THE RIO GRANDE DO NORTE ALKALI — OLIVINE BASALT ASSOCIATION, NORTHEAST BRAZIL

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ABSTRACT The Tertiary volcanic suite of Rio Grande do Norte, Brazil, composed of ankaratrites, basanites, and olivine-basalts with basanitic or tholeiitic affinities formed plugs, necks, flows and dikes which cut the Precambrian basement and Cretaceous sediments of the Apodi Basin in a north-south trend. Crystallization began with olivine followed in sequence by pyroxene, iron oxides, apatite and nepheline whereas the olivine-basalts started with olivine, followed in sequence by plagioclase, augite and iron oxides. The magma crystallized under fO_2 equivalent to the FMQ buffer. Xenocrysts of olivine, orthopyroxene, clinopyroxene, spinels and granular and sheared spinel-lherzolite and harzburgite nodules are found as inclusions in several necks and plugs. The entire xenolith suite was derived from depth of approximately 64 km. The alkali basaltic magma formed by partial melting under pressure of at least 20 kb. Fractionation gave rise to the ankaratrites and basanites. The increase of partial melting generated an olivine basaltic magma which gave rise to the flows, dikes and some necks. The emplacement of this suite is related either to internal readjustment within the South American plate during its westward displacement or to the Tertiary pressure release of arched zones formed in the Upper Mesozoic during the opening of the South Atlantic Ocean.

RESUMO A suíte vulcânica terciária do Rio Grande do Norte, composta de ankaratritos, basanitos e olivina-basaltos com afinidades toleíticas ou basaníticas, formou *plugs*, *necks*, derrames e diques que cortam o embasamento cristalino e os sedimentos cretácicos da bacia do Apodi. A cristalização magmática nos ankaratritos e basanitos iniciou-se com olivina, seguida sucessivamente por piroxênio, (plagioclásio), óxidos de ferro, apatita e nefelina, enquanto que, nos olivina-basaltos, iniciou-se com olivina seguida sucessivamente por plagioclásio, augita e óxidos de ferro. O magma cristalizou-se sob fO_2 equivalente ao *buffer* FMQ. Xenocristais de olivina, ortopiroxênio, clinopiroxênio, espinélios e nódulos de espinélio-lherzolitos e hazburgitos, granulares e cisalhados, são encontrados como inclusões em diversos *necks* e *plugs*. A suíte xenolítica foi inteiramente derivada de uma profundidade de aproximadamente 64 km. O magma álcali-basáltico formou-se por uma fusão parcial de um espinélio-lherzolito, no manto, sob pressão de 20 kb. O fracionamento desse magma deu origem aos ankaratritos e basanitos. Um incremento no processo de fusão parcial gerou um magma olivina-basáltico que deu origem aos derrames, diques e alguns *necks*. O posicionamento dessa suíte tanto pode ter sido relacionada com os reajustamentos internos da placa sul-americana durante seu deslocamento para oeste ou ao alívio de pressão no Terciário de zonas arqueadas no Mesozóico Superior, durante a abertura do Oceano Atlântico sul.

INTRODUCTION The Tertiary basaltic suite which is mainly concentrated in the state of Rio Grande do Norte, with some occurrences in the state of Paraíba, is represented by plugs, small flows, and less commonly by dikes. They are mostly restricted to the Precambrian shield where they occupy a N-S trending band which extends about 120 km and has a width of about 25 km. Some of them are also found cutting through the Cretaceous sediments of the Apodi Basin.

In Rio Grande do Norte, there is a change from south to north in the structural forms taken by this Tertiary basaltic magma. The magma had a tendency to form flows where it pierced the sediments of the Apodi Basin. Small flows are found near Açu and in Macau

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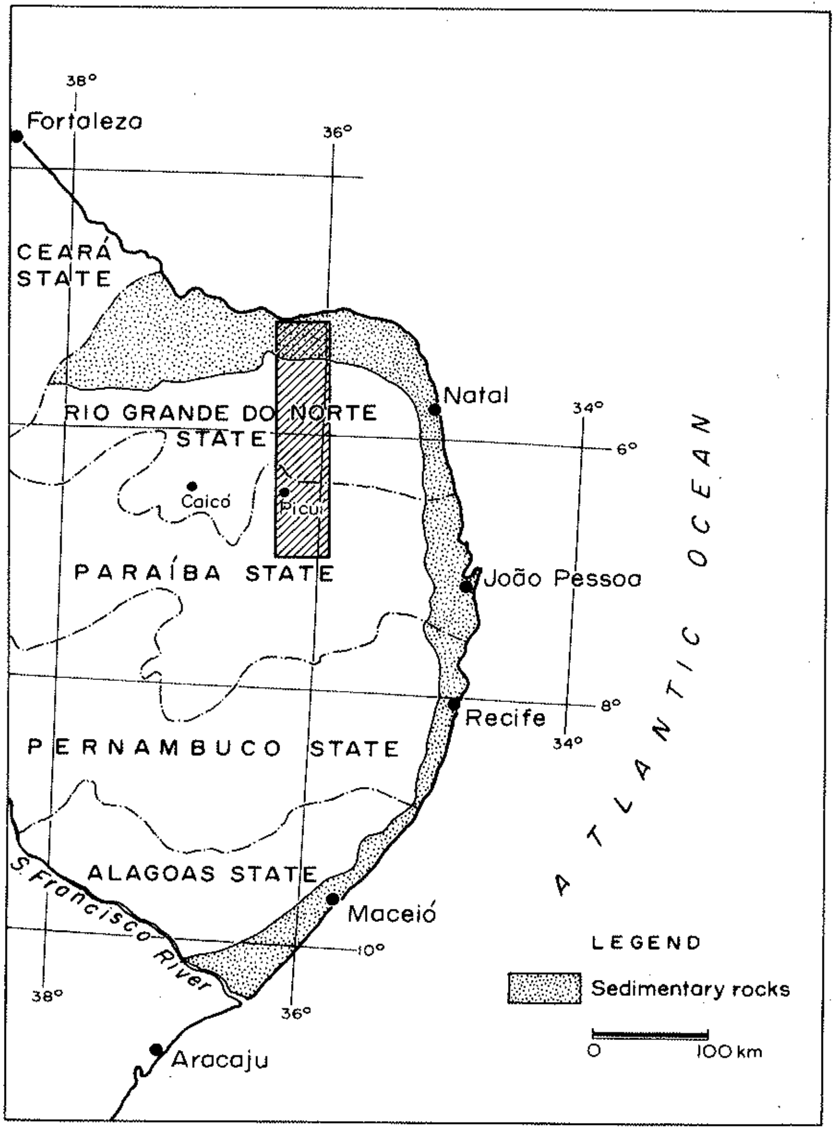

Figure 1 – Principal location of the Tertiary basaltic suite of Northeast Brazil, states of Rio Grande do Norte and Paraíba

(RN) where a thickness of 45 m was determined at a place named Alagamar (Kegel, 1957). In Paraíba at Boa Vista small flows of platy basalt can also be observed, where the magma followed some E-W trending fractures in its way up to the surface, and at about 15 km north of Cubati where a very decomposed small flow was recorded.

Between the two areas cited above, plugs are the predominant form of igneous bodies. Some of them show a conical shape and to them the designation of "necks" should be more appropriate (Rolff, 1965). Among them are the Cabugi Peak, 7 km west of Lajes, Serra Aguda, 17 km west from Pedra Preta, Cabugizinho da Arara, 20.7 km southwest of Lajes, and Caracarazinho, on the road Pedro Avelino, 6 km north of its junction with Lajes--Angicos road all of them in Rio Grande do Norte.

The best known plugs are represented by Serrote Preto, 18 km northwest of São Tomé, Serra Preta and Cabeço Preto, 6.5 km northeast of Pedro Avelino, Cabelo do Negro, 25 km southwest of Lajes, João Félix, 7 km northwest of Jandaíra, Serra Preta, 51 km north of Cerro Corá, in Rio Grande do Norte; in Paraíba, Malhada Escondida, 5.2 km west of Nova Palmeira, and a plug 6 km south of Frei Martinho.

Olivine nodules which are well known from alkaline basaltic association all over the world (Augustithis, 1972) are common inclusions in this Tertiary suite. In addition to this, gabbroic nodules, pieces of the metamorphic country rocks and several high pressure phases (xenocrysts) are commonly found as inclusions in these rocks at Cabugizinho, Caracará, and Nova Palmeira.

Narrow olivine basaltic dikes, probably related to the plugs and flows, are found in several places usually not very far from the sites where the plugs are located. The dikes are sometimes confused with the Mesozoic olivine-bearing diabases, from which they may be distinguished by their finer grain size, narrower width, presence of MgO-rich olivine, more sharply defined contacts, and by their strike which is normally other than east-west. They very often show columnar jointing perpendicular to the contacts, and this is a very good criteria to distinguish them from the Mesozoic suite. All the Tertiary basaltic dikes in this study were seen cutting only the Precambrian crystalline basement.

GEOCHRONOLOGY The age of the Tertiary basalts in Rio Grande do Norte and Paraíba is known from stratigraphic relationships since some of them cut Cretaceous sediments. A plug located at 7 km NW of Jandaíra in Cabeço de João Félix Ranch, cut the limestone of the Jandaíra Formation of Cretaceous age. The basalt of Serra Preta, 6.5 km NE of Pedro Avelino, formed a flow around it which covers outcrops of the Açu sandstone, Cretaceous in age and which constitutes the bottom of the sequence of the Apodi Basin. Near Macau, flows are also found on top of the Jandaíra Formation and overlain by Pleistocene and Holocene sediments.

Radiometric ages indicated 19.7 m.y. for the basalt of Pico do Cabugi (Cordani, 1970), 7 km west of Lajes, 18 m.y. for the Logradouro Peak, NE from Pedro Avelino (Ebert and Brochini, 1968), and 19.1 m.y. for the flows near Cubati, Paraíba (Benjamim B. Brito Neves, written communication, 1974). Ebert and Rodrigues (1973) indicated radiometric ages equivalent to 30.42 m.y. for the Boa Vista flows and 38.60 m.y. for the Queimadas flow in the state of Paraíba. A sample of the basalt of Macau, Rio Grande do Norte, from a drill hole (A. Thomaz Filho, written communication, 1975) yielded an age of 42 ± 3 m.y..

A mechanical separation of apatite from ten samples of this Tertiary suite was attempted, but failed due to the small amount of minute needles of this interstitial mineral. This eliminated the possibility of fission track dating.

PETROGRAPHICAL DESCRIPTIONS Flows and dikes in this suite are mostly olivine basalts, whereas the plugs and necks are mainly basanites and less frequently ankaratrites. In some cases feldspathic varieties are also observed.

Ankaratrites were observed in the neck of Cabugizinho da Arara located 20.7 km south of Lajes, and in the plug of Cabelo do Negro, about 25 km SW of the same town. The rock at Cabugizinho da Arara shows a seriate porphyritic texture, the phenocrysts of which are euhedral to anhedral, highly birrefringent olivine phenocrysts whose edges are altered to bowlingite, and very elongated crystals of violet titaniferous augite. These phenocrysts are set in a very fine grained matrix of microlites of titanaugite, magnetite, nepheline, potassium-feldspar, and some glass. The elongated phenocrysts of augite show a subparallel alignement which indicates that the lava was very fluid by the time it was extruded. The matrix is mostly composed of nepheline, potassium-feldspar, apatite and glass, and it is rich in magnetite which comprises about 15% of the rock. Nepheline occurs as very well preserved interstitial, anhedral grains which sometimes make up a kind of mosaic enclosing several previously crystallized phases. A small amount of chlorite is also present.

In contrast to the plug of Cabugizinho da Arara, the ankaratrite of Cabelo do Negro plug shows a much higher proportion of phenocrysts to matrix. Its bulk composition is similar to that described above, but euhedral to subhedral olivine phenocrysts predominate. Euhedral to subhedral, zoned titaniferous augite, frequently shows polysynthetic twinning commonly in phenocrysts as large as those of olivine. Elongated crystals of augite are also present in the matrix which is crowded with euhedral to subhedral iron oxides. These oxides are also found included in the augite close to the edges of the grains, indicating that they crystallized before the matrix but toward the end of the crystallization of the pyroxene. Needles of apatite in the matrix are mostly enclosed poikilitically by nepheline whose grains are well preserved or in some cases partially transformed into a mass of radial arranged zeolites.

Basanites occur at Cabeço de João Félix, 7 km NW of Jandaíra, at a plug situated 8 km NW of São Tomé, and at Serra Preta, 6.5 km NE of Pedro Avelino, in Rio Grande do Norte, and at Malhada Escondida, 5.2 km west of Nova Palmeira, and at a plug situated 6 km south of Frei Martinho, in Paraíba. It is possible to see in the basanites from Nova Palmeira, Frei Martinho and Serra Preta (Pedro Avelino) that more than 50% of those rocks is invariably constituted by clinopyroxene both as phenocrysts and in the groundmass. The amount of olivine, which is always present as phenocrysts, is variable. In the matrix, nepheline, potassium feldspar, plagioclase, magnetite, apatite and some glass are the main constituents. In the porphyritic rocks, the phenocrysts of clinopyroxene are euhedral to subhedral, elongated, nonpleochroic, green, pale brownish or violet, sometimes twinned, prismatic crystals of titanaugite.

Some olivine xenocrysts, which are very common in these basanites, are distinguished from the phenocrysts by deformation indicated by wavy extinction and deformation lamellae. Euhedral to anhedral grains of iron oxides usually occupy more than 10% of the volume of the rock, and some tiny grains of magnetite were seen inside of olivine very close to the edges of their undeformed grains. Nepheline forms mosaics which poikilitically enclose crystals of euhedral to anhedral augite and minute needles of apatite. The distinction between nepheline and plagioclase, which is seldomly twinned was made mostly with the aid of the electron probe microanalyzer. The potassium-feldspar is also present in minor amounts and due to its small size it is very difficult to distinguish it from the nepheline.

The basanites from Cabeço de João Félix Ranch (Jandaíra) and from a plug situated 8 km NW of São Tomé are much more feldspathic than those described above. Laths of plagioclase (labradorite An_{60}) constitute the main felsic component of the rock. Subordinated nepheline is present interstitially, sometimes with a zonal structure indicated by row of inclusions of minute grains of pyroxenes and apatite. Augite is represented by long prisms with variable length, from phenocrysts down to the size of the grains in the matrix. Sometimes it shows flow alignments which indicate fluidity during the time the magma reached the present level of exposure. Cumulates of clinopyroxenes are frequently seen with an internal radial arrangement of the prisms as cognate nodules.

Nepheline-free olivine basalts are present at Cabugi Peak, 7 km west of Lajes, at the plug of Serra Preta, 51 km north of Cerro Corá, at Serra Aguda, 17 km west of Serra Preta, at the plug of Cabeço Preto, 8 km east of Pedro Avelino, and Serrote Preto, 18 km northwest of São Tomé, all of them in Rio Grande do Norte. The small basaltic flows at about 3.5 km southeast of Açu, and Serra do Luzeiro or Cuó, 6 km east of Açu are mostly composed of nepheline-free olivine basalts, mineralogically and texturally similar to those of the plugs. The basalt found in the flows in Macau, Rio Grande do Norte, and Boa Vista and Cubati, Paraíba, and the small basaltic dikes are also nepheline-free olivine basalts.

These varieties are essentially composed of olivine which occupies from 10 to 20% of the volume of the rock, titanaugite, iron oxide minerals, plagioclase, apatite, and glass in some of them.

Olivine occurs as euhedral to subhedral grains which partially underwent reactions with the liquid. Olivine grains believed to be xenocrysts, because they exhibit some deformation, kink-bands and wavy extinction, are abundant. Some olivine phenocrysts include minute grains of iron oxide minerals close to their edges. This indicates an early crystallization for iron oxide minerals which exhibit frequently euhedral habit, although anhedral grains are also found. Ilmenite, however, was always recorded in the matrix wherein it forms skeletal structures. Plagioclase forms long laths which are included by augite. Some plagioclase grains very altered and with an anhedral habit are present in several of these rocks, and are of dubious origin. Titaniferous augite appears as phenocrysts but it is also present in the matrix. Even some of the smaller grains are euhedral. They are violet, highly titaniferous and twinned. Sector zoning and herringbone structures are seen in the large grains. Apatite is a common accessory which normally shows euhedral habit. Interstitial glass is also present in some sections.

Leonardos and Araújo (1968) made reference to nepheline in the basalt of Pico do Cabugi. Although this mineral was not found in any of the thin sections examined in this study, the possibility of its presence is not excluded since more than one eruption took place and chemical variations in the nature of the magma could have occurred.

The small basaltic flows at about 3.5 km southeast of Açu, and Serra do Luzeiro or Cuó, are mostly composed by a nepheline-free olivine basalt, mineralogically and texturally similar to those described above. The former is the best exposed among all the Tertiary flows included in this study. Actually this is composed by two successive flows separated by a zeolite-rich zone. It is mostly constituted of blocks which show flat surfaces and suggest columnar jointing, formed on cooling. Similar behavior is found in the Serra do Luzeiro or Cuó where the basalt crops out around the SW side of a Cretaceous sedimentary mesa (Açu sandstone).

The rocks are porphyritic with olivine phenocrysts usually five to ten times larger than the grains in the matrix. A second generation of olivine is represented by grains twice as long as those in the matrix. Usually all the olivine is intensely weathered and transformed into chlorite or less frequently into serpentine. Olivine grains believed to be xenocrysts because they show signs of deformation are common. The olivine phenocrysts, plus the olivine xenocrysts, make up about 10% of the volume of the rock.

The matrix is mainly composed by augite, plagioclase and opaque minerals. Violet titaniferous augite is normally untwinned and anhedral although a few euhedral grains were recorded. Laths of twinned plagioclase, the main component of the groundmass, are very weathered. Some skeletal forms indicate that some of them are late crystallized ilmenite.

Amygdales are filled with natrolite, calcite, and chlorite. Chlorite, when filling the whole cavity, shows a radial arrangement and intense green color.

The nepheline-free olivine basalts found in the flows in Macau, Rio Grande do Norte, and Boa Vista and Cubati, Paraíba, are very similar to those occurring at Açu, except for the fact that they frequently show an amygdaloidal facies. They are mainly composed of olivine, plagioclase, augite, iron oxide minerals, and glass. Anhedral grains of olivine, usually altered to chlorite or serpentine, are the main phenocrysts and occupy from 10 to 20% of the volume of the rock. Twinned plagioclase is usually present as phenocrysts, although some microlites of this mineral are seen in the matrix. Plagioclase crystals are often agglomerate when found inside of augite grains. Sometimes the groundmass microlites of plagioclase are aligned by flow as a consequence of the fluidity of the magma during eruption. Augite grains are pale purplish brown, anhedral, rarely twinned. They poikilitically enclose plagioclase and some grains of olivine.

The Tertiary basaltic dikes are also nepheline-free olivine basalt mineralogically and texturally similar to those found in some of the plugs and flows. They frequently show porphyritic texture, and plagioclase is the most common phenocryst. Their size is sometimes fifteen times larger than the grains in the groundmass. Olivine phenocrysts, less abundant, are also present, often almost completely altered to chlorite. The relative proportion between olivine, plagioclase, and augite varies from dike to dike.

CRYSTALLIZATION HISTORY The petrographic study of this Tertiary suite indicates slight differences in the crystallization history of the different members. In the flows and dikes, normally characterized by olivine basalt with tholeiitic affinities, the plagioclase preceeded augite in the crystallization, whereas in the more feldspathic basanites and olivine basalts with basanitic affinities, this mineral came after the pyroxene. The dikes with few exceptions have large plagioclase phenocrysts and indicate that there was a long time interval during which plagioclase was crystallizing from the magma.

To gain an insight of the chemistry of the original magma, course of crystallization and partition of the elements during the fractionation of the basaltic liquid which gave rise to the three petrographic types described, fifteen representative samples were selected for analysis in the electron probe microanalyser. An Applied Research Laboratories Model EMX-SM electron microprobe was utilized, with the X-ray intensities corrected for drift and background. The theoretical correction technique described by Boyd *et al.* (1969) was used to correct for absorption, fluorescence and atomic number effects.

Most of the selected grains were analyzed at the core and at the edge. In some cases, three points were analyzed in the same grain, depending on its size. After this stage, step scan across was done on grains which showed optical zoning or interesting chemical variation evidenced from the analyses at the core and edge of them. The very fine grained interstitial material was analyzed in some cases using a 50 μm diameter broad beam.

The scan across single olivine grains indicated that this phase crystallized early and in the ankaratrites it partially equilibrated with the basaltic liquid before a fractional crystallization was finally established. Seriate textures with olivine and augite as phenocrysts in the ankaratrites suggest that these two phases were crystallizing from the magma while it was rising to the surface, where it underwent final crystallization and the residual liquid quenched to form interstitial glass. Some augite cummulates in some basanites and olivine basalts with basanitic affinities also suggest that this mineral was crystallizing alone for a long period of time.

Magnetite is an early crystallized phase and its crystallization interval extended almost until the time nepheline was formed in some of the studied rocks. Apatite was also an early crystallized phase in some of these Tertiary basalts.

The AFM plots (Figure 2) for the whole chemistry of this suite generated a trend which does not coincide with the classical Skaergaard or the calc-alkaline end members fractionation trends. Chemical analyses of the groundmass of some rocks in this Tertiary suite were attempted using the microprobe broad beam technique. A 50 μm diameter

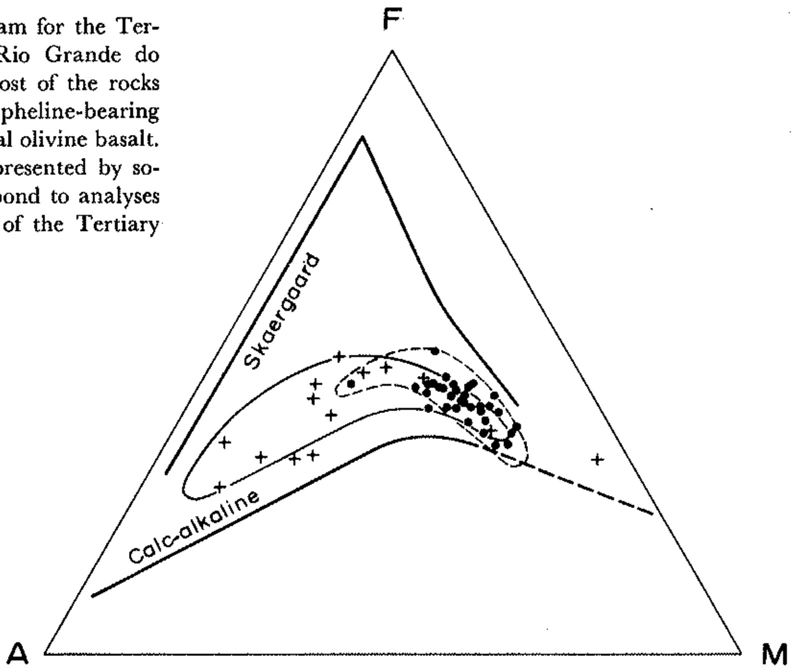

Figure 2 – AFM diagram for the Tertiary alkalic suite of Rio Grande do Norte and Paraíba. Most of the rocks are nepheline-rich or nepheline-bearing basalts. A few are typical olivine basalt. Whole analyses are represented by solid dots; crosses correspond to analyses of the matrix of some of the Tertiary basaltic rocks

spot was used, and interstitial areas supposed to represent the possible composition of the liquid at the end of the crystallization were analyzed.

As indicated by Gancarz and Albee (1973) some biases can account for poor results in some analyses by the broad beam technique. One of them is due to the fact that the correction procedures for inter-element interactions assume a homogeneous sample. Another results from the polishing of the section, because pyroxenes tend to pit more than

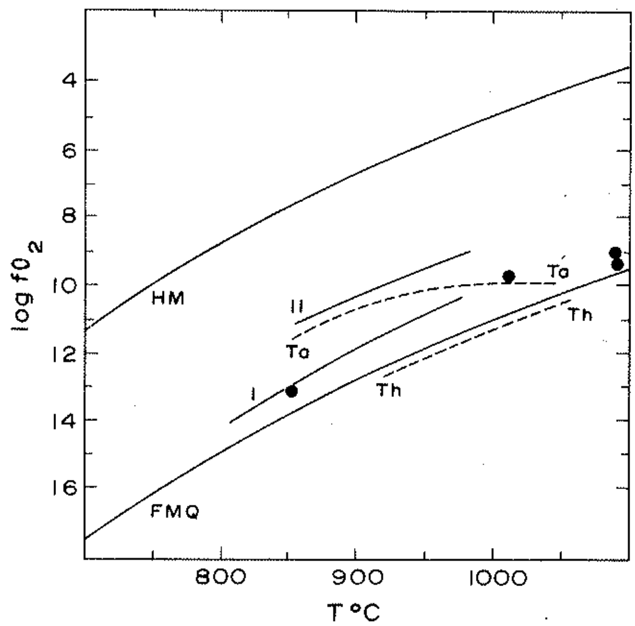

Figure 3 – Log fO_2-T diagram based on Carmichael (1967). FMQ = fayalite-magnetite-quartz buffer. HM = hematite-magnetite buffer. Th-Th = serie Thingmulli (Carmichael, 1967). Ta-Ta = calc-alkaline lavas of Talasea (Lowder, 1973). Curve I corresponds to the case in which magnetite and ilmenite coexist with orthopyroxene. Curve II corresponds to the case in which magnetite and ilmenite coexist with amphibole or biotite (curves I and II, Carmichael, 1967). The data for the Tertiary basalts of Rio Grande do Norte plot around the curve I

plagioclases. An additional bias is due to the fact that some Al_2O_3 used in polishing can be lodged in cracks and pits despite ultrasonic cleaning. All these problems reduced the possibility of obtaining acceptable results in all cases. Only fourteen of the analytical results were considered to be acceptable. The data obtained are shown in Fig. 2. Apparently these points seem to be in continuity with the ones obtained from the whole chemistry, in the same figure, constituting a general trend roughly ressembling that for the Tertiary – Recent lavas of West Africa (Black and Girod, 1970).

From this trend it can be seen that there was a little iron enrichment during the fractionation of the basaltic magma, mostly crystallized under high oxygen fugacity (around −10.0) as deduced from the ilmenite-magnetite pairs (Buddington and Lindsley, 1964). The crystallization initiated with magnesian olivine and was followed by magnetite with a long time interval of crystallization. This approaches Osborn's (1962) scheme for the calc-alkaline rocks of orogenic regions.

The temperature with which the magma reached the surface was around 1 100 °C or slightly below that determined from the composition of the iron oxide minerals (Table 1). The knowledge of this temperature was also obtained using Hakli and Wright's (1967) approach through the Ni fractionation between olivine and pyroxene or between one of these two phases and the groundmass (Table 2). The results obtained (Table 3) seem to be consistent with and very similar to those found using the oxide mineral composition.

Table 1 – fO_2 and T data for some of the Tertiary basaltic plugs of Rio Grande do Norte, Brazil, with coexisting titanomagnetite and ilmenite

Sample number	*Ulvospinel* (moles %)	*Ilmenite* (moles %)	$-\log fO_2$	*Temperature*	*Observations*
A-93	73.78	89.89	9.8	1 110	Edge of the grains have been used
A-93	71.88	90.70	10.0	1 100	Core of the grains have been used
L-53	37.75	91.39	13.0	840	Core of the grains have been used
A-42	59.39	90.42	9.8	1 010	Edge of the grains have been used

For location of samples, see Appendix 1

Table 2 – Ni fractionation between olivine and pyroxene in Tertiary basaltic plugs, small flows and dikes of Rio Grande do Norte and Paraíba, Brazil
(For location of samples, see Appendix 1)

Sample n.	Ni *content of groundmass* (W%)	Ni *content of olivine* (W%)	Ni *content of pyroxene* (W%)	$K = Ol_{Ni}/Gm_{Ni}$	$K = Py_{Ni}/Gm_{Ni}$	$K = Ol_{Ni}/Py_{Ni}$
A-93	0.01	0.160	0.033	16.0	3.30	4.84
BV-22	0.01	0.206	—	20.60	—	—
BV-23	0.01	0.180	0.056	18.0	5.60	3.21
A-42	—	0.200	0.044	—	—	4.54
A-74	—	0.266	0.040	—	—	6.65
A-52	—	0.193	0.040	—	—	4.82
A-35	—	0.155	0.050	—	—	3.11
A-2	—	0.210	0.072	—	—	2.91
L-53	—	0.200	0.05	—	—	4.00
PP-3	—	0.260	0.043	—	—	6.04

Table 3 – Estimated temperature for the samples listed on Table 2, using Hakli and Wright's approach (1967)

Sample n.	*Temperature*, °C $K = Ol_{Ni}/Gm_{Ni}$	*Temperature*, °C $K = Py_{Ni}/Gm_{Ni}$	*Temperature*, °C $K = Ol_{Ni}/Py_{Ni}$
A-93	1 080	1 118	1 085
BV-22	970	—	—
BV-23	1 020	1 020	1 018
A-42	—	—	1 078
A-74	—	—	1 160
A-52	—	—	1 078
A-35	—	—	1 006
A-2	—	—	1 120
PP-3	—	—	1 150
L-53	—	—	1 076

For location of samples, see Appendix 1

These temperatures approximately indicate that the quenching disturbed the crystallization of the pyroxene which had a tendency of forming a metastable "quench trend" (Fig. 4). The association of albite and nepheline which occurs in some basanites indicates a crystallization around or below 1 068 °C. It also indicates that the silica activity in the liquid was buffered (Carmichael *et al.*, 1970).

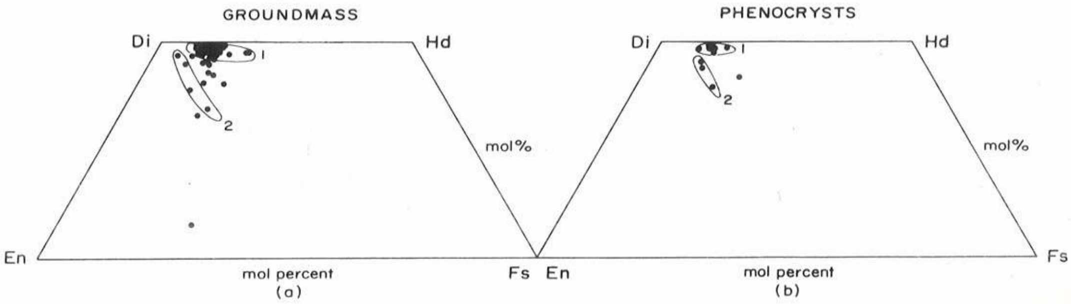

Figure 4 – Pyroxene quadrilateral diagrams with the compositions of pyroxenes of the Tertiary basaltic rocks of Rio Grande do Norte and Paraíba. 1, Augite trend. 2, Augite – subcalcic augite trend

The temperatures determined for the lherzolite nodules (Davis and Boyd's method, 1966) included in these Tertiary basalts, around 900 °C (Table 4), are much lower than the temperature found for the basaltic liquid when it reached the surface. This apparently requires the abandonment of the idea of a mantle origin for the nodules if they were assumed to be fractionation products from the basaltic liquid on its way up to the surface. However, this anamalous situation can be explained if it is assumed that the nodules represent refractory pieces of mantle rocks which were brought up to the surface not in equilibrium with the basaltic liquid as indicated by the magmatic corrosion at their margins. The rapidity of the intrusion may also be responsible for this thermal anomaly.

ORIGIN OF THE TERTIARY SUITE All the Tertiary suite is here assumed to be related to a single magmatic chamber at a depth equal or greater than 64 km, as determined from the nodules (Table 5). This estimate for the depth was obtained combining Davis and Boyd's (1966) and MacGregor's (1974) approaches. It is assumed that only a

Table 4 – Temperature for some nodules included in the Tertiary basaltic plugs and necks of Rio Grande do Norte and Paraíba, Brazil, based on Davis and Boyd's diagram (1966)

Sample n.	Ca/(Ca + Mg)	*Temperature* (°C)
A-46	0.506	≤900
A-46	0.486	917
A-46	0.504	≤900
A-46	0.499	≤900
A-46	0.498	≤900
A-46	0.507	≤900
A-46	0.509	≤900
A-46	0.474	960
A-56	0.494	900
A-56	0.496	≤900
A-76	0.492	900
A-76	0.491	900
A-76	0.492	900
A-76	0.493	900
A-48-B	0.474	960
A-48-B	0.491	900
A-48-B	0.471	960
FM-10	0.499	≤900
FM-10	0.500	900
FM-10	0.504	≤900

For location of samples, see Appendix 1

Table 5 – Pressure and approximate depth for the nodules listed on Table 4, based on the alumina content of the orthopyroxene, using MacGregor's approach

Sample n.	*Alumina in orthopyroxene* (%)	*Pressure* (kb)	*Average pressure* (kb)	*Approximate depth assuming average pressure*
A-76	3.12	18.6		
A-76	2.94	18.8		
A-76	3.44	17.5	17.85	60 km
A-76	3.28	18.3		
A-76	3.61	16.9		
A-76	3.46	17.0		
A-46	4.14	15.0		
A-46	3.50	17.2		
A-46	3.76	16.1	16.1	55 km
A-46	3.72	16.1		
A-56	4.04	15.0		
A-56	4.08	15.0		
A-56	3.46	17.0		
A-56	3.78	16.1	15.70	52.33 km
A-56	4.04	15.0		
A-56	3.88	16.0		
FM-10	3.82	16.0		
FM-10	3.94	15.50	15.75	52.50 km
A-48-B	4.04	19.16		
A-48-B	3.98	19.16	19.16	64 km

For location of samples, see Appendix 1

small amount of partial melting of spinel-lherzolite in the mantle took place since the volume of outpoured lava is restricted to rather small bodies in the surface. Kushiro (1973) proposed from the experimental studies on partial melting of iron-rich spinel-lherzolite under anhydrous conditions that alkali basalt is formed at a pressure not less than 20 kbar. A slight increase of degree of partial melting produces a picritic melt over a wide pressure range.

The maximum pressure obtained from the study of Al_2O_3 content of the orthopyroxene of the lherzolite inclusions is 19.1 (Fig. 5). The corresponding pressures for the nodules were determined with the already known temperature from the Ca and Mg contents of the diopside (Davis and Boyd's approach, 1966) and the petrogenetic grid proposed by MacGregor (1974).

This value, which indicates the minimum pressure corresponding to the depth of magma generation, is comparable to that proposed by Kushiro (1973) in his experimental studies for formation of alkali basaltic liquid. As the ankaratrites and basanites are less common than the olivine basalts that have basanitic or tholeiitic affinities, it is suggested that as a magma chamber began to form the first liquid was an alkali basaltic which was

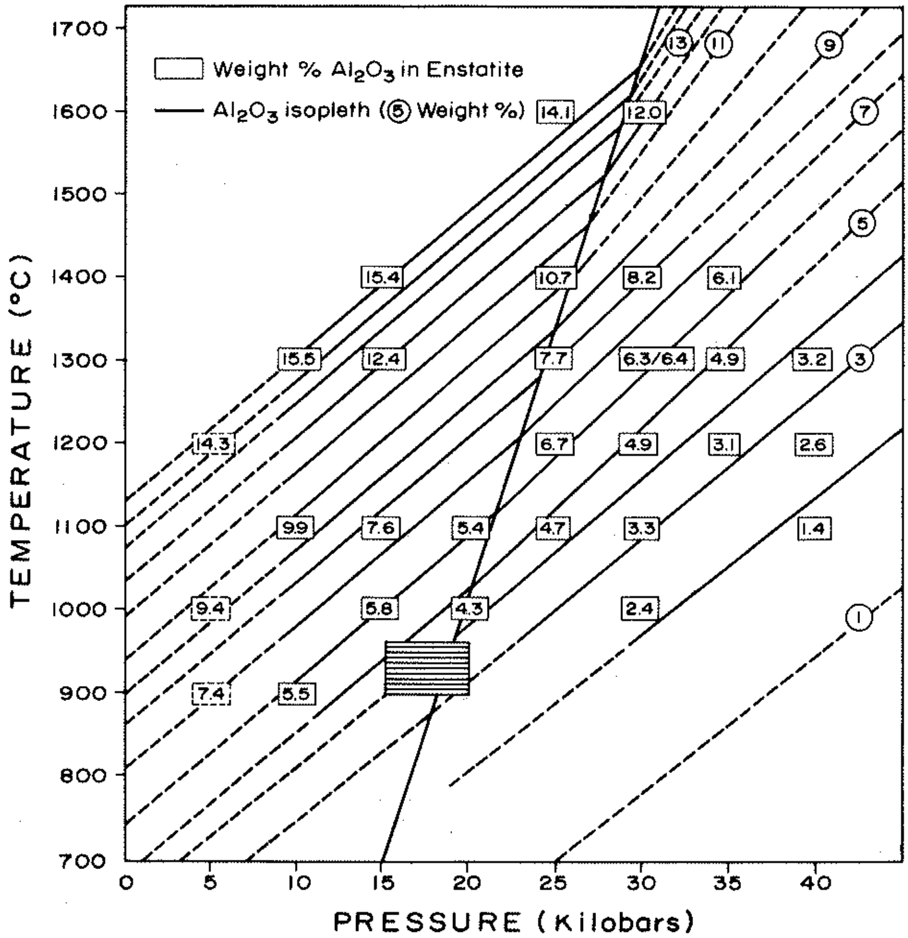

Figure 5 – Pressure and temperature ranges for five nodules included in the Tertiary basaltic plugs and necks of Rio Grande do Norte and Paraíba (MacGregor, 1974)

erupted. With a slight increase of melting a picritic liquid was formed that gave rise to the rest of the basalts in this suite.

Another possible explanation of the variation in composition is that it is due to a differentiation of the original basaltic liquid while it rose toward the surface caused by the differences in order of crystallization. The complexity of the crystallization history, rather than different processes of magma generation, would be responsible for the petrographic types present in this suite. A similar interpretation has been given by Wright (1972) for the tholeiites observed within the Nigerian alkaline Cenozoic province. The lack of more geochronological data does not allow the testing of the validity of the first interpretation.

As previously mentioned most of the basalts in this suite show high contents of K_2O, P_2O_5 and TiO_2. The enrichment of these incompatible elements in basalts is embarassing and difficult to explain. O'Hara's (1968) suggestion of an eclogite fractionation at depth to explain these high amounts of K_2O, TiO_2 and P_2O_5 could be a possible explanation for their enrichment in this Tertiary suite. Another explanation was provided by Flower (1971) who, based on available experimental and petrochemical data, proposed that the breakdown of titaniferous phlogopite in the upper mantle during formation of basaltic magma at a depth exceeding 60 km was responsible for the enrichment of incompatible elements in the alkaline rocks. No phlogopite was recorded in the studied lherzolite nodules although that does not eliminate the possibility of its existence at the depth where the basaltic magma was formed.

The emplacement of this suite is related either to internal readjustment inside of the South American plate due to pressure release of arched zones or continental horizontal displacement or both. The difference observed in the available radiometric ages suggest that the emplacement of the Tertiary suite happened in a relatively short period of time. This is reinforced by the lack of E-W chains which would be probably formed assuming the westward displacement of the South American plate.

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APPENDIX 1: Sample location

Sample Number	Location
A-2	Olivine basalt collected from the small flow located at about 3.5 km SE of Açu, Rio Grande do Norte.
A-42, A-46, A-48-B	Olivine basalt forming a plug located 18 km NW of São Tomé, Rio Grande do Norte. It exhibits columnar structure (hexagonal and tetragonal columns), and many peridotitic xenoliths ranging from 1 up to 10 cm have been found. It is named Serrote Preto.
A-35	Ankaratrite collected at the foot of the Serra do Luzeiro or Cuó (Açu sandstone), around the SW side of the Serra (Mesa).
A-52 and A-56	Olivine basalt forming a plug located 51 km North of Cerro Corá, Rio Grande do Norte, following the road Cerro Corá-Recanto. It is 70 m high and shows an elongation in N40E direction. Many peridotitic xenoliths have been found in this basalt ranging from 1 to 5 cm. It is named Serra Preta.
A-74 and A-76	Olivine basalt forming a cone-shaped hill about 100 m high, located at São Francisco Ranch, Pedro Avelino, Rio Grande do Norte, 17 km West of Pedra Preta, Pedro Avelino. Many peridotitic xenoliths have been found in this basalt ranging from 1 up to 20 cm. This hill is named Serra Aguda.

A-93	Olivine basalt forming a cone shaped hill located about 7 km West of Lajes, Rio Grande do Norte. It is named Pico do Cabugi, and lies 500 m above the Lajes Plain level. Several peridotitic nodules are found in this basalt, ranging from few cm up to 1 m according to Leonardos and Araújo (1968).
BV-22	Olivine basalt occurring as a small flow at about 3.6 km from Boa Vista, Paraíba.
BV-23	Olivine basalt collected from the main flow, at about 5 km from Boa Vista, Paraíba.
L-53	Ankaratrite forming a cone-shaped hill located 20.7 km SW of Lajes, Rio Grande do Norte. It is named Cabugizinho da Arara. It is 80 m high and it lies at Cacimba de Cima Ranch, and shows many peridotitic xenoliths ranging from 0.5 cm up to 5 cm.
PP-3	Olivine basalt forming a narrow dike located at about 2 km West of Pedra Preta close to the road Pedra Preta-Jandaíra. The dike trends N40E and lies on the Monte Alegre Ranch.
FM-10	Basanite occurring as a plug (?) located 6 km South of Frei Martinho, Paraíba in the Varzea Verde Ranch. Small peridotitic xenoliths ranging from 0.5 up to 5 cm are included in those basalts.