

## PRECAMBRIAN MAFIC AND ULTRAMAFIC ROCKS OF THE CANA BRAVA COMPLEX, BRAZIL — MINERAL COMPOSITIONS AND EVOLUTION

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**ABSTRACT** The Cana Brava mafic-ultramafic complex, Goiás State, Brazil, is an Early Precambrian differentiated massif formed by intrusion and differentiation of a presumably basaltic parental material. Rock types cover a continuous sequence ranging from harzburgites to pyroxenites to ferromylonites and ferrogabbros, as indicated by changes in mineral associations and mineral compositions. After the emplacement, the mafic-ultramafic suite was affected by several sub-solidus reequilibrations. The first one took place at approximately 900°C and pressures of 6-7 kb. Textural features as well as mineral distribution of certain elements show that complete equilibrium was not achieved during this event. A successive partial recrystallization converted some of the rocks on an high-grade amphibolite assemblage. A late low-temperature event caused the formation of serpentinites, rodingites and talc schists. P-T estimates for the high-temperature reequilibration at Cana Brava coincide broadly with results obtained from other Early Precambrian Brazilian mafic-ultramafic complexes. The values thus estimated were plotted to obtain geothermal gradients to be compared with those presented in the literature for other Precambrian occurrences.

**INTRODUCTION** The Cana Brava massif is situated about 300 km N of Brasília in the State of Goiás, Brazil (Fig. 1). It is part of a belt-like chain of gabbro-pyroxenite-peridotite massifs of approximately 300 km extension from the Barro Alto massif in the south to the Cana Brava complex in the N. This belt contains important and economic mineralizations of nickel (Niquelândia and Barro Alto) and asbestos (Cana Brava) (Berbert, 1970). According to Danni *et al.* (1982) these complexes belong to an Archean or Lower Proterozoic granulitic mobile belt, a geotectonic unit which extends from the north of Goiás State to the W of Minas Gerais State. The Cana Brava complex forms a topographic high, the Serra Cana Brava. The complex is bordered by faults which generally run in a NNE direction (Fig. 1). On the E there is a major fault. The whole complex seems to be an uplift block fault thrust upon the eastern gneisses. It consists of metagabbros, metagabbro-norites, metanorites, amphibolites, metapyroxenites, and serpentinites. Mafic rocks dominate strongly over ultramafic ones. The ultramafic rocks are generally associated with amphibolites which form the E border unit. Beside the major mafic and ultramafic rocks the complex contains also minor units of magesian schists and rodingites (Girardi *et al.*, 1976).

Two satellite mafic-ultramafic bodies are present in the E and W of the main massif. Their stratigraphic position is not clear yet, but they seem to be related to the main massif.

The gneisses of the E border of the Cana Brava complex belong to the Serra da Mesa Group, according to Marini *et al.* (1977).

Quartz-kyanite-garnet-muscovite schists with biotite-garnet gneisses, calc-silicate rocks, quartzites and amphibolites occur to the W border of the complex. According to Danni *et al.* (1982) these rocks form the Palmeirópolis Group, a sequence of volcano-sedimentary origin.

Several hypothesis have been proposed for the genesis of the mafic-ultramafic belt of Goiás. For the Cana Brava

massif an alpine-type classification was suggested (Marini *et al.*, 1977). In order to shed some light on the genesis of the belt, we are carrying out geochemical and petrological studies, starting with the Barro Alto Complex (Girardi *et al.*, 1981).

### GENERAL PETROGRAPHY AND SUCCESSION OF EVENTS

As mentioned above the Cana Brava complex consists of several mafic and ultramafic rocks being the mafic rocks much more abundant than the ultramafic ones. Relict structures are present from the original igneous formation process through several subsequent recrystallization events.

The ultramafic suite of rocks comprises serpentinites, harzburgites, and pyroxenites with either orthopyroxenes or clinopyroxene being the dominating phase. These rocks generally occur in massive bodies, but in places they form composite units with alternating thin layers (cm-sized) of serpentinite and pyroxenite. These rhythmically layered ultramafic rocks give clear evidence for gravitational differentiation processes having been involved in their formation. Most pyroxenites show relict cumulate textures with either orthopyroxene or clinopyroxene as cumulus phases. These cumulus phases generally have exsolution lamellae and are set into a granoblastic matrix. This texture reflects subsolidus reequilibration under granulite facies conditions. Some pyroxenites contain amphibole that apparently was formed after the pyroxenes and from them, thus indicating a subsolidus reequilibration under amphibolite facies conditions. Late low temperature alterations are manifested by the formation of talc and serpentine. Carbonate veins and rodingites that in some parts of the massif are associated with the serpentinites certainly are also the products of this late stage low-temperature event (Girardi *et al.*, 1976).

The mafic suite of gabbros, gabbro-norites, norites and amphibolites reflects in several cases the same events.

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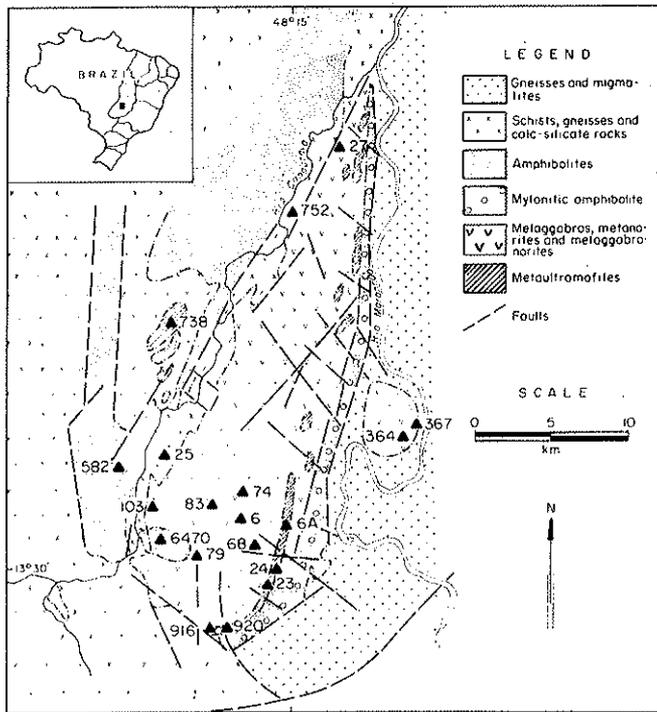


Figure 1 – Geological map of the mafic-ultramafic complex Cana Brava, Goiás (simplified after Matsui, 1977) with locations of samples taken for this study

Some pyroxenes and plagioclases occur as large grains set in a granoblastic matrix. The plagioclases have relict compositional zoning. Such crystals reflect part of the igneous formation event. The first subsolidus reequilibration led to the formation of exsolution lamellae in pyroxenes and of a granoblastic matrix. The subsolidus reequilibration under amphibolite facies conditions led to the formation of late amphibole from pyroxenes or in a complete recrystallization to amphibolite. Some hornblendes, however, seem to be in equilibrium with the pyroxenes and, consequently, must have been formed during the first reequilibration event. Mylonitic low grade amphibolites containing relict igneous pyroxenes occur on the E border, in contact with blastomylonitic gneisses (Fig. 1).

In summary, we postulate that after the emplacement, the Cana Brava complex experimented a first subsolidus reequilibration. This process could be caused either by a granulite facies metamorphism or by the slow postmagmatic cooling of the complex, intruded into the crust. In both cases a granulitic mineral assemblage would result, because the PT conditions are similar. A better knowledge of the country rocks environment will be necessary to resolve this question. This event was followed by a partial recrystallization under amphibolite facies conditions. Finally a low temperature event caused recrystallization of some rocks mainly of the ultramafic suite.

The satellite bodies in the E and W of the main massif are somewhat different and pose some additional problems. The E body located at the Maranhão river contains somewhat different gabbroic rocks, some of which are olivine-bearing, a feature not observed in the main body. Relict igneous textures are very common, as are coronas of orthopyroxene plus spinel and clinopyroxenes (or horn-

blendes) around olivines. This reaction reflects the first subsolidus reequilibration. The W satellite complex located W of the Cana Brava river has so far only been poorly sampled. Only serpentinites and metaharzburgites are known from that locality.

The country rocks on the W border are metasediments metamorphosed under conditions of the amphibolite facies. Calc-silicate rocks occur as thin lenses within the schists and normally are of the same metamorphic grade. Close to the contact to the Cana Brava massif, however, they tend to develop granoblastic textures and contain diopside and scapolite, which could indicate higher grade. At the tectonic contact in the E border blastomylonitic varieties of the normal quartz feldspar-gneisses are very common. Also migmatites are widespread consisting of amphibolitic paleosomes and granitic to granodioritic neosomes. Obviously, in this region sufficient water had been present to partially melt the rocks during the amphibolite facies metamorphism.

Low metamorphism overprinting is shown by mafic-ultramafic rocks of the massif, by the W schists and calc-silicate rocks; and by the E gneisses. In these rocks secondary muscovitization, chloritization and formation of epidote reflect this event.

**AGE RELATIONSHIPS** Geochronological studies of rocks of the Cana Brava massif and the surrounding country rocks were carried out by Matsui *et al.* (1976) and Girardi *et al.* (1978). Data obtained are not entirely conclusive but some correlation with metamorphic events which occurred during the evolution of the South-American continent is possible. Rocks of the mafic-ultramafic complex are of yet unknown age, being probably Lower Proterozoic or Archean. The Rb/Sr isochron obtained from the schists and calc-silicate country rock of the west side of the Cana Brava massif gives an apparent age of 1,150 Ma, which can be correlated with the amphibolite facies metamorphism that affected such rocks, and corresponds to the "Uruaquano" Cycle (Almeida *et al.*, 1976). Gneisses from the east side of the massif recrystallized at about 650 Ma which corresponds to the "Brasiliano" Cycle (Cordani *et al.*, 1973). These rocks have an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.736, indicating a long-lasting crustal history.

**ROCK DESCRIPTIONS** Rocks from the main complex of Cana Brava and from both satellite bodies are studied. The approximate locations are indicated in Fig. 1. In Table I short descriptions are given.

**ANALYTICAL PROCEDURES** Polished thin sections of selected rock samples were studied microscopically in transmitted and reflected light. Mineral analyses were made using an automated ARL-SEM-Q electron microprobe X-ray analyzer. Operating conditions were held at 15 kV acceleration potential and 15  $\mu\text{A}$  sample current. Wet chemically analysed minerals (augite, kaersutite, olivine, chromite, vanadinite, orthoclase, tephroite), synthetic NiO, and glasses (of different feldspar compositions) were used as standards. Corrections for drift, absorption and fluorescence were made on-line using a modified version of the method by Bence and Albee (1968). Bulk analyses of exsolved large pyroxenes were obtained by analysing in TV-mode at 5 magnification and integrating over the entire grain.

Table 1 – A) Rock descriptions from Cana Brava main massif rocks

Type	Mineral composition	Observations
G-24 Serpentinite	Serp, opx and cpx, oliv, sp, talc and opaques	Few relicts of pxs, olivine and spinel
CB-AK-6A Metapyroxenite	Opx and cpx, plag (< 5%), brown hornb, sp and opaques	Granoblastic texture. Small and large crystals of opx (cumulate phase)
MCB-920 Metapyroxenite	Opx and cpx. Minor opaques	Somewhat deformed granoblastic texture. Small and large crystals of opx. Some exsolution lamellae in pxs
MCB-916 Metapyroxenite	Cpx, opx, trem, sp and opaques	Texture equigranular granoblastic
G-23 Metapyroxenite	Cpx and opx. Minor sp and opaques	Cpx are generally larger (cumulates). Abundant exsolution lamellae in pxs
V-108 Metanorite	Plag, opx and cpx. Minor brown hornb, quartz and opaques	Granoblastic texture. A few larger grains of opx show exsolution lamellae. Hornb formed after pxs
KV-6 Metagabbro	Plag, cpx and opx, green hornb, quartz and opaques	Banded rock formed by alternating granoblastic layers rich in pxs and plag. Cpx show exsolution lamellae of ilm
G-25 Metanorite	Plag, opx, green hornb, biot, quartz, magnetite, apatite and carbonates	Poikiloblastic opx and apparently relict igneous plag are set in a granoblastic matrix. Late hornb from pxs
V-79 Metagabbro	Plag, opx and cpx, brownish hornb, quartz, apatite and carbonates	Banded rock. Alternated granoblastic layers rich in plag and pxs respectively
V-74 Metagabbro	Plag, cpx and opx, biot, opaques, apatite, quartz and orthoclase	Some larger zoned relict plag crystals are set in a granoblastic matrix
V-68 Metanorite	Plag, opx and cpx, brownish hornb, talc, opaques, zoisite, quartz	Texture is granoblastic and well equilibrated
MCB-752 Metanorite	Plag, opx, brown hornb, apat, talc, chlor, epid, quartz, zoisite, ilm	Poikiloblastic hornb, generally associated with opx is set in a granoblastic matrix
KV-27 Hornblendefels	Green hornb. Minor sphene, apatite and muscovite	Rock slightly deformed. Hornb partly oriented
CBE-6470 Amphibolite	Green hornb and plag. Minor epid, rut, ilm and sphene	Granoblastic texture. Rut. bordered by ilm
V-83 Amphibolite	Green hornb, plag, sphene, zoisite, quartz, opaques	Granoblastic texture

## 3) Rocks from outside the main massif

MCB-738 Metaharzburgite	Oliv, opx, trem, chlor, serp, sp, opaques	Oliv partly serpentinized. Pxs somewhat deformed
MCB-I-364 Metagabbro	Plag, cpx and opx, brown hornb, ilm, sp, magnetite	Granoblastic texture and relict igneous features. Compositional zoning and complex twinning in plag. Compositional zoning and exsolution lamellae in pxs.
MCB-10-367 Metanorite	Plag, opx and cpx, olivine, hornb. sp. and opaques	Complex coronas consisting of opx plus sp and amphiboles are present at olivine-plag contacts. The amphibole was formed from cpx. Granoblastic texture. Zoning in plag.
MCB-582 Metagabbro	Plag, cpx, green hornb. sphene and zoisite	Poikiloblastic hornb is set in a granoblastic matrix

## RESULTS AND DISCUSSION

**A) Metaperidotites** Mineralchemical data for metaperidotites MCB-738 (metaharzburgite) and G-24 (serpentinite) are given in Table 2. Typically, all major silicate phases are highly magnesian. Olivine is homogeneous and has Fo 90.9 and Fo 87.9 in sample 738 and 24 respectively. Ni contents of olivine are high and comparable to upper mantle peridotites (*e. g.* Kurat *et al.*, 1981; Frey and Prinz, 1978) and some peridotitic cumulates of layered intrusions (*e. g.* Irvine and Smith, 1967) suggesting crystallization from a primitive magma rich in Ni (and Mg). Minor element contents in olivine are low and (probably) reflect partial subsolidus equilibration with other silicate phases or crystallization under high-P conditions (compare Mysen, 1978).

Orthopyroxene in MCB-738 is low in Al<sub>2</sub>O<sub>3</sub> and minor elements. The Al<sub>2</sub>O<sub>3</sub> content of ortho and clinopyroxenes of G-24 is higher and variable. There is also a considerable range in minor elements (Table 2). The Al<sub>2</sub>O<sub>3</sub> content of the pyroxenes is similar to several layered bodies and lower than many mantle peridotites (Rivalenti *et al.*, 1979; Jackson and Thayer, 1972; Kornprobst, 1969).

The sample MCB-738 indicates the effects of several reequilibration events, as shown by textural relationships and mineralogy. Instead of clinopyroxene MCB-738 contains tremolite. This amphibole is very low in Al, Ti, and alkali and was formed very probably during the late low-T event.

Compositions of all spinels differ drastically from those of upper mantle peridotites (Best, 1974; Evans and Frost,

1975; Frey and Prinz, 1978; Kurat *et al.*, 1980; Rivalenti *et al.*, 1981). In spite of very similar Fe/Fe + Mg ratios in olivines of the Cana Brava peridotites and upper mantle lherzolites, the Fe/Fe + Mg ratios of the spinels are very different (~0.45 and ~0.23 for Cana Brava and upper mantle peridotites respectively, if total Fe is used). Spinels of the Cana Brava peridotites are inhomogeneous in composition and show considerable spread in Cr/Cr + Al and Fe/Fe + Mg ratios (Fig. 2) within each sample, a feature which is observed in all samples.

Three types of serpentines can be distinguished on a compositional basis:

- 1) The "normal" common serpentine (see averages in Table 2), rich in Mg.
- 2) An intermediate Fe-Ni serpentine (NiO 8%, FeO 23%), and
- 3) A high Fe-Ni serpentine (FeO 44%, NiO 18%).

The high Fe-Ni serpentines clearly formed by reaction of "normal" serpentine with Fe-Ni-rich solutions from degraded Fe-Ni sulfides. The composition of "normal" serpentine is somewhat variable with regard to minor elements. With increasing Al<sub>2</sub>O<sub>3</sub> content (0.4%) the TiO<sub>2</sub> and Cr<sub>2</sub>O<sub>3</sub> contents increase and the NiO content decreases. Compositions cluster around high-Ni low-Al and low-Ni high-Al and thus indicate derivation of serpentines from both olivine and orthopyroxene (Fig. 3). Sample MCB-738 is only slightly serpentinized and can clearly be identified as a harzburgite. Sample G-24 is a serpentinite with very

Table 2 — Averaged and selected electron microprobe analyses of minerals from metaperidotites MCB-738 (metaharzburgite) and G-24 (serpentinite), Cana Brava complex, Brazil

Rock	Metaharzburgite MCB-738					Serpentinite G-24							
	Ol	Opx	Tr	Sp	Serp	Ol	Opx Av. hi-Al		Cpx Av. hi-Al		Sp	Serp Av. hi-Ni-Fe	
N.° of Analyses	41	26	33	25	25	4	15	1	10	1	9	14	1
SiO <sub>2</sub>	40.9	56.5	55.1	0.11	42.5	41.8	56.9	54.7	54.1	54.1	0.09	39.6	14.3
TiO <sub>2</sub>	0.02	<0.02	0.04	<0.02	<0.02	<0.02	0.07	0.07	0.23	0.37	0.05	0.05	<0.02
Al <sub>2</sub> O <sub>3</sub>	0.02	1.17	4.6	40.1	1.11	<0.02	2.50	3.0	2.90	4.6	47.0	1.04	0.15
Cr <sub>2</sub> O <sub>3</sub>	0.02	0.18	0.56	26.2	0.13	<0.02	0.29	0.45	0.51	0.88	19.0	0.13	0.04
V <sub>2</sub> O <sub>3</sub>	—	—	—	0.19	—	—	—	—	—	—	0.18	—	—
FeO*	8.7	6.0	2.09	18.3	6.7	11.3	7.6	7.2	2.53	2.89	20.4	8.1	44.1
NiO	0.42	0.08	0.12	0.09	0.25	0.36	0.05	0.12	0.06	0.07	0.14	0.20	18.5
MnO	0.12	0.14	0.06	0.21	0.08	0.17	0.20	0.11	0.07	0.06	0.20	0.14	0.19
MgO	48.8	35.2	22.1	13.9	33.6	46.2	32.5	32.2	16.1	15.9	12.5	33.6	2.75
ZnO	—	—	—	0.42	—	—	—	—	—	—	0.20	—	—
CaO	<0.02	0.14	12.3	0.03	0.37	0.02	0.31	0.35	22.6	22.2	0.02	0.12	0.25
Na <sub>2</sub> O	<0.02	<0.02	0.76	—	0.05	<0.02	<0.02	<0.02	0.58	0.71	—	0.04	0.04
K <sub>2</sub> O	0.02	0.02	0.11	—	0.08	<0.02	<0.02	<0.02	0.02	<0.02	—	0.04	0.06
Total	98.94	99.41	97.84	99.55	84.87	99.85	100.42	98.20	99.70	101.78	99.78	83.06	80.38

\* Total Fe as FeO

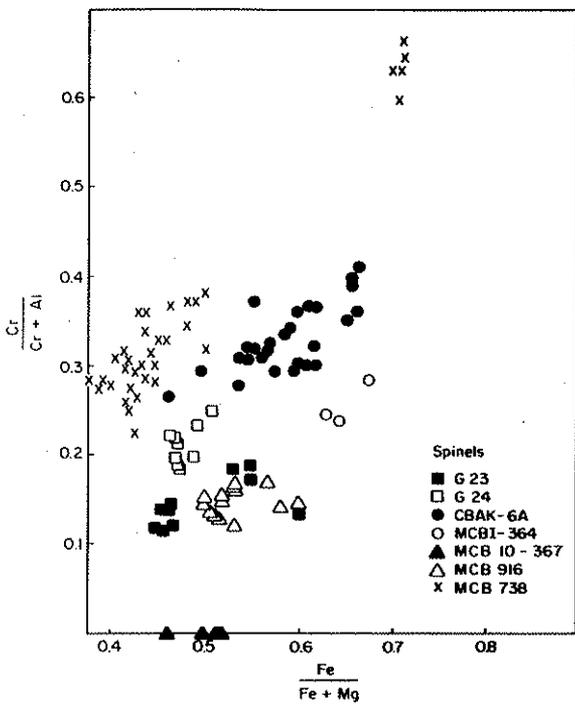


Figure 2 - Projection of spinel compositions from meta-igneous rocks of the Cana Brava massif, Brazil

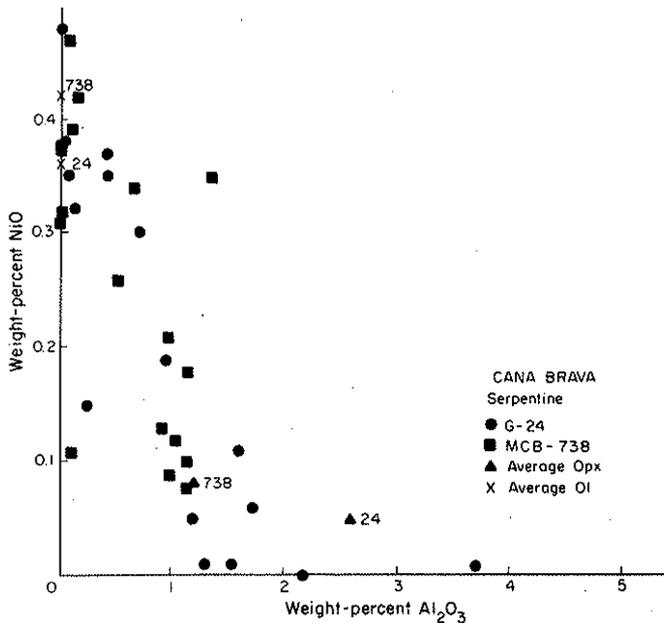


Figure 3 - Distribution of Al and Ni in "normal" serpentines from samples MCB-738 and G-24. Alumina and NiO contents range from pyroxene to olivine composition. Projections of the average olivine and orthopyroxene compositions are given for comparison

few relicts of original minerals. On the basis of serpentine compositions which show approximately equal abundances of high-Al and low-Al types, we conclude that G-24 has also been a harzburgite before serpentinization took place.

In sample MCB-738 clinocllore of a peculiar composition is quite abundant. This chlorite is high in Cr<sub>2</sub>O<sub>3</sub> (~1.3%)

and NiO (~0.3%) and probably formed by a reaction of spinel with silicates and water during the low-T metamorphic event.

In summary, the peridotites of the Cana Brava complex investigated here show evidence for the following:

- 1) They are cumulate rocks derived from gravitational differentiation of a magma which crystallized olivine as the first solidus phase. Both rocks are harzburgites with very low contents of incompatible elements.
- 2) Both rocks experimented subsolidus reactions comparable to granulite facies conditions without achieving complete equilibration of mineral phases.
- 3) Subsequent lower temperature events took place causing formation of amphiboles, serpentines, chlorites and talc.

**B) Metapyroxenites** Mineral analyses from four metapyroxenites, all of them from the main complex, are given in Table 3. Mineral associations within each rock are quite different from one to another and range from opx + cpx (MCB-920) over cpx + opx + sp (G-23) and cpx + opx + tr + sp (MCB-916) to opx + cpx + hbl + sp + plag (CB- AK-6A). All minerals have higher Fe/Mg ratios than those from the peridotites discussed above.

Orthopyroxene compositions range from En 85.8 (6A) to En 85.4 (920) and En 82.9 (916) to En 80.5 (23) (Table 3), and thus indicate a differentiation sequence whereby the opx-dominated rocks show lower Fe/Mg ratios than do the cpx-dominated ones. Orthopyroxenes are generally somewhat variable in composition with either CaO(6A) or Fe/Mg (920, 916, 23) showing some limited range.

The largest variation is found in G-23 where the En content of opx ranges from 79.5 to 83.0, probably reflecting changes in the Fe/Mg ratio of the interstitial melt during final crystallization. Al<sub>2</sub>O<sub>3</sub> contents are between 2.6 and 4.1%. CaO is generally low (0.21, 0.31%) and reflects equilibration at subsolidus temperatures.

Clinopyroxenes show similar features (Table 3). They are generally rich in CaO with some changes within each sample reflecting some relict magmatic composition. Al<sub>2</sub>O<sub>3</sub> contents approximately follow the Al<sub>2</sub>O<sub>3</sub> in opx and are only slightly higher (2.66, 4.4%) than in opx.

Amphiboles are present in two of the pyroxenites investigated. They are, however, of drastically different composition and, consequently, of dissimilar genesis. Sample CB-AK-6A contains pargasitic hornblende (compare discussion on hornblendes below). It is characteristically rich *not only* in Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, but also in Cr<sub>2</sub>O<sub>3</sub> and NiO. It was formed probably during the first recrystallization event. Sample MCB-916 contains a tremolite very similar to that of metaharzburgite MCB-738. The composition of the MCB-916 tremolite is probably governed by the rock bulk composition which is strongly depleted in large ion lithophile elements. Non-equilibrium distribution of some minor elements between tremolite and clinopyroxene (Ti, Al, Cr and Na) indicates formation during the late low-T event.

Spinel compositions are, as usual, somewhat variable within each sample and are also different in distinct samples (Fig. 2). The most Cr-rich spinel (28.2% Cr<sub>2</sub>O<sub>3</sub>) is present in sample CB-AI-6A (Table 3).

The differences in average spinel compositions between samples CB-AK-6A on one hand MCB-916 and G-23 on the other, clearly reflect primary magmatic fractionation of Cr whereby minerals of rock 6A, crystallizing from a less

Table 3 — Averaged electron microprobe analyses of minerals from metapyroxenites CBAK-6A, MCB-920, MCB-916, and G-23, Cana Brava complex, Brazil. Samples are arranged in order of increasing Fe/Mg ratio

Sample n.º	CBAK - 6A				MCB - 920						G - 23			
	OpX	Cpx	Hbl	Sp	OpX	Cpx	OpX	Cpx	Tr	Sp	OpX	Cpx	Sp hi-Cr	Sp low-Cr
N.º of Analyses	10	5	16	13	22	6	4	9	8	18	7		3	5
SiO <sub>2</sub>	55.6	52.5	45.4	0.12	55.9	53.5	55.1	52.3	55.6	0.04	53.6	51.4	0.09	0.17
TiO <sub>2</sub>	0.08	0.58	1.80	0.04	0.06	0.29	0.03	0.28	0.08	0.02	0.04	0.32	0.03	0.02
Al <sub>2</sub> O <sub>3</sub>	3.5	4.2	13.2	39.3	2.63	2.66	3.8	4.4	2.47	52.0	4.1	4.4	47.6	53.4
Cr <sub>2</sub> O <sub>3</sub>	0.54	0.92	1.51	28.2	0.33	0.47	0.33	0.55	0.34	12.8	0.57	0.74	16.0	12.2
V <sub>2</sub> O <sub>3</sub>	—	—	—	0.18	—	—	—	—	—	0.13	—	—	0.24	0.17
FeO*	9.0	2.49	3.8	21.3	9.3	2.61	10.3	3.2	5.6	20.9	12.4	3.6	24.0	20.2
NiO	0.07	0.07	0.13	0.12	0.05	0.03	0.05	0.03	0.04	0.19	0.06	0.03	0.09	0.29
MnO	0.20	0.09	0.05	0.24	0.22	0.10	0.24	0.11	0.17	0.23	0.29	0.13	0.21	0.17
MgO	31.5	15.4	16.3	9.5	31.5	16.1	28.8	15.1	20.4	11.1	29.6	15.7	11.4	13.4
ZnO	—	—	—	0.76	—	—	—	—	—	0.42	—	—	0.57	0.77
CaO	0.21	22.8	12.2	0.05	0.23	23.8	0.25	23.5	12.6	0.02	0.31	23.3	0.07	0.18
Na <sub>2</sub> O	<0.02	0.53	2.1	—	<0.02	0.16	<0.02	0.23	0.26	—	<0.02	0.26	—	—
K <sub>2</sub> O	<0.02	0.02	0.48	—	<0.02	0.03	<0.02	0.03	0.04	—	<0.02	0.03	—	—
<b>Total</b>	<b>100.70</b>	<b>99.60</b>	<b>96.97</b>	<b>99.81</b>	<b>100.23</b>	<b>99.75</b>	<b>98.90</b>	<b>99.73</b>	<b>97.60</b>	<b>97.83</b>	<b>100.97</b>	<b>99.91</b>	<b>100.30</b>	<b>100.97</b>

\* Total Fe as FeO

fractionated melt, took up more Cr than those of rocks 916 and 23. Plagioclase is only present in CB-AK-6A. It is somewhat variable in composition (An 81-88) (Fig. 4).

In summary, textural (see Table 1) and chemical relationships support a cumulate origin, probably from basaltic melts, for the metapyroxenites. This is reflected mainly by the Mg/Fe and Cr/Al variations in pyroxenes and spinels.

Separation of a liquid from the cumulate apparently was quite effective in most pyroxenites except for CB-AK-6A. That rock contains both plagioclase and pargasitic hornblende, a mineral association which probably represents the former intercumulus liquid.

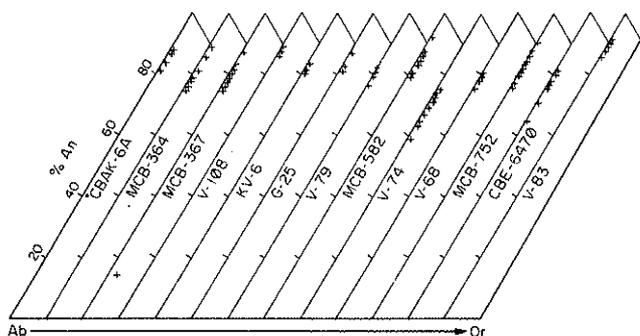


Figure 4 — Projection of plagioclase compositions from rocks of the Cana Brava complex, Brazil, onto the Na-K-Ca plane

All pyroxenites have experimented a high-temperature recrystallization that did not succeed in a complete equilibration of mineral phases.

**C) Metagabbros and Metanorites** A variety of mineral associations is present among the Cana Brava mafic rocks. The following combinations have been observed.

- 1) plag + opx + cpx (V-7)
- 2) plag + opx + hbl (G-25, MCB-752)
- 3) plag + cpx + hbl (MCB-582)
- 4) plag + opx + cpx + hbl (V-108, KV-6, V-79, V-68)
- 5) plag + opx + cpx + hbl + sp (MCB-I-364)
- 6) plag + ol + opx + cpx + hbl + sp (MCB-10-367)

Mafic mineral compositions show a wide range in Fe/Mg ratios (Table 4); all of which are higher than those of the minerals from ultramafic and mafic rocks discussed above. The whole suite of ultramafic and mafic rocks clearly represents a differentiation sequence as is evidenced by the projections of mafic mineral compositions into the pyroxene quadrilateral (Fig. 5).

Orthopyroxene compositions range from En 77.5 (MCB-I-364) to En 45.3 (MCB-752) (Table 4). Al<sub>2</sub>O<sub>3</sub> contents are low and generally around 1% but range from 1.96 to 0.7 wt.% with a tendency towards higher contents for rocks with higher Mg/Fe ratios. Orthopyroxenes of many rocks of the mafic suite show exsolution lamellae of clinopyroxene and occasionally ilmenite. As an example, one bulk analysis

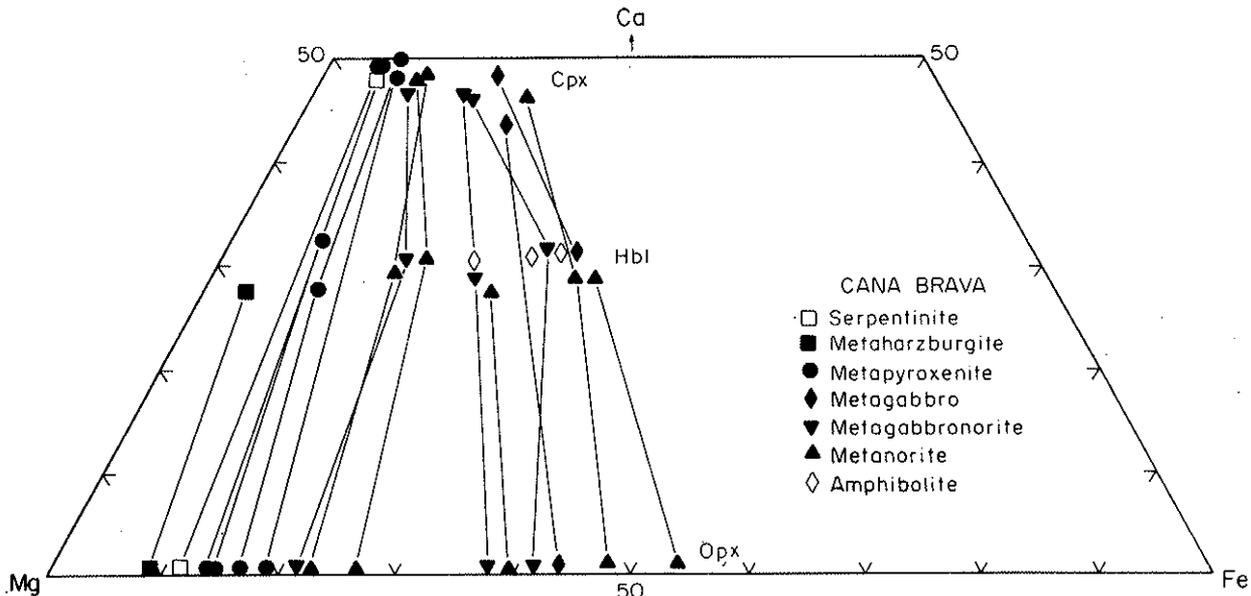


Figure 5 — Projection of average opx, and hbl compositions from rocks of the Cana Brava complex, Brazil, onto the Mg-Fe-Ca plane. Mineral compositions reflect a differentiation sequence from harzburgite to ferrogabbro and ferronorite

obtained by integration analysis over a large orthopyroxene crystal is given for sample MCB-I-364 (Table 4). This presumably igneous composition is, as expected, drastically different from the exsolved orthopyroxene composition, especially in TiO<sub>2</sub> and CaO contents.

Clinopyroxenes, if present, follow the general compositional trends of the orthopyroxenes quite closely. They have a tendency towards somewhat variable Ca/Ca + Mg + Fe ratios but generally cluster at the high Ca end. Minor elements contents vary over a wide range. TiO<sub>2</sub> ranges from 0.82% (MCB-10-367) to 0.09% (MCB-582) and reflects in some cases subsequent ilmenite exsolution from cpx (*i. e.* MCB-I-364). Al<sub>2</sub>O<sub>3</sub> contents are normally low and not very much higher than in opx. They range between 3.2 and 1.32% and loosely follow the TiO<sub>2</sub> contents. Pyroxenes of gabbroic rocks of the Cana Brava complex are characterized by low contents, in Al<sub>2</sub>O<sub>3</sub>, similar to stratiform complexes, and much lower than alpine bodies, according to data tabulated by Jackson and Thayer (1972).

Olivine is only present in metanorite MCB-10-367. It is homogeneous and has a composition of Fo 74.9. Minor element contents are low and NiO is much lower (0.16%) than in olivines from harzburgites. The rather low Fo and NiO contents indicate crystallization from a fractionated melt which, however, still had olivine at the liquidus.

Olivine is not in equilibrium with plagioclase in rock MCB-10-367 and has reacted and formed symplectitic intergrowths of orthopyroxene + spinel + clinopyroxene or hornblende. The pyroxene compositions inside the symplectites differ drastically from those outside these intergrowths (Table 4). The Mg/Fe ratio is higher (En 77.3) and minor element contents are much lower (TiO<sub>2</sub> < 0.1, Cr<sub>2</sub>O<sub>3</sub> < 0.03, NiO < 0.02) in the symplectite pyroxenes as compared to the normal pyroxenes of the rock. The reaction products reflect the low minor element contents of the reactants olivine and plagioclase.

Amphibole from metagabbros and metanorites cover a range in compositions from pargasitic amphibole to hornblende (Fig. 6) similar to what has been observed in other

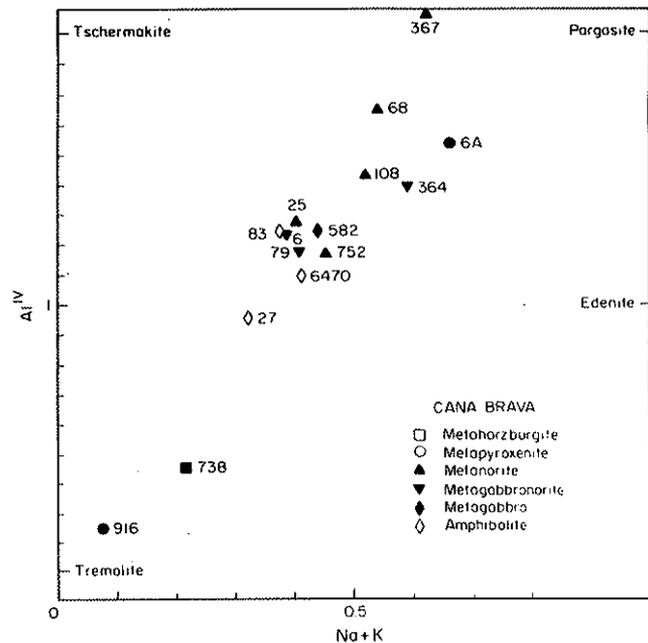


Figure 6 — The chemical variation of amphiboles from rocks of the Cana Brava massif, Brazil, expressed as cation numbers of (Na + K) and Al<sup>IV</sup> per formula unit (23 O)

areas (*e. g.*, Engel and Engel, 1962; Grapes *et al*, 1977; Girardi, 1978). Accordingly, colors in thin sections change from brown (MCB-10-367, V-68, V-108, CB-AK-6A, and MCB-I-364) to green (G-25, MCB-582, KV-6, V-79, V-83, CBE-6370 and MCB-752). Textural relations show that the brown or brownish pargasitic amphiboles are related to the first reequilibration event. The green hornblendes were formed after clinopyroxenes during the subsolidus reequilibration under amphibolite facies conditions. The amphiboles are generally rather homogeneous within each rock with a small variation in the Fe/Mg ratios that on average follow the general Fe/Mg fractionation trend of the pyro-

Table 4 — Averaged and selected electron microprobe analyses of minerals from metagabbros, metanorites and amphibolites, Cana Brava complex, Brazil: Samples arranged in order of increasing Fe/Mg ratio of Opx or the main mafic mineral

Sample n.º	MCB - I - 364				MCB - 10 367									V - 108			KV - 6		
	Metagabbronorite				Metanorite												Metagabbronorite		
Rock type	Opx Bulk	Cpx unmix	Bulk	unmix	Hbl	Sp	Ol	Opx Rock	Opx Sympl.	Cpx Rock	Cpx Sympl.	Hbl Sympl.	Sp Sympl.	Opx	Cpx	Hbl	Opx	Cpx	Hbl
N.º of Analyses	11	1	8	5	2	3	7	18	4	4	4	18	4	14	10	11	20	8	8
SiO <sub>2</sub>	55.0	55.3	52.4	52.7	45.7	0.19	39.2	54.9	55.0	51.9	54.3	42.9	0.18	55.5	54.4	45.9	52.2	52.1	46.2
TiO <sub>2</sub>	0.27	0.05	1.27	0.43	1.65	1.83	0.02	0.16	0.04	0.82	0.07	0.23	0.02	0.05	0.29	1.90	0.07	0.23	1.17
Al <sub>2</sub> O <sub>3</sub>	1.93	1.65	2.40	2.40	10.2	38.5	0.02	1.91	2.24	3.2	2.16	17.6	65.0	1.52	2.13	11.8	1.45	2.07	11.0
Cr <sub>2</sub> O <sub>3</sub>	0.33	0.32	0.40	0.45	1.03	20.0	0.02	0.08	0.03	0.13	0.02	0.02	0.06	0.06	0.13	0.17	0.02	0.04	0.08
V <sub>2</sub> O <sub>5</sub>	—	—	—	—	—	0.65	—	—	—	—	—	—	0.02	—	—	—	—	—	—
FeO*	13.9	14.2	7.2	4.8	8.3	28.5	22.6	14.7	14.7	5.1	4.1	7.7	22.0	16.2	4.9	8.8	23.4	7.7	11.4
NiO	0.03	0.03	0.02	0.05	0.10	0.03	0.16	0.04	<0.02	0.02	<0.02	0.03	0.17	0.02	0.03	0.04	0.02	0.02	0.03
MnO	0.29	0.32	0.17	0.12	0.10	0.19	0.38	0.32	0.28	0.11	0.11	0.09	0.11	0.41	0.16	0.10	0.59	0.24	0.15
MgO	27.3	28.5	16.7	15.9	15.6	8.6	37.9	28.3	28.6	14.7	15.7	16.8	12.0	25.0	15.3	14.8	21.6	14.1	13.8
ZnO	—	—	—	—	—	1.36	—	—	—	—	—	—	—	—	—	—	—	—	—
CaO	1.95	0.45	19.5	22.8	12.5	0.06	<0.02	0.36	0.20	22.8	23.1	11.6	0.13	0.29	23.2	12.2	0.44	22.2	11.8
Na <sub>2</sub> O	0.03	0.02	0.35	0.39	1.73	—	<0.02	<0.02	<0.02	0.37	0.20	2.37	—	0.02	0.40	1.27	0.02	0.44	1.02
K <sub>2</sub> O	—	—	0.03	0.03	0.55	—	<0.02	<0.02	<0.02	0.03	0.03	0.48	—	0.02	0.02	0.93	0.02	0.02	0.51
Total	101.03	100.84	100.44	100.07	97.46	99.91	100.16	100.77	101.09	99.18	99.77	99.82	99.69	99.05	100.98	98.01	99.79	99.26	96.86

Sample n.º	G-25		V - 79			MCB - 582		V - 74		V - 68				MCB - 752		KV-27	CBE-6470	V-83
	Metanorite		Metagabbronorite			Metagabbro				Metanorite						Hbl. fels	Amph	Amph
Rock type	Opx	Hbl	Opx	Cpx	Hbl	Cpx	Hbl	Opx	Opx low-Al	Cpx	Opx	Cpx	Hbl	Opx	Hbl	Hbl	Hbl	Hbl
N.º of Analyses	6	8	13	3	1	8	18	5	1	3	9	6	3	4	12	18	19	22
SiO <sub>2</sub>	52.5	46.8	53.3	53.6	48.8	52.6	46.2	51.7	52.1	53.4	52.2	53.1	43.1	51.2	46.0	48.6	48.0	45.8
TiO <sub>2</sub>	0.06	1.02	0.07	0.12	1.27	0.09	0.79	0.06	<0.02	0.29	0.07	0.23	1.45	0.05	1.13	0.60	1.16	0.68
Al <sub>2</sub> O <sub>3</sub>	1.40	12.4	0.96	1.35	11.8	1.32	11.4	1.33	0.38	1.69	1.24	2.28	13.9	0.71	10.6	9.4	11.2	12.6
Cr <sub>2</sub> O <sub>3</sub>	0.06	0.23	0.02	0.04	0.14	0.04	0.12	0.05	0.04	0.06	0.02	0.06	0.05	0.02	0.04	0.09	0.13	<0.02
FeO*	23.5	12.0	25.5	8.3	13.0	8.9	14.6	26.6	26.7	10.9	28.2	10.7	15.2	32.5	16.2	11.1	12.8	13.7
NiO	0.02	0.02	<0.02	<0.02	<0.02	0.02	0.03	<0.02	0.05	<0.02	0.02	0.02	<0.02	<0.02	<0.02	0.02	0.04	0.03
MnO	0.58	0.22	0.64	0.24	0.16	0.36	0.18	0.51	0.52	0.25	0.83	0.37	0.15	0.76	0.18	0.20	0.22	0.27
MgO	20.0	13.3	20.1	14.1	11.0	12.8	16.7	19.0	19.4	13.6	17.0	11.9	11.1	15.4	10.7	13.8	11.8	10.8
CaO	0.30	10.5	0.45	22.3	11.6	22.1	11.9	0.40	0.34	21.3	0.52	21.5	11.0	0.48	11.2	12.0	11.8	11.6
Na <sub>2</sub> O	<0.02	1.15	<0.02	0.26	0.87	0.36	1.25	<0.02	0.02	0.37	0.02	0.44	1.44	0.02	1.04	0.73	1.16	1.13
K <sub>2</sub> O	<0.02	0.44	<0.02	0.03	0.82	0.03	0.41	0.02	<0.02	0.02	0.02	0.02	0.69	0.02	0.60	0.63	0.47	0.27
Total	98.42	98.08	101.04	100.33	97.56	99.52	97.58	99.65	99.53	101.88	100.10	100.60	98.06	101.12	97.69	97.17	98.78	96.39

\* Total Fe as FeO

xenes (Fig. 5). TiO<sub>2</sub> contents vary over a wide range (1.90-0.23%) with the highest contents being present in the paragenetic amphiboles with the exception of rock MCB-10-367, where amphibole is not in contact (and equilibrium) with a Ti-bearing phase. Since this amphibole was formed from pyroxenes with low Ti-contents, it has the lowest TiO<sub>2</sub> content observed (0.23%). TiO<sub>2</sub> contents of green hornblendes have a narrow range between 0.79 and 1.27% and reflect lower solubility of Ti.

Spinel is present only in the two more magnesian rocks MCB-I-364 and MCB-10-367. In 10-367 they are rather unusual in composition because of the almost complete lack in Cr<sub>2</sub>O<sub>3</sub>. The composition of these spinels which exclusively occur in pyroxene symplectites is determined by the compositions of olivine and plagioclase.

Plagioclase compositions of metagabbros and -norites are not given in the table but projections are given in Fig. 4. Anorthite contents are generally high even in the soundly differentiated ferroan rocks. Plagioclases in all rocks exhibit some compositional zoning which normally covers a restricted range. Average compositions show a rather small range from An 78.5 (MCB-10-367) to An 87.9 (V-108) with the exception of metagabbro V-74 which has the most sodic plagioclase encountered at Cana Brava (An 68.9).

In summary, the metagabbros and metanorites of the Cana Brava complex represent a differentiation sequence from a primary magma rich in olivine and low in alkalis. The most ferroan rocks occur to the W of the massif. On the W border several leucogabbros were also collected. The rocks subsequently experimented a subsolidus reequilibrium

under granulite facies conditions. A second recrystallization led to the formation of green hornblendes.

**D) Amphibolites** A hornblendefels (KV-27) and two amphibolites (CBE-6470 and V-83) were studied. They are from the main massif and represent bodies and lenses within metagabbros and metanorites in the W part of the massif. No sample was studied from the E mylonitic amphibole unit because of heavy alterations of the lower temperature facies grade.

Amphibole compositions of the three samples follow the general trend of amphibole compositions of metagabbros and -norites (Table 4). The Fe/Fe + Mg ratio is within the range of metanorites but confined to the ferroan end (Fig. 5). Amphiboles from the three samples cluster in the (Na + K) vs. Al<sup>IV</sup> diagram (Fig. 6) with the amphibolite facies amphiboles. Plagioclase compositions of amphibolites do not differ in any respect from those of metagabbros and -norites. The average compositions are An 89.7 (V-83) and 76.4 (CBE-6470). Plagioclase compositions suggest that the amphibolite reequilibration event was of conditions comparable to a higher amphibolite facies grade.

In summary, amphibolites from the main body of the Cana Brava complex represent basically the same rock types as do the metagabbros and meta-norites and they belong to the same fractionation sequence. Whether amphibolites formed during the second subsolidus reequilibration, apparently was governed by the availability of water. Water metasomatism within the main body was confined to rather small quantities of H<sub>2</sub>O and complete conversion to water-bearing assemblages was restricted to

small volumes. The exception to this is the low-grade amphibolite series at the E border.

**E) P-T Conditions** We have applied several geothermometers and geobarometers to evaluate the physical conditions that prevailed during the evolution of the Cana Brava rocks (Table 5). Temperature data calculated according to Wells (1977) for first subsolidus reequilibration vary from 850 °C to 960 °C. The figures obtained for the pyroxenes of the metagabbro-norite MCB-I-364, from the W satellite body, give as expected, a magmatic crystallization temperature of 1,100 °C. The thermometer proposed by Herzberg (1978, a, b) gives comparable values, ranging from 5 to 8 kb (except for one sample). The average equilibration temperatures are approximately 900 °C (Wells, 1977) and 1,030 °C (Herzberg, 1978 a, b) for comparable pressures of 6-7 kb. These temperatures calculated according to Wells (1977) and the pressures were plotted in Table 5 and Fig. 7.

**CONCLUSIONS** Exposed rocks of the Cana Brava massif represent at least part of a differentiated magmatic intrusive body that was uplifted by block faulting. Rock types range from harzburgites and pyroxenites to ferrogabbros and ferronorites. This sequence is well documented by changes in mineral associations and mineral compositions. Mg/(Mg + Fe) ratios of ferromagnesian minerals vary between 0.92 (harzburgite cumulates) and 0.46 (ferronorite) (Fig. 5) and in conjunction with textural and minor element data clearly reflect gravitational differentiation of parental

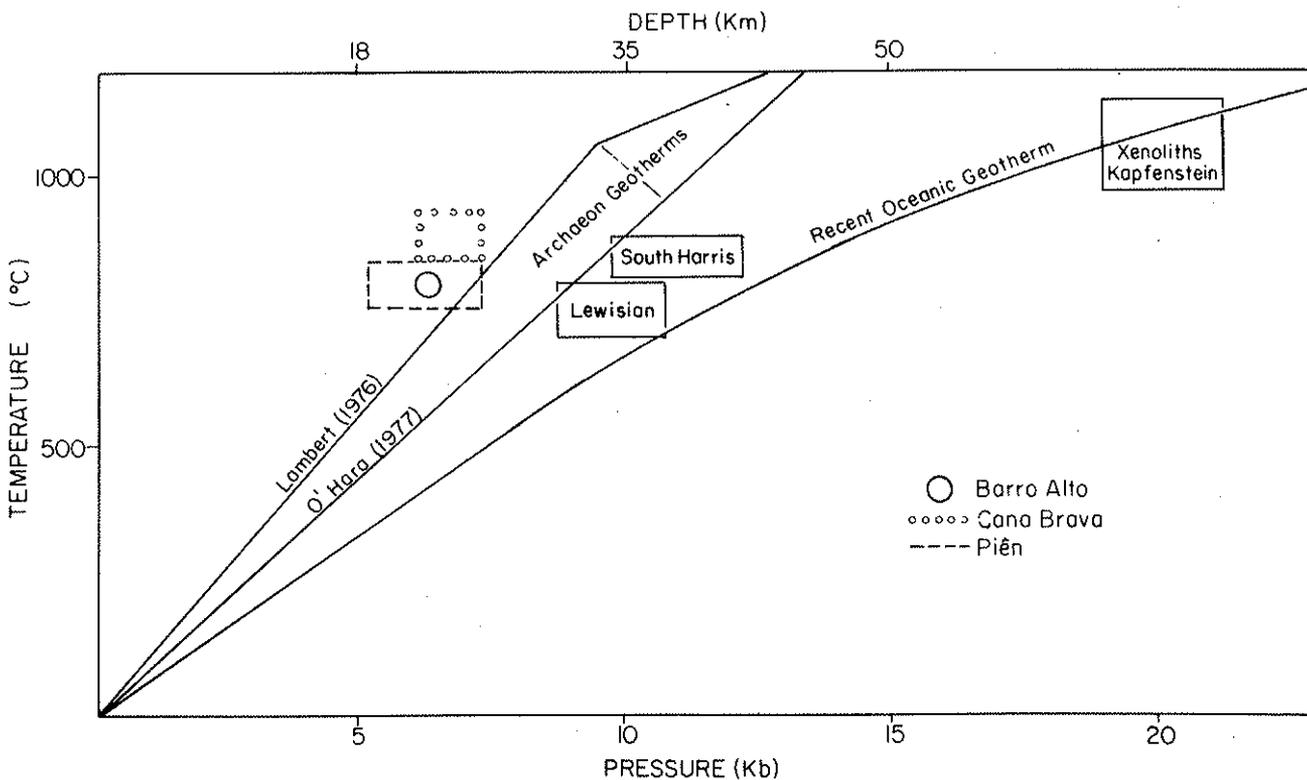


Figure 7 — The equilibration P-T estimates on rocks of the Cana Brava massif. T and P calculated according to Wells (1977) and Obata (1976). Other early precambrian metamorphic rocks and xenolithic peridotites in a P-T diagram revised after Tarney and Windley (1977). Granulite xenoliths in Lesotho kimberlites: Rogers and Nixon (1975). Lewisian complex granulites: Dickinson and Watson (1976). South Harris granulites: Wood (1975). Piên complex granulitic rocks: Girardi and Ulbrich (1980). Peridotite xenoliths from alkali basalt Kapfenstein: Kurat et al. (1981). Barro Alto rocks: Girardi et al. (1981)

Table 5 — Estimation of T and P of equilibration of pyroxenes in rocks from the Cana Brava massif

Sample N.º	Rock type	Associaton	T(1)	P(2)	T(3)	P(4)	Remarks
G-24	S	Ol-Sp-Cpx-Opx	940	4,5	1 050	3	Average Pxs
G-24	S	Ol-Sp-Cpx-Opx	960	5	1 100	5	High-Al Pxs
CB-AK-6A	MP	Opx-Cpx	900	6	1 100	5	Average Pxs
MCB-920	MP	Opx-Cpx	880	5	940	8	Average Pxs
MCB-916	MP	Opx-Cpx-Sp	905	6	950	7	Average Pxs
G-23	MP	Cpx-Opx-Sp	870	7	1 050	7	Average Pxs
MCB-I-364	MGN	Pl-Cpx-Opx-Sp	1 100	—	—	—	Bulk Pxs
MCB-I-364	MGN	Pl-Cpx-Opx-Sp	920	—	—	—	Exsolved Pxs
MACB-10-367	MN	Pl-Cpx-Opx-Sp-Ol	850	—	—	—	Rock Pxs
MACB-10-367	MN	Pl-Cpx-Opx-Sp-Ol	920	—	—	—	Symplectites
V-108	MN	Pl-Opx-Cpx	880	—	—	—	Average Pxs
KV-6	MGN	Pl-Opx-Cpx	850	—	—	—	Average Pxs
V-79	MGN	Pl-Opx-Cpx	880	—	—	—	Average Pxs
V-74	MG	Pl-Opx-Cpx	930	—	—	—	Average Pxs
V-68	MG	Pl-Opx-Cpx	890	—	—	—	Average Pxs

Temperatures in °C; pressures in kb; T(1) Wells, 1977; P(2) Obata, 1976; T(3) and P(4) Herzberg, 1978a and 1978b. For rock symbols see Table 1.

magmas of basaltic composition similar to what is known from a variety of layered intrusions (*e. g.* Jackson, 1967; Irvine and Smith, 1967). Whether all the rocks studied here have been derived from a single parental magma or not can not be decided unequivocally. The geographical distribution of ultramafic, magnesian mafic, and ferroan mafic rocks within the Cana Brava complex shows some stratification. From Fig. 1 it can easily be recognized that the ultramafic suite of the main body is confined to the E side of the massif. Magnesian mafic rocks show the same tendency and all ferroan mafic rocks have been collected W of the eastern first third of the massif. This observation and the general inclination of the entire massif (Matsui, 1977), suggest that the floor is exposed to the East.

The early igneous history of the Cana Brava Complex was followed by several recrystallization events. In the main body, the principal effects of the first one were the exsolution and reequilibration of the pyroxenes and the formation of pargasitic hornblende. There are two possible explanations for this phenomenon: a granulite facies metamorphism or a subsolidus re-equilibration due to a slow cooling of the complex intruded into the crust under conditions *similar* to those of a granulitic metamorphism.

There is no agreement about the nature of thermal gradients in the Archean and Early Proterozoic. Estimates vary from about 25 to 100 °C/km (Windley, 1978) and are related to speculations about the influence of the thickness of ancient crust.

According to Saggerson (1973) low pressure and high thermal gradient were typical of the Early Precambrian, and intermediate thermal gradients prevailed during the Late Precambrian. O'Hara (1977) proposed an Archean geotherm of about 25 °C/km. According to Lambert (1976) steeper gradients, of about 36 °C/km, existed in the Archean or Early Proterozoic crust, caused by intrusion of basic magma, thus providing an additional heat source and hence increasing the gradient.

A few available PT data for Brazilian Archean or Lower Proterozoic mafic-ultramafic complexes were plotted in Fig. 7. These data are estimates of PT conditions of the first subsolidus process that affected the massifs after their emplacement. In the Piên Area (Girardi and Ulbrich, 1980)

PT values of 5-7 kb and 750-880 °C were obtained. In the Barro Alto Complex the subsolidus reequilibration of pyroxenes occurred at about 800 °C and 5-6 kb (Girardi *et al.*, 1981).

The geothermometric values obtained through these data are close to the geotherm proposed according to Lambert's 1976 basic intrusion model. Some speculations may be pertinent about the thermal régimes of the Cana Brava and Barro Alto areas. If the first subsolidus process is the result of a regional granulite facies metamorphism, then a gradient of about 40 °C/km, or even higher, has to be supposed for those areas, thus corresponding to a thin crust, according to models by several authors (*e. g.* Lambert, 1976; Fyfe, 1973; Windley, 1978). This seems to be an unlikely model to fit a crust into which basaltic magma was intruded and differentiated into mafic-ultramafic complexes. Estimated thicknesses of the Barro Alto and Cana Brava massifs range from about 8-22 and 6-11 km, respectively. Both of them derive from crystallization and differentiation of basaltic material (Girardi *et al.*, 1981). A better hypothesis would interpret the first subsolidus reequilibration as a slow post-magmatic cooling of the complex, under conditions comparable with those of a granulite facies metamorphism. In this case the resulting geothermometric data would be a reflection of the cooling history of the intrusion, which occurred at low pressure and high temperatures; and not necessarily a product of a regional granulite facies metamorphism.

The Cana Brava complex was affected by a latter partial recrystallization, under amphibolite facies conditions, in conjunction with water influx causing either partial conversion of clinopyroxenes into hornblendes or complete recrystallization of gabbros into amphibolites.

A late low-T event had little effect on the mafic rocks, but affected severely the ultramafic suite, forming amounts of serpentinites, rodingites and talc schists.

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