). However, in the sample of 20 cm, the terrestrial sporomorphs begin to dominate, as evidenced by a relative increase in the frequency of fern spores. Nevertheless, the dominance of the autochthonous over the allochthonous elements in this association remains due to the increase in the frequency and the peak of *Pseudoschizaea* (15.02%), which is rather high compared with other associations (FIG. 9). In contrast to *Pseudoschizaea*, the average values of *Botryococcus* (46.60%) and other algae (4.08%) are reduced, which suggest a slightly different pattern of response to changes in moisture content by *Pseudoschizaea* (FIG. 9).

The Association IV is characterized by samples of 5, 10 and 15 cm (FIG. 8). The particles that reach the peak frequency in this association are AP, PTA and spores (FIG. 9), which are closely related to the Palynofacies C (FIG. 7). The average of the phytoclast group is 50.04% and the average of the palynomorph group is 34.52%. The average of the AP group is 15.44% and represents the highest average achieved by the particles relative to other associations (FIG. 9). The phytoclast group predominates in samples of 10 and 15 cm and is overtaken by the palynomorphs in the sample of 5 cm, in which it reaches 47.20% due to a sharp increase in the frequency of fern spores (FIG. 9). This association is characterized by a decrease of the algalic elements and the dominance of terrestrial sporomorphs, indicating significant changes in patterns of moisture and fluctuations in water depth, especially in the sample of 5 cm, in which the frequency of *Botryococcus* decreases dramatically and is accompanied by a gradual reduction in the frequency of other algae (FIG. 9 and 10). Although *Pseudoschizaea* suffer a considerable reduction in this association, this reduction is proportionally less than that occurring with other algalic elements. This observation can be demonstrated in the sample of 5 cm, in which the frequency of *Pseudoschizaea* surpasses *Botryococcus* (FIG. 9). Such data suggest that environmental changes influenced the decrease of all algalic elements but are subtler with respect to *Pseudoschizaea*. The increase in the frequency of AP and PTA may have influenced the moderate increase in the concentration of TOC, because such particles tend to contribute to the high contents of organic carbon in the system due to their more advanced stage of molecular degradation.

The Association V is represented by the shallow sample of the core (FIG. 8). The particles that reach the peak frequency in this association are POL, POE and PTNS (FIG. 9), which are related to the Palynofacies D (FIG. 7). In this association, the dominance of the phytoclasts (53.54%) occurs, followed by the palynomorphs (38.79%) and the AP (7.68%) (FIG. 9). Among the palynomorphs, the sporomorphs derived from the terrestrial macrophytes completely dominate this association, because the algae disappears as a result of a marked alteration in the moisture pattern (FIG. 9). The fern spores remain dominant, although they suffer a subtle reduction in their frequency relative to the immediately preceding sample (5 cm, FIG. 9 and 10), followed by angiosperm pollen, which increase their frequency in this sample compared with previous samples (5-35 cm, FIG. 9). The exclusive occurrence of terrestrial esporomorfos in this Association discloses the establishment of the driest stage concomitant with the changes in the vegetational dominance of the area. The high frequency of woody phytoclasts in this sample exerts strong influences on the high levels of the TOC. However, the peak frequency of the opaque phytoclasts in the most recent portion of the analyzed intervals may be indicative of anthropogenic interference on the system.

4.4.3 Paleo-environmental Characterization based on Intervals generated by cluster analysis Q-Mode

Based on the associations generated by cluster analysis (Q-mode), the sedimentary section (FIG. 2) was subdivided into seven intervals (FIG. 11), from the base to the top of the core, with the aim of inferring the hydrological fluctuation during a time interval of 8050 years BP to the present day for the pond and surrounding area, influenced by autochthonous and allochthonous particles (FIG. 9). Estimations of the pond water level wereas constructed based on the frequency of *Botryococcus* and other algae.

The Interval 1 (7963 cal yr BP, FIG. 9 and 10) corresponds to Association II (65 cm depth) and is marked by the peak of cuticles and membranes, wich are particles related to Palynofacies B. The predominance of *Botryococcus* and other algae over the terrestrial sporomorphs indicate the existence of a body of water, with a predominance of wet periods and strong contribution of terrigenous elements, especially unlignified phytoclasts.

The Interval 2 (7611 cal yr BP, FIG. 9 and 10) corresponds to Association I (60 cm depth). The particles that reach their frequency peak in this range are *Botryococcus* and other algae related to Palynofacies A. This interval marks the highest water depth reached by the pond. Considering the altitude of the paleo-environment and the absence of fluvial inference, it is possible to infer a period of wetness marked by a high rainfall periodicity.

The Interval 3 (7260 cal yr BP, FIG. 9 and 10) corresponds to Association II (55 cm depth). In this interval of Association II there is a moderate increase in the frequency of cuticles and membranes, particles related to the Palynofacies B. In this interval, the environmental conditions that occurred were similar to those inferred for the Interval 1. However, the higher frequency of *Botryococcus* (relative to the interval of 65 cm depth) suggests a higher water depth, which is a reflection of the moisture peak that occurred in the previous interval (60 cm).

The Interval 4 (6908 to 6205 cal yr BP, FIG. 9 and 10) corresponds to Association I. The particles that reach their frequency peak in this interval (50-40 cm) are PTS and pollen grains, related to Palynofacies D. Although this interval reveals an increase in the input of terrigenous elements within the pond, the saturation level of the water remains relatively constant because it continues to harbor a high frequency of algalic elements.

The Interval 5 (6050 to 5584 cal yr BP, FIG. 9 and 10) corresponds to Association III and is characterized by a peak frequency of *Pseudoschizaea*, particle related to the Palynofacies B. In this interval, the frequency of *Botryococcus* is high (especially in the interval of 30 cm), up to depth of 25 cm. Thereafter, the predominance of autochthonous elements over allochthonous elements remains solely due to the high concentration of *Pseudoschizaea*. The saturation level of the water reaches a peak at the 30 cm and decreases until it reaches a depth of 20 cm, at which point a marked change appears in the rainfall patterns and moisture regulators because the rate of *Botryococcus* and other algae tends to decrease progressively toward the top. In this interval, *Pseudoschizaea* behave slightly differently, reaching a high frequency precisely at this level. This observation allows us to speculate that this genre, in addition to being more resistant to drier periods, may play a role in the successional process of vegetation because the terrestrial sporomorphs begin to prevail in the top intervals. This evidence agrees with the observations of van Gell (1978) and van Gell and van der Hammen (1978) in that certain algalic taxons can act as biological markers of transitional intervals. However, Scott (1992) observed that *Pseudoschizea* is a common form in relatively warm areas of the world in recent environments where moisture is available and can possibly indicate local seasonal drying. It is possibly that, the variation in water depth that will result in the intermittent pattern of the pond starts to become more meaningful from the final portion of the interval (20 cm) in wich the alternation between periods of greater and lesser moisture seems to acquire a seasonal pattern.

The Interval 6 (5429 to 5118 cal yr BP, FIG. 9 and 10) corresponds to Association IV and is characterized by the peak frequency of AP, PTA and spores, particles that compose the Palynofacies C. This interval is characterized by a considerable reduction in algalic elements, and consequently, in the water depth. The intermittent pattern of the pond was possibly established from this interval when the level of rainfall that flooded the pond constantly decreased or deregulated, reducing the capacity of the water depth to sustain a high algalic biomass. From a depth of 5 cm, the autochthonous elements suffer a drastic reduction in frequency, resulting in their disappearance at the next level and in the establishment of drier periods characterized by erratic rainfall. In contrast, the dominance of fern spores over the other palynomorphs suggests the continuity of wet conditions that were insufficient to maintain a water depth capable of sustaining the same algalic biomass of the initial intervals (65-20 cm, FIG. 9 and 10). Furthermore, the dominance of terrestrial palynomorphs in this association, which persists until the top of the profile, suggests that the ecological succession of the area was conditioned by environmental and climatic changes that were conducive to vegetational evolution in the areas surrounding the pond. This scenario led to a biomass deposition that was more abundant and diverse than that represented in the basal levels.

The Interval 7 (Recent, FIG. 9 and 10) corresponds to Association V, characterized by peak frequencies of particles such as POL, POE and PTNS that are related to Palynofacies D. This interval is marked by the disappearance of the algalic element, which indicates the consequent absence of water depth. This scenario corresponds to the situation in the study area at the sampling time because this interval corresponds to the sample at the top of the core (FIG 10). This interval possibly involves the most recent years of the pond, which reflect a relative decline in the rainfall frequency in the region, rendering it unable to maintain a sufficient water depth to sustain an algalic biomass but with a humidity level sufficient for the persistence of a high frequency of spores of parautochtonous origin. From the establishment of the intermittent pattern of the pond, the variations in the thickness of the water depth begin to interfere with the preservation of algalic elements, rendering them more exposed to degradation.

Alternatively, the reduction of the water level may also be linked to the sedimentary filling of the pond over the years. Currently, the pond is most evident during the rainiest months, but its prevailing depth is possibly lower than in the initial intervals of the sedimentation. According to Esteves (2011), lakes are generally not permanent features of the landscape, and their disappearance over geologic time is linked to phenomena such as the accumulation of organic matter and the deposition of sediments. Ponds have a short durability in the geological scale, and their destiny is to succumb to their own sedimentary metabolism.

5. Discussion

The plotted curve of the pond water level (FIG. 10) provides evidence that there were significant changes in the level of aqueous saturation of the pond over the last 7963 years BP (8050 to 7950 cal yr BP), which resulted in a reduced water depth and in an intermittent flood pattern of the pond, such as that currently observed. The present pattern, however, was not prevalent in the past, when the higher levels of aqueous saturation were maintained in the pond despite certain water-level oscillations, which are attributed to possibly more intense rainfall due to the wetter periods that prevailed in the past. The more conspicuous alteration of the wetness patterns begins at 5584 years BP (20 cm depth) and intensifies from 5118 years BP (5 cm depth) up to recent times. This curve shows a trend stemming from the establishment of drier periods in the present-day, which constitutes evidence that could be linked to larger-scale climate changes in the region.

Based on the striking correlation between the ice-rafted debris records in the North Atlantic sediment cores and the tropical rainfall, the Bond events (Bond et al., 1997) have been used to link shifts in the intensity of the Atlantic thermohaline circulation to changes in the sea surface temperature (SST) and the related precipitation anomalies in Asia and South America (Fleitmann et al., 2003; Wang et al., 2005; Haug et al., 2001; Baker et al., 2001, 2005; Cruz et al., 2005). In this context, Bond et al. (2001) argued that most of the North Atlantic sea surface temperature oscillations are likely tied to solar activity; hence, at least a portion of the Bond events (the events at 9.4, 8.2, 7.4, 5.4, 2.7, and 2.3 kyr B.P) coincide with periods of low solar activity.

Amongst such events, the ice cores from Greenland (Alley et al., 1997) and Africa (Thompson et al., 2002) suggest that the 8.2 ka event was global in extent. This event is characterized by a relatively short period of time in which the climatic conditions have abruptly changed (Kobashi et al., 2007; Thomas et al., 2007). Bond et al. (1997) argue that the origin of the 8200-year cooling period is linked to the climate cycle and that its large amplitude in the climate records reflects a mechanism that amplified the climate signal at that time in some way. There is evidence that the 8.2 ka event caused significant sea level changes in the Norwegian Sea (Klitgaard-Kristensen et al., 1998), a temperature drop of approximately 2°C in Europe (Wick and Tinner, 1997), glacial advances in the New Zealand Southern Alps (Salinger and McGlone, 1990), notably dry conditions on the southeastern edge of the Sahara (Gasse and Van Campo, 1994), a pronounced climate cooling from 8.9 to 8.3 ka in the USA (Hu et al., 1999), and an increase in precipitation and/or a decrease in temperature in South America and the central South Atlantic (Douglass et al., 2005; Ljung et al., 2008).

The results of Stríkes et al. (2011), based on the high resolution oxygen isotopic records of Brazilian speleothems (1.3 to 10.2 Kyr B.P) are synchronous with those obtained by Bond et al. (1997). The abrupt decreases in the $^{\delta18}$O values associated with increased precipitation in central eastern Brazil, according to Stríkes et al. (2011), closely correspond to an anomalously cold North Atlantic period during the Bond events. This observation demonstrates that the slowdown of the Atlantic meridional overturning circulation (AMOC) associated with freshwater pulses in the North Atlantic can promote abrupt changes in monsoonal precipitation in South America, which is potentially influenced by feedback processes.

Based on Quaternary sediments of a paleo-lagoon in Southeastern Brazil, Sallum et al. (2012) found a relationship with the 8.2 ka event. The decadal scale anomalous oscillations in the sediments occurred between 9400 and 7500 cal yr BP and were correlated with long- and short-term natural events that generated high sedimentation rates, mainly between 8385 and 8375 cal yr BP (10 cm/yr). These results suggest that a modern-day short-duration North Atlantic climatic event, such as the 8.2 ka event, could affect the environmental equilibrium in South America and intensify the South American summer monsoon.

According Sallum et al. (2012), the 8.2 ka event was characterized by effects of short duration, approximately a few hundred years, and the data obtained to the southeast of Brazil suggest that the event should have significantly affected the environmental conditions in the coastal area. Such anomalies show a high degree of correlation with cooler conditions associated with the North Atlantic 8.2 ka event, which appears to have affected the environmental equilibrium in South America and intensified the South American summer monsoon. In Brazil, this event would have increased local precipitation and humidity as well as the sea level rise.

The higher precipitation events inferred by the palynofacies analyses in South Brazilian inland pond sediments occurring between 7963 to 7260 years BP can be related to the "Bond events" (especially the 8.2 and 7.4 ka events). The process of water accumulation in the gossan and the sedimentation of the pond were consequences of increased rainfall at approximately 8000 years BP.

The record of a period of high humidity associated with the Bond events is of great importance related to the observation that the global extent of this event is still not well-known because the paleo-climatic records are still quite scarce in Brazil (Cheng et al., 2009; Stríkes et al. 2011; Sallum et al., 2012). Selected data for this period of time were not correlated to the Bond events by other authors (especially 8.2 ka event), possibly due to small differences between the ages obtained, result of uncertainties in ^{14}C reservoir age corrections (Salgado-Labouriau et al., 1998; Behling, 1998).

An increase in rainfall was also inferred in the interval of 5895 years BP (30 cm depth), which has not been directly related to the cycles reported by Bond et al. (1997). According Carlson et al. (2008), differences in the climate response to typical Northern Hemisphere cold events throughout the Holocene might be the result of glacial boundary conditions that persisted until 7.0 ka years BP. The 5.9 ka event reported in this work could be a consequence of intrinsically driven and abrupt ecological changes. These changes, as indicated by Williams et al. (2011), are strongly controlled by local biotic and abiotic processes and also by localized disturbances and climatic events.

6. Conclusion

Palynofacies and geochemical organic analyses have proved to be powerful tools in the paleo-environmental and paleo-climatic study of a Holocene continental inland pond in southern Brazil. The study produced the following conclusions:

1 - Although the granulometric texture of the samples favors the preservation of organic compounds, the relatively low concentrations of TOC and TS at the lower and middle portion of the section reflect an oxic setting in the pond due to a low to moderate sedimentation rate. However, the higher values of the TOC at the upper portion of the section can be related to the lesser degradation suffered by OM at the latest levels or may be a reflection of the vegetational evolution of the area. The ratio between the concentrations of TOC and TS is high and is typical of freshwater environments.

2 - The predominance of phytoclasts indicates that this group controls the organic carbon content of the sediments of almost all intervals. The palynomorphs are the second most dominant group and the AP is the least abundant group.

3 - The saturation level of the pond remained relatively constant for 7963 to 5584 years BP, when changes in the patterns of moisture created a drier environment and resulted in an intermittent pattern in the water depth that currently exists at the site.

4 – Fluctuations in water depth are inferred from the frequency of *Botryococcus* and other algae, which tend to decrease progressively toward the top where the autochthonous elements are replaced by parautochthonous (spores) and allochthonous (pollen grains) elements.

5 - *Pseudoschizaea* appears to be relatively more resistant to dry periods than other algalic elements and seems to act as a biological marker of the transitional intervals related to seasonal drying.

6 - Although the predominance of spores in the most recent intervals indicates the persistence of a certain amount of moisture, this moisture was not sufficient for the maintenance of the same algalic biomass that prevailed in the pond during the older intervals. Concurrently, the increase in the biomass input from the terrestrial system could be related with to the reduction in the saturation level of water that may have promoted the densification of the surrounding vegetation.

7 - The increase in the frequency of spores and pollen grains in the topmost intervals suggests the establishment of terrestrial vegetation surrounding the pond that was more abundant and diverse than that represented at the basal levels (dominated by algae). This change in palynomorph composition may be a reflection of the process of ecological succession of vegetation.

8 – A increased rainfall event detected between 7963 to 7260 BP, which was responsible for the beginning of the processes of water accumulation in the gossan and the sedimentation of the pond, can be related to the “Bond events” (8.2 and 7.4 ka events).

9 – The present results are of great importance for understanding the global extent of the “Bond events”, which are still not well known for Brazil and demonstrate the need for new

studies to improve the understanding of global climate changes and their local and regional environmental impacts.

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Appendix A. supplementary information

Supplementary information associated with this article can be found, in the online version, at:

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Table and Figure captions:

Table 1. Values in percentage of the geochemical (TOC, ST, Ratio C:S and IR) and granulometric (sand, silt and clay) analysis of the T1 core (Mina do Museu)

Figure 1. a1) location of Ametista do Sul; a2) map legend; b) model sections of lava units in the Ametista do Sul mining districts (adapted from Hartmann et al., 2010)

Figure 2. General classification of POM used in this work

Figure 3. Chronological framework for the sedimentary profile of the T1 core (Mina do Museu) showing the calibrated radiocarbonic age (cal yr BP) and interpolated ages (*). The analyses performed by Beta Analytic are highlighted in bold. The other ages are calculated as the median probability.

Figure 4. a) Ternary diagram showing the relationships of the major groups of POM of all samples; b) Ternary diagram showing the relationship of samples Association I, II, III, IV and V.

Figure 5. Palynomorph group. A-B, *Botryococcus*; C, *Pseudoschizaea*; D-E, *Spyrogira*; F, *Debaria*; G, *Mougeotia*; H, *Desmídia*; I, Pteridophyte spore. Scale bars: 20 µm.

Figure 6. A-D, amorphous product (AP); E-M, phytoclast group. E-H, cuticles; I-J, membrane; K-M, phytoclasts. Scale bars: 20 μm.

Figure 7. Dendrogram produced by cluster analysis R-mode for groups and subgroups of the POM from the T1 core (Mina do Museu). The red vertical lines divide the four palynofacies. Abbreviations are in accordance with FIG. 2.

Figure 8. Dendrogram produced by cluster analysis Q-mode for groups and subgroups of the POM from the T1 core (Mina do Museu) in relation to depth. The red vertical lines divide the five Associations. Abbreviations are in accordance with FIG. 2.

Figure 9. Table showing the percentages of the TOC and ST and the percentages of the major groups and subgroups of the POM and of the averages of the sample groups. (*) Percentage value of the three main groups of POM related to total organic matter. (**) Percentage value of palynomorphs related to the total palynomorph group. Abbreviations are in accordance with FIG. 2.

Figure 10. Variation of the palynofacial and geochemical parameters of the main groups and subgroups of POM. The red vertical lines indicate the midline. Abbreviations are in accordance with FIG 2.

Figure 11. Table showing the Palynofacies, the Associations and the Intervals generated by statistical analyses

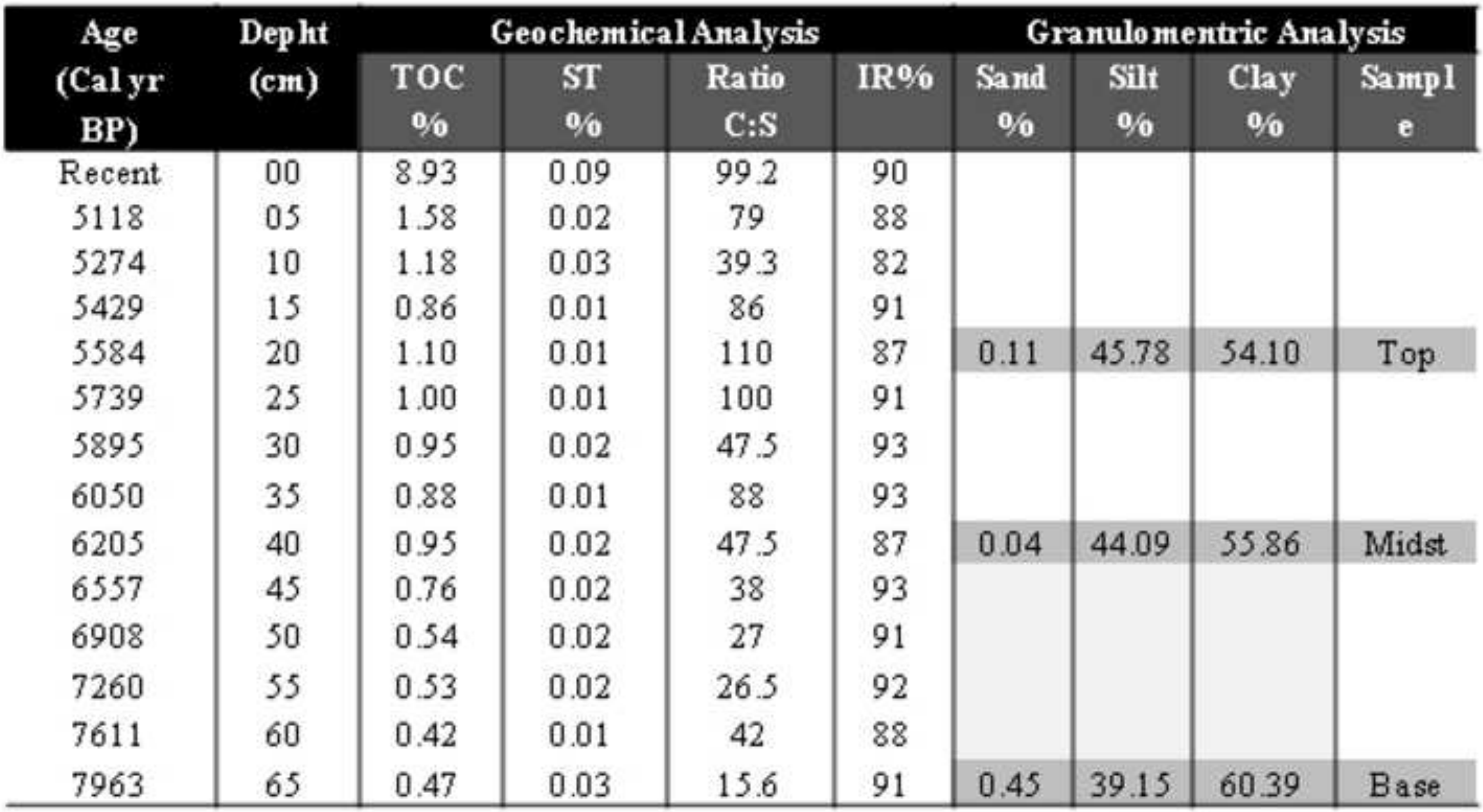
Appendix A. supplementary information

Table 2. AMS (Accelerator Mass Spectrometry) radiocarbon ages from the sediments of the T1 core (Mina do Museu). The analyses were performed by Beta Analytic, Inc.

Figure 12. Table showing the ranges of higher frequency of the TOC and TS and the higher frequency of the major subgroups of the POM. Abbreviations are in accordance with FIG. 2.

Figure 13. Table showing the frequency peaks of major subgroups of POM. The percentage values of the subgroups are related to the total organic matter, including the palynomorphs and the frequency peaks are highlighted. Abbreviations are in accordance with FIG. 2. Assoc (Association).

Table 1



Age (Cal yr BP)	Depht (cm)	Geochemical Analysis				Granulomentric Analysis			
		TOC %	ST %	Ratio C:S	IR%	Sand %	Silt %	Clay %	Sample
Recent	00	8.93	0.09	99.2	90				
5118	05	1.58	0.02	79	88				
5274	10	1.18	0.03	39.3	82				
5429	15	0.86	0.01	86	91				
5584	20	1.10	0.01	110	87	0.11	45.78	54.10	Top
5739	25	1.00	0.01	100	91				
5895	30	0.95	0.02	47.5	93				
6050	35	0.88	0.01	88	93				
6205	40	0.95	0.02	47.5	87	0.04	44.09	55.86	Midst
6557	45	0.76	0.02	38	93				
6908	50	0.54	0.02	27	91				
7260	55	0.53	0.02	26.5	92				
7611	60	0.42	0.01	42	88				
7963	65	0.47	0.03	15.6	91	0.45	39.15	60.39	Base

Figure 1

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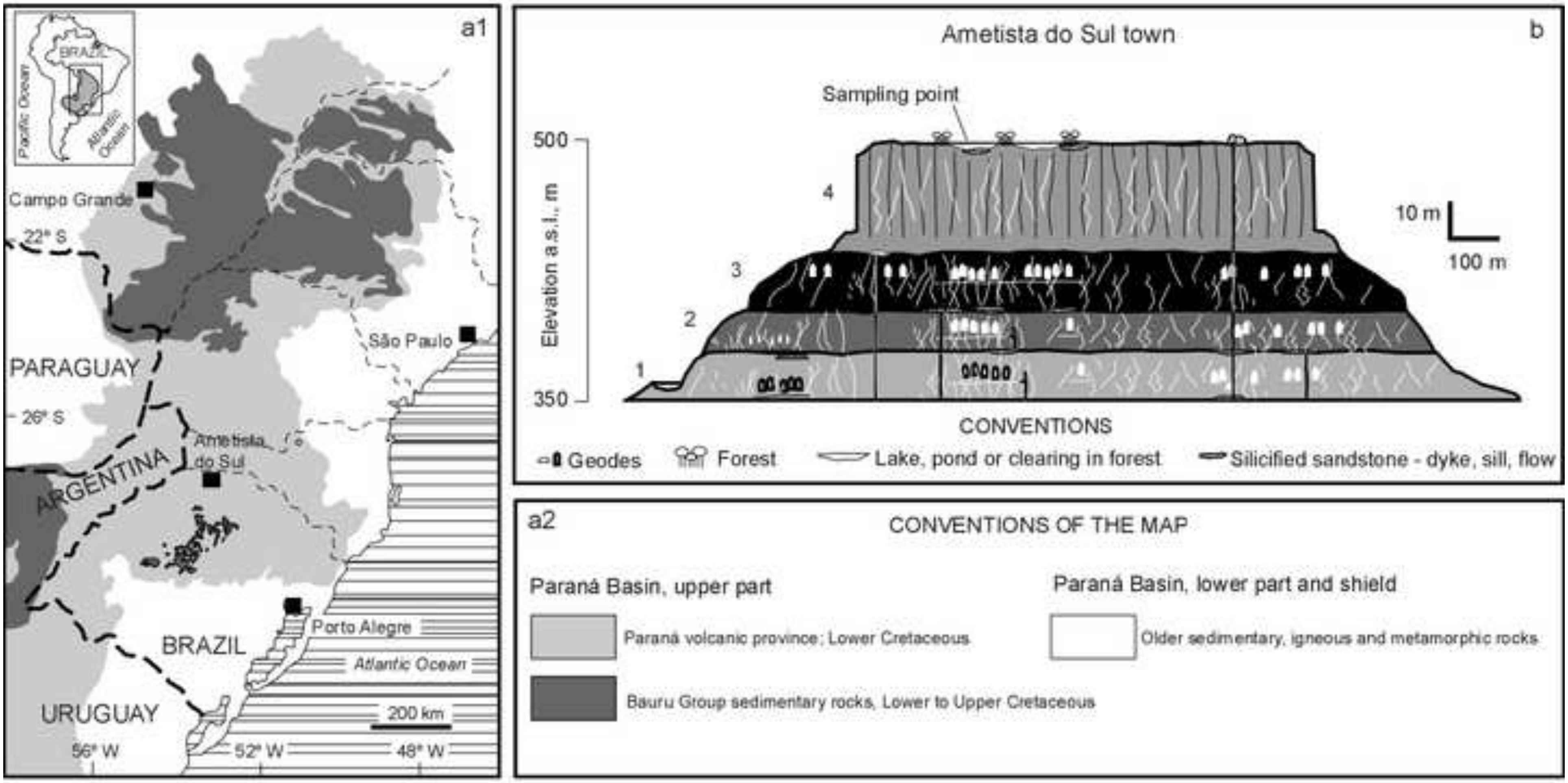


Figure 2

GROUP	SUBGROUP			ABREVIATTION
PHYTOCLAST	Opaque	Lath		POL
		Equidimensional		POE
	Translucent	Structured		PTS
		No Structured		PTNS
		Amorfous		PTA
		Cuticle		CUT
		Membrane		MEMB
PALYNOMORPH	Sporomorph	Spores	Briophyte	Spores
			Pteridophyte	
		Pollen grains	Gymnosperm	Pollen
			Angiosperm	
	Freshwatermicroplankton	*Botryococcus* (Chlorophyceae)		Botry
		Other algae (Zygnemaphyceae)	*Spyrogira*	Algae
			Debaria	
			Mougeotia	
			Zignema	
			Desmidia	
	Incertae sedis	*Pseudoschizaea*		Pseud
AMORPHOUS PRODUCT				AP

Figure 3

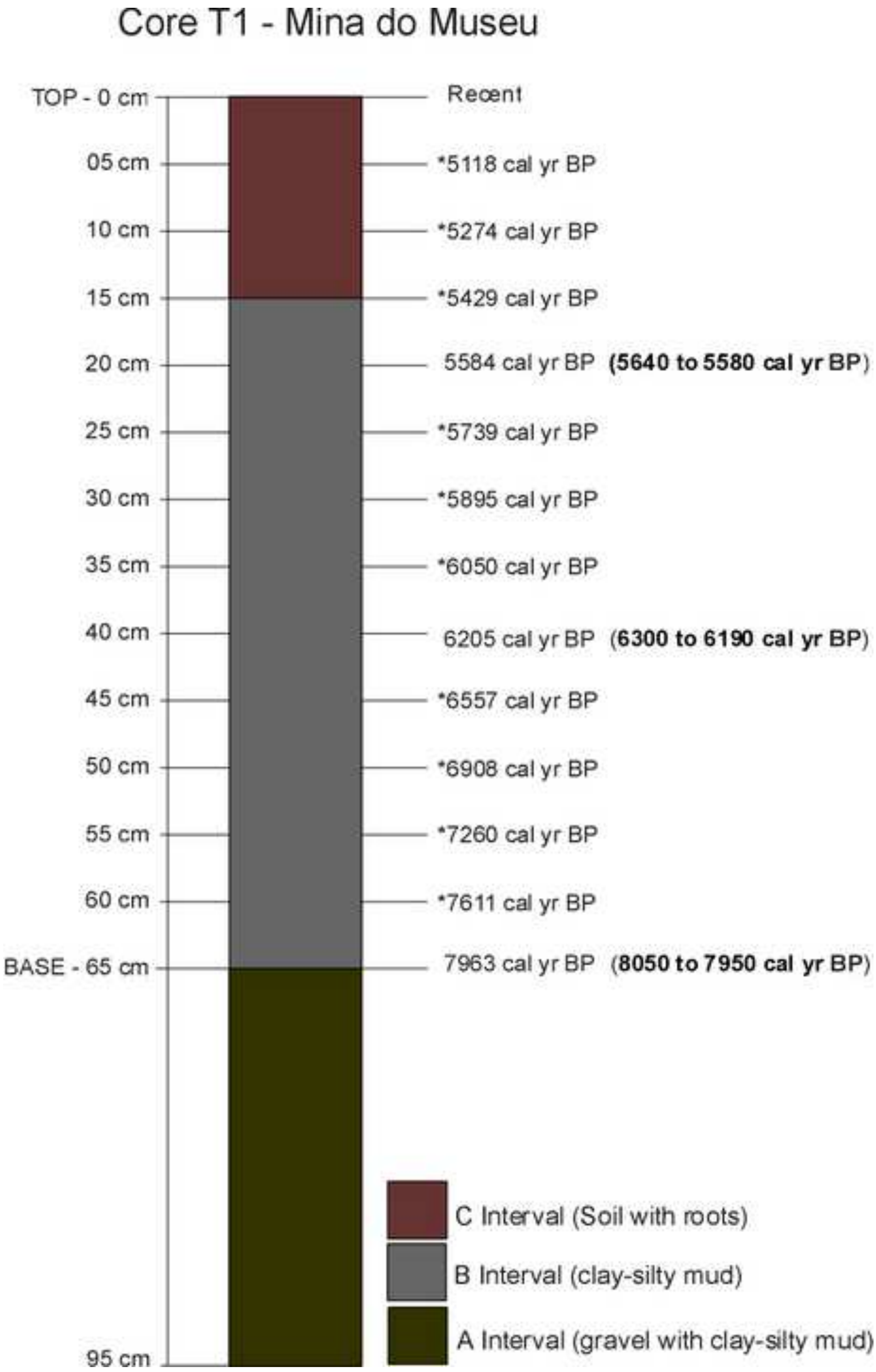
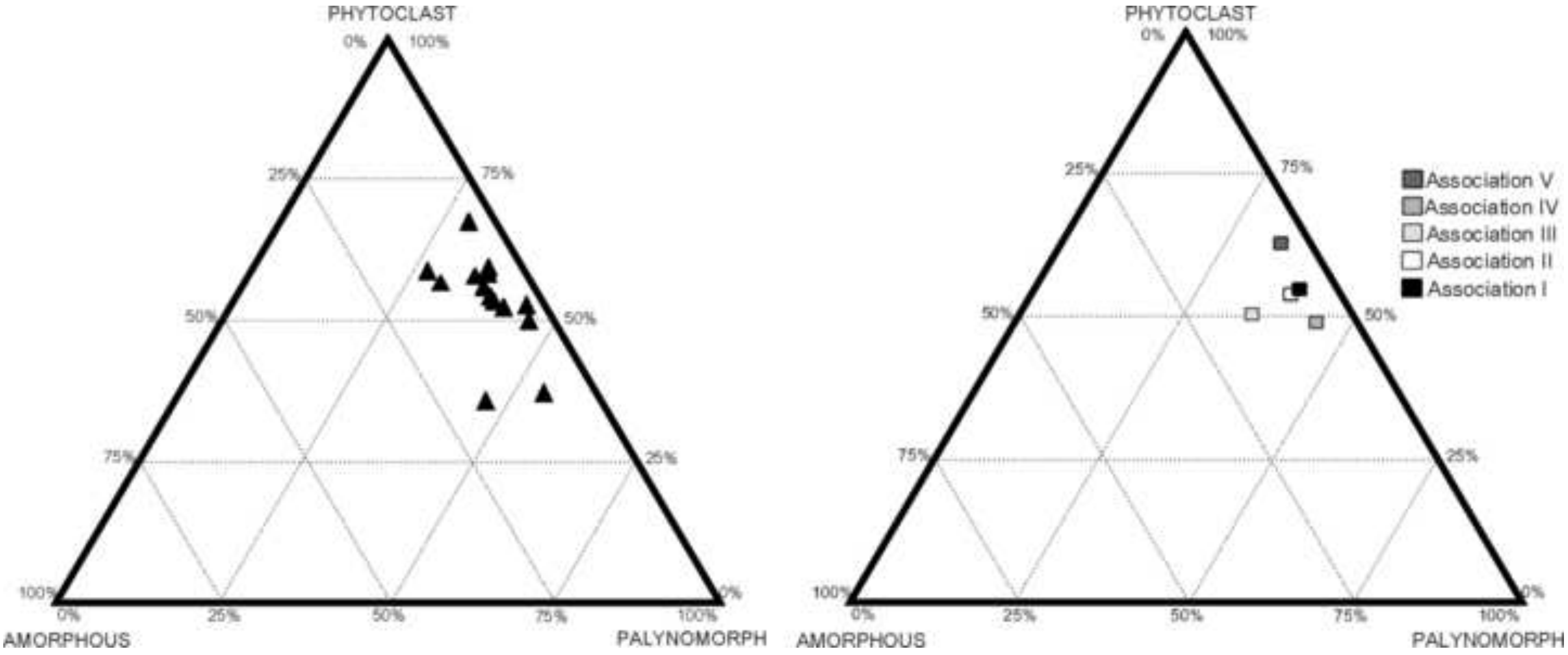

Core T1 - Mina do Museu
TOP - 0 cm
05 cm
10 cm
15 cm
20 cm
25 cm
30 cm
35 cm
40 cm
45 cm
50 cm
55 cm
60 cm
BASE - 65 cm
95 cm
Recent
*5118 cal yr BP
*5274 cal yr BP
*5429 cal yr BP
5584 cal yr BP (5640 to 5580 cal yr BP)
*5739 cal yr BP
*5895 cal yr BP
*6050 cal yr BP
6205 cal yr BP (6300 to 6190 cal yr BP)
*6557 cal yr BP
*6908 cal yr BP
*7260 cal yr BP
*7611 cal yr BP
7963 cal yr BP (8050 to 7950 cal yr BP)
C Interval (Soil with roots)
B Interval (clay-silty mud)
A Interval (gravel with clay-silty mud)

Figure 4


PHYTOCLAST
0%
100%
25%
75%
50%
50%
75%
25%
100%
0%
0%
25%
50%
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AMORPHOUS
PALYNOMORPH
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25%
50%
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AMORPHOUS
PALYNOMORPH
▨ Association V
▨ Association IV
☐ Association III
☐ Association II
■ Association I

Figure 5

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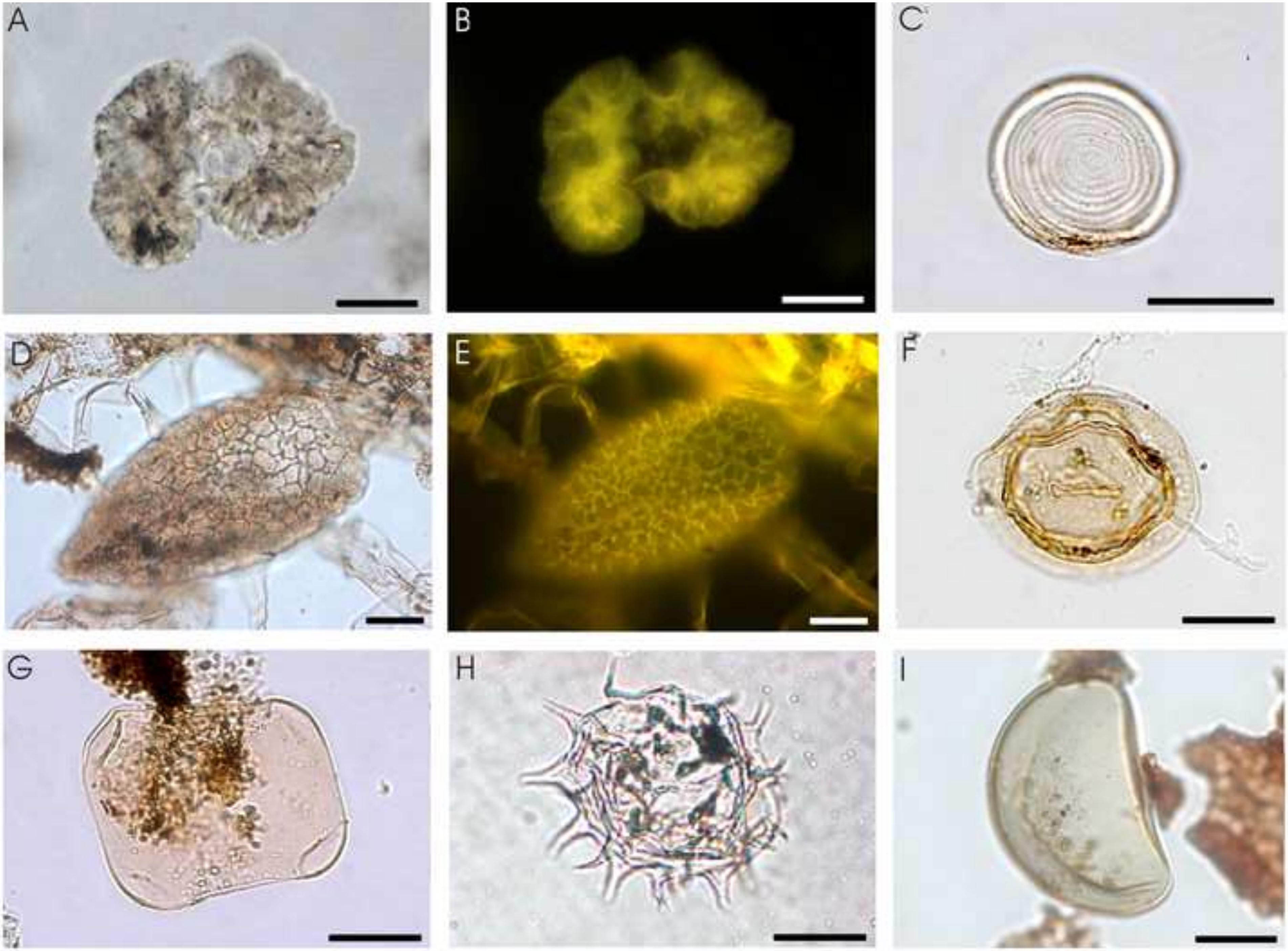

Figure 6

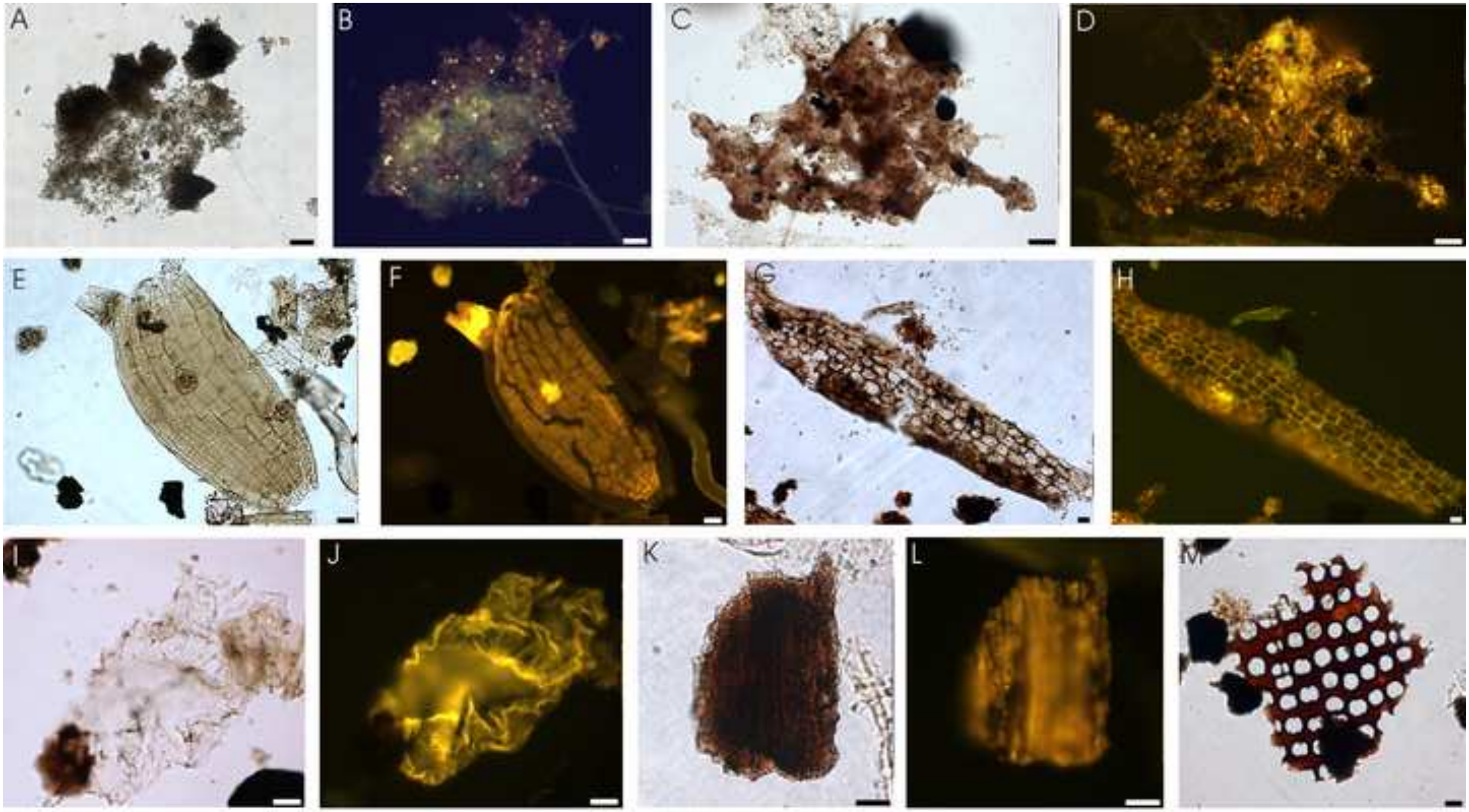

Figure 7

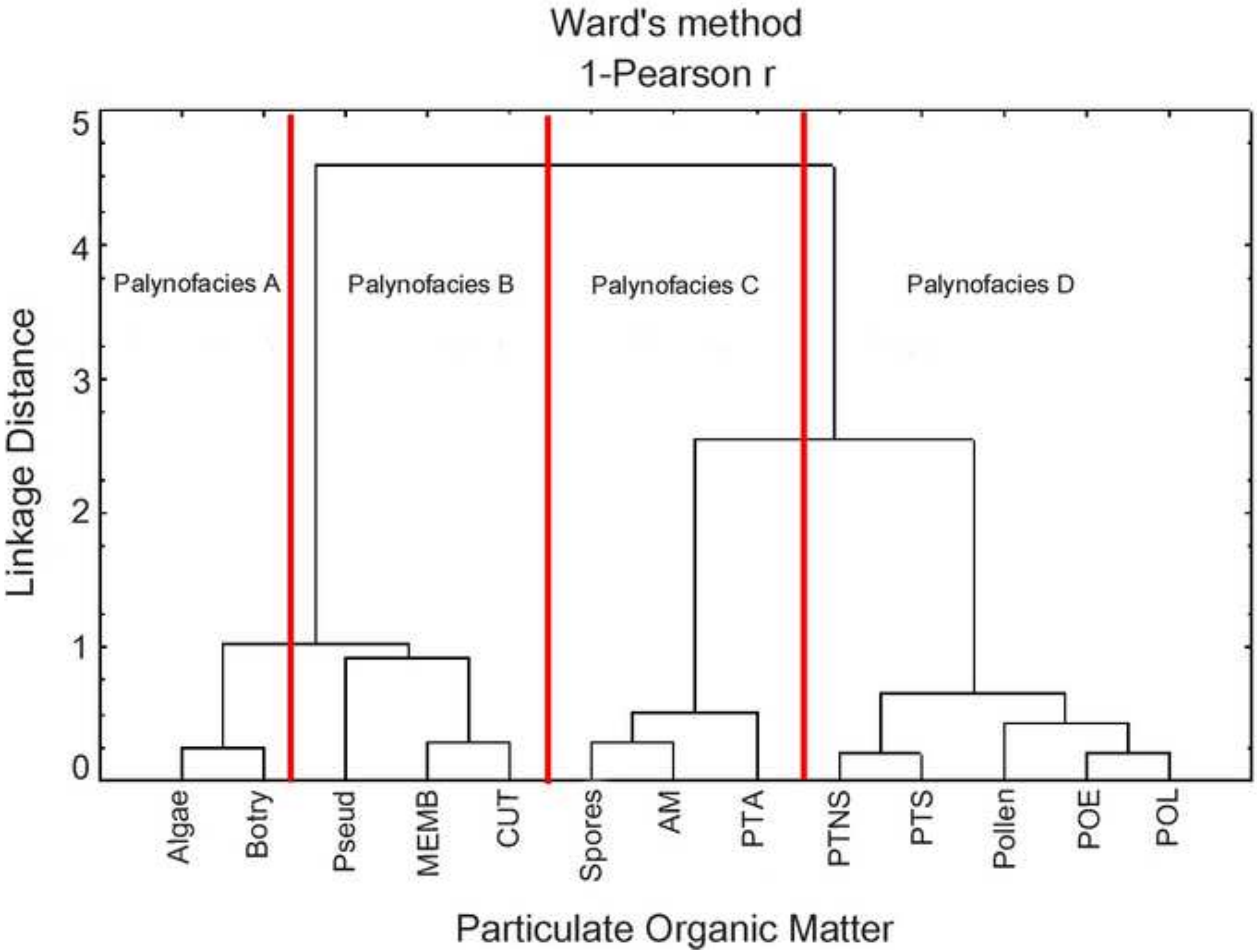
Ward's method
1-Pearson r
Linkage Distance
0
1
2
3
4
5
Palynofacies A
Palynofacies B
Palynofacies C
Palynofacies D
Algae
Botry
Pseud
MEMB
CUT
Spores
AM
PTA
PTNS
PTS
Pollen
POE
POL
Particulate Organic Matter

Figure 8

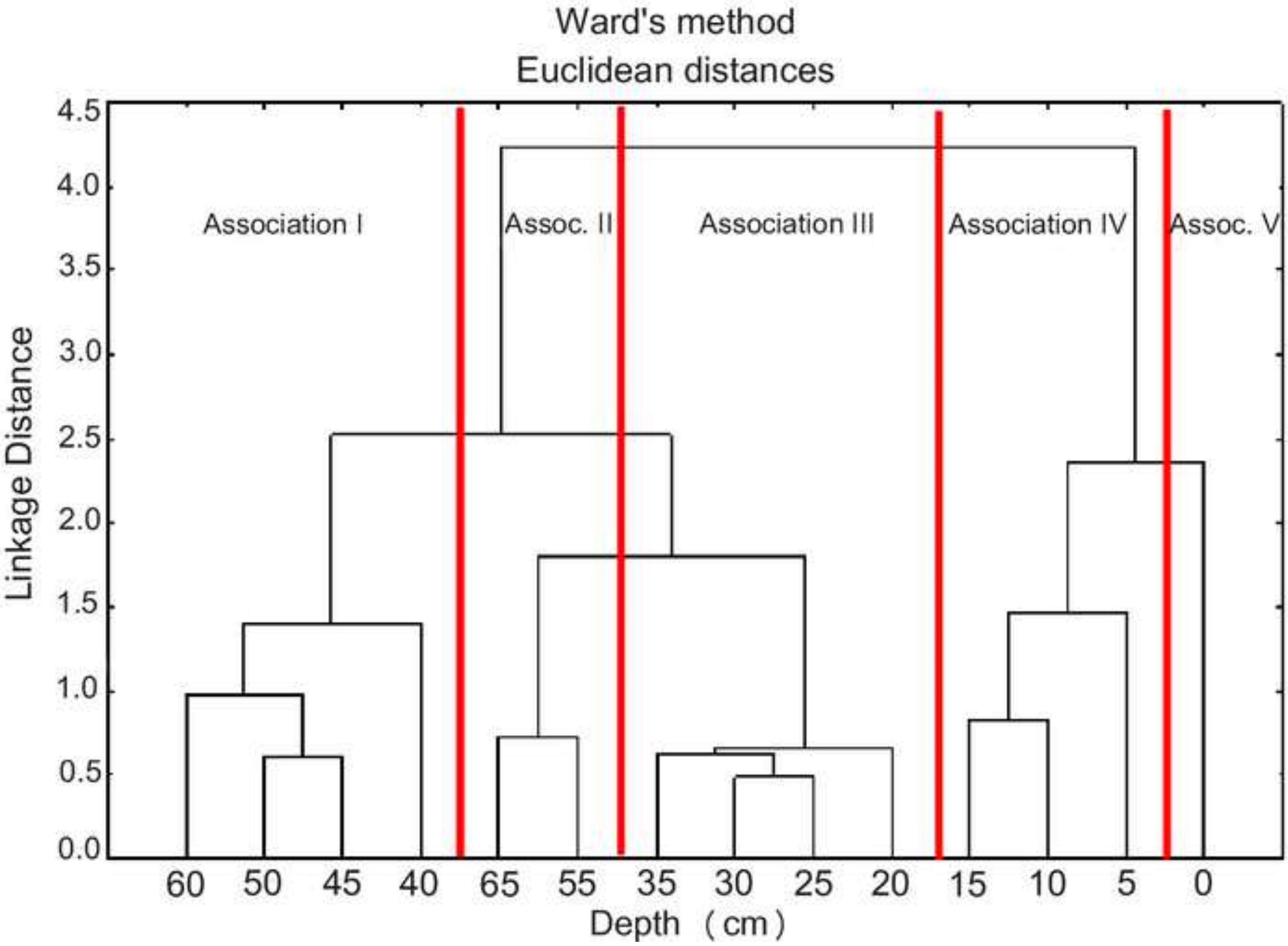
Ward's method
Euclidean distances
Linkage Distance
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Association I
Assoc. II
Association III
Association IV
Assoc. V
60
50
45
40
65
55
35
30
25
20
15
10
5
0
Depth (cm)

Figure 9

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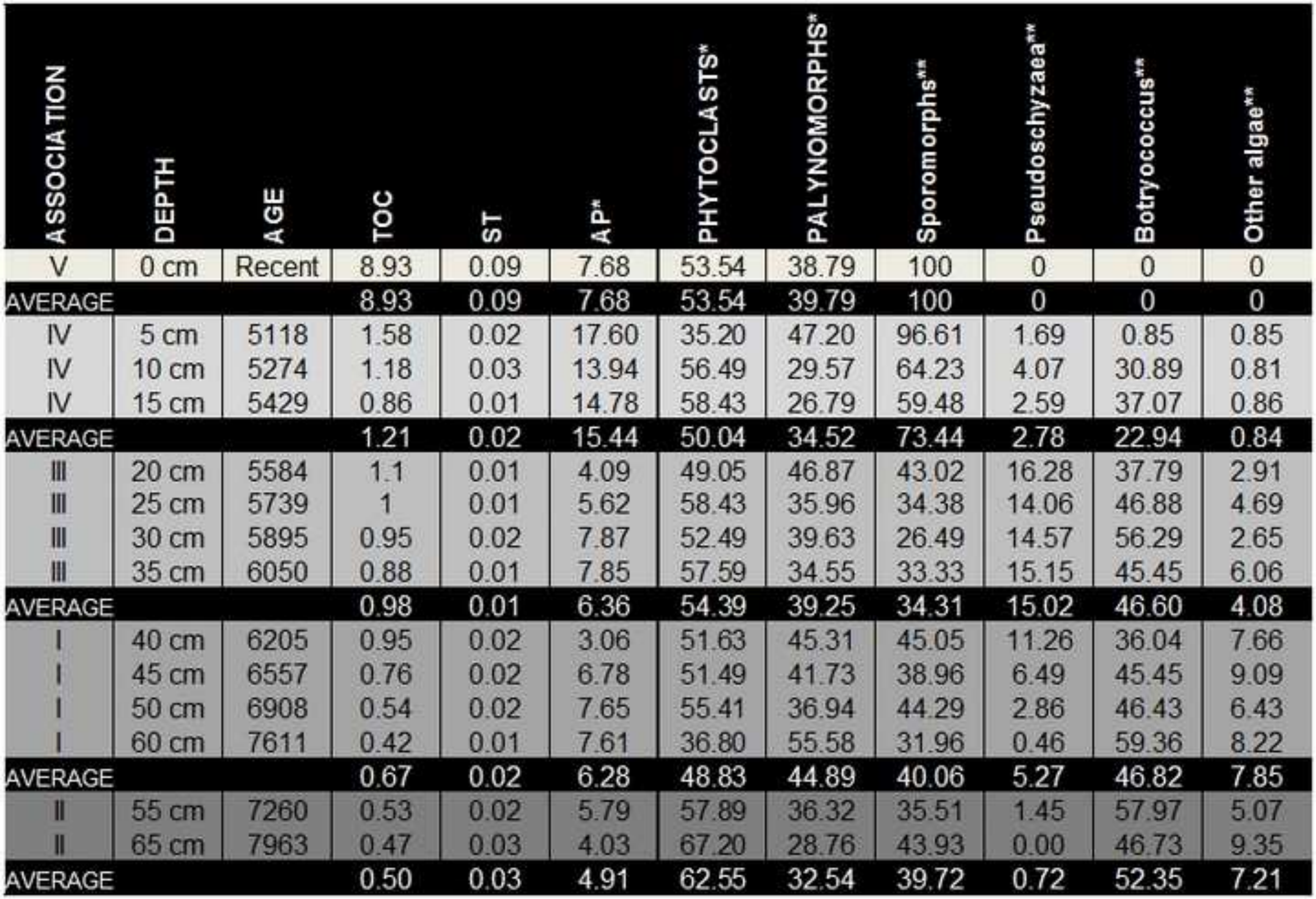

ASSOCIATION	DEPTH	AGE	TOC	ST	AP*	PHYTOCLASTS*	PALYNOMORPHS*	Sporomorphs**	Pseudoschyzaea**	Botryococcus**	Other algae**
V	0 cm	Recent	8.93	0.09	7.68	53.54	38.79	100	0	0	0
AVERAGE			8.93	0.09	7.68	53.54	39.79	100	0	0	0
IV	5 cm	5118	1.58	0.02	17.60	35.20	47.20	96.61	1.69	0.85	0.85
IV	10 cm	5274	1.18	0.03	13.94	56.49	29.57	64.23	4.07	30.89	0.81
IV	15 cm	5429	0.86	0.01	14.78	58.43	26.79	59.48	2.59	37.07	0.86
AVERAGE			1.21	0.02	15.44	50.04	34.52	73.44	2.78	22.94	0.84
III	20 cm	5584	1.1	0.01	4.09	49.05	46.87	43.02	16.28	37.79	2.91
III	25 cm	5739	1	0.01	5.62	58.43	35.96	34.38	14.06	46.88	4.69
III	30 cm	5895	0.95	0.02	7.87	52.49	39.63	26.49	14.57	56.29	2.65
III	35 cm	6050	0.88	0.01	7.85	57.59	34.55	33.33	15.15	45.45	6.06
AVERAGE			0.98	0.01	6.36	54.39	39.25	34.31	15.02	46.60	4.08
I	40 cm	6205	0.95	0.02	3.06	51.63	45.31	45.05	11.26	36.04	7.66
I	45 cm	6557	0.76	0.02	6.78	51.49	41.73	38.96	6.49	45.45	9.09
I	50 cm	6908	0.54	0.02	7.65	55.41	36.94	44.29	2.86	46.43	6.43
I	60 cm	7611	0.42	0.01	7.61	36.80	55.58	31.96	0.46	59.36	8.22
AVERAGE			0.67	0.02	6.28	48.83	44.89	40.06	5.27	46.82	7.85
II	55 cm	7260	0.53	0.02	5.79	57.89	36.32	35.51	1.45	57.97	5.07
II	65 cm	7963	0.47	0.03	4.03	67.20	28.76	43.93	0.00	46.73	9.35
AVERAGE			0.50	0.03	4.91	62.55	32.54	39.72	0.72	52.35	7.21

Figure 10

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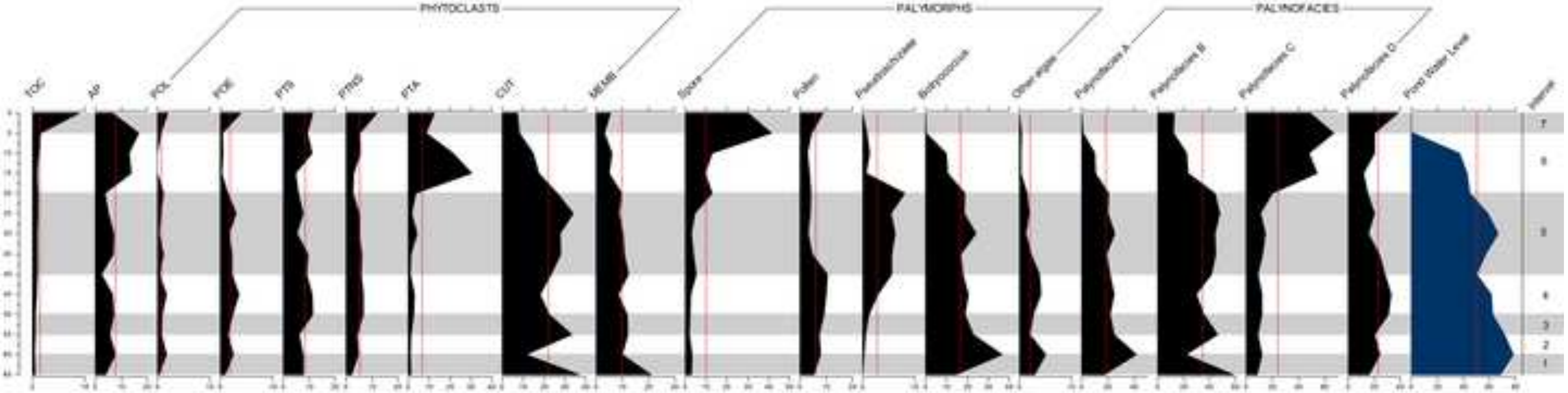
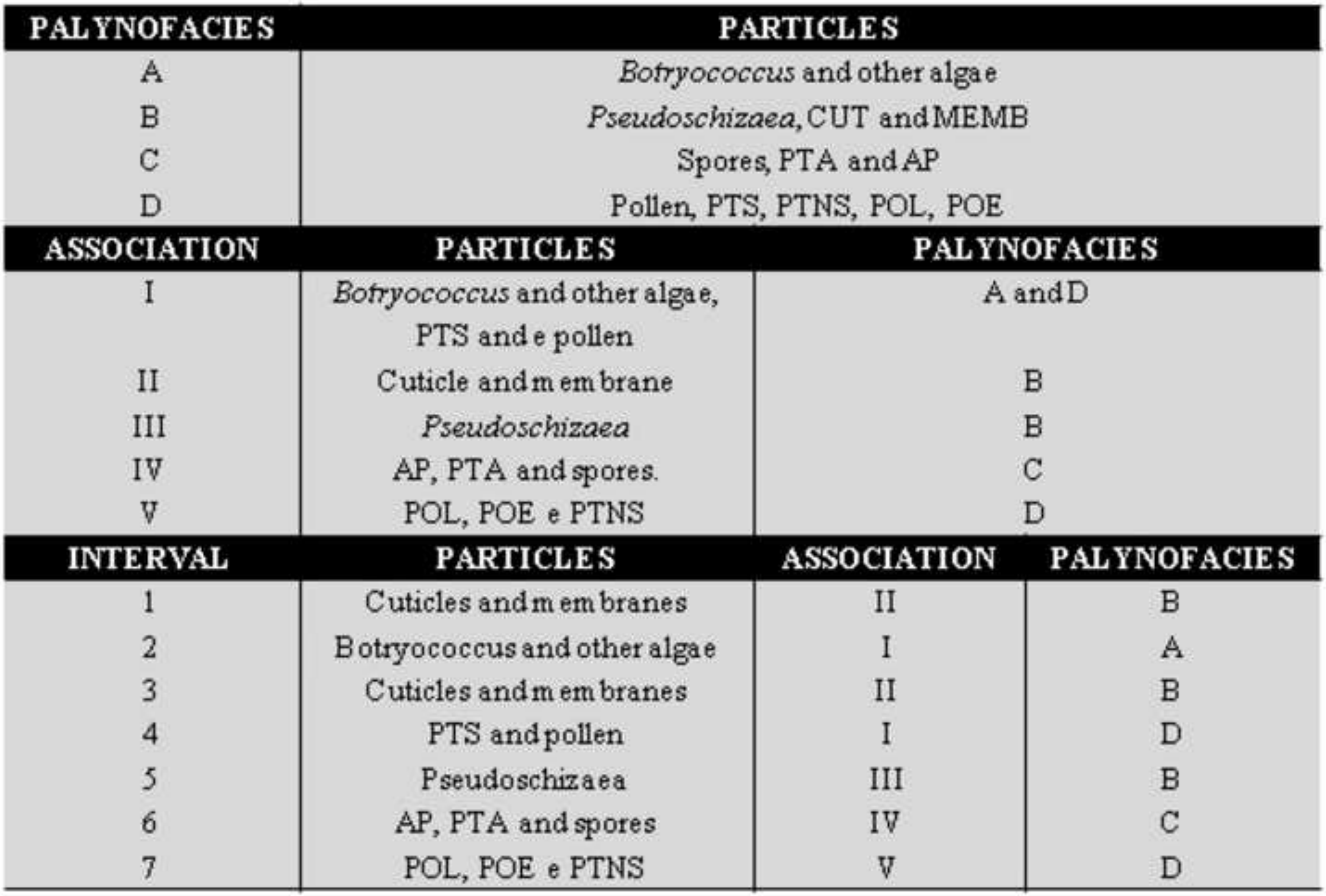


Figure 11

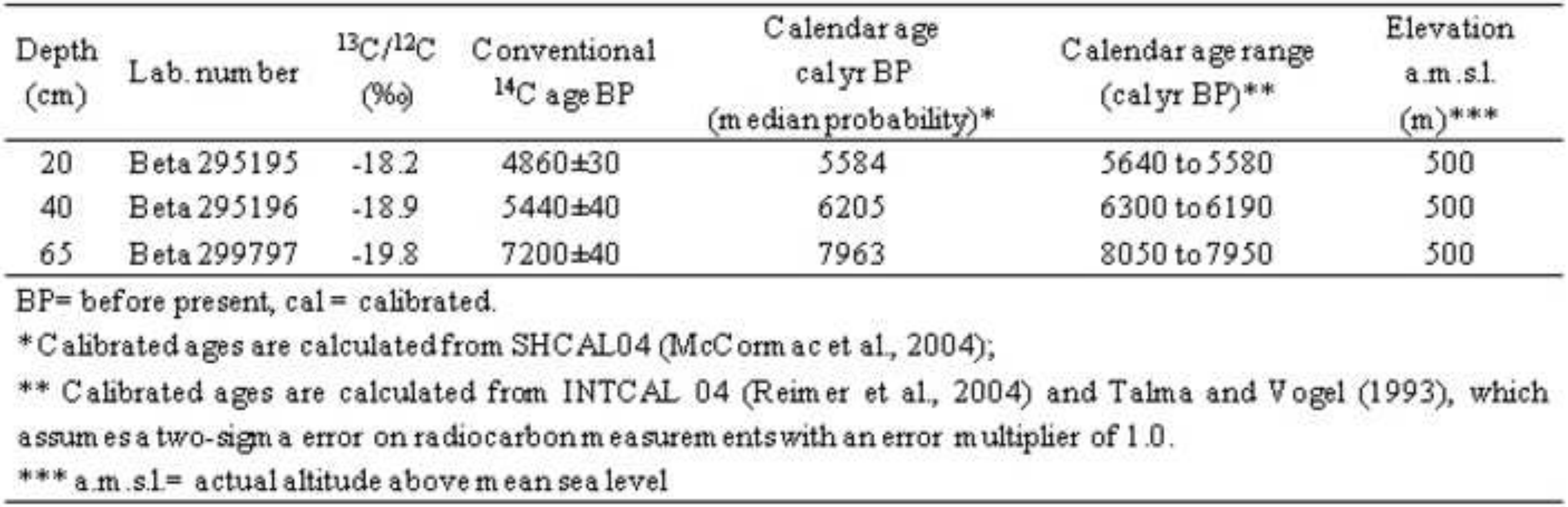


PALYNOFACIES	PARTICLES
A	*Botryococcus* and other algae
B	*Pseudoschizaea*, CUT and MEMB
C	Spores, PTA and AP
D	Pollen, PTS, PTNS, POL, POE

ASSOCIATION	PARTICLES	PALYNOFACIES
I	*Botryococcus* and other algae, PTS and e pollen	A and D
II	Cuticle and membrane	B
III	*Pseudoschizaea*	B
IV	AP, PTA and spores.	C
V	POL, POE e PTNS	D

INTERVAL	PARTICLES	ASSOCIATION	PALYNOFACIES
1	Cuticles and membranes	II	B
2	Botryococcus and other algae	I	A
3	Cuticles and membranes	II	B
4	PTS and pollen	I	D
5	Pseudoschizaea	III	B
6	AP, PTA and spores	IV	C
7	POL, POE e PTNS	V	D

Table 2 (Suppl. data)



Depth (cm)	Lab. number	$^{13}C/^{12}C$ (‰)	Conventional ^{14}C age BP	Calendar age cal yr BP (median probability)*	Calendar age range (cal yr BP)**	Elevation a.m.s.l. (m)***
20	Beta 295195	-18.2	4860±30	5584	5640 to 5580	500
40	Beta 295196	-18.9	5440±40	6205	6300 to 6190	500
65	Beta 299797	-19.8	7200±40	7963	8050 to 7950	500

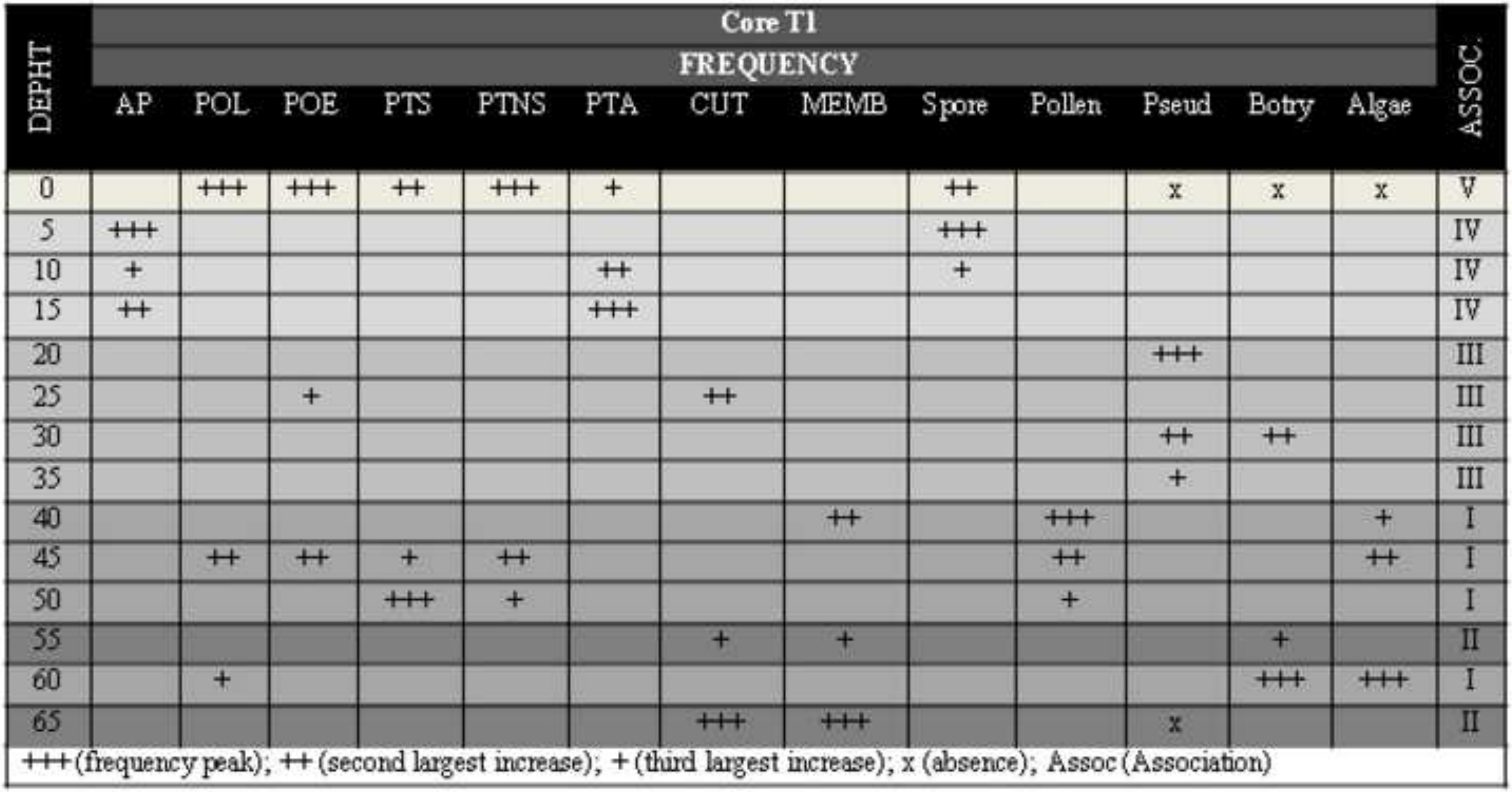
BP= before present, cal = calibrated.

*Calibrated ages are calculated from SHCAL04 (McCormac et al., 2004);

** Calibrated ages are calculated from INTCAL 04 (Reimer et al., 2004) and Talma and Vogel (1993), which assumes a two-sigma error on radiocarbon measurements with an error multiplier of 1.0.

*** a.m.s.l.= actual altitude above mean sea level

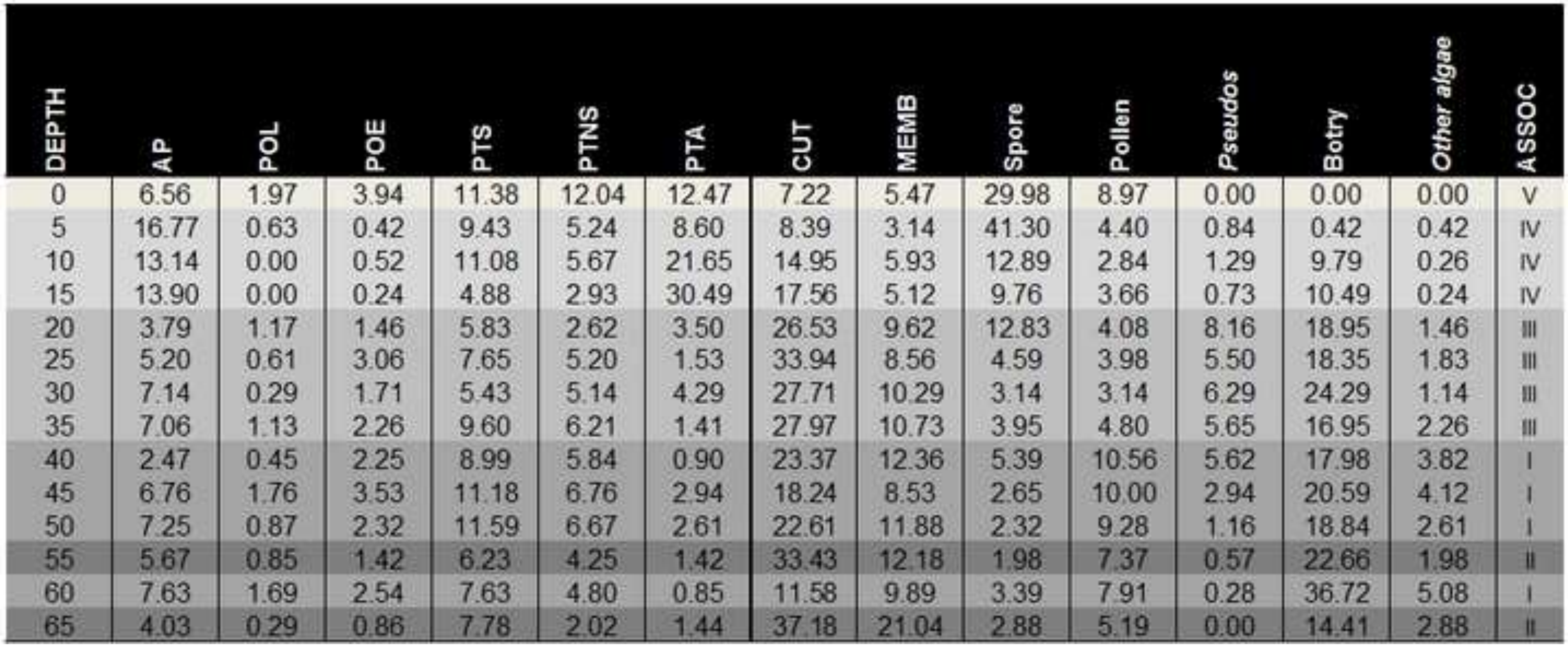
Figure 12 (Suppl. data)



DEPHT	Core T1													ASSOC.
	FREQUENCY													
	AP	POL	POE	PTS	PTNS	PTA	CUT	MEMB	Spore	Pollen	Pseud	Botry	Algae	
0		+++	+++	++	+++	+			++		x	x	x	V
5	+++								+++					IV
10	+					++			+					IV
15	++					+++								IV
20											+++			III
25			+				++							III
30											++	++		III
35											+			III
40								++		+++			+	I
45		++	++	+	++					++			++	I
50				+++	+					+				I
55							+	+				+		II
60		+										+++	+++	I
65							+++	+++			x			II

+++ (frequency peak); ++ (second largest increase); + (third largest increase); x (absence); Assoc (Association)

Figure 13 (Suppl. data)



DEPTH	AP	POL	POE	PTS	PTNS	PTA	CUT	MEMB	Spore	Pollen	*Pseudos*	Botry	*Other algae*	ASSOC
0	6.56	1.97	3.94	11.38	12.04	12.47	7.22	5.47	29.98	8.97	0.00	0.00	0.00	V
5	16.77	0.63	0.42	9.43	5.24	8.60	8.39	3.14	41.30	4.40	0.84	0.42	0.42	IV
10	13.14	0.00	0.52	11.08	5.67	21.65	14.95	5.93	12.89	2.84	1.29	9.79	0.26	IV
15	13.90	0.00	0.24	4.88	2.93	30.49	17.56	5.12	9.76	3.66	0.73	10.49	0.24	IV
20	3.79	1.17	1.46	5.83	2.62	3.50	26.53	9.62	12.83	4.08	8.16	18.95	1.46	III
25	5.20	0.61	3.06	7.65	5.20	1.53	33.94	8.56	4.59	3.98	5.50	18.35	1.83	III
30	7.14	0.29	1.71	5.43	5.14	4.29	27.71	10.29	3.14	3.14	6.29	24.29	1.14	III
35	7.06	1.13	2.26	9.60	6.21	1.41	27.97	10.73	3.95	4.80	5.65	16.95	2.26	III
40	2.47	0.45	2.25	8.99	5.84	0.90	23.37	12.36	5.39	10.56	5.62	17.98	3.82	I
45	6.76	1.76	3.53	11.18	6.76	2.94	18.24	8.53	2.65	10.00	2.94	20.59	4.12	I
50	7.25	0.87	2.32	11.59	6.67	2.61	22.61	11.88	2.32	9.28	1.16	18.84	2.61	I
55	5.67	0.85	1.42	6.23	4.25	1.42	33.43	12.18	1.98	7.37	0.57	22.66	1.98	II
60	7.63	1.69	2.54	7.63	4.80	0.85	11.58	9.89	3.39	7.91	0.28	36.72	5.08	I
65	4.03	0.29	0.86	7.78	2.02	1.44	37.18	21.04	2.88	5.19	0.00	14.41	2.88	II

6.2 Artigo 2

“Relation between sedimentary organic record and climatic fluctuations in the Holocene attested by palynofacies and organic geochemical analyses from an inland pond of highlands in southern Brazil”
Periódico: GEOLOGICA ACTA

CARTA DE RECEBIMENTO

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Barcelona, 22nd February 2013

Dear authors,

I am pleased to inform you that the paper "Relationships between the sedimentary organic record and the climatic fluctuations in the Holocene attested by palynofacies and organic geochemical analyses from a high-altitude inland pond in southern Brazil" by G.T. Gadens-Marcon, M. Guerra-Sommer, J.G. Mendonça-Filho, J.O. Mendonça, M.A. Carvalho, L.A. Hartmann have been received at the Geologica Acta office and will be sent to referees.

Thank you for your fine submittal to the Geologica Acta.

With best regards,

Editorial committee

CARTA DE SUBMISSÃO

Instituto de Geociências

Programa de Pós-Graduação em Geociências

Porto Alegre, February 20, 2013.

Dear editor of Geologica Acta

Ref. Manuscript "**Relationships between the sedimentary organic record and the climatic fluctuations in the Holocene attested by palynofacies and organic geochemical analyses from a high-altitude inland pond in southern Brazil".**

We are pleased to send you the manuscript entitled above. Based os palynofacies and geochemistry organic data, it documents the paleoclimatica and paleoenvironmental evolution from Holocene deposits placed in the southernmost Brazil.

The manuscript is part of the PhD Thesis of the first author at the Geosciences Post-Graduate Course (UFRGS), under coordination of Prof. Dra. Margot Guerra Sommer (Brazil), including Prof. Dr. João Graciano Mendonça-Filho as collaborator. These data were not published yet; they constitute an original contribution, derived from the present authors.

Certainly Geologica Acta constitutes on of the most important journal to divulgue our data, besides its tradition, world scientific qualification.

Sincerely,

Gabrielli Teresa Gadens Marcon

Programa de Pós Graduação em Geociências

Profa. Dra. Margot Guerra Sommer

Advisor

RELATIONSHIPS BETWEEN THE SEDIMENTARY ORGANIC RECORD AND THE CLIMATIC FLUCTUATIONS IN THE HOLOCENE ATTESTED BY PALYNOFACIES AND ORGANIC GEOCHEMICAL ANALYSES FROM A HIGH-ALTITUDE INLAND POND IN SOUTHERN BRAZIL

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ABSTRACT

This paper focuses on the interpretation of the palynofacies and organic geochemistry analyses performed on a sedimentary profile, which covers 9542 cal yr BP from a pond at a high altitude, located in the Mina Modelo, Ametista do Sul, southernmost Brazil. The main goal of this study is to establish the relationship between the sedimentary record and the climatic fluctuations in the Holocene by attempting to correlate the changes in the organic matter with regional climatic changes and perhaps even with events on a global scale. The hydrological isolation renders this pond highly sensitive to climatic effects. The fluctuations in the water depth are inferred from the concentrations of the autochthonous elements (algae), which predominate in the basal intervals and tend to decrease progressively toward the top. The variety of the spores of ferns and the pollen grains in the topmost interval indicates an increased vegetal diversity and is most likely related to the process of successional evolution of the area. *Pseudoschizaea*, in turn, could have some role in the successional process of vegetation and serve as a biological marker of the transitional intervals. An increased rainfall event that was detected between 8.6 to 7.4 ka yr BP may be responsible for the beginning of the sedimentation and water accumulation process in the pond and may be related to the Bond events. The saturation level of the pond remained relatively constant until 6.8 ka yr BP, when changes in the moisture patterns resulted in an intermittent pattern of water depth, which persists to this day.

KEY-WORDS: *organic matter (OM); total organic carbon (TOC); total sulfur (TS); paleoclimatic change; rainfall influence.*

INTRODUCTION

Ponds at high altitudes can be excellent archives of the previous changes in the depositional and ecological conditions under which they formed because they collect sediments only from a restricted basin. Some conclusions can be drawn from the analyses of the particulate organic matter (POM) preserved in these deposits; however, more meaningful reconstructions can be achieved by combining palynofacies and geochemical organic analyses. The studies of organic matter (OM) from present-day terrestrial environments are particularly important because of their sensitivity to environmental changes caused by climate and human impacts.

We rely for this investigation on the concept of palynofacies defined by Tyson (1995), which corresponds to “a body of sediment containing a distinctive assemblage of palynological organic matter thought to reflect a specific set of environmental conditions or to be associated with a characteristic range of hydrocarbon-generating potential”. According to this author, the advantage of applying the palynofacies technique is that it provides direct information about the origin and characteristics of the particulate organic matter, which allows for a more detailed analysis of the subtle variations in the sedimentary environment.

Many of the interpretive models that are available in the scientific literature and that deal with organic geochemical and palynofacies analysis were designed for use in marine and epicontinental sections because their main objective was the exploration of hydrocarbon source rocks. Although it is a relatively recent approach, palynofacies analysis has been applied to many different depositional systems, which has resulted in a powerful research tool that is used to characterize the OM of present-day samples in continental deposits (Di-Giovanni et al., 1999; Noël et al., 2001; Gastaldo and Huc, 1992; Cohen et al., 1999a,b; Sebag et al., 2006a), coastal environments (Marchand et al.,2003; Sparica et al., 2005) and marine deposits (Lallier- Vergès et al., 1993a; Lückge et al., 1996; Valdés et al., 2004; Lallier-Vergès and Albéric, 1990).

In Brazil, palynofacies and organic geochemistry analyses of organic matter were first applied by Mendonça-Filho (1999) to the bitumen-prone Permian sedimentary rocks of the Paraná Basin. Later, these methods were widely applied to the investigation of Mezosoic deposits of marine and epicontinental origin (Carvalho et al., 2006 a,b; Iemini et al.; 2007) and of Cenozoic deposits (Del Papa et al., 2002; Menezes & Mendonça-Filho, 2004; Meyer et al., 2005, 2006, 2010; Medeanic & Silva, 2010; Chagas et al., 2009; Mendonça-Filho et al., 2010a, Silva et al., 2010).

The Holocene Brazilian lacustrine systems were also studied through their organic matter content in numerous regions, using Total Organic Carbon, Rock Eval Pyrolysis, C/N determination, petrography, sedimentology and radiocarbon dating (e.g., Sifedine et al., 2001, 2003; Tturq et al., 2002; Jacob et al., 2004), with an emphasis on the paleonvironmental implications. However, only a few papers addressed the environmental changes in continental areas through the palynofacies analyses of peatlands (Medeanic & Silva, 2010) or in inland lacustrine deposits (Meyer et al., 2010; Silva et al., 2010).

The palynofacies method is a valuable tool to relate particulate OM to the depositional environments in Holocene deposits. This idea is reinforced by the study by Sebag et al. (2006b) on the main approaches used for characterizing particulate OM from Quaternary deposits in recent terrestrial environments, which draws from applied examples in surficial deposits, soil profiles, wetland, lacustrine ecosystems and within catchments.

In this study, we apply palynofacies and organic geochemical analyses to a particular Holocene inland ephemeral pond at a high altitude, which is located in the sub-tropical climatic belt of southernmost Brazil. The pond dries up periodically and receives water input from a direct pluviometric regime; the source area is small. The hydrologic isolation makes this pond very sensitive to climatic changes. According to Hartmann (2008), pools showing a similar morphology are common in the study area; these pools could have originated from the claying of Cretaceous basalts by the action of hydrothermal fluids. Because these amethyst-bearing, smectite-rich basalts directly underlie the ponds, it is understood that the soil at the surface is nearly impermeable, because it inherited the expansive clays as a result of the weathering of the rocks.

Because the ingress of water into the system depends exclusively of the precipitation index, alternative analyses may lead to inferences about rainfall indices that are similar to the inferences obtained through a speleothems analysis.

The speleothems analysis (1.3 to 10.2 Kyr BP) of Stríkes et al. (2011) produced correlations within the Brazilian Holocene across a global scale that provided evidence for strong events of increased precipitation that were centered at 9.2, 8.2, 7.4, 7.0, 6.6, 5.2, 4.0, 3.2, 2.7, 2.3, 2.2 and 1.9 ka yr BP, which are synchronous with the Bond events (Bond et al., 1997). Based on the striking correlation between the ice-rafted debris (IRD) records in North Atlantic sediment cores and the tropical rainfall records, the Bond IRD events have been used to link shifts in the intensity of the Atlantic thermohaline circulation to changes in the sea surface temperature (SST) and related precipitation anomalies over areas affected by the monsoons in Oman (Fleitmann et al., 2003), Asia (Wang et al., 2005), South America (Haug et al., 2001; Baker et al., 2001, 2005) and Brazil (Cruz et al., 2005; Stríkes et al., 2011; Sallum et al., 2012).

In light of the above considerations, the main goals of the present study are (i) to present the results obtained from the palynofacies analyses that were performed on a sedimentary profile encompassing 9542 cal yr BP (median probability) of sedimentation from a Holocene subtropical ephemeral pool at altitude located in Ametista do Sul in southernmost Brazil; (ii) consider the paleoenvironmental significance of the palynofacies analyses; (iii) determine if the particulate organic matter record was affected by paleoclimatic change, that is, if it is climatically sensitive; and (iv) determine whether these changes in the organic matter record reflect local or regional climatic changes or even events of global scale.

GEOLOGICAL BACKGROUND AND SITE DESCRIPTION

The present investigation is focused on the sedimentary record that was recovered from a Holocene inland pool at a high altitude, which currently dries up periodically (Keddy, 2010). The pond is located near the edge of a hill in the mining district of Ametista do Sul, Rio Grande do Sul State, in the southernmost part of Brazil, at an altitude of 500 m (Fig. 1) (Hartmann, 2008). This district is the largest world producer (300 t/month) of amethyst and agate geodes from hydrothermally altered basalts of Cretaceous age (135 Ma) (Hartmann, 2008).

FIGURE 1

The area was selected based on several favorable factors, such as (i) the absence of any hydrodynamic influence from the alluvial plains, which may exert severe interference on adjacent systems; (ii) the very fine-grained sediments that fill the pond area; and (iii) the fact that the area is directly subordinated to the regional pluviometric regime.

The present-day local climate is included within the subtropical climatic zone that is designated as climatic type Cfa (subtropical-humid) by Köppen (1948), and the modern-day vegetation is dominated by semi-deciduous forests that belong to the Mata Atlantica rainforest. The local mineralized bedrocks are basalts from the Cretaceous (133 Ma) Paraná volcanic province and are included in the Serra Geral Group. These units cover 1,300,000 km^2 of South America: mostly Brazil, but also Uruguay, Argentina and Paraguay (Bellieni *et al*. 1984). The volcanic province is at the top of the sedimentary Paraná Basin, which contains the very large Guarani aquifer located directly below the lava formations (Araújo *et al*. 1999). This aquifer mostly consists of sandstones from the Botucatu Formation (Scherer 2000). According to Hartmann (2010), heating by volcanism produced a widespread, large volume of hot water and vapour that resulted in basalt alteration and the related processes of cavity formation and filling.

The amethyst geodes were formed, according to Hartmann (2008), Duarte et al. (2009), Rosenstengel and Hartmann (2012), by the intense circulation of the hot water and vapour that originated from the underlying Guarani aquifer and the consequent alteration of the basalts into clay minerals and zeolites. The hot water also brought fluidized detrital quartz grains from the aquifer, which are now observed in the forms of sandstone layers and breccias in the mines. This made a large quantity of silica available for the ore-forming hydrothermal event. The weathering of the altered basalt led to the formation of smectite-rich soils at the surface and the development of related ponds identified as “gossans” (Hartmann, 2008). These gossans are important guides for mineral prospecting (Pertille et al. 2013) because of their consistent relationship with underlying amethyst mines (Fig. 2). Pools that show similar morphology are common in the study area and, according to Hartmann et al. (2010; 2012), have a common origin; in other words, the formation of the gossans is due to supergenic processes, in which the weathering is superimposed on hydrothermal systems, constituting an anomaly coincident with mineralization of amethyst geodes.

FIGURE 2

MATERIAL AND METHODS

Sampling

The sampling point (27º19.536’S x 53º13.579’W) is known as “Mina Modelo” because it is located immediately above an underground amethyst mine. The site was originally selected with the aid of maps that were generated by satellite (*e.g., Google Earth*) and particularly because of its isolation from the surrounding native woods. Interviews with local residents were essential to confirm the spontaneous nature of the surrounding vegetation of the area. We therefore know that the pond has existed since “Indian times” and was not built by the white settlers.

The samples for the different analyses were recovered from a 160-cm-long sediment core, which was collected manually from the center of the pool. The sampling was performed with the assistance of a tractor backhoe that opened a trench of approximately 2.0 m in depth, which removed the surficial sediment layer until reveal the boundary with the underlying basalt. The corer consisted of a piece of PVC tube 2.0 m long and 7 cm in diameter, which had previously been cut into two halves. For the sample collection, the convex side of the semi-split corer was pressed against the wall of the trench. Once filled with sediment, the corer was sealed with a plastic film at both sides to prevent the loss of moisture. The core was split into subsamples in the laboratory for sedimentary, geochemical and palynofacies analyses.

Granulometric analyses

The granulometric analyses were performed at the Laboratório de Sedimentologia, Centro de Estudos Costeiros e Oceânicos, Instituto de Geociências, Universidade Federal do Rio Grande do Sul. The procedure of sieving and pipetting was performed with class intervals of 1 and ¼ *phi*, respectively, following the method proposed by Folk and Ward (1957).

Dating

To date the core and create a consistent age-depth model, samples were taken at the lithological boundaries. Three radiocarbon datings were performed: on the lower boundary (at a depth of 80 cm), on the middle part (at a depth of 45 cm) of the clay-silty mud (later referred to as Interval B) and on the upper portion (at a depth of 15 cm) of the silt-clayed mud (later referred to as Interval C). We used Acceleration Mass

Spectrometry (AMS) at the *Beta Analytic Radiocarbon Dating Laboratory* (Miami, Florida, USA). The interpolated ages were calculated by using the intercept of the mean conventional age interval in the calibration curve of ^{14}C (CALIB version 4.3 Stuiver et al., 1998). The unconsolidated surficial sediment (0-15 cm) was not sampled because the ambient or anthropic factors may distort the results of the dating metodology.

Geochemistry

The accumulation of Organic Matter (OM) in the sediments is estimated via Total Organic Carbon (TOC) analyses. According to Tyson (1995), TOC analyses are a convenient method to determine the relative abundance of OM in sediments. The accumulation of OM is controlled by major factors such as primary productivity, water depth and sediment grain size. TOC is controlled by three main variables: the input of OM, the preservation of the supplied OM, and the dilution of the OM by sediment accumulation (Tyson, 1995). The values of TOC in marine rocks range from ca. 0.1% (deep-sea pelagic deposits) to 94% (coals) (Tyson, 1995).

The Total Organic Carbon (TOC) analyses implemented the methods of ASTM D 4239 (American Society Testing and Materials, ASTM, 2008) and NCEA-C-1282 (United States Environmental Protection Agency, U.S.EPA, 2002). Following acidification to remove the carbonates, the TOC and ST analyses were performed on all of the samples using the LECO SC 144 equipment at the Laboratory of Palynofacies and Organic Facies (LAFO).

Sample preparation

The preparation of the material for the palynofacies analyses followed the standard non-oxidative palynological procedures that are described by Tyson (1995), Mendonça Filho (1999) and Mendonça Filho et al. (2010b, 2011). For the kerogen concentrate preparation procedure, the samples were ground to a size of approximately 2 mm. The samples were successively treated to remove carbonates (HCl 37% for 18 h), silicates (HF 40% for 24 h) and neoformed fluorides (HCl 37% for 3 h). Between each of the steps, the samples were washed with distilled water until the washing water was neutral. After this procedure, $ZnCl_2$ (density=1.9 to 2 g/cm^3) was added to the samples, which were then stirred and centrifuged to separate the sulfides. The floating material was washed in a similar manner, and HCl (10%) drops+distilled water was added to eliminate the heavy liquid. The isolated kerogen was sieved at 20 μm. After this procedure, strew slides were made with the organic residue.

The strew slides were analyzed at the Laboratório de Palinologia, Instituto de Geociências, Universidade Federal do Rio Grande do Sul under the identification numbers of MP-P 7139 to MP-P 7152 and MP-P 7485 to MP-P 7488.

Palynofacies analyses

The palynofacies analyses involved both quantitative (the counting of 300 to 500 particles) and qualitative (organic particle component identification) examinations of the kerogen component groups and subgroups. These were achieved using microscopic techniques under transmitted white light and blue/ultraviolet incident light (fluorescence). The counting process adhered to the classification of organic matter groups and subgroups that was proposed by Tyson (1995), Mendonça Filho (1999), and Mendonça Filho et al. (2002, 2010b, 2011). In this classification system, the particulate organic matter is organized into three main groups according to their optical properties: Phytoclasts, Amorphous Product (AP) and Palynomorphs.

In this study, all of the organic matter that was without form, had no sharp edges, was without angular contours, or that lacked any type of feature that permitted its classification in any other group of POM was classified as AP (Amorphous Product). Such particles most likely originated from algae or plant debris that was in an advanced state of degradation, which may have been the result of microbial action, or other transformational processes of POM that were active in the studied depositional environment, or both concurrently. The term “Amorphous Product” was chosen because of the exclusively continental origin of the analyzed sediment, thereby avoiding conflict with the term “Amorphous Organic Matter” (AOM), which commonly relates to marine environments or depositional systems that suffer the influence of eustatic variations.

The classification of the palynomorphs subgroups was established taking into account the peculiarities of the studied environment in which only freshwater algae and spores and pollen grains of exclusively continental origin are present (Fig. 3).

FIGURE 3

Statistical Treatment

The statistical treatment of the data was based on a quantitative analysis of the organic particulate components. These data were converted into percentage values and were submitted to multivariate statistical analyses (cluster analysis) of the kerogen groups and subgroups (correlation coefficient Pearson/R-Mode) and an observation of the similarities between the samples (Q-Mode), using the Statistic Basic program version 6.0 (Valentin, 2000).

RESULTS

Profile description

The visual observations that were associated with the granulometric analyses allowed for the identification of four sedimentary intervals that together extend from the base of the core (at a depth of 160 cm) to the surficial unconsolidated level (Fig. 4):

Interval A. Corresponds to the lower part of the core (160-80 cm) and shows a predominance of fragmented basalts that are yellowish-gray in color and that occur as coarse gravel mixed with sand and clay-silty mud, the latter of which most likely originated from suprajacent levels by percolation through the basalt.

Interval B. Corresponds to the lower middle section of the core (80-30 cm), where a significant disconformity is observed that involves a shift to a finer grained texture and a change in the granulometry and color patterns, relative to Interval A. Interval B is composed of a dark grayish, semi-compact and texturally homogeneous mud. The granulometric analysis classified the sediment as a degraded, clay-silty mud with a predominance of the clay fraction (Table 2). The fine grain size indicates a low energy depositional setting, and the absence of sedimentary structures suggests that the sediment was deposited through decantation under quiet lacustrine conditions.

Interval C. Corresponds to the upper middle section of the core (30-10 cm). It is composed of a grayish, semi-compact mud that is texturally homogeneous and shows few thin vegetal remains. The granulometric analysis classified the sediment in this section of the profile as a silty-clayey mud with a predominance of the silt fraction (Table 2).

Interval D. Represents the surficial sediments of the core (10-0 cm) and is composed of a brownish-gray soil, which shows thin rootlets and bioturbation.

Only the intervals B, C and D were employed in this study because their sedimentary composition indicated potential for the preservation of organic matter. Due to the extreme homogeneity of the sediment in Intervals B and C, only three samples were selected for granulometric analysis; these samples are referred to as Base (80 cm), Midst (45 cm) and Top (15 cm) (Table 2).

Radiocarbon dating

A chronological framework for the B and C sedimentary intervals was provided by the radiocarbon dates (Fig. 4, Table 1). A gradual and low mass accumulation rate in the pond can be inferred from the combination of a long interval of time and a short interval of sedimentation (80 cm). Additionally, the age of 9690 to 9540 years cal BP (median probability of 9542 cal yr BP) that was obtained from the sample at a depth of

80 cm is significant because the sample directly overlies the basalt at the roof of the underlying amethyst mine and the date represents the beginning of the pond sedimentation and should represent the age of the pond itself.

Table 1

FIGURE 4

Geochemical Organic Analysis

The geochemical organic characterization (Total Organic Carbon - TOC) expresses the amount of organic matter contained in the sediment (Tyson, 1995). Geochemical organic parameters are widely applied to deposits of marine and epicontinental origins (and are applied to the prospecting for hydrocarbon source rocks). Few studies have been performed in strictly continental areas that evolved without the influence of eustatic variations. However, according to Tyson (2001, p. 333), “in order to make sense of TOC data we must appreciate the way in which these three variables (the input, the preservation, and the dilution of organic) interact; this can only be done for Recent sediments as these are the only place where there is a possibility of quantifying the full set of critical parameters with sufficient accuracy”.

In the T2 core samples (Mina Modelo), the TOC contents reached a maximum percentage of 1.27% at a depth of 15 cm, and the TS content reached a maximum of 0.06% at a depth of 25 cm (Table 2). The phytoclast group constitutes the majority of the organic matter over the entire segment (80-0 cm) that was analyzed, and significantly influenced the carbon content of the sediment. The low concentrations of TOC and TS are related to oxic phases (Tyson, 2001), and the continental aquatic environments contain very low concentrations of dissolved sulfate (Tyson, 1995). In the analyzed samples, the low concentrations of ST indicate that the sulfate-reducing processes, which are typical of an anoxic environment, were not significant during the sedimentary deposition. This evidence, which is associated with the low concentrations of TOC in most of the samples, confirms the relatively oxic conditions of the depositional environment and can be related to a low to moderate sedimentation rate. Even considering that the percentage of TOC does not reach 1% in some of the intervals, the high C/S ratio (> 15) is typical of freshwater environments, according to the model proposed by Berner and Raiswell (1984).

Despite the references that assert that a silt-dominated sediment is less favorable to the preservation of organic matter than is a clay-dominated sediment, in the present paper, the change in the predominant grain size in the interval of 15-25 cm coincides with an increase in the TOC concentrations (Table 2).

In the samples taken at 25 and 15 cm, the TOC concentrations that are above 1% correlate with a high percentage of “associated cuticles” (containing appended subcuticular remnants). In the sample taken at 20 cm, on the other hand, the TOC contents above 1% can be correlated with the peak of PTA and an increase of AP. Each of these elements may have contributed to the moderate increase in the concentration of TOC because such particles tend to contribute to high quantities of organic carbon in the system due to the more advanced stage of molecular degradation.

The lowest TOC concentrations in the samples, which were taken at depths of 10, 5 and 0 cm (Table 2), may be related to their more surficial positions in the sediment, which offered more exposure to oxidation.

Table 2

Palynofacies Analysis

The phytoclast group forms the majority (61.48%) in each of the samples (Fig. 5), while the palynomorphs are the second most abundant group (32.05%) and the AP group is the least abundant (6.47%). The concentrations of TOC in the sediment are regulated by the most abundant group, in this case, the phytoclasts.

In general, the particles are highly fluorescent due to the young age of the sediment. Among the sporomorphs (Fig. 6), the fluorescence varies from yellowish-green (*Botryococcus*) to yellow or yellow-orange (spore and pollen), and among the phytoclasts (Fig. 7, A-K), it varies from yellow (cuticle and membrane) to yellow-orange or orange-brown (PTS, PTNS and PTA). The AP group (Fig. 7, L-M), in turn, exhibits fluorescence ranging from yellow-orange and reddish-orange to orange-brown.

FIGURE 5

FIGURE 6

FIGURE 7

Hierarchical cluster analysis in R-mode

Through the application of the statistical R-Mode, using the Ward's method with a 1-Pearson distance, the samples were classified into four main clusters of particles, denoted Palynofacies A, B, C and D (Fig. 8 and 12).

FIGURE 8

Palynofacies A is represented by autochthonous (*Pseudoschizaea*) and parautochthonous (spores) elements, which are indicative of moist environments and which have undergone little if any transport. Palynofacies B is represented by *Botryococcus*, which are autochthonous elements that are indicative of the presence of a water body, and by cuticles, which are allochthonous, non-woody elements of plant origin. Palynofacies C is represented by amorphous components (AP and PTA) and PTNS, all of which are allochthonous. Palynofacies D comprises autochthonous elements designated as "other algae," which indicate the presence of a water body, and allochthonous elements (pollen grains, membrane, PTS, POL and POE) of terrigenous origin.

Hierarchical cluster analysis in Q-mode

Through the application of the statistical Q-mode, using the Ward's method with Euclidian distance, four main associations of samples were observed and identified as

Associations I, II, III and IV (Fig. 9 and 12). These associations are related to the palynofacies defined by the cluster R-mode (Fig.8).

FIGURE 9

Association I comprises the samples from 40, 45, 50, 55, 60, 65 and 70 cm. The particle that reaches the peak frequency in this association is *Botryococcus* (FIG. 13 and 14, Appendix), which is related to Palynofacies B. The Phytoclast group predominates (average 58.69%) over the Palynomorph and AP groups, which average 35.75% and 5.56%, respectively (Fig. 10). The cuticles are the most abundant subgroup of phytoclasts. Among the palynomorphs, the algalic elements prevail over the terrestrial elements in all of the samples. In the association as a whole, *Botryococcus* predominates over the other freshwater algae, and the spores predominate over the pollen grains.

Association II is characterized by the samples taken from depths of 15, 25, 30 and 35 cm. The particles that reach the peak frequency in this association (FIG. 13 and 14, Appendix) are the cuticles (Palynofacies B) and the spores and *Pseudoschizaea* (Palynofacies A). The phytoclasts are the dominant group (average 58.47%), while the AP Group is the least abundant (5.60%). The Palynomorph group, although reaching a higher frequency in this association (average 35.93%), is only the second largest group in the association (Fig. 10). The average percentages of the three major groups of OM (phytoclasts, palynomorphs and AP) in this association are very similar to those of Association I; however, the prevailing subgroup and the dominant types of particles differ greatly. The terrestrial sporomorphs (particularly the spores) predominate among the palynomorphs. One exception is the sample taken from a depth of 30 cm, in which the algalic elements are more abundant (52.52%) due to the presence of *Pseudoschizaea*, which reaches a high percentage in this association and even surpasses *Botryococcus* in the samples taken from 25 and 15 cm. *Pseudoschizaea* displays a slightly different behavior than do the other algae because its percentage increases in the samples in which the concentrations of *Botryococcus* and other algae decrease; however, it seems to correspond with the distribution of the spores.

Association III is represented by the samples from 75 and 80 cm. The particles that reach the peak frequency in this association (FIG. 13 and 14, Appendix) are the other algae, pollen grains, membrane, PTS, POL and POE, which compose Palynofacies D. The phytoclasts predominate (average 62.20%) over the palynomorphs (average 31.83%) and the AP (average 5.97%) (Fig. 10) Among the palynomorphs, the terrestrial sporomorphs (53.84%) predominate over the algalics in the sample at the base (80 cm), particularly the pollen grains (39.42%). In the sample taken at 75 cm, the algalic sporomorphs become dominant (51.43%) because of an increase of the Botryococcus concentrations (38.10%). The frequency of spores (30.48%) also exceeds that of the pollen grains (18.10%) in the sample taken at 75 cm.

Association IV is characterized by the samples from 0, 5, 10 and 20 cm. The particles that reach the peak frequency in this association are AP, PTNS and PTA (FIG. 13 and 14, Appendix), which are related to Palynofacies C. The Phytoclast group and the AP group achieve higher average frequencies in this association, 70.01% and 9.28%, respectively (Fig. 10). The Palynomorph group, however, is at its lowest average value (20.70%). Among the palynomorphs, the terrestrial sporomorphs dominate in the samples of 20, 10 and 5 cm, but they are surpassed by algalic sporomorphs at the top of the core because of the significant increase in the frequency of *Botryococcus*. The pollen grains also become predominant over the spores in the topmost sample.

FIGURE 10

Paleoenvironmental characterization based on intervals generated by Q-Mode cluster analysis

Based on the associations generated by the Q-mode cluster analysis, the sedimentary section (Fig. 4) was subdivided into six intervals (Fig. 11), from the base to the top of the core, with the aim of inferring the hydrological fluctuations that occurred during the time interval of 9542 cal yr BP to the present day in the pond and the surrounding area from the evidence of autochthonous and allochthonous particles (Fig.11 and 12).

The estimates of the pond's water level (Fig. 11) were constructed based on the frequency of *Botryococcus* and other algae. *Pseudoschizaea* is considered a genus *incertae sedis* (Christopher, 1976) and shows a somewhat different behavior when compared to *Botryococcus* and other algae. Hence, the construction of the water level curve does not take into account its distribution.

FIGURE 11

The first interval (9542 to 9238 cal yr BP) corresponds to Association III (80-75 cm) and is marked by the peak frequencies of the other algae, pollen grains, membrane, PTS, POL and POE, which are related to Palynofacies D. From the base (80 cm) up to the next sample (75 cm), a change is observed in the dominance of terrestrial sporomorphs by algalic sporomorphs. *Botryococcus* and other algae indicate the presence of a water body that is sufficient to support this type of biomass, which tends to increase in the subsequent samples. The terrestrial sporomorphs are represented by spores of ferns and pollen grains (Cyperaceae and *Ludwigia*), which are indicative of a moist environment (Leonhardt and Lorscheitter, 2008, 2010). This interval marks the beginning of the water accumulation process in the *gossan* and of the pond sedimentation. The high frequency of woody phytoclasts (PTS), non-woody (membrane) and opaques (POL and POE) in this interval is the result of entrainment by rainwater of these terrigenous elements within the depositional system.

The second interval (8935 to 7113 cal years BP) corresponds to Association I (70-40 cm) and is marked by the peak of *Botryococcus* and the high frequency of cuticles, which are particles that are related to Palynofacies B. The average frequency of the algalic sporomorphs (65.47%) is much higher than that of the terrestrial sporomorphs (34.53%), which indicates the highest water level in the pond in this interval. This allows us to infer a period of wetness, especially in the samples of 65 cm (8631 cal years BP) and 45 cm (7417 cal years BP), in which the *Botryococcus* frequencies are exceptionally high (above 60%). Among the terrestrial sporomorphs, the spores predominate over the pollen grains, which may be due to the aquous saturation level of the soil or to the vegetational evolution of the area. The high frequency of the cuticles may also be related to an increased sedimentation rate, triggered by a high rainfall periodicity.

The third interval (6810 to 6203 cal yr BP) corresponds to Association II (35-25 cm) and is marked by the peak concentration of cuticles (related to Palynofacies B) and an increased frequency of *Pseudoschizaea* and spores (related to Palynofacies A). The average frequency of the terrestrial sporomorphs increases in comparison to the algalic sporomorphs. The frequencies of *Botryococcus* and the other algae begin to oscillate, with a tendency to gradually decrease. However, the same trend does not occur with *Pseudoschizaea,* whose peaks of abundance seem to have a closer relationship with those of the spores than with those of the other algae. This allows us to speculate that this form is an algalic taxon that can serve as a biological marker of transitional intervals (Van Gell, 1978; van Gell and van Der Hammen, 1978) and that has some role in the successional process of vegetation because its distribution pattern along the core intersperses the expansion phases of the algalics and the terrigenous elements. Although the decreased concentration of algalic elements indicates a decrease in the aqueous saturation, the increases in the frequencies of the spores and *Pseudoschizaea* demonstrate a persistently high level of local humidity. Scott (1992) observed that *Pseudoschizea* can be an indicator for local seasonal drying because it is a common form in recent environments in relatively warm areas of the world where moisture is available. Possibly, the variation in water depth, which would produce the intermittent pattern observed in the pond, started to become more meaningful from the initial portions of this interval (35-30 cm), where the alternations between periods of greater and lesser moisture seem to acquire a seasonal pattern.

The fourth interval (5899 cal yr BP) corresponds to Association IV (20 cm) and is marked by a peak in PTA and a high frequency of AP, which are particles that are related to Palynofacies C. The average frequencies of algalic sporomorphs (18.82%) and terrigenous (81.18%) are striking, with a preponderance of spores of ferns. This interval, however, is characterized by a significant reduction in the frequencies of all of the palynomorphs, which may be due to a decrease in moisture that is regulated by accented oscillations in the rainfall patterns. The ephemeral nature of the pond most likely dates from this period. The predominance of amorphous particles is a result of the organic matter undergoing a prolonged exposure to oxic degradation processes, which resulted in a decreased water depth.

The fifth interval (5467 cal yr BP) corresponds to Association II (15 cm) and is marked by a peak of *Pseudoschizaea* and spores, which are related to Palynofacies A. The difference between the average frequencies of the terrestrial sporomorphs (63.9%) and the algalics (36.1%) decreases slightly, although the spores remain prevalent. In this interval, the rainfall conditions necessary for the reestablishment of algalic biomass have returned, although they are quantitatively more modest than those of the first and second intervals. The increase in moisture is also corroborated by the increased frequency of spores and the high frequency of algae. The low frequency of the amorphized elements is most likely attributable to the deep water depth, which protected the particles from degradation.

The sixth interval (5142 cal yr BP to Recent) corresponds to Association IV (10-0 cm) and is marked by a peak of AP and PTNS, which are related to Palynofacies C. The frequency of the terrestrial sporomorphs is higher in the samples of 10 and 5 cm, while the frequency of the algalic sporomorphs is higher at the top of the core (0 cm). Similar to the pattern in the fourth interval, the predominance of amorphized elements in the samples of 10 and 5 cm may be related to a lower level of water saturation in these layers. The sample of 10 cm revealed conditions of low humidity, which is evidenced by the reduced frequency of all palynomorphs (12.78%), especially those of algalic origin. From the sample at 5 cm, however, the changes in the rainfall patterns result in an increased frequency of palynomorphs (22.47%), mainly *Botryococcus*. From the next interval (top sample), the spores frequency decreases, but the pollen grains frequency increases, indicating a change in the dominant vegetation. Unlike what occurs at the base, the variety of spores of ferns and pollen grains in this sample indicates an increased vegetal diversity, which is most likely related to the process of successional evolution of the area. The frequency of *Pseudoschizaea* decreases by half in this interval, and the other algae disappear, possibly as a response to the constant fluctuations in water depth. The ephemeral nature of the pond starts to act as a limiting factor to the permanence of certain organisms (the other algae) that were initially present. The intermittency does not seem to affect other organisms, such as *Botryococcus*, which increases its frequency at the top of the core, indicating the return of moisture conditions sufficient to maintain this type of algal biomass. The high frequency of opaque phytoclasts (POL and POE) and non-opaques of woody origin (PTS and PTNS) at the top of the core are the result of the entrainment of these terrigenous elements into the depositional system by rainwater and corroborate the interpretation of an increase in moisture during this interval. Additionally, the presence of opaque particles in the more recent interval may also be indicative of human interference in the environment.

In addition to being connected to pluviometric periodicity, the reduction of the water level may also be linked with the progressive sedimentary filling of the pond over time. According to Esteves (2011), lakes are generally not permanent features of the landscape, and their eventual fate is to succumb to their own sedimentary metabolism over geologic time. Currently, the pond forms during the rainiest months, but its current depth is possibly even lower than it was at the beginning of its sedimentation.

FIGURE 12

DISCUSSION

The curve of the water level in the pond (Fig. 11) indicates significant changes in the level of aqueous saturation of the pond since 9542 cal yr BP, which resulted in a reduction in water depth and in an intermittent flood pattern, such as are currently observed. The current pattern, however, was not prevalent in the past, when the pond maintained high levels of aqueous saturation, which is possibly attributed to the more intense rainfall patterns that prevailed in previous time periods. The higher precipitation events occurred between 8631 and 7417 years cal BP (65 to 45 cm), despite some oscillations in the water-level. The more conspicuous alterations in the wetness patterns started at 6810 cal yr BP (35 cm depth) and intensified at 5899 cal yr BP (20 cm); subsequently, interspersed periods of higher and lower moisture began to take place, which is a pattern that has endured until now. The pond water level, however, is lower now than it was in the past.

The water accumulation process in the gossan and the sedimentation of the pond were initiated at approximately 9500 years BP and were intensified by the increased rainfall, which started nearly 8500 years BP and lasted until approximately 7400 years BP. The rainfall remained relatively constant until approximately 7000 years ago. Thereafter, the rainfall patterns become irregular. The oscillations between high and low rainfall periods became progressively more frequent, and the high moisture levels of the early Holocene tended to decrease toward the present day. The higher precipitation events of the early Holocene can be correlated with the Bond events (Bond et al., 1997), especially the 9.4, 8.2 and 7.4 ka events. These events may have been global in scope because they coincide with periods of low solar activity (Bond et al., 2001) and because the glacial boundary conditions persisted until 7.0 ka yr BP in the Northern Hemisphere (Carlson et al., 2008). The events subsequent to 7000 years BP that are reported here may be a consequence of abrupt ecological changes that were intrinsically driven. All of the changes reported for the Holocene, as indicated by Williams et al. (2011), were strongly controlled by the local biotic and abiotic processes and also by localized disturbances and regional climatic events, which, ultimately, can be linked to events on a global scale. The gradual reduction of the moisture in the middle and late Holocene, however, may be related to local climate change but could also be a reflection of global events related to climate warming.

According to Sallum et al. (2012), the anomalies in southeastern Brazil show a high degree of correlation with the cooler conditions associated with the North Atlantic 8.2 ka event, which appears to have affected the environmental equilibrium in South America and intensified the South American summer monsoon. In Brazil, this event had effects of short duration, approximately a few hundred years, and would have increased local precipitation, humidity and sea level (Sallum et al., 2012). The 8.2 ka event is one of the most well-known climate events of global extent (Salinger and McGlone, 1990; Gasse and Van Campo, 1994; Alley et al., 1997; Wick and Tinner, 1997; Klitgaard-Kristensen et al., 1998; Hu et al., 1999; Thompson et al., 2002; Douglass et al., 2005; Ljung et al., 2008; Sallum et al., 2012). These results suggest (according to Sallum et al., 2012) that a modern-day short-duration North Atlantic climatic event, such as the 8.2 ka event (and perhaps other Bond events), could affect the climate dynamics in South America.

The records of the high moisture periods, particularly those associated with the Bond events, are of great importance because the global extent of these events is still not well-known. The paleoclimatic records are still very scarce in Brazil (Cheng et al., 2009; Stríkes et al. 2011; Sallum et al., 2012). This is due to the small differences between the ages obtained, arising of the uncertainties in ^{14}C reservoir age corrections.

CONCLUSION

Palynofacies and geochemical organic analyses are powerful tools in the palaeoenvironmental and paleoclimatic study of a Holocene, strictly continental, inland pond in southern Brazil. This study allows the following conclusions to be drawn:

1 - The low amounts of TOC and TS in the samples can be related to the relatively oxic conditions of the depositional environment and to a low to moderate sedimentation rate. The ratio between the concentrations of TOC and TS is high and typical of freshwater environments.

2 - The predominance of phytoclasts indicates that this group controls the organic carbon content of the sediments in all of the samples. The palynomorphs are the second most dominant group, and the Amorphous Product is the least abundant group.

3 - The saturation level of the pond remained relatively constant from 8935 to 6810 cal yr BP, when changes in the moisture patterns made the environment drier and resulted in an intermittent pattern of water depth, which currently exists at the site.

4 – The fluctuations in the water depth are inferred from the frequency of *Botryococcus* and other algae, which predominate in the basal intervals. However, the autochthonous elements tend to decrease progressively toward the top and begin to

alternate periods of high and low frequency with the parautochthonous (spores) and allochthonous (pollen grains) elements. This pattern is due to the reduction in the water depth and to the establishment of the intermittent flood pattern of the pond.

5 - *Pseudoschizaea* seems to have a closer relationship with the spores than with the other algae. We thus speculate whether this form is an algalic taxon that can serve as a biological marker of transitional intervals related to seasonal drying or that has some role in the successional process of vegetation.

6 - Once established, the intermittent pattern of the pond acts as a limiting factor for the permanence of certain organisms that were initially constantly present. However, it seems not to affect others, such as *Botryococcus*, which increases in frequency where *Pseudoschizaea* decreases and the other algae disappear. This may be a response to the constant fluctuations in water depth.

7 - The variety of the spores of ferns and pollen grains in the topmost interval indicates an increased vegetal diversity and is most likely related to the process of the successional evolution of the area. In the top sample, the frequency of spores decreases, but the pollen frequency increases, which indicates a change in the dominant vegetation.

8 – An increased rainfall event that was detected between 8631 to 7417 years cal BP can be related to the Bond events; this event was responsible for the beginning of the water accumulation process in the gossan and the sedimentation of the pond.

9 - The gradual reduction in moisture subsequent to 7000 years BP may be related to local climate change but may also be a reflection of global events related to climate warming.

10 – These results are of great importance for the understanding of the global extent of the Bond events, which is not well-known for the Brazilian territory. Further

studies are required to improve the understanding of the global climate changes and their local and regional environmental impacts.

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APPENDIX

FIGURE 13 – Table showing the ranges of higher frequencies of the TOC and TS and the major subgroups of the POM. Abbreviations are in accordance with FIG. 3.

FIGURE 14 – Table showing the frequency peaks of major subgroups of particulate organic matter. The percentage values of the subgroups are related to the total organic matter, including the palynomorphs, and the frequency peaks are highlighted. Abbreviations are in accordance with FIG. 3. Assoc (Association)

FIGURE CAPTIONS

FIGURE 1 – Location map of Ametista do Sul (adapted from Hartmann et al., 2010)

FIGURE 2 - Model sections of lava units in the mining districts from Ametista do Sul (adapted from Hartmann et al., 2010)

FIGURE 3 - General classification of POM used in this work

Table 1 - AMS (Accelerator Mass Spectrometry) radiocarbon ages from the sediments of the T2 core (Mina Modelo). The analyses were performed by Beta Analytic, Inc.

FIGURE 4 – Chronological framework for the sedimentary profile of the T2 core (Mina Modelo), showing the calibrated radiocarbonic age (cal yr BP) and the interpolated ages (*). The analyses performed by Beta Analytic are highlighted in bold. The other ages are calculated as the median probability.

Table 2 – Percentage values of the TOC and ST and granulometric analysis of the T2 core (Mina Modelo)

FIGURE 5 – a) Ternary diagram showing the relationships of the major groups of POM in each of the samples; b) Ternary diagram showing the relationship of the sample associations I, II, III and IV.

FIGURE 6 - Palynomorphs group. A-B, *Botryococcus*; C-D, *Pseudoschizaea*; F-G, *Spyrogira*; H, *Debaria*; I, *Desmídia*; J, *Mougeotia*; K-M, Pteridophyte spores; N-O, pollen grain. Scale bars: 20 μm.

FIGURE 7 - A-E, Phytoclasts group. F-I, cuticles; J-K, membrane; L-M, Amorphous Product (AP). Scale bars: 20 μm

FIGURE 8 – Dendrogram produced by cluster analysis R-mode for groups and subgroups of the POM from the T2 core (Mina Modelo). The red vertical lines divide the four palynofacies. Abbreviations are in accordance with FIG. 3.

FIGURE 9 – Dendrogram produced by Q-mode cluster analysis for groups and subgroups of the POM from the T2 core (Mina Modelo) in relation to depth. The red vertical lines divide the four associations. Abbreviations are in accordance with FIG. 3.

FIGURE 10 – This table shows the percentages of the TOC and ST and the percentages of the major groups and subgroups of the POM and of the averages of the sample groups. (*) Percentage value of the three main groups of POM related to total organic matter. (**) Percentage values of the sporomorphs related to the total palynomorph group. Abbreviations are in accordance with FIG. 3.

FIGURE 11 – Variation of the palynofacial and geochemical parameters of the main groups and subgroups of POM. The red vertical lines indicate the midline. Abbreviations are in accordance with FIG 3.

FIGURE 12 - Table showing the Palynofacies, the Associations and the Intervals generated by statistical analyses**.** Abbreviations are in accordance with FIG 3.

FIGURE 1

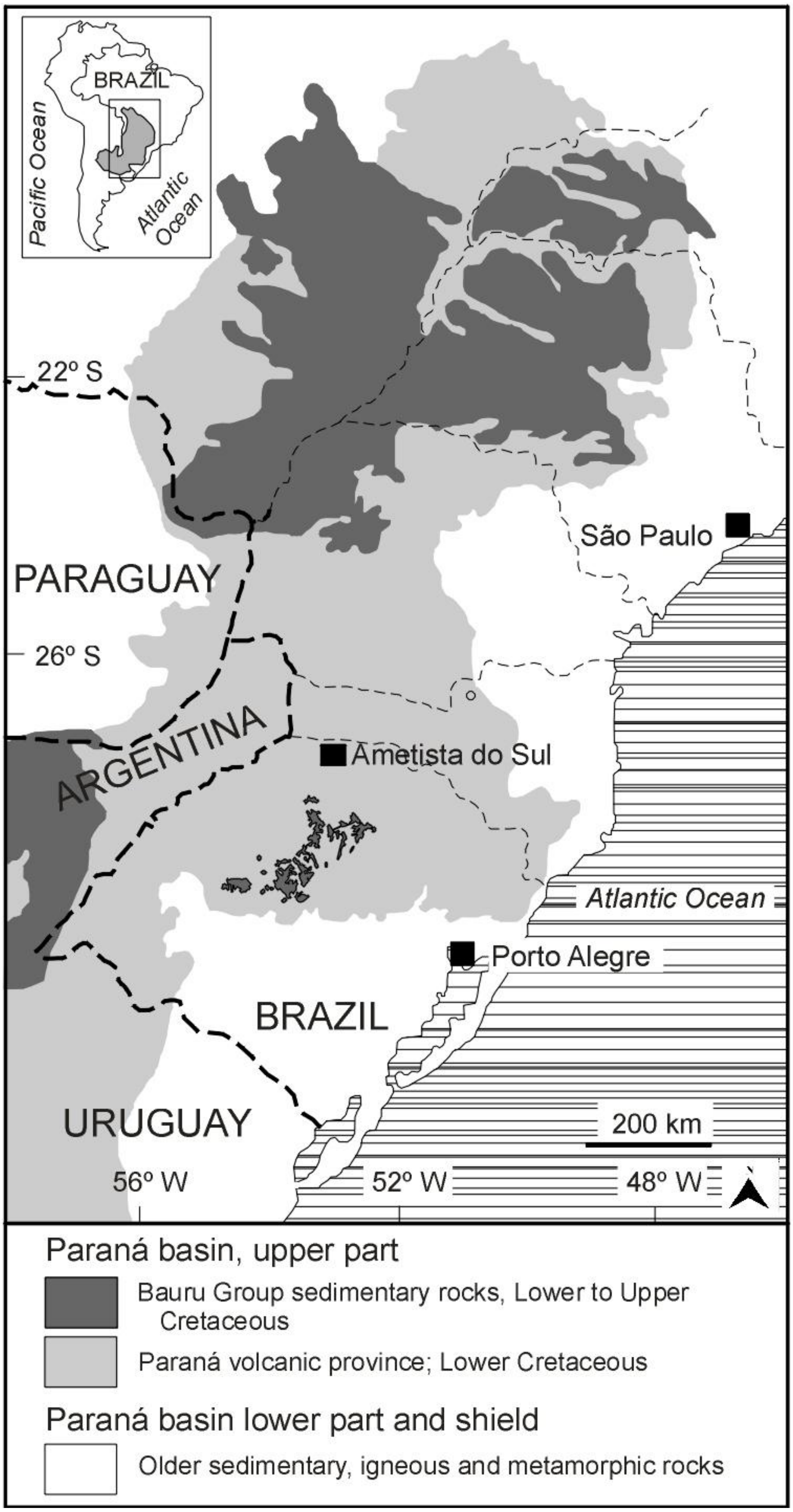

BRAZIL
Pacific Ocean
Atlantic Ocean
22º S
26º S
PARAGUAY
ARGENTINA
São Paulo
Ametista do Sul
Atlantic Ocean
Porto Alegre
BRAZIL
URUGUAY
200 km
56º W
52º W
48º W
Paraná basin, upper part
Bauru Group sedimentary rocks, Lower to Upper Cretaceous
Paraná volcanic province; Lower Cretaceous
Paraná basin lower part and shield
Older sedimentary, igneous and metamorphic rocks

FIGURE 2

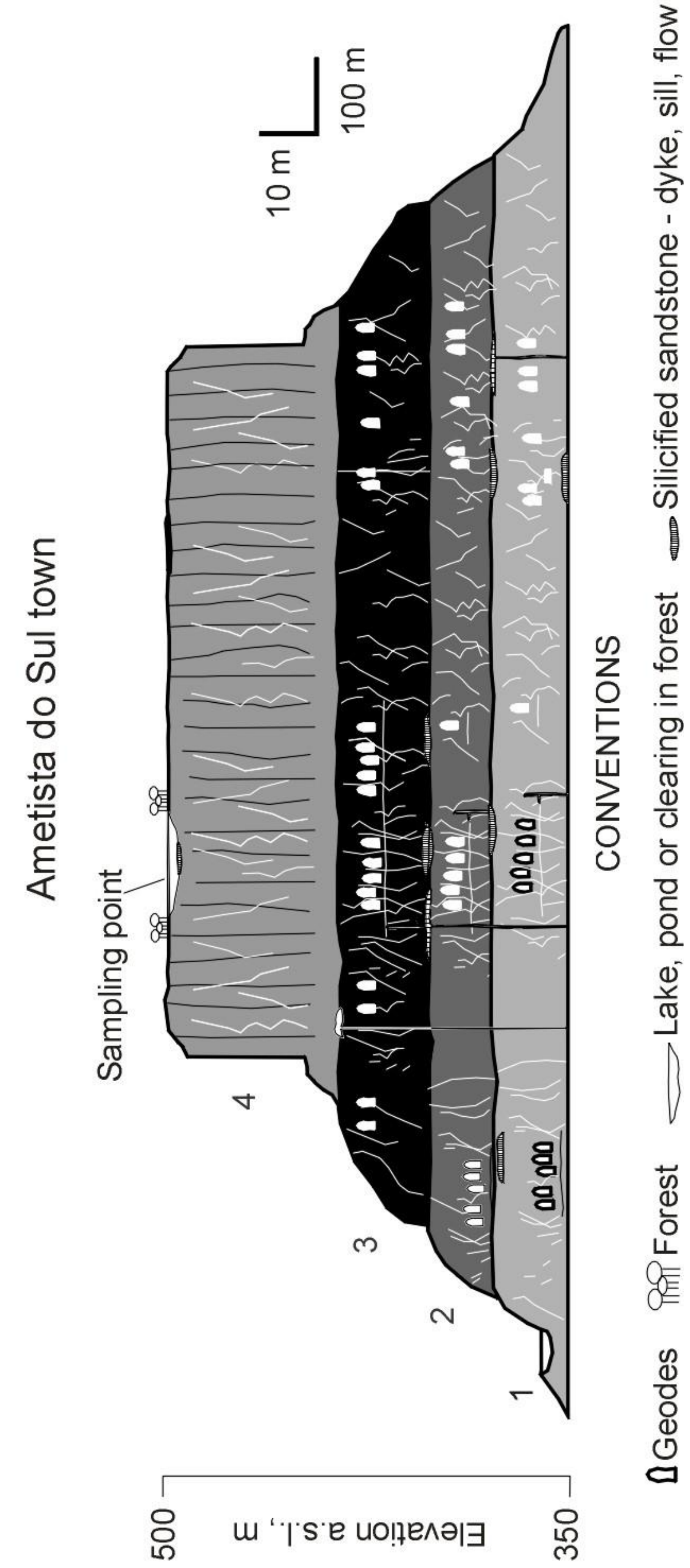
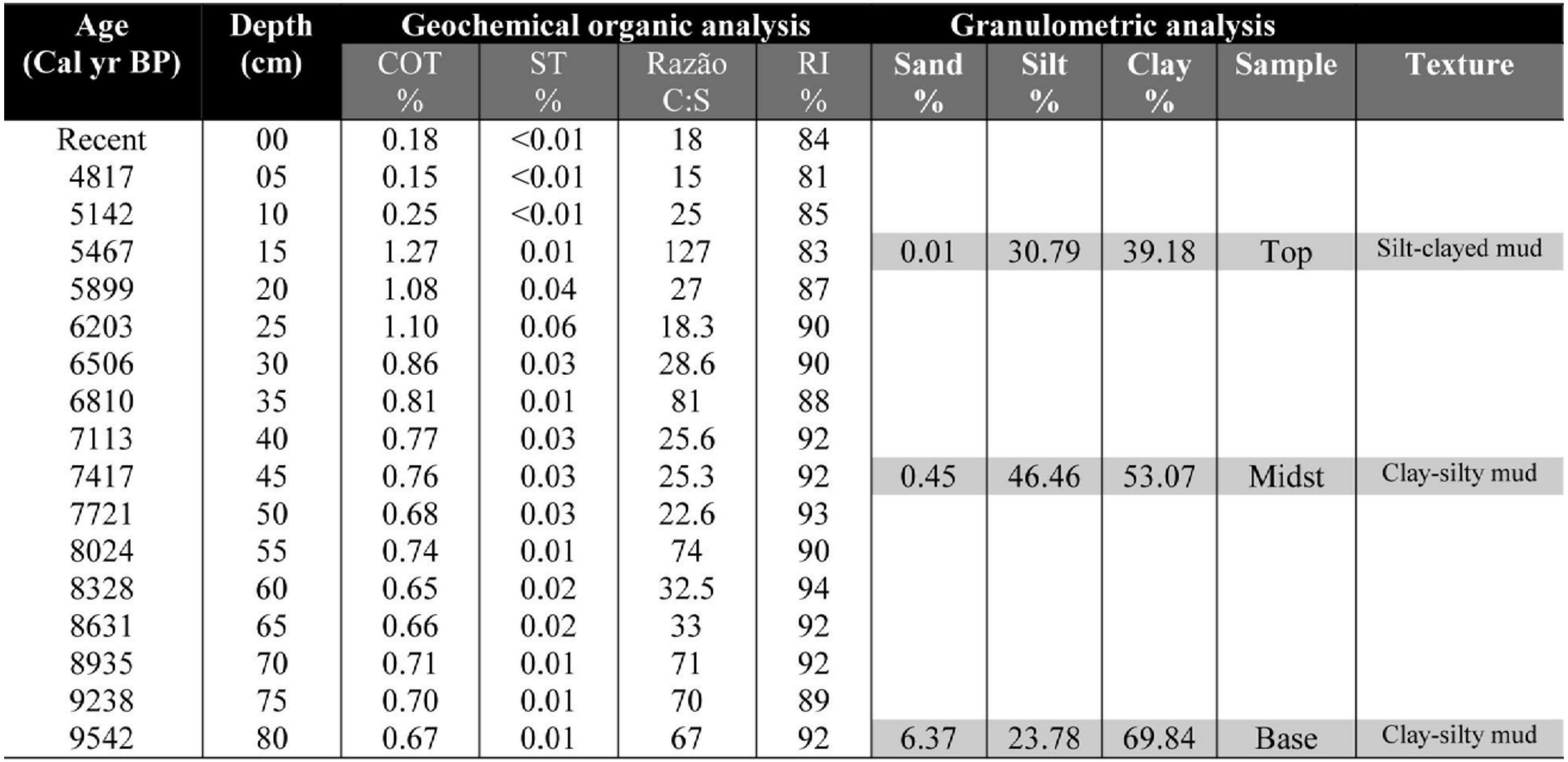

Ametista do Sul town
Sampling point
1
2
3
4
10 m
100 m
500
350
Elevation a.s.l., m
CONVENTIONS
Geodes
Forest
Lake, pond or clearing in forest
Silicified sandstone - dyke, sill, flow

FIGURE 3

GROUP	SUBGROUP			ABREVIATTION
PHYTOCLAST	Opaque	Lath		POL
		Equidimensional		POE
	Translucent	Structured		PTS
		No Structured		PTNS
		Amorphous		PTA
		Cuticle		CUT
		Membrane		MEMB
PALYNOMORPH	Sporomorph	Spores	Briophyte	Spores
			Pteridophyte	
		Pollen grains	Gymnosperm	Pollen
			Angiosperm	
	Freshwater microplankton	*Botryococcus* (Chlorophyceae)		Botry
		Other algae (Zygnemaphyceae)	*Spyrogira*	Algae
			Debaria	
			Mougeotia	
			Zignema	
			Desmídia	
	Incertae sedis	*Pseudoschizaea*		Pseud
AMORPHOUS PRODUCT				AP

TABLE 1



Age (Cal yr BP)	Depth (cm)	Geochemical organic analysis				Granulometric analysis				
		COT %	ST %	Razão C:S	RI %	Sand %	Silt %	Clay %	Sample	Texture
Recent	00	0.18	<0.01	18	84					
4817	05	0.15	<0.01	15	81					
5142	10	0.25	<0.01	25	85					
5467	15	1.27	0.01	127	83	0.01	30.79	39.18	Top	Silt-clayed mud
5899	20	1.08	0.04	27	87					
6203	25	1.10	0.06	18.3	90					
6506	30	0.86	0.03	28.6	90					
6810	35	0.81	0.01	81	88					
7113	40	0.77	0.03	25.6	92					
7417	45	0.76	0.03	25.3	92	0.45	46.46	53.07	Midst	Clay-silty mud
7721	50	0.68	0.03	22.6	93					
8024	55	0.74	0.01	74	90					
8328	60	0.65	0.02	32.5	94					
8631	65	0.66	0.02	33	92					
8935	70	0.71	0.01	71	92					
9238	75	0.70	0.01	70	89					
9542	80	0.67	0.01	67	92	6.37	23.78	69.84	Base	Clay-silty mud

FIGURE 4

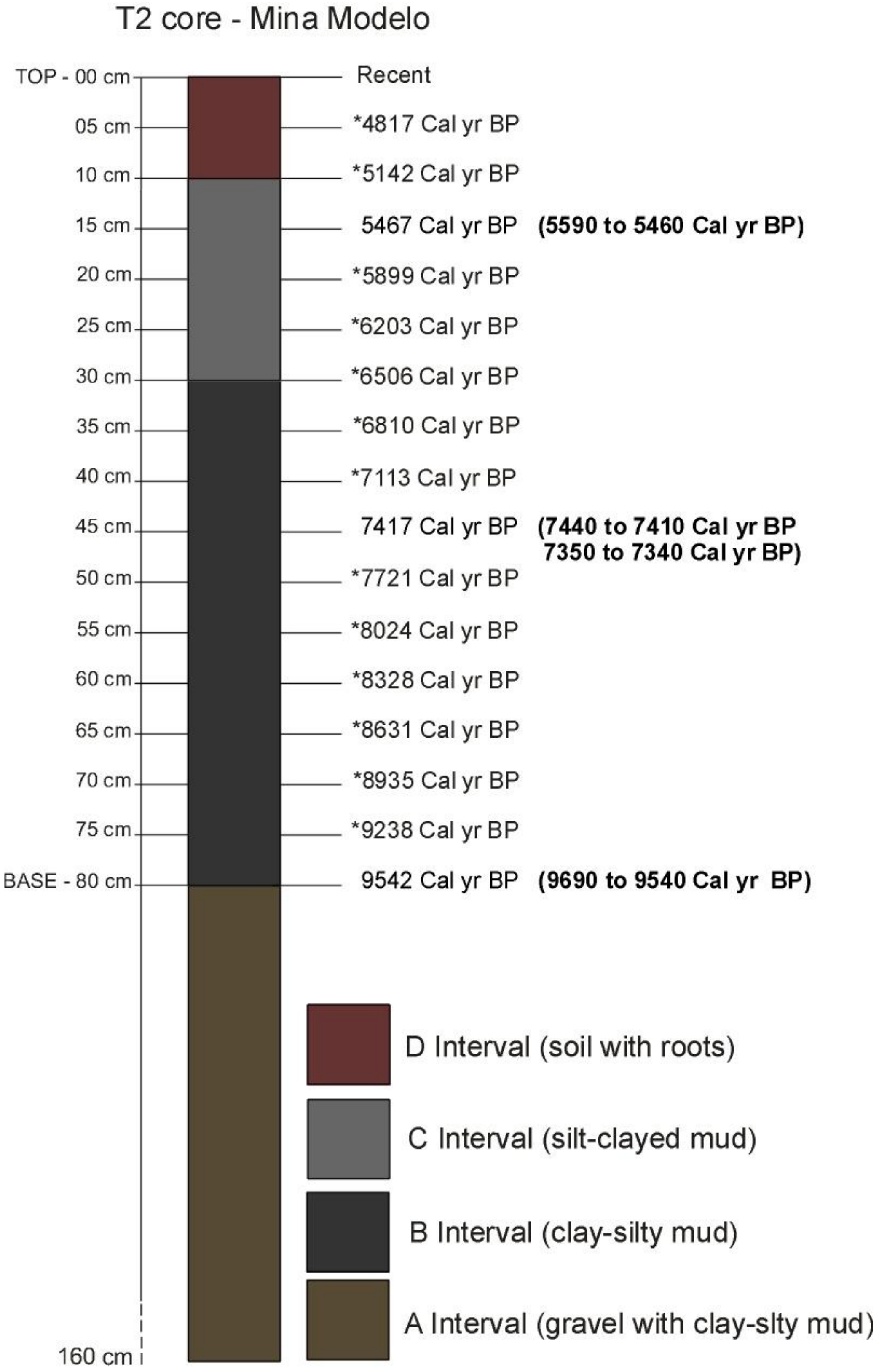

T2 core - Mina Modelo
TOP - 00 cm
05 cm
10 cm
15 cm
20 cm
25 cm
30 cm
35 cm
40 cm
45 cm
50 cm
55 cm
60 cm
65 cm
70 cm
75 cm
BASE - 80 cm
160 cm
Recent
*4817 Cal yr BP
*5142 Cal yr BP
5467 Cal yr BP (5590 to 5460 Cal yr BP)
*5899 Cal yr BP
*6203 Cal yr BP
*6506 Cal yr BP
*6810 Cal yr BP
*7113 Cal yr BP
7417 Cal yr BP (7440 to 7410 Cal yr BP 7350 to 7340 Cal yr BP)
*7721 Cal yr BP
*8024 Cal yr BP
*8328 Cal yr BP
*8631 Cal yr BP
*8935 Cal yr BP
*9238 Cal yr BP
9542 Cal yr BP (9690 to 9540 Cal yr BP)
D Interval (soil with roots)
C Interval (silt-clayed mud)
B Interval (clay-silty mud)
A Interval (gravel with clay-slty mud)

TABLE 2

Depth (cm)	Lab. number	$^{13}C/^{12}C$ (‰)	Conventional ^{14}C age BP	Calendar age cal yr BP (median probability)†	Calendar age range (cal yr BP)§	Elevation a.m.s.l.(m) #
15	Beta 295198	-17.9	4770±30	5467	5590 to 5460	200
45	Beta 295199	-21.4	6500±30	7417	7440 to 7410 7350 to 7340	200
80	Beta 295200	-19.5	8650±40	9542	9690 to 9540	200

BP= before present, AD 1950; cal = calibrated.

† Calibrated ages are calculated from SHCAL04 (McCormac et al., 2004);

§ Calibrated ages are calculated from INTCAL 04 (Reimer et al., 2004) and Talma and Vogel (1993), which assumes a two-sigma error on radiocarbon measurements with an error multiplier of 1.0.

a.m.s.l.= actual altitude above mean sea level

FIGURE 5

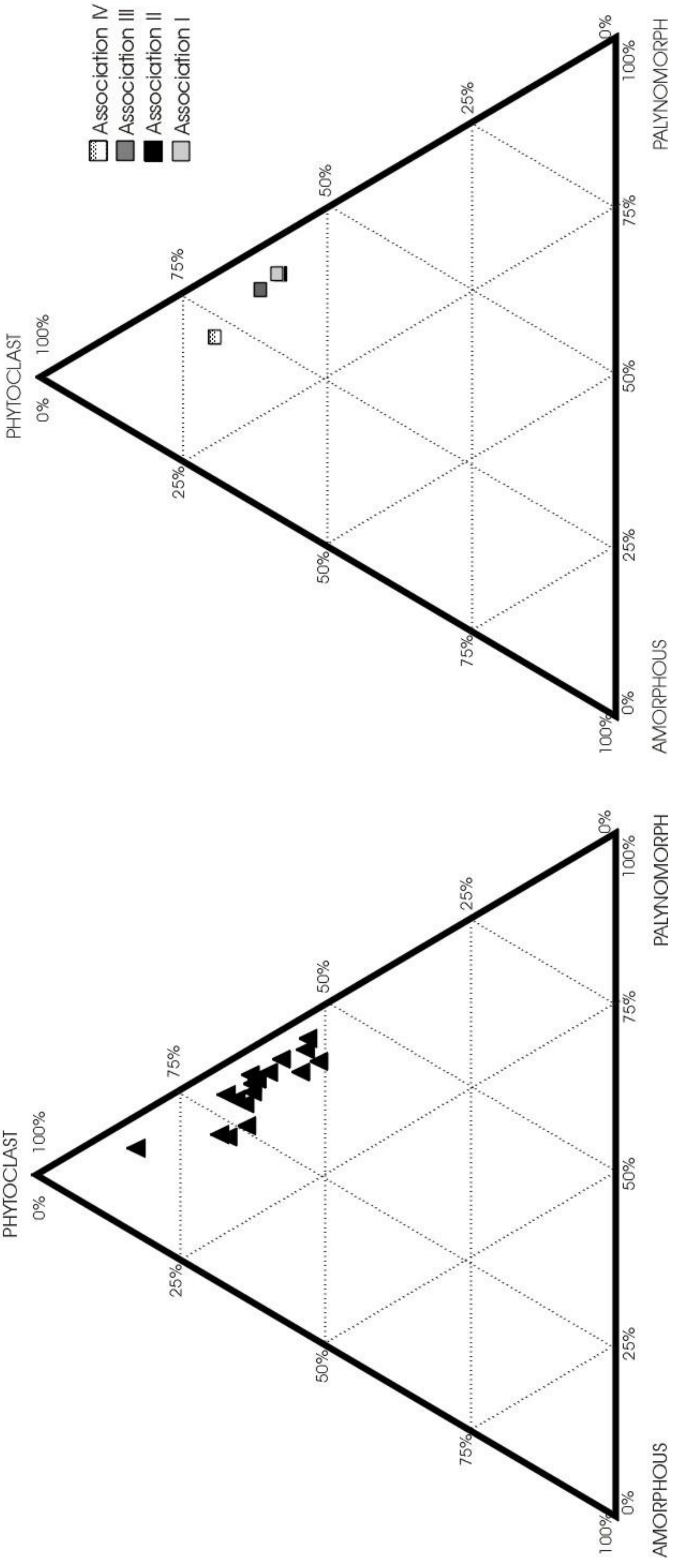

PHYTOCLAST
AMORPHOUS
PALYNOMORPH
0%
25%
50%
75%
100%
Association IV
Association III
Association II
Association I

FIGURE 6

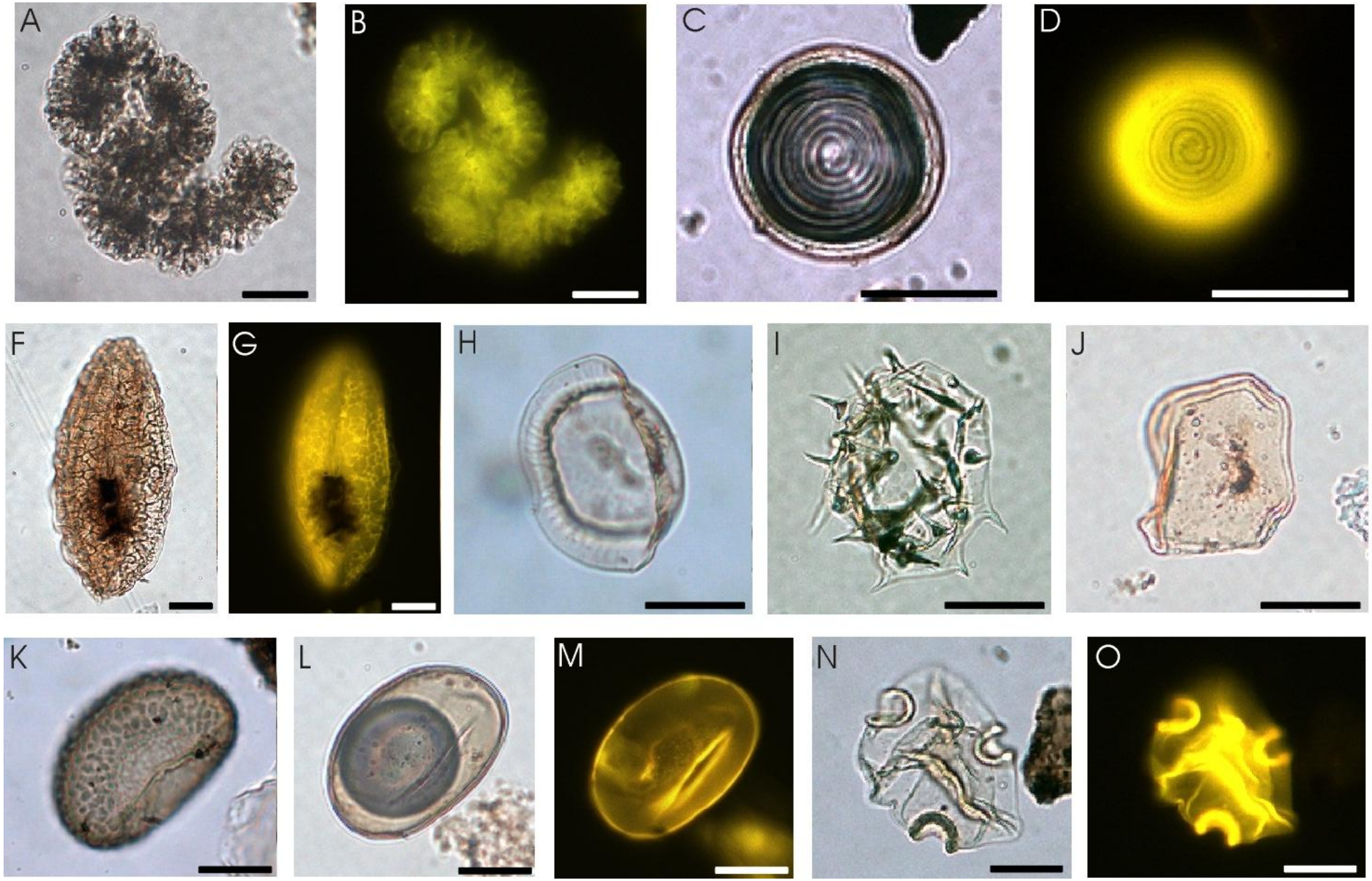


FIGURE 7

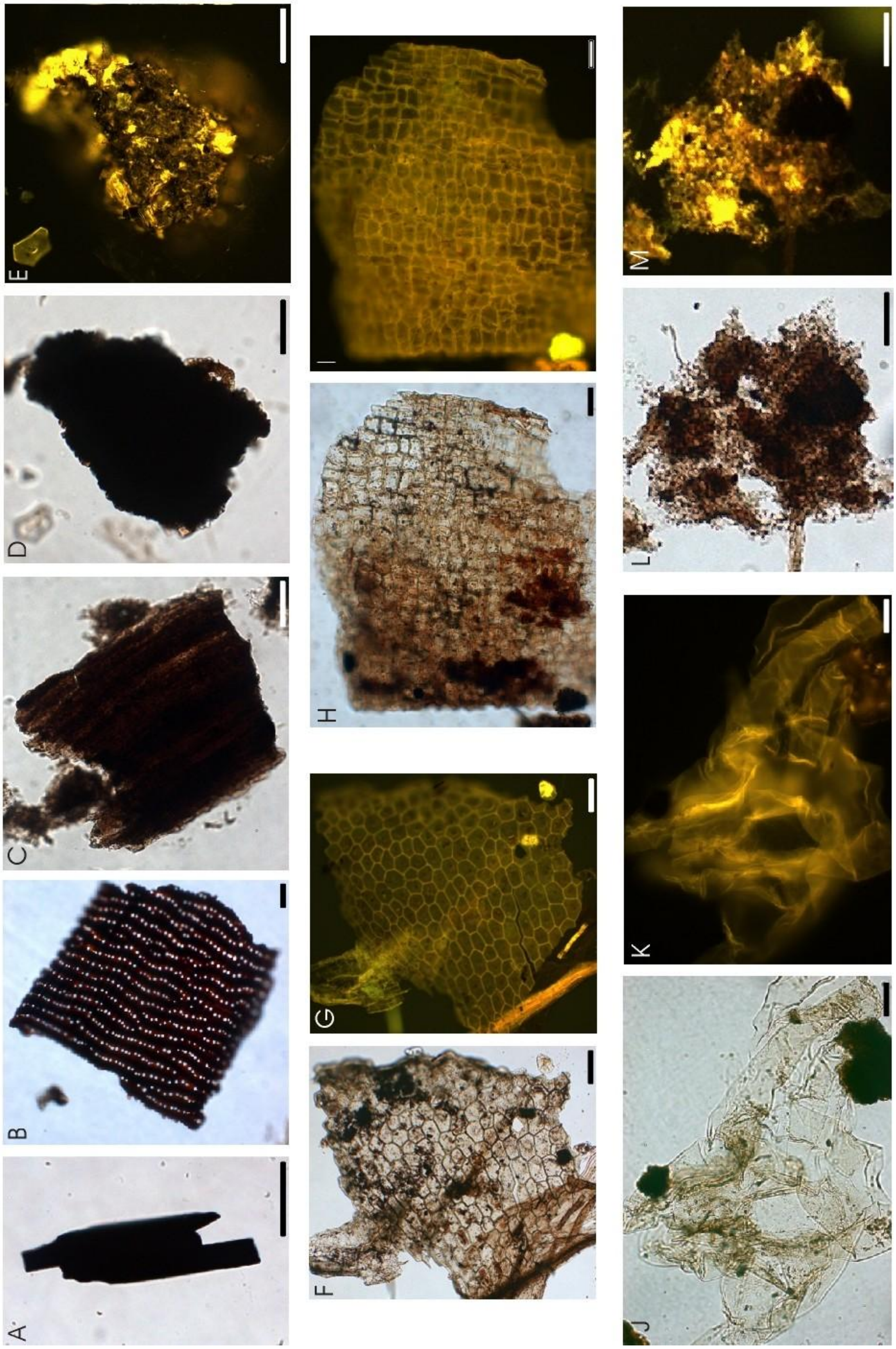


FIGURE 8

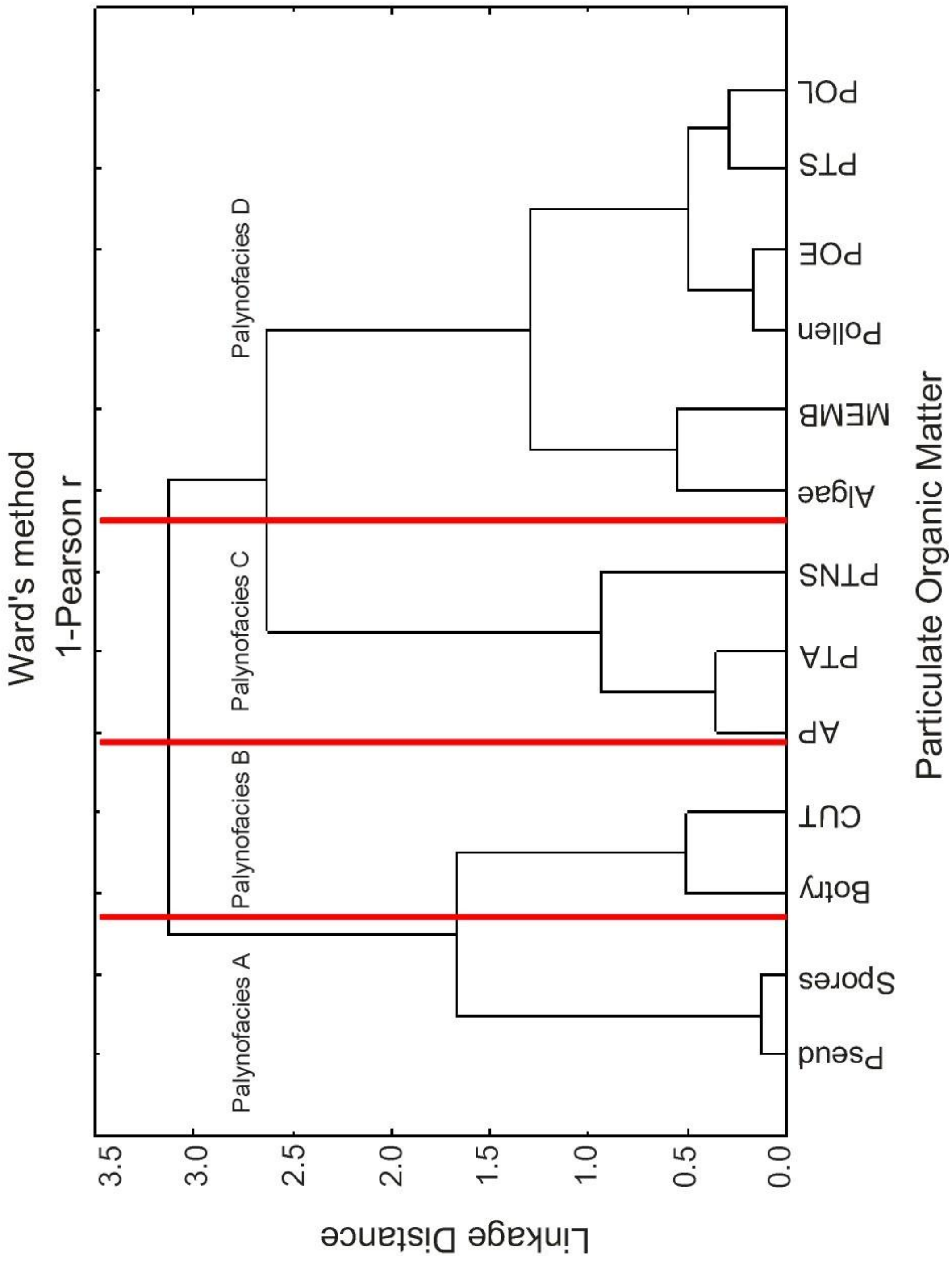

Ward's method
1-Pearson r
Palynofacies A
Palynofacies B
Palynofacies C
Palynofacies D
Pseud
Spores
Botry
CUT
AP
PTA
PTNS
Algae
MEMB
Pollen
POE
PTS
POL
Particulate Organic Matter
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Linkage Distance

FIGURE 9

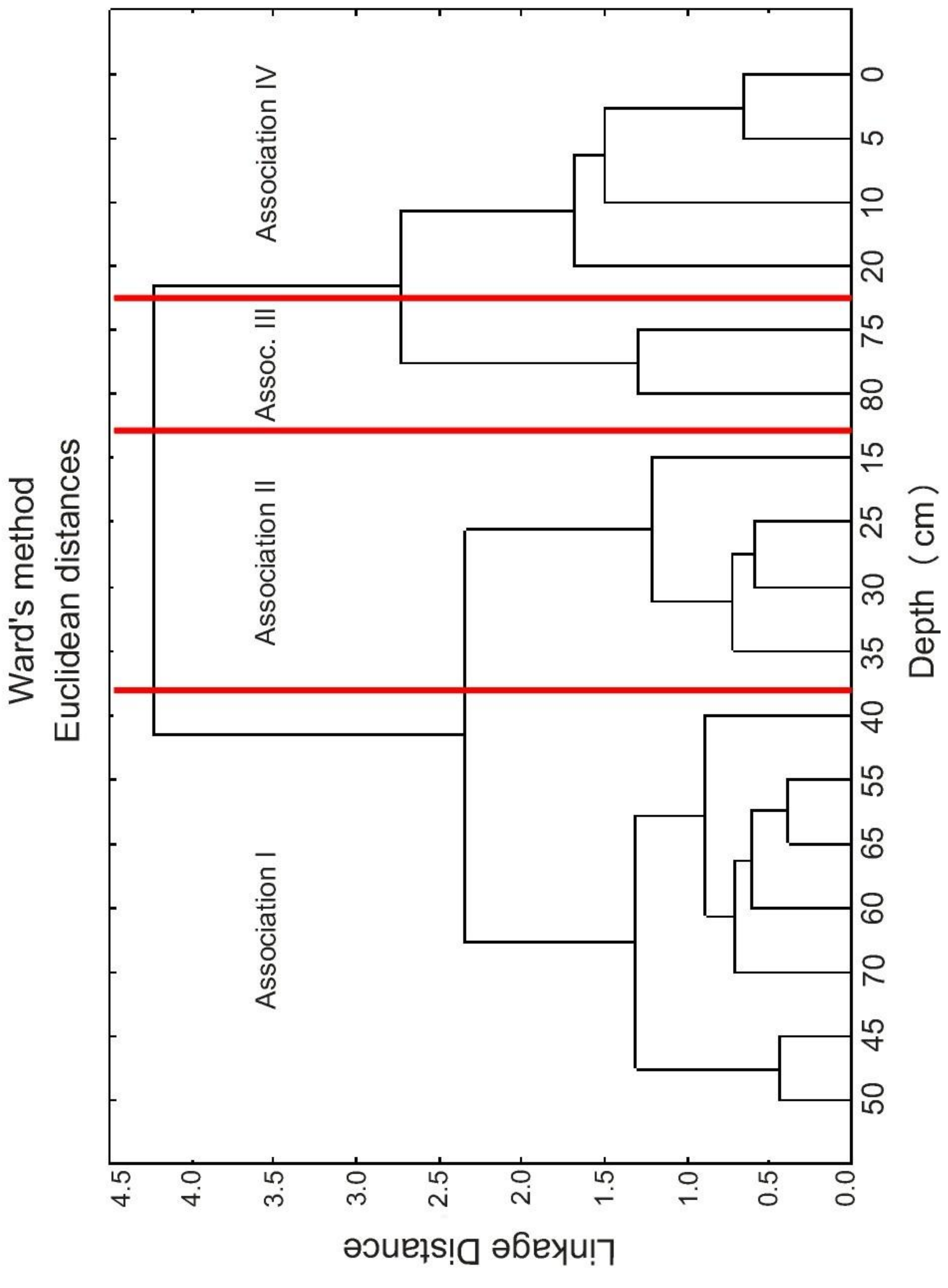

Ward's method
Euclidean distances
Association IV
Assoc. III
Association II
Association I
0
5
10
20
75
80
15
25
30
35
40
55
65
60
70
45
50
Depth (cm)
Linkage Distance
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

FIGURE 10

ASSOCIATION	DEPTH	AGE	TOC	TS	AP*	PHYTOCLASTS*	PALYNOMORPHS*	Spore**	Pollen**	Botryococcus**	Pseudoschizaea**	Other algae**
IV	0	Recent	0.18	0.01	11.11	63.41	25.47	12.82	26.92	58.97	1.28	0.00
IV	5	4817	0.15	0.01	10.96	66.58	22.47	56.58	14.47	26.32	2.63	0.00
IV	10	5142	0.25	0.01	5.11	82.10	12.78	67.57	21.62	8.11	2.70	0.00
IV	20	5899	1.08	0.04	9.95	67.96	22.09	77.65	3.53	5.88	11.76	1.18
AVERAGE			0.42	0.02	9.28	70.01	20.70	53.65	16.64	24.82	4.60	0.29
II	15	5467	1.27	0.01	3.65	52.31	44.04	56.21	7.69	11.83	17.75	6.51
II	25	6203	1.10	0.06	7.43	63.66	28.91	66.04	5.66	9.43	14.15	4.72
II	30	6506	0.86	0.03	6.20	65.35	28.45	39.39	8.08	30.30	15.15	7.07
II	35	6810	0.81	0.01	5.13	52.56	42.31	46.91	3.70	30.86	12.35	6.17
AVERAGE			1.01	0.03	5.60	58.47	35.93	52.14	6.28	20.61	14.85	6.12
I	40	7113	0.77	0.03	3.92	62.50	33.58	30.53	3.05	49.62	5.34	11.45
I	45	7417	0.76	0.03	7.85	53.66	38.48	25.53	5.67	60.28	3.55	4.96
I	50	7721	0.68	0.03	8.01	50.34	41.65	28.49	6.40	55.23	4.07	5.81
I	55	8024	0.74	0.01	4.30	56.96	38.73	33.80	5.63	52.82	3.52	4.23
I	60	8328	0.65	0.02	5.02	61.24	33.73	21.88	14.06	54.69	3.91	5.47
I	65	8631	0.66	0.02	4.99	59.56	35.46	19.66	6.84	64.10	3.42	5.98
I	70	8935	0.71	0.01	4.81	66.58	28.61	29.41	10.78	49.02	0.98	9.80
AVERAGE			0.71	0.02	5.56	58.69	35.75	27.04	7.49	55.11	3.54	6.82
III	75	9238	0.70	0.01	5.32	62.23	32.45	30.48	18.10	38.10	4.76	8.57
III	80	9542	0.67	0.01	6.61	62.17	31.22	14.42	39.42	28.85	0.96	16.35
AVERAGE			0.69	0.01	5.97	62.20	31.83	22.45	28.76	33.47	2.86	12.46

FIGURE 11

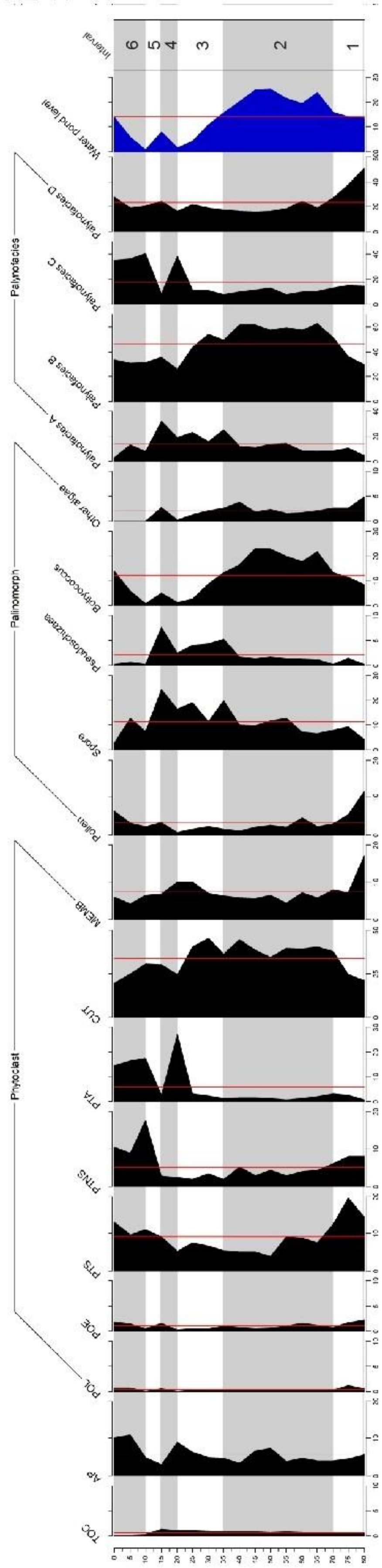

Interval
6
5
4
3
2
1
Water pond level
Palynofacies
Palynofacies D
Palynofacies C
Palynofacies B
Palynofacies A
Palinomorph
Other algae
Botryococcus
Pseudoschizaea
Spore
Pollen
Phytoclast
MEMB
CUT
PTA
PTNS
PTS
POE
POL
AP
TOC

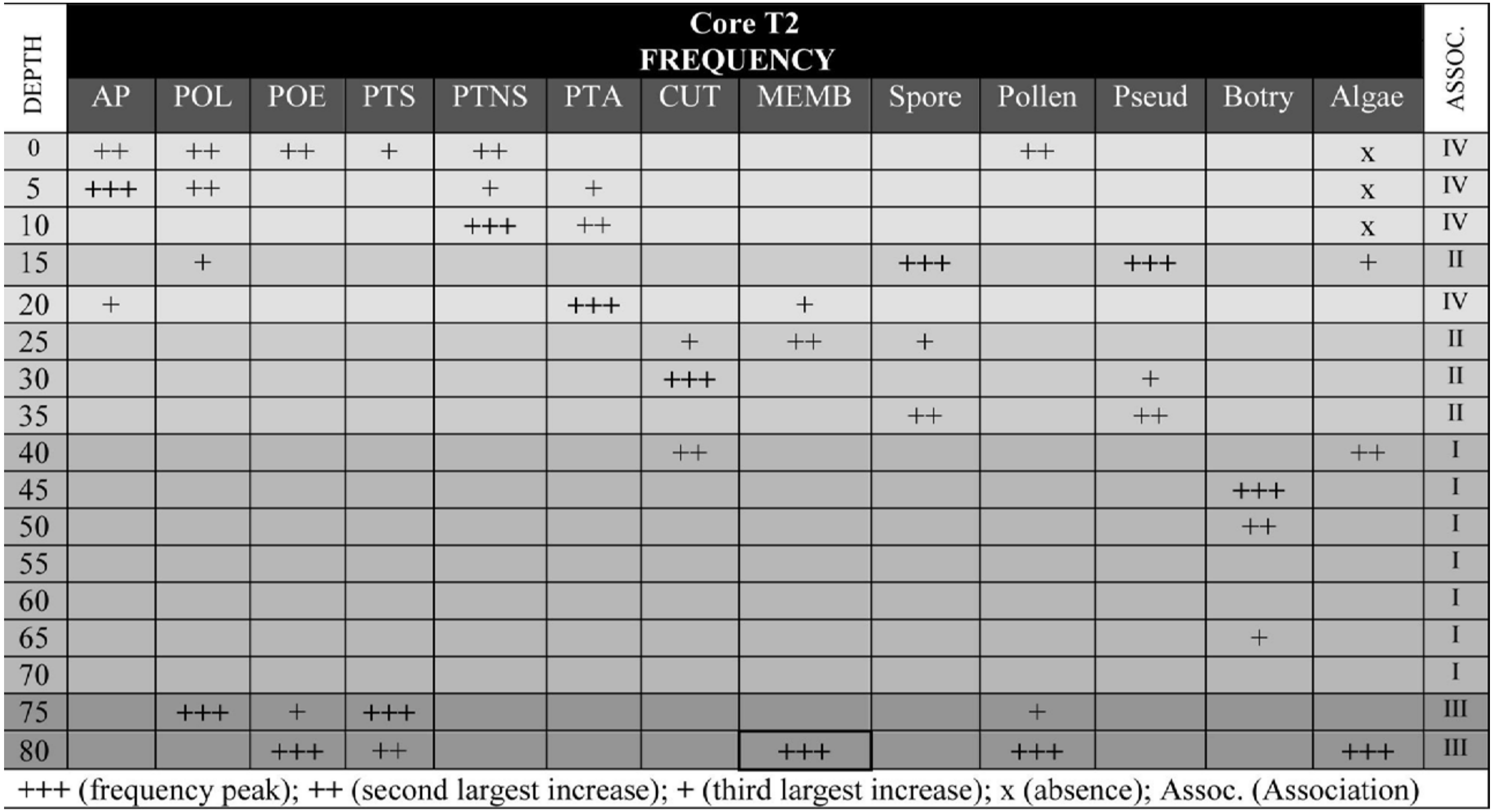
FIGURE 12

PALYNOFACIES	PARTICLES
A	*Pseudoschizaea* and spores
B	*Botryococcus* and CUT
C	PTNS, PTA and AP
D	Pollen, Other algae, MEMB, PTS, POL and POE

ASSOCIATION	PARTICLES	PALYNOFACIES
I	*Botryococcus* and CUT	B
II	*Pseudoschizaea,* spores and CUT	A and B
III	Pollen, Other algae, MEMB, PTS, POL and POE	D
IV	PTNS, PTA and AP	C

INTERVAL	PARTICLES	ASSOC.	PALYNOFACIES
1	Pollen, Other algae, MEMB, PTS, POL and POE	III	D
2	*Botryococcus* and CUT	I	B
3	*Pseudoschizaea,* spores, and CUT	II	A and B
4	PTNS, PTA and AP	IV	C
5	*Pseudoschizaea,* spores and CUT	II	A and B
6	PTNS, PTA and AP	IV	C

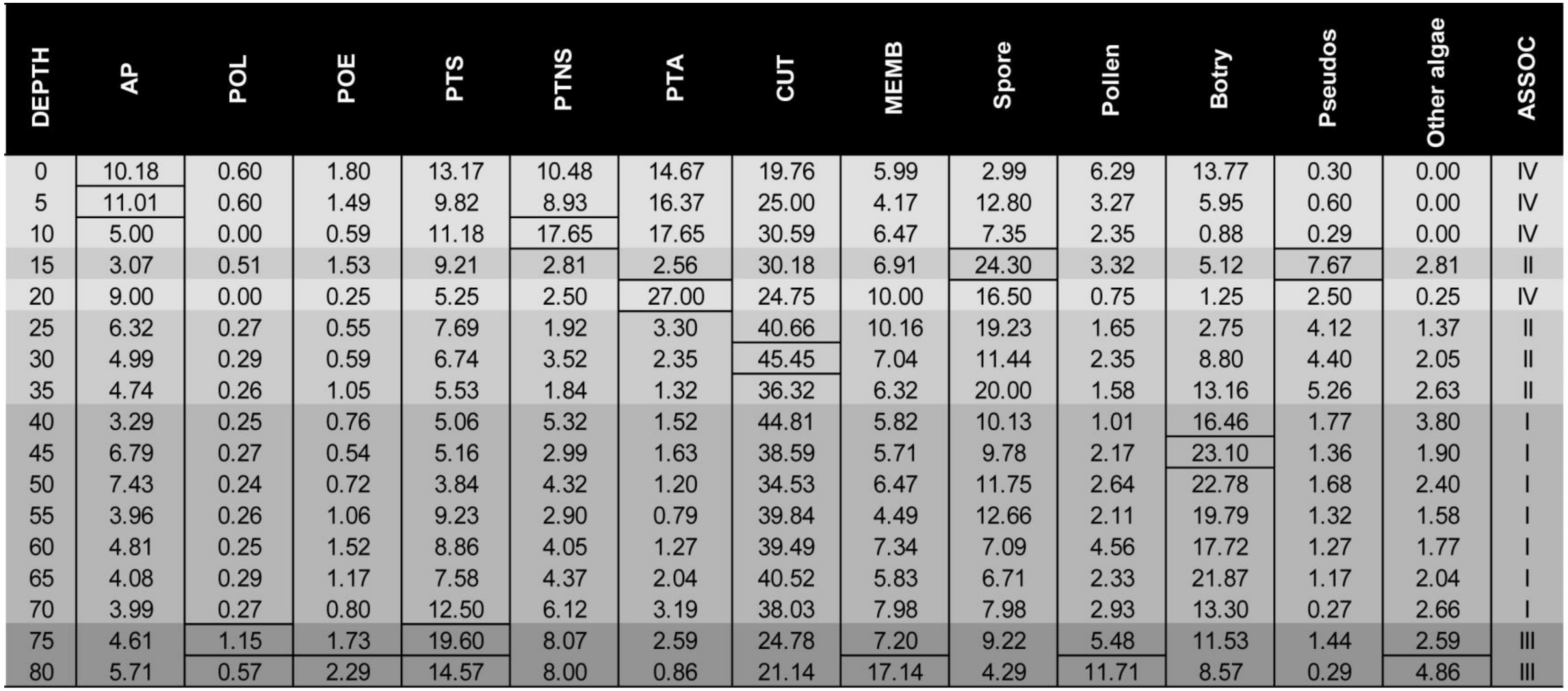
FIGURE 13



DEPTH	Core T2 FREQUENCY													ASSOC.
	AP	POL	POE	PTS	PTNS	PTA	CUT	MEMB	Spore	Pollen	Pseud	Botry	Algae	
0	++	++	++	+	++					++			x	IV
5	+++	++			+	+							x	IV
10					+++	++							x	IV
15		+							+++		+++		+	II
20	+					+++		+						IV
25							+	++	+					II
30							+++				+			II
35									++		++			II
40							++						++	I
45												+++		I
50												++		I
55														I
60														I
65												+		I
70														I
75		+++	+	+++						+				III
80			+++	++				+++		+++			+++	III

+++ (frequency peak); ++ (second largest increase); + (third largest increase); x (absence); Assoc. (Association)

FIGURE 14



DEPTH	AP	POL	POE	PTS	PTNS	PTA	CUT	MEMB	Spore	Pollen	Botry	Pseudos	Other algae	ASSOC
0	10.18	0.60	1.80	13.17	10.48	14.67	19.76	5.99	2.99	6.29	13.77	0.30	0.00	IV
5	11.01	0.60	1.49	9.82	8.93	16.37	25.00	4.17	12.80	3.27	5.95	0.60	0.00	IV
10	5.00	0.00	0.59	11.18	17.65	17.65	30.59	6.47	7.35	2.35	0.88	0.29	0.00	IV
15	3.07	0.51	1.53	9.21	2.81	2.56	30.18	6.91	24.30	3.32	5.12	7.67	2.81	II
20	9.00	0.00	0.25	5.25	2.50	27.00	24.75	10.00	16.50	0.75	1.25	2.50	0.25	IV
25	6.32	0.27	0.55	7.69	1.92	3.30	40.66	10.16	19.23	1.65	2.75	4.12	1.37	II
30	4.99	0.29	0.59	6.74	3.52	2.35	45.45	7.04	11.44	2.35	8.80	4.40	2.05	II
35	4.74	0.26	1.05	5.53	1.84	1.32	36.32	6.32	20.00	1.58	13.16	5.26	2.63	II
40	3.29	0.25	0.76	5.06	5.32	1.52	44.81	5.82	10.13	1.01	16.46	1.77	3.80	I
45	6.79	0.27	0.54	5.16	2.99	1.63	38.59	5.71	9.78	2.17	23.10	1.36	1.90	I
50	7.43	0.24	0.72	3.84	4.32	1.20	34.53	6.47	11.75	2.64	22.78	1.68	2.40	I
55	3.96	0.26	1.06	9.23	2.90	0.79	39.84	4.49	12.66	2.11	19.79	1.32	1.58	I
60	4.81	0.25	1.52	8.86	4.05	1.27	39.49	7.34	7.09	4.56	17.72	1.27	1.77	I
65	4.08	0.29	1.17	7.58	4.37	2.04	40.52	5.83	6.71	2.33	21.87	1.17	2.04	I
70	3.99	0.27	0.80	12.50	6.12	3.19	38.03	7.98	7.98	2.93	13.30	0.27	2.66	I
75	4.61	1.15	1.73	19.60	8.07	2.59	24.78	7.20	9.22	5.48	11.53	1.44	2.59	III
80	5.71	0.57	2.29	14.57	8.00	0.86	21.14	17.14	4.29	11.71	8.57	0.29	4.86	III

6.3 Artigo 3

“Palynofacies and organic geochemistry studies of organic matter from a wetland system of Southern Brazil influenced by different hydrological regimes in the Quaternary”
Periódico: JOURNAL OF SOUTH AMERICAN EARTH SCIENCES

CARTA DE RECEBIMENTO

Ms. Ref. No.: SAMES-D-13-00028
Title: Palynofacies and organic geochemistry studies of organic matter from a wetland system of Southern Brazil influenced by different hydrological regimes in the Quaternary
Journal of South American Earth Sciences

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Manuscript Number: SAMES-D-13-00028

Title: Palynofacies and organic geochemistry studies of organic matter from a wetland system of Southern Brazil influenced by different hydrological regimes in the Quaternary

Article Type: Full Length Article

Keywords: continental environment; organic matter; total organic carbon; total sulfur; peaty sediments; water table; river overflow.

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Abstract: The main goal of this study was to quantitatively and qualitatively characterize the sedimentary organic matter (OM) and demonstrate the usefulness of geochemistry and palynofacies analysis for obtaining paleoenvironmental data for the Holocene in southernmost Brazil. The results indicated that during the time interval from 10586 cal yr BP to the present, the study area housed a wetland characterized by different hydrologic regimes. The basal peaty deposits correspond to a phase influenced mainly by the groundwater table, whereas the upper deposits composed of silty organic mud indicate fluvial influence related to river overflow events. In a similar manner, the TOC (total organic carbon) and TS (total sulfur) contents are higher in the basal portion of the profile, decreasing toward the top. These findings could be related to granulometry alterations that are linked to hydrologic regimes or anthropogenic interference in the landscape dynamics. Anomalous TS content observed in one of the samples might be due to an external source and perhaps related to the presence of thermal springs in the region. These types of areas have potential as a modern reference that can be applied in the reconstruction of past analogous environments such as coal deposits associated with fluvial paleoenvironments.

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Cover Letter

Instituto de Geociências

Programa de Pós-Graduação em Geociências

Porto Alegre, March 02, 2013.

Dear editor of Journal of South American Earth Sciences

We are pleased to send you the manuscript “**Palynofacies and organic geochemistry studies of organic matter from a wetland system of Southern Brazil influenced by different hydrological regimes in the Quaternary**” which allows to document the paleoenvironmental evolution during the Quaternary based on palynofacies and geochemistry organic data from southernmost Brazilian wetland sediments.

The manuscript is part of the PhD Thesis of the first author at the Geosciences Post-Graduate Course (UFRGS), under coordination of Prof. Dra. Margot Guerra Sommer (Brazil), including Prof. Dr. João Graciano Mendonça-Filho as collaborator. The data were not yet publishied and constitute an original contribution.

Certainly Journal of South American Earth Sciences constitutes one of the most important journal to divulgue our data, besides its tradition and world scientific qualification.

Sincerely,

Gabrielli Teresa Gadens Marcon

Programa de Pós Graduação em Geociências

Profa. Dra. Margot Guerra Sommer

Advisor

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HIGHLIGHTS

- The sedimentary organic matter from a continental peatland of subtropical latitude was analyzed.
- Meangniful interpretations were achieved by combining organic geochemistry with palynofacies analyses.
- Major environmental changes were related to alternation of hydrologic regimes.
- The anthropogenic interference was an important factor in the landscape dynamics

Palynofacies and organic geochemistry studies of organic matter from a wetland system of Southern Brazil influenced by different hydrological regimes in the Quaternary

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ABSTRACT

The main goal of this study was to quantitatively and qualitatively characterize the sedimentary organic matter (OM) and demonstrate the usefulness of geochemistry and palynofacies analysis for obtaining paleoenvironmental data for the Holocene in southernmost Brazil. The results indicated that during the time interval from 10586 cal yr BP to the present, the study area housed a wetland characterized by different hydrologic regimes. The basal peaty deposits correspond to a phase influenced mainly by the groundwater table, whereas the upper deposits composed of silty organic mud indicate fluvial influence related to river overflow events. In a similar manner, the TOC (total organic carbon) and TS (total sulfur) contents are higher in the basal portion of the profile, decreasing toward the top. These findings could be related to granulometry alterations that are linked to hydrologic regimes or anthropogenic interference in the landscape dynamics. Anomalous TS content observed in one of the samples might be due to an external source and perhaps related to the presence of thermal springs in the region. These types of areas have potential as a modern reference that

can be applied in the reconstruction of past analogous environments such as coal deposits associated with fluvial paleoenvironments.

KEY-WORDS: *continental environment; organic matter; total organic carbon; total sulfur; peaty sediments; water table; river overflow.*

1. Introduction

Wetlands are important ecosystems that are favorable for organic matter preservation and peat accumulation (Clymo, 1983). The characterization of currently existing peaty areas is established according to the nature of the water resources, the origin and nature of sedimentary particles supply and the local ecological supply (Mesnage et al., 2002). Studies of Holocene peats have been improved because of their sensitivity to environmental changes caused by climate and human impacts (Sebag et al., 2006a). As wetlands, and particularly peaty sediments, are important areas for organic matter storage, studies based on organic geochemistry and palynofacies analyses of these types of Holocene deposits allow the identification of relationships between distinct organic patterns with their corresponding depositional environment.

The concept of palynofacies, as defined by Tyson (1995), corresponds to ~~a~~ body of sediment containing a distinctive assemblage of palynological organic matter thought to reflect a specific set of environmental conditions or to be associated with a characteristic range of hydrocarbon-generating potential.” According to this author, the advantage of applying the palynofacies technique lies in the fact that it provides direct information about the origin and characteristics of the particulate organic matter, allowing a more detailed analysis of subtle variations in the sedimentary environment.

Much of the interpretive models available in the scientific literature that concern organic geochemical and palynofacies analysis were designed for use in marine and epicontinental sections with the main objective being the exploration of hydrocarbon source rocks. Although relatively recently developed, palynofacies analyses have been applied to different depositional systems, resulting in a powerful research tool used to characterize the OM of present-day samples in continental deposits (Di-Giovanni et al., 1999; Noël et al., 2001; Gastaldo and Huc, 1992; Cohen et al., 1999a,b; Sebag et al., 2006a,b), coastal environments (Marchand et al.,2003; Sparica et al., 2005) and marine deposits (Lallier-Vergès et al., 1993a; Lückge et al., 1996; Valdés et al., 2004; Lallier-Vergès and Albéric, 1990).

In Brazil, studies based on palynofacies and organic geochemistry analyses of organic matter on Permian sedimentary bitumen-prone rocks of the Paraná Basin were first applied by Mendonça-Filho (1999). Later, these techniques were widely applied in the investigation of deposits of marine and epicontinental origin from Mesozoic (Carvalho et al., 2006 a,b; Iemini et al.; 2007) and Cenozoic deposits (Del Papa et al., 2002; Menezes & Mendonça-Filho, 2004; Menezes et al., 2005; Meyer et al., 2005, 2006, 2010; Medeanic & Silva, 2010; Chagas et al., 2009; Mendonça-Filho et al., 2010a, Silva et al., 2010).

Analysis results of Holocene Brazilian lacustrine systems have also been obtained for the organic matter content in different regions, using total organic carbon, Rock-Eval pyrolysis, C/N determination, petrography, sedimentology and radiocarbon dating (e.g., Sifedine et al., 2001, 2003; Tturq et al., 2002; Jacob et al., 2004) with emphasis on the paleoenvironmental implications. Nevertheless, only a few studies have improved the knowledge of environmental changes in continental areas through palynofacies analyses of peatlands (Medeanic & Silva, 2010) or inland lacustrine deposits (Meyer et al., 2010 and Silva et al., 2010).

The wetland study area of the present study area overlies a packet of igneous rocks of the Serra Geral Formation, the topmost lithological unit of the Paraná Basin (FIG. 1). The bedrocks are Upper Cretaceous basalts of the Alto Uruguai region, which are known for sheltering the amethyst deposits and hot springs containing mineral water. The thermal springs are resurgences located in fractures present in the basaltic rocks of the ―fractured" aquifer of the Serra Geral Formation (Freitas et al., 2002). The Guarani Aquifer System, found in sedimentary rocks of the Botucatu Formation, underlies the volcanic rocks of the Serra Geral Formation. Large magnitude faults allow hydraulic interconnection of the two aquifers, which results in a mixture of waters with high chloride and sulfate content (Freitas et al., 2011). In the city of Iraí, beyond these mineral water springs, deposits of organic mud popularly known as "medicinal mud" (scientifically unproven) occur. This sediment, which is used for therapeutic purposes in the spas of Iraí is possibly derived from weathering of the basalts and deposited in low-lying areas. The organic mud is extracted in an open place, often saturated with water, due to the influence of the groundwater table, rainfall and the overflow of the Uruguay River (this river extends 2200 km^2 and delimits boundaries between countries such as Brazil, Argentina and Uruguay). The region surrounding the well open for commercial purposes displays the same silty organic mud composition, extending for an area of 1.0 ha within a privately owned. The surface of the wetland is at an altitude of approximately 200 m above sea level.

Considering that wetland deposits can be excellent archives of depositional past changes, the primary objectives of this study were as follows: (a) quantitatively and qualitatively characterize the sediment of the T3-Iraí core, which covers 10586 cal yr BP (median probability) of sedimentation in a wetland area under the influence of a fluvial system and (b) demonstrate the usefulness of geochemistry and palynofacies analyses for this type of environment in obtaining paleoenvironmental data for the Quaternary in the southernmost region of Brazil.

FIGURE 1 – A) Location map of Iraí (adapted from Hartmann et al., 2010); B) Satellite image taken from Google Earth

2. Materials and Methods

2.1 Sampling

For sampling the T3 core (27°10’822” S x 53°14’980” W), aluminum tubes that were 10 cm in diameter and 2.0 meters long were used. Once collected, the core samples were labeled and packaged in plastic bags. Thereafter, the core samples were split into subsamples in the laboratory for sedimentary, geochemical and palynofacies analyses.

2.2 Granulometric analyses

Granulometric analysis was performed in the “Laboratório de Sedimentologia, Centro de Estudos Costeiros e Oceanicos (CECO), Instituto de Geociências, Universidade Federal do Rio Grande do Sul (UFRGS)” and applied a sieving and pipetting method, with class intervals of 1 e ¼ of *phi*, according to the method proposed by Folk and Ward (1957).

2.3 Dating

To date the material and create a consistent age-depth model, the sampling was performed at lithological boundaries. Two radiocarbon datings were performed, respectively, on the lower boundary (115 cm depth) and upper boundary (15 cm depth) of the mud interval using acceleration mass spectrometry (AMS) at the *Beta Analytic Radiocarbon Dating Laboratory* (Miami, Florida, EU). The interpolated ages were calculated using the intercept of the mean conventional age interval in the calibration curve of ^{14}C (CALIB version 4.3 Stuiver et al. (1998). The unconsolidated surficial sediment (0-10 cm) was not sampled because environmental or anthropic factors could alter the results of the dating.

2.4 Geochemistry

The accumulation of organic matter (OM) in sediments was estimated using total organic carbon (TOC) analyses. According to Tyson (1995), TOC analysis is a convenient method to determine the relative abundance of OM in sediments. The accumulation of OM is controlled by major factors such as primary productivity, water depth, and sediment grain size. TOC is always controlled by three main variables: input of OM, preservation of the supplied OM, and dilution of the OM by sediment accumulation (Tyson, 1995). The values of TOC in marine rocks range from ca. 0.1% (deep-sea pelagic deposits) to 94% (coals) (Tyson, 1995).

The total organic carbon (TOC) analyses were performed using the methods of ASTM D 4239 (American Society Testing and Materials, ASTM, 2008) and NCEA-C-1282 (United States Environmental Protection Agency, U.S. EPA, 2002). Following acidification to remove carbonates, the TOC and ST analyses of all samples were conducted using a LECO SC 144 device at Laboratory of Palynofacies and Organic Facies (LAFO).

2.5 Sample preparation

The material preparation for the palynofacies analyses was performed using the standard non-oxidative palynological procedures described by Tyson (1995), Mendonça Filho (1999) and Mendonça Filho et al. (2010b; 2011). For the kerogen concentrate preparation procedure, the studied samples were ground to an approximately 2-mm size. The samples were successively treated to remove carbonates (HCl 37% for 18 h), silicates (HF 40% for 24 h), and neoformed fluorides (HCl 37% for 3 h). Between the steps, the samples were washed with distilled water until the washing water was neutral. After this procedure, $ZnCl_2$ (density=1.9 to 2 g/cm3) was added, stirred, and then centrifuged in order to separate sulfides. The floated material was washed similarly and HCl (10%) drops and distilled water were added to eliminate the heavy liquid. The isolated kerogen was sieved at 20 µm. After this procedure, strew slides were made with the organic residue.

The strew slides were analyzed in the ―Laboratório de Palinologia, Instituto de Geociências, UFRGS" under the following numbers: MP-P 7167 to MP-P 7188 and MP-P MP-P 7489 to MP-P 7491.

2.6 Palynofacies analyses

The palynofacies analyses involved the quantitative (counting from 300 to 500 particles) and qualitative (organic particle component identification) examinations of the kerogen component groups and subgroups. These analyses were achieved via microscopy under transmitted white light and blue/ultraviolet incident light (fluorescence). The count followed the organic matter groups and subgroups classification proposed by Tyson (1995), Mendonça Filho (1999), and Mendonça Filho et al. (2002, 2010b; 2011). In this classification, the particulate organic matter was organized into three main groups according to their optical properties: phytoclasts, amorphous product (AP) and palynomorphs.

In the present paper, all organic matter without form, no sharp edges, without angular contours, or any type of feature permitting its classification in any other group of particulate organic matter (POM) was classified as AP. Such particles are most likely derived from algae or plant debris in an advanced state of degradation, which may have resulted either from microbial action during other transformation processes of POM active in the depositional environment in study or by both processes concurrently. The term ―amorphous product” was chosen because of exclusively continental origin of sediment analyzed, and to avoid conflicts with the amorphous organic matter (AOM), which is commonly related to marine environments or depositional systems that suffer the influence of eustatic variations.

According Mendonça-Filho et al. (2011, p. 43), ―the Amorphous Group consists of all particulate organic components that appear structureless at the scale of light microscopy; including phytoplankton derived amorphous organic matter (traditionally referred to as ―AOM”), bacterially derived amorphous organic matter (also traditionally referred to as ―AOM”), higher plant resins, and amorphous products of the diagenesis of macrophyte tissues.”

The classification of the palynomorph subgroups was established based on the peculiarities of the studied environment in which only freshwater algae are present and associated with spores and pollen grains of exclusively continental origin (FIG. 2).

FIGURE 2 - General POM Classification used in this work

2.7 Statistical Treatment

The statistical treatment of the data was based on the quantitative analysis of the organic particulate components. These data were recalculated as percentage values and submitted to a multivariate statistical analyses (cluster analysis) of the kerogen groups and subgroups (correlation coefficient Pearson/R-Mode) and the similarities between the samples (Q-Mode) using the Statistic Basic program version 6.0 (Valentin, 2000).

3. Results and discussion

3.1 Profile description

The T3-Iraí core has a 115-cm depth. The depth range of 10-115 cm corresponds to a dark sediment, relatively homogeneous, not displaying any sedimentary particular structures, with meaningful content of decaying plant and coloring varying from dark-gray in the levels near the base up to light-gray levels toward the top. The depth range of 0-10 cm, in turn, corresponds to the portion of soil containing small roots, plant debris and some bioturbations.

The results of granulometric analysis revealed the predominance of silt grain throughout the entirety of the core selected (Table 2). In the basal portions, the sediment was corresponds to silt-clayey mud, and in the surface portions, it corresponds to silty mud.

Due to the extreme homogeneity of the sediment, only five samples were selected for granulometric analysis. These samples are listed in Table 2.

3.2 Radiocarbon dating

A chronological framework for the sedimentary interval was provided by the radiocarbon date (FIG. 3, Table 1). The sediment accumulation rates in the pond can be inferred based on the relationship of the long time interval (10586 cal yr BP) with the short interval of sedimentation (115 cm) and offers important data about the Holocene in this region.

Table 1 - AMS (accelerator mass spectrometry) radiocarbon ages of the sediments of the T3 core. Analyses were performed by Beta Analytic, Inc.

FIGURE 3 – Chronological framework for the sedimentary profile T3-Iraí core displaying the calibrated radiocarbonic age (cal yr BP) and interpolated ages (*). The analyses performed by Beta Analytic are highlighted in bold. The other ages were calculated as the median probability.

3.3 Geochemical Organic Analysis

The TOC values vary greatly throughout the core, from 2.80% (minimum) to 27.10% (maximum), and reflect both the high quantity of organic matter deposited and the high degree of conservation. The ST values also vary substantially, reaching a minimum value of 0.06% and maximum of 5.10%. The concentrations of TOC and ST are higher in the basal portion of the range and decrease toward the top (Table 2). The percentage of clay tends to decrease toward the top (Table 2) and could be related to the decrease in TOC and ST content in the same direction.

In general, the amounts of the TOC and ST may be considered high, especially in the basal samples (115-85 cm). Such data indicate a high primary productivity, due to the high input of the phytoclast particles that predominate widely over the entire core. The relatively anoxic and stagnant environment conditions also favored the preservation of OM.

The decrease of organic matter input in the depositional environment in the shallower portions of the core (10-0 cm) may be related to anthropogenic interference in the landscape dynamics, such as due to the removal of much of the vegetation of the area with an aim of economic exploitation of the silty organic mud. In addition, the anthropogenic impact may also have contributed to the decrease of the water depth via artificial draining during extraction of the "medicinal mud." These human activities have most likely resulted in an increased exposure of organic matter and contributed to the change of the environmental conditions from typically anoxic to relatively oxic and characterized by lower contents of TOC and ST.

The fluctuations in the concentration of TOC and ST along the other intervals could be linked to the climate influence that regulates the hydrological regime. The groundwater table and the floods of the Uruguay River provide moisture and have a strong influence in OM preservation. Rainfall can be directly related to the input of sediment and organic matter into the depositional system because it adds to level saturation of the groundwater table and the overflow frequency of the river.

The C:S ratio aids in the identification of sulfate-reducing paleoenvironments. Values lower than 3 indicate reducing environments and values above 3 indicate oxic environments, according the criteria of Berner (1995) and Borrego et al. (1998). Based on this model, it can be inferred that the anoxic processes of sulfate-reducing may have been significant in those portions of the interval wherein the ratio C:S was low (115 to 99 cm) and coincided with the higher sulfur concentrations.

The 99-cm sample (8908 cal yr BP) is peculiar because the TS levels were higher than the TOC levels, and the C:S ratio was very low (0.65). These results can be considered "anomalous" for this type of strictly continental environment, according to the model proposed by Berner and Raiswell (1984), which characterizes freshwater environments by a high C:S ratio (> 10) and the marine sediments with a low C:S ratio (0.5-5.0). The low C:S ratio was most notably observed in the 99-cm sample but also occurred in the 115-cm sample (C:S ratio = 3.60) and could be related to both a highly anoxic event and the sediment type, preventing comparisons with the environmental paleosalinity model of Berner and Raiswell (1984).

High sulfur content tends to occur around volcanoes and thermal springs, in addition to being the result of the reduction of sulfur compounds by anaerobic bacteria. In the 99-cm, the high TS content may be related to the sulfate-reduction process of OM present in the sediment, but the lower organic carbon contents does not entirely support this hypothesis. Thus, the unusually higher ST content in relation to TOC suggests the presence of an external source adding to the sulfur content. The causes of this ~~–s~~ulfur anomaly" have not yet been established but may be related to different processes, i.e., the occurrence of thermal springs containing mineral water in the region surrounding Iraí (Freitas et al., 2011) or a volcanism event that occurred in the Andean region over the past 8000-9000 years (Naranjo and Stern, 2004). However, there is no evidence of tephra in the sedimentary records of equivalent ages in southern Brazil that supports the volcanism hypothesis as being an external source subsidizing the high sulfur content of the sediment.

The thermal-springs hypothesis appears quite reasonable because according to Freitas et al. (2011), a mixture of waters with high chloride and sulfate content resulted from the interconnection of two aquifers (~~–f~~ractured" and Botucatu). In addition, the hydrogeochemical characteristics of the mineral waters also suggest that other aquifers deeper that the Guarani System can be connected hydraulically with the ~~–f~~ractured" aquifer of the Serra Geral Formation through large faults or fractures (Freitas et al., 2011). Therefore, the additional sources of sulfur could be derived from these deeper aquifers, although such studies are still incomplete. However, it is evident that some factor not yet identified has restricted the accumulation of sulfur mainly to the peat-deposition level.

From the 90-cm sample (7964 cal yr BP), the TS values decreases below 1% and, from the 80-cm sample (7440 cal yr BP), the TOC values decreases below 10% and remain below this threshold until the top of the core. Notwithstanding these findings, the TOC and TS values remained relatively high, ranging between 4 and 7%. However, a possible change in the dynamics of the sedimentary environment must have occurred, influenced by changes in depositional conditions that regulate the input and preservation of OM within the system.

A decrease in primary productivity also may have altered the amount of OM deposited. In addition, changes in hydrologic regimes and consequent depositional hydrodynamics may have made the conditions of the sedimentary environment relatively more oxic, promoting the degradation of OM and reducing the TOC and ST contents towards the top of the core sample.

The reduction in the organic content and increase of the silt fraction in the middle and upper portions of the core altered the geochemical and textural characteristics of the sediment, which became a silty organic mud (Table 2) instead of peat. This transition from peat to silty organic mud appears to coincide with the increasing influence of the overflow events of the Uruguay River. According to Ljung and Bjorck (2007), the transition from peat to silty organic mud has been generally attributed to significant increases in effective humidity during processes of paludification, but these increases in moisture content have been inferred from rainfall. Nevertheless, in the present study, such inference for the study area near Iraí is hindered by the type of sedimentary environment, which is characterized as an open system, because this environment has been influenced by both the groundwater table and by overflow of the river that continually adds to the site moisture.

Table 2 – Geochemical organic and granulometric analysis of the T3-core (Iraí)

3.4 Palynofacies Analysis

The fluorescence intensity of the particles was usually very intense, due to the recent nature of sediment (Mendonça-Filho et al., 2011). Among the sporomorphs (FIG. 5), the fluorescence varied from yellow to yellow-orange (spore and pollen) and among the phytoclasts (FIG. 6 and 7) varied from yellow (cuticle and membrane) to yellow-orange or orange-brown (PTS, PTNS and PTA). The AP group (FIG. 6), in turn, exhibited fluorescence ranging from yellow-orange and reddish-orange to orange-brown.

The phytoclast group predominated (78.1%) in all samples (FIG. 4), while the palynomorphs were the second-most dominant group (14.5%) and the AP Group the least dominant (7.4%). The TOC concentrations in the sediment are regulated by the most abundant group (Tyson, 1995), in this case, the phytoclasts. The main organic fraction, comprised of terrestrial plant-derived elements, is typical for peatland systems according to Sebag (2006b).

FIGURE 4 – Ternary diagram showing the relationship of the major POM groups of all samples (left side) and Ternary diagram showing the relationship of Samples Association I, II, III, IV and V (right side).

FIGURE 5 - Palynomorph group. A-C, monolete spores; D-F, trilete spores; G-I, pollen grains. Scale bars: 20 µm.

FIGURE 6 - A-B: AP Group; C-D: Phytoclast group. Scale bars: 20 µm.

FIGURE 7 – A-X, Phytoclast Group. A-B, membrane; C-D, associated cuticle; E-X, Cuticles with varied patterns of epidermal organization. Scale bars: 20 um

3.4.1 Hierarchical cluster R-mode analysis

According to the statistical R-Mode analysis, using the Ward’s method with 1-Pearson distance, the samples were classified into three main particle clusters, denominated Palynofacies A, B and C. (FIG. 8, Table 4).

FIGURE 8 – Dendrogram produced by cluster R-mode analysis for groups and subgroups of the Organic Matter from T3 core (Iraí). Red vertical lines divide the three palynofacies. Abbreviations are in accordance with FIG. 2.

The Palynofacies A is represented by allochthonous elements as PTA and by cuticles, non-woody elements of plant origin. The Palynofacies B is represented by autochthonous (algae), along with parautochthonous (spores) and allochthonous elements (pollen grains, membrane and AP). The Palynofacies C is represented by POL, POE, PTS and PTNS, all allochthonous woody elements of terrigenous origin.

The Palynofacies B is indicative of phases of relative humidity, which is evidenced by the presence of autochthonous (algae) and parautochthonous (spore) elements and due to the preservation of delicate particles such as membranes.

The Palynofacies A and C indicate the phases of great terrigenous influence with predominance of elements of terrestrial origin. In the Palynofacies A, the high frequency of associated cuticle (with subcuticular debris attached) may be related to the amorphized phytoclasts, as these can be a byproduct of leaf epidermis tissue. The presence of such particles could indicate that the degradation processes were not efficient enough to break down all the leaf elements and denotes the high preservation potential of sedimentary environment.

3.4.2 Hierarchical cluster Q-mode analysis

According to the statistical Q-mode analysis, using the Ward's method with Euclidian distance, five main associations of samples were observed and identified as Association I, II, III, IV and V (FIG. 9, Table 5), which are related to the palynofacies defined by the cluster R-mode analysis (FIG. 8).

FIGURE 9 – Dendrogram produced by cluster Q-mode analysis for the groups and subgroups of the organic matter from T3 core (Iraí). The red vertical lines divide the five associations. The abbreviations are in accordance with FIG. 2.

Association I is represented by the 103-, 106-, 110- and 115-cm samples. The particles that reach the peak frequency in this association are the POL and cuticles (FIG. 13, Appendix), which are related to the Palynofacies A (cuticles) and C (POL). The average frequency of TOC (21.65%), ST (2.60%) and phytoclasts (82.38%) is the highest of all associations. The average frequency of palynomorphs is the lowest (11.05%), with a predominance of the terrestrial sporomorphs (97.98%) over the algalic sporomorphs (2.02%), which are absent in the 106-cm sample. The peak frequency of cuticles (50.93%) is much higher than POL (5.29%) and coincides with the peak frequency of TOC (FIG. 14, Appendix).

Association II is represented by the 15-, 75-, 80-, 85-, 90- and 95-cm samples. The particles that reach the peak frequency in this association are PTA (FIG. 13, Appendix), which are related to the Palynofacies A. The AP group reaches its the lowest frequency (6.45%) in this association, whereas the phytoclasts strongly dominate (81.19%), followed by the palynomorphs (12.36%). The terrestrial sporomorphs subgroup absolutely dominates (100%) because the algalic sporomorphs are absent in all samples.

Association III is characterized by the 35-, 40-, 45-, 50-, 55-, 60- and 65-cm samples. The particles that reach the peak frequency in this association are membrane and algae (FIG. 13, Appendix), which are related to the Palynofacies B. The phytoclast group predominates (77.30%) over the palynomorphs (15.80%) and the AP (6.90%). The algalic sporomorphs subgroup reaches its highest frequency (9.70%) in this association.

Association IV is characterized by the 20-, 25-, 30-, 70- and 99-cm samples. The particles that reach the peak frequency in this association (FIG. 13, Appendix) are AP, spores and pollen grains (Palynofacies B) and POE (Palynofacies C). The average frequency of the phytoclasts is the lowest (73.57%), whereas the average frequency of AP (9.34%) and palynomorphs (17.09%) is the highest of all associations. The terrestrial sporomorphs (94.81%) predominate over the algalic sporomorphs (5.19%) in all samples. The peak frequency of ST, AP and spore is observed in the 99-cm samples, whereas the peak frequency of POE occurs in the 70-cm sample, and the peak frequency of pollen grains occurs in 30-cm sample; however, all samples contain a relatively high amount of all these particles.

Association V is represented by the 0-, 5- and 10-cm samples. The particles that reach the peak frequency in this association are PTS and PTNS (FIG. 13, Appendix), which are related to the Palynofacies C. The average TOC (4.82%) and TS (0.10%) contents is the lowest of all associations. The phytoclast group predominates (76.19%) over the palynomorphs (15.52%) and AP (8.29%). The peak frequency of PTNS and PTS occurs in sequence in the 5-cm and 0-cm sample, respectively.

FIGURE 10 – Table listing the percentages of TOC and ST and the percentages of the major groups and subgroups of POM and of the averages of samples groups. (*) percentage value of the three main groups of POM related to total Organic Matter. (**) Percentage value of sporomorphs related to total Palynomorph Group. Abbreviations are in accordance with FIG. 2.

3.4.3 Palaeoenvironmental Characterization based on intervals generated by cluster Q-Mode analysis

Based on the associations generated by cluster analysis (Q-mode), the sedimentary section (FIG. 3) was subdivided into eight intervals, from the base to the top of the core, with an aim of inferring the paleoenvironmental changes during a time interval of 10586 years BP to the present day on the area, as influenced by the autochthonous, parautochthonous and allochthonous particles (FIG. 11).

FIGURE 11 – Variation of the palynofacial and geochemical parameters of the main groups and subgroups of particulate organic matter. Red vertical lines indicate the midline. Abbreviations are in accordance with FIG 2.

Interval 1 (10586-9327 cal yr BP, FIG. 10 and 11) corresponds to Association I (115-103-cm depth), which is marked by peak of cuticles and POL and particles related to the palynofacies group A and C. The high frequency of cuticles presenting intense fluorescence and with preserved stomata indicates the high level of preservation of the OM. Moreover, the varied patterns of cellular organization disclose the diversification of the local vegetation composition in these wetlands at time. The high content of TOC and ST, associated with the good condition of preservation of the particles, indicates the presence of a highly reducing environment (Mendonça-Filho et al., 2010a), which nevertheless was not conducive to the development of a significant amount of algalic biomass. In this interval, the sedimentary environment propitiated the peat formation, i.e., the stable groundwater table assured enough moisture to the preservation of a great deal of land vegetation (Stach et al., 1975). The fluvial overflow events must have had very little influence during this period because they would have otherwise disrupted the formation of peat (Hofmann and Zetter, 2005). However, the significant presence of POL suggests that such elements might have been transported by the river or might be a result of the charring processes of surrounding terrestrial vegetation. Sebag (2006b) confirmed the importance of opaque phytoclasts as tools for tracking allochthonous inputs. Nevertheless, it was observed, by the same author, that the opaque particles include heterogeneous constituents that can have various origins, such as combustion residues.

Interval 2 (8908 cal yr BP, FIG. 10 and 11) corresponds to association IV (99-cm depth), which is defined by a peak of AP and spores, particles related to the Palynofacies B group. In this interval, the ST content is rather high, suggesting the existence of anoxic conditions, a reducing environment and the presence of an external sulfur source, which are not yet firmly established, but perhaps related to the presence of thermal springs in the region. The significant presence of AP is possibly derived from the degradation of OM by microbial action, which is benefited by the depositional environments characterized by anoxic conditions (Mendonça-Filho et al., 2010a, 2011). The increase in the percentage of spore of ferns indicates an increased relative moisture (Chagas et al, 2009; Mendonça-Filho et al., 2010a), and this moisture may be related to the increase of saturation level of the groundwater table in response to a relatively increased rainfall frequency. The share of algalic elements; however, remains limited by anoxic conditions of the depositional environment.

Interval 3 (8489-6392 cal yr BP, FIG. 10 and 11) corresponds to Association II (95-75-cm depth), which is marked by a PTA peak, a particle related to the Palynofacies A, which most likely derives from subcuticular tissues crumbled by microbial action because the proportion of associated cuticles is quite significant in this association. The absence of algalic elements indicates a decrease in moisture when compared with the underlying samples. However, the fluorescence intensity and the degree of preservation of the particles suggest the prevalence of favorable conditions for the preservation of OM. Therefore, if there was less humidity, the decrease was not severe enough to cause extensive degradation of the OM.

Nevertheless, the absence of algalic elements and the decreased TOC and TS contents, when compared with the base samples, suggest a possible alteration in the sedimentary dynamics, which may be related to a relatively decrease in saturation level of the groundwater table.

Interval 4 (5867 cal yr BP, FIG. 10 and 11) corresponds to Association IV (70-cm depth), which is marked by a POE peak, a particle related to the Palynofacies C. The significant percentage of POE suggests that such allochthonous particles may have been loaded into the system due to the overflow of the Uruguay River, which becomes more influential on the depositional system from this interval. The studies of Sebag et al (2006b) also have demonstrated fluvial influence in the Holocene alluvial deposits of the lower Seine Valley (France) from the gradual increasing frequency of opaque particles. The reappearance of algae, even if not significant, can also be attributed to increased moisture subsidized by fluvial influences. Changes in the geochemical and textural characteristics of the sediment from peaty to silty organic mud may be a consequence of river overflow events, which started from this interval and culminated in this next interval. Hofmann and Zetter (2005), studying the different wetlands of the Neogene of Austria, observed that the peat formation was terminated by an abrupt drowning and was succeeded by deposition of algal material.

Interval 5 (5343-2198 cal yr BP, FIG. 10 and 11) corresponds to Association III (65-35-cm depth), which is defined by a membrane and algae peak, particles related to the Palynofacies B group. The constant presence of algalic elements throughout the interval indicates the persistence of a high level of moisture able to allow the preservation of an expressive percentage of delicate particles such as membranes. This moisture event may have resulted from a relative increase in rainfall, which led both to the overflow of the Uruguay River and to the raise of the saturation level of the groundwater table. On the other hand, the margin erosion may have approximated the riverbed of the investigated area or definitely broken a bank-barrier between the river and the depositional environment, which can be linked to the process of paludification of the system along the years. Sebag et al (2002) also observed a similar case in alluvial wetland systems sometimes opened to fluvial contribution from the Seine River. Likewise, Wust and Bustin (2001) reported that the inundation of the lowland led to paludification of the low-lying riparian area in the peat deposits in Paya Belinau, Tasek Bera Basin (Malaysia).

Interval 6 (1673-625 cal yr BP, FIG. 10 and 11) corresponds to Association IV (30-20-cm depth), which is defined by a peak in pollen grains, particles related to the Palynofacies B. The alternation between spores and pollen grains is constant over the entire profile and could indicate phases of the vegetation mastery change. However, the incursions of the Uruguay River start to contribute with to the increase of the allochthonous elements for into the depositional system, not necessarily indicating paleofloristic changes.

Interval 7 (101 years ago, FIG. 10 and 11) corresponds to Association II (15-cm depth). This interval is not characterized by the frequency peak of any particle, but as in the other samples of Association II, this sample is marked by the absence of algae, which indicates a decrease in moisture. However, the TOC and TS contents remain relatively constant compared with the previous interval, as well as the amorphized elements and the cuticles intense fluorescence. Thus, the amendments in the moisture content were insufficient to establish meaningful oxidative processes. In this type of open depositional environment, when the overflow of the river fails to occur, the moisture content would be balanced by the groundwater table and thus, the wetland never dried completely, therefore, it is very difficult to infer drought periods for this type of environment.

Interval 8 (50 years ago to Recent, FIG. 10 and 11) corresponds to Association V (10-0-cm depth), which is marked by a peak of PTS and PTNS, particles related to the Palynofacies C. The recurrence of algalic elements suggests an increase in moisture compared with the previous interval. On the other hand, the contents of TOC and TS are at lowest levels of the entire profile in the 10-cm depth (50 years ago), which may indicate that the sedimentary environment was more exposed to oxidative processes in this layer, which might be attributed to anthropic activities of drainage of sedimentary deposit for the extraction of ―medicinal mud.” However, in the overlying layers (5 and 0 cm), the TOC and TS contents rise again and were most likely regulated by an increase in the frequency of woody fragments (PTS and PTNS). In this interval, the cuticle frequency and the diversity of epidermal organization patterns decrease considerably compared with deeper layers. This occurred perhaps in response to vegetation removal for extraction of ―medicinal mud” that resulted in reduction of local floristic diversity. Sjogren et al. (2007) and Chambers et al. (2007) have also indicated human impact as an important factor on Holocene peat development and decomposition. Many European mires contain a layer of increased decomposition at the surface. Whereas some researchers have explained these changes in terms of climatic conditions (Granlund, 1932), von Bulow (1929) claimed that human impact was the cause of what he called the "kultureller Trockenhorizont." Recently, Sjogren et al. (2007) also suggested that near-surface changes are related to human activities and recommended a more cautious view about of the future development of peatlands studied. The same recommendations would apply to the peatlands of Iraí, whose top layer also has evidence of the effects of human action.

In addition, McGlue et al. (2012) obtained data from Lagoa Gaíva, located along the western margin of the Paraguay River (straddling the border of Brazil and Bolivia), that support the hypothesis that suggests that Southern Hemisphere wetlands were an important source of CH4 after 5000 cal yr BP (Singarayer et al., 2011). This fact reinforces the importance of well-planned management actions of wetlands the purpose of preserving its potential as a source of organic-mineral resources and methano reservoir, since human interference can destabilize the delicate homeostasis of such environments.

FIGURE 12 - Table listing the Palynofacies group, the Associations and the Intervals generated by statistical analyses**.** Abbreviations are in accordance with FIG 2.

4. Conclusions

The palynofacies and geochemical analyses indicated that during the time interval from 10586 cal yr BP to the present, the study area housed a wetland that was characterized by different hydrologic regimes.

Between 10586 and 8908 cal yr BP, the environment was highly reducing with an unexpressive algalic biomass due to the anoxic and stagnant conditions during peaty sedimentation. A change of the depositional environment can be observed from the 8489 to 6392 cal yr BP and is evidenced by the decrease of TOC and ST contents and the disappearance of the algae, possibly in response to a decrease in the saturation level of the groundwater table. From 5867 cal yr BP, river influence starts to contribute with an increase of the allochthonous elements far into the depositional system, and the algae reappears. An increase in moisture occurs from 5343 to 2198 cal yr BP and can be attributed to the large increase in the frequency of the algalic elements possibly caused by the increasing fluvial influence in the sedimentary record. Between 1673 to 625 cal yr BP, the algalic biomass decreased somewhat, but the fluvial influence still contributed with the input of the allochthonous elements for into the depositional system. At 101 years ago, the algalic elements disappear, but the local moisture was maintained by the groundwater table, which prevented the establishment of meaningful oxidative processes.

The last 50-year period provides evidence of the existence of relatively oxidizing processes that may have resulted from anthropic activities. From this interval, it is difficult to distinguish the natural causes of the anthropogenic interference because the latter cause disturbances in the sedimentary record.

The cuticle frequency displays varied patterns of epidermal organization and is higher in the deeper layers and decreases considerably in toward the top, indicating the existence of greater floristic diversity in the past compared with current on-site observations. This occurred perhaps in response to vegetation removal for extraction of medicinal mud, which resulted in alterations of the landscape dynamics via anthropic influence.

Generally speaking, the basal peat deposits might correspond to a phase of terrestrialization that was mainly influenced by a stable groundwater table, where the stagnant environment and anoxic conditions favored a high preservation of OM, and the upper silty organic mud deposits provide evidence of fluvial influence related to water flood events. The wetland never dried completely because in this type of open depositional environment, the moisture content is balanced by both the water table and river overflow. However, the local moisture never been enough to allow the development of a significant amount of algalic biomass throughout the sedimentary record.

In addition, the TOC and ST concentrations are higher in the basal portion of the profile, decreasing toward the top and could be (i) related to granulometry alterations in the same direction or (ii) linked to climate influence that regulated the hydrologic regimes (iii) and the anthropogenic interference in the landscape dynamics. The anomalous TS content existing in Interval 2 might be due to an external source, not yet well established, but may also be closely related to the presence of thermal springs in the region.

Changes in the geochemical and textural characteristics of the sediment from peat to silty organic mud might be a consequence of the gradual alterations in hydrodynamic patterns related mainly with the river overflow events, which started approximately 5.8 ka (Interval 4) and culminated in Interval 5. The increased decomposition in the surface layers, in turn, can be related to human activities.

This type of particular study, which integrates analyses of palynofacies and organic geochemistry, can serve as an adjunct in defining modern reference frames that can be applied in environmental reconstructions because the area can be assumed to be analogous to coal deposits associated with fluvial paleoenvironments in subtropical belts. Moreover the importance of wetlands as a source of organic-mineral resources and methano reservoir reinforces the importance of well-planned management actions with the purpose of preserving this areas, since the human interference can destabilize the delicate homeostasis of such environments. Nevertheless, a general understanding of the hydrological and geomorphological regional systems is a necessary foundation for better understanding the evolution of the Holocene wetlands of Irai.

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Appendix

FIGURE 13 – Table showing the ranges of higher frequency of TOC and TS and the major subgroups of POM. Abbreviations are in accordance with FIG. 2.

FIGURE 14 – Table listing the ranges of the frequency peaks of the major subgroups of POM. Percentage values of subgroups are related to total OM, including the palynomorphs. The frequency peaks are highlighted. Abbreviations are in accordance with FIG. 3. Assoc (Association)

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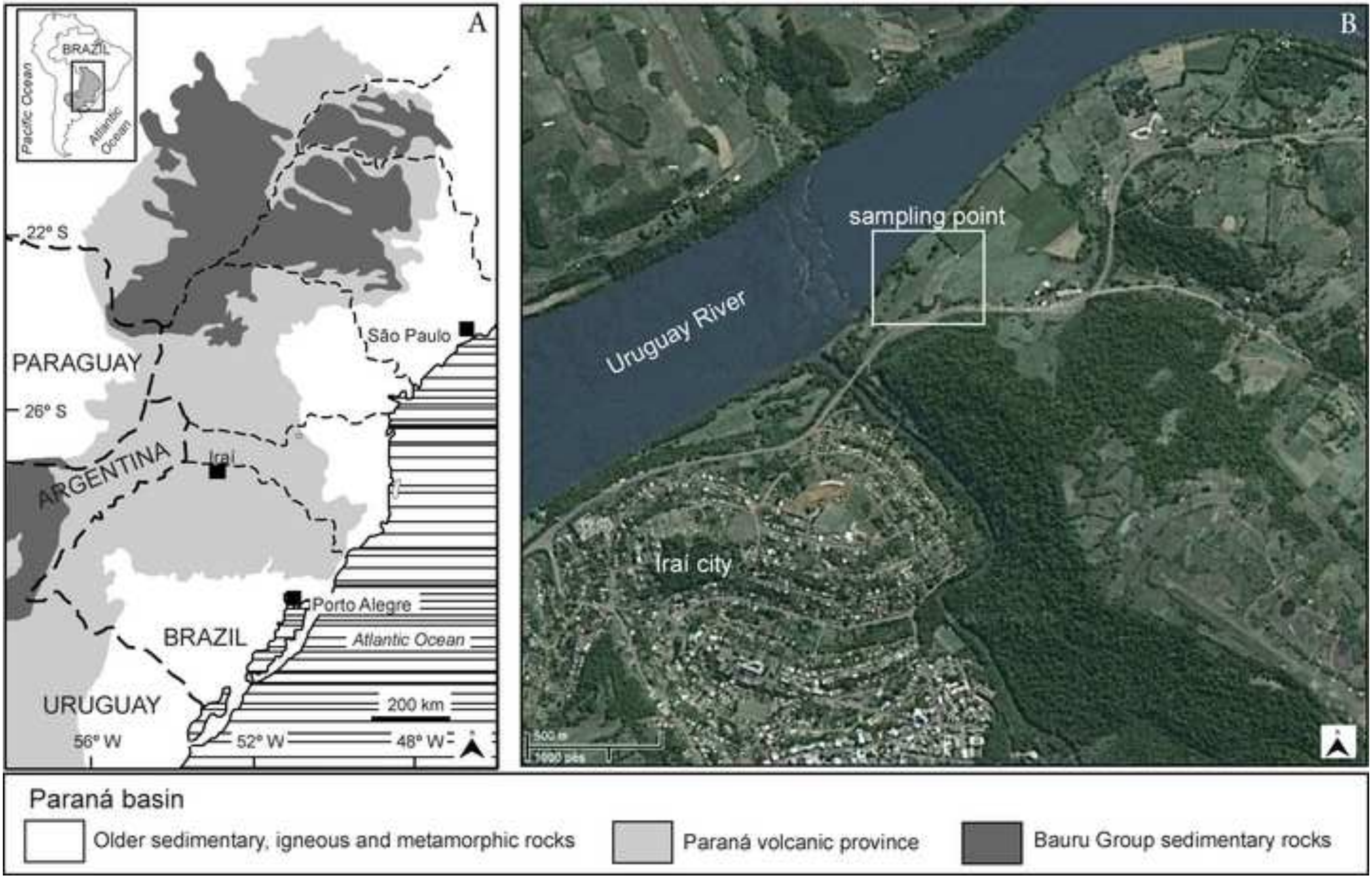
A
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Iraí
São Paulo
Porto Alegre
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URUGUAY
200 km
56° W
52° W
48° W
B
sampling point
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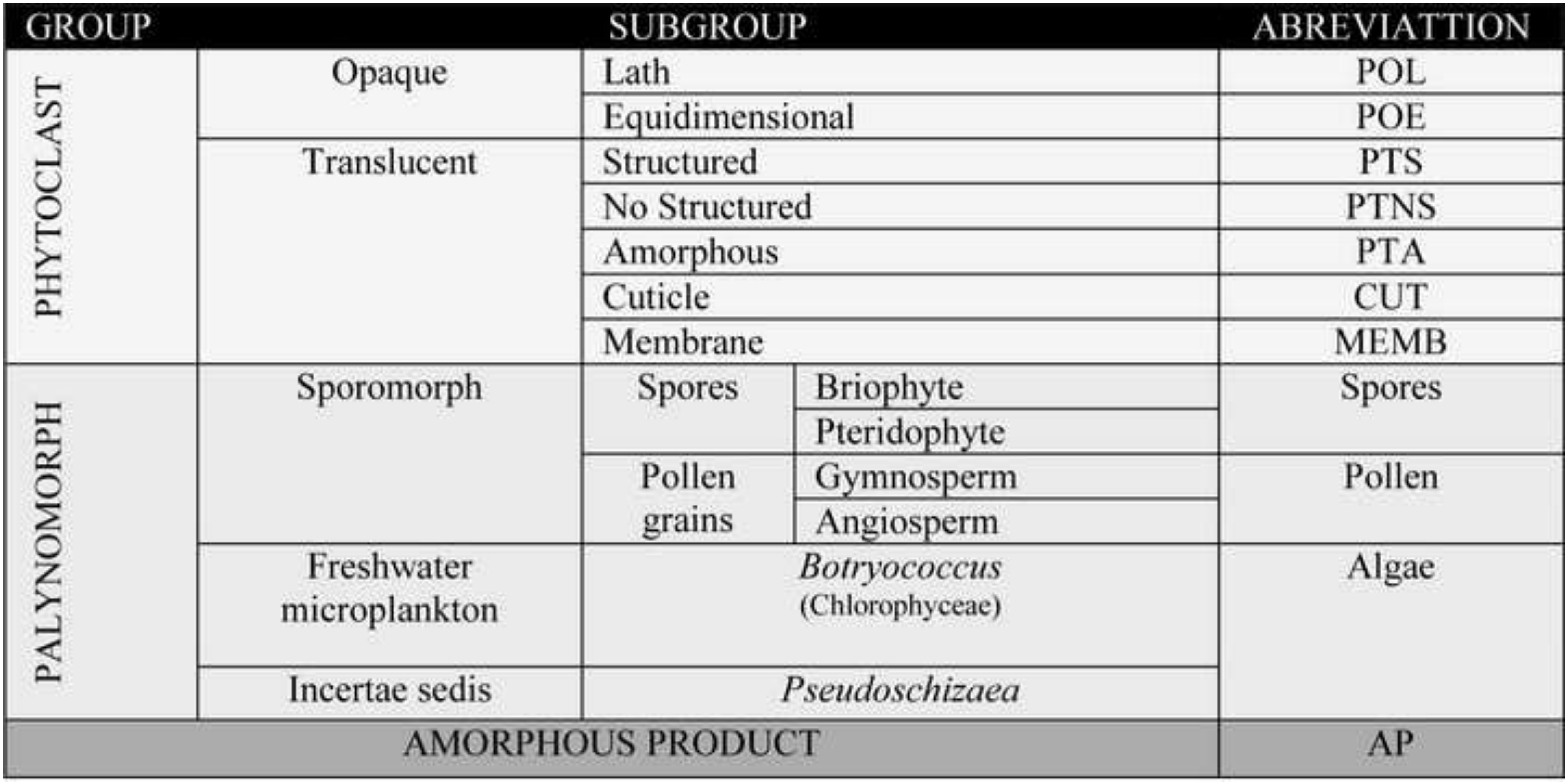
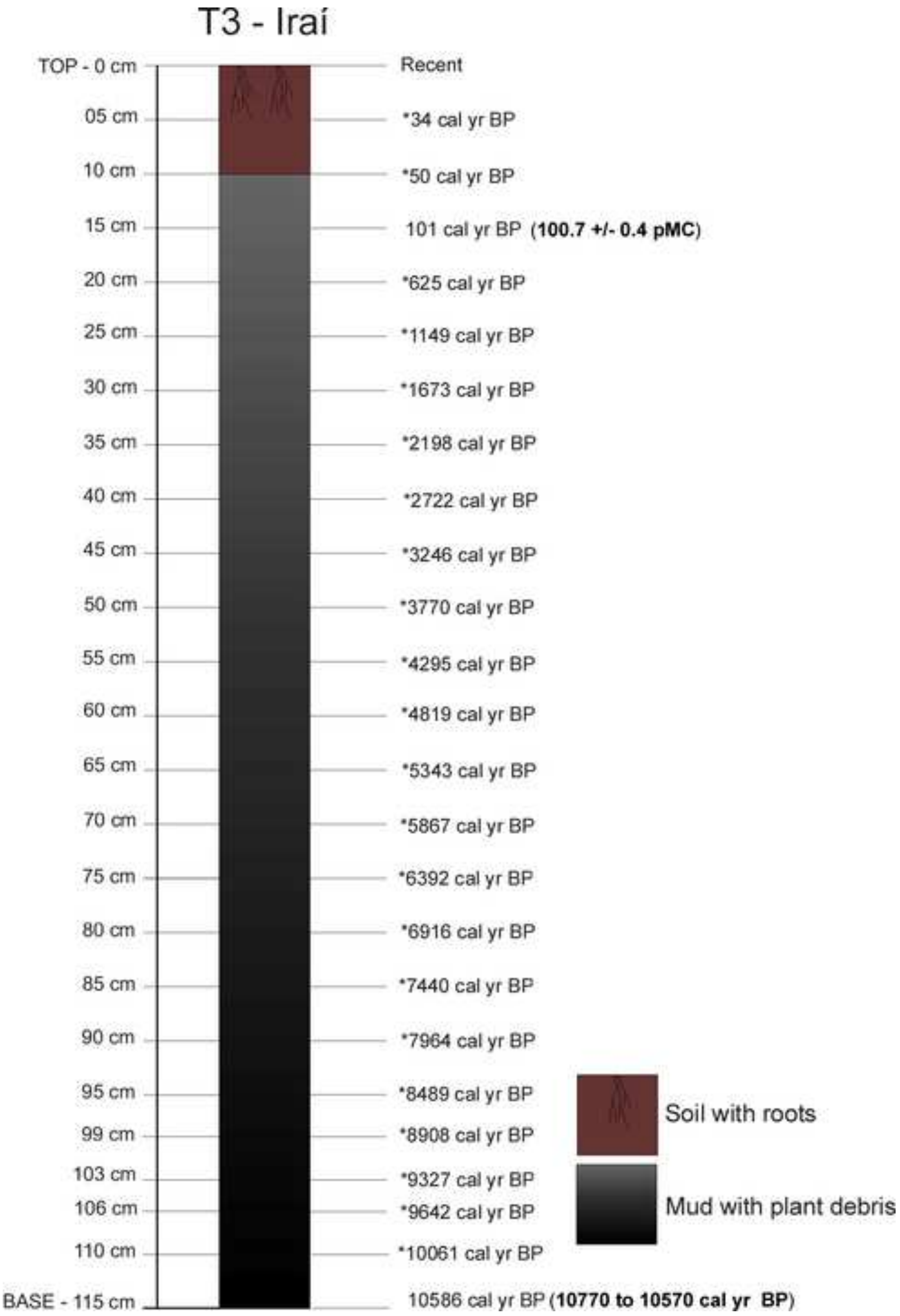
Paraná basin
Older sedimentary, igneous and metamorphic rocks
Paraná volcanic province
Bauru Group sedimentary rocks



GROUP	SUBGROUP			ABREVIATTION
PHYTOCLAST	Opaque	Lath		POL
		Equidimensional		POE
	Translucent	Structured		PTS
		No Structured		PTNS
		Amorphous		PTA
		Cuticle		CUT
		Membrane		MEMB
PALYNOMORPH	Sporomorph	Spores	Briophyte	Spores
			Pteridophyte	
		Pollen grains	Gymnosperm	Pollen
			Angiosperm	
	Freshwater microplankton	*Botryococcus* (Chlorophyceae)		Algae
	Incertae sedis	*Pseudoschizaea*		
AMORPHOUS PRODUCT				AP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106 cm
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BASE - 115 cm
Recent
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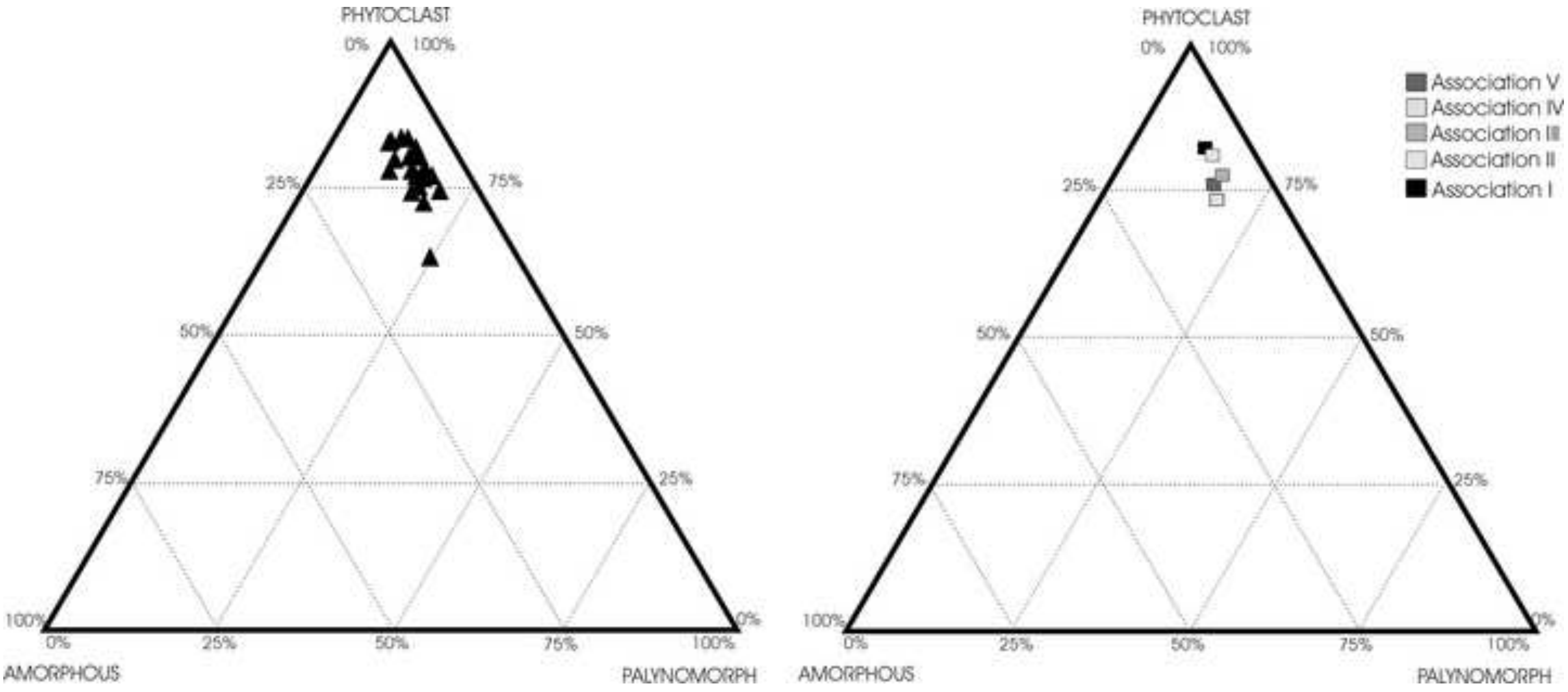
*50 cal yr BP
101 cal yr BP (100.7 +/- 0.4 pMC)
*625 cal yr BP
*1149 cal yr BP
*1673 cal yr BP
*2198 cal yr BP
*2722 cal yr BP
*3246 cal yr BP
*3770 cal yr BP
*4295 cal yr BP
*4819 cal yr BP
*5343 cal yr BP
*5867 cal yr BP
*6392 cal yr BP
*6916 cal yr BP
*7440 cal yr BP
*7964 cal yr BP
*8489 cal yr BP
*8908 cal yr BP
*9327 cal yr BP
*9642 cal yr BP
*10061 cal yr BP
10586 cal yr BP (10770 to 10570 cal yr BP)
Soil with roots
Mud with plant debris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PALYNOMORPH

Figure

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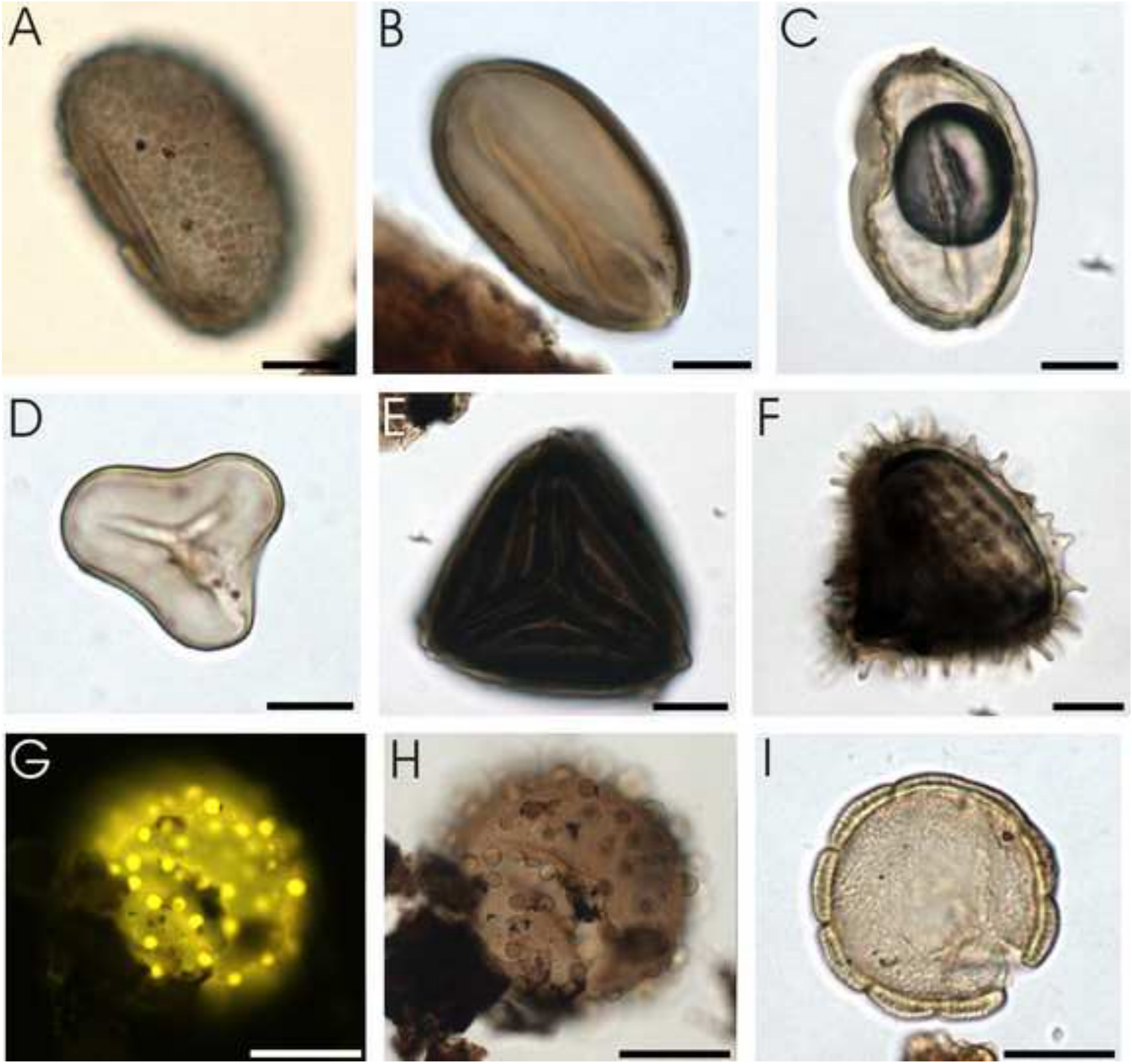
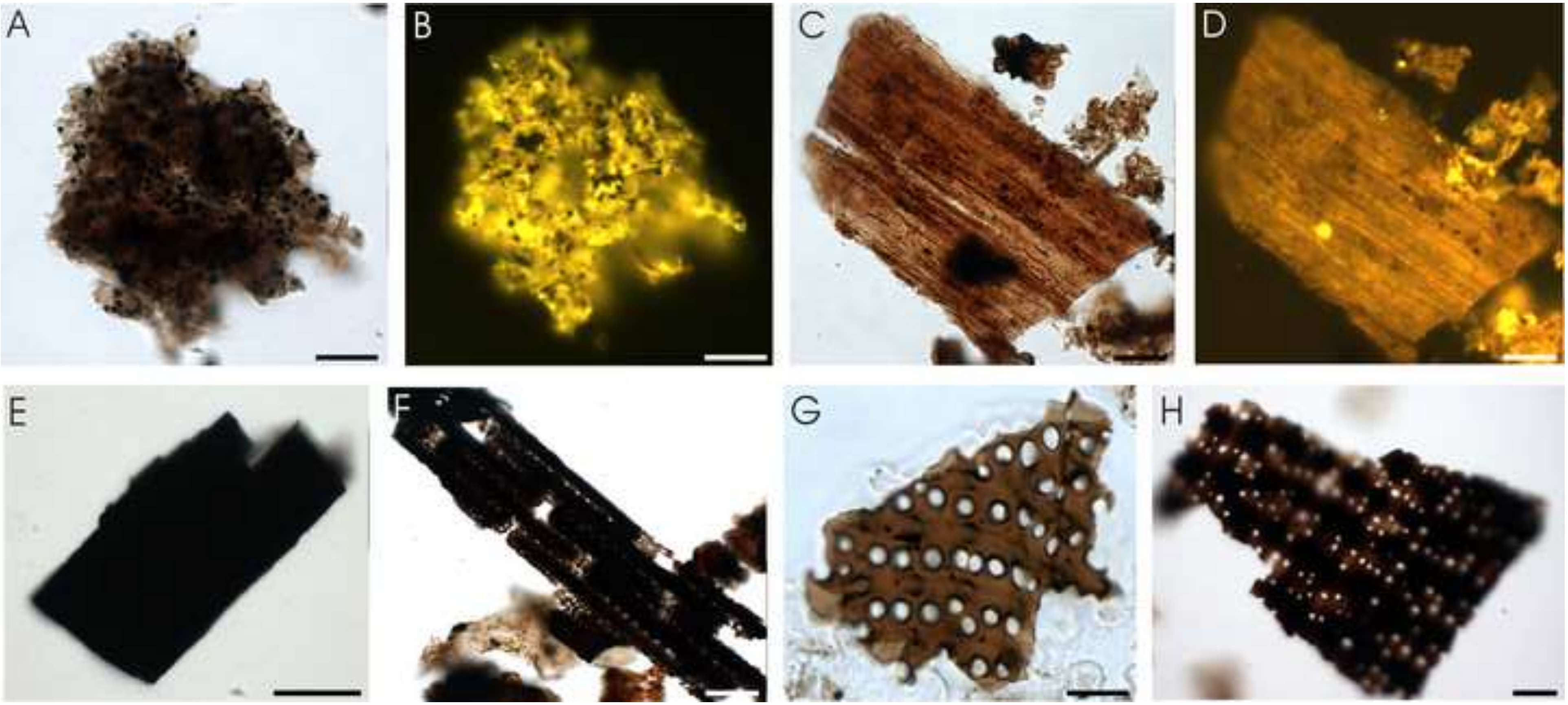


Figure



Figure

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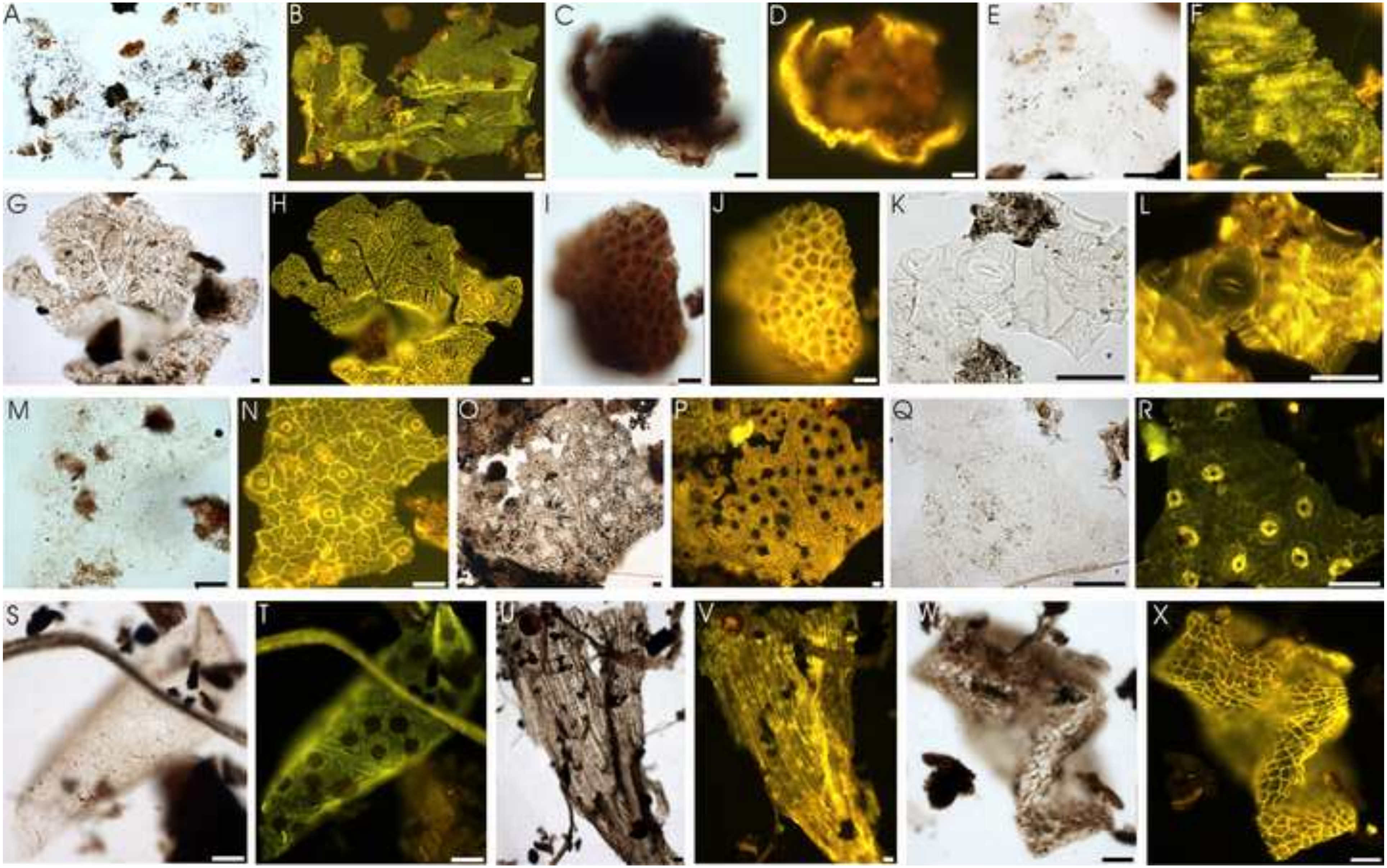

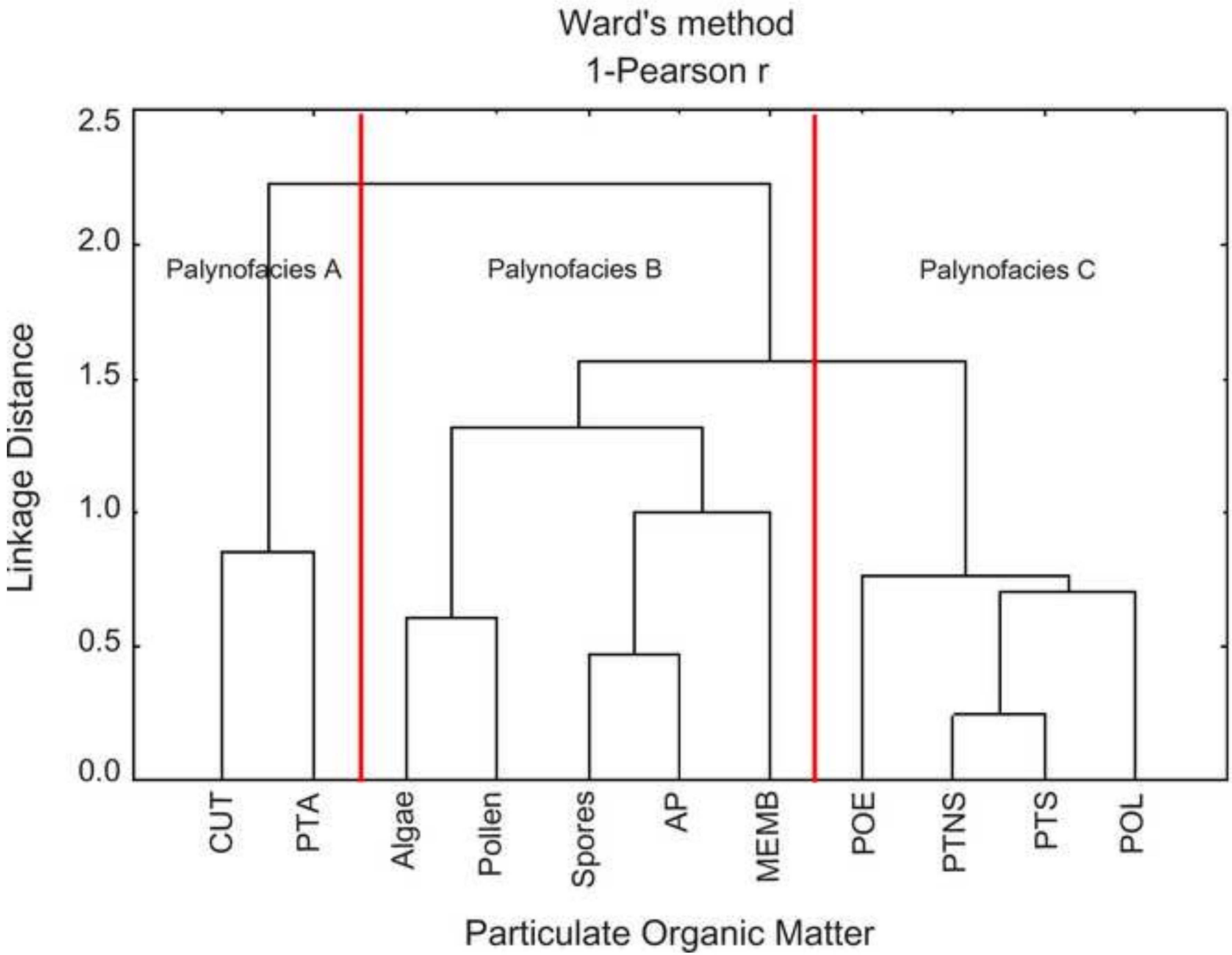
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POL
Particulate Organic Matter

Figure

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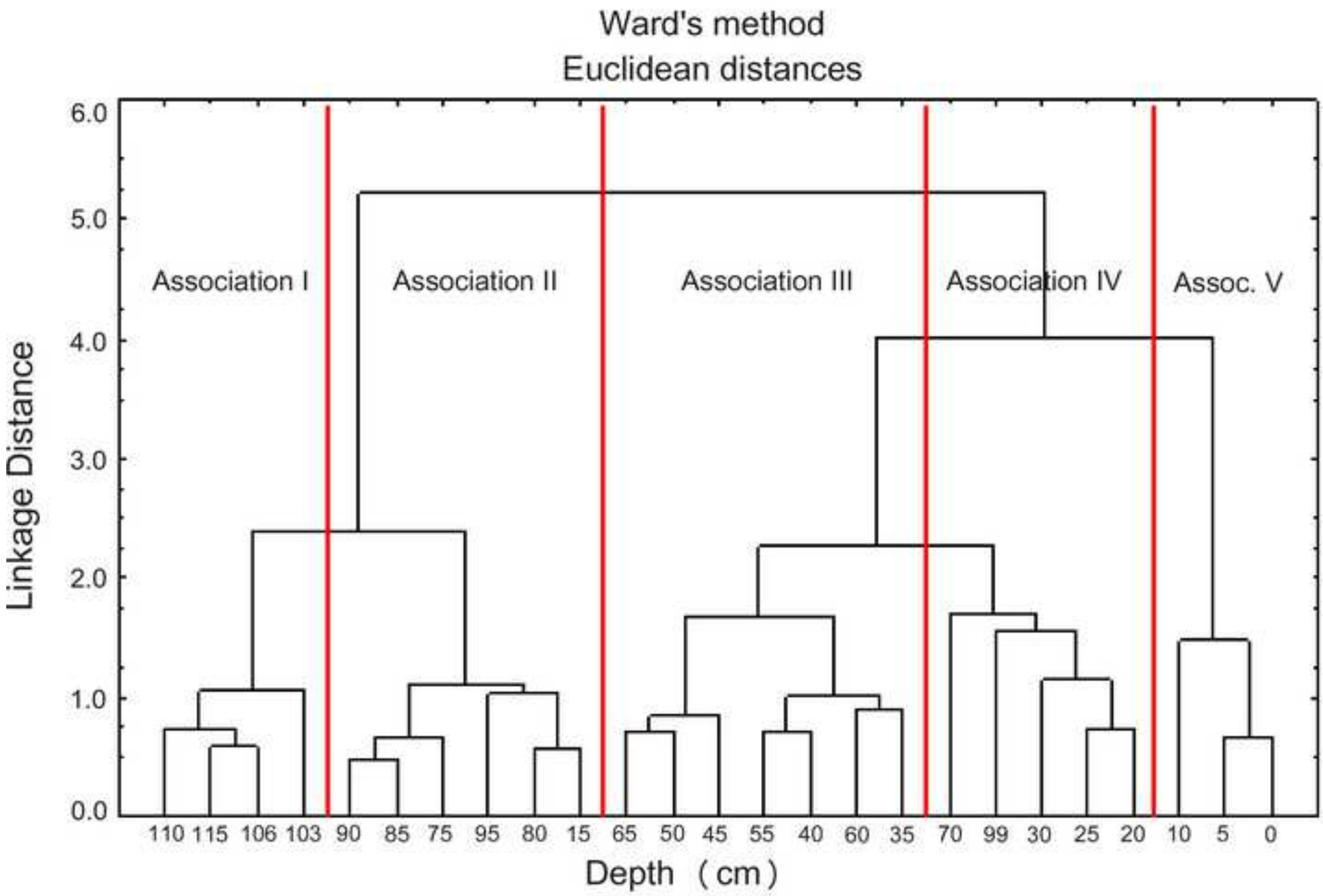
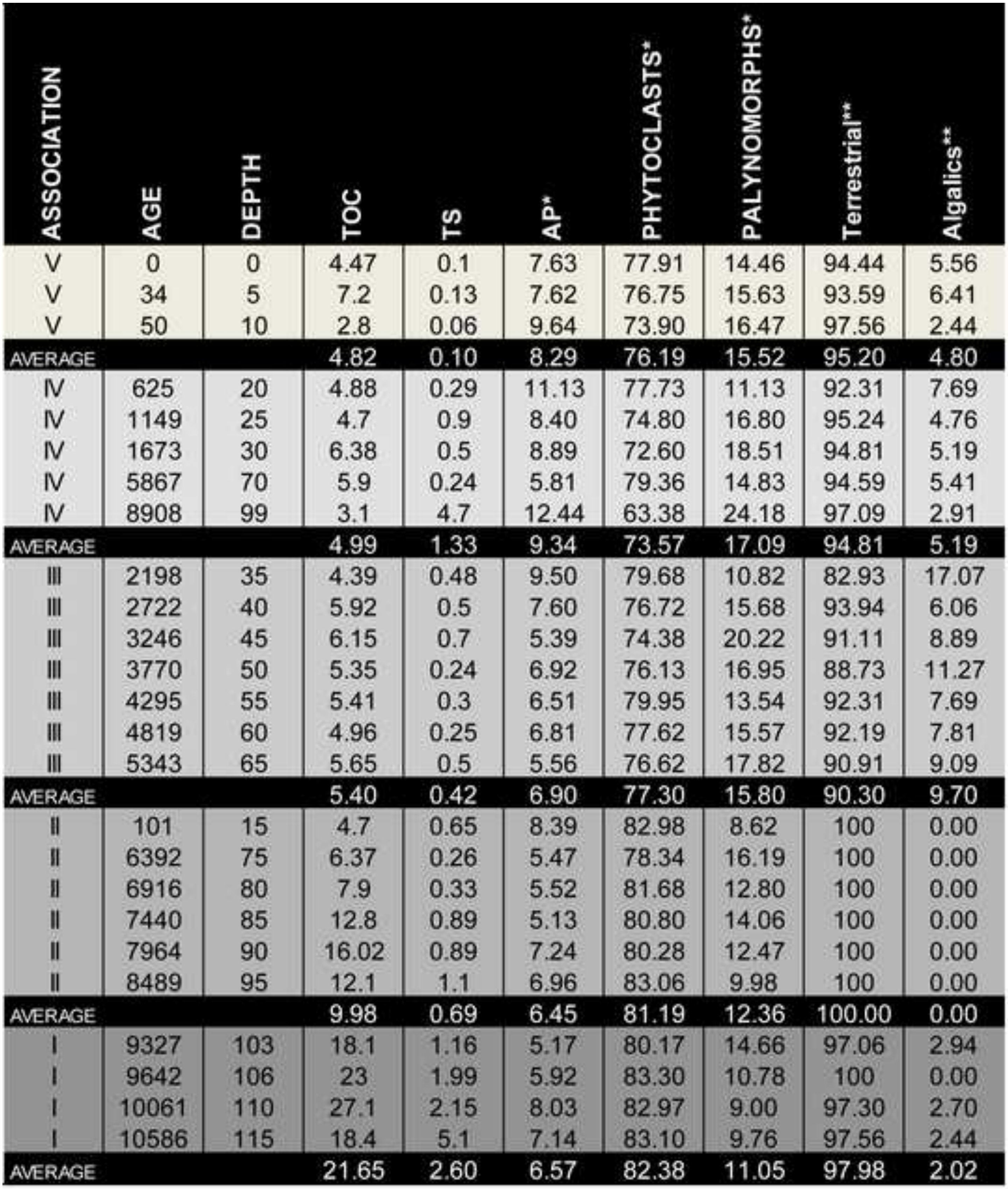
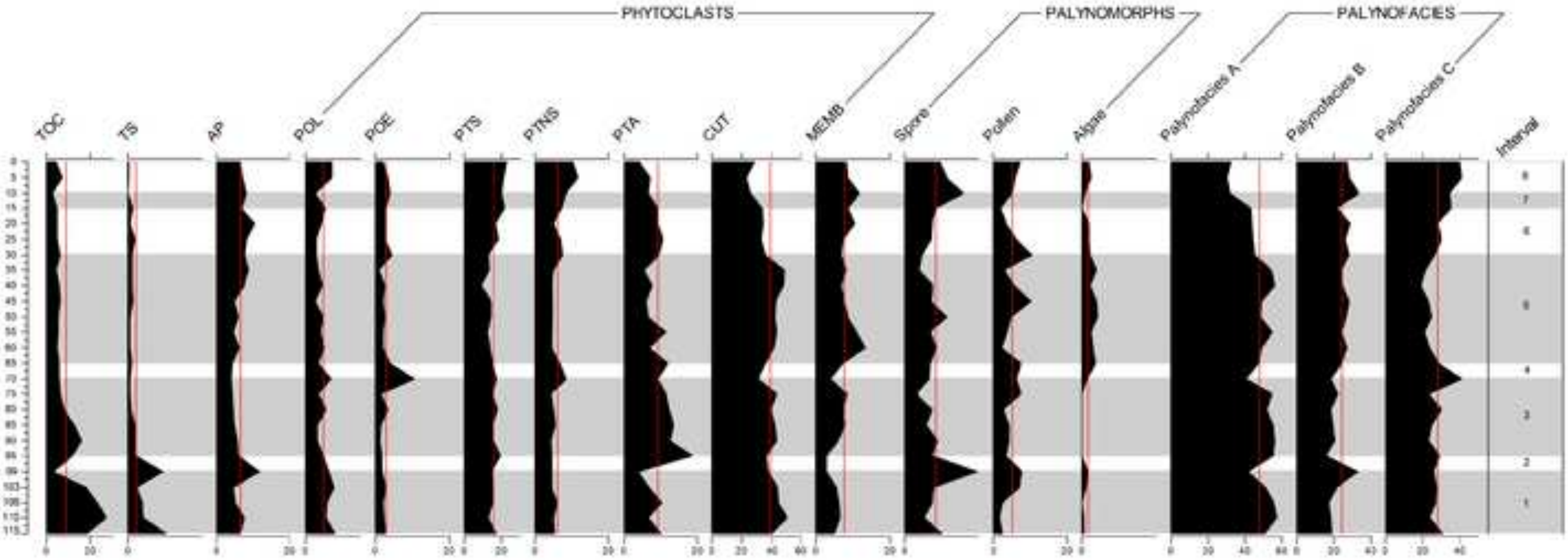




ASSOCIATION	AGE	DEPTH	TOC	TS	AP*	PHYTOCLASTS*	PALYNOMORPHS*	Terrestrial**	Algalics**
V	0	0	4.47	0.1	7.63	77.91	14.46	94.44	5.56
V	34	5	7.2	0.13	7.62	76.75	15.63	93.59	6.41
V	50	10	2.8	0.06	9.64	73.90	16.47	97.56	2.44
AVERAGE			4.82	0.10	8.29	76.19	15.52	95.20	4.80
IV	625	20	4.88	0.29	11.13	77.73	11.13	92.31	7.69
IV	1149	25	4.7	0.9	8.40	74.80	16.80	95.24	4.76
IV	1673	30	6.38	0.5	8.89	72.60	18.51	94.81	5.19
IV	5867	70	5.9	0.24	5.81	79.36	14.83	94.59	5.41
IV	8908	99	3.1	4.7	12.44	63.38	24.18	97.09	2.91
AVERAGE			4.99	1.33	9.34	73.57	17.09	94.81	5.19
III	2198	35	4.39	0.48	9.50	79.68	10.82	82.93	17.07
III	2722	40	5.92	0.5	7.60	76.72	15.68	93.94	6.06
III	3246	45	6.15	0.7	5.39	74.38	20.22	91.11	8.89
III	3770	50	5.35	0.24	6.92	76.13	16.95	88.73	11.27
III	4295	55	5.41	0.3	6.51	79.95	13.54	92.31	7.69
III	4819	60	4.96	0.25	6.81	77.62	15.57	92.19	7.81
III	5343	65	5.65	0.5	5.56	76.62	17.82	90.91	9.09
AVERAGE			5.40	0.42	6.90	77.30	15.80	90.30	9.70
II	101	15	4.7	0.65	8.39	82.98	8.62	100	0.00
II	6392	75	6.37	0.26	5.47	78.34	16.19	100	0.00
II	6916	80	7.9	0.33	5.52	81.68	12.80	100	0.00
II	7440	85	12.8	0.89	5.13	80.80	14.06	100	0.00
II	7964	90	16.02	0.89	7.24	80.28	12.47	100	0.00
II	8489	95	12.1	1.1	6.96	83.06	9.98	100	0.00
AVERAGE			9.98	0.69	6.45	81.19	12.36	100.00	0.00
I	9327	103	18.1	1.16	5.17	80.17	14.66	97.06	2.94
I	9642	106	23	1.99	5.92	83.30	10.78	100	0.00
I	10061	110	27.1	2.15	8.03	82.97	9.00	97.30	2.70
I	10586	115	18.4	5.1	7.14	83.10	9.76	97.56	2.44
AVERAGE			21.65	2.60	6.57	82.38	11.05	97.98	2.02

Figure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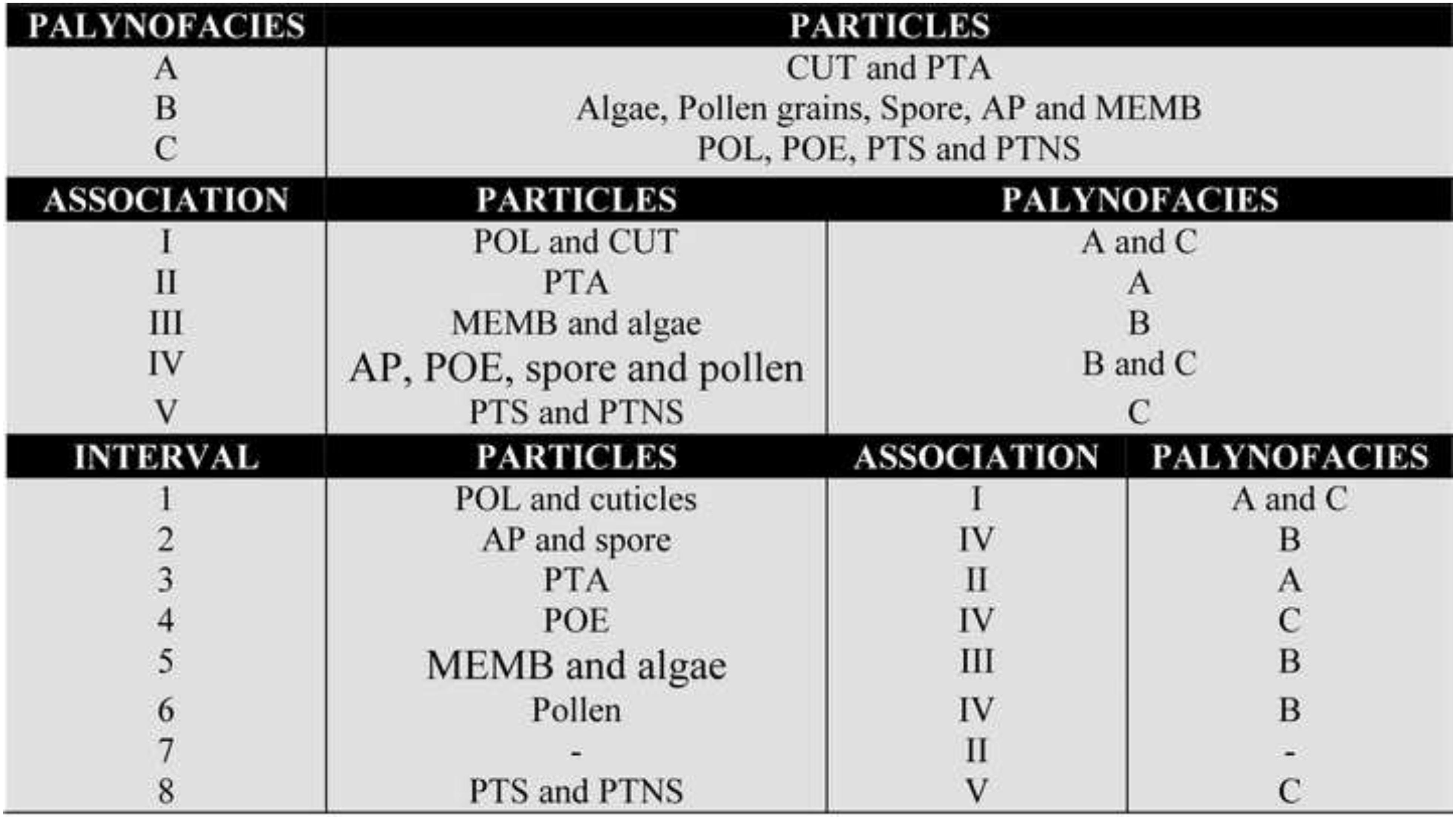
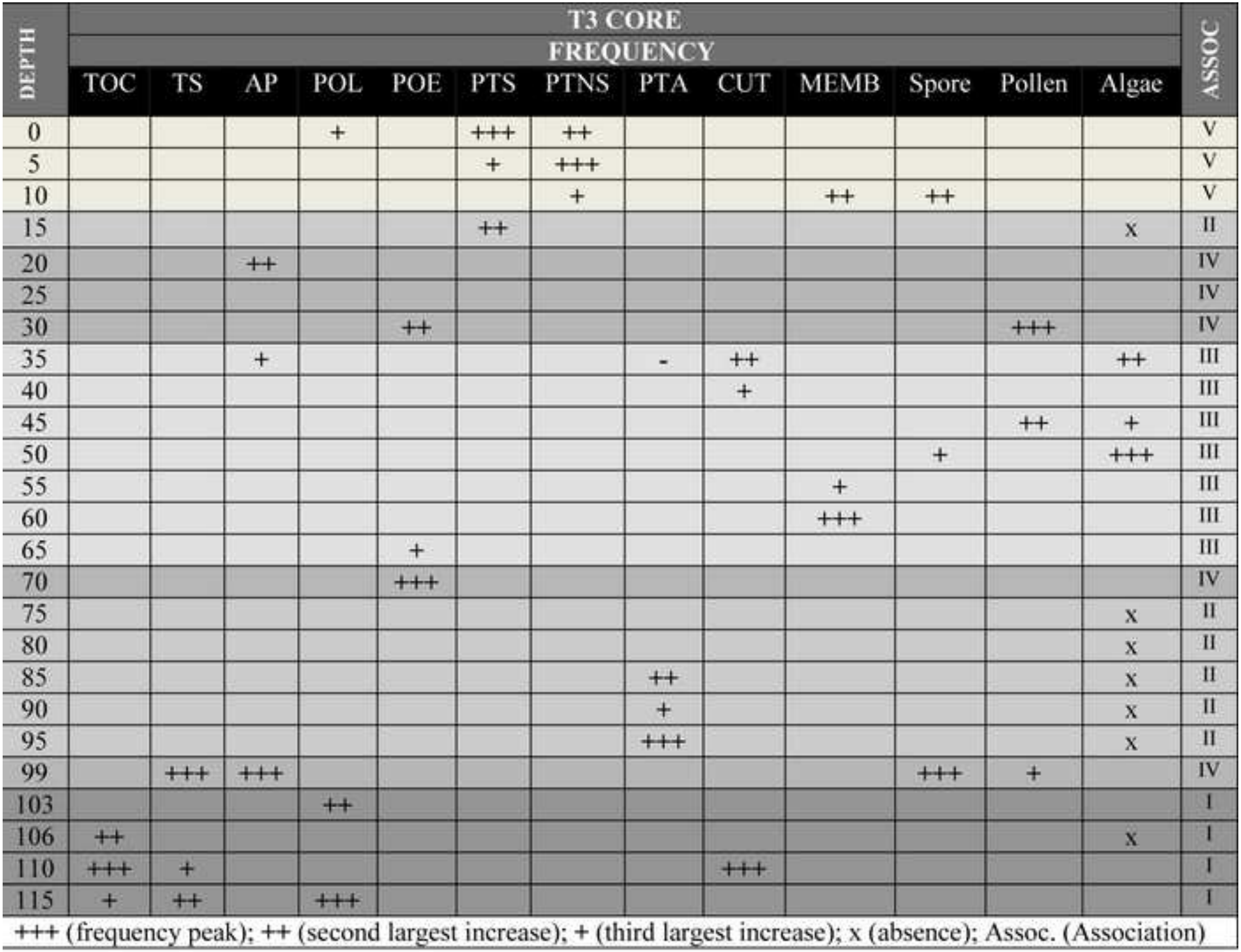


PALYNOFACIES	PARTICLES
A	CUT and PTA
B	Algae, Pollen grains, Spore, AP and MEMB
C	POL, POE, PTS and PTNS

ASSOCIATION	PARTICLES	PALYNOFACIES
I	POL and CUT	A and C
II	PTA	A
III	MEMB and algae	B
IV	AP, POE, spore and pollen	B and C
V	PTS and PTNS	C

INTERVAL	PARTICLES	ASSOCIATION	PALYNOFACIES
1	POL and cuticles	I	A and C
2	AP and spore	IV	B
3	PTA	II	A
4	POE	IV	C
5	MEMB and algae	III	B
6	Pollen	IV	B
7	-	II	-
8	PTS and PTNS	V	C



DEPTH	T3 CORE FREQUENCY													ASSOC
	TOC	TS	AP	POL	POE	PTS	PTNS	PTA	CUT	MEMB	Spore	Pollen	Algae	
0				+		+++	++							V
5						+	+++							V
10							+			++	++			V
15						++							x	II
20			++											IV
25														IV
30					++							+++		IV
35			+					-	++				++	III
40									+					III
45												++	+	III
50											+		+++	III
55										+				III
60										+++				III
65					+									III
70					+++									IV
75													x	II
80													x	II
85								++					x	II
90								+					x	II
95								+++					x	II
99		+++	+++								+++	+		IV
103				++										I
106	++												x	I
110	+++	+							+++					I
115	+	++		+++										I

+++ (frequency peak); ++ (second largest increase); + (third largest increase); x (absence); Assoc. (Association)

Figure

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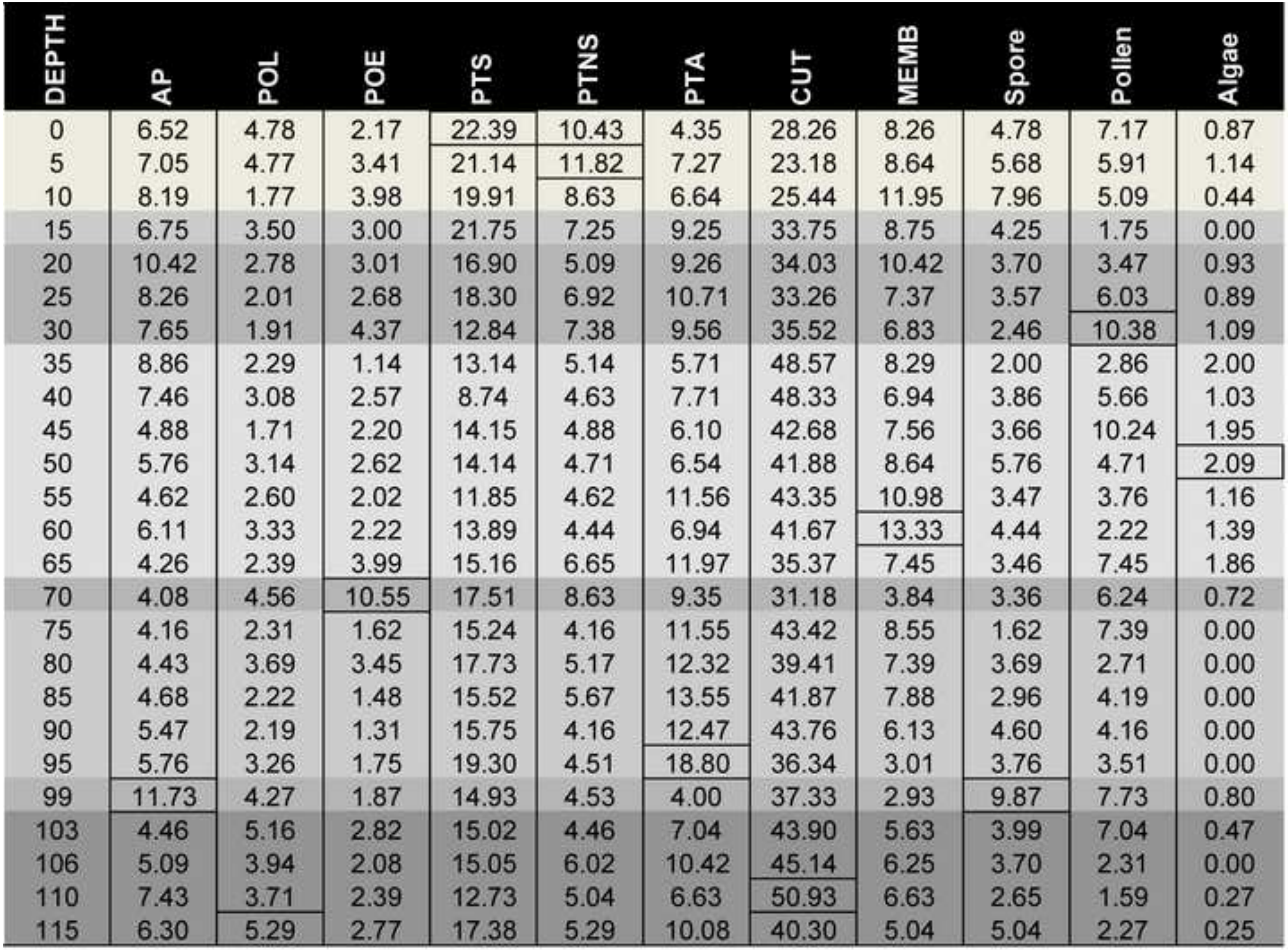
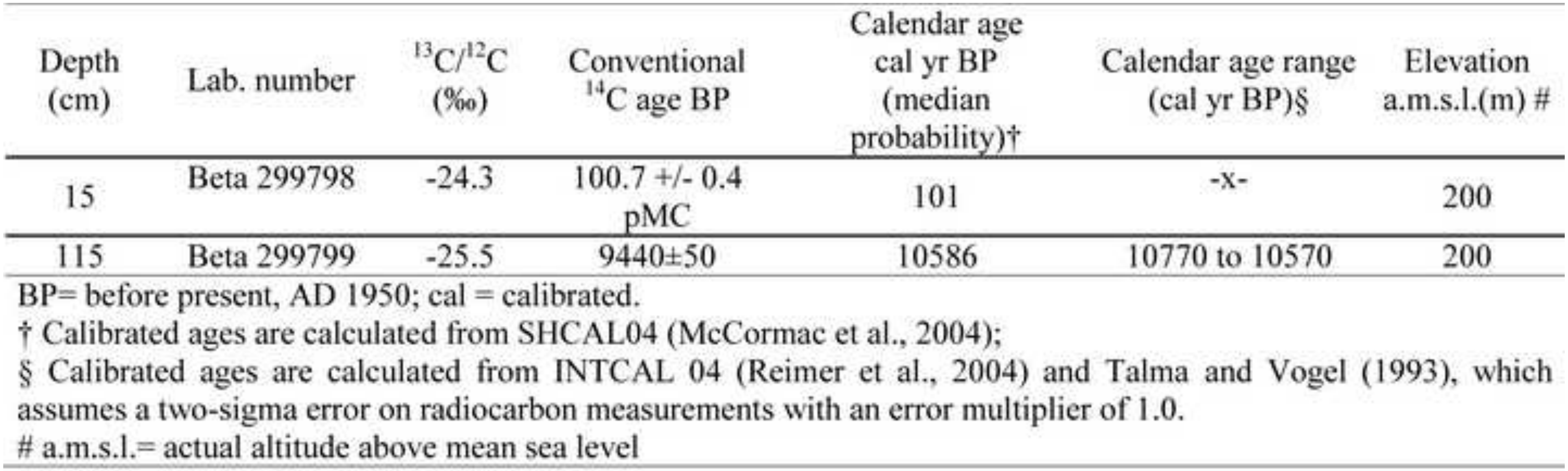


DEPTH	AP	POL	POE	PTS	PTNS	PTA	CUT	MEMB	Spore	Pollen	Algae
0	6.52	4.78	2.17	22.39	10.43	4.35	28.26	8.26	4.78	7.17	0.87
5	7.05	4.77	3.41	21.14	11.82	7.27	23.18	8.64	5.68	5.91	1.14
10	8.19	1.77	3.98	19.91	8.63	6.64	25.44	11.95	7.96	5.09	0.44
15	6.75	3.50	3.00	21.75	7.25	9.25	33.75	8.75	4.25	1.75	0.00
20	10.42	2.78	3.01	16.90	5.09	9.26	34.03	10.42	3.70	3.47	0.93
25	8.26	2.01	2.68	18.30	6.92	10.71	33.26	7.37	3.57	6.03	0.89
30	7.65	1.91	4.37	12.84	7.38	9.56	35.52	6.83	2.46	10.38	1.09
35	8.86	2.29	1.14	13.14	5.14	5.71	48.57	8.29	2.00	2.86	2.00
40	7.46	3.08	2.57	8.74	4.63	7.71	48.33	6.94	3.86	5.66	1.03
45	4.88	1.71	2.20	14.15	4.88	6.10	42.68	7.56	3.66	10.24	1.95
50	5.76	3.14	2.62	14.14	4.71	6.54	41.88	8.64	5.76	4.71	2.09
55	4.62	2.60	2.02	11.85	4.62	11.56	43.35	10.98	3.47	3.76	1.16
60	6.11	3.33	2.22	13.89	4.44	6.94	41.67	13.33	4.44	2.22	1.39
65	4.26	2.39	3.99	15.16	6.65	11.97	35.37	7.45	3.46	7.45	1.86
70	4.08	4.56	10.55	17.51	8.63	9.35	31.18	3.84	3.36	6.24	0.72
75	4.16	2.31	1.62	15.24	4.16	11.55	43.42	8.55	1.62	7.39	0.00
80	4.43	3.69	3.45	17.73	5.17	12.32	39.41	7.39	3.69	2.71	0.00
85	4.68	2.22	1.48	15.52	5.67	13.55	41.87	7.88	2.96	4.19	0.00
90	5.47	2.19	1.31	15.75	4.16	12.47	43.76	6.13	4.60	4.16	0.00
95	5.76	3.26	1.75	19.30	4.51	18.80	36.34	3.01	3.76	3.51	0.00
99	11.73	4.27	1.87	14.93	4.53	4.00	37.33	2.93	9.87	7.73	0.80
103	4.46	5.16	2.82	15.02	4.46	7.04	43.90	5.63	3.99	7.04	0.47
106	5.09	3.94	2.08	15.05	6.02	10.42	45.14	6.25	3.70	2.31	0.00
110	7.43	3.71	2.39	12.73	5.04	6.63	50.93	6.63	2.65	1.59	0.27
115	6.30	5.29	2.77	17.38	5.29	10.08	40.30	5.04	5.04	2.27	0.25



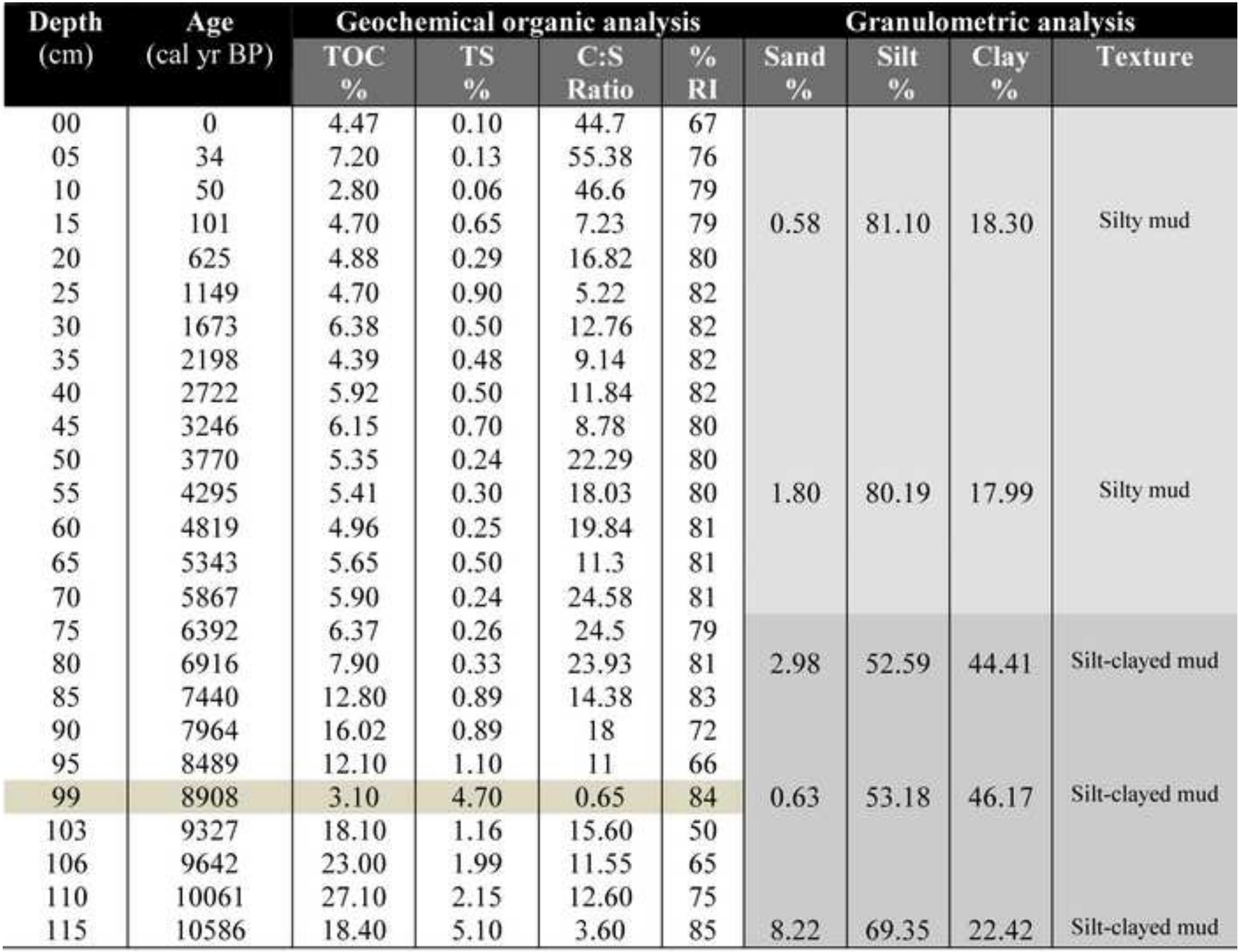
Depth (cm)	Lab. number	$^{13}C/^{12}C$ (‰)	Conventional ^{14}C age BP	Calendar age cal yr BP (median probability)†	Calendar age range (cal yr BP)§	Elevation a.m.s.l.(m) #
15	Beta 299798	-24.3	100.7 +/- 0.4 pMC	101	-x-	200
115	Beta 299799	-25.5	9440±50	10586	10770 to 10570	200

BP= before present, AD 1950; cal = calibrated.

† Calibrated ages are calculated from SHCAL04 (McCormac et al., 2004);

§ Calibrated ages are calculated from INTCAL 04 (Reimer et al., 2004) and Talma and Vogel (1993), which assumes a two-sigma error on radiocarbon measurements with an error multiplier of 1.0.

a.m.s.l.= actual altitude above mean sea level



Depth (cm)	Age (cal yr BP)	Geochemical organic analysis				Granulometric analysis			
		TOC %	TS %	C:S Ratio	% RI	Sand %	Silt %	Clay %	Texture
00	0	4.47	0.10	44.7	67				
05	34	7.20	0.13	55.38	76				
10	50	2.80	0.06	46.6	79				
15	101	4.70	0.65	7.23	79	0.58	81.10	18.30	Silty mud
20	625	4.88	0.29	16.82	80				
25	1149	4.70	0.90	5.22	82				
30	1673	6.38	0.50	12.76	82				
35	2198	4.39	0.48	9.14	82				
40	2722	5.92	0.50	11.84	82				
45	3246	6.15	0.70	8.78	80				
50	3770	5.35	0.24	22.29	80				
55	4295	5.41	0.30	18.03	80	1.80	80.19	17.99	Silty mud
60	4819	4.96	0.25	19.84	81				
65	5343	5.65	0.50	11.3	81				
70	5867	5.90	0.24	24.58	81				
75	6392	6.37	0.26	24.5	79				
80	6916	7.90	0.33	23.93	81	2.98	52.59	44.41	Silt-clayed mud
85	7440	12.80	0.89	14.38	83				
90	7964	16.02	0.89	18	72				
95	8489	12.10	1.10	11	66				
99	8908	3.10	4.70	0.65	84	0.63	53.18	46.17	Silt-clayed mud
103	9327	18.10	1.16	15.60	50				
106	9642	23.00	1.99	11.55	65				
110	10061	27.10	2.15	12.60	75				
115	10586	18.40	5.10	3.60	85	8.22	69.35	22.42	Silt-clayed mud

PARTE III

7 CONSIDERAÇÕES FINAIS

A matéria orgânica preservada em depósitos provenientes de ambientes estritamente continentais constitui excelente arquivo de mudanças nas condições deposicionais, ambientais, ecológicas e climáticas sob as quais esses depósitos se originaram, e diversas ferramentas de investigação costumam ser utilizadas para acessar tais informações. Dessa forma, os resultados aqui obtidos a partir de análises integradas de Palinofácies e Geoquímica Orgânica em sedimentos de lagos efêmeros de altitude associados a *gossan* (Ametista do Sul) e em sedimentos turfosos (Iraí) localizados na região do Alto Uruguai (noroeste do RS) com idades correlacionáveis (FIG. 8) permitiram demonstrar que o histórico dessas mudanças tem sido afetado por fatores diversos, tais como oscilações dos padrões pluviométricos em escala regional e global, regimes hidrológicos diferenciados, alterações da vigência vegetacional decorrentes do processo natural de sucessão ecológica e, finalmente, ação antrópica, cuja interferência causa distúrbios no registro deposicional.

As análises palinofaciológicas e organogeoquímicas demonstraram ser efetivas ferramentas de investigação de dados de caráter paleoambiental, paleoclimático e paleoecológico em ambientes que não sofrem influência direta das variações eustáticas. Contudo, o uso de tais ferramentas em ambientes continentais estritos exige tratamento relativamente diferenciado, pois essas análises foram inicialmente desenvolvidas para estudos em ambientes influenciados diretamente por eventos de transgressão e regressão marinha. Portanto, dado o caráter eminentemente terrestre da matéria orgânica a ser analisada, todas as interpretações devem considerar as características peculiares ao ambiente deposicional estritamente continental, levando-se em conta cuidadosamente todas as variáveis envolvidas.

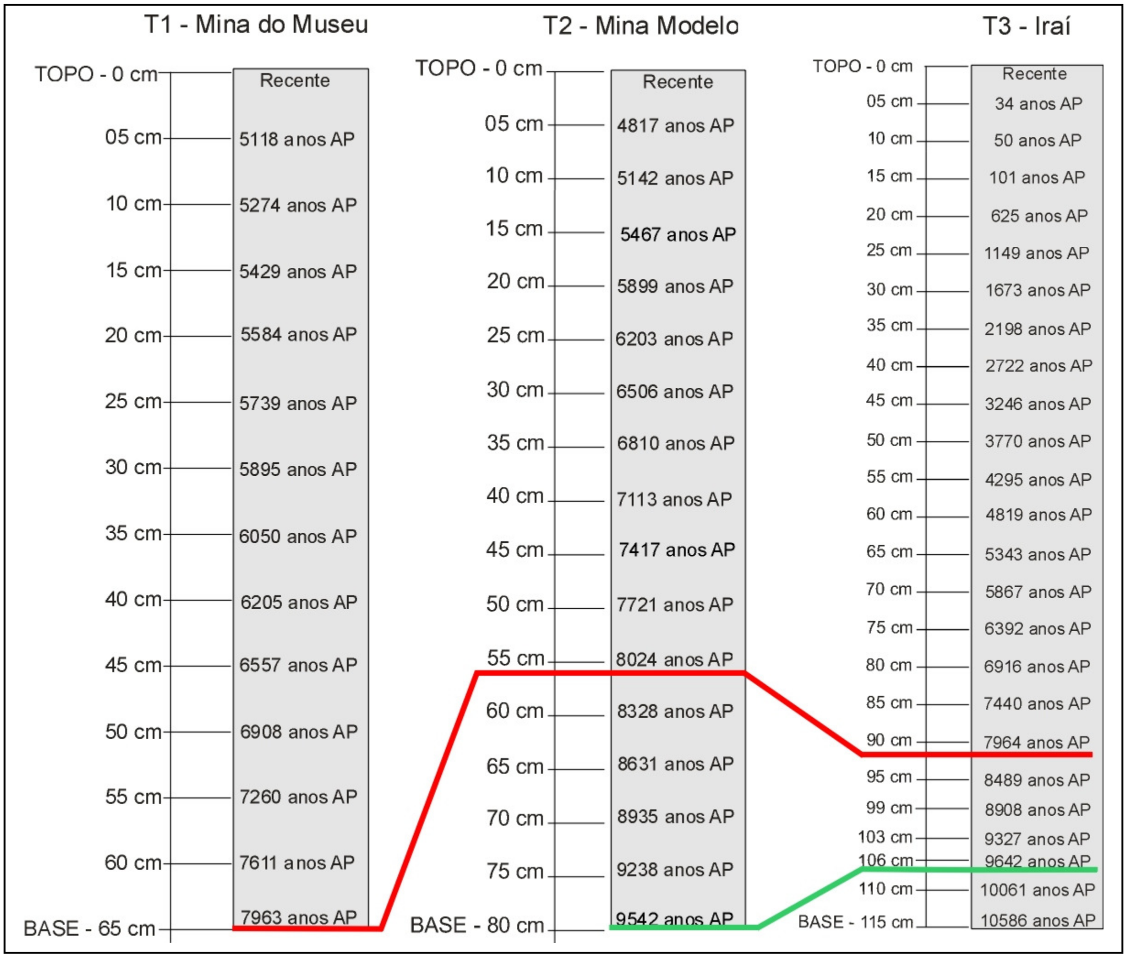


FIGURA 8 – Esquema demonstrando a profundidade e as idades estimadas para os três testemunhos analisados. As linhas em vermelho e verde fazem a correlação entre a profundidade e as idades aproximadas dos testemunhos T1, T2 e T3.

As análises palinofaciológicas realizadas para os três testemunhos (T1 - Mina do Museu, T2 - Mina Modelo e T3 - Iraí) revelaram uma ampla dominância do Grupo Fitoclasto, tanto de partículas lenhosas como não lenhosas. O Grupo Palinomorfo, o segundo em dominância, abrangeu esporomorfos terrestres e algálicos, esses últimos de origem exclusivamente dulciaquícola. O Grupo Produto Amorfo, por sua vez, foi pouco expressivo e derivou, em grande parte, de tecidos vegetais em estado avançado de degradação (FIG. 9, 10 e 11).

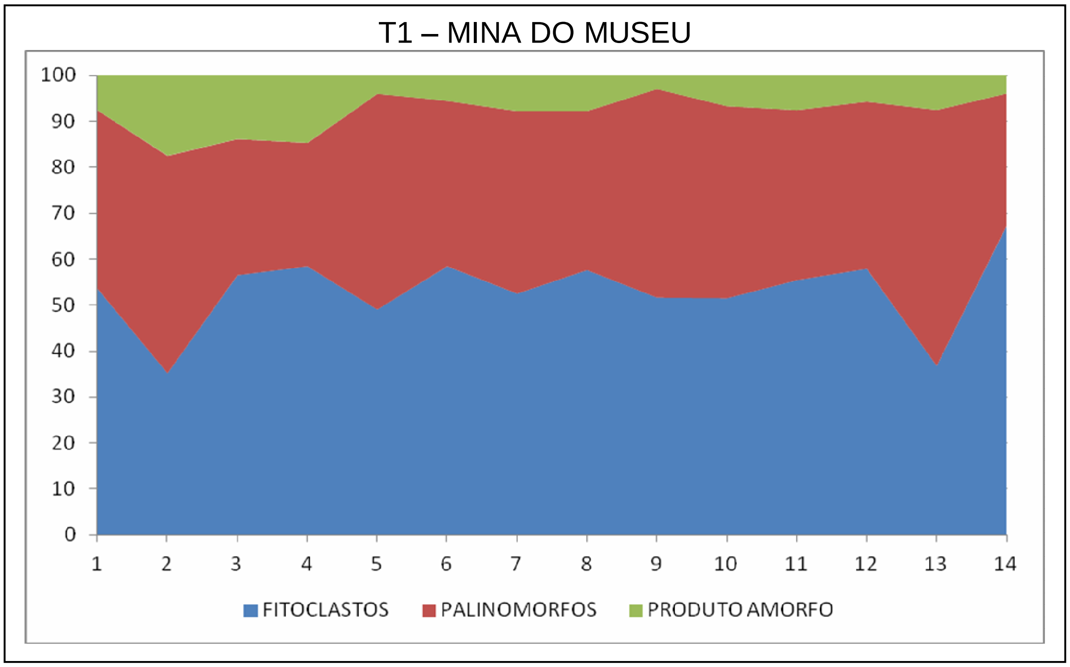


FIGURA 9 – Resultado das análises palinofaciológicas realizadas para o testemunho T1 - Mina do Museu, demonstrando o percentual aproximado dos três principais grupos da matéria orgânica. O eixo vertical corresponde ao percentual de 100% de partículas contadas. O eixo horizontal corresponde ao número de amostras analisadas e os números estão ordenados em ordem crescente, partindo da amostra de topo até a amostra da base.

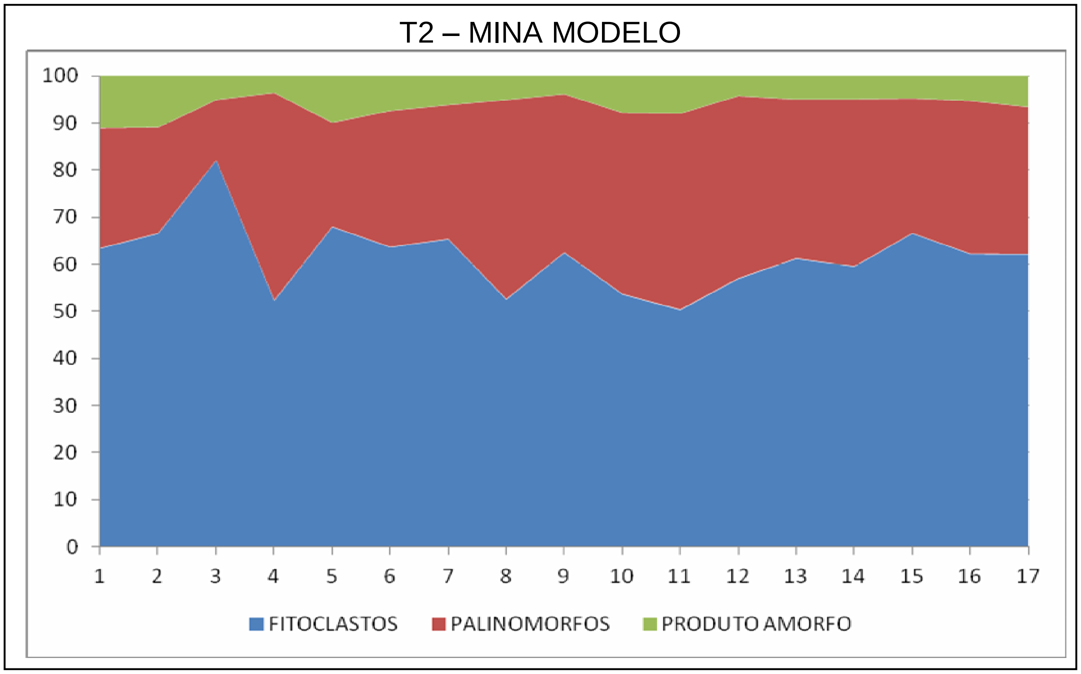


FIGURA 10 – Resultado das análises palinofaciológicas realizadas para o testemunho T2-Mina Modelo, demonstrando o percentual aproximado dos três principais grupos da Matéria Orgânica. O eixo vertical corresponde ao percentual de 100% de partículas contadas. O eixo horizontal corresponde ao número de amostras analisadas e os números estão ordenados em ordem crescente, partindo da amostra de topo até a amostra da Base.

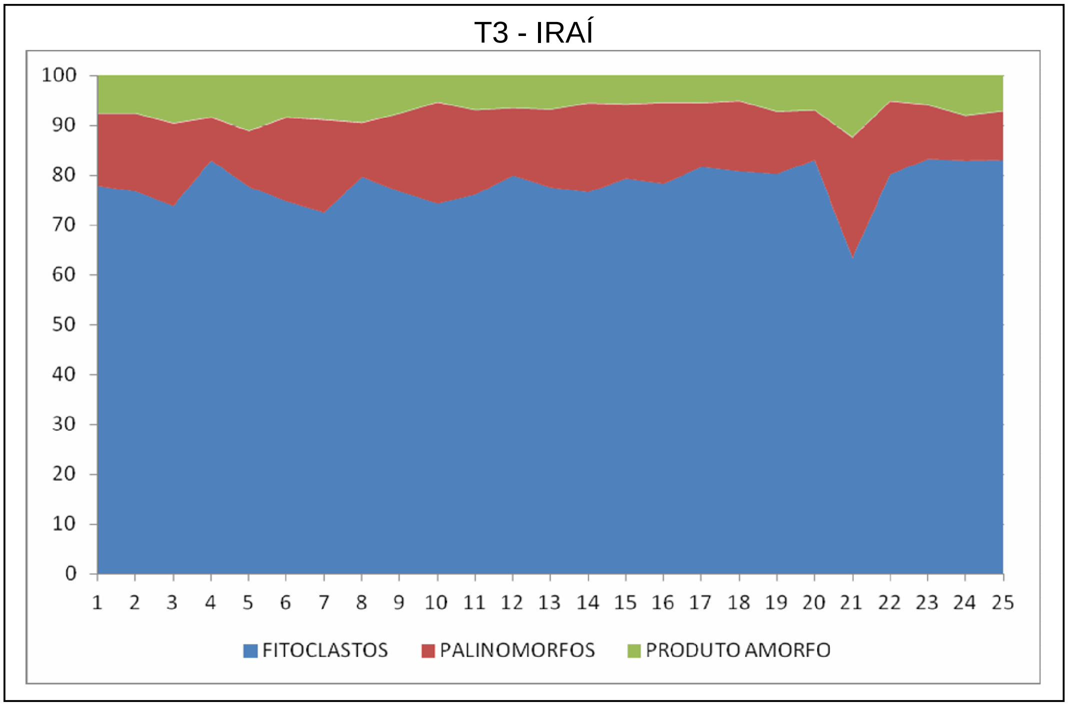


FIGURA 11 – Resultado das análises palinofaciológicas realizadas para o testemunho T3 - Iraí, demonstrando o percentual aproximado dos três principais grupos da matéria orgânica. O eixo vertical corresponde ao percentual de 100% de partículas contadas. O eixo horizontal corresponde ao número de amostras analisadas e os números estão ordenados em ordem crescente, partindo da amostra de topo até a amostra da base.

A análise de palinofácies foi particularmente efetiva nas interpretações de eventos de precipitação e de sucessão vegetacional para os alagados de altitude de Ametista do Sul. A alta percentagem de elementos algálicos no registro sedimentar desses corpos d’água e a expressiva variação observada em suas freqüências ao longo dos testemunhos foram decisivas para as interpretações de cunho paleoambiental, paleoclimático e paleoecológico aqui estabelecidas.

Entre os elementos algálicos, de maneira geral, *Botryoccocus* predominou amplamente nos intervalos basais, tendendo a decrescer progressivamente em direção ao topo em ambos os testemunhos (T1 e T2), bem como o grupo “outras algas” (*Spyrogira*, *Debaria, Mougeotia, Zignema e Desmídia*), assim identificado em virtude da sua ocorrência esporádica e percentualmente baixa em todas as amostras. O gênero *incertae sedis, Pseudoschizaea*, por sua vez, demonstrou comportamento ligeiramente diferente das demais algas, atingindo altas frequências nas mesmas amostras que os esporos de pteridófitas. As observações realizadas a partir do T1 e T2 permitiram a formulação da hipótese de que esse gênero tem uma resistência diferenciada em relação às demais algas no que diz respeito à umidade, podendo ter algum papel no processo de sucessão ecológica da vegetação, porque essa forma prevalece naqueles intervalos intermediários entre o declínio das algas e a expansão dos esporomorfos terrestres. Essa hipótese concorda com as observações feitas por van Gell (1978) e van Gell & van der Hammen (1978) de que alguns táxons algálicos podem atuar como marcadores biológicos de intervalos transicionais, embora Scott (1992) observe que *Pseudoschizea* é uma forma comum em ambientes relativamente quentes do mundo todo onde haja alguma umidade disponível, podendo inclusive indicar locais de secas sazonais. Nesse sentido, é possível que as variações na profundidade dos alagados, que resultaram em seu padrão intermitente, começaram a se tornar mais significativas naqueles intervalos onde ocorre a expansão de *Pseudoschizea*.

A análise comparativa entre os resultados obtidos dos alagados de altitude associados a *gossan* (T1 e T2), indica que houve, de maneira geral, mais umidade no passado (Holoceno inicial e médio), subsidiada por eventos de alta pluviosidade, do que a atualmente observada no registro sedimentar do Recente.

Os eventos mais intensos de precipitação, inferidos através das análises de palinofácies, podem estar relacionados, em ambos os alagados, aos eventos Bond (especialmente os eventos 9.4, 8.2 e 7.4). O processo de acumulação de água no *gossan* e o inicio da sedimentação dos alagados foi consequência, portanto, de tais eventos.

O T1 - Mina do Museu tem idade estimada em 7963 anos AP (probabilidade média). Um período de alta precipitação foi inferido entre 7963 e 7260 anos AP (65 a 55 cm de profundidade) e relacionado especialmente com os eventos Bond 8.2 e 7.4 ka. As alterações no padrão de umidade começam a ocorrer a partir de 5584 anos AP (20 cm de profundidade) e intensificam-se há 5118 anos AP (5 cm), seguindo progressivamente até o Recente (FIG. 12).

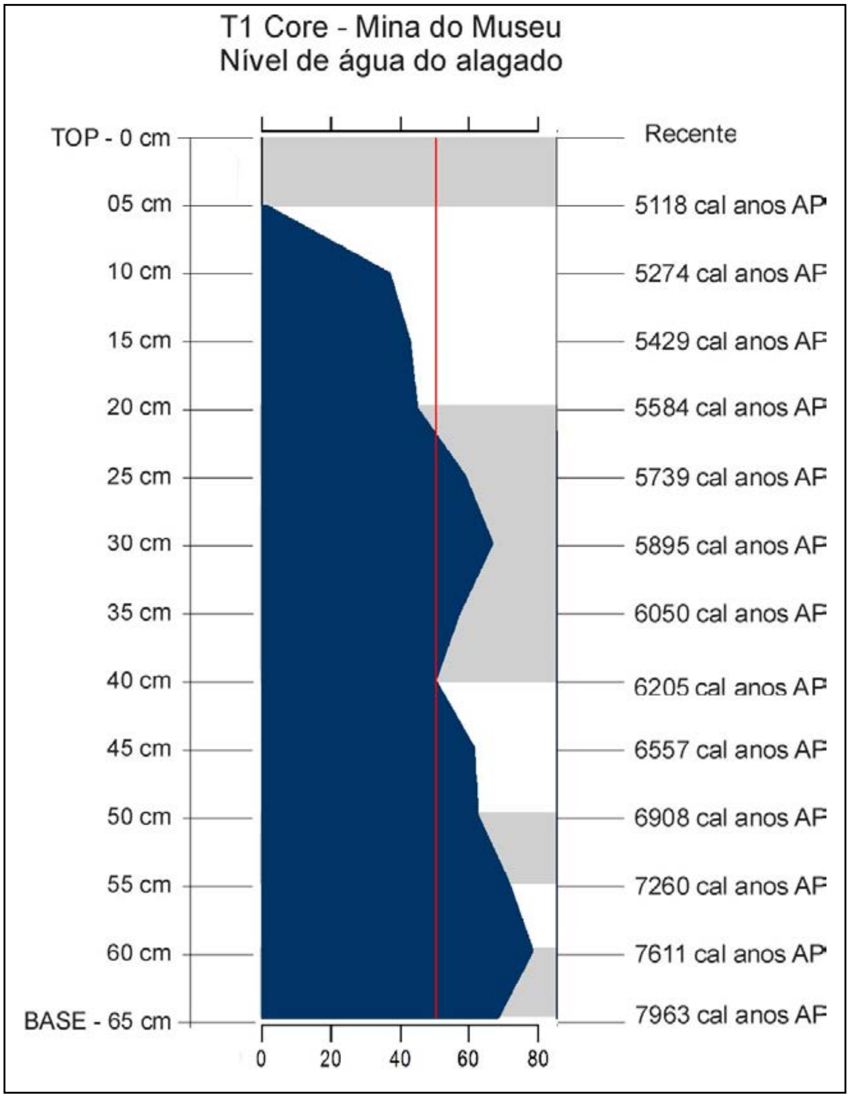


FIGURA 12 – Gráfico demonstrando a curva do nível de água do alagado do testemunho T1 – Mina do Museu, com a profundidade e idades correspondentes a cada nível amostrado. A curva foi construída a partir da percentagem de elementos algáceos (*Botryococcus* e outras algas). A linha vermelha corresponde à média percentual de todas as análises.

O T2 - Mina Modelo tem 9542 anos AP (probabilidade média). Um período de alta precipitação foi inferido entre 8631 e 7417 anos AP (65 a 45 cm de profundidade) e foi relacionado com os eventos Bond (especialmente os eventos 9.4, 8.2 e 7.4 ka.) A pluviosidade permaneceu relativamente alta até aproximadamente 7000 anos AP (FIG. 13). As alterações nos padrões de precipitação começaram há 6810 anos AP (35 cm) e intensificaram-se a partir de 5899 anos AP (20 cm).

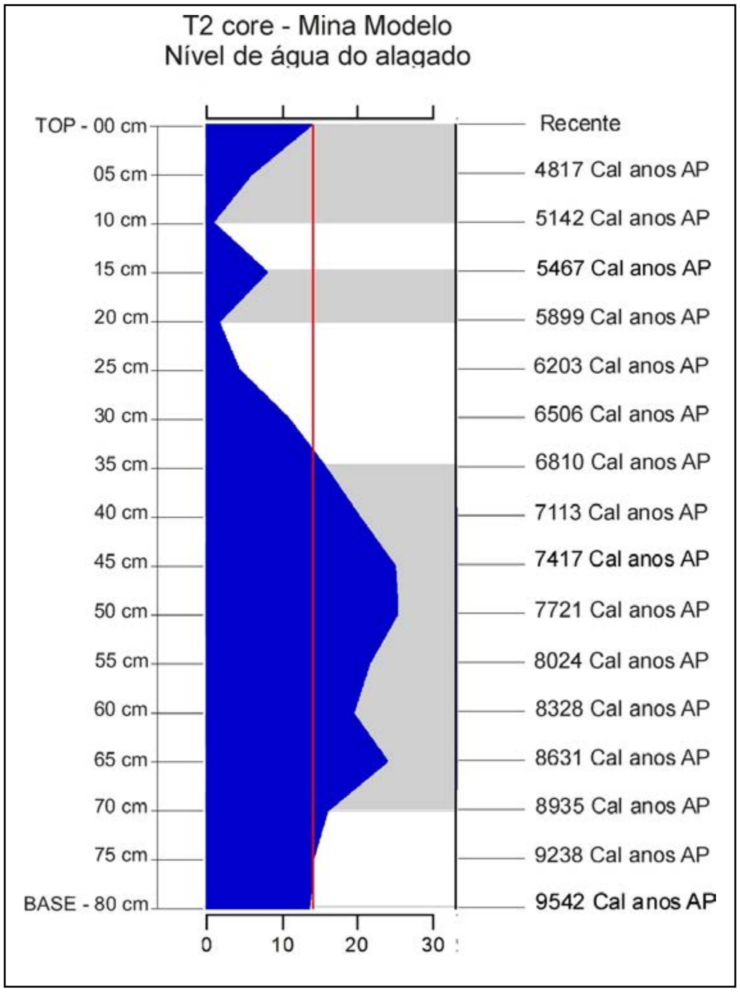


FIGURA 13 – Gráfico demonstrando a curva do nível de água do alagado do testemunho T2 – Mina Modelo, com a profundidade e idades correspondentes a cada nível amostrado. A curva foi construída a partir da percentagem de elementos algáceos (*Botryococcus* e outras algas). A linha vermelha corresponde à média percentual de todas as análises.

Os eventos de precipitação coincidentes entre os dois banhados datam entre 8500 e 7200 anos AP. No início de sua sedimentação, esses alagados não eram intermitentes, pois havia umidade suficiente para que permanecessem saturados de água. O T1 - Mina do Museu, por ser mais raso, teve um ciclo mais curto (7963 anos AP), enquanto o T2 - Mina Modelo, por ser um pouco mais profundo, teve um ciclo mais longo (9542 anos AP) e, em virtude disso, permitiu uma investigação mais acurada das transformações locais. A profundidade de cada um desses alagados também influiu na continuidade do registro, o qual parece ter sido encerrado pela sedimentação quase completa do T1 - Mina do Museu, mas ainda tem continuidade no T2 - Mina Modelo.

A principal diferença entre o registro desses dois banhados está nas camadas do topo, pois, enquanto o T2 - Mina Modelo registra a continuidade dos eventos de precipitação para o Recente, embora menos intensos e mais desregulados em relação ao passado, o T1 - Mina do Museu registra o estabelecimento de uma fase crescente e contínua de grande estiagem em direção ao Recente. O T1 - Mina do Museu encontra-se atualmente bastante preenchido por sedimentos, embora ainda permaneça alagado durante os períodos chuvosos. Contudo, é possível admitir que o fato desse banhado estar sucumbindo ao seu próprio metabolismo sedimentar pode estar influenciando o registro do Recente, para o qual se infere períodos de maior estiagem em virtude da ausência de algas no sedimento.

Os alagados de altitude atuam como um tanque de captação de água meteórica, por isso fornecem dados confiáveis sobre eventos de aumento da precipitação, sendo excelentes registros da pluviosidade pretérita, à semelhança de espeleotemas e outros registros *proxy* de alta resolução.

Nos sedimentos de Iraí, a fração orgânica mais bem representada é constituída por elementos derivados de plantas terrestres, característica essa típica da matéria orgânica preservada em turfeiras. Os parâmetros organogeoquímicos foram particularmente úteis nas interpretações de eventos de anoxia e de vigência de regimes hidrológicos para os sedimentos turfosos de Iraí, que responderam melhor a essas análises porque dispunham de uma quantidade bem maior de carbono orgânico e enxofre em sua constituição quando comparados com os sedimentos dos alagados de Ametista do Sul.

O T3 - Iraí tem 10.586 anos (probabilidade média). Em virtude do regime hidrológico diferenciado, não foi possível constatar os mesmos eventos de precipitação dos testemunhos de Ametista do Sul. Esse tipo de ambiente úmido nunca chegou a secar completamente, uma vez que os teores de umidade eram subsidiados por diferentes fatores, seja pelo lençol freático como pela água da chuva ou pelos eventos de inundação do Rio Uruguai. Logo, quando um mecanismo falhava, era compensado pelo outro. A ocorrência muito baixa de algas, contudo, indica que a lâmina d’água não foi espessa o bastante para o desenvolvimento desse tipo de biomassa, embora o ambiente redutor e anóxico também possa ter limitado a expansão desse grupo.

O período entre 10.586 e 6392 anos AP (115 a 75 cm) é caracterizado pela forte influência do lençol freático e da chuva, e o período entre 5867 anos AP até o Recente (70 a 0 cm) apresenta uma influência crescente dos eventos de transbordamento do Rio Uruguai. O evento de maior umidade observado ocorre entre 5343 a 2198 anos AP (65 a 35 cm de profundidade) e os eventos de umidade relativamente reduzida ocorrem entre 8489 a 6392 anos AP (95 a 75 cm) e há 101 anos. Os eventos de umidade relativamente reduzida são inferidos em virtude da ausência de algas, embora a característica de ambiente redutor, estagnado e anóxico possa ter tido mais influência na limitação ao desenvolvimento desse tipo de microorganismos do que propriamente a falta de umidade. De qualquer forma, ocorreram flutuações no nível do lençol freático cujas causas não estão ainda bem estabelecidas, mas poderiam ter relação com a anomalia de enxofre que ocorreu aos 99 cm de profundidade (8908 anos AP). Contudo, enquanto não se esclarecerem as causas de tal evento “anômalo”, as demais inferências referentes ao mesmo são meramente especulativas, embora sua origem possa estar associada a eventos que excedem os limites locais, tanto em escala de longitude como em profundidade.

A discrepância entre os períodos de maior umidade inferidos para Ametista do Sul e Iraí está diretamente relacionada ao tipo de ambiente deposicional e aos regimes hidrológicos predominantes em cada uma dessas áreas. O ambiente deposicional aberto e continuamente subsidiado por umidade oriunda de fontes diversas em Iraí contrasta com o ambiente deposicional fechado de Ametista do Sul, cujo nível de umidade depende exclusivamente da pluviosidade. Enquanto o regime hidrológico predominante nos *gossans* de Ametista do Sul permite a compilação de dados pluviométricos muito mais precisos, em Iraí tais inferências são limitadas por um regime hidrológico “compensatório”, pois nos períodos em que não ocorre aumento de umidade subsidiada pelos eventos de transbordamento do rio, ocorre a compensação pelo nível do lençol freático, o qual se mantém continuamente saturado e influente sobre o ambiente deposicional. Consequentemente, os dados geoquímicos e palinofaciológicos procedentes de Iraí refletem um ambiente que sofreu pouca influência de processos oxidantes por estar continuamente protegido por um regime hidrológico mais variado.

A posição topográfica de cada uma das áreas aqui analisadas também tem grande influência sobre o registro, pois o isolamento hidrológico dos alagados de Ametista do Sul é resultado de sua localização no topo de morros. Os sedimentos turfosos de Iraí, por sua vez, estão localizados em uma área de relevo mais baixo, próxima às margens de um rio, o que torna esse sistema deposicional mais exposto a influências diversas.

O período de maior umidade em Iraí está associado aos eventos de transbordamento do Rio Uruguai, que passam a predominar a partir dos 70 cm de profundidade (5867 anos AP), possivelmente em virtude do leito do rio ter se aproximado da área de deposição através da erosão das margens e/ou pela remoção de alguma barreira previamente existente entre o rio e o ambiente turfoso (FIG. 14). Estes eventos de transbordamento acabaram por introduzir água e sedimentos no ambiente deposicional dando a impressão que o aumento da umidade foi causado por uma pluviosidade mais intensa, em vez de alterações no relevo. Essa hipótese parece a mais viável para explicar as diferenças nos registros de aumento e diminuição da umidade entre os municípios vizinhos de Iraí e Ametista do Sul.

As ingressões cada vez mais freqüentes do Rio Uruguai também alteraram as características do sedimento, que foi se tornando mais fluido e perdendo as características típicas de turfa, para se tornar um “sedimento turfoso”, ou a lama orgânica síltica de “propriedades medicinais”, como é popularmente conhecido. A ingressão de água do rio sobre a área de deposição possivelmente contribuiu com uma umidade adicional no sistema, diluindo o conteúdo orgânico do depósito sedimentar, o que resultou na redução dos teores de COT e ST (enxofre total) no sedimento. A atividade antrópica nos últimos 50 anos vem acelerando esse processo de diminuição do conteúdo orgânico através da drenagem dos depósitos para remoção da “lama medicinal”, o que resulta em uma maior exposição dos sedimentos à oxidação. Adicionalmente, a remoção da vegetação local, que é a principal fonte de carbono orgânico sedimentar, também contribuiu para essa redução no teor orgânico, dado que as análises palinofaciológicas comprovaram a ampla dominância dos fitoclastos sobre os demais grupos da MO.

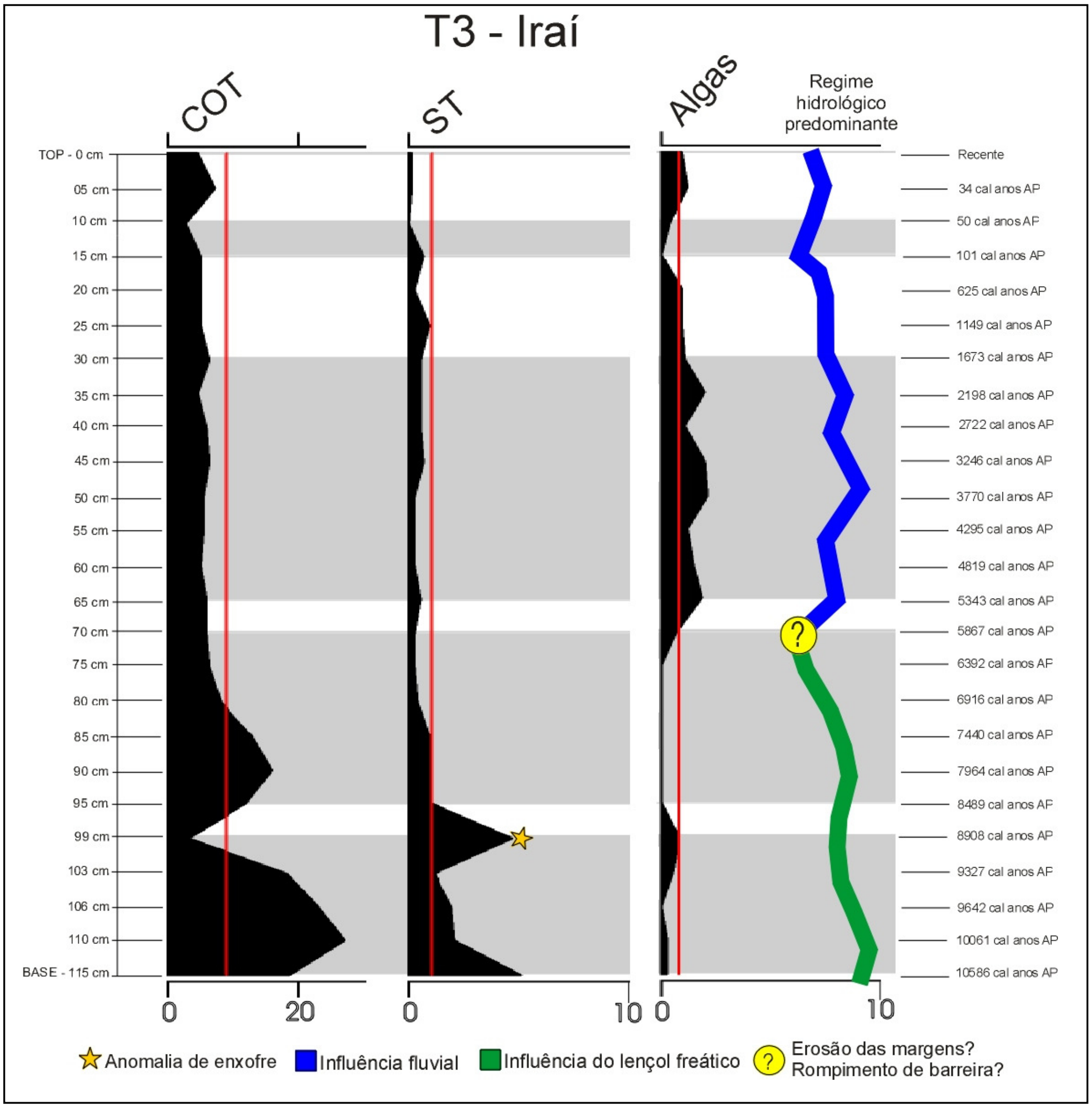


FIGURA 14 – Variação nos teores de COT e ST e na percentagem de algas do testemunho T3-Iraí. A curva verde foi estimada com base nos parâmetros organogeoquímicos e representa o período de vigência do lençol freático como regime hidrológico predominante. A curva azul foi estimada com base nos parâmetros organogeoquímicos e palinofaciológicos (distribuição das algas) e representa o período de vigência fluvial. O círculo amarelo entre as duas curvas indica o momento em que possivelmente houve alteração da vigência hidrológica e o ponto de interrogação infere as possíveis causas dessa mudança.

A comparação entre os resultados obtidos da análise palinofaciológica da MO proveniente de ambientes deposicionais distintos, correspondentes respectivamente aos alagados associados a *gossan* e aos sedimentos turfosos evidenciou que a vegetação em tais ambientes também demonstrou uma evolução diferenciada. Enquanto que em Ametista do Sul a diversidade e a abundância da vegetação aumentaram em direção ao Recente, em Iraí a vegetação associada ao ambiente de deposição sofreu uma redução nesses dois aspectos. A avaliação da diversidade vegetacional em Ametista do Sul foi estabelecida através do aumento dos padrões de diversificação dos esporos e grãos de polens, enquanto que para Iraí, a perda de diversidade pôde ser inferida pela diminuição progressiva dos padrões de organização epidérmica das cutículas presentes no sedimento.

Em Ametista do Sul, a vegetação evoluiu concomitantemente com o alagado no topo dos morros, onde o processo de sucessão ecológica levou à evolução da diversidade vegetacional. Em Iraí, o mesmo processo sucessional não pôde ser observado, pois a vegetação foi incialmente mais exuberante do que a atualmente observada no local, onde adicionalmente a remoção da vegetação para extração da lama medicinal resultou em uma paisagem atualmente dominada por gramíneas e algumas poucas árvores.

Os resultados obtidos em áreas de pesquisa relativamente próximas, tais como os alagados de altitude de Ametista do Sul e os sedimentos turfosos de Iraí, foram diferenciados porque em ambientes continentais estritos, onde os depósitos sedimentares abrangem áreas pouco extensas, a influência climática é muito mais localizada do que nos ambientes marinhos ou costeiros, cujos depósitos sedimentares abrangem áreas de grande extensão. Essas evidências permitem ratificar que as generalizações climáticas em ambientes continentais devem estar baseadas na investigação de mais de uma área de estudo e, se possível, abarcando várias áreas dentro de uma mesma região a fim de se obter uma resolução mais acurada das alterações climáticas e ambientais ocorridas.

Em geral, em ambientes continentais que evoluíram sem a influência de variações eustáticas e caracterizados por áreas de extensão limitada, os dados paleoambientais, paleoecológicos e paleoclimáticos poderão oscilar largamente em virtude das variáveis físicas, químicas e biológicas influentes no sistema deposicional e dependerão amplamente do regime hidrológico e da topografia locais, além das condições edáficas resultantes da interação de tais fatores. Talvez, em virtude disso, os resultados obtidos por diferentes pesquisas, utilizando os mais variados dados *proxy*, podem levar a resultados divergentes, dificultar a correspondência entre os dados levantados e até mesmo impedir uma analogia positiva entre os ambientes deposicionais estudados, nos quais a idade radiométrica pode vir a ser o único dado correspondente.

Estudos de ambientes fechados, semelhantes aos alagados de altitude associados a *gossan* em Ametista do Sul, ou de dados *proxy* de alta resolução, como os espeleotemas, são aqueles que têm maior potencial para inferências precisas sobre dados paleoclimáticos, especialmente relacionados à frequência pluviométrica, os quais podem estar correlacionados com eventos de escala global, como os eventos Bond, por exemplo. Em ambientes abertos, por outro lado, onde o sistema deposicional é influenciado por uma gama maior de variáveis, as interpretações devem considerar as limitações que elas impõem à definição de dados mais precisos. Em virtude disso, as generalizações paleoambientais, paleoecológicas e paleoclimáticas devem levar em consideração as características particulares dos ambientes que estão sendo analisados, buscando explicações para os resultados divergentes encontrados através de comparações entre as distintas variáveis que atuam sobre os sistemas deposicionais estudados. Portanto, ambientes deposicionais distintos podem responder de maneira distinta às mesmas variáveis, não significando, necessariamente, contradições no registro. Tais constatações podem ser também extrapoladas para ambiente análogos do passado geológico a fim de permitir uma melhor integração de dados contemporâneos aparentemente pouco correlacionáveis.

7.1 Contribuição para o desenvolvimento regional

A partir das análises realizadas em Ametista do Sul, pôde-se observar uma contínua redução da pluviosidade local e aumento, ou prolongamento, dos períodos de estiagem, que permitem projetar um estresse hídrico progressivo para aquela região, sendo aconselhável o estabelecimento de políticas de médio e longo prazo envolvendo o gerenciamento dos recursos hídricos locais.

A partir das análises realizadas em Iraí, pôde-se observar uma alteração nas características do sedimento turfoso, causada principalmente por ação fluvial e antrópica, que permitem projetar a perda progressiva do conteúdo orgânico e geoquímico que possivelmente confere à lama suas propriedades terapêuticas, sendo aconselhável, portanto, o estabelecimento de políticas de manejo adequado de tal recurso, sob o risco de se perder essa fonte de renda complementar em médio e longo prazo. É importante ressaltar que as análises palinofaciológicas e organogeoquímicas revelaram o conteúdo orgânico do sedimento analisado;

contudo, a confirmação de suas propriedades terapêuticas ainda depende de estudos mais detalhados e de análises mais diversificadas.

7.2 Reflexões de caráter genérico

As mudanças climáticas observadas para o Holoceno inicial e médio na região do Alto Uruguai não foram desencadeadas por ação humana, pois estão relacionadas a ciclos que tiveram início muito antes do estabelecimento dos primeiros indígenas e colonizadores naquela região. Contudo, a interferência antrópica no registro sedimentar das camadas superiores e mais recentes (Holoceno tardio) pode ser detectada através da perda de diversidade vegetal e de uma maior exposição dos sedimentos a processos oxidativos (a exemplo do que foi observado em Iraí). Embora as alterações climáticas em curso desde o início do Holoceno não dependam diretamente da ação humana, os processos antrópicos têm interferido de maneira irremediável não somente sobre os ecossistemas, mas também sobre os depósitos sedimentares, prejudicando a integridade do registro sedimentar para o Recente.

Os fenômenos globais que desencadeiam as mudanças climáticas têm efeitos de larga escala que podem se refletir em locais remotos do globo, à semelhança dos registros de pluviosidade de Ametista do Sul, os quais puderam ser relacionados aos eventos Bond. Embora globais, as alterações no clima têm efeitos locais que podem ser detectados por sistemas deposicionais peculiares, como é o caso dos alagados associados a *gossan* em Ametista do Sul. Esses registros de alta resolução podem servir à semelhança de um “grupo controle” e como ponto de partida para estudos comparativos em escalas regionais envolvendo ambientes com características diferenciadas.

Portanto, em um contexto global, pode se considerar que os fenômenos climáticos estão além do alcance humano, mas em um contexto local, a interferência antrópica sobre o registro sedimentar parece potencializar os efeitos do clima, criando uma espécie de “ruído antrópico” no ambiente deposicional que pode dificultar a interpretação dos dados e a elucidação dos fatores verdadeiramente influentes. Nem por isso a magnitude de um evento climático de proporções globais deve ser desconsiderada, uma vez que os mecanismos de regulação do clima estão interligados de forma a transpor as fronteiras e os limites humanos. Se por um lado a “culpa” dos seres humanos sobre as mudanças climáticas parece estar vinculada apenas ao prejuízo que eles causam a si mesmos quando interferem sobre ecossistemas já fragilizados por fenômenos naturais que estão além do seu controle, por outro, diferentes registros encontrados no Holoceno tardio têm demonstrado que as atividades antrópicas têm um efeito bem menos “passivo” sobre o controle climático do que se imagina.

Os efeitos da civilização humana sobre a deposição e o sepultamento dos sedimentos e da matéria orgânica sedimentar suscitam a possibilidade de considerarmos que o registro de nosso passado recente não resulta apenas de processos deposicionais naturais, mas da ação antrópica, inaugurando assim novas formas de interpretar o registro do Holoceno tardio a partir da perspectiva da “pegada ecológica”. A intensificação das atividades humanas decorrentes da aceleração do processo civilizatório pode estar interferindo não somente na história do planeta, mas também na forma como essa história é “contada” através do registro sedimentar. Isso pode ter efeitos negativos no discernimento das gerações futuras sobre o destino da Terra e gestão de seus recursos naturais, porque obstrui a interpretação do passado e, consequentemente, a projeção do futuro.

7.3 Sugestões para trabalhos futuros

- Analisar mais ambientes continentais quaternários com características deposicionais diferenciadas, a fim de estabelecer o grau de similaridade e de divergência entre os dados obtidos;
- Analisar mais alagados de altitude relacionados a *gossan* em outras regiões onde há mineração na tentativa de correlacionar dados paleoambientais, paleoecológicos e paleoclimáticos, especialmente os pluviométricos ;
- Realizar novas coletas em Iraí para tentar investigar as causas da anomalia de enxofre, desta vez realizando análises isotópicas;
- Realizar estudos geológicos detalhados da área que contém os sedimentos turfosos de Iraí, com a finalidade de detectar a proximidade de fontes termais

contendo água mineral e compreender como estas podem ter influenciado a "anomalia de enxofre" observada no presente estudo;

- Observar a ocorrência de níveis elevados de enxofre com idade entre oito e nove mil anos em outros depósitos sedimentares do Quaternário no sul do Brasil, buscando reconhecer se estes têm alguma relação com eventos de vulcanismo na região andina;
- Determinar as propriedades terapêuticas dos sedimentos turfosos de Iraí através de análises específicas para esta finalidade.

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ANEXO I

Título da Dissertação/Tese:

“INFERÊNCIAS PALEOAMBIENTAIS E PALEOCLIMÁTICAS PARA O QUATERNÁRIO CONTINENTAL DO SUL DO BRASIL BASEADAS EM ANÁLISES DE PALINOFÁCIES E DE GEOQUÍMICA ORGÂNICA DE AMBIENTES INFLUENCIADOS POR DIFERENTES REGIMES HIDROLÓGICOS”

Área de Concentração: Paleontologia

Autora: Gabrielli Teresa Gadens Marcon

Orientador: Profa. Dra. Margot Guerra Sommer

Examinador: Profa. Dra. Maria do Carmo Ruaro Peralba

Data: 03/05/2013

Conceito: A – com louvor

PARECER:

O presente trabalho de TESE está muito bem estruturado e escrito, tornando a leitura de fácil entendimento, acompanhado de uma vasta bibliografia atualizada.

O desenvolvimento experimental ocorreu de modo sistemático, criterioso e com aplicação de metodologias oficiais proporcionando aos dados obtidos alto grau de confiabilidade.

Pelo acima exposto sou de parecer totalmente favorável a aprovação da mesma.

Assinatura: Data: 03/05/2013

Ciente do Orientador:

Ciente do Aluno:

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Área de Concentração: Paleontologia

Autora: Gabrielli Teresa Gadens Marcon

Orientador: Profa. Dra. Margot Guerra Sommer

Examinador: Prof. Dr. Mauro Parolin

Data:

Conceito: A com louvor

PARECER:

A tese apresenta relevante contribuição para a ciência, abordando a questão do uso das técnicas empregadas para análise de palinofacies agora para sedimentos holocênicos no margeante do Estado do Rio Grande do Sul. Cabe salientar a ineditismo de tal empreita e o sucesso obtido quanto aos dados e interpretações paleoambientais, principalmente no tocante ao município de Ametista do Sul. A autora esmerou-se em correlacionar suas interpretações a outros trabalhos de destaque, como por exemplo, os eventos Bond. Os dados, principalmente datações por carbono 14 trazem para o interior do Rio G. do Sul uma nova e necessária perspectiva de evolução paleoambiental ~~[illegible]~~ Os resultados também abrem perspectivas de estudo mais detalhados envolvendo outros proxy como por exemplo espículas, fitolitos, N^{15}, C^{13} entre outros.

Vale destacar que os resultados em uma análise preliminar, também corroboram outras interpretações realizadas e documentadas no interior do Estado do Paraná, Mato G. do Sul e São Paulo. Embora a autora não as tenha correlacionado.

Assinatura: Data: 03 / 05 / 2013

Ciente do Orientador: MAURO PAROLIN

Ciente do Aluno:

ANEXO I

Título da Dissertação/Tese:

“INFERÊNCIAS PALEOAMBIENTAIS E PALEOCLIMÁTICAS PARA O QUATERNÁRIO CONTINENTAL DO SUL DO BRASIL BASEADAS EM ANÁLISES DE PALINOFÁCIES E DE GEOQUÍMICA ORGÂNICA DE AMBIENTES INFLUENCIADOS POR DIFERENTES REGIMES HIDROLÓGICOS”

Área de Concentração: Paleontologia

Autora: Gabrielli Teresa Gadens Marcon

Orientador: Profa. Dra. Margot Guerra Sommer

Examinador: Profa. Dra. Etiene Fabbrin Pires

Data: 03/05/2013

Conceito: A - com LOUVOR

PARECER:

Esta tese aborda um tema atual, de interesse acadêmico, mas que com muita astúcia a doutoranda aponta uma aplicabilidade e sugere novas perspectivas de estudo. Possui a consistência de uma tese de doutorado, com a utilização de dados robustos, tratamento estatístico adequado, linguagem harmoniosa e discussões cientificamente interessantes. A estruturação do volume facilita seu entendimento, sendo que as partes estão apresentadas de forma lógica e coerente. Há algumas sugestões com relação à forma e alguns caracteres de escrita, mas nenhuma sugestão que afete o conceito.

Assinatura: Data: 03/05/2013

Ciente do Orientador:

Ciente do Aluno:

UFRGS
UNIVERSIDADE FEDERAL
DO RIO GRANDE DO SUL

Instituto de Geociências
Programa de Pós-Graduação em Geociências

ATA Nº 002/2013

Às quatorze horas e dez minutos do dia três de maio de dois mil e treze, no Anfiteatro do Centro de Estudos em Geologia Costeira e Oceânica – CECO, no Campus do Vale, reuniu-se a Comissão Examinadora constituída pelos professores Mauro Parolin da Universidade Estadual do Paraná e Etiene Fabbrin Pires da Universidade Federal do Tocantins e Maria do Carmo Ruaro Peralba do Instituto de Química/UFRGS, para a defesa da tese intitulada: **"INFERÊNCIAS PALEOAMBIENTAIS E PALEOCLIMÁTICAS PARA O QUATERNÁRIO CONTINENTAL DO SUL DO BRASIL BASEADAS EM ANÁLISES DE PALINOFÁCIES E DE GEOQUÍMICA ORGÂNICA DE AMBIENTES INFLUENCIADOS POR DIFERENTES REGIMES HIDROLÓGICOS"**, a que se submete **GABRIELLI TERESA GADENS MARCON**, depois de haver cumprido as exigências regulamentares do Programa. A Profa. Dra. Margot Guerra Sommer, na qualidade de orientador fez a abertura da sessão e presidiu os trabalhos de acordo com o previsto no artigo 69 do Regimento do Programa. A candidata fez a apresentação do seu trabalho e a seguir foi arguido pelos membros da Comissão Examinadora. Às dezessete horas a e cinco minutos sessão foi suspensa por quinze minutos para julgamento e atribuição dos conceitos, que foram os seguintes: Mauro Parolin **"A" (EXCELENTE)**, Etiene Fabbrin Pires **"A" (EXCELENTE)**, Maria do Carmo Ruaro Peralba **"A" (EXCELENTE)**. Por decisão unânime da Banca Examinadora foi atribuído o "VOTO DE LOUVOR" ao referido trabalho. Face aos conceitos atribuídos foi conferido ao candidato o grau de **DOUTOR EM CIÊNCIAS** pela Universidade Federal do Rio Grande do Sul. Às dezessete horas e vinte minutos a sessão foi encerrada, do que para constar, eu,
Roberto Martins Pereira, lavrei a presente Ata que é assinada pela Comissão Examinadora.

Prof. Dr. Mauro Parolin

Profa. Dra. Etiene Fabbrin Pires

Profa. Dra. Maria do Carmo Ruaro Peralba

Profa. Dra. Margot Guerra Sommer
(Presidente)

Homologação pela Comissão de Pós-Graduação,
Ata nº **Data:**
Conceito Final:
Rubrica: