

Petrology and mineral chemistry of peridotite nodules included in Tertiary basaltic rocks of northeast Brazil

ALCIDES NOBREGA SIAL *Institute of Geosciences, UFPe, Recife, C.P. 1538, Brazil*

ABSTRACT

The Tertiary volcanic suite in central Rio Grande do Norte and Northern Paraíba, which is composed of ankaratrites, basanites, and olvine basalts with basanitic affinities, forms plugs, necks, flows, and dikes that cut the Precambrian basement and Cretaceous sediments of the Apodi basin in a north-south trend. Xenocrysts of olvine, orthopyroxene, clinopyroxene, spinels, and granular and sheared spinel-lherzolite and harzburgite nodules are found as inclusions in several necks and plugs. The entire xenolithic suite was derived from depths of approximately 64 to 55 km. The mineralogical and textural aspects of the nodules, as well as their mineral chemistry, are discussed.

INTRODUCTION

In recent years many petrologists have devoted much attention to the study of ultramafic nodules usually included in alkali basalts all over the world. These nodules have been utilized as indicators of pressure, temperature, and chemistry of their source location in the mantle. Previous examples from South America include lherzolite nodules from the little island of São José, in the Fernando de Noronha archipelago (Almeida, 1958), from Cabugi Peak, a volcanic neck in Rio Grande do Norte, northeast Brazil (Leonardos and Araújo, 1968), from Guaratiba, Guanabara (Helmbold, 1968), and from Asunción, Paraguay (Stormer and others, 1975). This paper describes a few new localities.

GENERAL GEOLOGY

Xenoliths of peridotite of different grain size and texture were found in several of the Tertiary alkali basaltic plugs and necks in the states of Rio Grande do Norte and Paraíba, Brazil (Fig. 1). They are often rounded, magmatically corroded, and (less frequently) exhibit angular shapes. They are found in the basanites and olvine basalt with basanitic affinities but are less abundant in the ankaratrites. Aggregates of olvine and clinopyroxene have been found only rarely in the olvine basaltic (tholeiites) flow of Boa Vista, Paraíba. The size of these nodules usually ranges from 1 to 20 cm. Leonardos and Araújo (1968), however, mentioned that nodules as large as 1 m have been found on the northeastern slope of Cabugi Peak in Rio Grande do Norte.

Some of these nodules have been partially altered into a red hydrous material. Fresh xenoliths, however, can be obtained in some localities. The least altered samples occur at Serra Preta and Serra Aguda (Pedro Avelino), Serrote Preto (São Tomé), Serra Preta (Cerro Corá), Cabugi Peak, and Cabugizinho da Arara (Lages) in Rio Grande do Norte and Malhada Escondida (Nova Palmeira and Frei Martinho) in Paraíba. Gabbroic nodules were found in two localities, Serra Aguda and Serra Preta, where they are present in a subordinate amount.

Xenocrysts of olvine, orthopyroxene, clinopyroxene, spinel, and less abundant potassium feldspar and quartz also occur, and plagioclase is present in those localities where gabbroic inclusions are found. The anhedral potassium feldspar and rounded quartz

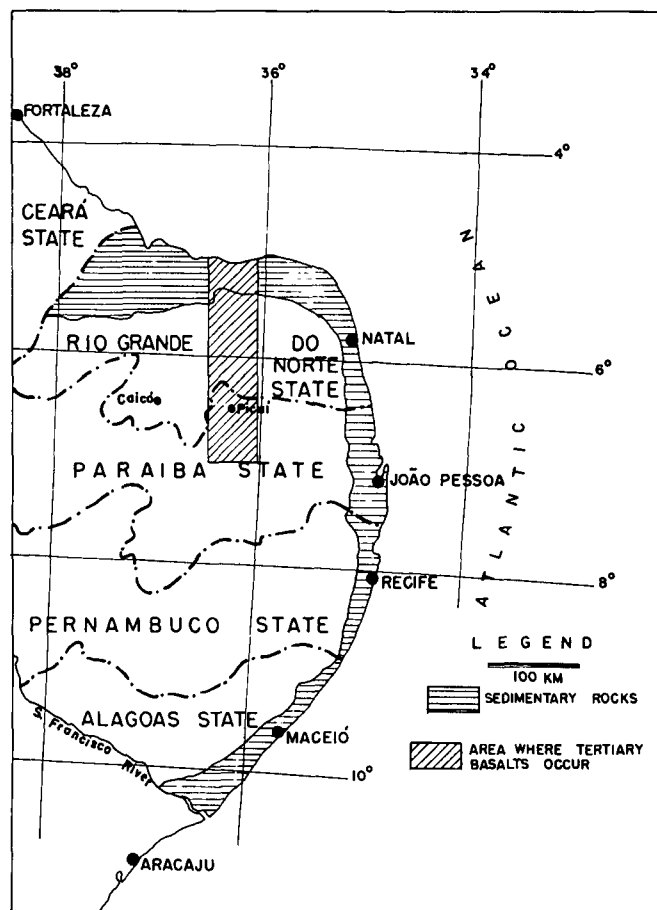


Figure 1. Location of the Tertiary basaltic province in northeast Brazil.

were probably picked up from the wall rocks by the magma on its way to the surface. Plagioclase, however, is of a dubious source; usually it shows corroded margins indicating reactions with the basaltic liquid. It has grain sizes 5 to 10 times larger than the grains in the basaltic groundmass and is sodic labradorite. This mineral, which sometimes shows signs of deformation, could represent an early crystallized phase that reacted with the magma during its ascent, or it could be a xenocryst picked up from the underlying metamorphic basement or from the lower crust. Because its composition approaches that of the plagioclase in the groundmass, an early crystallization origin is unlikely, and a xenocrystic origin is suggested. The fact that gabbroic nodules and plagioclase xenocrysts are always found included in the same basalt suggests that the plagioclase represents a phase disaggregated from the gabbroic nodules: A mantle origin is ruled out by the composition, which is much more sodic than one would expect from a mantle plagioclase.

The olvine, orthopyroxene, clinopyroxene, and spinel xenocrysts are assumed to be high-pressure phases disaggregated from the lherzolite nodules. The olvine shows signs of deformation

(kink bands and deformation lamellae), sometimes normal zoning, and anhedral crystals. Many pyroxenes have reacted with the magma, and around the orthopyroxene a granular mosaic of olivine is formed, whereas around the clinopyroxene a spongy material of indeterminate composition is always present. The brown spinel shows a dark rim, which is chrome-magnesian magnetite resulting from the reaction with the host rock.

Sparse metamorphic country rocks have been found in the Tertiary suite at Cabugizinho da Arara and Caracará necks in Rio Grande do Norte and in the Malhada Escondida plug (Nova Palmeira) in Paraíba.

PETROGRAPHY OF XENOLITHS

Modal analysis

The ultramafic nodules in the Tertiary basaltic rocks are mostly spinel lherzolites. Subordinate amounts of harzburgite have been found at Serra Aguda. All the lherzolites have the same minerals — olivine, bronzite, chrome diopside, and spinel — but show a pronounced modal variation that strongly suggests an inhomogeneous or layered distribution of anhydrous phases in the source mantle peridotites (Wilshire and Trask, 1971).

Modal compositions of six nodules whose phase chemistry has also been determined using the microprobe technique are listed in Table 1.

Olivine makes up 20% to 68% orthopyroxene from 10% to 71%, clinopyroxene from 5% to 17%, and spinel from 3% to 7% of the volume of the lherzolite nodules. One of the analyzed harzburgites shows very little clinopyroxene and some spinel. The harzburgites show less pronounced variation in the volume percent of olivine and orthopyroxene than the lherzolites.

Textures

The average grain size is about 3mm, and the largest grains are normally olivine or bronzite. The phases present are readily recognizable in the hand specimens, and proportions can be estimated with a hand lens. Clinopyroxene is apple green, orthopyroxene is almost black but showing a translucent brown color, spinel is metallic black, and olivine is pale green. In thin section, olivine is usually anhedral and sometimes shows evidences of deformation such as undulatory extinction and kink bands. The olivine is usually unaltered, and only at Frei Martinho, Paraíba, was subordinate serpentinization observed. Bronzite is always anhedral. In a few cases it shows polysynthetic twinning with the main lamellae at an angle to the cleavages. Deformation in the bronzite is frequently evidenced by wavy extinction. When this mineral reacted with the enclosing basaltic magma, it formed a marginal myrmekite-like fringe composed mainly of basaltic material (plagioclase, for example). Reaction margins around bronzite with small olivine grains are also found, and, less frequently, a corona reaction between bronzite and olivine is present.

Clinopyroxene represented by chrome diopside is less abundant than olivine and bronzite, and sometimes its grains are smaller and interstitial to the other minerals. It is anhedral, pale green in color under the microscope, and is a little more weathered than the olivine and bronzite. Exsolution lamellae were not found in this mineral.

The spinel, which is a chromiferous variety, shows anhedral grains, brown or, less frequently, green, with dark rims that result from reactions with the basaltic liquid. Very often it forms graphic intergrowth with bronzite or olivine. The size and amount of spinel varies from nodule to nodule, and this mineral is absent only in a few of them.

Deformed and nondeformed textures are observed. The former have weakly deformed grains with kink bands and wavy extinction.

TABLE 1. MODAL COMPOSITION OF SOME ULTRABASIC NODULES INCLUDED IN THE TERTIARY BASALTIC PLUGS OF RIO GRANDE DO NORTE AND PARAIBA

	Sample no.					
	A-46	FM-10	A-76	A-56	A-48-B	A-70
Olivine	65.5	20.4	79.1	60.0	68.2	71.6
Orthopyroxene (bronzite)	10.5	71.2	19.0	26.6	25.6	28.4
Cr-diopside	17.5	4.9	0.5	10.0	2.4	..
Cr-spinel	6.5	3.3	1.4	3.4	3.8	..

Note: Sample locations: A-46 and A-48-B — lherzolite, plug named Serrote Preto, 18 km northwest of São Tomé, Rio Grande do Norte. FM-10 — lherzolite, plug(?), located on Várzea Verde Ranch 6 km south of Frei Martinho, Paraíba. A-76 and A-70 — harzburgite, plug named Serra Aguda, at São Francisco Ranch 17 km west of Pedra Preta, Rio Grande do Norte. A-56 — lherzolite, plug named Serra Preta, located 51 km north of Cerro Corá, Rio Grande do Norte, following the road Cerro Corá to Recanto.

The latter are less common and have a granular mosaic of polygonal olivine grains between large strained olivine and bronzite grains.

In the granular mosaic the grains are arranged in such a way that grain boundaries meet at triple points, which is a good indication of an equilibrium texture. This also suggests that some of these aggregates underwent adjustment of grain boundaries in the solid state (Talbot and others, 1963). The granular mosaics of polygonal olivine commonly are surrounded by large, rounded, deformed grains of olivine and bronzite. The deformed olivine often shows minor serpentinization along its fracture.

In the rocks with deformed textures, the large grains are mostly invaded by the basaltic liquid, which caused several reactions and changes in the original texture. The main consequences of such an infiltration are represented by modifications in the boundaries of the grains with the appearance of myrmekite-like fringes, spongy zones of formation of granular olivine around the bronzite. All these reactions are witness to the instability of these nodules in the basaltic magma that brought them up to the surface and support their accidental origin.

The xenolithic origin of the peridotitic inclusions is supported by their intense magmatic corrosion. This is exhibited not only in the margins of the nodules, which indicates they were unstable in the host magma, but also by the penetration of groundmass plagioclase that resulted from infiltration of the basaltic liquid. The deformation exhibited by the inclusions indicates an earlier history in the mantle, and in this study they are assumed to be mantle fragments picked up at great depth.

MINERAL CHEMISTRY

The mineral chemistry of six ultramafic nodules and several high-pressure xenocrysts found in these alkali basalts was determined with the microprobe. X-ray intensities were corrected for drift and background. A theoretical correction technique described by Boyd and others (1969) was used to correct for absorption, fluorescence, and atomic number effects. Five of the six nodules are four-phase lherzolites, and one is a two-phase harzburgite. The detailed microprobe data that will be discussed below have been placed in the GSA depository.¹

Twenty-seven chemical analyses of olivine grains in the peridotite nodules were made. The forsterite (Fo) content ranges from 73

¹ Copies of GSA supplementary material 77-5 may be ordered from Documents Secretary, Geological Society of America, 3300 Penrose Place, Boulder, Colorado 80301.

to 92 mole percent. Of the 27 analyses, 20 have compositions between 90 and 92 mole percent of Fo, which indicates a high homogeneity of this phase in all the samples. Six analyses have compositions between 81 and 90 mole percent of Fo, and only one analysis (sample A-48-B from Serrrote Preto) has a composition of 73 mole percent of Fo. The analyses at the cores and edges of most of these grains revealed an outstanding homogeneity, except for two. The NiO and MnO contents are about the same in all grains except in sample A-48-B, where the MnO content is twice as high. The Na₂O content is very low, and CaO, TiO₂ and Al₂O₃ are absent in most of the grains.

Thirty-five chemical analyses of orthopyroxene from the same peridotite nodules were made. Orthopyroxene is fairly homogeneous with little variation of the Al₂O₃ content, which ranges from 2.94% to 5.96%. The highest alumina content was found in sample A-70 from Serra Aguda, Rio Grande do Norte, which also has the highest CaO, Na₂O, and TiO₂ contents. FeO ranges from 5.46% to 7.87%, and the highest values are also found in sample A-70, which has the lowest SiO₂ and MgO contents. The CaO ranges from 0.36% to 0.58% but in sample A-70 is much higher, reaching a value of about 1.90%. The Na₂O content, usually of about 0.10% or a little lower, exhibits a value of about 0.23% in sample A-70. The NiO value, lower than in the olivine, ranges from 0.03% to 0.14%. The MnO content is more or less equivalent to the olivine content, ranging from 0.07% to 0.13%. The grains are fairly homogeneous as attested by analyses of their cores and margins.

Twenty-one chemical analyses of the clinopyroxenes from the same peridotite nodules were made and the results indicate a fairly good homogeneity of this phase. Some differences appear in the TiO₂, Al₂O₃, and Na₂O contents in sample A-48-B, which also has a slightly higher content of MgO and FeO than the clinopyroxenes in the other analyzed nodules. Cr₂O₃ exhibits an overall variation from 0.55% to 1.09%. FeO ranges from 2.23% to 5.23% whereas the Na₂O ranges from 0.56% to 2.51%. Cr₂O₃ varies from 0.55% to 1.09%. The Ca/(Ca + Mg) ratio ranges from 0.47 to 0.49, and the lowest value is found in sample A-48-B.

Twenty-nine chemical analyses of spinel were made. All the spinels have a high chromium content. FeO as determined by the microprobe has been recalculated assuming spinel stoichiometry (Irvine, 1965). All the spinels analyzed show little variation of the Mg/(Mg + Fe²⁺) ratio, which has a value of about 0.80. The Cr/(Cr + Al) ratio ranges from 0.10 to 0.18, which is the highest ratio found in sample A-76 from Serra Aguda neck. The chrome diopside in this nodule also shows the highest Cr₂O₃ content. The Cr/(Cr + Al + Fe³⁺) ratio ranges from 0.10 to 0.18, whereas the Fe³⁺/(Cr + Al + Fe³⁺) ratio ranges from 3.39 to 7.40. The TiO₂ and MnO contents are very low and show little variation.

The analyses of the component phases of the ultramafic nodules suggest that most of the nodules come from similar depths in the mantle because of the similarities in their chemistry. Sample A-48-B is believed to have been derived from greater depth because of the major chemical differences of its olivine and diopside.

Thirty analyses of olivine xenocrysts were made. Most of the grains showed uniform compositions of their cores and edges, but some grains showed pronounced variation in that they were enriched in FeO near the edges. This indicates a normal zoning, which is probably an effect of reaction with the host magma. Most of the grains have compositions equivalent to forsterite, although some magnesian chrysolite was also recorded. The olivine xenocrysts are more MgO-rich than the phenocrysts of the host basalt and are very similar to those found in the nodules. The MgO exhibits an overall variation from 42.94% to 50.98%, and the FeO content ranges from 4.95% to 18.14%. The CaO, TiO₂, and Al₂O₃ contents are very low or absent.

Some fresh anhedral bronzite xenocrysts from Cabugizinho da Arara, Serra Preta (Cerro Corá), and Serra Aguda, were analyzed.

The analyses are comparable to those of bronzite xenocrysts from the Cabugizinho da Arara neck (sample L-53) but exhibit higher Al₂O₃ content than those from Serra Aguda and Serra Preta (Cerro Corá) ranging from 3.18% to 4.67%. The FeO content shows little variation and ranges from 5.66% to 6.09%. Slight differences from the cores to the edges are observed in a few grains, and this probably indicates some reactions between this type of xenocryst and the host magma.

Clinopyroxenes are commonly found in aggregates with olivine in the Boa Vista flows, Paraíba. Eight chemical analyses indicate a very uniform composition with little variation among the major elements. The Ca/(Ca + Mg) ratio ranges from 0.46 to 0.49. Na₂O is notably much lower than in the clinopyroxenes in the xenoliths except those from sample A-48-B, which have comparable amounts of Na₂O. The Al₂O₃ values range from 2.59% to 4.82% and FeO shows less pronounced variation, ranging from 5.55% to 6.28%.

Spinel xenocrysts are present in several localities and are especially abundant in the potash ankaratrite of the Cabugizinho da Arara neck (sample L-53). They normally show dark reaction rims. Attempts to analyze these spinels and to determine the composition of the dark margins were made, but because the chemical analyses obtained usually totaled well over 100% owing to analytical problems, they have been discarded. However, they suggested that two varieties of spinel xenocrysts are present in the ankaratrite mentioned above with very different contents of Cr₂O₃, MgO, and Al₂O₃, and they resemble some magnetite grains found in some of the Tertiary basalts.

Plagioclase xenocrysts from Serra Aguda and Serra Preta were analyzed. Their composition varies from An₄₅ to An₆₃ (andesine to calcic labradorite), with the more calcic varieties predominating. They show some differences between the compositions of the cores and edges of the grains. As these grains are believed to be xenocrysts for reasons already discussed, probably the chemical changes can be ascribed to reactions with the basaltic liquid during transport toward the surface.

Some potassium feldspar xenocrysts found at Cabugizinho da Arara were also analyzed, and the results show that they have a K₂O:Na₂O ratio of approximately 3:1 and SiO₂:Al₂O₃ ratio equivalent to 5:1.

There is no special reason to admit a cognate origin for these alkali feldspar grains. They clearly show evidence of reaction with the magma as attested by their embayed edges.

DEPTH AND TEMPERATURE OF ORIGIN

Peridotite nodules may be used to reconstruct environmental conditions in the mantle. The coexistence of clinopyroxene and orthopyroxene, characteristic of these peridotites, and the Ca distribution between these two phases potentially provides a useful geothermometer. The Di enstatite solvus in the pure system Mg₂Si₂O₆-CaMgSi₂O₆ has been determined by Boyd and Schairer (1964) at atmospheric pressure and by Davis and Boyd (1966) at 30 kb. The location of this curve has been confirmed by experiments carried out by Warner and Luth (1974), who have investigated this system at pressures of as much as 10 kb, and who have also made extrapolation at pressures as high as 30 kb. Equilibration temperatures for natural pyroxenes that depart substantially in composition from the join Mg₂Si₂O₆-CaMgSi₂O₆ can be determined through a semi-empirical relation developed by Wood and Banno (1973). Boyd (1973) emphasized that equilibration temperatures of the diopsidic pyroxenes should not be estimated from Ca/(Ca + Mg) ratios when the diopsides contain more than 10% FeSiO₃, because the results would be seriously underestimated. Finally, Wilshire and Jackson (1975) proposed that temperature estimates obtained utilizing the Di enstatite solvus are only reliable if the suite of four-phase lherzolites in question is an isochemical one.

Among the six nodules chemically analyzed in this study, five

showed ortho- and clinopyroxene in paragenesis in their mineralogical composition. The diopside compositions of these nodules, which range from 4.10 to 8.30 mole percent of FeSiO_3 , lie below the limits of Fe that Boyd (1973) considered acceptable for application of the experimentally based geothermometer. For this reason, their equilibration temperatures were estimated using their $\text{Ca}/(\text{Ca} + \text{Mg})$ ratios and the Di enstatite solvus at 30 kb. Most of the results obtained for one single nodule were very consistent, and the overall temperature variation ranged from 900 to 960 °C, with values predominating around 900 °C. Unfortunately, the bulk chemical compositions of these nodules are not available to verify how this suite approaches an isochemical one.

Mercier and Carter (1975) pointed out that Ca diopside was pressure sensitive at temperatures above 1100 °C. All temperatures determined in the present study are below this limit, suggesting that the Ca distribution between enstatite and diopside has not been affected by the pressure, and the results are probably satisfactory.

MacGregor (1974), in experimental studies on the $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ system, illustrated the nature of the reactions in this system which describe a petrogenetic grid providing an assignment for the conditions of formation of the Ca-poor ultramafic rocks. If the equilibration temperature is known, the equilibration pressure may be estimated from the Al_2O_3 content of the pyroxene that has crystallized in equilibrium with garnet or spinel, utilizing his petrogenetic grid. The equilibration pressure can be estimated either from the raw weight percent of Al_2O_3 in the enstatite or after some allowance has been made for the presence of Na pyroxene (Boyd, 1973).

Using the equilibration temperatures indicated above and the raw Al_2O_3 of the coexisting enstatites, pressures equivalent to depths from 55 to 64 km are obtained for the analyzed nodules. The Na_2O content of the enstatite is usually about 0.10% or lower, and the Cr_2O_3 content of the enstatite has not been determined. For this reason, the corrections to pressure estimates proposed by Mercier and Carter (1975), applicable for solid solution effects, have not been applied here. MacGregor (written commun. 1975) in writing with A. Basu concerning their Mount Alberta data, found that the apparent pressures derived from the simple system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ were drastically affected by the $\text{Cr}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$ ratio of the coexisting spinel. The higher the ratio, the higher the apparent pressure. However, if the $\text{Cr}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$ ratio of the coexisting spinel was approximately the same, the relative values were probably satisfactory. The spinels in the nodules studied here show the $\text{Cr}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$ ratios very constant, and this suggests that the pressure estimates in the present study are sufficiently accurate to be useful. The depths equivalent to these pressure estimates are assumed to be those where the nodules have been picked up by the magma, and they indicate the minimum probable depth of magma generation. The maximum depth obtained was 64 km for a nodule from the Serrote Preto plug (sample A-48-B). Sample A-46 collected from the same locality yielded a depth equivalent to 55 km. This suggests that nodules have been picked up from wall rocks at different depths by the magma ascending from the mantle.

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