BRAZILIAN CRETACEOUS PALEOCLIMATES: EVIDENCE FROM CLAY-MINERALS, SEDIMENTARY STRUCTURES AND PALYNOMORPHS*

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ABSTRACT This paper deals with the paleoclimatic inferences on the Brazilian Cretaceous formations derived from the interpretation of sedimentary structures, clay-minerals and palynomorphs. Hot climates were predominant during the period. The palynomorphs suggest a rather cooling episode in Late Wealdian and Late Maestrichtian though not cooler than a subtropical climate. The clay-minerals and sedimentary structures of the Late Maestrichtian formations do not support an inference of a great deal of cooling in Late Maestrichtian times.

Humid climates were the rule during Wealdian. Dry climates are well documented in Late Aptian times and dry climates may have lasted till Cenomanian. The driest climates may have occurred in Late Albian according to the palynomorphs. Santonian to Maestrichtian witnessed predominant humid climates in coastal regions but rather drier climates inland.

RESUMO Este trabalho sintetiza as inferências paleoclimáticas obtidas das estruturas sedimentares, argilominerais e palinórmorfs das formações cretáceas brasileiras. Climas quentes predominaram durante os tempos cretáceos. Os palinórmorfs sugerem ligeiro resfriamento no Neo-Wealdiano e no Neo-Maestrichtiano; os climas contudo nunca teriam sido mais frios do que o subtropical. Os argilominerais e as estruturas sedimentares dos sedimentos neo-maestrichtianos não suportam, contudo, inferências de grande resfriamento nestes últimos tempos do Cretáceo.

Climas úmidos foram a regra durante o Wealdiano. Climas secos estão bem documentados no Neo-Aptiano e climas secos prevaleceram até o Cenomaniano. Os climas mais secos do período Cretáceo têm ocorrido no Neo-Albiano, de acordo com os palinórmorfs. No Santoniano-Maestrichtiano, climas úmidos teriam prevalecido nas regiões costeiras e climas mais secos teriam prevalecido no interior.

INTRODUCTION Brazilian Cretaceous deposits are well developed both in intracratonic and coastal basins, being thicker in the latter. They are closely related to the country's tectonic evolution. The so-called "basins" of the Brazilian Northeast are parts of an originally single basin, now only partly preserved in downfaulted blocks. The Recôncavo-Tucano-Jatobá basin is related to the coastal basins (Fig. 1).

The Sobral, Pernambuco and Patos lineaments as well as the Canastra and Asunción arcs are important for understanding the distribution of sediments (Fig. 1).

Four phases of sedimentation can be distinguished in the coastal basins: pre-rift, rift, proto-oceanic and oceanic phases. The Sergipe-Alagoas Basin, the most complete one for the Cretaceous record, may be picked up as a standard of reference. In this basin, the pre-rift and rift phases form a sequence in the sense of Sloss (1963), here referred by the letter A. The proto-oceanic phase (B) is characterized by evaporites, and evaporites are present in all the southern and eastern basins, from Santos to Sergipe-Alagoas except the Pelotas Basin. The oceanic phase (C) comprises three sequences in the Sergipe-Alagoas Basin. The age of these sequences in the southern and eastern basins are:

Sequence C₃ – Late Santonian-Eocene

Sequence C₂ – Late Cenomanian-Early Santonian

Sequence C₁ – Albian-Early Cenomanian

Sequence B – Late Aptian

Sequence A – Portlandian-Early Aptian

The northern coastal basins from Potiguar to Bragança-Viseu (Fig. 1) are characterized by an Albian-Cenomanian age for sequence A and by the absence of sequence B (evaporites). Aptian evaporites however are present in the Maranhão and Araripe basins.

The Cassiporé Basin, the northernmost coastal basin, also has an Albian-Cenomanian sequence A, and in the basin at the mouth of the Amazon sequence A, is younger (Campanian-Maestrichtian). Albian-Cenomanian deposits in this basin are present only in places close to the Cassiporé Basin.

Sequence A is especially well displayed in the Recôncavo Basin, where it is 6,500 m thick.

The Sobral Lineament and the Ilha de Santana Platform (Fig. 1) delimit a section where the sediments of the coastal basins exceptionally exhibit east-west folds believed to be Early Cretaceous to Albian in age. Folds are not present in other Cretaceous Brazilian basins. Rather, they are characterized by faulting.

PALEOCLIMATES From the correlation tables of the Brazilian Cretaceous (Fig. 2-4), it is evident that Late Aptian evaporites and chronologically equivalent sediments strikingly separate the older from the younger formations.

The pre-evaporitic deposits are non-marine. No marine Early Cretaceous sediments are known in Brazil, and so it is rather difficult to establish a precise correlation with the world-wide standard marine column. Thus, Brazilian geologists utilize a regional column based on ostracodes

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Figura 1 - Geographical distribution of the Brazilian Cretaceous Formations

and palynomorphs for the Early Cretaceous including the evaporite beds. The Brazilian stages and their possible international equivalents are as follow:

Brazilian stage	International stage
Alagoas	Late Aptian
Jiquiá	Late Barremian-Early Aptian
Buracica	Early Barremian
Aratu	Late Valanginian-Hauterivian
Rio da Serra	Early Valanginian
Dom João	Portlandian-Berriasian

The pre-evaporitic deposits are best developed in north-eastern Brazil from the Almada-Camamu Basin to the Sergipe-Alagoas Basin and are also present in the interior of the Northeast. They also occur in the following areas:

a) Acre Basin eventually extending into the upper Amazon Basin (Fig. 1). Here, the Dom João index ostracod *Bisulcocypis* is found reworked in Cenozoic beds. b) Parnaíba Basin in sediments associated with basic volcanic rocks. c) Southern Brazil where mainly basic volcanic rocks predominate, with thin sandstone and, more rarely, mudstone lenses.

The Aliança Formation of the Recôncavo Basin and equivalent beds in Sergipe-Alagoas and other basins are the oldest Cretaceous sediments, being Portlandian to Berriasian in age. They are made up of clastics with sedimentary structures suggestive of deposition in flood plains of meandering rivers. Mudstones and shales are interpreted as having been laid down in ponds and oxbow lakes. The rivers ran over an irregular topographic landscape with many Pre-cambrian and Paleozoic inselbergs. These Port-

Figure 2 – Correlation of the Cretaceous formations of Northern Brazil

landian to Berriasian sediments are primary red beds bespeaking derivation from the erosion of red, argillaceous lateritic soils. The flood plains and some lacustrine sediments were laid down under oxidizing conditions. There were however larger lakes deep enough to permit the development of reducing conditions where green shales and limestones beds were formed. Scarce, thin, reddish sandstone beds are present but become more frequent at the top of the Berriasian record, suggesting denudation of the regoliths and erosion of source rocks. This evidence points to a warm humid climate in the source area, an interpretation reinforced by palynological evidence. Chronologically equivalent beds are present in the Tucano, Jatobá, and Sergipe-Alagoas basins and as far into the Northeastern interior as Araripe. Outside this area no Portlandian-Berriasian beds are known except in the Acre Basin (Juruá-Mirim beds) and perhaps in the upper Amazon Basin. Evaporites (anhydrite and halite) are present in the Juruá-Mirim Basin, so its climate was dry. However, its age is not well established as no fossils have yet been recovered from it. The assumed age is based on possible correlations with Peruvian Pastanza Basin sediments.

The Sergi Formation in the Recôncavo and equivalent beds in Sergipe-Alagoas and other basins is Berriasian to Early Valanginian in age (Rio da Serra). The trend for the denudation of sources areas, as deduced from the older Dom João Beds, increased during Rio da Serra times, resulting in predominant reddish sandstones with some red argillaceous beds in their basal part. Cross-bedded conglomerates with tree trunks as long as 22 m oriented down-slope along the foresets suggest torrential currents. The red hues are restricted to the sandstone matrix. The fluvial sedimentary environment then changed from meandering to braided. The richness of tree trunks suggest heavily vegetated areas, at least along the valleys. The climate would have been rather dry with heavy, concentrated rains. Wet climates however would have prevailed in the Northeast interior as judged by the lithologies and fossils (including dinosaurs) found in their sedimentary "basins". The shales and sandstones of the Rio do Peixe "basin" with their hydrodynamic sedimentary structures suggest meandering flood plains that evolved to lakes which gradually filled up to form flood plains once again. The rhythmic sandstones and marls passing

Figure 3 – Correlations of the Cretaceous formations of Northeastern Brazil

laterally to sandstones suggest a long lasting lake passing laterally to flood plains. The Lima Campos marls with reptiles and fish suggest a lacustrine environment.

The depositional environments of Barremian sediments of the Potiguar Basin are also interpreted as lacustrine passing laterally to fluvial.

The alternating sandstones and reddish shales as well as the types of cross-beds present in the Pastos Bons-Corda Formation of the Parnaíba Basin suggest meandering channels and flood plain environments. Limey and dark betuminous shales suggest lakes deep enough to develop reducing conditions. Hot and humid climates (with dry seasons) are the most probable environment.

The thin fine-sandstone lenses interbedded with the basaltic rocks of the Serra Geral Formation, widespread in the Paraná Basin of Southern Brazil, are made up of well-sorted sands with well-rounded, pitted grains bespeaking an eolian origin. However they are not necessarily indicative of dry climates as the basaltic landscape apparently was devoid of vegetation and thus naturally subject to a good of wind action. Moreover, the source rocks were

mostly the desertic Triassic Botucatu Sandstone. Small cavities in the basaltic rocks are filled up with argillaceous deposits which may have originated in small ponds of rain water.

Humid climates lasted in the Northeast up to at least the Early Barremian as shown by evidence of broad persistent lakes as in the Recôncavo Basin which accumulated over 3,000 m of mainly argillaceous sediments. As betuminous shales are common, these lakes were evidently deep enough for reducing conditions to develop. Limestone also formed. Gradually, these lakes were filled by sediments brought in by braided deltas. The end of the cycle resulted in braided flood plains in the Early Aptian. A similar evolution of lakes is observed in the Sergipe-Alagoas Basin. Lacustrine deposits were also developed in Valanginian-Barremian times in the Potiguar Basin.

Barremian times, as dated palynologically, witnessed a humid climate. However a trend to drier climates would have already begun in the Barremian and earliest Aptian. The Espírito Santo, Campos and Santos pre-evaporitic deposits are mineralogically and texturally immature,

Figure 4 - Correlations of the Cretaceous formations of Central and Southern Brazil

which could be related either to dry climate or to active fault tectonism or to both. Locally in the southern part of the inland basin of São Francisco, rhythmic lacustrine limestone beds were laid down, forming part of the earlier beds of the Areado Formation, attesting to a short period of humid climate. Fish, arthropods and plants are common in these beds. However, a conglomeratic facies, present at the base of the Areado Formation, below the lacustrine facies, and representing filled paleochannels, includes ventifacts. Thus, it could record a desert paleoclimate. The main portion of the Areado Formation is sandstone with conspicuous and rather large (up to 2 m long) cross-beds, mostly tangential at their bases. These sandstones and the fan-deposits with partially weathered volcanic rock fragments are suggestive of a dry desertic paleoclimate.

The approximately synchronous Caiuá Formation of the Paraná Basin bears several indications of dry climates: a) there is a basal polymictic conglomerate which looks like a paleopavement; b) its sediments are mineralogically

and texturally immature; c) sandstones are present which have large cross-beds, tangential at their bases, and individual beds of well-sorted and rounded grains, although, on the whole, these sandstones are poorly sorted. The cross-beds are intercalated within massive immature sandstone banks. The southern Caiuá, cropping out in the State of Paraná, exhibits sandstones with large scale cross-beds intercalated with horizontal beds. The cross-bedded sandstones may represent dune deposits and the horizontal beds may be deposits generated in short-lived ponds developed between the dunes. The paleowinds came mainly from the southwest. According to Suarez (1975, 1976) the same would be true for winds in southwestern São Paulo. The prevailing climate during Caiuá deposition would have been arid to semi-arid. Short-lived fluctuations of wetter conditions produced some paleosol horizons within the dune sands (Popp & Bigarella, 1975).

The Areado and Caiuá formations are partially syn-

chronous with the Late Aptian evaporites of the coastal and northeastern basins. No evaporites are present in the Recôncavo, Tucano, Jatobá, Mirandiba and Almada-Camamu basins of the Northeast. Instead, the Marizal Formation was developed there. It is characterized by polymictic conglomerates and immature, poorly sorted sandstones, often with cross-beds and cut-and-fill structures. Its great irregular variability of thickness resulted from the differential uplift of local sources on rising fault blocks. Mud flows near the slopes and laminar currents far from the slopes transported the sediments. Though no evaporites are known, the climate is believed to have been arid with internal drainage on the basis of geographical proximity to the evaporite and the lithological characteristics of the formation.

The lithology of the synchronous deposits in the southern Recôncavo Basin and in the Almada-Camamu Basin is not the same. Well laminated dark shales, rich in organic matter and with non-marine fossils (pollen, ostracods and fish), interfinger with conglomeratic arkosic sandstones. The environment was lagoonal, with reducing conditions prevailing at its bottom. High energy streams brought the conglomeratic arkosic sands to the lagoons. The lagoons were fed by the sea, and the climate apparently was semi-arid.

The clay mineral smectite is common in the red beds of Late Aptian non-marine sediments of the Potiguar Basin which were laid down in braided rivers with predominantly coarse clastics and subordinate argillaceous beds. The climate was arid or semi-arid both in the source area and at the site of deposition. Long, dry episodes and short, wet episodes were responsible for the fixation of oxides and hydroxides (Ramos 1980).

Outcrops of Aptian argillaceous beds on the western border of the Parnaíba Basin (Marabá, State of Pará) contain palynomorphs typical of xerophytic plants, thus attesting to widespread dry climates in Aptian times (Lima *et al.* 1980).

The widespread Late Aptian evaporites are the most striking evidence of dry climates in Brazil. The evidence for dry climates is seen even in the beds just below the evaporites, such as in the Sergipe-Alagoas Basin, where polymictic conglomerates (Carmópolis Member of the Muribeca Formation) were generated during several cycles of deposition, prograding over lagoons under semi-arid conditions. The cycles started with conglomerates, grading to shales, and ending with evaporites. Above this evaporite cycle come bituminous shales, limestones and sandstones. The limestones bear stromatolitic structures, and laminated, mud-cracked calcilutites with beds of evaporites are present. The environment is interpreted as sabkha plains. The synchronous deposits of the coastal basins from Almada-Camamu to Santos are interpreted as lagoons passing upwards to restricted seas where evaporites were formed. Highly soluble salts such as tachydrate, bischofite and carnallite formed in the Sergipe-Alagoas and Santos basins, attesting to high salinities. Evaporites also are present in the Parnaíba (Codó Formation) and Araripe (Santana Formation) basins.

It seems that dry climates lasted till Albian and Cenomanian times. Coral reefs are present in the Albian of the Sergipe-Alagoas Basin, which indicate detrital contributions from the continent. The first Albian-Cenomanian sediments on the continental side of the Potiguar Basin were laid down in a fluvial braided-channel environment (Castro *et al.* 1982). Coral reefs also developed on the ocean side, thereby isolating internal lagoons (Tibana & Terra 1981). Synepigenetic dolomites with birdseye structures, stromatolites, mud-cracks, and some anhydrite lenses in the Cenomanian of the Potiguar Basin were interpreted by Carozzi *et al.* (1973) as forming under semi-arid supratidal conditions. The Albian to Cenomanian non-marine sediments of the Barra Nova Formation of the Espírito Santo Basin are similar to the Aptian clastics (Mossman & Pereira, 1972). The depositional landscape was non-marine, braided channels. The reddish hues point to an oxidizing subaerial environment. The Campos Basin in Albian-Cenomanian times probably witnessed the evolution from a hot and dry climate to a hot and humid one with corresponding modifications in the pattern of water circulation. According to Dias-Brito (1982), the lower Albian-Cenomanian formation of this basin bears foraminifera and radiolaria characteristic of shallow waters. Oncolitic calcarenites point to warm water temperatures. The salinity was probably high in view of the poorness of the benthonic fauna. Supratidal to high intertidal calcilutites and dolomitic calcilutites contain local evaporite deposits (halite and anhydrite). Early dolomitization occurred in this supratidal zone associated with a sabkha environment (Falkenheim *et al.* 1981). The pattern of water circulation would have made it difficult for oceanic water to enter some of the restricted basins, thereby allowing the development of an anoxic environment and deposition of highly organic, dark, pyritic sediments. Later, in Cenomanian times the basin lost its anoxic conditions.

Dry climates prevailed in the continental interior in Albian-Cenomanian times. Sandstones are the main lithology of the Parecis Formation (Fig. 1). Several discontinuous conglomeratic beds bear cobbles up to 20 cm long, commonly filling cut-and-fill structures. Poorly sorted siltstones and thin sandstone lenses also occur within the main sandstone body. Northward there are poorly sorted basal argillaceous beds with a great number of chaotically dispersed gneiss pebbles, cobbles and even boulders (Petri & Fulfaro 1981). These structures suggest braided channels fed by laminar currents and mud flows in hot, semi-arid climates. The Santo Anastácio Formation of the Paraná Basin exhibits pebble and cobble conglomerates presumably representing torrential deposits reworked by stream currents. Massive deposits in this formation could be a result of mass movements, and thus may suggest a semi-arid climate.

Lithologic evidence suggests, therefore, that dry climates prevailed from Late Aptian to Cenomanian time. Palynological studies support this interpretation. According to Lima (1983), the harshest dry climates would have occurred in the Late Albian. The pollen content of the

Cenomanian sediments recovered from the mouth of the Amazon Basin to the São Francisco Basin in the State of Minas Gerais are exclusively indicative of xerophytic plants.

No information on paleoclimates is yet available for Late Cretaceous sediments of the Acre Basin and the basin at the mouth of the Amazon. The Bom Gosto and Humberto de Campos Formation of the Barreirinhas Basin are made up of marine sediments passing gradually westward to red beds, suggesting that in post-Cenomanian times the main source regions were subjected to climates characterized by rainy and dry seasons. The coastal basins of the Late Cretaceous were developed under transgressive conditions and therefore offer scarce indications of paleoclimates. The lowermost beds of the Santonian Beberibe Formation of the Recife-João Pessoa Basin are fluvial argillaceous beds probably laid down in flood plains of anastomosing river. Coastal sediments laid down in a reduced salinity environment, as judged from the fossil content, constitute the upper beds of this formation.

One of the lithologic facies of the Campanian-Maestrichtian of the Sergipe-Alagoas Basin was formed as clastic deltaic lobes prograding on to continental shelf limestones. The long axis of the largest and thickest (800 m) deltaic lobe is colinear with the imaginary extension of the channel of the São Francisco river seaward of this mouth. Similarly, two other deltaic lobes also have their long axes colinear with those of the imaginary extensions of two other large rivers (the Sergipe and the Vaza Barris rivers). Two others are approximately colinear with two minor rivers. This situation seem to indicate that by the Late Cretaceous the present drainage pattern was already established and that a humid climate prevailed similar to that now present along the Sergipe-Alagoas coast. Similar deltaic lobes occur in the Jequitinhonha and Espírito Santo basins. The predominant prograding (offlap) pattern of sedimentation in these coastal basins suggests humid climates on the continent. Subordinate regressive (onlap) patterns coincide with the active erosion of submarine canyons, which would seem to indicate cycles of drier climates, so far impossible to date precisely.

Red beds began to form on the continental side of the Campos Basin during Late Cretaceous, although the Tertiary red beds are more important, bespeaking alternating hot, rainy and dry seasons on the continent. The Carapebus submarine cone developed in the Campos Basin during the Late Cenomanian to Maestrichtian suggesting the presence of great rivers along the coast and therefore a humid climate for most of Late Cretaceous time.

The sediments of the Bauru Group of the Paraná Basin bear evidence of climatic fluctuations. The dry climates inferred for the Caiuá and Santo Anastácio formations have already been mentioned. The Coniacian to Campanian Adamantina Formation exhibits converging evidence of humid climates passing later to alternating humid and dry climates. The evidence for humid climates is: a) small-scale, subaquatic cross-beds; b) abundance of fossils (dinosaurs, crocodilians, fish, molluscs, conifers, and char-

ophytes); and c) detrital kaolinite which would have come from source rocks weathered under hot humid climates. In the central eastern part of the Bauru basin, State of São Paulo, authigenic kaolinite apparently derived from the weathering of feldspars, and authigenic smectites, which presumably formed under semi-arid conditions, gradually replace the detrital kaolinite of the lower beds of the Adamantina Formation. Limey sandstones and nodular arenaceous limestones bearing the clay mineral paligorskite occur sporadically near the base of the formation, then gradually increase in frequency, and predominate at the top. This successive replacement of clay mineral types is interpreted as indicating the gradual establishment of drier climates from Coniacian to Campanian time.

Nodular limestones, which may be interpreted as calcretes, as well as the clay mineral paligorskite are more abundant in the Maestrichtian Marília Formation. A warm and dry (semi-arid) paleoclimate is thus inferred as prevailing in the Paraná Basin during Maestrichtian times. This interpretation for the Marília Formation is further favored by the following evidence: a) pebble and cobble deposits formed by torrential currents that reworked stream deposits and were later cemented to form a conglomeratic, hardpan-type detrital pavement; b) cross-bedded rudaceous sediments laid down as alluvial fan deposits; c) textural and mineralogical immaturity of the sediments; d) scarcity of hydrodynamic sedimentary structures which suggests mass movements as the predominant sedimentary mechanism; e) presence of charophytes, suggesting alkaline waters, which are more common in semi-arid environment.

CONCLUSIONS In synthesis the evidence points to prevailing warm climates during the Brazilian Cretaceous with fluctuations occurring mostly with respect to the available amount of humidity. Humid climates were the rule for Berriasian to Barremian times, at least in the eastern coastal basins. This was not the case for the inland São Francisco Basin, which had only minor fluctuation in humidity. The dry climate present during deposition of the Juruá-Mirim Formation (Acre Basin) should not be taken into consideration due to doubts as to its age. Dry climates were evident during Late Aptian not only in the eastern and southern coastal basins, where evaporites were formed, but also in inland basins as shown by their sediments and sedimentary structures. Palynological evidence not only reinforces this interpretation but extends the dry climates till Cenomanian time. Indeed, the Late Albian, according to its palynomorphs, would be even drier than the Aptian. Some fluctuations, of course, would be expected in such a long period of time (Late Aptian to Cenomanian). The humid climates returned after the Cenomanian, at least in the coastal regions. Beginning in the Cenomanian, the climate in the Paraná Basin became wetter with some dry episodes but returned to a semi-arid condition in the Maestrichtian with minor, undatable wet periods.

Palynological evidence suggests tropical to subtropical climates during the Cretaceous and a cooling toward the end of the period. A great deal of cooling is not supported by lithological evidence, however, as Maestrichtian-Cenozoic limestones are frequent not only in coastal basins from Santos to Barreirinhas but also inland, where they are abundant, as, for instance, in the Marília Formation of the Paraná Basin.

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