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# Petrology and geochemistry of the Neoproterozoic Guaxupé granulite facies terrain, southeastern Brazil

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**Abstract**

Geochemical and oxygen isotopic data on the Neoproterozoic granulite facies rocks (enderbites, charnockite and charnokitic augen gneisses) of Guaxupé, Brazil are assembled. Geochemical discrimination function calculations show an igneous origin for majority of the rock types in the area. Major and trace element data, especially REE, are similar to tonalite and granodiorite. Oxygen isotope composition for charnockitic gneisses and mafic granulites yield $\delta^{18}O$ values in the range of +8.8 to +11‰ and fall in the range of quartzofeldspathic rocks of medium- to high-grade terrains elsewhere. A small-scale variation of $\delta^{18}O$ values, compatible with the chemical data, imply the preservation of pre-metamorphic oxygen isotope compositions. Minimum peak pressure–temperature conditions are 8.5 kbar and 850°C. The high-grade metamorphism did not appear to have altered significantly the geochemical and oxygen isotope compositions of the protoliths. Approximately 2.5 kbar of pressure decrease accompanied by 200°C cooling has been recorded for a portion of the cooling path. The *P–T* path is consistent with a single event, namely the formation and uplift of the Guaxupé nappe in the Neoproterozoic Brasiliano cycle.

## 1. Introduction

The nature and composition of the earth's lower crust can be inferred from the study of granulite facies rocks (Smithson and Brown, 1977; Harley, 1989; Bohlen, 1991). Geological and geochemical data from granulites also provide information on the tectonic and chemical processes responsible for the accretion and stabilization of new crust and hence continental evolution. Recent years have witnessed accumulation of large amount of geological and geochemical information on granulite facies rocks from different parts of the world. The accumulated data have provided conflicting views on certain aspects of granulite formation, such as (i) significance of "peak" *P–T* conditions (Frost and Chacko, 1989; Pattison and Bégin, 1994), (ii) nature of the fluids (Touret, 1986; Valley, 1992), (iii) source of heat (Frost et al., 1987), (iv) large ion lithophile fractionation (Barbey and Cuney, 1982; Rudnick et al., 1985), (v) nature and extent of isotope homogenization during metamorphism (Kempton and Harmon, 1992) and (vi) exhumation of granulite terrains. The controversies can be understood best if we consider the "diversity in the mode of formation of granulites" (Harley, 1989).

Regional granulite facies metamorphic terrains occur in all continents and Harley (1989) has listed more than eighty such terrains. Curiously, granulite facies terrains of Brazil are not cited, possibly due to the paucity of published *P–T* data on Brazilian granulites in international journals. Brazil, with its extensive area of high-grade metamorphic terrains ranging in age


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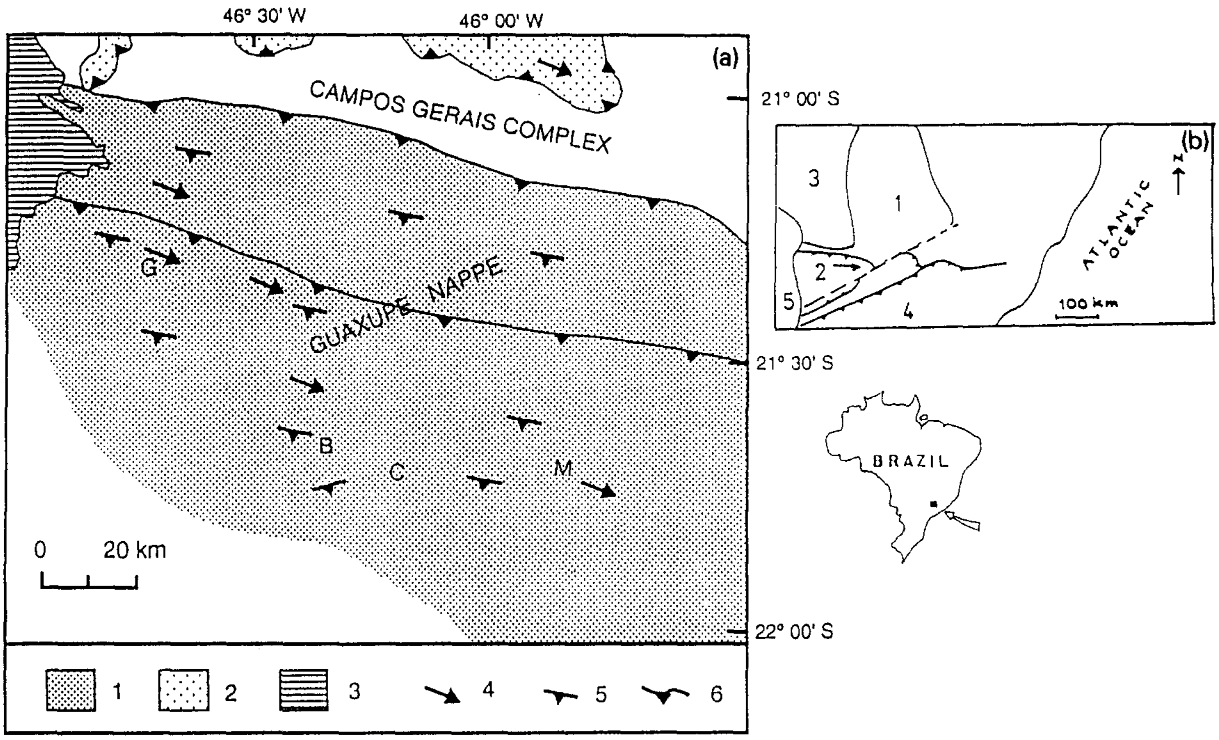


Fig. 1. (a) Structural geological map of the Guaxupé area. Campos Gerais Complex is made up of Archaean granite greenstone terrains set in tonalites and tonalitic gneisses and migmatites. Legend: 1 = granulite facies rock of the Guaxupé nappe; 2 = Neoproterozoic metasedimentary sequence of the Araxá–Canastra Group; 3 = Phanerozoic Paraná Basin; 4 = stretching lineations; 5 = dip of gneissic foliation; 6 = thrust faults. Towns: *G* = Guaxupé; *B* = Botelhos; *C* = Campestre; *M* = Machado. (b) Location of the Guaxupé Massif in relation to the Brasilia and Ribeira fold belts (after Trouw et al., 1994). 1 = São Francisco Craton; 2 = Guaxupé Massif, arrows point to direction of oblique transport in shear belt that forms the northern limit of the massif; 3 = Brasilia belt; 4 = Ribeira belt; 5 = Paraná basin (Palaeozoic).

from Archaean to Neoproterozoic, offers a good opportunity to evaluate the nature and evolution of the continental crust in South America (Iyer et al., 1987; Cordani et al., 1989). Some of the granulite facies terrains of Brazil have unusual geochemical characteristics such as undepleted LILE concentration and high radiogenic heat production values, especially in felsic rocks (Iyer et al., 1984; Fernandes et al., 1987; Barbosa, 1990). Most of the investigations in Brazil have been confined to the Archaean granulite terrains of São Francisco Craton in Bahia, one of the largest outcropping granulite provinces of the world (Cordani and Iyer, 1979; Figuereido, 1980; Sighinolfi et al., 1981; Oliveira, 1982; Iyer et al., 1984; Barbosa, 1986). In comparison, published data from the high-grade metamorphic terrains of central and southern Brazil are limited (Oliveira and Hypolito, 1978; Wernick and Oliveira, 1982; Fernandes et al., 1987).

In the present paper we present geochemical, oxygen isotope and geothermo-barometric data on the granulite rocks of the Guaxupé Massif (Fig. 1), which forms a part of the high-grade Alfenas mobile belt (Almeida, 1979). In an earlier publication we discussed the trace element distribution in theses rocks (Fernandes et al., 1987). The present study focuses on deciphering the nature of the protolith, thermal conditions of the crust during the metamorphism and elemental and isotope fractionation during metamorphism.

## 2. Geological setting

The Guaxupé Massif, situated to the south of the São Francisco Craton, is made up of high-grade gneisses and belongs to the Tocantins structural province (Almeida et al., 1981). Hasui et al. (1984) described this massif as an extensive area of granulite facies rocks associated with partly migmatized amphibolite facies gneisses; the occurrence of granulites decreases towards the south giving way to migmatites and granitic rocks. The massif is bounded to the north by the Campos Gerais Complex, an Archaean greenstone–granite terrain, over which the Neoproterozoic metasediments of the Araxá–Canastra Group have been thrust in a WNW–ESE direction (Fig. 1).

Regional gravity sections over the high-grade terrain have been interpreted by Haralyi et al. (1985) in terms of crustal thickening by which high-grade rocks were thrust over lower-grade rocks to the north. This is also the interpretation given by Oliveira (1984). In their study of tectonic transport at the southern border of the São Francisco Craton, Schrank et al. (1990) modified the model by suggesting that the Guaxupé Massif was transported from west-northwest to east-southeast and uplifted during the Brasiliano orogenic cycle in the form of a tangential nappe—the Guaxupé nappe (Fig. 1). Their findings were based on kinematic indicators such as stretching lineations, S/C foliations and boudinage. The direction of transport of the Guaxupé nappe proposed by them and also by Roig and Schrank (1992) is corroborated by the work of Trouw et al. (1994) who have interpreted this area as a result of being caught up in a zone of interference between the Brasilia Fold Belt to the northwest and the Ribeira Fold Belt in the southeast, with west to east tectonic transport contemporaneous with the peak of metamorphism. The WNW–ESE direction also represents the regional gneissic foliation, parallel to the trend of a 120 km ductile shear zone that is evidently responsible for the compositional banding and gneissic structure of the granulites and the migmatites that injected them. The intensity of ductile deformation decreases from Guaxupé to low-strain regions to the south. Morales et al. (1992, 1994) noted that the major structural feature is a low-angle penetrative gneissic foliation, in keeping with the regional structure described above. They also mention that granulite facies conditions prevailed at the beginning of deformation, passing gradually to amphibolite facies with the same structural style with decreasing pressure and temperature, and that during this process partial fusion, remobilization and granitic intrusions also occurred. The above lines of evidence suggest that the tectono-metamorphic evolution and uplift of the Guaxupé nappe took place as a continuous process. In this respect the Guaxupé high-grade terrain is different from that of South India where low-grade terrains pass laterally to higher grades (Condie et al., 1982; Newton, 1992). Furthermore, in Guaxupé there is no evidence of the typical South Indian charnockitization.

Although detailed geochronological investigations have not been carried out in this area, whole-rock Rb–Sr isochrons (Campos Netto et al., 1988) and U–Pb dates of zircons (Oliveira et al., 1986) indicate ages between 600 and 700 Ma for charnockites, whereas a Rb–Sr isochron age of age of 2.0 Ga has been obtained for some enderbites (M.C.H. Figueiredo, pers. commun.). The age of granulite metamorphism in this region is uncertain. However, geochronological studies of the granulite facies rocks on the eastern and western regions of the São Francisco craton have yielded a protolith age of 1600 Ma and a metamorphic age around 780 Ma (Ferreira Filho and Naldrett, 1993; Trouw and Pankhurst, 1993). The Guaxupé rocks are situated roughly midway between the two dated granulite terrains and hence the age of metamorphism may be in the same interval (600–750 Ma). The difficulty in dating the granulite metamorphism may be due to the partial or complete resetting of the isotopic clocks by the late regional migmatization and nappe forming events associated with the Brasiliano orogenic cycle (Oliveira et al., 1986). The Brasiliano orogenic cycle (600–750 Ma), represents a major wide spread geotectonic event(s) in Brazil. The present view among the Brazilian geochronologists is that the Brasiliano cycle may consist of more than one episode (Cordani et al., 1992).

## 3. Petrography

The predominant rock types in the area are enderbites, mafic enderbites, charnockite and charnokitic augen gneisses. These rocks commonly enclose mafic granulites in the form of long folded bands or layers, as well as larger (1–2 km) boudinaged bodies. Pelitic gneisses, which occur to a less extent in the study area, are mostly garnet–biotite $\pm$ sillimanite gneisses with subordinate sillimanite–garnet quartzites and in certain places these gneisses also enclose narrow layers of mafic rocks. Abundant pink K-feldspar-rich veins and

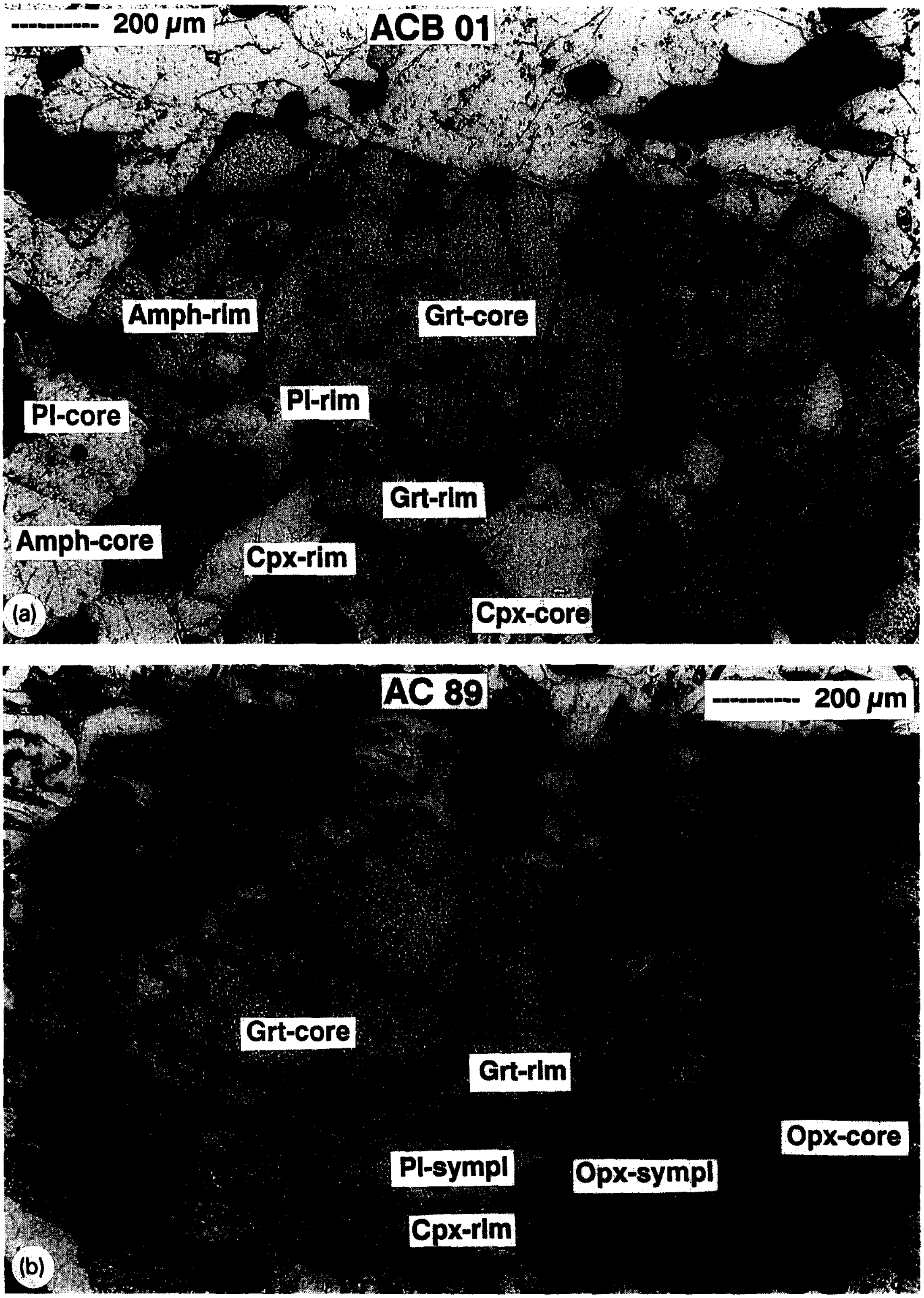


Fig. 2. (a) Photomicrograph of ACB01. Dots represent the location of the analysis points corresponding to the analyses in Tables 2–6. (b) Photomicrograph of AC89. Note the plagioclase + orthopyroxene symplectite mantling the garnet in the centre of the photograph. Dots represent the location of the analysis points corresponding to the analyses in Tables 2–6. Just outside of the field of view are the clinopyroxene and plagioclase grains (similar grain size to the garnet) used for the estimation of maximum $P$–$T$ conditions.

Table 1
Major, trace element and oxygen isotope composition of granulite facies rocks of Gauxupé, Brazil

| | AC 6/14 | AC 7/14 | AC 7/14a | AC 5/15 | AC 5/15a | AC 1/4c | AC 7/16 | AC 6/17 | AC 13/5 | AC 6/15 | AC 111a | AC 110a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (%) | | | | | | | | | | | | |
| $SiO_2$ | 66.1 | 52.4 | 61.0 | 62.3 | 57.1 | 69.4 | 54.0 | 61.6 | 65.2 | 71.0 | 52.5 | 48.7 |
| $TiO_2$ | 0.66 | 0.85 | 0.16 | 0.89 | 1.33 | 0.39 | 1.8 | 0.8 | 0.6 | 0.22 | 1.47 | 2.05 |
| $Al_2O_3$ | 15.6 | 14.8 | 19.5 | 18.6 | 16.4 | 14.8 | 13.72 | 15.86 | 14.32 | 13.38 | 13.9 | 14.7 |
| $Fe_2O_3$ | 0.86 | 1.95 | 0.23 | 0.49 | 1.64 | 1.91 | 2.31 | 1.14 | 1.51 | 1.08 | 4.88 | 4.64 |
| FeO | 4.14 | 6.86 | 3.01 | 4.13 | 6.11 | 1.29 | 10.1 | 4.05 | 3.2 | 1.97 | 8.28 | 7.10 |
| MnO | 0.13 | 0.15 | 0.09 | 0.09 | 0.13 | 0.08 | 0.36 | 0.1 | 0.15 | 0.07 | 0.21 | 0.17 |
| MgO | 0.42 | 4.57 | 1.22 | 1.86 | 3.09 | 1.57 | 1.47 | 1.92 | 1.14 | 1.25 | 5.61 | 6.95 |
| CaO | 2.16 | 7.63 | 5.13 | 5.32 | 6.21 | 3.33 | 5.34 | 5.2 | 2.3 | 1.70 | 7.39 | 8.86 |
| $Na_2O$ | 3.38 | 4.31 | 4.95 | 4.17 | 3.77 | 2.76 | 3.56 | 5.09 | 2.8 | 4.06 | 3.32 | 3.53 |
| $K_2O$ | 5.77 | 2.79 | 4.04 | 1.55 | 2.08 | 3.11 | 3.77 | 1.54 | 6.01 | 5.9 | 1.54 | 1.92 |
| $P_2O_5$ | 0.19 | 0.32 | 0.27 | 0.34 | 0.37 | 0.17 | 0.65 | 0.25 | 0.13 | 0.07 | 0.16 | 0.4 |
| LOI | 0.61 | 2.59 | 1.45 | 0.71 | 1.74 | 0.43 | 2.1 | 1.65 | 1.7 | 1.1 | 1.45 | 1.22 |
| Total | 100.00 | 99.2 | 101.05 | 100.45 | 99.97 | 99.24 | 99.2 | 99.2 | 99.1 | 100.3 | 100.16 | 100.24 |
| $DF^a$ | 3.8 | 0.1 | 7.7 | 3.7 | 3.0 | 0.7 | 4.0 | 5.1 | 3.0 | 3.4 | 3.2 | 1.7 |
| (ppm) | | | | | | | | | | | | |
| La | 55 | 81 | | 50 | | | 77 | | | 53 | | |
| Ce | 92 | 141 | | 88 | | | 144 | | | 104 | | |
| Nd | 48 | 54 | | 47 | | | 140 | | | 42 | | |
| Sm | 14 | 7.5 | | 5.2 | | | 26 | | | 6.7 | | |
| Eu | 3.8 | 2.7 | | 1.6 | | | 3.3 | | | 2.2 | | |
| Tb | 1.9 | 0.8 | | 0.6 | | | 3.9 | | | 0.8 | | |
| Yb | 2.0 | 1.2 | | 1.34 | | | 6.3 | | | 1.6 | | |
| Lu | 0.55 | 0.3 | | 0.22 | | | 1.4 | | | 0.31 | | |
| Rb | 124 | 88 | | 50 | | | 63 | 106 | | | | |
| Sr | 210 | 233 | | 481 | | | 225 | 16769 | | | | |
| Nb | 86 | 47 | | 23 | | | 139 | 1062 | | | | |
| Zr | 802 | 808 | | 350 | | | 1355 | 40 | | | | |
| Cu | 40 | 28 | | 26 | | | 42 | 21 | | | | |
| Ni | 22 | 25 | | 12 | | | 29 | 120 | | | | |
| Zn | 115 | 67 | | 109 | | | 130 | 0.7 | | | | |
| U | 1.1 | <0.5 | | 4.9 | | | <0.5 | <0.2 | | | | |
| Th | 0.3 | 1.3 | | 7.3 | | | 0.2 | | | | | |
| $La/Yb)_n$ | 17.8 | 44.3 | | 24.8 | | | 8.1 | 401 | | 22.4 | | |
| K/Rb | 363 | 340 | | 302 | | | 403 | 113 | | | | |
| Rb/Sr | 0.59 | 0.38 | | 0.1 | | | 0.28 | <0.29 | | | | |
| Th/U | 0.27 | >2.6 | | 1.49 | | | >0.4 | | | | | |
| Radio. heat ($\mu W/m3$) | 0.86 | 0.49 | | 1.93 | | | 0.5 | 0.34 | | | | |
| $\delta^{18}O$(‰) | 11.2 | | 10.1 | 9.8 | 9.7 | 8.2 | 9.6 | 10.2 | 8.8 | 9.4 | | 8.0 |
| Mg number$^b$ | 0.16 | 0.55 | 0.45 | 0.4 | 0.49 | 0.6 | 0.22 | 0.47 | 0.38 | 0.51 | 0.53 | 0.61 |

$^a DF$ = Discrimination function value (Shaw, 1972).
$^b$Mg number = Mg/(Mg + 0.85$Fe^{tot}$) (Kempton and Harmon, 1992).

segregations give many of the above-mentioned rocks a migmatitic appearance and despite strong ductile deformation, the migmatites occasionally show cross-cutting relations and the presence of schollen. Though less common, mafic migmatites with tonalitic leucosome also occur, and these are considered to have formed by local melting of mafic rocks or injection of tonalitic melts (Choudhuri et al., 1992), as has been observed in other high-grade terrains (e.g., Tait and Harley, 1988; Sawyer, 1991 and reference therein),

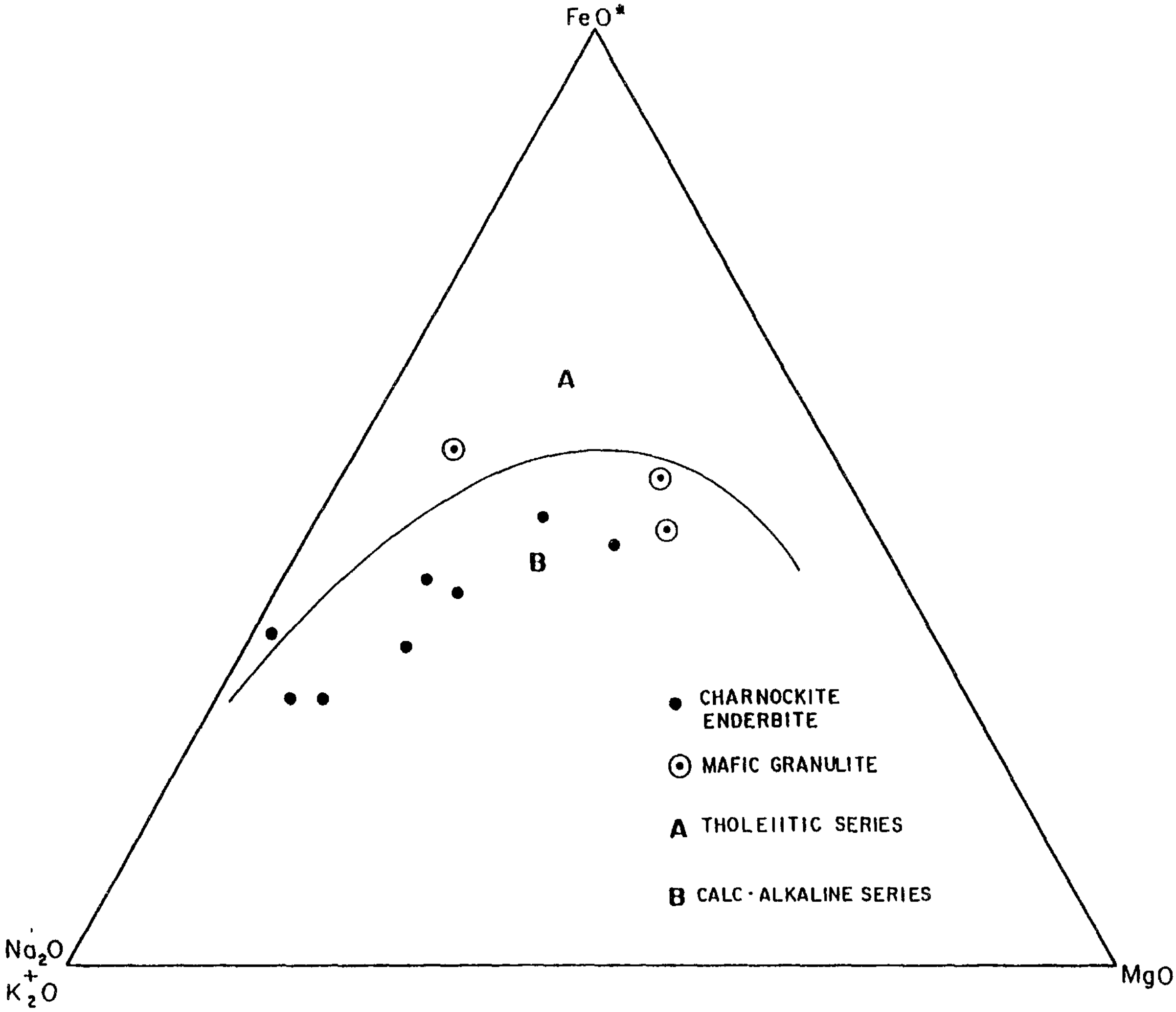


Fig. 3. AFM diagram showing that the protoliths of the granulites belong to calc-alkaline series.

The enderbites and mafic-rich enderbites are dark grey, granoblastic quartz-plagioclase rocks with little or no potash feldspar. Their foliation is marked by trails of pale green diopside, pale pink pleochroic hypersthene, and minor olive green hornblende. The pyroxenes are stretched into long prismatic to sigmoidal shapes, and the hornblende occurs as a wedge-shaped grains. These textures indicate that the rocks were subjected to strong deformation at granulite facies conditions. Little is known as to the lower limit of the onset of such deformation, but it seems that temperatures in excess of 600°C are required for plastic deformation of amphiboles (Brodie and Rutter, 1985).

Charnockites and charnockitic augen gneisses are dark bluish-grey to greenish-grey, coarse grained and granoblastic to blastoporphyritic rocks. In the augen gneisses, green diopside and strongly pleochroic hypersthene form trails around mesoperthite megacrysts, and quartz in the matrix is stretched into thin band or ribbons. Garnet is very rare in these felsic granulites and occurs either as small grains on the margins of diopside crystals or as relict anhedral grains with a moat of plagioclase separating them from surrounding grains of orthopyroxene. The latter texture is probably related to garnet breakdown consequent to uplift of the nappe structures and accompanying decompression (see

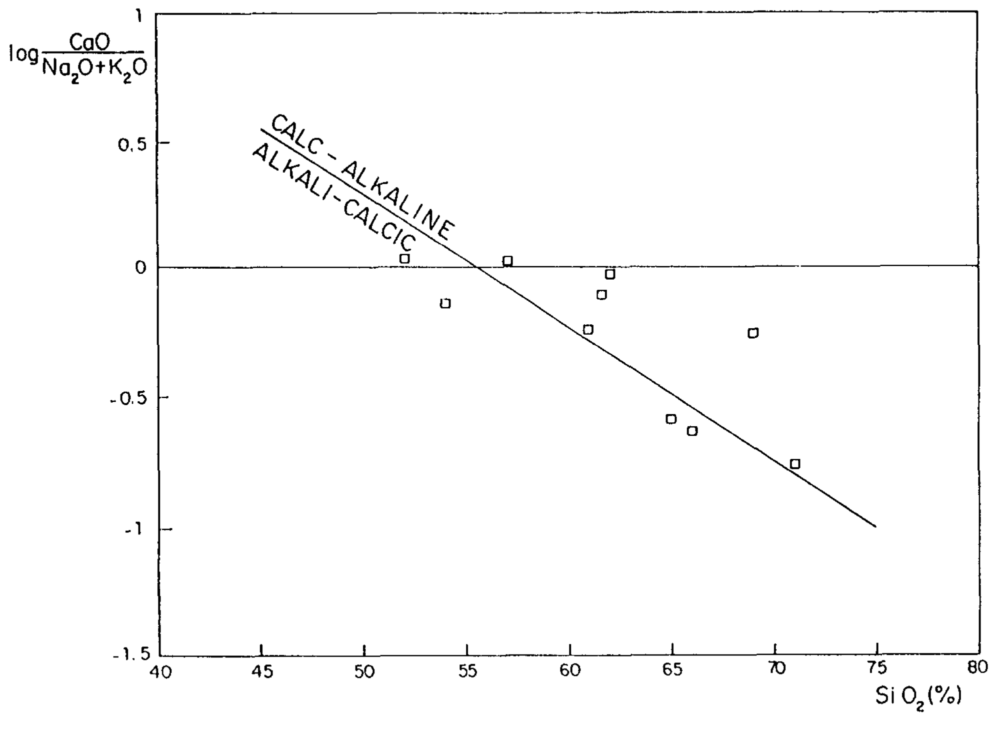


Fig. 4. Differentiation index of $CaO/(Na_2O+K_2O)$ plotted against $SiO_2$. The charnockites and enderbites of Guaxupé plot on a calc-alkaline trend. (diagram from Brown, 1981).

below). Considering their massive and uniform nature, the charnockites possibly represent dry granitic melts emplaced syntectonically.

Further indications of decompression comes from some of the garnet-bearing mafic granulites. In a few samples garnet is frozen in the process of reacting to orthopyroxene–plagioclase symplectite (Fig. 2a), a texture which typically results from decompression (Harley, 1989). From the extrapolation of the data of Green and Ringwood (1967), garnet probably formed in these mafic granulites at pressures in excess of 8 kbar, followed by its breakdown as pressure declined at the time of nappe emplacement. In the majority of these rocks olive green hornblende appears to be a stable phase coexisting with the pyroxenes. However, in a large metagabbro body with the paragenesis opx–cpx–green spinel–plagioclase, hornblende appears to be a late phase. In this rock cpx–green spinel occurs in a symplectite possibly formed by the reaction:

olivine + plagioclase = opx + cpx + green spinel

Based on the work of Kushiro and Yoder (1966), this reaction has a gentle slope in the *P–T* space, setting a lower pressure estimate for the metagabbro of around 8 kbar (Choudhuri et al., 1990).

## 4. Analytical methods

Major and trace element (except U, Th and REE) concentrations of whole-rock samples were determined by X-ray fluorescence technique at the Geology Department of the University of Campinas, Brazil. Glass fusion discs were used for major elements, whereas trace elements were determined on pressed powder pellets. The precision and accuracies of the method are of the order of 5% (Choudhuri and Enzweiler, 1993). U, Th and rare earth elements were measured by Instrumental Neutron Activation (INAA) at the Instituto de Pesquisas Energeticas e Nucleares (IPEN) São Paulo, Brazil. The analytical details are given in Iyer et al. (1984) and Moraes and Iyer (1990).

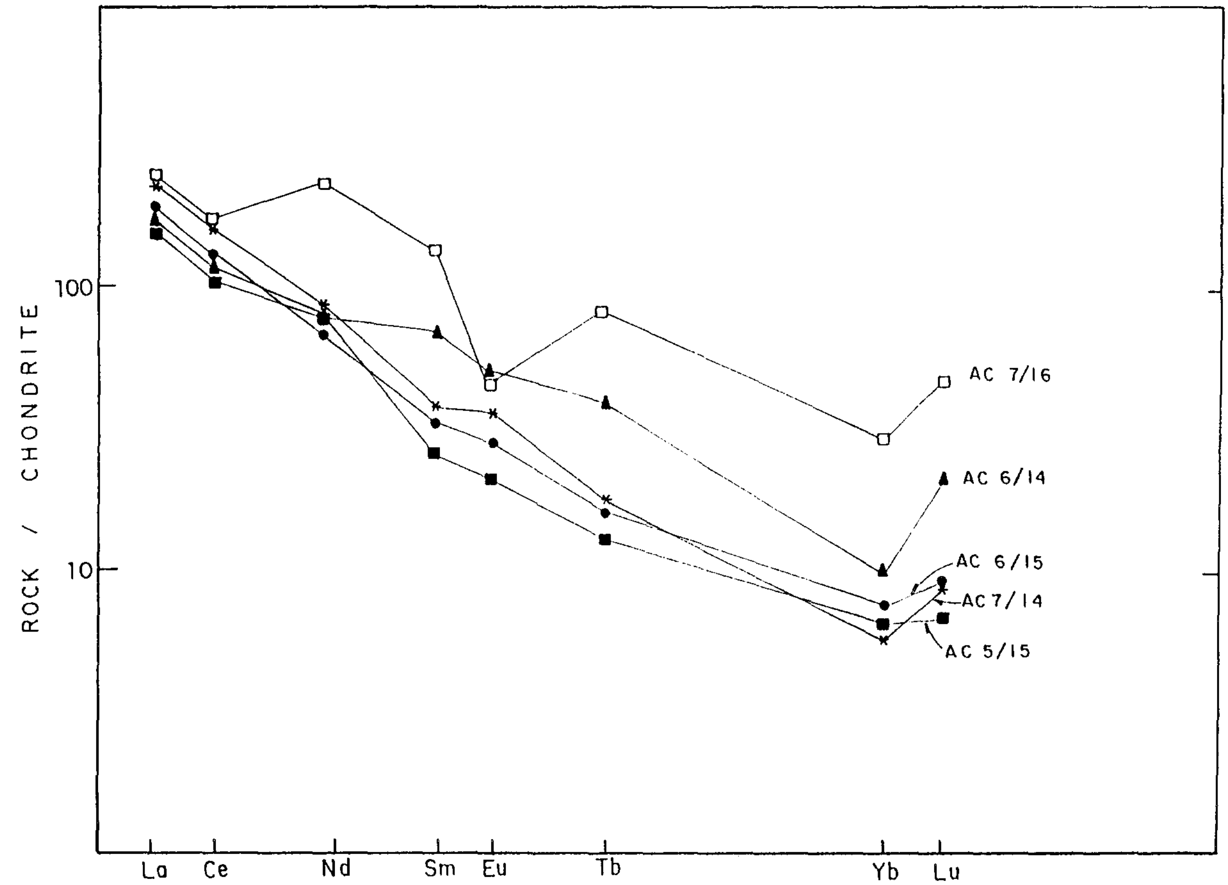


Fig. 5. Rare earth element distribution pattern for granulites of Guaxupé

Based on duplicate analyses and results of USGS and other standards the accuracy of REE determination is of the order of 10% for all elements, whereas the precision and accuracy of U, Th measurements are about 1–2%.

Mineral analyses were performed using wave length dispersive analysis on the automated ARL–SEMQ electron microprobe at the University of Calgary. Operating conditions, data reduction methods, detection limits and analytical precisions are described in Pattison (1991). Oxygen isotope analyses of whole-rock samples were carried out at the Geochemical Institute of the University of Göttingen, Germany. Oxygen was extracted from 15 to 25 mg of whole-rock sample by reacting with $BrF_5$ and converting to $CO_2$ following the technique of Clayton and Mayeda (1963). A Finnigan MAT 251 triple collector spectrometer was employed in the measurement of isotope ratios. The data are reported with respect to Standard Mean Ocean Water (SMOW). The precision based on triplicate analyses is calculated to be $< 0.3‰$. Measurements on NBS-28 reference standard yielded a value of $+9.6‰$.

## 5. Geochemistry

### 5.1. Major element composition

The analytical data for the major, trace element and oxygen isotope composition of the granulites are presented in Table 1. Except for minor sillimanite–garnet quartzites and gneisses, the granulite gneisses of Guaxupé can be conveniently separated into two compositional groups. The groups are basic granulites ($SiO_2 = 48–50\%$) and intermediate to felsic granulites ($SiO_2 = 57–70\%$). In order to determine whether the

Table 2
Representative microprobe analyses of orthopyroxenes, Guaxupé, Brazil

| Sample number | AC89 core | AC89 symplectite |
|---|---|---|
| $SiO_2$ | 49.81 | 50.35 |
| $TiO_2$ | 0.07 | 0.03 |
| $Al_2O_3$ | 1.54 | 1.14 |
| FeO | 33.32 | 30.81 |
| MnO | 0.42 | 0.39 |
| MgO | 15.25 | 16.83 |
| CaO | 1.63 | 0.82 |
| $Na_2O$ | 0.00 | 0.00 |
| Total | 102.04 | 100.37 |
| | | |
| Si | 1.926 | 1.951 |
| Ti | 0.002 | 0.001 |
| Al | 0.070 | 0.052 |
| Fe | 1.078 | 0.999 |
| Mg | 0.879 | 0.972 |
| Mn | 0.014 | 0.013 |
| Ca | 0.068 | 0.034 |
| Na | 0.000 | 0.000 |
| Sum | 4.037 | 4.022 |
| | | |
| Mg/(Mg+Fe) | 0.449 | 0.493 |
| $Fe^{3}/Fe_t$ | 0.061 | 0.044 |
| $X_{Wo}$ | 0.034 | 0.017 |
| $X_{en}$ | 0.449 | 0.496 |
| $X_{Fs}$ | 0.517 | 0.487 |

protoliths of the granulites were igneous or sedimentary, the discriminatory function (*DF*) of Shaw (1972) was applied. The function is given by the relation:

$$DF = 10.44 - 0.21SiO_2 - 0.32Fe_2O_3(\text{total Fe}) - 0.98MgO + 0.55CaO + 1.46Na_2O + 0.54K_2O$$

The equation is generally applicable to quartzo-feldspathic rocks with MgO < 6% and $SiO_2$ < 90%. In general positive *DF* values suggest an igneous parentage and negative values are associated with sedimentary precursors. The positive *DF* values (Table 1) for samples imply an igneous parentage for majority of the rocks. The chemical data, when plotted in the conventional AFM diagram (Fig. 3) show a calc-alkaline trend. This trend is also seen in the lime/alkali vs. $SiO_2$ diagram (Fig. 4). The modal mineralogy of all samples, except the mafic varieties, vary from quartz diorite to granitic types (Fig. 2; Fernandes et al., 1987) and as we shall see further the protoliths themselves may have been products of partial melting at mid- to deep crustal levels.

### 5.2. Rare earth element variation

The rare earth element data for two enderbitic and three charnockitic gneisses are presented in Table 1 and their chondrite-normalised REE distribution patterns are shown in Fig. 5. The REE pattern shows a fractionated trend with light REE ( = LREE) enrichment with $(La/Yb)_n$ ratio ranging from 8 to 44. Such trends are similar to Archaean tonalitic gneisses (Cullers and Graf, 1984). Wide ranges of $(La/Yb)_n$ ratios have been found in many Archaean tonalites from granite–greenstone terrains (Condie 1981; Jahn et al., 1981) and in granulites from Scourie, Lewisian Complex (Pride and Muecke, 1980; Weaver and Tarney, 1980, 1981), Qianxi, China (Jahn and Zhang, 1984) South India (Condie et al., 1982; Allen et al., 1985) and Qianan region, China (Kaiyi et al., 1985). Rudnick and Presper (1990) compiled geochemical data from the literature for high-pressure granulites and evaluated the compositional differences between granulite terrains and xenoliths. They observed a systematic LREE enrichment across the three granulite groups with the Archaean granulites having the highest median $(La/Sm)_n$ and $(La/Yb)_n$, granulite xenoliths having the lowest $(La/Sm)_n$ and $(La/Yb)_n$ with post-Archaean terrains lying intermediate between the two groups. The data for Guaxupé granulites conform to the trend observed for post-Archaean granulites (Fig. 4; Rudnick and Presper, 1990). The REE pattern for the Guaxupé granulites are similar to those of basic and intermediate granulites from the southeastern part of the Jequié–Mutuipe Complex, Bahia, Brazil (Barbosa, 1990, fig. 16) as well as granulites of eastern Minas Gerais, Brazil (Herbert et al., 1991). However, their total REE is higher and their slope at the LREE end much steeper than for two-pyroxene mafic granulite from Guaxupé (Choudhuri and Barrueto, 1994). Nevertheless the REE pattern is consistent with the major element geochemical interpretation of a calc-alkaline trend for the precursor rocks. A notable feature of the REE distribution is the absence of a positive Eu anomaly that is observed in many Archaean TTG rocks and high-grade gneisses (Rudnick and Taylor, 1986). In this respect the Guaxupé granulites resemble some of

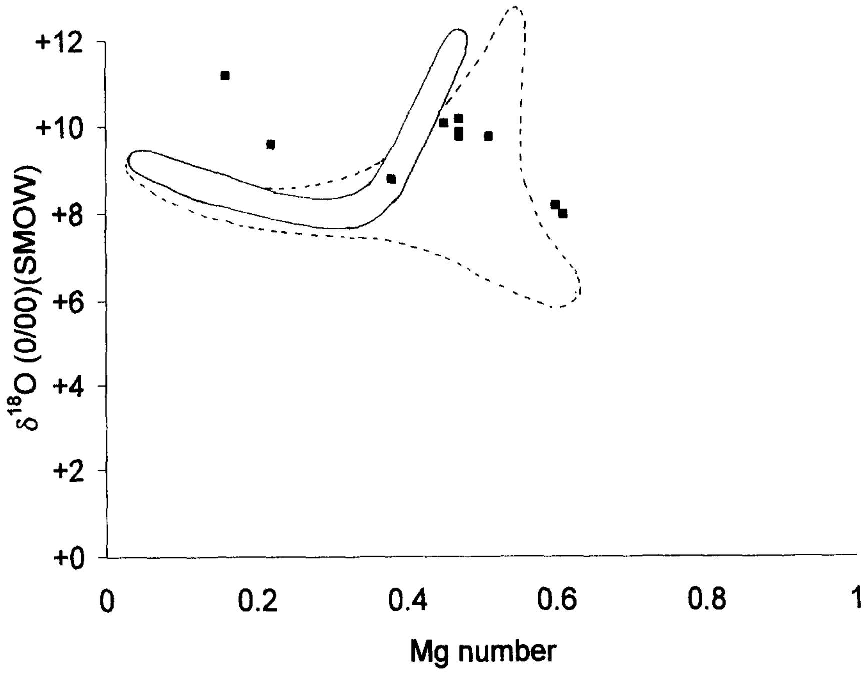


Fig. 6. Mg number vs. $\delta^{18}O$ for the granulite facies rocks of Guaxupé region, Brazil. Also shown are the range of values from intermediate (broken lines) and silicic (closed line) granulite xenoliths world wide (Kempton and Harmon, 1992).

the charnockites of South India (Condie and Allen, 1984; Allen et al., 1985), where the positive Eu anomaly could be correlated with total REE concentration. Samples with high REE concentration display no or negative Eu anomaly and are also low in plagioclase. A similar correlation was observed for charnockites and tonalitic–granodioritic gneisses from the Qianan region, China (Kaiyi et al., 1985). In Guaxupé most of the granulites are low in plagioclase ( < 60%; Fernandes et al., 1987) and are in the same range as those of Nilgiri and Toppur in South India (Allen et al., 1985).

### 5.3. Large ion lithophile element (LILE) fractionation

The LILE concentration in the granulite facies rocks of Guaxupé has already been discussed in an earlier publication (Fernandes et al., 1987). The K/Rb ratios of the granulites are in the range of 300–600 (average = 421) and these values are high compared with many of the granulite facies rocks of Brazil (Table 2; Fernandes et al., 1987). Covariant analysis of the K/Rb ratios with K shows that the distribution pattern may be explained by complete or partial rehomogenization of K/Rb ratios among different precursor rocks that underwent prograde metamorphism. The major factor controlling the fractionation is the composition and nature of the fluid that participated in the reactions promoting or prohibiting the growth of the OH-bearing minerals in the rocks (Glassley, 1983). The U and Th values in the granulites are low probably due to the very low abundances of radioactive accessory minerals like zircon and apatite. The spread in the Th/U ratios (0.3–3.0) is due to the large variation of Th abundances. The U, Th contents of the granulites are similar to meta-igneous granulites and the distribution appears to be a characteristic primary feature of the rock types. The data on K, Rb, U and Th seem to indicate that LILE fractionation, if present, is small and variable. A comparison of the REE data with the LILE concentration shows a similar REE pattern for same rock types with varying K/Rb and Th/U values, implying the preservation of the original REE pattern, even though there may have been variable loss of LILE elements. Many authors have suggested immobility of REE during high-grade metamorphism (Tarney and Windley,

Table 3
Representative microprobe analyses of clinopyroxenes, Guaxupé, Brazil

| Sample number | ACB01 core | ACB01 rim | AC89 core | AC89 rim |
|---|---|---|---|---|
| $SiO_2$ | 49.48 | 52.45 | 50.31 | 51.05 |
| $TiO_2$ | 0.39 | 0.16 | 0.15 | 0.12 |
| $Al_2O_3$ | 5.13 | 3.15 | 2.79 | 1.92 |
| FeO | 10.66 | 8.06 | 15.70 | 13.91 |
| MnO | 0.52 | 0.37 | 0.17 | 0.14 |
| MgO | 11.67 | 13.6 | 10.28 | 11.58 |
| CaO | 21.34 | 22.44 | 20.75 | 21.58 |
| $Na_2O$ | 0.38 | 0.28 | 0.33 | 0.34 |
| Total | 99.57 | 100.58 | 100.48 | 100.64 |
| Si | 1.872 | 1.937 | 1.924 | 1.937 |
| Ti | 0.011 | 0.004 | 0.004 | 0.003 |
| Al | 0.229 | 0.137 | 0.126 | 0.086 |
| Fe | 0.337 | 0.249 | 0.502 | 0.441 |
| Mg | 0.658 | 0.752 | 0.586 | 0.655 |
| Mn | 0.017 | 0.012 | 0.006 | 0.004 |
| Ca | 0.865 | 0.888 | 0.850 | 0.877 |
| Na | 0.028 | 0.020 | 0.024 | 0.025 |
| Sum | 4.017 | 4.000 | 4.021 | 4.029 |
| Mg/(Mg+Fe) | 0.661 | 0.751 | 0.538 | 0.597 |
| $Fe^{3}/Fe_t$ | 0.098 | 0.0 | 0.086 | 0.132 |
| $X_{Wo}$ | 0.393 | 0.417 | 0.403 | 0.423 |
| $X_{en}$ | 0.415 | 0.438 | 0.334 | 0.364 |
| $X_{Fs}$ | 0.192 | 0.145 | 0.262 | 0.213 |

1977; Drury, 1978; Jahn and Zhang, 1984; Barbosa, 1990).

From the radioactive element distribution a radiogenic heat production value of 0.8 $\mu W/m^3$ was obtained for the granulites of Guaxupé (Fernandes et al., 1987). This value is within the range of values (0.25–2.7 $\mu W/m^3$) obtained for different granulite facies terrains worldwide (Iyer et al., 1984) and higher than the median value of 0.53 $\mu W/m^3$ calculated for post-Archaean terrains by Rudnick and Presper (1990). The large spread in the radiogenic heat production values for granulite terrains is the result of the inherited chemistry, as well as the complex nature of the fractionation of radioactive elements, especially U, during high-grade metamorphism.

## 6. Whole-rock oxygen isotope data

Oxygen isotope data for seven charnockitic gneisses and three mafic granulites (Table 1) yield $\delta^{18}O$ values in the range +8.8 to +11‰. These values fall within the range of quartzo-feldspathic rocks found in medium- and high-grade portions of Precambrian shields of Canada, Africa and Australia (Fourcade and Javoy, 1973; Shieh and Schwarcz, 1974; Barker et al., 1976; Longstaffe and Schwarcz, 1977; Wilson, 1981; Taylor and Sheppard, 1986). Amphibolite facies rocks (hornblende tonalite and biotite–hornblende tonalite gneisses) present in the Guaxupé region (Fernandes et al., 1987) also yielded $\delta^{18}O$ values (+8 to +10‰) in the same range as the granulites (our unpublished data). Oxygen isotope studies of granulite terrains have led to widely opposing conclusions regarding the role of fluid activity in the lower crust. Homogeneous isotope composition in some terrains such as the Grenville province (Shieh and Schwarcz, 1974) has been interpreted as evidence of large-scale isotope exchange with a deep seated mafic and ultramafic reservoir via a pervasive intergranular fluid. In other areas (e.g., Adirondacks and Kapuskasing structure zone) preservation of large isotope heterogeneity argues against pervasive

Table 4
Representative microprobe analyses of garnets, Guaxupé, Brazil

| Sample number | ACB01 core | ACB01 rim | AC89 core | AC89 rim |
|---|---|---|---|---|
| $SiO_2$ | 38.72 | 38.93 | 38.12 | 38.25 |
| $TiO_2$ | 0.04 | 0.04 | 0.02 | 0.01 |
| $Al_2O_3$ | 20.84 | 20.35 | 20.68 | 20.98 |
| FeO | 23.42 | 24.22 | 29.47 | 29.89 |
| Mno | 2.90 | 3.65 | 0.77 | 1.08 |
| MgO | 7.56 | 6.04 | 4.56 | 3.88 |
| CaO | 6.48 | 6.61 | 7.08 | 7.15 |
| Total | 99.96 | 99.84 | 100.70 | 101.24 |
| Si | 3.005 | 3.047 | 2.999 | 3.001 |
| Al | 1.907 | 1.878 | 1.918 | 1.940 |
| Ti | 0.002 | 0.002 | 0.001 | 0.001 |
| $Fe^2$ | 1.520 | 1.585 | 1.939 | 1.961 |
| Mg | 0.874 | 0.704 | 0.535 | 0.454 |
| Mn | 0.191 | 0.242 | 0.051 | 0.072 |
| Ca | 0.539 | 0.554 | 0.597 | 0.601 |
| Sum | 8.039 | 8.012 | 8.041 | 8.029 |
| $X_{alm}$ | 0.487 | 0.514 | 0.621 | 0.635 |
| $X_{prp}$ | 0.280 | 0.228 | 0.171 | 0.147 |
| $X_{sps}$ | 0.061 | 0.078 | 0.016 | 0.023 |
| $X_{grs}$ | 0.172 | 0.180 | 0.191 | 0.195 |
| Mg/(Fe+Mg) | 0.365 | 0.308 | 0.216 | 0.188 |
| $Fe^{3+}/Fe_{tot}$ | 0.061 | 0.077 | 0.042 | 0.030 |

Table 5
Representative microprobe analyses of plagioclases, Guaxupé, Brazil

| Sample number | ACB01 core | ACB01 rim | AC89 core | AC89 symplectite |
|---|---|---|---|---|
| $SiO_2$ | 46.89 | 45.69 | 56.31 | 48.14 |
| $Al_2O_3$ | 33.94 | 35.17 | 27.12 | 33.36 |
| FeO | 0.21 | 0.33 | 0.15 | 0.62 |
| MgO | 0.00 | 0.000 | 0.00 | 0.00 |
| CaO | 17.01 | 18.360 | 9.89 | 16.91 |
| $Na_2O$ | 1.80 | 1.120 | 5.93 | 2.29 |
| $K_2O$ | 0.00 | 0.010 | 0.36 | 0.01 |
| Total | 99.92 | 100.68 | 99.76 | 101.33 |
| Si | 2.156 | 2.093 | 2.541 | 2.186 |
| Al | 1.840 | 1.900 | 1.443 | 1.786 |
| Fe | 0.008 | 0.013 | 0.006 | 0.024 |
| Mg | 0.000 | 0.000 | 0.000 | 0.000 |
| Ca | 0.838 | 0.901 | 0.478 | 0.823 |
| Na | 0.160 | 0.099 | 0.519 | 0.202 |
| K | 0.004 | 0.001 | 0.021 | 0.001 |
| Sum | 5.006 | 5.007 | 5.008 | 5.022 |
| $X_{AB}$ | 0.160 | 0.099 | 0.510 | 0.197 |
| $X_{AN}$ | 0.836 | 0.900 | 0.470 | 0.803 |
| $X_{OR}$ | 0.004 | 0.001 | 0.02 | 0.001 |

Table 6
Representative microprobe analyses of amphiboles, Guaxupé, Brazil

| Sample number | ACB01 core | ACB01 rim |
|---|---|---|
| $SiO_2$ | 42.61 | 44.09 |
| $TiO_2$ | 1.65 | 1.04 |
| $Al_2O_3$ | 12.22 | 10.17 |
| FeO | 14.29 | 12.57 |
| MnO | 0.25 | 0.17 |
| MgO | 11.92 | 13.46 |
| CaO | 11.75 | 12.27 |
| $Na_2O$ | 1.17 | 1.14 |
| $K_2O$ | 1.95 | 1.67 |
| Total (anhydrous) | 97.81 | 96.58 |
| Si | 6.356 | 6.595 |
| Ti | 0.185 | 0.117 |
| Al | 2.148 | 1.793 |
| Fe | 1.782 | 1.572 |
| Mg | 2.650 | 3.000 |
| Mn | 0.032 | 0.022 |
| Ca | 1.878 | 1.967 |
| Na | 0.338 | 0.331 |
| K | 0.371 | 0.319 |
| Sum | 15.741 | 15.716 |
| Mg/(Mg+Fe) | 0.598 | 0.656 |
| $Fe^{3+}/Fe_{tot}$ | 0.177 | 0.178 |

fluid rock interaction during granulite facies metamorphism (Valley and O'Neil, 1984; Li et al., 1990; Puris and Wickham, 1994). In the high-grade metamorphic terrain of Nevada Wickham and Peters (1990) observed a sharp O isotope discontinuity between a lower zone of lighter $\delta^{18}O$ rocks (+6 to +8.5‰ in silicates) and an isotopically heavier and more heterogeneous overlying region (+7 to +12‰ in silicates). These data were interpreted by the authors as evidence of large-scale equilibration of middle or lower crust. However, unlike Guaxupé, the study area of Wickham and Peters (1990) involves a significant change in grade so that their interpretation may not be strictly relevant to Guaxupé.

In the classification scheme of Kempton and Harmon (1992) the majority of the samples analysed from Guaxupé may be classified as silicic ($SiO_2 > 66\%$) and intermediate ($SiO_2 = 54–66\%$). The oxygen isotope composition of these samples are in the same range as those of intermediate and silicic granulite xenoliths from different parts of the world (Kempton and Harmon, 1992). A rough inverse correlation between the Mg number [$Mg/(Mg+Fe^{tot})$] and $\delta^{18}O$ can be seen in the samples from Guaxupé (Fig. 6) and a similar trend was observed for lower crustal granulite xenoliths worldwide by Kemton and Harmon (1992). Such a trend suggests that the oxygen isotope composition in Guaxupé granulites appears to be related to the bulk chemical composition. In the Guaxupé granulites small-scale heterogeneity in $\delta^{18}O$ data (>2‰), compatible with the chemical composition of the rock types, implies preservation of premetamorphic $\delta^{18}O$ values. This inference gains further support from the similar range of oxygen isotope values (+8 to +10‰) for amphibolite gneisses in the same area. Thus in Guaxupé oxygen isotope data suggest that pervasive fluid rock and oxygen isotope homogenization are not major processes operating on a regional scale.

## 7. Metamorphic conditions

Two samples were selected to determine the metamorphic conditions of the Guaxupé granulites (see Fig. 1 for sample locations). Both are mafic granulites, one of which is an equigranular garnet–clinopyroxene–plagioclase–hornblende–quartz rock with plagioclase–quartz segregations (ACB01; see Fig. 2a), the second a garnet–clinopyroxene–orthopyroxene–plagioclase–quartz rock with no obvious plagioclase–quartz segregations (AC89; see Fig. 2b). In AC89, garnet is mantled by a symplectite of plagioclase and hypersthene, suggestive of the simplified reaction (abbreviations from Kretz, 1983):

$$Grt + Cpx = Opx + Pl + Qtz$$

Progress of this reaction, which has a flat slope in $P–T$ space (Harley, 1989), is suggestive of a component of decompression during cooling from higher-grade conditions.

To obtain the maximum preserved $P–T$ conditions in the rocks, the most refractory compositions of the minerals were selected. For ferromagnesian minerals, these were found in the cores of the largest grains or in grains surrounded by plagioclase and/or quartz; the latter isolated the ferromagnesian minerals from later intergranular exchange (cf. Harley, 1988; Pattison and Bégin, 1994). The most refractory plagioclase com-

Table 7
Pressure–temperature results

| | | ACBO1 cores | | ACBO1 rims | | AC89 cores | | AC89 rims | |
|---|---|---|---|---|---|---|---|---|---|
| | | *P* (kbar) | *T* (°C) | *P* (kbar) | *T*(°C) | *P* (kbar) | *T* (°C) | *P* (kbar) | *T* (°C) |
| TWQ | GCPQ | 9.0 | 880 | 6.6 | 710 | 8.9 | 840 | 6.1 | 680 |
| | GOPQ | – | – | – | – | 7.9 | 750 | 5.4 | 580 |
| | GCOPQ | – | – | – | – | 8.4 | 800 | 5.6 | 630 |
| GC | PN | (8.5) | 820 | (6.5) | 530 | (8.5) | 810 | (5.5) | 590 |
| | K | – | 850 | | 620 | | 800 | | 650 |
| | EG | – | 900 | | 680 | | 840 | | 710 |
| GO | LG | – | – | | – | (8.5) | 890 | (5.5) | 720 |
| | H | – | – | | – | | 750 | | 590 |
| | HG | – | – | | – | | 800 | | 650 |
| GCPQ | ENK | 7.4 | (850) | 5.5 | (600) | 8.4 | (800) | 5.2 | (650) |
| | MEA(Mg) | 8.0 | | 6.5 | | 8.6 | | 6.5 | |
| | MEA(Fe) | 8.8 | | 6.9 | | 8.6 | | 5.6 | |
| GOPQ | ENK | – | – | – | – | 6.2 | (800) | 4.4 | (650) |
| | BWB(Fe) | – | – | – | – | 8.9 | | 4.8 | |
| | MEA(Fe) | – | – | – | – | 10.2 | | 6.5 | |

G = garnet; C = clinopyroxene; O = orthopyroxene; P = plagioclase; Q = quartz; Sympl = symplectite; TWQ = Berman (1991, Jan. 92 update); GC = garnet–clinopyroxene Fe–Mg exchange; PN = Pattison and Newton (1989); K = Krogh (1988); EG = Ellis and Green (1979); GO = garnet–orthopyroxene Fe–Mg exchange; LG = Lee and Ganguly (1988, expression 11.1); H = Harley (1984); HG = Harley and Green (1982); GCPQ = garnet–clinopyroxene–plagioclasde–quartz barometer; ENK = Eckhert et al. (1991); MEA(Fe), MEA(Mg) = Moecher et al. (1988), Fe and Mg end member expressions; GOPQ = garnet–orthopyroxene–plagioclase–quartz barometer; BWB = Bohlen et al. (1983); pressures in brackets are assumed values used in the thermometric calculations; temperatures in brackets are assumed values used in the barometer calculations.

positions came from the centres of medium-large grains. Symplectite minerals in AC89 and mineral rims in ACB01 were analyzed to obtain information on the cooling and decompression history.

Mineral compositions are listed in Tables 2–6. The location of the analysis points are shown in Figs. 2a and b. Overall, sample AC89 is Fe-richer than ACB01, consistent with the more complete reaction of amphibole to garnet and pyroxenes seen in AC89 compared to ACB01. The orthopyroxene and plagioclase compositions in the symplectites in AC89 are different (plagioclase, Ca-richer; orthopyroxene, Ca- and Al-poorer, Mg-richer) from the matrix in the rock. The plagioclase rim compositions in ACB01 are Ca-richer than in the centres of the grains.

*P–T* conditions were estimated using a range of individual thermobarometers and the TWQ software of Berman (1991), using the January 1992 update of Berman's (1988) thermodynamic data base. The results and calibrations are listed in Table 7. An advantage of the TWQ approach is the internal consistency of the thermodynamic data and mixing models. Only equilibria involving the anhydrous minerals garnet, orthopyroxene, clinopyroxene, plagioclase and quartz are reported here, owing to uncertainty in amphibole thermodynamic data and mixing models, and possible resetting problems.

Using the TWQ approach for AC89 there is a general tendency for garnet–orthopyroxene equilibria to return lower *P–T* conditions than garnet–clinopyroxene equilibria by 0.5–1 kbar and 50–100 °C; it is unknown if this effect is due to a problem in the thermodynamic data or to a greater tendency for orthopyroxene to exchange to lower temperatures than clinopyroxene. *P–T* results from the individual thermobarometers show considerable scatter, but overall give comparable results to TWQ.

*P–T* conditions from the two samples are similar: 8–9 kbar and 800–900°C for ACB01; and 8–9 kbar and 800–850°C for AC89. Minimum temperatures required to produce garnet and pyroxenes by reaction of amphibolite in the absence of low $a_{H_2O}$-fluid infiltration are about 850°C at crustal pressures (Beard and Lofgren, 1991). Under these conditions, the garnet/pyroxeneproducing reactions are dehydration-melting reactions which simultaneously produce a trondhjemitic melt, consistent with the presence of plagioclase–quartz segregations in ACB01 and other rocks in the area (see above). Although the *P–T* conditions are consistent with minimum temperatures required for amphibolite dehydration melting, they still may not represent the highest *P–T* conditions the rocks experienced because of the possibility of resetting during cooling from higher-temperature conditions (Frost and Chacko, 1989; Pattison and Bégin, 1994). Nevertheless, these *P–T* conditions are higher than reported previously (Oliveira and Hypolito, 1978; Dos Santos, 1988) from granulites about 100 km to the southeast and might be indicative of deeper levels in the Guaxupé nappe structure.

*P–T* conditions for the formation of the symplectites in AC89, using orthopyroxene and plagioclase in the symplectite and garnet compositions in immediate contact with the symplectite (see Fig. 2b), are 5–6 kbar and about 600–700°C. These *P–T* conditions are unlikely to have been significantly reset from the conditions of symplectite formation because the analysed garnet and pyroxene grains are separated from each other by plagioclase which isolated them from continued down-temperature intergranular (especially Fe–Mg) exchange (cf. Pattison and Bégin, 1994). *P–T* results from ACB01 using mineral rim compositions are probably less reliable than those from the symplectites in AC89 because of greater uncertainty in the timing of closure of different elements in the minerals. Nevertheless, the calculated *P–T* results, 5.5–6.5 kbar and 530–700 °C, are similar to those obtained from AC89. Preliminary fluid inclusion measurements reveal low density CO2-rich fluids possibly related to this lower *P–T* portion of the rocks history (D. Silva, pers. commun., 1994).

Taking an average *P–T* estimate of 8.5 kbar, 850°C for the maximum (but not necessarily peak) *P–T* conditions, and 6.0 kbar and 650°C for symplectite formation, results in a *P–T* path involving 2.5 kbar of pressure decrease accompanied by 200°C of cooling (ca. $-12.5$ bar/°C). This *P–T* path, which represents only a segment of the rocks' overall *P–T* path, is midway between an isothermal decompression path and an isobaric cooling path, using the criteria of Harley (1989). Such a *P–T* path is consistent qualitatively with the tectonic model for the area involving uplift and cooling of the granulites in response to thrust emplacement over lower-grade rock (see Section 1).

## 8. Conclusions

The granulite facies rocks of the Guaxué Massif are made up of enderbite, charnockite and charnockitic augen gneisses. Discrimination function calculations show igneous parentage for the majority of the rocks. The geochemical nature of the rock types is similar to tonalite and granodiorite. The rocks have been subjected to minimum metamorphic pressure temperature conditions of 8.5 kbar and 850°C. The high-grade metamorphism did not appear to have altered the geochemical and oxygen isotope composition of the protoliths. In considering tectonic causes of metamorphism, high thermal gradients generated by mantle upwelling beneath an older continental keel may have provided heat for granulite facies metamorphism in this region (see, e.g., Keith, 1993). A *P–T* path involving 2.5 kbar of pressure decrease accompanied by 200°C of cooling has been recorded for a portion of the cooling path, consistent with a tectonic model of uplift and cooling of the granulites in response to thrust emplacement over lower-grade rocks to the north. It is not clear if the uplift of the Guaxupé region is associated with the tectonic cycle that produced the granulites or is related to a later episode.


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