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Ages of the Magmatism and the Opening of the South Atlantic Ocean

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Abstract - The analysis of published and unpublished 368 K/Ar radiometric ages of basic, intermediate and alkaline volcanic rocks, related to the post-Palaeozoic magmatism linked to the opening of the South Atlantic Ocean, yields some important evidence concerning the break up of the Gondwana supercontinent. At the Brazilian Equatorial margin, the Gondwana break up started in the Permo-Triassic, when the opening of the Equatorial South Atlantic Ocean began and spread out south-eastward up to the present -day Amazon River mouth. During the middle Jurassic/lower Cretaceous (pre-Aptian), the continuity of this separation, towards the Potiguar Basin, was coeval with the northward opening of the south-east Brazilian margin, up to the Espírito Santo State latitude. The relationship between large volcanic events in the basins and the resistance to the rifting process development offered by the cratonic area was shown by the trend of the magmatic age. Along the equatorial margin, the fragmentation resistance caused by the São Luis/West African craton is manifested by a large basic magmatism described in the Tacutu, Acre, Solimões, Amazonas and Parnaíba basins. A similar mechanism, along the south-east margin, is proposed for the magmatism described in the Paraná Basin which is associated with the fracturing resistance offered by the São Francisco/Congo cratonic area. The integration of geochronological, micropalaeontological, sedimentological and geochemical data from the basins of the east Brazilian continental margin supports a model to explain the final disruption between South America and Africa during Cenonian/Turonian time. This model implies that 90 Ma basic magmatic rocks, related to the oceanic crust formation, probably occur offshore from the present-day eastern Brazilian coast line.

Key words: radiometric ages, magmatism, South Atlantic Ocean

GEOLOGICAL SETTING OF THE MAGMATISM

The South American continent is divided into three large tectonic regions - the South American Platform, the Patagonian Platform and the Andean Cordillera (Schobbenhaus *et al.*, 1984) (Fig. 1). The Brazilian territory is entirely set on the South American Platform where the last major orogenic activity was the Brazilian/Pan African tectonic event (late Neoproterozoic and early Palaeozoic). The Amazon and São Francisco cratons (Fig. 1) are the most important pre-Brasiliano cratonic areas of the South American platform (Schobbenhaus *et al.*, 1984). During the Ordovician, moderate subsidence led to the development of the large intracratonic Amazonas, Solimões, Parnaíba and Paraná basins (Fig. 1). A large tectono-magmatic event, by the end of the Jurassic, coincided with the formation of the Brazilian offshore marginal basins. This event is related to the break up of the Palaeozoic Gondwana supercontinent and the drift apart of the South American and African continents. Following this crustal separation, the Atlantic margins of both sides evolved into passive margins.

Mesozoic igneous rocks (intrusive and extrusive), which occur both in the Brazilian interior and marginal basins, are closely related to this continental break up. This study is based on published (Thomaz Filho *et al.*, 1974; Asmus & Guazelli, 1981; Schobbenhaus *et al.*, 1984; Almeida, 1986; Almeida *et al.*, 1988; Mizusaki *et al.*, 1992; Pereira, 1992;) and unpublished 368 radiometric Potassium/Argon (K/Ar) ages for these igneous rocks wich their composition ranges from basic to alkaline. The age data were grouped into three broad groups: Equatorial, East and Southeast Brazilian basins (Fig. 1).

The equatorial group includes all the coastal basins from the border of French Guyana and Brazil to the Potiguar Basin (Fig. 1) plus the interior Acre, Solimões, Amazonas and Parnaíba interior basins. In the equatorial margin, the continental shelf is wide (more than 300 Km wide near the Amazon River mouth) and its main morphological features are the Amazon River Mouth, the North Brazilian and Fernando de Noronha ridges and the São Paulo and Romanche fractures zones (Fig. 1).

The eastern group, which roughly coincides with the São Francisco cratonic area and the interior rift basins (Recôncavo, Tucano and Jatobá) (Fig. 1),

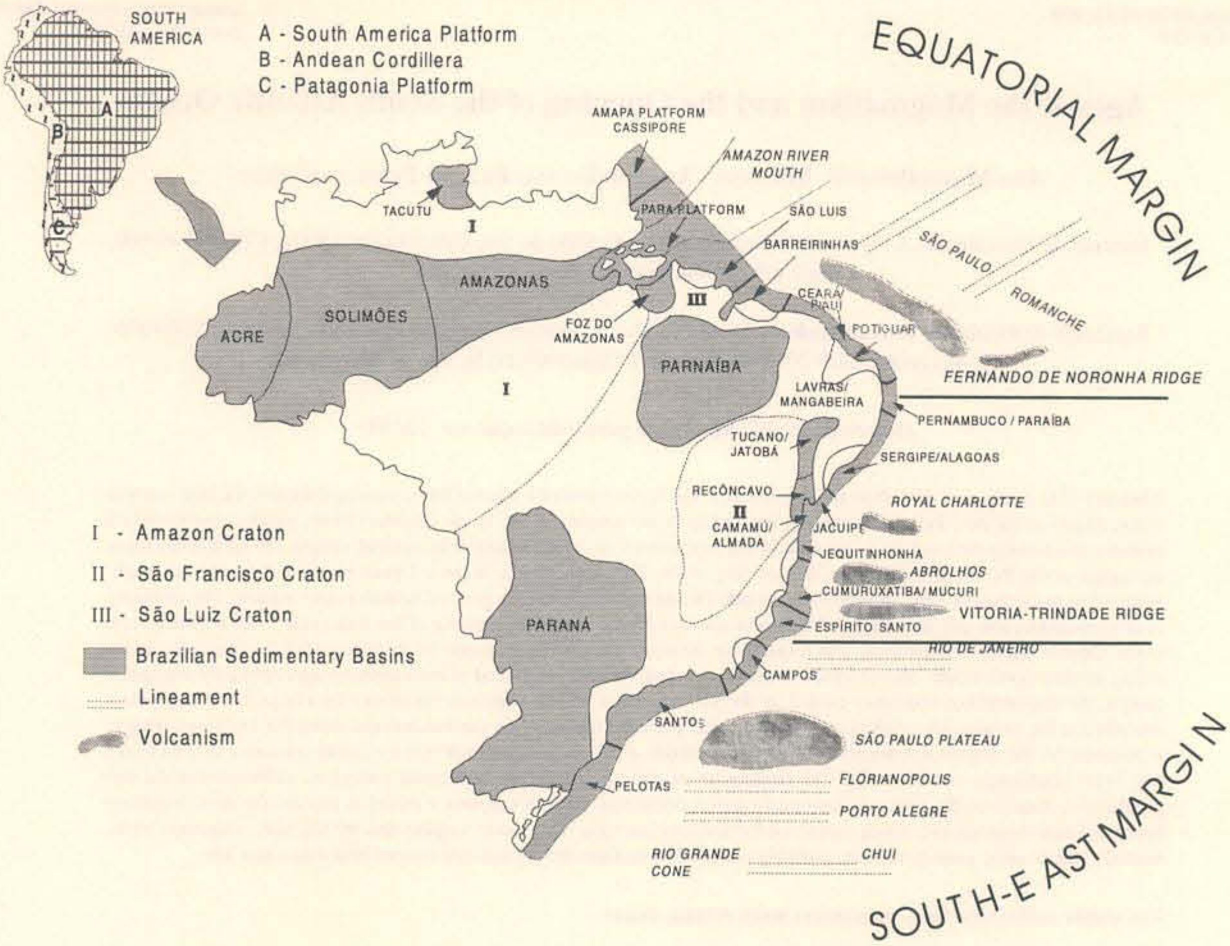

Figure 1 - Sedimentary basins and physiography of the Brazilian continental margin (after Palma *et al.*, 1979 and Rajagabaglia & Figueiredo, 1990).

covers a wide region with scarce magmatic activity, where only a few dikes and flows of Mesozoic age occurs. This eastern segment has a narrow continental shelf (nearly 40 km wide) and a steep slope (around 25^0), without any structural barrier. The volcanic rocks of Royal Charlotte, Abrolhos and the ridge chain of Vitoria/Trindade are the main structural features (Fig. 1).

The south-eastern group is represented by a large area - from the Campos to Pelotas basins - including the huge interior Paraná Basin (Fig. 1). This region has a large continental shelf (150 km wide) and a gently dipping wide slope. The main structural features are the São Paulo Plateau, the Rio Grande sedimentary cone and the Rio de Janeiro, Florianópolis, Porto Alegre and Chuí fracture zones (Fig. 1).

The adopted geological time scale was that proposed by Harland *et al.* (1989).

GEOCHRONOLOGY OF THE MAGMATISM (K/Ar DATING)

Potassium/Argon (K/Ar) is one of the most important and widely used routine methods based on parent/daughter isotope ratios. The decay of ^{40}K into radiogenic ^{40}Ar is the basis of this conventional age method (Faure, 1986). In this study, K was determined by atomic absorption spectrophotometry while Ar was extracted by vacuum fusion and determined by isotope dilution, using the procedure described by Teixeira (1985) following Amaral *et al.* (1966). Most of the determinations were made using whole-rock (WR) samples due to the fine texture of the analyzed samples.

The K/Ar method indicates the crystallisation age, except if later hydrothermal, diagenetic or weathering alterations have resulted in Ar loss. This problem was constrained by selecting only fresh rocks, based on detailed petrographic description of the samples. If weathered materials are analyzed, minimum ages are always obtained.

This paper incorporates all published and unpublished K/Ar ages, nearly 70% of them were determined at the Geochronological Research Centre of Earth Sciences Institute at São Paulo University (USP) from 1972 to 1994, through agreement with Petrobras Research and Development Center (CENPES). All the K/Ar analytical results are stored at the Central Memoir of the Petrobras Research and Development Center (Rio de Janeiro, Brazil).

Basin**	Margin	PERMO-CARBONIFEROUS (300)		TRIASSIC (200)	JURASSIC	CRETACEOUS (100)		TERTIARY	DETERMINATIONS *
TACUTU	EQUATORIAL MARGIN				11	2			13
ACRE	EQUATORIAL MARGIN	1	2		2				5
SOLIMÕES	EQUATORIAL MARGIN		3	22	17	7			49
AMAZONAS	EQUATORIAL MARGIN	1	13	17	15	9			55
AMAZON RIVER MOUTH	EQUATORIAL MARGIN	1	1	1					3
AMAPA PLATFORM	EQUATORIAL MARGIN			1	4	8	6		14
SÃO LUIS	EQUATORIAL MARGIN				1	1	1		3
CEARA/PIAUI	EQUATORIAL MARGIN			1			2	3	6
PARNAIBA	EQUATORIAL MARGIN			3	14	9	3	4	33
POTIGUAR	EQUATORIAL MARGIN			1	4	13	3	39	60
LAVRAS MANGABEIRA	EQUATORIAL MARGIN			6					6
PERNAMBUCO/PARAIBA	EAST MARGIN					1			1
CUMURUXATIBA	EAST MARGIN						2	2	4
ESPIRITO SANTO	EAST MARGIN					8	16	33	57
CAMPOS	SOUTHEAST MARGIN			4		12	5		21
SANTOS	SOUTHEAST MARGIN				1	3	3	2	9
PELOTAS	SOUTHEAST MARGIN					2	1		3
PARANA	SOUTHEAST MARGIN			1	5	20			26
TOTAL		3	19	51	80	90	42	125	368

Figure 2 - Distribution of the K/Ar ages in the Brazilian sedimentary basins.

** See Figure 1

Almost all analyzed rocks are core samples from wells located on the Brazilian continental shelf and interior basins. Outcrops of magmatic rocks in the interior basins were also sampled for K/Ar dating.

The distribution of the 368 age data, according to the proposed subdivision into equatorial, east and south-east margins, is shown in figure 2.

The magmatic events in the equatorial margin are supported by 247 K/Ar determinations, with ages ranging from 300 Ma to a few millions years. The most dated interval ranges from 120 to 150 Ma while the volcanic activity apex is around 170-230 Ma. Concerning K/Ar age determination, this portion of the Brazilian continental margin includes the majority of the data (Figs. 2 and 3).

The eastern margin has 62 K/Ar determinations. One of them represents a 105 ± 9 Ma diabase dike of the eastern portion of the Tucano Basin. In the western portion, an age around 73 Ma has been determined by Magnavita *et al.* (1994) (Figs. 2 and 3).

The south-east margin has 59 magmatic age determinations, mostly from the Cretaceous of the Campos and Paraná basins (Fig. 3).

Generally, Jurassic, Cretaceous and Tertiary are the most representative periods of magmatic activity in the Brazilian continental shelf and interior basins, as can be seen in figures 2 and 3.

RIFTING MODEL OF THE MARGINAL BASINS

The disruption of the Gondwana Palaeozoic supercontinent - which included South America, Africa, India, Australia and Antartic - and the consequent opening of the South Atlantic Ocean were

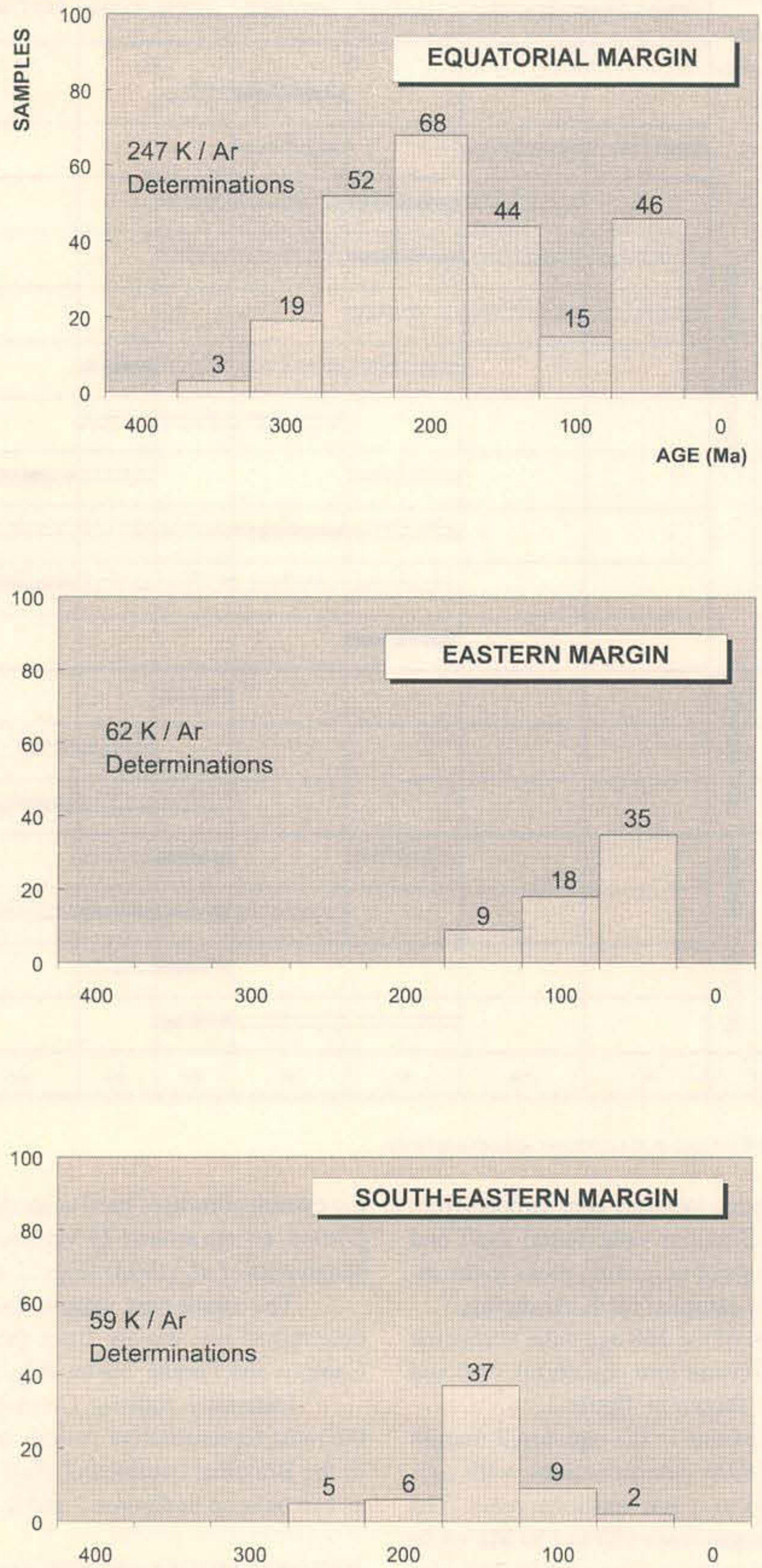

Figure 3 - Histogram showing the distribution of the K/Ar radiometric ages.

accompanied by significant tectonic, sedimentary and both intrusive and extrusive magmatic events that extended over a large portion of the South American Platform (Almeida, 1972). The first manifestation of this magmatism, represented by basic intrusions and extrusions, occurred in the northern equatorial portion of the study area during the Permian-Triassic (Fig. 3) although the maximum intensity was reached during the middle- Jurassic/early-Cretaceous (pre-Aptian), specially in the south-eastern margin (Fig. 3).

The most important outcome associated with this event is the East Brazilian Rift System (EBRIS) (Chang *et al.*, 1992) wich represents the northern segment of the South Atlantic rift during the Mesozoic break-up of South America and Africa. This rift system developed as a result of a late-Jurassic/early Cretaceous lithosphere extension. In the late Aptian, EBRIS evolved to a passive margin where continental (Sergipe/Alagoas, Jacuipe, Camamu, Almada, Jequitinhonha, Cumuruxatiba, Mucuri, Espírito Santo, Campos, Santos and Pelotas basins from north to south (Fig. 1) and onshore (Recôncavo, Tucano and Jatobá grabens) basins were formed. The onshore basins are associated with the Afro-Brazilian Depression (Ponte *et al.*, 1971; Estrella, 1972), a huge N-S Jurassic intracratonic basin, bounded by the Alagoas (north) and Almada basins (south) and rapidly filled with continental sediments. The Afro-Brazilian Depression coincides with the region that constitutes the east margin and is the only known portion of the Brazilian margin that contains non-marine, Jurassic and Permian sedimentary rocks deposited during a time of relative tectonic quiescence (the Sin-rift sequence I of Chang *et al.*, 1992). In other basins, along the equatorial and south-east continental margins, deposits older than Neocomian age were not recognised. A possible exception to this pattern is the Barreirinhas Basin in the Equatorial margin (Fig. 1), where Jurassic and Permian sedimentary rocks were found. However, these rocks could just represent a north-eastern extension of the Palaeozoic Parnaíba Basin into the equatorial margin (Northfleet *et al.*, 1972; Bol. Geociências Petrobrás, 1994).

From the east to the south-east margin, the oldest sedimentary sequences described in the Jequitinhonha and Cumuruxatiba basins (Fig. 1) are Neocomian and Aptian, respectively. It is important to emphasise the absence of Neocomian magmatic rocks of these basins. Otherwise, the Espírito Santo Basin contains intercalated basic igneous volcaniclastic and sedimentary rocks. K/Ar ages of this sequence indicate a large volcanic event, around 120-140 Ma (Figs. 2 and 3), coeval with Neocomian and Barremian sedimentation (Conceição *et al.*, 1994).

Southwards from the Cumuruxatiba Basin, in the basins along the south-eastern margin, Neocomian sedimentary rocks are replaced by basaltic lava floods, which are overlain by lava flows and sedimentary rocks of the Syn-rift sequence II (according to Chang *et al.*, 1992). This situation is similar to the magmatic activity that occurs in the Campos, Santos and Pelotas basins, where the base of the volcanic sequence, which is covered by sedimentary rocks of Barremian age, has not been reached. Neocomian and older sedimentary deposits were still not recognised in these basins.

The Potiguar Basin of the equatorial margin (Fig. 1), which contains basal Neocomian sediments, has tholeiitic diabase dikes along its southern portion, with a preferencial east-west direction and ages in the range between 120 and 140 Ma. However, these magmatic rocks are not associated with Neocomian sedimentary rocks as they only cross-cut basement rocks. The oldest rocks in the Ceará/Piauí and São Luis basins, and in the Pará Platform, are Aptian. An exception to this pattern is the Barreirinhas Basin, as discussed above. On the other hand, the Amazon River Mouth Basin and the Amapá Platform (equatorial margin) contain a thick volcano-sedimentary sequence with tholeiitic magmatic rocks of late-Triassic/early-Jurassic (180-220 Ma).

Taking into account this information, and the different magmatic events shown in figures 2 and 3 it is possible to infer that the rifting process, responsible for the separation of the South America and Africa, has actually begun along the equatorial margin, where the oldest magmatic events were recognized. The magmatism in the Amazon River Mouth, Tacutu, Acre, Solimões, Ama zonas and Parnaíba basins, and in the Amapá Platform, had its climax around 170-230 Ma ago (Mizusaki *et al.*, 1992), probably accompanying the early South Atlantic event (160-225 Ma), as proposed by Conceição *et al.* (1988), following Schobbenhaus *et al.* (1984) conception. In these basins, and also in the basins along the eastern equatorial margin, it is possible to observe the temporal evolution of the basic magmatism around 120-130 Ma (Fig. 3). Coeval magmatic activity is also registered in the São Luis and Barreirinhas basins, and also basic dikes of the same K/Ar age occur in the southern portion of the Potiguar Basin. This south-east extension of the magmatism could be related to the South-Atlantic Event (115-160 Ma), as defined by Conceição *et al.* (1988), with tectonic reactivation taking place from the Ilha de Santana Platform towards the Potiguar Basin (Fig. 1).

Along the south-east margin, the rifting process has probably been driven by the NE-SW Precambrian structures, specially those related to the Brazilian/Pan African mobile belts. The rifting process has started around 200 Ma in the southernmost portion of South America. According to Uliana & Biddle (1988), this prelude of the Gondwana supercontinent disruption occurred from the middle to upper Triassic, taking into account the occurrence of contemporary basic dikes along the southernmost area of South America.

The opening of the southern portion of the South Atlantic Ocean, from the Malvinas Plateau to the Pelotas Basin, is called the Early South Atlantic event (160-225 Ma) (Schobbenhaus *et al.*, 1984; Conceição *et al.*, 1988). On the other hand, the 2nd cycle of this event (115-160 Ma) evolved through the opening of the coast, from teh São Paulo Plateau to the Sergipe/Alagoas Basin.

The northward trending, initial rifting of the south-east Brazilian margin was associated with basic volcanism taking place from the Pelotas to Espírito Santo Basins. These 120-140 Ma volcanic rocks are intercalated with volcano-sedimentary layers and represent the economic basement of the Campos Basin. The same magmatic event was described in the Santos and Pelotas basins and also in the Paraná Basin. Concerning the presented data, this stage of opening of the South Atlantic Ocean has probably spread out to the Espírito Santo Basin.

DISCUSSION

Concerning the available data, there is a remarkable scarcity of magmatic ages within the interval 120-130 Ma in the eastern margin (Fig. 2) when compared with the others portions of the continental margin. Possibly, this magmatic quiescence is related to the evolution of the South Atlantic rifting. Asmus (1982) concluded that the south-eastern marginal basins, characterized by an intense magmatic activity, probably associated with thermal anomalies, are rift type basins. This author also characterized the eastern marginal basins as deep rifts with no volcanic activity and denominated them fissural rifts. The same paper considered the São Francisco/Congo craton as the main feature responsible for this remarkable absence of volcanic events in the eastern Brazilian marginal basins.

Therefore, it is possible to suggest that the 2nd cycle of the South Atlantic event, along the south-east margin, progressed northwards, associated with basic volcanism, up to the Espírito Santo Basin. The northward continuity of the rifting was influenced by an area of thick lithosphere and crust (Szatmari *et al.*, 1987), represented by the São Francisco/Congo craton, the oldest basement province in the eastern Atlantic margin (Fig. 4). The strength of this cratonic area lead to the development of the Curitica-Maringá fault zone (Brazil) and the Salado and Colorado rifts (Argentina) (Fig. 4) (Conceição *et al.*, 1988), both nearly orthogonal to the initial rifting direction. The Serra Geral Formation in the Paraná Basin and the Kaoko basalts in Namibia (Siedner & Mitchell, 1976), both comprised within the 120-140 Ma interval, are considered to be the result of the pouring of basic magmas throughout these tensional structures. According to Leyden (1976) and Chang *et al.* (1992) this volcanism is related to the Torres-Posadas lineament (Fig. 4). Furthermore, the apex of this volcanic activity is correlated with the main period of crustal stretching of the Brazilian south-east margin, probably reaching the Campos Basin (Françolin & Cobold, 1994) where a synchronous magmatic basic activity took place.

The evolution of the South Atlantic ocean was divided by Conceição *et al.* (1988) into two distint stages: tensional accumulation in the lithosphere (ductile deformation, stretching and crustal extension) and tensional discharge (intense normal faulting with lithosphere rupture and oceanic crust generation). The tensional build up, ascribed to the resistence to rupture of the São francisco/Congo cratonic area, was followed by the liberation of a large amount of energy, represented by a huge basic magmatism (120-140 Ma) and consequent release of the accumulated lithosphere tension. This event might be responsible for the delay on the rifting propagation northwards from the Espírito Santo Basin.

Taking into account the aforementioned ideas, it is proposed that the eastern portion of the Brazilian continental margin remained as the effective link between South America and Africa, with consecutive lithosphere stretching and faulting during the 100-120 Ma interval, wich has been characterized by a significant absence of magmatic rocks in the Espirito Santo and Potiguar basins. A basic magmatic pulse, within the 80-100 Ma interval, was recognised in these basins and ascribed to tectonic movements during the final rupture.

The complete disruption of South America and Africa, and consequent oceanic crust generation, was also recognised by sedimentological, micropalaentological and geochemical studies undertaken in the Brazilian sedimentary marginal basins (Dias Brito, 1987; Schlanger *et al.*, 1981; Chang & Kowsmann, 1987; Koutsoukos, 1992; Koutsoukos *et al.*, 1991 A, B; Koutsoukos & Bengston, 1993; Pereira, 1992,1994).

Northfleet *et al.* (1972) proposed that the first marine flooding in the eastern margin has been from south to north, probably during the Albian-Aptian, and has originated a large sea - the South Atlantic Ocean precursor. Initially, this interior sea was restricted and characterized by evaporite sedimentation. From the Albian to the Cenomanian, true marine

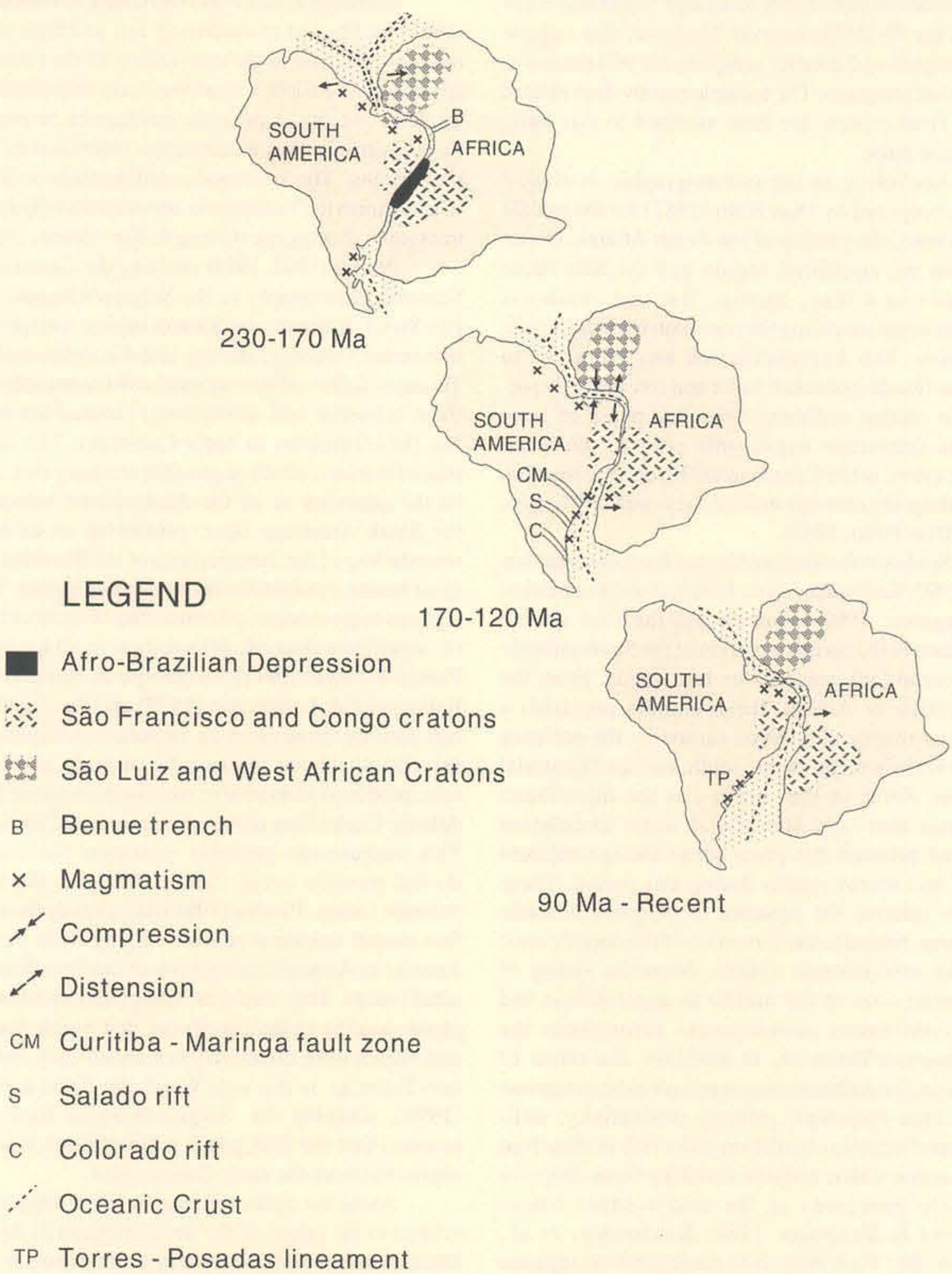

Figure 4 - Relative positions of South America and Africa during the opening of the South Atlantic Ocean and associated magmatism.

conditions were gradually reached although the two continents were still linked. According to these authors, the disruption has actually happened in the late Cretaceous, more specifically in the late-Cenomanian/early-Turonian, and it was followed by basic magmatism, with radiometric ages around 90 Ma. Therefore, the junction of the North and South Atlantic Oceans was completed only in the Turonian, when the sedimentation in an open sea of high energy environment took place in the marginal basins of both continents.

Conceição *et al.* (1994) studied the tectonic control of the middle-Cenozoic magmatism in the Espírito Santo, Mucuri and Cumuruxatiba basins and considered the possibility of a large magmatic event around the 70-80 Ma interval. However, new seismic data coupled with a better sampling are still needed to test this assumption. The tectonic reactivation related to the final rupture are here ascribed to this basic magmatic pulse.

According to the oceanographic evolution model, proposed by Dias Brito (1987) for the middle -Cretaceous, the portion of the South Atlantic Ocean between the equatorial region and the São Paulo Plateau was a long, narrow, flat and continuos epicontinental sea during the transition from the Aptian to Albian. This hypersaline sea was submitted to periodic flooding of ocean water and consequently pre-oceanic marine sedimentation. The phase of truly oceanic deposition began only after a significant anoxic event, at the Cenomanian/Turonian transition, when deep sea currents eroded these strata (Morgan, 1978; Dias Brito, 1987).

Studies in the Sergipe/Alagoas Basin (Koutsoukos *et al.*, 1992; Koutsoukos *et al.*, 1991A, B and Koutsoukos & Bengston, 1993) showed that the first marine deposition in the northern portion of the South Atlantic proto-ocean took place in the late Aptian. From the late Aptian to Albian, these authors proposed a restricted marine circulation caused by the presence of the Walwis ridge, in the south, and the Equatorial Fracture Zone, in the north , as the microfauna indicates that only superficial water circulation occurred between this proto-ocean and the adjacent (north and south) oceans during this period. These authors inferred the presence of deep-sea volcanic processes, related to the formation of the oceanic crust and the mid-oceanic ridges, from the rising of radiolarian ooze in the middle to upper-Albian and their continuous development throughout the Cenomanian/Turonian. In addition, the onset of radiolarian assemblages was supposed to be a response to the high epipelagic primary productivity, well-developed oceanic circulation and a rich in dissolved silica ocean water, perhaps resulting from deep-sea volcanic processes in the mid-oceanic ridges (Berthou & Bengston, 1988; Koutsoukos *et al.*, 1991 A, B). Therefore, it is reasonable to suppose that the oceanographic and structural connection between the South Atlantic and South Equatorial oceans only occurred during the early and middle-Turonian. The final structural disruption between the African and the South American plates only happened during the late Conician/early-Santonian, when deep oceanic circulation was stablished and the essentially carbonate deposition cycle was extinguished.

Schlanger *et al.* (1981) and Chang & Kowsmann (1987) interpreted an extremely fast and high amplitude eustatic pulse as the main reason for the extinction episode of all middle-Cretaceous carbonate platforms. To these authors, a possible mechanism to produce this catastrophe was a submarine volcanism of large proportions. The subsequent sedimentary sequence (Cenomanian to Coniacian) is considered a fully marine transgressive sequence (Chang & Kowsmann, 1987).

Pereira (1992, 1994) studying the Cenomanian/Santonian stratigraphy in the Sergipe/Alagoas, Espírito Santo, Campos and Santos basins, interpreted a maximum flooding, during late-Cenomanian/early Turonian, followed by a regional erosive unconformity (both subaerial and subaqueous) scoured around 90 Ma (late-Turonian to early-Conician). The author related this last event to a possible readjustment, either on the geometry or on the displacement velocity of the South American plate, promoting an extensive remodelling of the deep portions of the Brazilian marginal basins associated with basic magmatism. These regional scale changes are connected to the occurrence of significant post-rift deformation in all basins. Le Pichon & Hayes (1971), LaBrecque & Hayes (1979), Rabinowitz & LaBrecque (1979) and Pereira (1992) had already recognised an important readjustment, associated with the 34 magnetic anomaly, that would have produced an extensive modification on the South Atlantic Ocean floor during the Santonian/Campanian. This readjustment probably represents the Cruzeiro do Sul tectonic event (Souza, 1991) in the South Atlantic Ocean. Pereira (1994) had already described five crustal tensional phases, ranging from the late-Jurassic to Albian/Cenomanian, in the Brazilian marginal basins. They could be interpreted as a long rift phase, leading to the conclusion that South America and Africa were effectively connected only until the late-Turonian. In this way, Wanderley Filho & Destro (1994), studying the Sergipe/Alagoas Basin, had asserted that the drift phase sedimentation was only registered from the early-Cenomanian.

Along the equatorial margin, the rifting process, related to the origin of the South Equatorial Atlantic Ocean, continuously evolved up to the Amazon River Mouth Basin where sedimentary rocks are intercalated with contemporary basic igneous rocks. Consequently, as observed in the south-east margin, it is possible that the resistence to the rift evolution, associated with the necessity to cross cut basement preferential directions, including the breakage of the São Luis/West African craton (Almeida *et al.*, 1986), could have been enhanced in the 160-230 Ma interval due to a change from a brittle to a ductile behaviour of the lithosphere.

Inland, this last phase is represented by isolated dikes and sills, mostly in the Tacutu, Amazonas, Solimões, Acre and Cassiporé basins, and also by north-northwest diabase dike swarms, along the Cassiporé Basin and the Amapá platform (Thomaz-Filho *et al., 1974*).

The continuity of the tholeiitic basic magmatism up to 120-130 Ma, as recognised in the Potiguar Basin, is an evidence that the rifting fracturing activity followed a southeastward trend and was already coeval with the south-east margin rifting. Northfleet *et al.* (1972) and Asmus (1982) suggested that the rifting process in the equatorial margin was controlled by the shearing effect of the transform faults whereas in the south-eastern and eastern margins only tensional features can be observed. Such stress was associated with displacements in the Atlantic mid-ocean ridges, mostly along the Romanche fracture zone (Fig. 1). Similarly, Chang *et al.* (1992) proposed two different types of behaviour along the Brazilian margin, based on the pattern of tectonic stress. The north equatorial Brazilian margin was dominated by transcurrent movements and all the basins were consequently influenced by complex shearing, whereas the east margin was characterized by passive basins associated with crustal extension (essentially orthogonal). The complete break up of the continents in the eastern margin promoted an acceleration of the continental plates displacement and intensified the transcurrence along the equatorial margin, as indicated by the shearing effects observed in the Ceará Basin and in the Maranhão continental shelf (Miura & Barbosa, 1972). Françolin & Cobbold (1994) related the lower Cretaceous deformation to transcurrent movements along the equatorial margin and used it to explain the complexity of the tectonic structures in this area. Szatmari *et al.* (1987) suggested an early-Cretaceous mechanism of clockwise rotation of South America relative to Africa. This movement caused compression and the development of the Ferreira-Urbano Arch; basement uplift and the absence of Neocomian layers eastwards of the Fortaleza city. Further to the east, the tensional process was associated with the origin of the Potiguar Basin.

The extensional tectonics promoted the intrusion of lower Cretaceous diabase dike swarms along the Cabugi Lineament, southern of the Potiguar Basin. This E-W lineament is around 300 km long and is associated with the Rio Ceará-Mirim volcanism (Gomes *et al.*, 1981; Almeida *et al.*,1988). Coeval volcanic activity was reported in the Benue Trough (Africa) (Milani & Latgé, 1987). It is important to emphasise that the Benue Trough, by the end of the cretaceous, was intensively folded and thrusted. These events are recorded from the Albian to the Turonian sequences (along the lower and middle Benue) up to the Maastrichian (upper Benue) (Szatmari *et al.*, 1987).

The Aptian is a period marked by westward propagation of the rift along the equatorial margin and eastward propagation along the Benue trench. From the Albian, a dextral transcurrent tectonic (Azevedo *et al.*, 1985; Zalan & Warme, 1985; Azevedo, 1986) promoted the development of a north-western rombo-graben system.

CONCLUSIONS

The available, mostly unpublished, data concerning the K/Ar ages of basic, intermediate and alkaline post-Paleozoic magmatic rocks from several Brazilian sedimentary basins and also from some portions of the adjacent basement, has allowed us to interpret the rifting evolution ascribed to the opening of the South Atlantic Ocean (Fig. 4).

The oldest volcanic episode recorded in the equatorial margin was dated as Triassic/Jurassic and related to the opening of the North Equatorial Atlantic Ocean. This volcanic episode can be continuously observed up to the Amazon River Mouth. However, its south-east evolution has been hindered by the strong resistence caused by basement transverse structures, particularly in the São Luis/West African craton. This event is linked to a large energy release and has resulted in basic igneous extrusions and intrusions in the Tacutu, Acre, Solimões, Amazonas, Parnaíba and Cassiporé regions.

Likewise, along the south-east margin, the rifting process has started during the upper - Jurassic/lower - Cretaceous but, in this case, spreading northwards, from the Pelotas to Espírito Santo basins. The resistence offered by the São Francisco cratonic area promoted intense volcanism in the interior of the disrupting continents, specially in the Paraná Basin. This pouring promoted energy atenuation during the rifting evolution. Concurrently, the Equatorial margin, east of the Amazon River Mouth, was submitted to transcurrence due to clockwise rotation of the plate, producing transtension and transpression, east and westwards, respectively, from the Fortaleza city.

The distribution of the radiometric age shows a peculiarity in the area between the Espírito Santo and Potiguar basins, the northern and southern boudaries of the east margin. The basic rocks, within the 100-120 Ma interval, are apparently absent. This suggests that the final disruption between the South American and African continents is probably younger than 100 Ma. The integration of radiometric data with geochemical, sedimentological and micropalaentological studies indicates that marine sedimentation in the eastern margin has begun in the Aptian although the actual separation between the South Atlantic and South Equatorial Atlantic oceans has only happened in the Cenonian/Turonian (90 Ma).

The data presented has also led us to the conclusion that basic volcanic rocks, with radiometric ages around 90 Ma, are likely to occur in deeper portions of the present-day eastern coastline. However, this hypothesis needs to be tested as this area has not been drilled yet.

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