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Evolution of the Pernambuco-Paraíba-Rio Grande do Norte Basin and the problem of the South Atlantic connection

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Abstract

The easternmost sedimentary basin of the NE Brazilian Atlantic margin shows special tectonic and sedimentary features due to the fact that it was the last link between South America and Africa. The basin is strongly influenced by the rotational separation of both continents and by the reactivation of Precambrian faultlines.

The basin may be subdivided into seven subbasins which all have a homoclinal structure. The differential downwarp of the crystalline basement resulted in deeper and shallower parts that are bounded by faults. A crystalline basement high disrupts continuity between the three southern subbasins in Pernambuco and Paraíba States, and the four northern ones in Rio Grande do Norte State.

Sedimentation in the basin started in about Santonian time with meandering, sometimes braiding fluvial sandstone systems passing seaward into calcareous littoral sandstones. In the Maastrichtian the sea advanced over the area. As a consequence, sedimentation in the southern subbasins began then with the accumulation of transgressive phosphorites and calciclastics from a South Atlantic source. Later, somewhat deeper-water limestones were deposited. A Paleocene regression is represented by detrital limestones and calcareous clays. Marine sediments of Maastrichtian age in the northern subbasins, which belong to the Equatorial Atlantic, are restricted to shallow-water shelf limestones which became strongly recrystallized and partly dolomitized.

From the structural, geophysical, sedimentological and paleontological analyses of the basin we conclude that (1) the last link between South America and Africa was broken only at the end of the Cretaceous, (2) the sill tilted southward before its rupture, (3) the sedimentary fills north and south of the sill came from different sources, and (4) upwelling in the South Atlantic against the sill caused phosphorite deposition.

Introduction

The Atlantic margin basins of the Northeast Brazilian bulge (Fig. 1) are known as the Potiguar (Rio Grande do Norte State) and the Sergipe-Alagoas Basin (see maps of St. Johns 1980, and Miall 1984 – Fig. 9.46). They are separated by the Pernambuco-Paraíba-Rio Grande do Norte sedimentary strip which, however, is not depicted as such on the above-cited maps. This latter sedimentary area occupies a position coincident with the final Cretaceous link between South America and Africa. The configuration and history of the breakup of this last link are documented in the magnetic and gravity anomalies, and in the sediments of these basins.

The Pernambuco-Paraíba-Rio Grande do Norte Basin is characteristically different from the other sedimentary basins along the Brazilian Atlantic

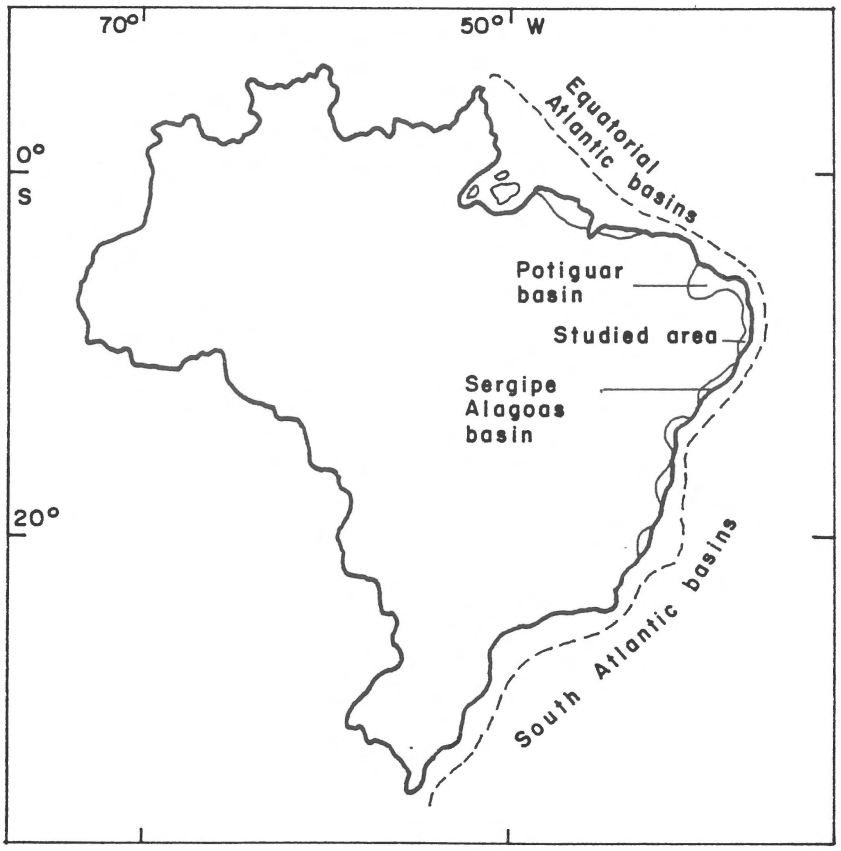

Fig. 1. Map of Brazil showing location of Pernambuco-Paraíba-Rio Grande do Norte Basin (studied area) among the Brazilian Atlantic margin basins.

margin, as was already emphasized by Asmus & Carvalho (1978). However, due to its small size and to the absence of detailed studies (no exploration for oil and gas), the area did not draw much attention. In this paper we present those aspects which make the basin different from the others along the Brazilian coast, and we sketch its geological history.

Tectonic setting

Opening of the South and Equatorial Atlantic Oceans

A sedimentary basin of Atlantic margin type represents the end of the evolution of a rift valley system, opening a new ocean and separating continental shields.

The opening of the South and Equatorial Atlantic Oceans and the consequent separation of South America and Africa have been the subject of various studies. The opening of the South Atlantic is quite well understood and there are almost no divergent opinions. This is not the case, however, for the formation of the Equatorial Atlantic Ocean. There, at the site of the present Northeast Brazilian bulge, are problems with respect to the opening of both parts of the ocean to either side.

The formation of the South Atlantic Ocean is best explained by the model proposed by Rabinowitz & LaBrecque (1979), as described in more detail by the study group of Petrobrás (Szatmari et al. 1984). A clock-wise, supposedly Neocomian rotation of South America with respect to Africa, opened the wedge-shaped South Atlantic, by rifting propagating from south to north. This rifting seems to have finished against the so-called Pernambuco Lineament, just at the latitude of Recife. This linea-

ment, according to most authors, is considered to continue in the African continent as the Ngaoundere Lineament (e.g. Torquato & Cordani 1981, Popoff 1988). There are no doubts about the rift formation, and all South Atlantic basins up to that of Sergipe-Alagoas are bordered by normal high-angle faults at their continental side.

The opening of the Equatorial Atlantic Ocean is more controversial. Initially it was thought that this part of the ocean opened by rifting from west to east, continuing even into the Benue trough in Africa (Ponte et al. 1972), a supposition not confirmed by the ages of the sedimentary fills of the marginal basins. Rabinowitz & LaBrecque, as elaborated by Szatmari et al. (1987), postulated for this opening a highly complex rifting and tectonic evolution whereby the eastern tip of Brazil would have been pressed against Africa. Caputo (1988) did not agree with these interpretations and presented evidence for wrenching which, in northern Brazil, generated pull-apart basins along the Equatorial Atlantic transcurrent fault. All authors agree that the last link between the continents occurred in the Northeast Brazilian bulge of which the area under study forms part.

Another problem is the time at which this last link was broken. Some authors suggest that this has taken place during the Albian or shortly thereafter; others suppose the definitive breakup to have occurred only in the Late Cretaceous, probably Maastrichtian. Rand & Mabesoone (1982) discussed the problem to a certain extent. Those who insist on an early opening of the whole Atlantic Ocean (e.g. Sclater et al. 1977, Smith & Briden 1977, Berggren & Hollister 1974, Melguen et al. 1978) base themselves chiefly on fossil associations and geophysical, chiefly paleomagnetic data. However, the geophysical data as expressed by various maps (e.g. Cande & Rabinowitz 1978, Rabinowitz & Cochran 1978, Larsen & Pitman 1985) provide insufficient evidence for justifying an early opening; besides, the various anomalies do not correlate very well. Those authors who favour late opening (Beurlen 1971, Tinoco 1971, Asmus & Carvalho 1978, Rand 1978) take their arguments from sediments, tectonic behaviour of the separating continents, and geophysical data from the continents. There is no evidence that deep-water sediments older than Late Cretaceous exist in the area seaward of the basins studied. The ages could not be confirmed exactly, because the fossils show a rather wide age range. Since the aforementioned publications, almost no new data about this problem have been added. More recent investigations point to a late opening; there is no conclusive evidence for a continuous seaway between the Equatorial and South Atlantic Oceans already in middle Cretaceous time. On the contrary, current research suggests an exchange of freshwater ostracods, some running birds and burrowing mammals even until the Eocene between Brazil and Africa (Stinnesbeck 1991, Storch 1991).

Tectonic provinces

Almeida et al. (1981) recognized in Brazilian territory ten structural provinces which may be distinguished by the nature of the crystalline basement rocks and their sedimentary covers. They grouped the coastal basins in the so-called Coastal Province and Continental Margin. The structural character of these basins is determined by the Precambrian crystalline basement and shows strong relations with the adjacent provinces (Cordani et al. 1984).

For the coastal basins of the Northeast Brazilian bulge, this basement belongs to the Borborema Province (Fig. 2). This province consists of polycyclic supracrustal belts with a gneissic-migmatitic terrain, disposed in NE-SW zones and cut by E-W and NE-SW fault systems and lineaments. These structures became reactivated during the breakup of the Gondwana continent, facilitated the rupture, and caused basins to form both inland and along the margin.

The sedimentary basins bordering the South Atlantic are all limited at their continental side by normal high-angle faults. The Sergipe-Alagoas Basin which reaches up to the Pernambuco Lineament (Alheiros et al. 1989) belongs to this South Atlantic suite.

The basins along the Equatorial Atlantic are represented by rhomb-shaped grabens. The Potiguar Basin is considered to belong to this latter suite (Szatmari et al. 1987). However, we cannot agree

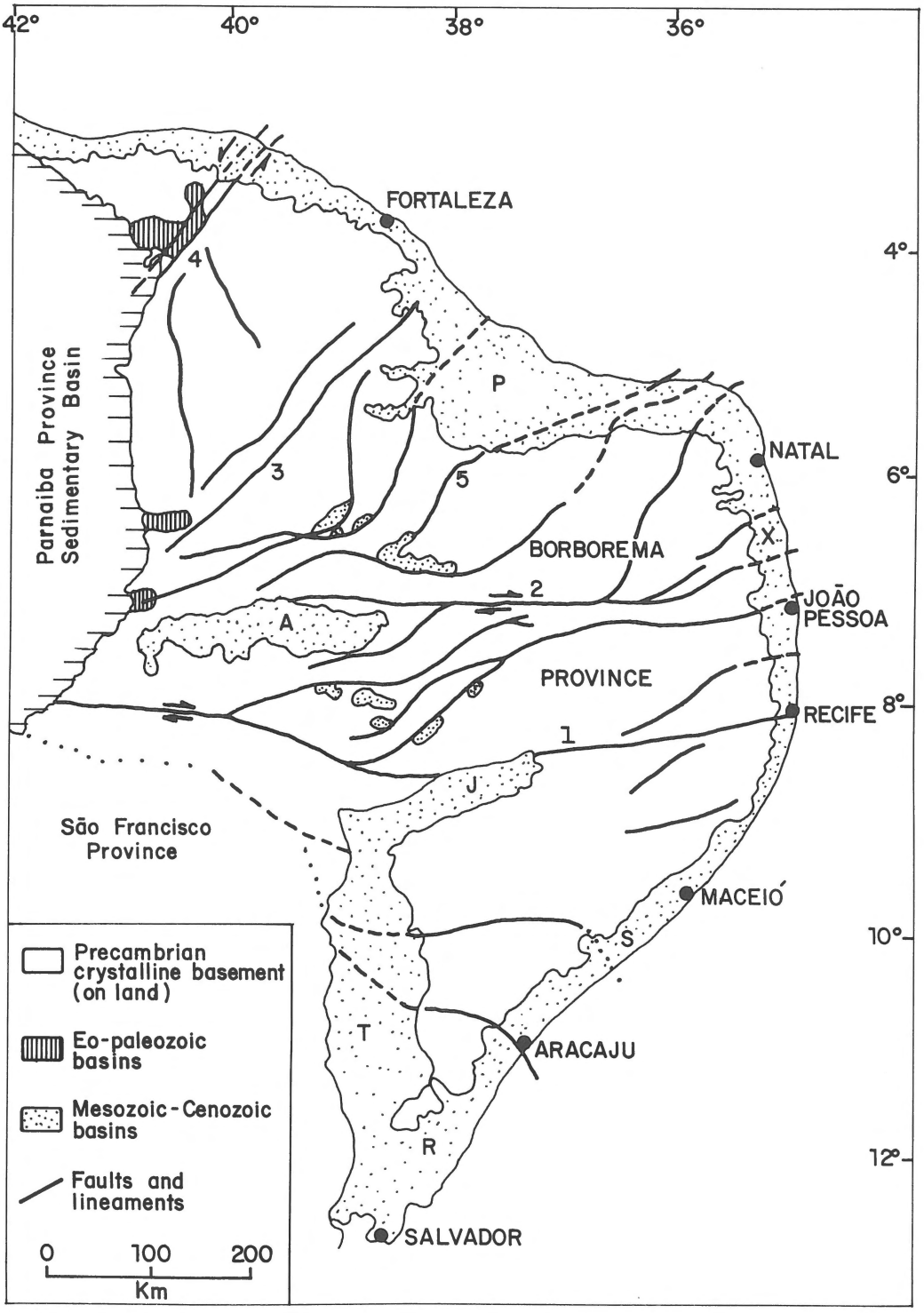

Fig. 2. Tectonic framework of NE Brazil, Borborema Province. Legend: 1. Pernambuco Lineament, 2. Paraíba Lineament, 3. Senador Pompeu Lineament, 4. Transbrasiliano Lineament, 5. Carnaubais fault system; X. Pernambuco-Paraíba-Rio Grande do Norte Basin, P. Potiguar Basin, S. Sergipe-Alagoas Basin, R. Recôncavo Basin, T. Tucano Basin, J. Jatobá Basin, A. Araripe intracontinental Basin.

completely with this idea. The basin consists of a central graben with a SW-NE axis, and tectonic highs at both sides of which the eastern one, the so-called Eastern Platform comprising the Lajes and Touros subbasins, is the most extensive. It seems that the central graben was originally an intracratonic basin which became later invaded by the Equatorial Atlantic Ocean. The lateral highs got their sedimentary cover in a later stage; the stratigraphy of the sedimentary fill favours these ideas (Damasceno et al. 1984). That is why the subbasins of the Eastern Platform have been included in the Pernambuco-Paraíba-Rio Grande do Norte Basin, which extends from the Carnaubais fault system to the Pernambuco Lineament (Fig. 3).

Between these fault systems the sedimentary area can be divided into various more or less individual units, called here subbasins, which together form the Pernambuco-Paraíba-Rio Grande do Norte Basin. At the continental side they show a homoclinal structure due to an irregular flexure, not a fault line. These subbasins developed upon different Precambrian lithological units separated by faults. The individual parts subsided differentially due to differences in competence of the crystalline basement rocks (Rand 1978, Fortes 1986).

Geophysical evidence

Data on magnetic and gravity anomalies have been published by Rand (1978), Rand & Mabesoone (1982), Fortes (1988) and Rand & Manso (1990).

On both the Bouguer anomaly and vertical magnetic field (Fig. 4) maps, each of the recognized subbasins is characterized by a concentration of isogal and isogam lines which coincide with lineaments and lineations, indicating faults.

The gravity method distinguishes three important contacts in the basin: (1) mantle-crust, (2) common basement rocks-diabase, and (3) basement-sediment. The first one reflects different depths of the Moho in neighbouring subbasins, the second density contrasts in the lower crust, and the third depths of the individual sedimentary subbasins.

The diabasic-basaltic rocks which are rather widespread in the subsurface are well identified through negative magnetic anomalies and their position is thus better defined than is shown on geological maps.

The integration of the two methods allows the interpretation of the crustal structure of the Northeast Brazilian bulge, and a comparison with the crustal structures on the opposite side in Africa (Rand 1978). The relative movement of the blocks along the coast suggests a gradual separation of South America and Africa. The differentially subsided slabs of basement rocks, representing the subbasins, are themselves broken up into deeper and less subsided fragments. The site of the last connection between the continents could have been the crystalline high between the Miriri and Canguaretama subbasins (Fig. 3).

Sedimentary fill

Lithological aspects

The sequence of deposits which fill the Pernambuco-Paraíba-Rio Grande do Norte Basin is different from those which appear in the other Atlantic margin basins of Brazil.

In the fault-limited basins of the Southern Atlantic margin the sedimentary fill reflects exactly the four phases of rift development. One finds:

(1) during the pre-rift thermal arching phase: red claystones to shales probably derived from the thick tropical soils formed during the Jurassic;
(2) during the rift phase proper: along the faults, conglomeratic alluvial fan systems, passing into braided and meandering river sytems which debouch into lakes of the deeper part of the rift valley;
(3) during development of the proto-oceanic gulf: shelf carbonate systems, locally with evaporitic basin centres;
(4) in open ocean setting, consequence of continental drift: from the continent seaward: fan-delta systems, carbonate shelf systems and shaly slope systems.

A good example of the complete succession is found in the Sergipe-Alagoas Basin, described by Ojeda & Fugita (1974).

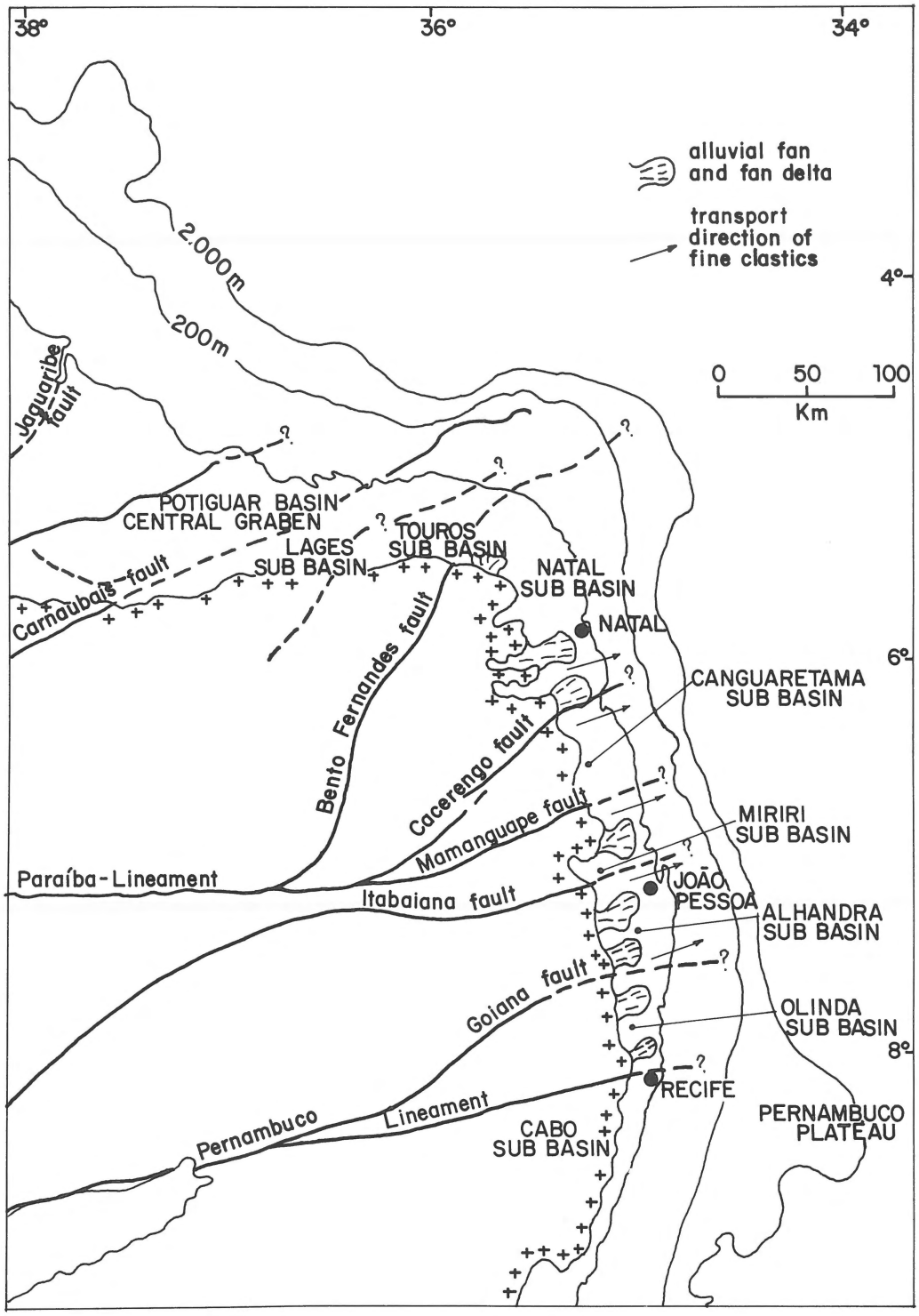

Fig. 3. Subbasins of study area and depositional systems of Upper Cretaceous Beberibe and Açu sandstone formations.

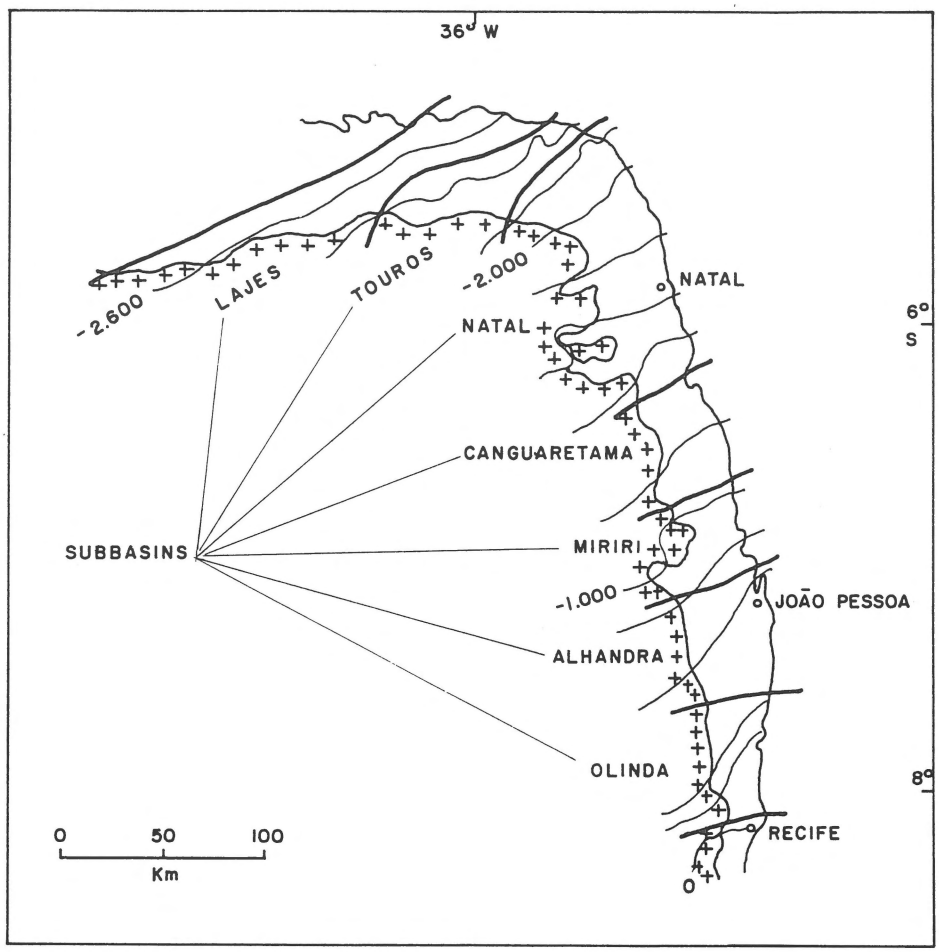

Fig. 4. Map of vertical anomaly magnetic field and division in subbasins (thick lines, cf. Fig. 3), after data from Rand & Manso (1990) and Fortes (1988). Isogam interval 200γ, value 0 = −6750γ absolute (1977, Internat. Geomagnetic Reference Field – IGRF).

The pull-apart basins formed along the Equatorial Atlantic margin show a sedimentary fill in which the proto-oceanic gulf is not represented. One distinguishes a rift phase with its common deposits, overlain by a drift phase during which fine clastics and marine limestones accumulated. In this case the example of the Piauí Offshore Basin (450km NW of the Potiguar Basin) presented by Zalan et al. (1985) may be mentioned.

In the southern subbasins Olinda, Alhandra and Miriri (Fig. 3), the accumulated sequence shows another aspect. Because these subbasins are not rifted, there is no fault at their continental side and no coarse alluvial fan systems have been determined. The succession starts with fluvial systems, more often meandering than braided. At some places fan-delta-like features, characterized by slightly coarser sandstones, have been interpreted by Ojeda (1976) and others (see Fig. 3). Towards the ocean, these systems pass into littoral and shelf sequences of mixed terrigenous-carbonate character (Beberibe Formation). Interesting in this lithostratigraphic unit is the intercalation of a silty-clayey facies, rather rich in fossils, indicative of a brackish lagoonal environment. Follows a rapid transgression which left a fairly coarse-grained fossiliferous calcarenite. Locally these calcarenites are substituted by a phosphatic calcareous sandstone, pointing to upwelling of cold deep-ocean water over a shallow shelf (Mabesoone 1981). These transgression sediments are

covered by a limestone section which, at its base, is composed of biomicrites (Gramame Formation), and at its top of bio- and pelmicrites alternating with calcareous clays in a regressive facies (Maria Farinha Formation; cf. Fig. 5 which, as mentioned further on, also shows the Cretaceous-Tertiary boundary). This succession finishes with a beach sand which is still present in a few places. As one may conclude from this complex, no definite distinction can be made between the different phases of a rift development. Obviously, the equivalent of the rift phase is represented by a fluvial system of lesser energy than the coarse alluvial fans. The proto-oceanic gulf sediments are absent; only the open ocean systems are developed. The here distinguished formations are taken together as the Paraíba Group.

The northern subbasins of Canguaretama, Natal, Touros and Lajes show less well-defined deposits. Here one finds also a lower sandstone section, in part only known in the subsurface from groundwater wells and from seismic investigations. On the top of this sandstone there occurs a limestone sequence of recrystallized microsparites, almost without fossils and often dolomitized. As the northern subbasins are separated by a structural high from the southern ones, and since there is no continuation of the sandstones and limestones over this high, the stratigraphical nomenclature adopted is that of the Potiguar Basin. The sandstones belong to the Açu Formation, the limestones to the Guamaré Formation.

Deposition of the above-mentioned Cretaceous-Tertiary sequences was followed by erosion and denudation. In fact the development of the basins finished because the next sedimentation phase took place independently from the Atlantic margin history.

Ages

The foregoing considerations become clearer when the respective paleontological ages are taken into account. The northern part of the South-Atlantic rift opened in the Aptian, with the accumulation of coarse alluvial-fan clastics south of Recife. These deposits became intruded by volcanics that have been dated radiometrically as Late Albian (Beurlen 1970). On top of this sequence finer clastics and a few limestones are found, dated as Late Cenomanian-Early Turonian. Sedimentation probably continued until the Eocene, as may be concluded from the sequences found on the offshore Pernambuco Plateau, southeast of Recife (Alves & Costa 1986).

Sedimentation started later in the area between the Pernambuco Lineament and the Carnaubais faults. The ages of these lithostratigraphic units are given in Table 1. The Beberibe Formation shows fossils of Santonian-Campanian age in its silty-clayey lagoonal facies. The Gramame calcarenites and other limestones are Late Campanian and chiefly Maastrichtian, based on foraminifera and macrofossils. The regressive Maria Farinha Formation is of Paleocene-Early Eocene age (Mabesoone et al. 1968). The basal sandstones of the Açu Formation in the northern subbasins supposedly have a Santonian age (Souza et al. 1990). The limestones of the Guamaré Formation show ages between Maastrichtian and Early Eocene, as concluded from the scarce fossil occurrences (Beurlen 1970). The Campanian may be present in a more or less continuous sediment sequence (Table 1).

Basin history

The history of the sedimentary coastal strip of Pernambuco, Paraíba and Rio Grande do Norte can be sketched as follows:

The South Atlantic rift opened in its northern part during the Aptian from south to north as far as the Pernambuco Lineament, i.e. the southern limit of the then still existing Brazil-Africa link. At this point, where two fault systems intersect, mantle material poured out and alkaline volcanics intruded the rift fill, predominantly in Albian times.

The first signs of a connection between the South and Equatorial Atlantic Oceans during the Albian come from paleontological data (Noguti & Santos 1972). However, north of Recife no Albian sediments have been found, and probably they were never deposited. This has been interpreted by Rand & Mabesoone (1982) to indicate that the link be-

Fig. 5. Poty quarry, 25 km N of Recife, showing Cretaceous-Tertiary boundary at middle level (white marks): Cretaceous – Gramame Formation, Tertiary – Maria Farinha Formation.

tween NE Brazil and Africa still existed at that time and became only submerged later. Information from the Pernambuco Plateau led Alves & Costa (1986) to conclude that there was a short period of erosion between Late Albian and Cenomanian. In the presently exposed part of the basin, however, the depositional record is too scarce for a further confirmation. During the Late Cenomanian and the

Table 1. Stratigraphy of the Pernambuco-Paraíba-Rio Grande do Norte Coastal Basin and the offshore Pernambuco Plateau

Ages		Northern subbasins: Canguaretama, Natal, Touros and Lajes	Southern subbasins: Olinda, Alhandra and Miriri	Pernambuco Plateau
Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	Hiatus, development of planation surface		turbidites (± 65 m thick)
		unconformity		
		Guamaré Formation (80–150 m)	Paraíba Group: Maria Farinha Formation (35 m)	continuous
Cretaceous	Maastrichtian		Gramame Formation (40 m)	limestone (± 600 m)
	Campanian Santonian	Açu Formation (± 150 m)	Beberibe Formation (± 300 m)	section
		?	?	
	Coniacian Turonian Cenomanian Albian	hiatus	hiatus	unconformity volcanics rift sandstones (± 3000 m)
	Aptian		unconformity	
Precambrian		crystalline	basement	

Early Turonian the sea invaded the South Atlantic rift, resulting in the deposition of shelf to littoral and even sabkha sediments, mainly fine clastics with shelf carbonates. In the now emerged part of the basin this lasted until the Middle Turonian, but more oceanward the carbonate accumulation continued.

From Late Albian onward, the continental link became thinner and narrower, was gradually breached and submerged during high, and emerged during low stands of the sea level. This permitted an exchange of planktonic marine faunas between Equatorial and South Atlantic during transgressions (Early Albian, Cenomanian-Turonian, Maastrichtian), and an exchange of continental and shallow marine faunas between South America and Africa during regressions (Late Albian, Coniacian-Campanian). Along the continental border a strip of basement rocks tilted oceanward, permitting the deposition of fluvial sediments in flood plains. The continental and littoral sandstones of the Beberibe Formation between Recife and João Pessoa, and of the Açu Formation in Rio Grande do Norte, represent the lower sea level during the Santonian and Campanian. Only during the Maastrichtian, with a new transgression, this area became partly submerged.

From the beginning onward, the Paraíba Group displays a South Atlantic affinity in its faunal association. Supposedly the last link between Brazil and Africa tilted towards the south before its final rupture (Mabesoone & Alheiros 1988). As the link tilted southward, but still continued as a sill, upwelling of cold South-Atlantic Ocean water could spill over the narrow shelf area, locally permitting the accumulation of phosphates. In other places, a transgressive calcarenite was deposited in high-energy realms. This phase lasted a rather short time and soon after the sea deepened somewhat, became less agitated and permitted the sedimentation of deeper-water biomicrites. Northward, the sill was still high so that the limestone there could assume a more littoral facies. The structural high along the Mamanguape fault which separates the Miriri and Canguaretama subbasins, is then the remainder of the former land connection on the continental side. The Canguaretama and more northern subbasins of Rio Grande do Norte State were filled with material coming from the north and thus constitute a continuation of the Equatorial Atlantic basins.

The sedimentary history of these northerly subbasins was similar. The differentially subsiding basement rock strips permitted the deposition of fluvial clastics and only later, in Maastrichtian time, the transgression of the sea provoked a limestone deposition (Eastern Platform) of shallow-water character. There is no continuity between the northern and southern limestones sections. During the Maastrichtian the link broke up at last.

Finally, during the Paleocene, probably even continuing into the beginning of the Eocene, the sea withdrew from the area, leaving behind regression calciclastics and clays. In that period the final link between the continents was severed, and South America started its westward drift, still rotating with respect to Africa. The seaway between the South and Equatorial Atlantic Oceans had been firmly established, although it remained narrow for a time and landbridges could have existed occasionally.

During the slow regression from the Paleocene onward, the continental area suffered tectonic adjustment in consequence of the continental breakup. The area became then subject to erosion and denudation, a phase which lasted until the end of the Tertiary.

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