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Paleo-oceanology and paleobiogeography of the Cretaceous South Atlantic Ocean

Cretaceous
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Eustasy
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Eustasie

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ABSTRACT

The interpretation of the origin of the South Atlantic Ocean made by oceanologists and paleontologists are shown to be in complete agreement. Several major phases in the opening of the ocean can be identified, each of which had recognizable effects on the paleobiogeography of marine and land organisms. The occurrences of closely related species on both sides of the South Atlantic in Late Cretaceous through Paleocene time can be explained in terms of islands on the Rio Grande Rise and the Walvis Ridge. This is especially relevant for plants, ostracods, pelecypods, and gastropods. It is possible that shallow-water marine benthic organisms could have crossed the Guinean fracture zone until Cenomanian, even early Turonian time. Eustatic high sea-levels occurred in the Late Aptian, Late Albian, Cenomanian-Turonian boundary, Coniacian, Late Campanian to Early Maastrichtian, and Paleocene, i. e. six episodes. The first four seem to have been mainly tectono-eustatic, while the latter two may have had an important geoidal eustatic component. The development of a deep-water system of currents in the Guinean zone took place over a period of time stretching from Late Turonian to Santonian.

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RÉSUMÉ

Océanologie et paléobiogéographie de l'Atlantique Sud

Les différentes interprétations sur l'origine de l'Atlantique Sud avancées par les océanologistes et les paléontologistes paraissent être en complet accord avec les théories actuelles. Un certain nombre de phases majeures de l'ouverture peuvent être identifiées, chacune ayant des effets évidents sur la paléobiogéographie des organismes marins et terrestres. Ceci est dû d'une part à la modification de la géographie de l'océan, d'autre part à l'évolution de la circulation des eaux océaniques. La présence d'espèces pratiquement identiques des deux côtés de l'Atlantique au Crétacé Supérieur-Paléogène peut être expliquée par l'existence de grandes îles au niveau des rides de Rio Grande et de Walvis. Cela est particulièrement net pour les plantes, les ostracodes, les lamellibranches et les gastéropodes. Il est possible que des organismes benthiques vivant en eau peu profonde aient pu traverser la zone de fracture de Guinée jusqu'au Cénomanien et peut-être au Turonien Inférieur. On note six épisodes de remontée du niveau marin d'origine eustatique : Aptien Supérieur, Albien Supérieur, limite Cénomanien-Turonien, Coniacien, Campanien Supérieur-Maestrichtien Inférieur et Paléocène. Les quatre premiers épisodes sont probablement d'origine tectono-eustatique alors que certainement les deux derniers sont partiellement dûs à la variation locale du niveau marin. Le développement d'un système de circulation océanique profonde dans le Golfe de Guinée se produit entre le Turonien Supérieur et le Santonien; ceci marque l'achèvement de l'ouverture de l'Atlantique Sud.

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INTRODUCTION

Ever since Krömmelbein and Wenger (1966) demonstrated exceptionally close relationships in Early Cretaceous freshwater ostracods from Gabon and Brazil (Province of Bahia), paleontologists have been interested in the paleobiogeography of the South Atlantic ocean during the Cretaceous Period. Most of the work that has been done recently has been concentrated on marine organisms (mainly ammonites, but also pelecypods). Naturally, marine fossils are less likely to yield such spectacular results as non-marine organisms (such as freshwater ostracods and, to a lesser extent, freshwater fishes) and the outcome of research on marine molluscs has not been unequivocal.

It may seem at first sight that there are several possible estimates for a dating of the opening of the South Atlantic. However, the seeming confusion is largely semantic being due to the particular meaning given to the concept of "opening". The formation of a permanent connexion between two oceans is not the outcome of a single catastrophic event, but rather the result of a gradual shift in a set of physical conditions.

It is now well established that the Albian to Paleocene was an interval during which several large-scale eustatic transgressions occurred on a world-wide scale (Kauffman *et al.*, 1978; Reyment and Mörner, 1977), the latest of which could well have been complicated by the effects of geoidal eustasy (see Mörner (1976) for a detailed account of geoidal eustasy). The transgressive peaks of North and West Africa are now reasonably well understood from field studies in the southern Sahara (Faure, 1966; Offodile and Reyment, 1977). There is agreement that major transgressive peaks occurred at the boundary between Cenomanian and Turonian, in the Early Coniacian, in the Early Maastrichtian and in the Paleocene (Faure, 1966; Furon, 1958, 1968; Greigert and Pougnet, 1967; Louis, 1970; Krasheninnikov and Trofimov, 1969; Offodile and Reyment, 1977, Trofimov *et al.*, 1969, to cite some of the many references).

PALEO-OCEANOGRAPHICAL FACTORS

Mascle (1977, p. 79) summarized the main criteria for dating the union between the North and South Atlantic oceans. These are: magmatic development, age of the first marine transgression, time at which a true pattern of oceanic circulation was established, and the development of a mid-oceanic ridge. To these may be added the criterion most frequently used by workers on ammonite distributions, to wit, the first connexion of surface waters. Mascle (1977, p. 79) considers the opening of the Atlantic oceans to have become effective in the oceanographic sense when oceanic crust had been formed in the Gulf of Guinea and the mid-oceanic ridge had developed in that region.

We shall briefly consider modern concepts of eustasy. Suess (1888) proposed the concept of eustasy for what is now known to be only one of the causes of changes in sealevel. Mörner (1976) analyzed eustasy in the light of recent geodetic results on satellite measurements of present-day sealevels and pointed out that in addition to the fundamental factor of Suessian eustasy, or tectono-eustasy, geoidal eustasy may be an important variable. For the Cretaceous Period, a third eustatic factor, glacial eustasy, is unimportant. Changes in the configuration of the seafloor, such as caused by ridge-growth and the formation of oceanic basins, produce tectono-eustatic shifts of sealevel, often recognizable on a world-wide scale. Geoidal eustasy is caused by interactions at the core-mantle interface. It is characterized today by humps and depressions of several tens of metres of the surface of the oceans (the most extreme example is the depression of some 110-120 m off the Maldive Islands and the hump of 70-80 m off New Guinea). During periods of seafloor spreading, geoidal eustatic effects would have been greater than they are at the present day: the Cretaceous Period was such a time.

High eustatic sealevels must be taken into account in assessments of oceanic connexions based on the interchange of surface waters and dated by, for example, ammonite distributions. Ephemeral connexions due to eustatic maxima can easily be misinterpreted as being evidence of a stable oceanic union.

MAGMATIC CONSTRAINTS

Rhodes (1971) and Morgan (1971) suggested that the successive southerly younging of the non-orogenic peralkaline intrusives stretching from the Air Mountains in the central North Sahara, through Niger and Nigeria, to Pernambuco (Brazil) could well mark the trace of a stationary plume in the lower mantle (cf. Sial, 1976). Whatever the explanation of this trend may be, there is doubtless a time-glide in the emplacement of the intrusive sequence from north to south over this vast region, which ranges over hundreds of millions of years. The Brazilian tip of the suite, the Cabo granite (90 MY BP = Turonian), is the youngest granite of that country. The youngest rocks of the petrographic province may occur in Cameroun. Cantagrel *et al.* (1979) have recently discussed the petrographic relationships between the Camerounian intrusives and the Younger Granites of Nigeria, pointing out the difference in age between these two areas (Middle Jurassic for Nigeria and Paleocene for Cameroun). If the Cabo granite really belongs to the Younger Granite suite, then the age difference between Nigeria and Cameroun becomes less of a problem. Brazil and Nigeria-Cameroun would then have been in mantle contact until Turonian time at least in order to guarantee the continuity of the intrusive event. In this respect it is worth remembering that the age differences between the undoubted Younger Granites of the northern Sahara and Nigeria are very considerable and there is no time continuity in the occurrences.

If the Camerounian Paleocene intrusives are genuine Younger Granites, this might indicate that the direction of movement of Africa changed in relation to the "plume" in post-Turonian Cretaceous time. This hypothesis fits in well with the dating of the pole of rotation suggested by LePichon and Hayes (1971) as being Santonian. I note here that the compression of the Benue rift (Nigeria) took place at about this time.

FIRST ONSHORE TRANSGRESSION

The first onshore marine transgression in the South Atlantic proper took place across the southernmost extremity of the sundering landmass during the Valanginian (Reyment, Tait, 1972). Around the passage from Jurassic to Cretaceous time, rift valleys began to form along sites of longitudinal doming (LeBas, 1971); from the geophysical point of view, this could be taken as being the birth of the South Atlantic. Vast lakes came into existence in parts of the rift in which great thicknesses of lacustrine sediments were deposited (see reconstruction in Reyment and Tait (1972, p. 81)). The northerly younging of initial onshore transgressions, with an important phase of Late? Aptian salt accumulation, can be explained by the geometry of plate tectonics (LePichon *et al.*, 1973; Mascle, 1977).

The Aptian salinity episode may have been connected with a tectono-eustatic rise of sealevel with flooding over the Walvis Ridge barrier (Burke, 1975). Leyden (1976, p. 166) believes that the salts are precipitates rather than evaporites, an opinion apparently shared by Kumar *et al.* (1977, p. 941) who concluded that it took 3×10^5 years for the salts to accumulate at a depth of 3 km. On the African side of the Atlantic, the salts have been proved by drilling in basins from Angola to Cameroun (Mascle, 1977). The Brazilian salts, likewise proven by drilling, occur in coastal basins up to the Sergipe-Alagoas basin (Ponte, Asmus, 1976, 1978). The first dated onshore transgression within the south Atlantic rift occurs in the Sergipe-Alagoas basin in beds overlying the Aptian salts; it is Late Aptian in age, as shown by the presence of the ammonite genus *Epicheloniceras* (Reyment, Tait, 1972, p. 76).

A more widely recognizable dating is provided by the beds with species of *Douvilleiceras,* of early Albian age, in Angola, Gabon and Sergipe. There is no evidence as yet of marine sediments of this age in the Nigerian coastal basin and there is still some doubt about the nature of the Aptian-Early Albian transgression(s).

The first onshore transgression in Western Nigeria and Bénin is Late Campanian in age, being dated on the occurrence of species of *Inoceramus, Sphenodiscus* and *Libycoceras.* However, a limestone penetrated by a borehole located near the international boundary between Nigeria and Bénin, on the coast, has been provisionally referred to Cenomanian on its pollen association, albeit meagre, (du Chêne *et al.*, 1979; de Klasz, du Chêne, 1979). This result accords with the geological evidence, as summarized by Mascle (1977, pp. 14-30, 90), who records that thick series of continental and lagoonal sediments (estimated to reach 3 500 m locally) were deposited in a double system of grabens, ranging from Liberia (with basalts) to Ghana-Bénin. On the whole, marine intercalations are more frequent in the younger reaches of the respective sequences; the datable marine levels appear to be correlatable with high eustatic stands of the sea. The best established of these derives from the Late Albian tectono-eustatic event (Cudjoe, Khan, 1972; Reyment, 1969; Reyment, Tait, 1972; de Spengler, Delteil, 1966).

In central Nigeria, the oldest proven onshore marine transgression is Late Middle Albian in age, as indicated by a diagnostic association of oxytropidoceratid ammonites including species of *Oxytropidoceras* s. str., *Manuaniceras* and *Adkinsites.* The geology of one of the critical areas has recently been described by Offodile and Reyment (1977). Within the South Atlantic realm, this Late Middle Albian transgressive event is identifiable in Angola (Kennedy, Cooper, 1975; Reyment, Tait, 1972) and northeastern Brazil, possibly also Gabon.

Various workers have sought to explain disparities in the ages of onshore transgressions around Africa, particularly for Senegal and the Atlantic coast of Morocco, by means of divers hypotheses of marginal tilting (Rona, 1973, p. 2862; 1974, pp. 288, 295; Faure, 1976, p. 84; Pitman, 1978, p. 1393; Reyment, 1969; Ponte, Asmus, 1976, p. 235). Although some kind of tilting mechanisms can be identified in some cases, others may be due to the effects of geoidal eustasy (Reyment, Mörner, 1977).

FIRST CONNEXION OF SURFACE WATER

The first passage of marine organisms between the two arms of the Atlantic took place in Late Middle Albian time during a phase of high eustatic sealevel, as indicated by ammonite occurrences (Förster, 1978; Kennedy, Cooper, 1975; Reyment, 1969, Reyment, Tait, 1972). The maximum of this rise in sealevel may have occurred in the Late Albian (zone of *Mortoniceras inflatum*).

Interchange of surface waters took place in the Gulf of Guinea during the Early Cenomanian, probably during the regressive phase of the Albian transgressive episode, possibly coupled with vertical crustal movement (Mascle, 1977, p. 91; Förster, 1978; Kennedy, Cooper, 1975).

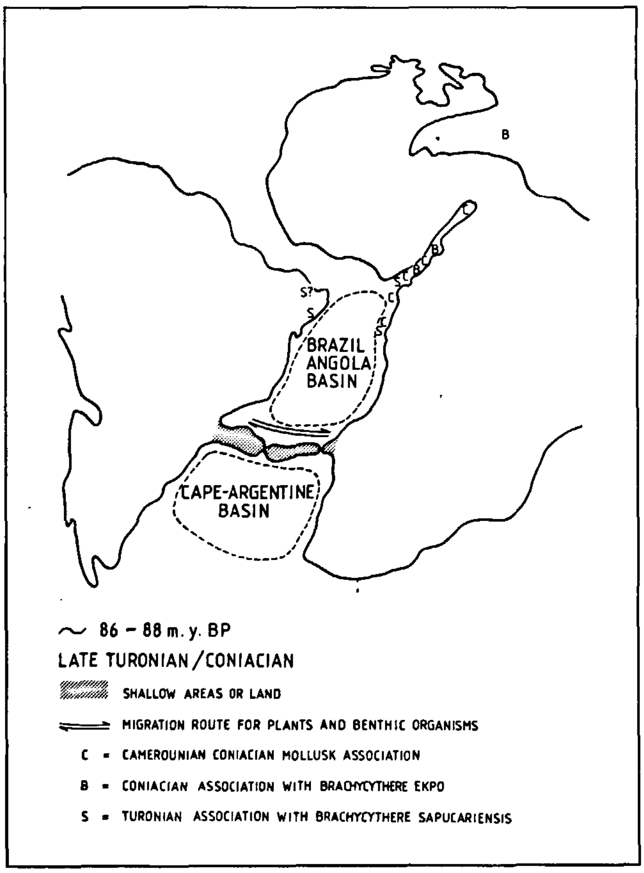
DEVELOPMENT OF TRUE OCEANIC CONDITIONS

Using different lines of evidence, van Andel *et al.* (1977), Melguen *et al.* (1979) and Reyment and Tait (1972) have arrived at approximately the same conclusions for the time at which true oceanic conditions were installed between the northern and southern arms of the Atlantic.

Briefly, this stage began in the Guinean region in the Turonian and was terminated in the Santonian (Fig. 1). The subsequent evolution of the ocean has been more in the nature of bathymetric adjustment. The evidence supporting this interpretation is drawn from the sedimentological history of the South Atlantic and the distributional patterns of benthic, nektic and planktic organisms. Reyment and Tait (1972) suggested that a modern system of surface currents began to develop during the Early Turonian their conclusions being based on the distribution patterns of stenohaline organisms such as ammonites and some groups of pelecypods. The geographic range of elements of the *Benueites*-association was considered important (*Benueites* spp., *Hoplitoides* spp. *Watinoceras* spp. and the unusual polymorphism exhibited by these groups). Gordon's (1973) otherwise stimulating ideas for reconstructing paleocurrent systems in surface waters cannot be applied directly to the problem at hand owing to an incorrect paleogeographic reconstruction for his Santonian case history (Gordon, 1973, p. 278, Fig. 4). Luyendyk's (1972) reconstruction of Late Cretaceous circulatory patterns by means of experiments using scale models is, in many respects, a good representation for parts of the Atlantic; these results differ, however, in significant respects from the inferences of Wiedmann (1976, p. 434) for northwestern Africa, obtained by extrapolating from faunal and geochemical analyses of the Tarfaya Basin in southwestern Morocco.

Figure 1

Reconstruction of the paleogeography of the South Atlantic in Turonian to Coniacian time. The Coniacian epicontinental transgression extended inland in a narrow belt. The locations of the Brachycythere *associations and the distribution of the Camerounian molluskan fauna (species of* Tissotia, *barroisiceratids, a diagnostic pelecypods and the* Ovocytheridea *fauna) are shown. Based mainly on Melguen* et al. (1979) *and Sclater* et al. (1977), *with corrections for the Saharan transgression.*



The Santonian change in plate geometry in the South Atlantic seems to have been associated with a shift in oceanic conditions, a breakdown in marine barriers and a distinct change in the conditions of sedimentation (Thiede, 1977).

BIOLOGIC CONSTRAINTS

As summarized in the foregoing, oceanologic data support the idea that marine connexions between the North and South Atlantic were restricted to the interchange of surface waters until post-Cenomanian time (van Andel *et al.*, 1977; Mascle, 1977; Melguen *et al.*, 1979). At the first documented flooding of the Guinean region, the relatively mobile ammonites were introduced into the Benue Trough. Oceanographic conditions in West Africa during the Cenomanian, although mainly regressive, were such as to permit increasingly frequent exchanges of surface water, probably the combined outcome of the movement apart of the continents, adjustments in the Guinean fault blocks and minor eustatic fluctuations. A reflection of the foregoing can be seen in the ammonite associations of Africa south of Nigeria which have a more cosmopolitan aspect than those of the Albian (Förster, 1978; Kennedy, Cooper, 1975).

Valuable information has been yielded by studies on marine ostracods of the Late Cretaceous and Paleogene. Reyment and Neufville (1974) analysed multivariate morphologic variation in the Cenomano-Turonian ostracod species *Brachycythere sapucariensis* Krömmelbein for material from Sergipe (Brazil), Gabon and Nigeria (cf. Fig. 1). It was found that morphologic agreement between the Brazilian and Gabonese individuals is statistically significantly greater than between either of these associations and the Nigerian association. This was taken to indicate the close proximity of Sergipe and Gabon around the Cenomanian to Turonian boundary. Beurlen (1961) seems to be the first person to have postulated a barrier in the South Atlantic at the level of Pernambuco, further elaborated on in Beurlen (1970). Ponte and Asmus (1978) have demonstrated the lack of structural evidence for this hypothesis and Schaller (1969) recorded *Brachycythere sapucariensis* in Late Cenomanian beds in Rio Grande do Norte, north of the supposed paleogeographic barrier.

Of great interest is the occurrence of closely related Maastrichtian and Paleocene ostracods on both sides of the Atlantic. Dingle (1978) observes that relationships between Late Cretaceous and Paleocene ostracods of South Africa and Argentina are slight, whereas there are many affinities between associations of the Gulf of Guinea and Argentina. Bertels (1969) found such typical West African genera as *Soudanella* (Nigeria, Senegal, Ivory Coast, Gabon), *Veenia (Nigeria)* (Morocco, Nigeria, Cameroun, Gabon), *Togoina* (Togo, Bénin, Nigeria) in Argentinian Maastrichtian and Paleocene associations. Neufville (1973) recorded *Soudanella triangulata* Apostolescu, a West African species, from the Danian of Itaporanga (Brazil) Analogous observations have been made by Freneix (1969) for pelecypods and Halffter (1975), analyzing distributions of modern insects, concluded that land insects could pass between northern South America and West Africa until the Paleocene.

Marine ostracods cannot be dispersed by birds, as can non-marine species, owing to their eggs being unable to withstand dessication. Some marine species colonize free-floating algae and can be distributed passively on seaweed over wide areas. For the South Atlantic a more certain route is suggested by the observations summarized in Melguen *et al.* (1979, pp. 481-483, Figs, 16, 17, 20-22). These authors conclude that large areas of the Rio Grande Rise and Walvis Ridge were exposed during the Late Cretaceous to Paleocene to form sizeable islands. Similar ideas have been expressed by Jardiné, Kieser and Reyre (1974), Thiede (1977, p. 939), Goslin *et al.* (1974), Sclater and McKenzie (1973) and Sclater *et al.* (1977).

The existence of a chain of large islands would have provided the bridge necessary for enabling many organisms to cross the South Atlantic at an advanced stage of opening (Fig. 2). It is noteworthy that closer faunal agreements between the two coasts of the South Atlantic cease after the Paleogene, which coincides with the disappearance of the east-west barrier in the early Tertiary and the opening of the Vema gap (or channel) (cf. Thiede, 1977).

The information provided by fossil plants is highly significant. The observations of Axelrod (1975) on the distributions of angiosperms on both sides of the South Atlantic seem to be explicable by assuming lateral migrations of plants across the Rio Grande–Walvis island chain.

Jardiné, Kieser and Reyre (1974) compared African Mesozoic microfloras with those of Europe, Australia and South America. Their analysis led them to conclude that South America and West Africa were in very close contact until the close of the Cenomanian and still close to each other in the Senonian. The pollen assemblages of the continental sequences of Brazil and West Africa indicate arid conditions to have appeared in Barremian to Aptian time, which these authors relate to the drying-out of the rift lakes. Jardiné, Doerenkamp and Biens (1974) have been able to date part of the continental sequence as Barremian, on the distribution of *Dicheiropollis etruscus* Trevisan.

The close of the Cenomanian is marked by a major palynologic break. The early Cretaceous *Classopollis* flora disappeared; thereafter, until latest Cretaceous, the microfloras of West Africa and South America, similar at first, diverged gradually, although species such as *Auriculiidites articulatus, Buttinia andreevi* and *Spinozonocolpites baculatus* indicate that plants could still be dispersed on both sides of the Atlantic until Maastrichtian. This is further evidence for the Walvis-Rio Grande island chain (Jardiné, Kieser, Reyre, 1974; Boltenhagen, 1979).

Chabaglian (1959) recorded two species of Paleocene echinoids on both sides of the Atlantic; the full significance of this observation will not be known until more detailed work on the group has been done.

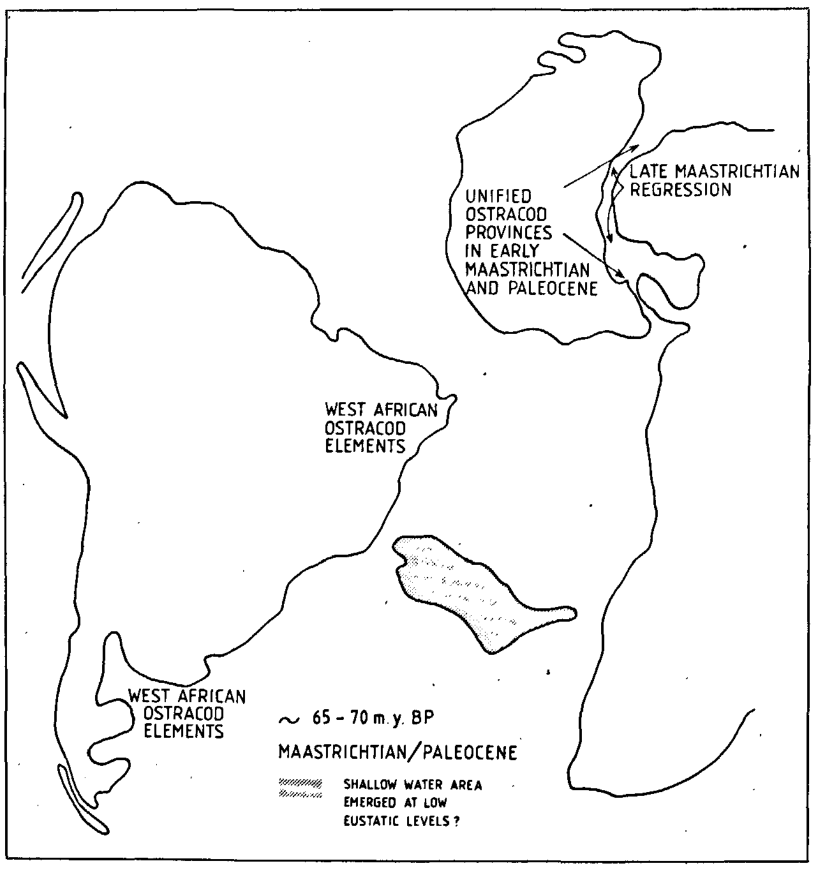
SYNOPSIS OF MAJOR EVENTS

1. Rift valleys formed during latest Jurassic to Barremian time, posterior to doming and uplift of the crust and associated volcanic events (cf. LeBas, 1971). Thick series of continental sediments filled deeper areas in the rift. Ostracods, fish, and locally *Estheria*, occurred in abundance in the vast freshwater lakes. Climatic conditions were such as to support a prolific flora.

2. The first onshore transgression took place in the Valanginian (South Africa/Argentine). Drying out of the inland lakes in Barremian time.

Figure 2

Reconstruction of the paleogeography of the South Atlantic in Early Maastrichtian time. The shallow region between southern Brazil and southern Africa provided a migrational route for benthic organisms. The trans-Saharan transgressions in Early Maastrichtian and Paleocene time are marked by homogeneous ostracod associations (Reyment, Reyment, in press). Elements of these associations have been proven in Brazil and Argentina.



3. Aptian to earliest Cenomanian. Uplifted blocks form reliefs in the Gulf of Guinea between the separating continents. Surface Atlantic water interchanged at increasingly frequent intervals, thus allowing the dispersal of inhabitants of superficial water layers and some benthic organisms. Two largely closed basins formed in the north and south of the South Atlantic (Fig. 2); euxinic conditions ended during Albian time in the southern basin but persisted intermittently until Santonian in the northern basin (Melguen *et al.*, 1979; Thiede, 1977). The Falkland Island plateau hindered the inflow of bottom water. The salinity episode belongs to the first part of the interval, probably connected with a eustatic rise of sealevel, while the increasing number of transgressions in the foundering Guinean region produced Cenomanian onshore deposits in Ghana, western and eastern Nigeria. The first major transgression in the Gulf of Guinea is Middle to Late Albian in age; it derives from a tectono-eustatic rise in sealevel.

4. Middle Cenomanian to Turonian. Deepening of the structural barriers in the Guinean region; the flow of middle and deep waters still obstructed by the submarine topography of the fracture zones. A tectono-eustatic high sealevel caused the major Late Cenomanian to Early Turonian transgression, which swamped many marginal areas temporarily and connected Mesogea with the Gulf of Guinea, thus permitting the introduction of Tethyan elements into the South Atlantic (as in the case of the ammonite associations of Brazil). Ostracod evolutionary relationships indicate the close proximity of Gabon and northeastern Brazil during this time interval. Palynological evidence points to homogeneity in the floras of Brazil and West Africa.

5. Turonian to Santonian. A change in the plate geometry in Santonian time seems to have initiated the development of true oceanic conditions (LePichon, Hayes, 1973). The Santonian rotational change may relate to the Benue folding episode and change in direction of the intrusive trend of the Younger Granites. The Walvis Ridge and Rio Grande Rise continued to hinder circulation in the southern part of the South Atlantic during the first part of the interval.

6. Campanian to Early Eocene. The east-west submarine barriers receded in the Paleogene and well oxygenated water began to circulate; this led to ameliorated conditions for phytoplankton. Northward penetration of bottom water through the Vema gap began, this route seemingly having displaced the former passage around South America.

Benthic organisms, such as marine ostracods and many species of plants were able to migrate between West Africa and South America across islands rising from the Walvis Ridge and Rio Grande Rise; this bridge would have been most effective during the low eustatic sealevel in the Early Campanian and Late Maastrichtian. In the Gulf of Guinea, the outgrowth of the Niger Delta began in the Danian (which agrees with Mascle's (1977, p. 54) dating of his reflector zone P as Late Maastrichtian).

The information used in making the foregoing synopsis of major events was obtained from the following publications: d'Almeida (1976), van Andel *et al.* (1977), Beurlen (1970), Cudjoe and Khan (1972), Delteil *et al.* (1975), Delteil (1977), Faure (1966, 1976), Goslin *et al.* (1974), Kumar *et al.* (1977), Lehner and de Ruiter (1977), Mascle (1977), Melguen *et al.* (1979), Mutvei and Reyment (1973), Ponte and Asmus (1978), Reyment (1973), Reyment and Tait (1972), Sclater and McKenzie (1973), Sclater *et al.* (1977), Smit (1966), Thiede (1977).

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