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# The implication of green algae (Chlorophyta) for palaeoecological reconstruction of the Holocene lagoon system in the Tramandaí Lagoon region, Rio Grande do Sul, Brazil*

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ABSTRACT. A palynological study of 19 lagoon sediment core samples from the well T-14 (200 cm) drilled on the beach near the Tramandaí Lagoon in the State of Rio Grande do Sul, Brazil was performed. A marine transgression and a marine regression were distinguished in the Tramandaí Lagoon region on the basis of algae (diatoms, acritarchs, silicoflagellates, green algae) and vascular-plant pollen and spores. A $^{14}C$ date of 5760 ± 120 yr BP at 140 cm depth corresponds to the marine transgression. A significant predominance of green algae was observed. Seven zones of the green algae genera *Botryococcus* and *Pediastrum* (coccal green algae), *Debarya, Mougeotia, Spirogyra,* and *Zygnema* (Zygnemophyceae) were identified, interpreted as climatic changes in this coastal region. The conclusions based on algal data fit well with those based on pollen and spores of terrestrial and aquatic vascular plants.

KEY WORDS: palynology, algae, palaeoenvironment, Holocene, Tramandaí Lagoon, Brazil

## INTRODUCTION

The Tramandaí Lagoon is situated in the northern part of coastal Plain of the state Rio Grande do Sul, southernmost state in Brazil (Fig. 1). The lagoon covers about 18.8 km$^2$. The formation of the lagoon and adjacent areas was connected with the development of the Holocene barrier-lagoon system, first recognized by Villwock (1984). According to Dillenburg (1994), the development of this system began in the Tramandaí Lagoon region about 7 ka BP as a result of sea-level rise and barrier migration. During the middle and late Holocene, the Tramandaí palaeolagoon and adjacent areas on the Coastal Plain were subject to climatic changes and to postglacial marine transgression and subsequent regression. Repeated changes in salinity, depth, and temperature occurred in an oscillatory manner.

Palynological study of the Holocene sediments in this region has a great significance for the reconstruction of palaeoenvironment and palaeoclimate. This was shown by Lorscheitter and Dillenburg (1998), who published the first palynological data on the palaeoenvironmental and palaeoclimatic evolution of the Tramandaí Lagoon region. They based their reconstructions of the terrestrial environment and climatic change during the middle and late Holocene on rich pollen and spore assemblages of vascular plants. Green algae

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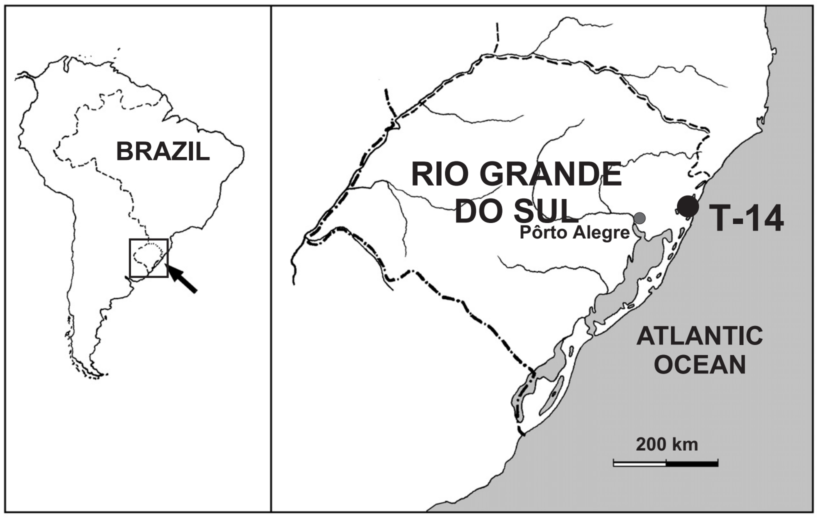


**Fig. 1**. Map showing the location of the core T-14 referred to in the text

were used only to characterize changes in salinity of aquatic environments during the Middle Holocene transgression and subsequent regression.

Some Holocene lagoonal and lacustrine sediments appeared to be poor in pollen and spores and were therefore considered unsuited for palaeoecological reconstruction. Such sediments, however, are abundant in algal remains (cysts, coenobia, and zygospores), especially colonies of coccal green algae and zygospores of Zygnemataceae. The cell walls of these Chlorophyta contain sporopollenin and are therefore, similar to the walls of terrestrial pollen and spores of vascular plants, resistant to destruction during fossilization and chemical preparation of samples for palynology.

The analysis of pollen and spores in the studied sediments appeared to be insufficient for the reconstruction of changes in the aquatic environment, such as temperature, depth, salinity, pH, and nutrient status. On the other hand, remnants of coccal green algae, dinoflagellate cysts, and acritarchs are very informative in this respect. Various publications demonstrate the applicability of green algae for palaeoecological interpretations (Van Geel 1976, van Geel & van der Hammen 1978, Van Geel et al. 1980/81, Tell & Mataloni 1990, Zamaloa 1996, Jankovská & Komárek 1998, 2000, and others). The value of green algae for palaeoenvironmental reconstruction was recently demonstrated by a study in recent sediments from a range of latitudes, longitudes, and altitudes in central Europe (Komárek & Jankovská 2001). Medeanic et al. (2000) published recently on the use of green algae and diatoms in Holocene sediments from the Maquiné River Valley (Rio Grande do Sul, Brazil) for palaeoenvironmental reconstruction and the recognition of marine transgressions and regressions.

It is well known that a great number of green algae live in a freshwater habitats (Blackburn & Temperly 1936, Traverse 1955, Nagappa 1957, Hoshaw & McCoortz 1988, Komárek & Marvan 1992, Nielsen & SØrensen 1992, Williams 1992, Canter-Lund & Lund 1995, Tyson 1995, and others). The most widespread coccal green algae in lagoonal and lacustrine sediments are *Botryococcus* and *Pediastrum*. Zygnemophyceae zygospores encountered in these sediments are *Debarya,* and rectangular, oval and sphaerical types of zygospores identified as *Zygnema, Spirogyra,* and *Mougeotia*. Zygnemophyceae and Chlorophyceae algae are typical for freshwater habitats, but they may also occur in brackish water. These floating planktonic organisms are known to adapt easily to changes in aquatic habitats.

The main effort of pollenanalysts concerns the determination of all microscopic objects occurring in pollen slides. Such “extrafossils” involve also the algae. Determinative key of the genus *Pediastrum* has been already presented by Komárek & Jankovská (2001). It is also partly possible to determine the species of *Botryococcus* (Komárek & Marvan 1992). During several past years, it is also possible to meet with the determination of Zygnemophyceae zygospores into the species of *Spirogyra, Mougeotia* and *Zygnema* according to oval, sphaerical and rectangular forms. Nevertheless, their inexact determination was brought to attention by prof. J. Komárek. All mentioned genera of filamentous zygnemophyceans can have zygosphores of all these forms in their different species. Thus, it is impossible for pollen analysts to determine the genus of Zygnemophyceae from the mere form of zygospores. This situation has to be solved as soon as possible. Before this will happen, we suggest within the framework of present article the following:

The findings of oval zygospores will be designated as *Spirogyra* type. The findings of rectangular forms are the *Zygnema* types while the *Mougeotia* type is of the spherical form. We are beware that such a provisional designation cannot be used in algological literature. However, it is the only way how to express the differentiation of such founds. The expression "type" is in common use by the pollen-analytical practice being designated for a specific form, e.g. a shape of an undeterminable pollen grain, spore, or even the finding of an animal. Such "types" get determined and classified with the correct taxonomical groups in accord with our gradually increasing knowledge. We respect competent notice to incorrect determination of Zygnemophyceae. We intend to solve the problem along with algological specialists in the group of filamentous zygnemophyceans.

Various Chlorophyceae taxa show a higher than average capacity of self-adapting to changes in salinity, depth, or pH. For example, *Botryococcus* is more widespread in brackish-water bodies than other Chlorophyceae algae, and develops usually most abundantly in shallow-water bodies subject to relatively low precipitation (Blackburn & Temperly 1936, Traverse 1955, Guy-Ohlson 1992, and others). *Pediastrum* is usually widespread in freshwater bodies. Only a few *Pediastrum* species have the capacity to survive under conditions of elevated salinity up to 1.7–3.5% (Whiteside 1965, Tyson 1995). Due to their high sensitivity to changes in salinity and depth, *Pediastrum* species are good indicators of palaeoenvironmental and climatic change (Nielsen & Sørensen 1992, Jankovská & Komárek 1998, 2000, and others)

The Zygnemataceae algae *Debarya, Mougeotia, Spirogyra*, and *Zygnema* thrive in a great variety of habitats and are common in shallow freshwater bodies such as ponds, lake margins, cold swift streams, warm stagnant pools, and moist soils and peats, usually with pH > 7 (Prescott 1962, Colbath & Grenfell 1995, and others).

Recently, during the palynological study of Holocene lagoon sediments from a well on the Coastal Plain of the State Rio Grande do Sul we noted the absolute predominance of zygospores, colonies and coenobia of green algae. This induced us to examine them more attentively and try to apply to this region the available information about habitat requirements of these algae. The presence of a great number of remains of green coccal algae and zygospores of filamentous zygnemophyceans had already been observed in the middle and late Holocene lagoon sediments of the Coastal Plain in the State of Rio Grande do Sul (Cordeiro & Lorscheitter 1994, Medeanic & Dillenburg 2001), but until recently, their indicative value for past environments has never been exploited in this region. Previous palaeoenvironmental reconstructions of the Holocene were based principally on pollen and spores.

On the basis of published data on the distribution of green algae in recent and Holocene sediments in various regions of the world, we reconstructed the palaeoenvironmental development and climate oscillations in the Coastal Plain of the State of Rio Grande do Sul.

## MATERIALS AND METHODS

Core T-14 was collected from a well on Jardim do Edem beach, 7 km south of Tramandaí Lagoon, 30°04'14" S and 50°09'36" W (Fig. 1). The core consists of sand from 0 to 12 cm, silt and silty clay from 12 to 200 cm, and sand from 200 to 245 cm. Nineteen samples were studied. One sample of silt at 140 cm depth was radiocarbon dated to 5760 ± 120 yr BP by BETA ANALYTIC INC., Florida, USA (lab. No BETA-56516).

Chemical treatment of the samples followed the procedure usual for pollen analysis as described by Faegri and Iversen (1975). HCl (10%) and NaOH (5%) were used, but the use of HF was avoided in order to preserve siliceous algal remains such as diatom valves and silicoflagellate cysts. Separation of inorganic and organic substances was carried out by dense medium, a solution in water of $ZnCl_2$ with a density of 2.2 g/cm$^3$.

All samples studied contain abundant zygospores, colonies and coenobia of green algae (Chlorophyta). Pollen and spores of terrestrial and aquatic vascular plants are rare. Acritarch and silicoflagellate cysts, which constitute the group of marine indicators, are also encountered but they are scarce. On the other hand, various diatoms were encountered in some samples. Evaluation of their tolerance to salinity (marine, brackish-water, freshwater) allows us to estimate the marine influence.

A sum of palynomorphs (100% by definition) was calculated including pollen and spores of vascular plants, Chlorophyta colonies and zygospores, and silicoflagellate and acritarch cysts, in order to determine the percentages of arboreal pollen (AP), non-arboreal pollen (NAP), pollen of aquatic plants (NAP aquatic), Bryophyta and Pteridophyta spores, and marine indicators. Diatoms were not included in the sum of palynomorphs. In addition, a green-algae sum was made in order to evaluate trends in the relation between genera of green algae, especially *Botryococcus*/*Pediastrum*. Seven zones were recognized on the basis of fluctuations in the *Botryococcus*/*Pediastrum* ratio.

The results were plotted in two percentage diagrams using TILIA software (Grimm 1991).

## RESULTS

### MARINE TRANSGRESSION

The constant presence of numerous marine diatoms from 200 to 112 cm depth indicates a marine transgression. The marine diatoms include mainly *Actinocyclus*, *Coscinodiscus*, *Cyclotella*, and *Triceratium*. Diatoms of usually brackish-water are represented by *Diploneis* cf. *smithii* var. *smithii* and *Terpsinoë* cf. *musica*. Acritarch cysts (*Cymatiosphaera* and *Microhystridium*), and silicoflagellate cysts (*Dictyocha*) were encountered, too, composing up to 6% of the total palynomorphs sum. A radiocarbon date at 140 cm depth gives 5760 ± 120 BP, which coincides with the maximum sea level during the transgression.

During the marine transgression, pollen and spores are usually low in abundance. Arboreal pollen (AP) accounts for 3.2–6.4%, non-arboreal pollen (NAP) 4.7–12.5%, pollen of aquatic plants (NAP aquatic) 3.2–10.4%, and Bryophyta and Pteridophyta spores 10.3–16.3% (Fig. 2). Arboreal pollen represent the trees *Alchornea*, *Rapanea*, *Rhus*, *Smilax*, *Trema*, Anacardiaceae, Apocynaceae, Canellaceae, Euphorbiaceae, Magnoliaceae, Mimosaceae, Moraceae-Urticaceae, Myrtaceae, Palmae, and Rubiaceae. Non-arboreal pollen is less diverse and represents the herbs Poaceae (predominant), *Amaranthus*-Chenopodiaceae, Apiaceae, Asteraceae, Lamiaceae, Polygona-

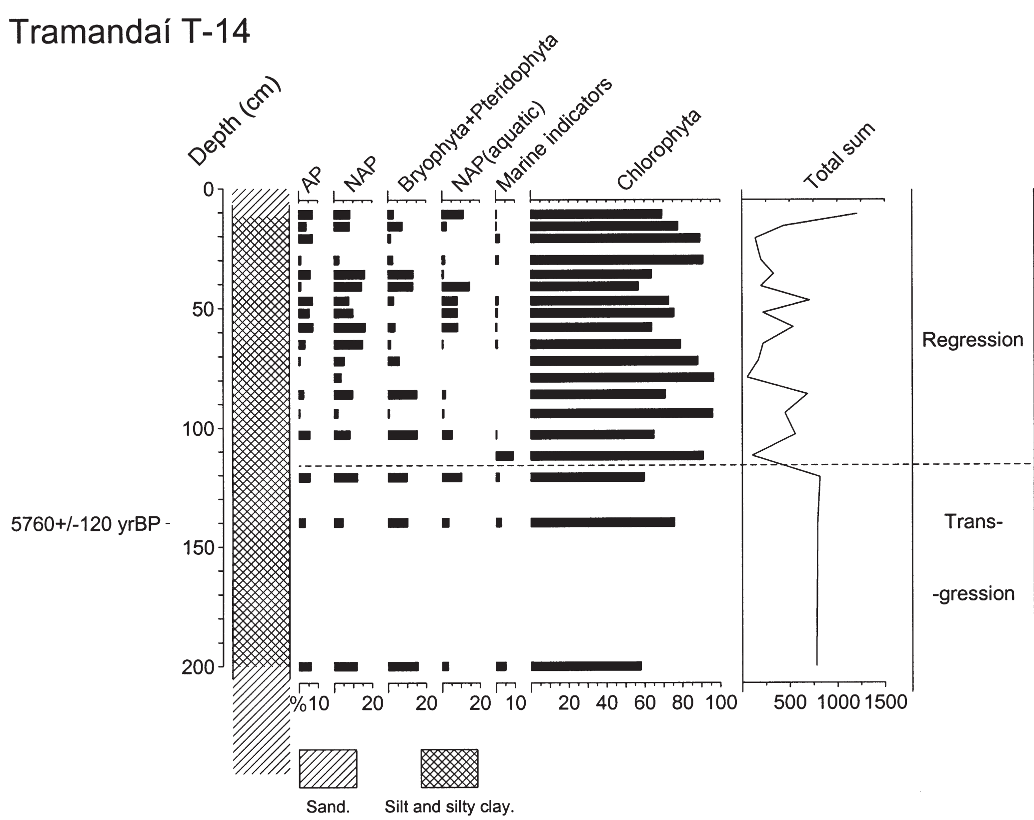


**Fig. 2**. Lithology and palynomorphs (%) in core T-14. AP = arboreal pollen, NAP = non-arboreal pollen, NAP aquatic = non-arboreal pollen of aquatic plants

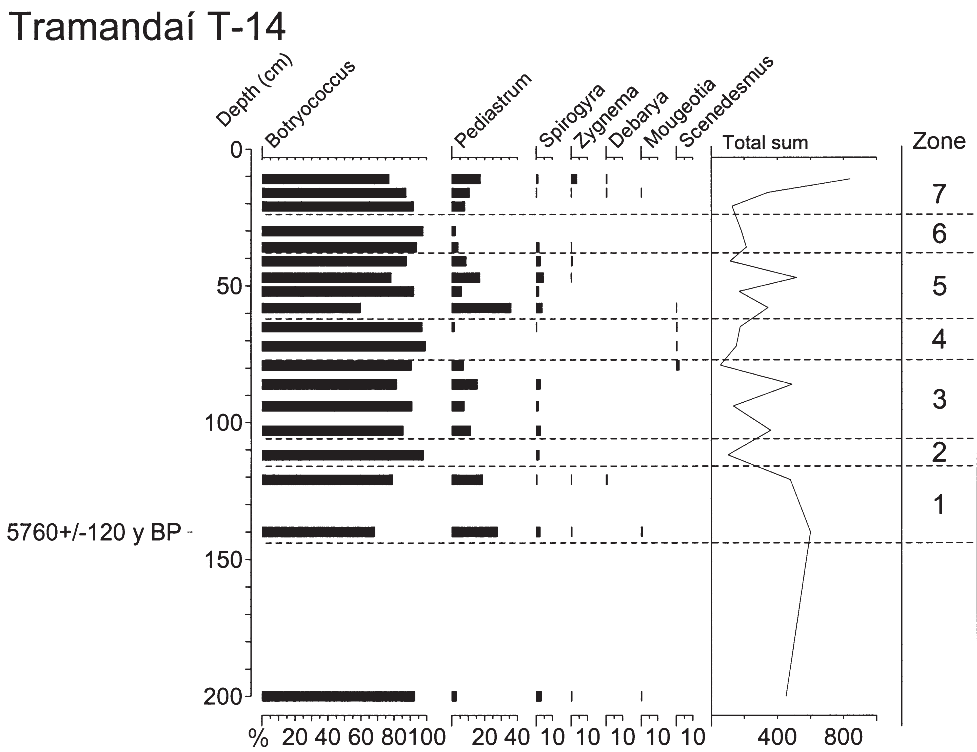


**Fig. 3**. Green algae genera (%) in core T-14

ceae, Scrophulariaceae, and Solanaceae. Pteridophyta and Bryophyta spores represent the ferns *Anogramma, Blechnum, Dicksonia, Dicranoglossum, Lycopodiella, Microgramma*, and *Pteris* and the moss *Phaeoceros*. Pollen of aquatic vascular plants is relatively rare, most frequent are Cyperaceae and Typhaceae.

All samples of the marine transgression (200–120 cm depth) are characterized by a significant predominance of Chlorophyta remains (60.4–99.0%) (Fig. 3, Pl. 1). Usually, *Botryococcus* prevails (68.3–98.0%). Other genera of green algae include *Pediastrum* (2.9–27.7%), zygospores of *Debarya* (0.0–1.2%), *Mougeotia* type (0.0–0.9%), *Spirogyra* type (0.6–3.3%), and *Zygnema* type (0.0–0.7%), corresponding to **zone 1**.

MARINE REGRESSION

The absence of marine diatoms and silicoflagellate cysts and the decrease of acritarch cysts in the more recent sediments from 112 to 12 cm depth indicate a decrease of salinity in the basin and therefore of marine influence, which is interpreted as a marine regression. This represents the late Holocene regression of the Atlantic Ocean. Fresh-water and brackish-water diatoms (*Terpsinoë musica, Diploneis* cf. *smithii, Navicula*, and *Pinnularia*) were identified in some samples. The proportion of acritarch cysts decreases to 1%.

Compared with the results for the marine transgression, samples from the marine regression show decreased diversity and lower percentages of arboreal pollen ( 0.7–7.4%) and Pteridophyta and Bryophyta spores (1.4–15.3%), whereas non-arboreal pollen has higher percentages ( 8.5–16.5%). Pollen of aquatic plants (NAP aquatic) accounts for 0.5–14.6%. The amount of pollen and spores of terrestrial plants and their taxonomic diversity is elevated in the samples at depths of 41, 58, 86, and 103 cm. Trees are represented by *Alchornea, Rapanea, Trema*, Fabaceae, Mimosaceae, Moraceae-Urticaceae, Euphorbiaceae, Tiliaceae, Palmae, and others. The taxonomic diversity of herb pollen is low, and includes Poaceae (predominant), Asteraceae, Cichoriaceae, Primulaceae, Solanaceae, and Verbenaceae. This period is characterized by an increase of pollen of drought- and salt-tolerant plants such as *Amaranthus*-Chenopodiaceae. Aquatic plants are represented by pollen of Cyperaceae and Typhaceae, and sometimes

*Myriophyllum*. The taxonomic diversity of Pteridophyta and Bryophyta significantly decreases (ferns *Anogramma, Blechnum, Microgramma,* and *Osmunda,* moss *Phaeoceros*).

The proportion of green algae increases (60.6–99.8%), *Botryococcus* predominates (77.2–99.8%). It is notable that especially high amounts of *Botryococcus* were encountered in samples with low amounts of freshwater algae, pollen, and spores. *Pediastrum* varies widely (0.0–35.9%) and is among the increasing algae. Other green algae such as *Spirogyra* type, *Mougeotia* type, *Debarya,* and *Zygnema* type are rare (up to 4%).

On the base of the fluctuating character of the *Botryococcus/Pediastrum* ratio, zones 2–7 in the interval 12–112 cm were recognized, as follows (Fig. 3):

**Zone 2** is characterized by the absolute predominance of *Botryococcus* (98.9–100%);

**Zone 3** *Pediastrum* (7.4–15.5%) and *Spirogyra* type zygospores (0.0–6.0%) increase, but *Botryococcus* (81.0–90.0%) decreases;

**Zone 4** *Pediastrum* (0.0–1.7%) and *Spirogyra* type (0.0–0.6%) significantly decrease, and *Botryococcus* predominates (92.6–100%);

**Zone 5** *Pediastrum* (5.9–35.0%), *Spirogyra* type (1.8–4.5%), and *Zygnema* type (0.0–0.5%) increase, and *Botryococcus* (59.7–88.1%) decreases;

**Zone 6** *Pediastrum* (2.2–3.8%) and *Spirogyra* type (0.0–1.8%), decrease, and *Botryococcus* (77.2–92.1%) increases;

**Zone 7** is characterized by an increase in diversity of freshwater algae, among which *Pediastrum* (7.9–17.3%), *Spirogyra* type (0.2–1.3%), *Zygnema* type (0.3–3.6%), and *Mougeotia* type (0.0–0.3%). *Botryococcus* (77.2–87.5%) decreases.

## DISCUSSION

### MARINE TRANSGRESSION

The presence of marine and brackish-water diatoms, acritarchs, and silicoflagellates indicate an increase in salinity in the lagoon during the marine transgression. The constant predominance of *Botryococcus* in the sediments is a reliable indicator of a shallow water depth in the lagoon. Increasing freshwater algae such as *Pediastrum, Debarya, Mougeotia* type, *Spirogyra* type, and *Zygnema* type may be due increased freshwater supply into the lagoon during a pluvial period when atmospheric precipitation increased. The freshwater algae were probably brought into the lagoon by streams and may, therefore, during the marine transgression be considered as allochthonous. Zone 1 is recognized on the basis of the *Botryococcus/Pediastrum* ratio, and corresponds according to pollen and spore data to a period of humid subtropical climate, with subtropical forests situated in areas sheltered from marine influence and widespread mesophilous grassland and freshwater marshes.

The conclusion of a subtropical and humid climate in this area during the marine transgression fits well with the data on Holocene sediments from a different core from the bottom of the Tramandaí Lagoon (Lorscheitter & Dillenburg 1998). A difference is that the material discussed in this paper has a higher abundance of green algae and a much lower abundance and taxonomic diversity of pollen and spores.

### MARINE REGRESSION

Sediment accumulation during the late Holocene regression occurred in a setting of decreasing salinity of the water in the small, shallow lagoon and in the surrounding soils. This resulted in a significant expansion of green algae, especially *Botryococcus*. During the dry periods represented by zones 2, 4 and 6, characterized by the predominance of *Botryococcus*, the volume of freshwater supply into the lagoon decreased. For that reason, the quantity of the allochthonous pollen and spores of terrestrial plants as well as *Pediastrum, Spirogyra* type zygospores, and other algae was small. The low frequency of pollen and spores in these zones hampers the reconstruction of terrestrial vegetation in the study area during dry periods.

Zones 3, 5 and 7 correspond to pluvial periods, when increased of precipitation and the resulting increase in freshwater supply into the lagoon led to an increase in remains of freshwater algae including *Pediastrum, Spirogyra, Mougeotia, Debarya,* and *Zygnema*, a decrease of *Botryococcus* as a result of greater water depth, and an increase of pollen and spores of terrestrial and aquatic plants. According to palynological data, subtropical forests in the Tramandaí Lagoon region were of limited extent. These coastal forests included *Alchornea, Rapanea, Smilax*, Anacardiaceae, Euphorbiaceae Fabaceae, Myrtaceae, and Palmae, and had a lower taxonomic diversity than during the forests the marine transgression. Different ferns (*Anogramma, Blechnum, Botrychium, Microgramma, Osmunda, Pteris*), mosses (*Anthoceros, Phaeoceros, Sphagnum*), and herbs (Poaceae predominant), Apiaceae, Asteraceae, Cyperaceae, Solanaceae, and Typhaceae) represent the vegetation of freshwater marshes and mesophilous grasslands, which were widespread in that period. In comparison with the marine transgression, the Coastal Plain during the marine regression was characterized by an enlargement of dune areas occupied by drought- and salt-resistent plants (*Amaranthus*-Chenopodiaceae, some species of Asteraceae and Poaceae).

## CONCLUSIONS

The obtained results show that green algae can have great importance for palaeoecological reconstructions of the history of small lagoons, such as the lagoon studied lying on the coastal plain of Rio Grande do Sul, whose Holocene evolution was influenced by sea-level changes of the Atlantic Ocean and by oscillations of annual precipitation in a subtropical climate. The importance of green algae for such reconstructions is particularly essential in the case of low pollen and spore frequencies.

The use of zygospores of Zygnemophyceae, and colonies and coenobia of coccal green algae of Chlorophyceae, confirmed by diatoms, acritarch and silicoflagellate cysts, pollen, and spores has enabled us to conclude that the oldest lagoon sediments in this region were formed in a relatively small shallow lagoon subjected to the Holocene marine transgression and subsequent regression.

Seven zones based on genera of green algae reflect the changes in the palaeoenvironmental development of this region in connection with marine influence and climatic oscillations during the middle and late Holocene.

During marine regression, *Botryococcus* was constantly abundant in the lagoon. The trends of coenobia and zygospores of fresh-water green algae (*Pediastrum, Spirogyra* type, and others) had a fluctuating character and probably were connected with large volumes of fresh-water effluents into lagoon during pluvial periods.

The sediments formed during the marine regression in the late Holocene contain abundant *Botryococcus*, with phases of absolute predominance indicative probably of drier periods. Periodical short-term increases in *Pediastrum* were ascribed to a rapid freshening of the lagoon, caused by a decline of marine influence probably connected with increased precipitation. During such pluvial periods, *Pediastrum* was transported into the lagoon by freshwater currents, together with other freshwater algae such as *Debarya, Mougeotia* type, *Zygnema* type, and *Spirogyra* type and increased quantities of pollen and spores of terrestrial and aquatic vascular plants.

These results are the first example of green algae used in this area for the reconstruction of palaeoecological conditions. They demonstrate the necessity to reinforce the study of green algae in the Holocene sediments of the other different lagoons in the Coastal Plain in the future.

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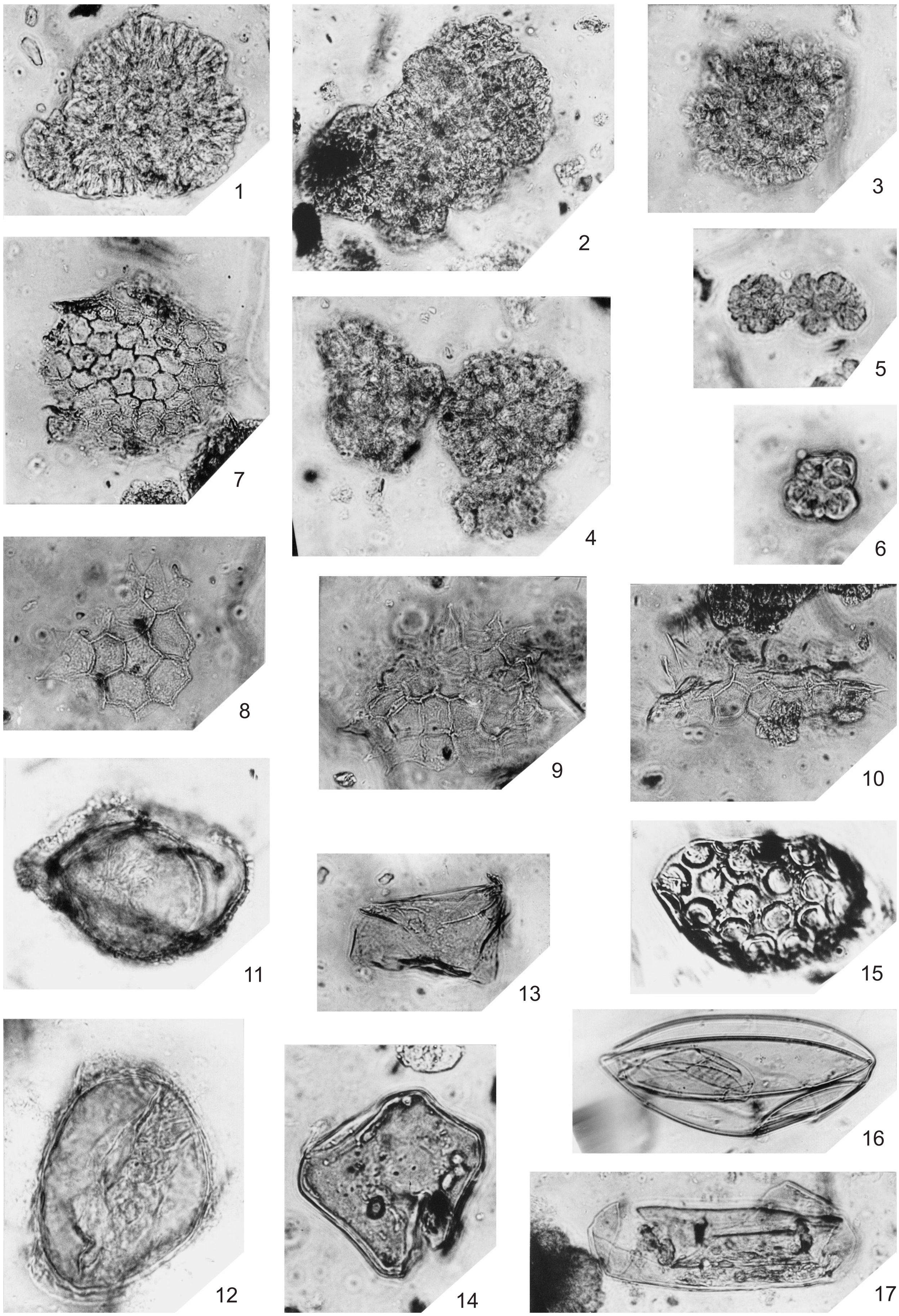
**P L A T E**

Plate 1

1. *Botryococcus neglectus*; sample 87/3; depth 121 cm; 100 µm
2. *Botryococcus* sp.; sample 89/5; depth 200 cm; 137.5 µm
3. *Botryococcus* sp.; sample 71/2; depth 12 cm; 70 µm
4. *Botryococcus* sp.; sample 87/3; depth 121 cm; 75 µm
5. *Botryococcus* sp.; sample 88/3; depth 140 cm; 67.5 µm
6. *Botryococcus pila* type; sample 89/4; depth 200 cm; 25 µm
7. *Pediastrum* sp.; sample 83/4; depth 86 cm; 112 µm
8. *Pediastrum* sp.; sample 89/4; depth 200 cm; 108.5 µm
9. *Pediastrum* sp.; sample 89/4; depth 200 cm; 120 µm
10. *Pediastrum* sp.; sample 89/4; depth 200 cm; 90 µm
11. *Debarya* sp.; sample 89/1; depth 200 cm; 68 µm
12. *Debarya* sp.; sample 89/1; depth 200 cm; 78 µm
13. *Zygnema* type; sample 89/2; depth 200 cm; 48 µm
14. *Zygnema* type; sample 89/2; depth 200 cm; 60 µm
15. *Mougeotia* type; sample 89/1; depth 200 cm; 67.5 µm
16. *Spirogyra* type; sample 89/3; depth 200 cm; 75 µm
17. *Spirogyra* type; sample 74/4; depth 200 cm; 137.5 µm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