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PALEOCLIMATIC RECONSTRUCTION OF THE BRAZILIAN CRETACEOUS BASED ON PALYNOLOGICAL DATA*

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ABSTRACT The Cretaceous is probably the best represented period of the Brazilian Phanerozoic. Palynological data for this interval, however, are very heterogeneous, and derived almost completely from the coastal basins. On the basis of these data, the present work reconstructs the Cretaceous climatic record. The paper is divided into two principal parts, the first one corresponding to a brief analysis of the paleoclimatic value of some plant groups present in the period, and the second representing an evaluation of the significance (abundance, diversity) of the same groups in Brazil.

RESUMO O Cretáceo é um dos períodos geológicos melhor representados de todo o Fanerozóico Brasileiro. A informação palinológica existente é, contudo, muito heterogênea, referindo-se quase completamente às bacias costeiras. Neste contexto, o artigo em foco pretende reconstruir as diversas fases climáticas do período, com base nos dados publicados. Duas partes principais compõem o trabalho. A primeira corresponde a uma breve análise do valor paleoclimático de alguns grupos vegetais do período, enquanto a segunda representa uma avaliação da presença (abundância e diversidade) destes mesmos grupos em território brasileiro.

INTRODUCTION Cretaceous sediments are possibly the best represented of all Brazilian Phanerozoic sequence with respect to area of occurrence, number of basins and great thickness of the deposits. Other reasons of interest are their tectonic framework, frequently abundant fossil content and economic potential.

The term basin (42 were inventoried) must be interpreted in the broadest sense of the word, because they differ enormously in origin (intracratonic, interior, coastal, blanket deposits, etc.), geologic evolution and dimensions (from "fragments" of 4 km^2 up to 1,600,000 km^2) (Fig. 1, Table 1). The best studied are the coastal basins because of their economic interest, chiefly petroleum. This is true as well for palynologic data, which have been widely used by Petrobrás for biostratigraphic purposes. For this reason, with few exceptions, knowledge of the Brazilian Cretaceous microfloras is irregular and largely restricted to the coastal areas.

Within this obviously limited context, the present paper is intended to serve as the basis for future work on the interpretation of palynologic information, important for the paleoclimatic reconstruction of the period.

PALEOCLIMATIC SIGNIFICANCE OF PLANT GROUPS Paleoclimatic reconstruction based on fossils is founded principally upon the behavior of living representatives of the *taxa*. Plants are no exceptions to this rule and, evidently, the most important groups are those best adapted to specific climatic conditions. For palynology, as Reyre (1979) has shown, the problem is theoretically simple, consisting of finding spores and pollen grains in the sediments that represent confirmed guide species (in a climatic sense) or that permit the reconstruction of the flora that, by comparison with the present, can furnish reliable climatic evidence. There are, however, some practical difficulties to consider, since the differences between extinct and modern floras become more and more accentuated the farther one goes back in time.

In Cretaceous times, the floras are already quite different, at the specifc level, from modern ones. The reconstructions are based either on the few species that continue till today, or on different species closely related to extant ones. It is preferable in this case to work with higher taxonomic categories, such as families. Several criteria considered by Reyre *(op. cit.)* as important to assure the reliability of the paleoclimatic value of a plant family are:

- sufficient representation, in number of species, in the living world;
- more or less restricted bioclimatic character;
- possibility of identifying a modern climatic *optimum* in which there is maximum development of the group in terms of number of species and specimens.

Despite all the methodological limitations (a problem common to other paleoclimatic methods as well), important conclusions may be drawn from the fossils of certain plant families.

Extant palynological groups (based on Reyre 1979) *PTERIDOPHYTES* Many Cretaceous spores are morphologically close to modern forms, thus allowing their relatively reliable assignment to modern families or, sometimes, even to genera. Among the families surely represented (and locally abundant) are the Osmundaceae, Matoniaceae, Marattiaceae, Gleicheniaceae, Cyatheaceae, Schizeaceae, Lycopodiaceae and Selaginellaceae, as well as aquatic forms like the Marsileaceae, Salviniaceae, etc. In general terms, all these groups are suggestive of a tropical to humid subtropical climate, with the exception of the Osmundaceae, Lycopodiaceae and Selaginellaceae,

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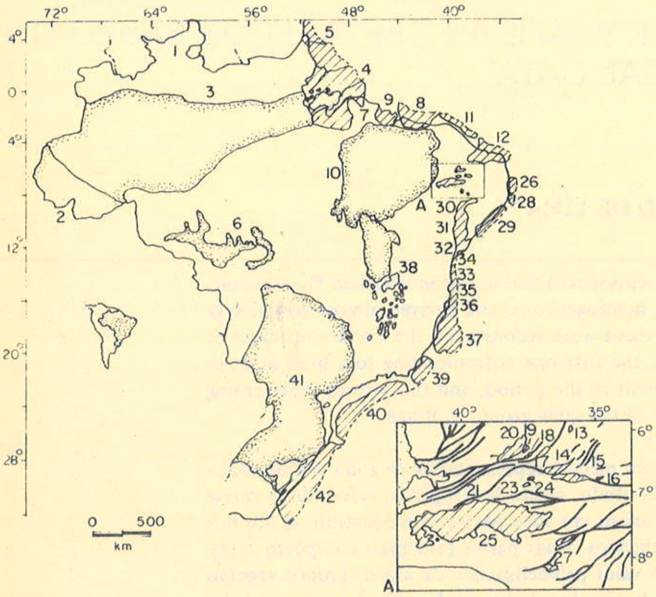

1. Takutu
2. Acre
3. Médio Amazonas
4. Foz do Amazonas
5. Cassiporé
6. Parecis
7. Bragança/Vizeu
8. Barreirinhas
9. São Luís
10. Parnaíba
11. Ceará
12. Potiguar
13. Rio Nazaré
14. Uiraúna
15. Souza
16. Pombal
17. Icó
18. Lima Campos
19. Cabeça de Negro/ Malhada Vermelha
20. Iguatu
21. Rio Bastiões
22. Lavras da Mangabeira
23. Quitaús
24. Iborepi
25. Araripe
26. Recife/João Pessoa
27. Mirandiba
28. Cabo
29. Sergipe/Alagoas
30. Jatobá
31. Tucano
32. Recôncavo
33. Almada
34. Camamu
35. Jequitinhonha
36. Cumuruxatiba
37. Espírito Santo
38. Sanfranciscana
39. Campos
40. Santos
41. Paraná
42. Pelotas

Figure 1 – Brazilian sedimentary "Basins" with representation of the Cretaceaus period (Adapted from Asmus, 1983)

which are more tolerant. Obviously, each family has its own characteristics, slightly different from those of other families, and it is the representation (abundance, diversity, etc.) of the family in the association that can have greater or lesser interpretative value for paleoclimatic reconstructions.

GYMNOSPERMS WITH DISACCATE POLLEN GRAINS Disaccate pollen grains confidently attributed to living conifer families generally are suggestive of cold to temperate climates with low humidities (Pinaceae, Abietaceae, etc.). The great exception is the Podocarpaceae, which is adapted to hotter and humider conditions, although topography may also play a very important role in the distribution of this group.

GYMNOSPERMS WITH INAPERTURATE POLLEN GRAINS The most important family in this group is the Araucariaceae, which is broadly suggestive of tropical to subtropical climates of oceanic type, with few differences between seasons.

GYMNOSPERMS WITH POLYPLICATE POLLEN GRAINS The pollen grains here referred to are unquestionably related to the Gnetales, including probable representatives of the genera *Ephedra* and *Welwitschia.* Their presence suggests essentialy dry (even arid) climates, with high diurnal temperatures.

GYMNOSPERMS WITH MONOCOLPATE POLLEN GRAINS These pollen grains, which indicate hot to very hot subtropical to tropical climates with slight humidity (but not arid), are attributed to the "Cycadales/Ginkgoales/Bennettitales complex" because of the difficulty to distinguish adequately among them.

ANGIOSPERMS Cretaceous angiosperms that permit assignment of affinities with living species are scarce. Paleoclimatic interpretations, with some exceptions, are not generally based on this group, which is extremely heterogeneous in its ecologic adaptations. The occurrence of some *taxa* can, however, reinforce conclusions drawn from the analysis of other groups. Examples include the Palmae (indicative of hot and humid climates), the Ulmaceae (temperate to subtropical) and Proteaceae (temperate to subtropical, tending to be somewhat dry), among others.

Extinct palynological groups (based on Reyre 1979)
"RIMULATE" POLLEN GRAINS The "rimulate" pollen grains *(Classopollis, Dicheiropollis, Circulina,* etc.) represent an extinct group of conifers, the Cheirolepidiaceae, extremely important in the Mesozoic Era. Not rarely, *Classopollis* appears in very high percentages, sometimes comprising up to 90% of the pollinic spectrum. Such abundance is always associated with hot climates (Lima 1976, Vakrameev 1982, Herngreen & Chlonova 1982) with a tendency toward aridity. Their association with polyplicate and monocolpate pollen grains is well known, as is also their antagonistic relationship with respect to pteridophyte spores.

"ELATERATE" POLLEN GRAINS The so-called "elaterate" forms, common in some Middle Cretaceous regions of Africa and South America, are still of unknown botanical affinity. Their morphology is very variable, and includes polycolpate forms *(Elateroplicites, Senegalosporites),* policolpate *(Elaterocolpites)* and some others that could have been spores. The majority, however, are so strange that they cannot be compared with extant plants. The presence of "elaters" seems to characterize a tendency among different groups in response to an as yet unknown environmental modification rather than a specific feature of a biologically related, heterogeneous group. By association, it is possible to deduce that these forms represent hot climates or, more specifically, drier phases of tropical conditions.

Table 1 – Some relevant data concerning the cretaceous sedimentary basins

Designation	Placement	Area (km^2) (in Brazilian territory)	Tectonic control	Palynological information
1. Takutu	North	30.000	+	Van der Hammen & Burger 1966
2. Acre	West	150.000	+	–
3. Mid-Amazonas	Northwest	300.000	+	Daemon 1975
4. Mouth Amazonas	North	145.000	+	Regali 1982
5. Cassiporé	North	4.000	+	Regali 1982
6. Parecis	West	157.000	–	
7. Bragança/Vizeu	North	8.000	+	Regali *et al.* 1974
8. Barreirinhas	Western Northeast	85.000	+	Müller 1966, Lima 1972, Herngreen, 1973, Regali *et al.* 1974, Regali *et al.* 1983
9. São Luís	Western Northeast	35.000	+	Lima 1972, Regali *et al.* 1974
10. Parnaíba	Western Northeast	700.000	+	Müller 1966, Lima & Campos 1979, Lima 1982
11. Ceará	Northeast	16.000	+	Regali *et al.* 1974, Regali 1980
12. Potiguar	Eastern Northeast	41.000	+	Regali *et al.* 1974, Regali & Gonzaga 1983
13. Rio Nazaré	Eastern Northeast	18	+	–
14. Uiraúna	Central Northeast	560	+	–
15. Souza	Central Northeast	770	+	–
16. Pombal	Central Northeast	60	+	–
17. Icó	Central Northeast	190	+	–
18. Lima Campos	Central Northeast	150	+	–
19. Cabeça de Negro/Malhada Vermelha	Central Northeast	48	+	–
20. Iguatu	Central Northeast	850	+	–
21. Rio Bastiões	Central Northeast	35	+	–
22. Lavras da Mangabeira	Central Northeast	25	+	–
23. Quitaús	Central Northeast	60	+	–
24. Iborepi	Central Northeast	4	+	–
25. Araripe	Central Northeast	7.200	+	Moraes 1976, Lima 1978a, 1978b, 1978c
26. Recife/João Pessoa	Eastern Northeast	3.000	+	–
27. Mirandiba	Central Northeast	400	+	–
28. Cabo	Eastern Northeast	700	+	–
29. Sergipe/Alagoas	Eastern Northeast	10.000	+	Müller 1966, Regali *et al.* 1974, Herngreen 1973, 1975
30. Jatobá	Central Northeast	6.200	+	–
31. Tucano	Eastern Northeast	28.800	+	–
32. Recôncavo	Eastern Northeast	12.000	+	Regali *et al.* 1974
33. Almada	East	200	+	Regali *et al.* 1974
34. Camamu	East	1.100	+	Regali *et al.* 1974
35. Jequitinhonha	East	15.000	+	Regali *et al.* 1974
36. Cumuruxatiba	East	10.000	+	Regali *et al.* 1974
37. Espírito Santo	East	50.000	+	Regali *et al.* 1974
38. Sanfranciscana	East	500.000	+	Lima, 1979, Chateauneuf *et al.* 1981
39. Campos	East	20.000	+	Regali *et al.* 1974
40. Santos	Southeast	120.000	+	Regali *et al.* 1974
41. Paraná	South-Southeast	1.600.000	+	–
42. Pelotas	South	50.000	+	–

* Area in Brazilian territory

HEXAPOROTRICOLPATE POLLEN GRAINS The hexaporotricolpate pollen grains (*Hexaporotricolpites* spp.) constitute a group characteristic of the Middle Cretaceous of Africa and South America that is surely related to the angiosperms. Nevertheless, doubts persist as to their family relationships. Boltenhagen (1979) suggests that they may have been early representatives of the Euphorbiaceae or Didymelaceae. Their highest abundance customarily occurs in marine rocks deposited under apparently humid tropical conditions, a fact that hints at a possible preference of the pollenbearing plant for coastal regions. Sporadic occurrences in inland areas have been noted however.

POLYPORATE POLLEN GRAINS These grains characterize the same chronologic interval as the hexaporotricolpate group, as well as the same regions, where they may be locally abundant. Possibly related to the Cariophyllaceae or Amaranthaceae, in spite of some doubts, the polyporate pollen grains show, nevertheless, a certain antagonism with respect to the hexaporotricolpate group (Boltenhagen, 1979, p. 66). This could mean small changes, impossible, at present, to evaluated, within the humid tropical conditions mentioned above.

POROTRICHOTOMOSULCATE POLLEN GRAINS This is a distinct group of pollen grains, characteristic of Africa and South America, and representative of Senonian sediments (*Victorisporis, Andreisporis, Constantinisporis*). Belsky & Boltenhagen (1963) suggest affinity of these grains (never confirmed) with the modern genus *Scleroderma* (Palmae). The paleoclimatic data for the group are quite uncertain, although an unquestionably hot climate, possibly in a coastal region, is inferred for these plants.

"NORMAPOLLES" These comprise another distinct group, very diversified (more than 60 Mesozoic genera), despite the group's great morphologic homogeneity. Indeed, they are all oblate, porate (chiefly triporate) pollen grains, characterized by high internal complexity of the openings, which frequently are protuberant. The affinities of the group are highly questionable, in spite of the affirmation of some authors, like Chateauneuf & Reyre (1974), who relate it to early Amentiferae or Myrtaceae. The normapolles chronologically characterize the Cenomanian-Eocene interval. Geographically, this group extended throughout Europe, including the Mediterranean region and the Soviet Union (east of the Ural Mountains), as well as over some parts of the United States and Canada. It defines a large microfloristic province in which the climate was roughly warm temperate, an interpretation still a bit controversial, given the large geographic extent of the group.

TRIPROJECTACITES This is a group of quite peculiar morphology, in that representatives possess projections bearing pores. It is abundant in Senonian associations from Asia, Europe and North America. The most important paleoclimatic conclusion regarding this group was drawn by Reyre (1979, p. 256), who states that this group must be interpreted paleoclimatically as subtropical to warm temperate, and not tropical. Thus, when present in the associations, these grains would be the most secure indicators of a climatic cooling of the region.

EVOLUTION OF BRAZILIAN CRETACEOUS POLYNOFLORAS

Purbeckian-Wealden (*sensu* Van Eysinga 1978) This interval is not recognized in Brazil in terms of the worldwide chronological scale. Representative sediments are identified through local chronostratigraphic units, corresponding, from base to top, to the Rio da Serra, Aratu, Buracica and Jiquiá Stages, plus the base of the Alagoas Stage. The palynologic associations are very constant and dominated by conifer pollen grains of the Cheirolepidiaceae (*Classopollis, Dicheiropollis, Circulina,* etc.). Frequently, pollen grains of other gymnosperms, chiefly of the Araucariaceae (*Araucariacites*) and representatives of the "Cycadales/Ginkgoales/Bennettitales complex", also occur. Pteridophyte spores, mainly of the Schizeaceae (*Cicatricosisporites, Appendicisporites*), Gleicheniaceae (*Gleicheniidites*) and Cyatheaceae or Dicksoniaceae (*Cyathidites*) families, also occur, as well as inaperturate pollen grains of uncertain relationships. Less abundant, in spite of frequently being present, are dissacate pollen grains (*Vitreisporites, Cedridites* (?), etc.). In the middle part of the section, these become more frequent and diversified, sometimes even being abundant. In the upper part, the polyplicate pollen grains (*Equisetosporites, Gnetaceaepollenites*) and the first forms attributed to the angiosperms (*Clavatipollenites*) appear.

These microfloras suggest an initially hot and wet climate, replaced by a short episode of cooler (possibly subtropical) conditions. In the last part of this interval, tropical, yet comparatively drier conditions return.

Aptian The chronostratigraphic equivalent of this interval is also recognized in Brazil as the upper part of the Alagoas Stage. From the base of the corresponding section upward, a greater abundance and diversity of polyplicate pollen grains is observed as opposed to the amount of spores, which gradually diminishes (with some important exceptions, including such swampy-plant spores, as *Crybelosporites, Perotrilites, Aequitriradites,* etc.). In the uppermost part, tricolpate pollen grains of angiosperms appear with relative (but low) frequency. Rimulate pollen grains (excluding *Dicheiropollis*) become increasingly abundant, chiefly in the levels that precede the first marine ingressions. In paleoclimatic terms, the general climate is still hot, but with less and less humidity, there being a gradual tendency toward more arid conditions as the Aptian draws to a close.

Albian For the first time in the Brazilian Cretaceous, the presence of marine fossils makes it possible to recognize a time interval of the international geological time scale. Floristic changes are significant, with the appearance of several remarkable groups (elaterate, polyporate, hexaporotricolpate pollen grains). The great abundance of rimulate pollen grains continues, as does the abundance and diversity of polyplicate pollen grains as well. Nevertheless, the distribution of these two groups, as well as that of the elaterate group, is not homogeneous. The region of greatest abundance seems to extend eastward from the Amazonas to the São Luís and Barreirinhas basins, and from there, southward across the Parnaíba basin through the continental interior as far as the State of Minas Gerais (Sanfranciscana basin, Chateauneuf *et al.,* 1981). All indications are that the opening of the South Atlantic favored the formation of a wetter climate, similar to the present one, in the coastal areas of the East and eastern-Northeast of Brazil, at least as far north as the coast of the State of Sergipe, while further inland aridity was higher. The pattern is also similar to the modern one for the northern coast from Ceará northward. For these regions, the data of Regali *et al.* (1974), Regali (1980) and Regali (1982) indicate assemblages reflecting xerophytic conditions rather than the wet littoral belt mentioned above. It is important to mention that in general terms the aridest part of the entire Cretaceous period occurs in the Late Albian.

Cenomanian This time interval is basically marked by the same groups present in the Albian, the only addition being the occurrence of triporate pollen grains, represented by the genus *Triorites.* There is no significant paleoclimatic modification with respect to the preceding interval.

Turonian The previously verified palynological conditions persist, with the exception of an appreciable reduction in the percentage of rimulate pollen grains *(Classopollis* and allied genera), as well as an increase in the amount of polyporate and hexaporotricolpates, here reaching their maximum abundance. Boltenhagen & Salard-Cheboldaeff (1979) state that similar conditions in Africa are suggestive of a general increase in humidity, yet with the permanence of high temperatures.

Early Senonian *(sensu* Van Eysinga 1978) A remarkable reduction in hexaporotricolpate and polyporate pollen grains is characteristic of the interval Coniacian-Santonian, together with the disappearance of elaterate forms. In contrast, several angiosperm groups notably among the Myrtaceae *(Syncolporites, Cupanieidites),* Proteaceae *(Proteacidites)* and Palmae *(Monocolpollenites)* families, become more important. Isolated porotrichotomosulcate forms *(Victorisporis)* occur. The climate seems to have been hot and probably humid (although this is based exclusively on information from coastal basins).

Late Senonian *(sensu* Van Eysinga 1978) Here, the angiosperms clearly dominate, although there are many spores from probably aquatic or swampy plants *(Ariadnaesporites, Zlivisporis).* The hexaporotricolpate and polyporate pollen grains disappear completely. Rimulate pollen grains also become extinct by the end of the Campainian. The Proteaceae, Myrtaceae and Palmae (all with new species that continue into the Tertiary) increase in importance. Representatives of the Ulmaceae family make their first appearance, as well as some rare specimens of the triprojectacites *(Aquilapollenites),* chiefly in the North. Diporate pollen grains are also represented. The climate seems homogeneous, although, as for the previous interval, all information comes from the coastal basins. Although warm conditions persist, the climate is humid and not excessively hot, there being indications that the end of the period marks the relatively coolest phase of the entire Cretaceous period.

CONCLUSIONS As shown above, much uncertainty envelopes the use of palynology for paleoclimatic purposes in the Brazilian Cretaceous. This observation, by the way, is valid pratically worldwide, since the period was relatively hot practically in the entire period (Barron 1983), and never cold. In addition to difficulties of a general character (taxonomy, paleoecology, chronology) are more specific ones, in this case represented by the heterogeneity in the level of knowledge concerning the microfloras, as evident from the published data. On the other hand, the reliability of the method is assured by the large quantity of forms generally present, which permit the utilization of a large number of families (or even genera) in paleoclimatic reconstructions. This makes it possible to sketch the principal regional climatic trends in a reasonable way, as follows:

During the Purbeckian-Wealdenian, the climate was initially uniformly hot and wet, including the inland regions. Next, there was a change to relatively cooler conditions for a short time. Finally, tropical conditions returned, but they were not as humid as before. Starting in the Aptian, a progressive aridization is evident in some places, notably in the northeast region. During the Albian-Turonian, this tendency became more accentuated (the climax seems to have been in the Late Albian) as the dry belt spread from the Amazon region at least to the State of Minas Gerais (palynological data is lacking south of this area). It should be noted that the recently formed, coastal regions of the East and eastern-Northeast of Brazil do not seem to have been affected by this excessive aridity, possibly due to the influence of nearby marine conditions. During the Early Senonian the climate continued warm in general terms, but the trend toward aridity seems to have diminished, as evidenced by more humid conditions. The same behavior continued into the Late Senonian. In the latter part of this interval, however, a general cooling (in a relative sense) can be observed, which represents the coldest episode of the entire Brazilian Cretaceous.

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