THE MACAÉ FORMATION, CAMPOS BASIN, BRAZIL: ITS EVOLUTION IN THE CONTEXT OF THE INITIAL HISTORY OF THE SOUTH ATLANTIC

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ABSTRACT The Macaé Formation (Albian-Lower Turonian, Campos Basin) is very significant for understanding the early history of the South Atlantic north of the Walvis Ridge/São Paulo Plateau system. Deposition of the unit immediately succeeded the Aptian evaporitic event, and preceded the oceanic phase that began in post-Early Turonian times. This is probably the best known Middle Cretaceous carbonate record in the South Atlantic. It consists of the Lower Macaé (Early to Middle Albian), formed dominantly by limestones deposited mostly in shallow neritic environment, and the Upper Macaé (Late Albian-Early Turonian) with calcilutites overlain by marls and shales, deposited during progressive sea level rise. A tidal flat system was developed in the southern portion of the basin during deposition of the lowermost Macaé Formation, with supratidal, intertidal, and lagoonal environments. Burrowed carbonate mudstones were deposited in shallow shelf environments, and ooids and peloids in a high energy offshore shoal system. Hypersalinity prevailed during that time, as suggested by the low biotic diversity and the carbon isotope values. Very negative oxygen isotope values indicate that surface water temperatures were high. Oncolite limestones and subordinate calcilutites prevail in the middle and upper parts of the Lower Macaé, chiefly deposited in shallow neritic environment. Hypersalinity and high water temperature persisted, as indicated by paleoecological and isotopic studies. The Macaé sea was then a juvenile ecosystem, unstable and poor in nutrients, with maximum depth values around 50 m. The Upper Macaé carbonate mudstones, Late Albian in age, are rich in calcispherulids. Its abundant pelagic biota probably reflects desalinization and increase in nutrients of surface waters related to the South Atlantic expansion and consequent increase in water volume and circulation. The benthic foraminifera are suggestive of deep neritic environments (100-200 m). "At the end of the latest Albian, a rhythmic deposition of calcilutites and marls was probably caused by climatic variations (dry/warm to warm/wet climate cycles). From the Cenomanian to the Turonian, already under a warm/wet climate, were deposited the fine-grained siliciclastics, mostly in upper bathyal environment; episodic anoxic conditions are represented by laminated black shales, frequently rich in radiolaria, and with a relatively high organic carbon content".

RESUMO A FORMAÇÃO MACAÉ, BACIA DE CAMPOS, BRASIL: SUA EVOLUÇÃO NO CONTEXTO DA HISTÓRIA INICIAL DO ATLÂNTICO SUL. A Formação Macaé (Albiano-Eoturoniano, Bacia de Campos) é muito significativa para o entendimento da história inicial do Atlântico Sul ao norte do sistema Walvis Ridge-Platô de São Paulo. Sua deposição sucedeu imediatamente ao evento evaporítico aptiano e precedeu a fase oceânica, que começou em tempos pós-eoturonianos. Ela é, provavelmente, o registro carbonático mesocretácico mais bem conhecido em todo o Atlântico Sul. É composta pelo Macaé Inferior (Eo- a Mesoalbiano), constituído predominantemente de calcários, depositados sobretudo em meio nerfítico raso, e pelo Macaé Superior (Neoalbiano-Eoturoniano), com calcilutitos sobrepostos por margas e folhelhos, acumulados em resposta a eventos transgressivos. Durante a deposição da parte mais inferior da Formação Macaé, um sistema de planícies de maré se desenvolveu a sul da bacia, com ambientes de supramaré, intermaré e lagunas. Calcilutitos bioturbados preencheram áreas calmas de ambiente nerfítico raso enquanto oóides e pelóides se acumularam em sistemas de bancos de alta energia desenvolvidos em áreas distais. A baixa diversidade biótica e os valores de isótopos de carbono sugerem que, naquele tempo, o corpo marinho era hipersalino. Valores muito negativos de isótopos de oxigênio indicam que as temperaturas das águas superficiais eram altas. Calcários oncolíticos, sobretudo, e calcilutitos predominam nas partes média e superior do Macaé Inferior, tendo sido depositados em ambiente nerfítico raso. O corpo d'água continuava hipersalino e quente, como sugerem os estudos paleoecológicos e isotópicos. O Mar Macaé era então um ecossistema juvenil, instável e pobre em nutrientes, com profundidades máximas em torno de 50 m. As rochas carbonáticas do Macaé Superior consistem em calcilutitos ricos em calcisferulídeos. Sua abundante biota pelágica provavelmente reflete a dessalinização e o incremento de nutrientes nas águas superficiais do corpo marinho resultantes de importante expansão do Atlântico Sul ocorrida no Neoalbiano. Uma melhor circulação de águas passou a ocorrer na bacia, cuja batimetria média oscilava entre 100 e 200 m. "Ao final do Albiano terminal ocorreu uma deposição rítmica de calcilutitos e margas, causada, provavelmente, por variações climáticas alternantes (ciclos quente/seco e quente/úmido). A partir do Cenomaniano, já sob clima quente e úmido, foram acumulados sedimentos siliciclásticos finos, em ambientes batial superior (200-500 m); condições episódicas de anoxia ocorreram neste intervalo de tempo, o que é atestado pela presença de folhelhos negros, laminados, não bioturbados, frequentemente ricos em radiolários, e relativamente ricos em carbono orgânico".

INTRODUCTION The Albian carbonate sequences of the eastern Brazilian margin contain the first typical records of the South Atlantic Ocean. Among all these carbonate sequences, the Macaé Formation of the Campos Basin is the one that presents of greatest number of data, recovered from more than 300 wells, which provide valuable information for the understanding of the South Atlantic evolution. The Macaé Formation is economically important, as it produces

hydrocarbons from structural-stratigraphic traps in six oil fields.

The main purpose of this work is to characterize the depositional history of the Macaé Formation in order to contribute to the global understanding of the initial context of the South Atlantic. The investigation was based on sedimentological, biostratigraphic, paleoecological, and geochemical data. The results summarizes the effort of many

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people in Petrobrás since the beginning of exploration in the Campos Basin.

Previous detailed facies analysis of the Macaé carbonates have been documented by several authors, following the pioneer discovery of Garoupa Field in 1974, the first oil field in the Campos Basin. Tessari & Tibana (1975) defined the general facies framework, establishing a generic depositional evolution. Carozzi *et al.* (1977) defined a diagenetic-depositional model for the Macaé Formation. Falkenhein (1981) concentrated on the general tecto-sedimentary setting, the identification of microfacies and environmental interpretation. Beltrami (1982), using wells and seismic data, established a regional distribution of the carbonate high energy facies along NE-SW structural trend. The siliciclastic section was studied by Guardado *et al.* (1983). Esteves *et al.* (1987) proposed a general sedimentary evolution model for the Lower Macaé. Guardado & Spadini (1987) established a depositional model relating previous rift structures and salt tectonics with the facies distribution. Detailed reservoir studies were performed by several authors (Franke 1981, Baumgarten *et al.* 1982, Spadini & Paumer 1983, Baumgarten *et al.* 1984, Paumer 1984, Scuta 1984, Franz 1987).

Strong efforts in the biostratigraphic research have been made in the Campos Basin since the first oil discovery in the Macaé carbonate reservoirs (Gomide 1976, Uesugui 1976, Dias-Brito 1982, Gomide 1982, Dias-Brito 1985a, Moura & Praça 1985, Azevedo *et al.* 1987a, Shimabukuro *et al.* 1985, Richter 1985, 1987, Shimabukuro 1988, Moura 1988, Antunes 1988). Gomide (1982), based on calcareous nanoplankton, defined an Albian/Cenomanian age for the entire Macaé sequence, recognizing only one biozone (*Nannoconus truiti*). Uesugui (*op. cit.*), based on palynomorphs, established a sequence of three informal biounits: the *alfa* interval defined as probably Early Albian in age; the *beta* interval defined as Middle Albian in age; and the *gamma* interval as Late Albian/Cenomanian in age. Dias-Brito (1985a), studying calcispherulids of the fine-grained limestones, defined two informal biozones: the *Pythonella sphaerica* and the *Pythonella sphaerica/Pythonella ovalis/Bonetocardiella conoidea* zones. Dias-Brito compared the distribution of the calcispherulids in the Campos Basin and those of the Leg 40, site 363, located in the Angola Basin (Bolli 1978), and considered the *alfa* zone as Early to Middle Albian in age, and the *beta* zone as Late Albian. In a recent paper where the biostratigraphy of the basin is summarized, Azevedo *et al.* (*op. cit.*), using planktonic foraminifera, calcareous nannofossils and palynomorphs, considered the *gamma* interval as Late Cenomanian to Early Turonian in age.

A series of paleoecological interpretations of the Macaé carbonates has been made in this decade. The first paleoecological work was performed by Dias-Brito (1982), studying microfossils in thin-section. Following this work, new contributions were given by several authors (Koutsoukos 1984, Dias-Brito & Azevedo 1986, Azevedo *et al.* 1987b, Dias-Brito 1987, Koutsoukos 1987, Viviers & Azevedo, 1988). Environmental interpretations based on carbon and oxygen isotope studies was made by Takaki & Rodrigues (1984).

STRATIGRAPHIC AND STRUCTURAL FRAMEWORK

The Campos Basin (Fig. 1) is a typical continental margin basin of the Atlantic type. The basin has a minor emergent area, and extends offshore to water depths greater than 3,000 m, covering an area of 100,000 km². The Campos Basin was originated during the breaking of the Gondwana supercontinent. The initial rifting occurred during the Rio da Serra Stage, a Brazilian local unit of the Lower Cretaceous (Asmus 1975, Asmus & Porto 1980).

The stratigraphy of the Campos Basin was first established

Figure 1 – Location map of the Campos Basin

by Schaller (1973). It comprises alluvial-lacustrine sediments of the rift phase, the evaporites of the transitional phase, and carbonates and siliciclastics of the pre-oceanic and oceanic phases (Fig. 2). The Macaé Formation, Albian to Early Turonian in age, characterizes the deposition during the pre-oceanic phase (Fig. 3), overlying the evaporites of the Lagoa Feia Formation. The relationship between the biostratigraphic and lithostratigraphic units of the Macaé Formation is showed in the figure 4.

The Macaé Formation is informally divided into Lower and Upper Macaé (Fig. 5). The former, Lower/Middle Albian, was deposited mostly in shallow neritic environment. The lowermost section of the Lower Macaé is characterized by dolomites, overlying in sharp contact the Lagoa Feia nodular anhydrite. The Upper Macaé, Late Albian to Early Turonian in age, is composed of calcilutites and marls, deposited as a result of a transgression over the former shallow platform.

The Macaé Formation is wedge-shaped, pinching out westward against the fault that limits the Lower Cretaceous basin (Fig. 6). During all the Macaé time, siliciclastic facies occur on the coastal portions of the basin.

Two principal structural elements are present in the Campos Basin: the high-angle normal faults of the rift phase, and the adiasporphic structures, mostly normal listric faults, that affected the post-salt sediments. The rift phase is represented by horsts and grabens involving both basement and pre-salt sediments. The adiasporphic structures were formed due to basin tilting and differential compaction (Figueiredo *et al.* 1983). Salt movement resulted in the formation of pillows which controlled the distribution of Albian shallow water carbonate facies and the thickness of the lowermost section of the Lower Macaé. With the continuing evolution of the salt structure, syndepositional listric faults were generated, developing structures of rollover type (Figueiredo *et al. op. cit.*), that caused abrupt lateral facies changes at the top of the Lower Macaé.

THE LOWER MACAÉ SEDIMENTATION AND PALEOECOLOGY

The Lower Macaé sequence is composed of two distinct sections: the basal one, just above the evaporites, is characterized by strong dolomitization; the upper one, corresponding approximately to the middle and

Figure 2 – Stratigraphy of the Campos Basin (after Petrobrás/Depex/Secamp/Sebipec) and related depositional sequences (modified from Dias-Brito & Azevedo 1986)

upper portions of the sequence, is characterized by the predominance of algal grains (oncolites). Each section can be related to a particular depositional model.

The basal section The change of environmental conditions from the previous evaporitic setting led to the installation of the Macaé carbonate system. A series of environments occur within a carbonate ramp (Fig. 7).

A tidal flat system developed in the southern portion of the basin. This system includes the supratidal, intertidal, and lagoonal environments as defined by Shinn (1983), exhibiting typical facies assemblages and vertical sequences (Fig. 8). The intertidal/supratidal belt is characterized by laminated mudstones, probably of algal origin (Plate 1b). Teepee structures and mudcracks are indicative of subaerial exposure (Plate 1a). Brecciation associated with collapse is a common

feature, usually showing calcite drusy cement. The fossil content is very poor, mostly ostracods and rare miliolids. Thin beds of oolite grainstones probably records deposition by storms. Periods of siliciclastic influx are represented by ripple-laminated, fine-grained arkosic sandstones.

The lagoonal environment that occurs associated with the tidal flat belt is represented by bioturbated pelletoidal mudstones, with a poor biotic content, including miliolids, agglutinated foraminifera, pelecypods and ostracods (Plate 2a and 2b). The occurrence of restricted lagoonal facies suggests the presence of a barrier seaward of the subtidal lagoonal sediments, probably barrier islands, associated with tidal deltas, composed by oolite grainstones, analogous to the modern Trucial Coast, Persian Gulf (Loreau & Purser 1973).

Open shallow shelf environment is represented by bioturbated pelletoidal mudstones with echinoderms, small

Plate 1 – Tidal flat Macaé facies, deposited just above the Lagoa Feia evaporites: a. teepee structures, characterizing subaerial exposure; b. algal lamination in carbonate mudstones. Brecciation and collapse developed locally

foraminifera and agglutinated foraminifera (Plate 2c). Graded dolograins (Plate 2d) occur interbedded with the mudstones.

Table 1 – Characteristics of the carbonate sedimentation, based on core analysis. Section just above the Lagoa Feia evaporites

Depositional Environment	Tidal flat	Lagoonal	Shallow neritic
Facies	Mudstones	Pelletoidal mudstones	Pelletoidal mudstones dolograins
Structures	Algal laminations Mud cracks Teepees	Bioturbation	Bioturbation
Biota	Ostracods Miliolids	Miliolids Agglutinated foram. pelecypods	Enchinoderms Rotalids Ostracods Pelecypods

The deeper areas of the basin were the site of deposition of carbonate mudstones, with a poor biotic content, mostly planktonic foraminifera, calcispherulids and echinoderm fragments. These mudstones are interbedded with marls and shales.

In the southern offshore portion of the basin, related to structural highs, were deposited facies composed by ooids and peloids, in a high energy shoal system. These facies were almost completely dolomitized, difficulting the recognition of the depositional texture.

In the northern portion of the basin, the marine carbonates grade westward to siliciclastic facies, mostly fan-delta sandstones and conglomerates and shelf sandstones (Guardado *et al.* 1983). Interbedded carbonate banks are composed by ooids, pelecypods, and rare red algae. Mixed facies were formed in response to storm and tidal processes (Fig. 9).

The general depositional model of the Lower Macaé correlates with a carbonate, ramp, mostly in shallow neritic environment (Fig. 7).

The scarcity of biotic content is indicative that restrictive conditions prevailed during the deposition of this sequence, probably related to physical and chemical properties. This is true even for the environments out of the embayments and lagoons. The light color, of shallow neritic carbonates, associated with common bioturbation indicates that hypersalinity was the restrictive factor of the environment. The carbon isotope values between 3,0 and 4,0‰ PDB standard (Fig. 10) are higher than that of a normal marine water and are also indicative of hypersalinity. The presence of evaporites just below the sequence also led to this interpretation. High water surface temperature is suggested by the oxygen isotope values around 5,0‰ PDB standard and by the predominance of oolitic and peloidal grains, which nowadays are observed only in tropical settings (Leonard *et al.* 1981).

The upper section The lithofacies of this part of the Lower Macaé were deposited on a carbonate ramp, in three depositional environments (Fig. 11): a. *high energy shoal* system, enveloped in the southern positive areas and in the NE shallow banks trend; b. *shelf environment* used here as defined by Wilson (1975) as an area on top of a ramp or platform, including a shallow portion adjacent to the shallow bank (few tens of meters) and the deeper offshore areas, implying in tens of meters, even a hundred meters deep; c. *basinal environment* corresponding to the deep-water areas, synonymous with "outermost ramp" (Budd & Loucks 1981). Each one of the environment is characterized by distinct facies assemblages and vertical sequences. Siliciclastic rocks

occurred at the onshore portions along the entire basin interfingering with shallow water carbonates.

The shoal system is composed by a series of facies formed by oncolites, peloids, and ooids, with rare bioclasts. The variety of depositional texture and composition reflects more directly the difference in the water agitation than water depth. Usually, the facies are arranged in a series of shallowing-upward cycles, beginning with peloidal packstones and ending with oolite grainstones.

The oolite grainstones are usually coarse-grained, sometimes crossbedded (Plate 3a), indicating deposition in a mobile sand shoal. Small ooids and composite grains are accessories. Where only ooids are present the facies is structureless. A facies composed by ooids and peloids commonly occurs associated with the oolite grainstones, usually showing parallel laminae. Commonly the growth laminae of the ooids were destroyed by micritization (Spadini & Faria 1986). Fossils are rare in the oolitic facies, including echinoderm fragments and pelecypods. Submarine hardgrounds, with a few centimeters in thickness, occur only locally. The oolitic facies corresponds to the highest depositional energy of the shoal system.

The oncolites display several sizes and shapes. They form three principal depositional facies, reflecting different water agitation. Peloids are the most common oncolite nuclei. Among the bioclastic nuclei, pelecypods and echinoderms are the most common constituents. Structureless *oncolite grainstone* facies (Plate 3b) are formed by regular concentric oncolite grains, usually 2-3 mm in diameter. Peloids, composite grains, and ooids are also present. Bioclasts are rare (1-2%), including agglutinate foraminifera, textulariids, miliolids, mollusks and echinoderms. *Peloidal/oncolite grainstones* are normally associated with the oncolite grainstones; this facies is massive, sometimes burrowed, locally with parallel or inclined laminae. The *oncolite packstones* are composed by oncolites 2-5 mm in diameter (Plate 3c), many of them displaying irregular growth bands. Oncolites up to 1 cm occur locally. This facies is massive to burrowed and shows a variable percentage of peloids and microoncolites. Bioclasts are rare, including textulariids, gastropods, pelecypods, echinoderms, miliolids, and hyaline foraminifera.

The peloidal grainstones are commonly burrowed, with a low percentage of ooids and oncolites. Bioclasts (up to 5%) include mostly echinoderm fragments, some textulariids, and miliolids, and very rare planktonic foraminifera. Peloidal packstones have a higher percentage of bioclasts, principally echinoderms (echinoids) and pelecypods. Other bioclasts, including textulariids, agglutinate foraminifera, and miliolids, are less important. Gastropods and planktonic foraminifera appear locally. Aggregate grains, oncolites, and ooids are accessories in the packstones.

The low energy shelf environment is characterized by the deposition of fine-grained limestones. These facies are mottled to wispy-laminated, with up to 5% of bioclasts (Plate 3d). The bioclasts include mostly foraminifera and small echinoderm fragments (possible related to pelagic species?). Micromollusks and ostracods are rare. The rare planktonic foraminifera are basically represented by hedbergellids and favusellids, while the scarce small benthic foraminifera comprises *Lenticulina* spp., nodosarids, *Trocholina* spp.; textulariids and miliolids are very rare. Calcispherulids are also rare, locally reaching up to 5%, represented mostly by the specie *Pithonella sphaerica*; *Pithonella ovalis* is scattered, and rare. In the inner portions of the shelf the matrix of the fine-grained limestones is peloidal (calcisiltite). In the outer shelf homogeneous matrix is common, but the biota is similar to that one of the inner portion.

The basinal environment is also characterized by fine-grained limestones, but with a greater amount of planktonic forams and calcispherulids. Shales and marls occur interbedded with the limestones.

Figure 3 – Diagrammatic chart showing the evolution of the Macaé sedimentation in the central area of the Campos Basin (from Dias-Brito & Azevedo 1986)

STAGES	BIOSTRATIGRAPHIC UNITS	LITHOSTRATIGRAPHIC UNITS
LOWER TURONIAN / UPPER CENOMANIAN	<i>Classopolis major</i>	MACAÉ FORMATION
UPPER ALBIAN	<i>Ticinella raynandi</i> <i>Nannoconus truitti</i> <i>Hystericosphaeridium maranhensis</i> <i>Favusella washitensis</i>	
MIDDLE/LOWER ALBIAN	<i>Cyclopsiella sp.</i>	
		UPPER MACAÉ
		LOWER MACAÉ

Figure 4 – Chart showing the correlation among the litho-, bio- and chronostratigraphic units of the Macaé Formation

The carbonate deposits grade westward to siliciclastic facies along all the basin (Fig. 12). In the northern area, the terrigenous influx is much stronger, causing a NE shifting of the carbonate belt.

At the end of the Lower Macaé, the bathymetric difference between the shallow shelf and the deeper parts of the basin was enlarged. It is believed that the maximum paleobathymetry in the present explored areas could have not exceeded 200 m (Fig. 13), as evidenced by paleoecological studies (Azevedo *et al.* 1987).

The paleo-oceanographic conditions practically remained unchanged when compared with that of the basal Macaé. The general restrictive conditions still persisted. It is evidenced from the scarcity and low diversity of the biota, as indicated by the several studies on the Macaé carbonates, already cited. The light color of the carbonates, presence of bioturbation and the low content in organic-carbon, indicating a well-oxygenated bottom, led to the conclusion that the hypersalinity was the chemical restrictive factor (Dias-Brito 1982). The carbon isotope values around 4.0 ‰ PDB standards (Fig. 14) support this interpretation about the hypersalinity. On the other hand, this carbon isotope values slightly more positive than that of the lower section (Fig. 10) could indicate an increase in oceanic photosynthetic activity, probably related to the oncolite (cyanobacteria) bloom. Bloom of

Figure 5 – Idealized vertical section of the Lower and Upper Macaé. The thickness corresponds to maximum values at the central portion of the basin

opportunistic species such as *Pithonella sphaerica* (now considered a calcareous dinoflagellate, Hulterberg 1985, Keupp 1987), that occurs in the Macaé fine-grained limestones, also contributed to the increase of the photosynthetic activity in the Macaé Sea, compared with the immediately preceding phase. This fact is clearly observed in the Cretaceous Potiguar Basin, northeastern Brazil, in similar paleoceanographic conditions (Dias-Brito 1985b). The surface water temperature still high, as evidenced by the presence of planktonic foraminifera with characteristics that are related to the subtropical-tropical belts, like the *Favusella washitensis*; it is also suggested by the occurrence of the calcareous nannoplankton *Nannoconus truitti*, which shows clear relationships with Tethyan forms (Wiedmann & Neugebauer 1978, *apud* Dias-Brito *op. cit.*). A slight lowering in the surface water temperature is indicated by oxygen isotope values gradually less negative (Fig. 14). During the entire Lower Macaé deposition, the basin, partly closed by shallow sills, and under hot and dry climate, was submitted to a negative water balance, the evaporation greater than precipitation and runoff (Dias-Brito 1982).

THE UPPER MACAÉ SEDIMENTATION AND PALEOECOLOGY

This section is informally divided into three intervals (Spadini 1982, Spadini *et al.* 1987). The basal one is composed by mudstones showing a significative enrichment in the planktonic content, mainly calcispherulids. The intermediate section is characterized by rhythmic limestones-marls. The upper section is composed by marls rich in radiolarians.

The basal interval is formed by dense mudstones, usually developing wispy laminations; the laminae are usually less than 5 cm thick, and are characterized by the high clay content. This interval is characterized by the significative presence of planktonic forms (Plate 4). Calcispherulids are dominant, including the species *Pithonella sphaerica*,

Figure 6 – Stratigraphic-structural dip section (datum at -1,500 m). Both shallow (Lower Macaé) and deep water (Upper Macaé) carbonates grade westward to siliciclastic facies. The entire unit pinches out against the fault that limits the Lower Cretaceous sequence

Figure 7 – Depositional model for the lowermost portion of the Lower Macaé. Legend: see figure 11

Plate 2 – Carbonate facies photomicrographs of the basal section, Lower Macaé: **a.** lagoonall facies. Micritic/pelletoidal mudstone with miliolids (center) and pelecypod fragments. Scattered quartz grains; **b.** pelletoidal lagoonall sediment, with pelecypod fragments; **c.** shelf facies. Mudstone with rare echinoderms (center) and small Foraminifera; **d.** cloudy center-clear rim anhedral to euhedral dolomite crystals. Scale bar equal to 0.5 mm

Plate 3 – Facies of the uppermost section of the Lower Macaé: **a.** crossbedded oolite grainstone; **b.** structureless oncolite grainstone; **c.** photomicrograph of large oncolite grains. Scale bar equal 1 mm; **d.** photomicrograph of shelf mudstones. Echinoderm fragments (E) and small foraminifera (arrow) are the most common fossils. Scale bar equal 0.2 mm

Figure 8 – Vertical core sequence of supratidal to subtidal facies, deposited just above the Lagoa Feia evaporites

Figure 9 – Vertical sequence of mixed carbonate-siliciclastic facies in the lowermost portion of the Lower Macaé

Figure 10 – Carbon and oxygen isotopic data of whole rock samples. The data are given as per mil deviation from PDB standard

Pithonella ovalis, *Bonetocardiella conoidea* and other spheres not formally described until now (Dias-Brito 1982/5a). Planktonic foraminifera are mostly represented by *Hedbergella* and *Ticinella* species. The benthic foraminifera association is relatively important when compared with that of the Lower Macaé, and are formed by *Gyroidinoides* aff. *praestans*, *Globorotalites michelinianus*, *Osangularia utaturensis*, *Dorothia levis*, *D. oxycona*, *Clavulina gabonica*, *Lagena apiculata*, *Lenticulina* spp., *Gavelinella* spp. *Bolivina*, *Haplophragmoides*, among others (Azevedo et al. 1987a).

Echinoderm fragments, pelecypods, and ammonoids are rare.

The intermediate interval is formed by rhythmic carbonate mudstones and marls with basinwide distribution (Fig. 15), characterizing a chronostratigraphic marker (Spadini et al. 1987). The faunal content of this interval is similar to that of the basal section, but with additional significant amount of radiolarians. On the other hand, the carbonate matrix is here formed by a large amount of coccoliths (calcite platelets of golden brown algae), characterizing a true chalk as defined by Scholle (1977).

The basal and intermediate interval facies were deposited in response to the progressive and accentuated sea level rise during the Late Albian, in accordance with the global eustatic curve (Haq et al. 1987). These limestones represent a typical pelagic sedimentation, as they are formed by coccoliths, which nowadays are responsible for generating significant amounts of pelagic sediment (Mullins 1986). The paleoecological data, based on the association of benthic foraminifera, indicate that the deposition occurred in middle/deep neritic environment (Azevedo et al. op. cit.), with bathyal depths recognized in the northern portion of the basin (Fig. 16). The higher biotic diversity and frequency, comparing with that of Lower Macaé sequence, is attributed to the desalinization of the oceanic water, a process related to the expansion of the South Atlantic (Dias-Brito 1982, 1985a, 1985b, 1987). The carbon isotope values are gradually less positive in this section (Fig. 16), pointing out to a better oceanic circulation, with the values approaching to those of normal marine limestones. The climate during the Late Albian was predominantly warm and dry, similar to that of the Lower Macaé, when the circulation pattern in the basin presented a negative water balance (Dias-Brito 1982). The calcilutite/marls rhythms that characterizes the intermediate interval represent alternating warm/dry and warm/wet climatic cycles, preceding the drastic climatic change occurred post-albian times causing the termination of the cretaceous carbonate deposition in the Campos Basin. The connection between the North and South Atlantic that started in the Early to Middle Albian was in an advanced stage (Dias-Brito 1987). The occurrence of some species of radiolarians described by Kotzian & Eilert (1987) suggests that the Macaé Sea was already connected even with the North Pacific and Central Pacific oceans.

The uppermost section of the Upper Macaé, Late Cenomanian to Early Turonian, is characterized by marls, with subordinate shales and sandstones turbidites. The marls are usually bioturbated (*Planolites* and rare *Zoophycus*). The faunal content of this section is totally different from those of the albian carbonates (Azevedo et al. 1987). The frequency and diversity of the biotic content along this interval is highly

Figure 11 – Depositional model at the end of the Lower Macaé (from Guardado & Spadini 1987)

Figure 12 – Facies map at the end of the Lower Macaé (from Esteves et al. 1987)

Figure 13 – Paleobathymetric map at the end of the Lower Macaé time (from Azevedo et al. 1987)

variated. Among the foraminifera, textularids are dominant; they include *Haplophragmoides*, *Ammodiscus*, *Trochammina*, *Glomospira*, *Ammobaculites*, *Clavulina gabonica* and *Dorothyia oxycona*. The benthic calcareous foraminifera are represented by *Lenticulina*, *Gavelinella*, *Gyroidinoides* aff.

Plate 4 – Late Albian carbonate mudstones: a. photomicrograph of calcispherulids-rich mudstones. Note the presence of *Bonetocardiella conoidea* specie (arrow) and rare radiolaria (R). Scale bar equal 0.15 mm; b. MEV photograph showing the matrix formed by coccoliths (CC). Euhedral crystals resulted from plates overgrowth

Figure 14 – Carbon and oxygen isotopic data of whole rock core samples. Uppermost section of the Lower Macaé and Upper Macaé. The data are given as per-mil deviation from PDB standard

praestans, *Lagena apiculata*, *Pleurostomella*, *Gyroidina*, *Globorotalites michelinianus*, bolivinids, and nodosarids. The paleozooplankton is formed by foraminifera and radiolarians. The former comprise the genera *Hedbergella*, *Heterohelix*, *Globigerinelloids*, and *Whiteinella*. Radiolarians are important elements in this interval, sometimes forming true siliceous ooze. As in the Late Albian, the radiolarian tests are frequently calcitized.

This unit was deposited dominantly in an upper bathyal setting (Fig. 17), the basin presenting a positive water balance, where evaporation was less than precipitation and runoff. At this time, already under a warm/wet climate, episodic anoxic events are registered as indicated by the deposition of evenly laminated black shales. These shales sometimes show a monofauna of the foraminifera *Neobulimina albertensis*?, taxon similar to that one nowadays adapted to anoxic

Figure 15 – Facies map of the Late Albian (Upper Macaé). From Spadini et al. 1987

conditions (Azevedo et al. 1987); other times these anoxic strata have no fauna, but in other cases they are rich in planktonic foraminifera and/or radiolarians.

Turbidites were channelized in the downthrown blocks of the growth faults (Guardado et al. 1986).

CONCLUSIONS The Macaé Formation nowadays is probably the best known mid-Cretaceous sedimentary record of the South Atlantic. The Macaé deposition records significant oceanographic events, important for the global understanding of the South Atlantic Ocean evolution in its initial phases.

The shallow carbonate neritic sequence, Early to Middle Albian in age (Lower Macaé unit), represents a deposition in an epicontinental sea similar to the present Persian Gulf, but in a more restricted regional setting. The sedimentation developed in an hypersaline environment, under high water temperatures. The climate was at that time warm and dry. The base of this unit is formed mostly by peloidal/oolitic

Figure 16 – Paleobathymetric map at the end of the Late Albian (from Azevedo et al. 1987)

packstones/grainstones, intensively dolomitized, whereas the middle and upper portions is formed mostly by oncolite-bearing limestones and mudstones. The biota content is characterized by the absence of typical bioelements known to be common in normal marine environments elsewhere at that time. A close relationship is established between subsidence/sea level rise and the carbonate production, contributing to maintain the shallow neritic conditions during the entire Lower Macaé time.

The Upper Macaé, comprising a carbonate sequence (Late Albian) and a predominantly marly section (Late Cenomanian to Early Turonian), records a progressive sea level rise. In the Late Albian, associated with the sea level change, the marine ecosystem became less saline due to a expressive increase in the water interchange with the North and South Atlantic oceans. The fine-grained limestones, with abundant ammounts of calcispherulids, accumulated mostly in a deep neritic environment, under warm/dry climatic conditions. At the end of the Late Albian mustone-marl rhythms were deposited as a response to warm/dry to warm/wet climatic cycles. These climatic alternances preceded the drastic climatic change that occurred in the Cenomanian which caused the termination of the Cretaceous carbonate

Figure 17 – Paleobathymetric map at the end of the Late Cenomanian/Lower Turonian (from Azevedo et al. 1987)

sedimentation in the Campos Basin.

The Late Cenomanian to Early Turonian deposits were accumulated in 200-300 m water depth. Opposing the preceding phases, when the system presented a negative water balance, the basin was submitted to a positive water balance. The climate was then warm and wet. Despite the advanced stage of the continental drifting, no fully normal marine conditions was reached at the time, as evidenced by the presence of black shales layers, accumulated in episodic anoxic events. Oceanic conditions are only recorded in the sediments overlying the Macaé deposits.

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