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Climatic changes in the coastal plain of the Rio Grande do Sul state in the Holocene: palynomorph evidences

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Abstract. Climatic changes during the Holocene were the principal factors influencing the coastal plain evolution and sea level oscillations. Climatic fluctuations were responsible for littoral sedimentation and palaeoenvironmental changes. Palynological data, obtained from core-drillings, performed at the bottom of the Patos and the Tramandaí lagoons and in adjacent areas, were used for palaeoclimatic reconstructions. Palynomorphs, represented by algal and fungal palynomorphs, pollen and spores of vascular terrestrial and aquatic plants, microforaminifers, and scolecodonts showed their indicative value for palaeoclimatic reconstructions. The samples, dated by ^{14}C method, allowed the comparison of the results when making interpretations. Increase in marine algal palynomorphs indicated sea level rise as a result of global temperature increase. The beginning of the marine transgression was about 10 kyrs BP after the last glacial period when temperature raised. Transgressive maximum (4-6 kyrs BP) was characterized by sea-level rise at about 4-5 m. Posterior regression began as result of temperature fall and drier climate, forcing dune formation in the coastal plain. Palynomorph records from the lagoon sediments in the coastal plains have a great potential and may serve for detail paleoclimatic reconstructions of the past and predictions of climatic changes in the future.

Keywords: Palynology, Palaeoecology, Lagoon sediments, Extreme Southern Brazil

Resumo. Mudanças climáticas na Planície Costeira do Rio Grande do Sul no Holoceno: evidências de palinomorfos. As mudanças climáticas ocorridas durante o Holoceno foram os principais fatores que influenciaram na evolução da zona costeira e nas oscilações do nível do mar. Flutuações climáticas foram responsáveis pela formação dos sedimentos litorâneos e as mudanças paleoambientais. Dados palinológicos, obtidos a partir de furos de sondagens e testemunhos executados no fundo da laguna dos Patos e da laguna de Tramandaí e nas adjacências, foram usados para reconstruções paleoclimáticas. Os palinomorfos representados pelas algas, fungos, grãos de pólens e esporos de plantas vasculares terrestres e aquáticas, microforaminiferos e escolecodontes mostram seus valores indicativos para as reconstruções paleoclimáticas. As amostras datadas pelo método de ^{14}C nos permitiram comparar os resultados obtidos quando foram efetuadas as interpretações. Aumento de palinomorfos de algas marinhas indicou a subida do nível do mar como resultado do aumento das temperaturas globais. Início da transgressão marinha foi a cerca de 10 ka AP depois da última glaciação quando as temperaturas subiram. O máximo transgressivo (4-6 ka AP) foi caracterizado pela subida do nível do mar de 4-5 m. A regressão posterior começou como resultado da queda das temperaturas e aridização do clima, que causou a formação de dunas na zona costeira. Os registros de palinomorfos nos sedimentos lagunares das zonas costeiras possuem um grande potencial nas reconstruções paleoclimáticas do passado e também como previsões de mudanças climáticas do futuro.

Palavras-chave: Palinologia, Paleoecologia, Sedimentos Lagunares, Extremo Sul do Brasil

Introduction

Paleoclimatic changes during the Quaternary (approximately 2.5 Ma BP) were relatively rapid in the past as compared with past climate changes in the last 60 Ma. Understanding of climate oscillations during the Quaternary is important to evaluate variability of the natural environments in the past and probably use of these data for a better understanding of actual climate situation and prediction of the future climate. Climatic changes occurred during the Holocene (10 ka BP till present) were the main factors influencing on the coastal plain evolution of the Rio Grande do Sul state, Brazil. The oscillations of global temperatures caused relatively high frequency changes on sea level. The climatic modifications were also responsible for the littoral sediments deposition in the coastal plains and palaeoenvironmental evolution.

There are many different methods (proxy data) for the Quaternary paleoclimate reconstructions in the world (Bradley 1999). Palynological analysis is one of the most important methods, providing information from continents to complement other proxy data about paleoclimates (Webb 1991, Bradshaw 1994, Ledru *et al.* 1998, Bradley 1999). In addition to pollen and spores of vascular plants, sediments usually include different non-pollen palynomorphs, which are organic-walled microfossils composed of sporopollenin-like or chitin (pseudochitin) polymers (Traverse 1988). These palynomorphs as a rule are more resistant to corrosion and oxidation than pollen and spores composed of sporopollenin (van Geel 1976, Komárek & Jankovská 2001). These palynomorphs are predominantly represented by cysts of Acritarcha (marine phytoplankton) and Dynophyta, zygospores, coenobiums and colonies of Chlorophyta, different fungal palynomorphs, palynomicroforaminifers, and scolecodonts. The forms, usually classified by palynologists as cysts of Acritarcha are *Prasinophycean phycomata* (Colbath & Grenfell 1995). In spite of uncertainties, regarding of their precise biological affinities, acritarchs are considered as remains of cysts of algal protists (Tappan 1980, Strother 1996). Prasinophycean algae are a class of green algae, which are known today from freshwater to marine environments, although in recent forms only the marine taxa produce a fossilized phycomata. The vast majorities of *Prasinophycean phycomata* are recovered from marine sediments and/or are associated with marine organisms. Furthermore, based on their distribution, morphology, and composition, most *Prasinophycean phycomata* are assumed to be phytoplankton, and therefore were the primary producers of the ancient marine ecosystem during the Proterozoic and Paleozoic (Martin 1993).

The study of non-pollen palynomorphs started at the early 1970s in the Netherlands, and since then, the interest in their use for palaeoclimatic reconstructions is growing (van Geel 1976, van Geel & van Hammen 1978, van Geel *et al.* 1980/81, van Geel & Aptroot 2006).

In the Quaternary lagoon sediments of coastal plains, the palynomorph variability is more diverse than in continental deposits. In addition to algal and fungal palynomorphs, there are frequent palynoforaminifers (Zamora *et al.* 2007, Medeanic *et al.* 2009), *Prasinophycean phycomata*, and cysts of Dynophyta (Grill & Quatroccio 1996, Medeanic *et al.* 2001, Weschenfelder *et al.* 2008) indicative of sediments deposited under sea water influence. Scolecodonts are palynomorphs, encountered in sediments formed in shallow water environments near the coast (Lorscheitter 1983, Cordeiro & Lorscheitter 1994).

The different scientific projects regarding Holocene paleoclimate and palaeoenvironmental reconstructions in the coastal Plain of the Rio Grande do Sul State, Brazil based on palynomorph study started in 1980s (Lorscheitter 1983, Cordeiro & Lorscheitter 1994, Lorscheitter & Dillenburg 1998, Medeanic *et al.* 2003, Medeanic 2006, Medeanic & Corrêa 2007). All obtained information so far allowed us to make proxy evaluation of climatic oscillations occurred since the last Pleistocene glaciations. The lowering of temperature that time caused the regression of the ocean with negative amplitude of 120-150 m. The temperature rise at about 10 kyrs BP (the Early Holocene) was the reason of the beginning of the marine transgression. The maximum of marine transgression occurred at about 5-6 kyrs BP (the Middle Holocene) with positive amplitude of sea level rise at about 4-5 m. Posterior marine regression at about 3-3.5 kyrs (the Late Holocene) was characterized by sea level fall at about 2 m. In this paper, we present a revision of our previous published results, based on palynomorph study focusing on the Holocene climatic paleoreconstructions.

Materials and Methods

Study area

The study area is situated in the southern part of the coastal plain of the Rio Grande do Sul state (Fig. 1). The climate of this region is warm-temperate, due to the joint influence of the warm Brazil and cold Falkland currents (Vieira & Rangel

1988). The average annual temperature is 18 °C, with monthly averages of 24.6 °C in January and 13.1 °C in July. The mean annual precipitation is about 1,200 mm. The coastal plain has a diverse geomorphology, with sandy beaches, dunes, freshwater, brackish-water, salt marshes, and wetlands (Costa *et al.* 1997).

In the Quaternary, the coastal plain was subjected by glacio-eustatic sea level oscillations (Villwock & Tomazelli 1995, Corrêa *et al.* 1996). During the Holocene, a vast part of the present Brazilian coastal plain was flooded by sea-waters (Angulo & Lessa 1997, Martin *et al.* 2003). The last glacio-eustatic sea level rise (transgressive phase) began at about 10 kyrs BP. The maximum of that transgression occurred around 5,600 yrs BP characterized by a sea level rise of approximately 5 m above the present sea level. The following regressive stage led to the present sea level.

Sandy sediments along the coast were deposited during regressive-transgressive events in the Quaternary. Lagoon formation was connected to the evolution of the Holocene barrier-lagoonal system (Villwock & Tomazelli 1995). The lagoonal sediment deposits started about 8 kyrs ago (Toldo *et al.* 2000). They consist mostly of mud or muddy sands, having an average thickness of about 6 m.

According to Ramos (1977), the present day vegetation of the coastal plain of the Rio Grande do Sul state consists of the plant communities of dry fields, humid depressions, flooded depressions, peat soils, flooded soils, freshwater marshes and coastal subtropical forests. A great specific diversity of species of Poaceae and Cyperaceae characterizes this region. The modern state of vegetation is a result of the effect of natural factors during the Holocene and the anthropogenic impact, especially during the last century.

Sample collections

A total of more than 100 samples were collected from cores T-64, TBJ-02, B-2, situated in the estuarine part of the Patos Lagoon, and from core FS-20, performed at the Cassino Beach region. Other 35 samples were collected from the cores FS-10 and T-14 performed at the bottom of the Tramandaí Lagoon and adjacent area (Fig. 1). Samples represented by mud and muddy sands were used for the palynomorph study. Samples, enriched by organic matter, were radiocarbon dated at Beta Analytic Inc., Florida, USA. Based on the correlation of the core T-64 (a sample 140 cm deep) with an adjacent core identical in sedimentological and seismical characteristics (Toldo *et al.* 2000), we concluded an approximate age of 5,500-6,000 yrs BP.

The chemical treatment of the samples followed Faegri and Iversen (1975) using HCl (10%) and NaOH (5%). The use of HF was avoided in order to preserve siliceous remains, such as silicoflagellate skeletons and diatoms. Separation of inorganic and organic substances was carried out using $ZnCl_2$ solution with a density of 2.2 g/cm^3.

Results and Discussion

The principal palynomorphs, identified from the Holocene lagoon sediments, were pollen and spores of vascular terrestrial and aquatic plants, algal palynomorphs (zygospores, coenobiums and colonies of Chlorophyta, *Prasinophycean phycomata*, and Dynophyta cysts), fungal palynomorphs (ascospores, hypnodia, fruit bodies), palynoforaminifers, and scolecodonts. Besides, silicoflagellate skeletons of Dictyocha were found in some samples, which were corresponded to transgressive maximum. The microphotographs of the most frequent palynomorphs, identified from the Holocene lagoon samples in the coastal plain of the Rio Grande do Sul state are shown in the plate.

Our reconstructions of paleoclimate were based on the ecological characteristics of all registered and identified palynomorphs taxa. Only the most representative palynomorphs and their ecological characteristics were mentioned for palaeoclimate reconstructions in the Table I. These palynomorphs were zygospores, coenobiums and colonies of Chlorophyta, whose identifications were made according to literature (van Geel 1976, van Geel & van der Hammen 1978, Jankovská & Komárek 2000). They were from freshwater environments, and may also be evidence of freshwater input into saline aquatic environments during pluvial periods (Medeanic *et al.* 2003, Medeanic 2006). Besides, dinoflagellate cysts and *Prasinophycean phycomata* were found, which are indicators of marine environments or sea water influence by tides and/or marine transgressions (Dale 1976, Hoek *et al.* 1995, Grill & Quattroccio, 1996).

The palynoforaminifers represent chitinous inner tests of different benthic and planktonic foraminifers which are widely spread in the oceans and in the seas (van Veen 1957, Pantic & Bajaktarevic 1988). The informal classification of palynoforaminifers was based on morphology, including number of chambers and the types of chambers arrangement. Biological affinities of the different morphological types of palynoforaminifers have not been established yet. Chitinous fungal

Table I. Indicative values of palynomorphs encountered in the Holocene lagoon sediments in the coastal plain of Rio Grande do Sul for paleoclimatic reconstructions.

Palynomorphs	Distribution	Palaeoclimatic implications
Pollen and spores of terrestrial and aquatic vascular plants	All ecosystems of the coastal plains	Increase in frequency, abundance and taxonomic variety from the lagoon samples indicate on augmentation of fresh-water input into lagoons (more humid climate)
MICROALGAE		
Dinoflagellate cysts	The oceans and the seas	Increasing of marine water influence (transgressions) occurred as a results of temperature rise
Prasinophycean phycomata	The oceans and the seas	Increasing of marine water influence (transgressions) occurred as a results of temperature rise
Chlorophyta		
Botryococcus	Freshwater-brackish water environments	Brackish-water lagoon environments, increasing in the past was connected with drier climate
Spirogyra, Pediastrum, Zygnema, Mougeotia	Freshwater fluvial, lacustrine environments	Significant freshwater input into lagoons may serve as indicator of humidity increase
Pseudoschizaea	Grow at the edge of streams and in ponds	Significant freshwater input into lagoons may serve as indicator for humidity increase
FUNGI		
Glomus	Principal plant in the coastal plain that fix and support dunes	Increase in frequency in lagoon sediments may be indicative for the shallow lagoons and an proximity of the coast indicative for drier climate
Tetraploa	Sporadically in salt and brackish-water marshes	Salt and brackish-water marshes and mangroves
Hyphae	Numerous hyphae in organic rich sediments	Indicative of humid and warm climate, freshwater input during pluvial periods and transport by rivers
SCOLECODONTS	Salt marshes and beaches	Indicators of shallow water basins, the beaches, showing the coast proximity to the lagoons occurred when climate changes became drier
PALYNOFORAMINIFERS	Oceans and seas	Sea level rise (transgressions) caused by temperature increase

palynomorphs, resistant to destruction and important for palaeoenvironmental reconstructions have been recently reported (Jarsen & Elsik 1986, van Geel & Aptroot 2006).

Use of fungal palynomorphs for the elevated salinity environments of the coastal plains, spread inthe Quaternary, has not been sufficiently elaborated yet. The abundance and taxonomic variability of mycorrhizic *Glomus* and its importance for dune stabilization was shown by Cordazzo & Stümer (2007), who studied *Glomus* in the roots of *Panicum racemosum*, a species that fixes and supports dunes. Limaye *et al.* (2007) registered an increase in *Glomus* in the sediments, formed during the Late Glacial Period of the Pleistocene in India, related to active erosion processes under a dry and continental climate. Fungal palynomorphs of *Tetraploa* are common in the salt and brackish-water marshes of coastal plains (Medeanic *et al.* 2001, Limaye *et al.* 2007).

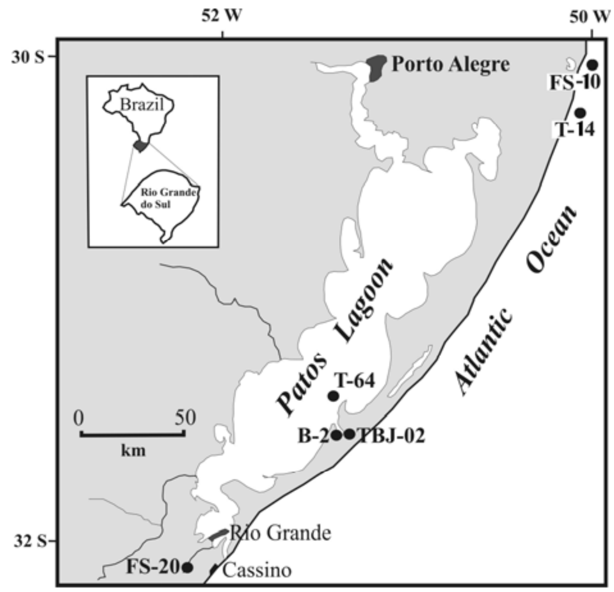

Figure 1. Map of the coastal plain of the Rio Grande do Sul State, Brazil, with the location of the core-drilling sites.

Scolecodonts are the jaws of polychaete annelids. They are fossilized due to their chitinous teeth and dwelling tubes. Representative amounts of scolecodonts are important indicators of sediment deposition near the shelf or near the beaches (Limaye *et al.* 2007). Silicoflagellate skeletons of Dictyocha are important marine indicator for the lagoon sediments subjected by the marine influence when temperatures were higher than in present (McCarthny & Loper 1989, Medeanic & Corrêa 2007).

For the reconstructions of palaeoclimate changes occurred in the different periods of the Holocene, based on palynomorphs, the absolute age data of some samples on ^{14}C were used (Table 2). Present day, using both absolute age data, and palynomorphs records, we can detect some periods of distinctive climatic changes.

Early Holocene

Some samples whose ages correspond to 9,620+/-160 and 9,400+/-140 yrs BP included palynomorphs, indicated on relatively humid and lower than present day temperatures. That time, freshwater marshes, sometimes subjected by sea-water entrance, were wide spread (Medeanic & Dillenburg 2001, Weschenfelder *et al.* 2008). Thin layers (30-40 cm) of peat were formed under such climatic conditions. Then, 8,620+/-170 yrs BP, a drier climate caused a decrease in the areas of freshwater marshes and an increase of xerophylous and halophylous herbaceous plants. At the same time, marine influence in the coast increased, which was revealed by marine palynomorphs (prasinophycean phycomata, cysts of dinoflagellates, and palynoforaminifers) appearance in the lagoon sediments.

Middle Holocene

Further results point to climatic and environmental changes in the coast during the Middle Holocene. Palynomorphs from one sample, dated as 7,840+/-140 yrs BP indicated a relatively humid climate and sea level rise, influenced on notable spreading of the salt-and-brackish-water marshes. Ahead of marine influence, freshwater marshes were inhabited by ferns, mesophylous and aquatic herbs. The obtained data delay with oscillate character of climate during the Middle Holocene. The period of time since 7,570+/-150 and 7,370+/-150 yrs BP was characterized by dry and hot climate, resulted in less dense vegetation cover, decrease in taxonomic variety of plants. In the coast, dunes were more spread, and lagoon were subjected by sea water entrance, ampli-tude of sea-level rise continuously grew (Medeanic *et al.* 2001, 2003, Weschenfelder *et al.* 2008). Maximum of sea water rise was detected from the samples dated as 5,500-6,000 and 4,940+/-80 yrs BP. There was a notable increase in marine algae palynomorphs and Dictyocha skeletons (Fig. 2). Frequency of freshwater algal palynomorphs (*Spirogyra*, *Pediastrum*, *Zygnema*, *Mougeotia*, *Pseudoschizaea*) was very low, indicating salinity increasing in paleolagoon in the maximum sea-level rise (Fig. 3). Predominance of *Botryococcus* colonies in the paleolagoon was evident. Hot and dry climate was the reason of relatively pure vegetation cover in the coastal plain – small frequency of pollen of aquatic vascular plants and arboreal pollen (Fig. 4). Increase in humidity caused more spreading of ferns, arboreal and herbaceous terrestrial and aquatic plants (Figs. 4-5). The final of marine transgression was a result of temperature lowering and climate drying. Sea level fall led to regressive stage.

Late Holocene

That time interval corresponds to regressive stage of the Holocene. We have not yet radiocarbon data on absolute age of sediments from the different depths of the core drillings. But palynomorphs data from the lagoon sediments indicate that oscillate climatic changes occurred after transgressive stage. Based on the evaluation of algal palynomorph taxa frequency and relation (%) between *Botryococcus*

Table II. The cores, absolute age of studied sediments and interpretations of climate, based on palynomorphs.

Cores	^{14}C dating, (yrs BP)	References	Paleoclimatic reconstructions
FS-10	9620+/-160	Medeanic & Dillenburg 2001	Relatively humid
B-2	9400+/-140	Weschenfelder *et al.* 2008	Relatively humid
FS-10	8620+/-120	Medeanic & Dillenburg 2001	Drier
FS-10	7840+/-140	Medeanic & Dillenburg 2001	More humid
T-14	7570+/-120	Medeanic *et al.* 2003	Relatively dry
TBJ-02	7370+/-150	Medeanic *et al.* 2001	Relatively dry
B-2	7370+/-150	Weschenfelder *et al.* 2008	Relatively dry
T-64	~5500-6000	Medeanic *et al.* 2001	Higher temperature and humidity
FS-20	4940+/-80	Clerot 2004	Higher temperature and humidity

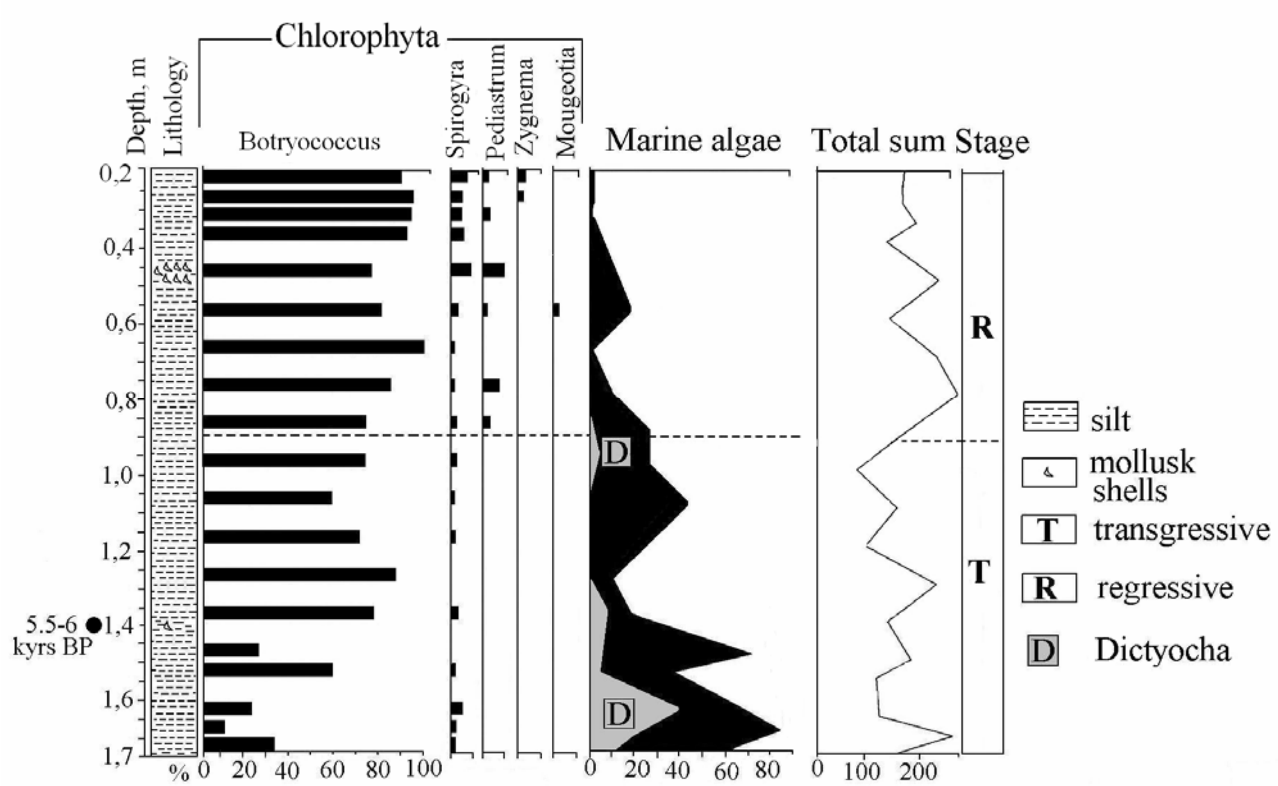

Figure 2. Percentage palynodiagram of algal palynomorphs from the samples of the core T-64 (adapted from Medeanic & Corrêa 2008).

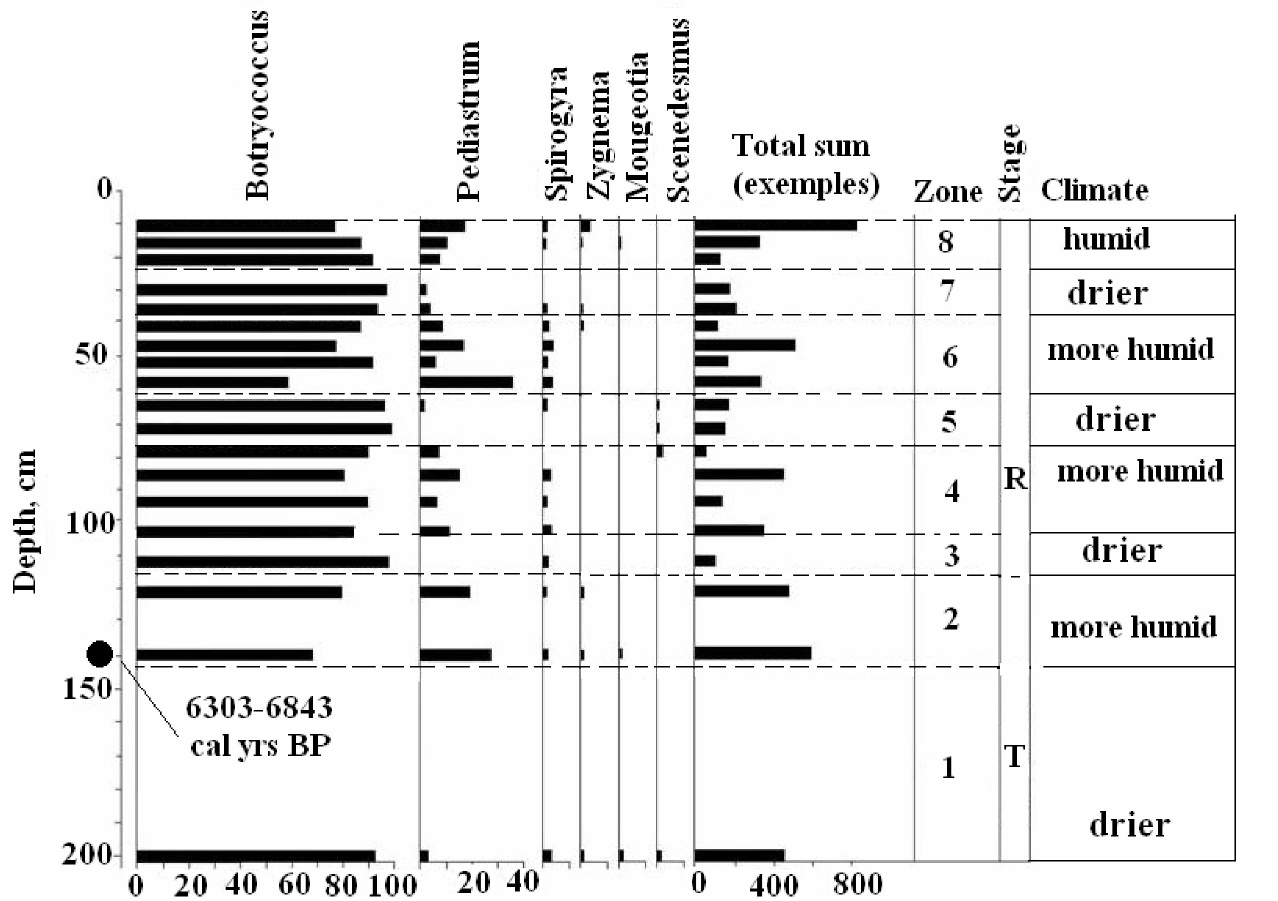

Figure 3. Percentage palynodiagram of algal palynomorphs of Chlorophyta from the samples of the core T-14 (adapted from Medeanic 2006).

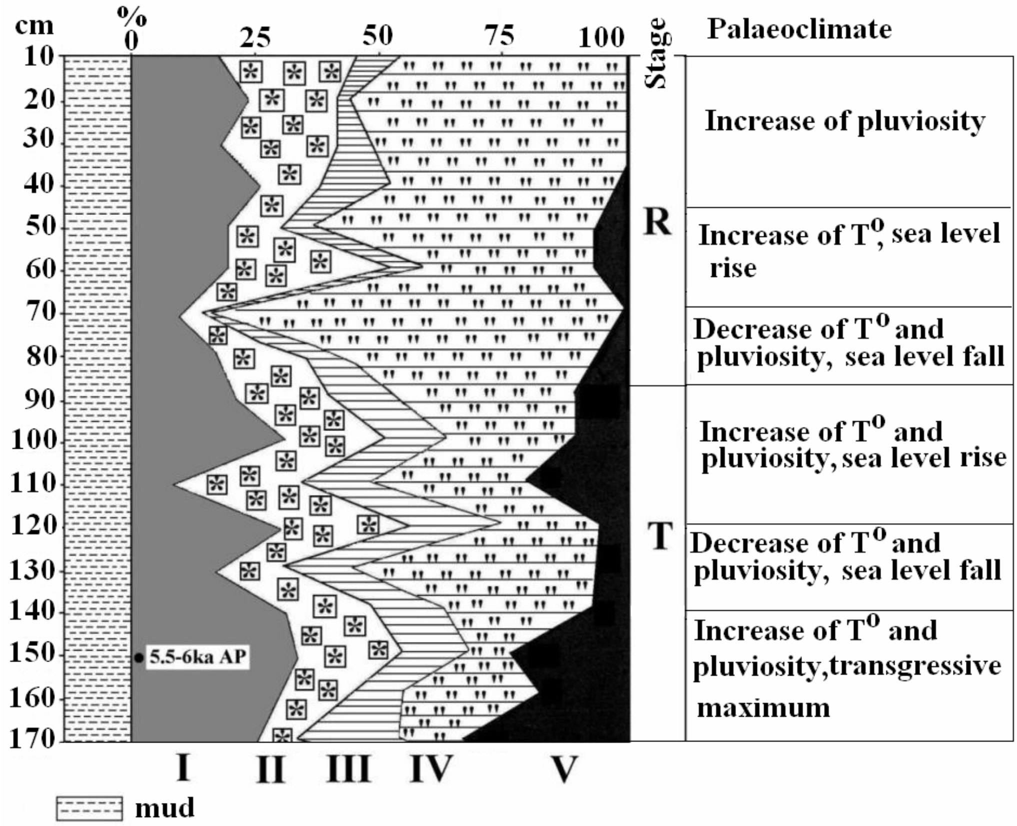

Figure 4. Generalized percentage palynodiagram from the samples of the core-drilling T-64: I – pollen and spores of terrestrial vascular plants, II – pollen and spores of aquatic plants, III – pollen of Poaceae, IV – palynomorphs of Chlorophyta, V – marine algal palynomorphs, T – transgressive stage, R – regressive stage.

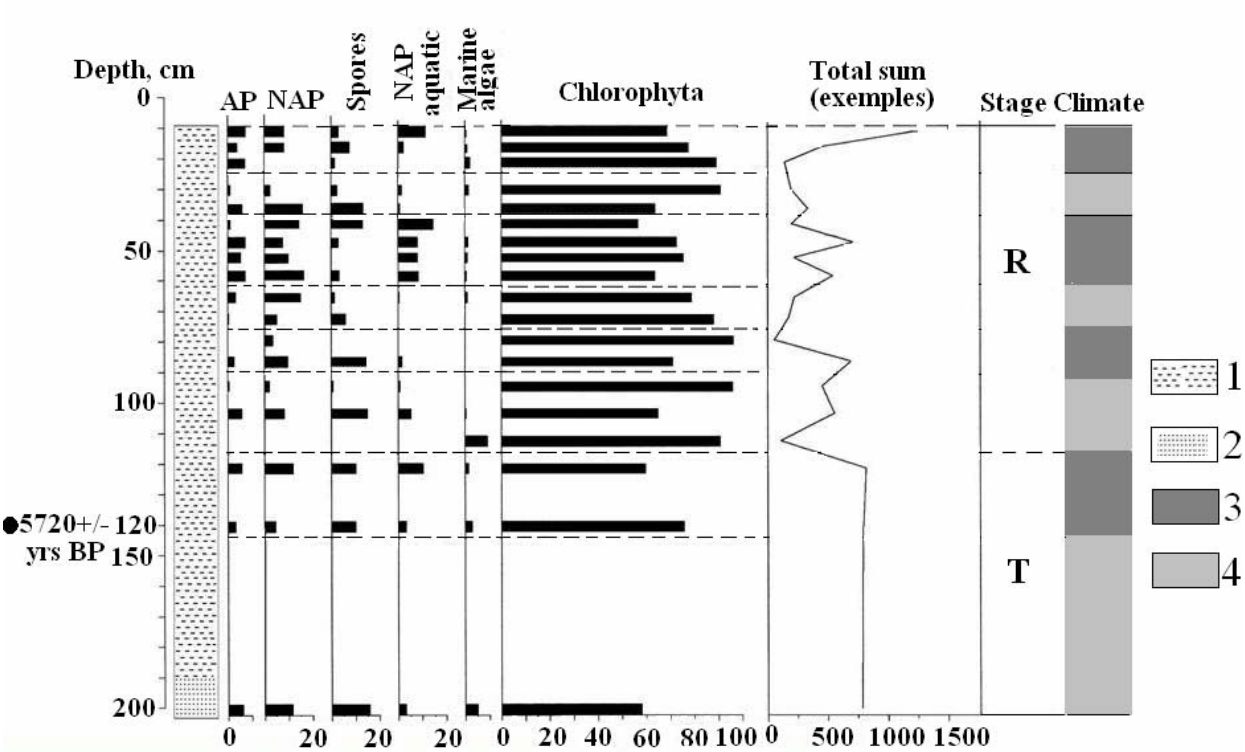

Figure 5. Percentage palynodiagram of palynomorphs counted from the samples of the core T-14: AP – arboreal pollen, NAP – non-arboreal pollen, T – transgressive stage, R – regressive stage, 1 – mud, 2 – sand, 3 – more humid climate, 4 – drier climate (adopted from Medeanic *et al.* 2003).

(indicative for drier climate) and *Pediastrum* (pointing to an increase in humidity) from lagoon sediments of the core drilling T-64, we concluded different sub/stages of climatic changes during regressive stage: drier-more humid-drier-more humid, drier and humid (Fig. 3). In the lagoon sediments formed in the periods of drier climate, a great number of scolecodonts and various fungal palynomorphs were recorded, indicating a lagoon shallowing and on the coast (beach) proximity.

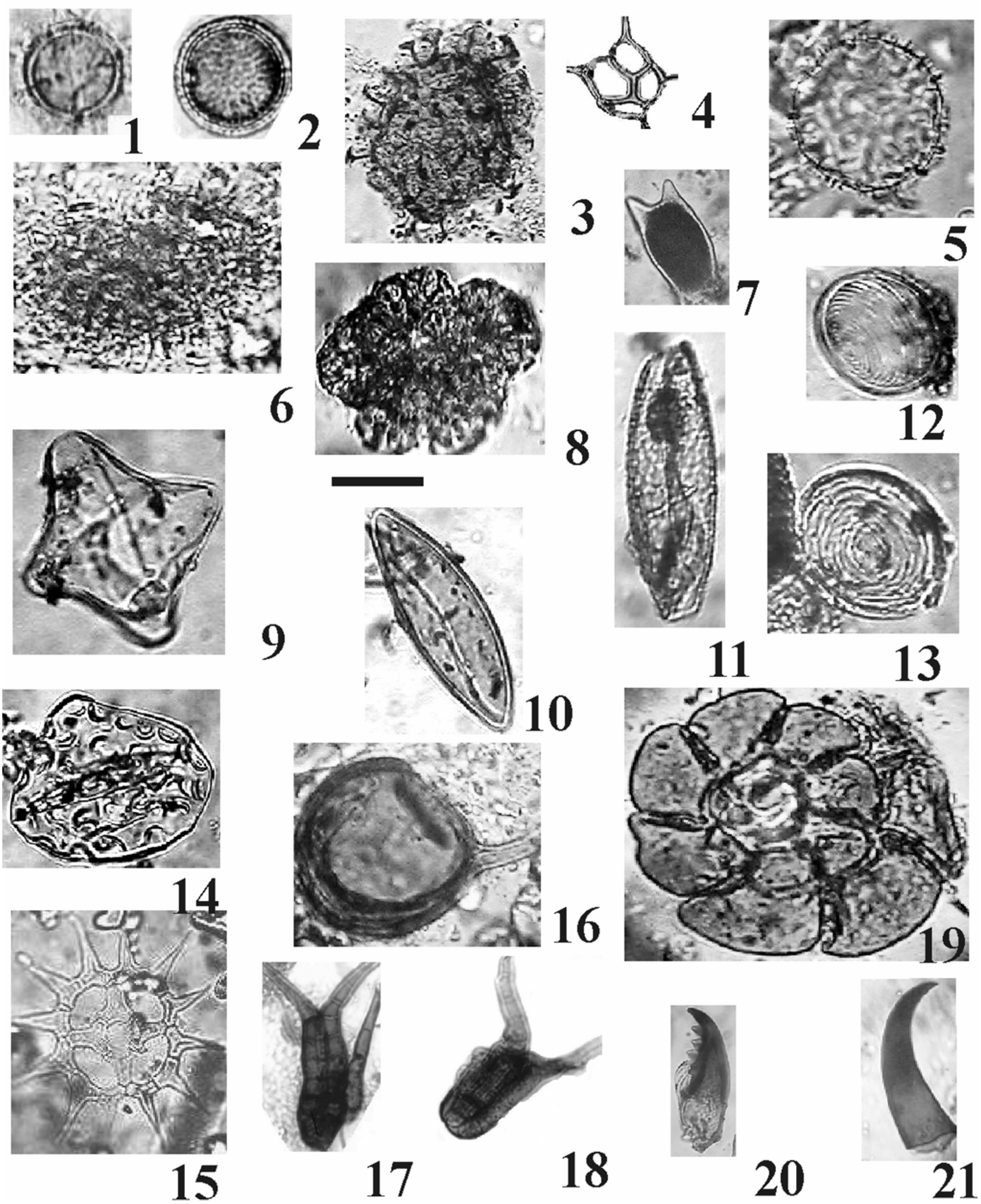

Plate captions: 1,2 – *Prasinophycean phycomata*, 3 – Spiniferites, 4 – *Dictyocha*, 5,6 – *Operculodinium*, 7 – dinoflagellate cyst undetermined., 8 – *Botryococcus*, 9 – *Mougeotia*, 10, 11 – *Spirogyra*, 12,13 – *Pseudoschizaea*, 14 – *Zygnema*, 15 – *Pediastrum*, 16 – *Glomus*, 17, 18 – *Tetraploa*, 19 – microforaminifera, 20,21 – scolecodonts. Scale: 10 µm.

Samples, corresponding to more humid period had more freshwater algal palynomorphs (*Zygnema*, *Mougeotia*, *Spirogyra*, *Pediastrum*, *Pseudoschizaea*), which were carried to paleolagoons by fluvial fresh-water flows (input) when it was heavy raining.

The same sequence of climatic changes based on analysis of increase-decrease frequencies of arboreal pollen (AP), pollen of aquatic herbs (NAP aquatic), and spores of ferns is shown in Figures 4 and 5. The end of the regressive stage (approximately last two thousand years) is characterized by notable increase in humidity, reflected in increasing in the lagoon sediments of freshwater algal palynomorphs and NAP aquatic. The more dense vegetation cover in dunes, salt-brackish water marshes, and arboreal and shrubs were reconstructed.

Conclusions

In this paper, we tried to show some time intervals of climatic changes occurred in the coastal plain of the Rio Grande do Sul state during the last 10 kyrs BP based on dated by ^{14}C samples and palynomorphs study from different core-drillings. Indicative value of some palynomorphs allowed paleoreconstructions of the relative climate changes, sea level oscillations, and coastal palaeoenvironmental changes.

Currently, we have a limited number of profiles conducted on the coastal plain of the Rio Grande do Sul and only a few data on radiocarbon absolute age. Therefore, our conclusions regarding climatic changes that occurred in this region during the last 10 kyrs BP are general and preliminary. Nevertheless, our obtained results clearly show that palynomorphs are important indicators of climate change and could be use to predict future scenarios based on the climatic change periodicity (more humid – drier, lower temperature – higher temperature) revealed in the present study.

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