SIGNIFICANCE OF GARNET-BEARING METAMORPHIC ROCKS IN THE ARCHEAN SUPRACRUSTAL SERIES OF THE CARAJÁS MINING PROVINCE, NORTHERN BRAZIL

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ABSTRACT The Archean evolution of the Carajás Mining Province was marked by the emplacement of syntectonic alkaline granites (cf. Estrela and Planalto granites) at 2,75 Ga. The Estrela Granite Complex produced changes in tectono-thermal conditions and rheology of its volcano-sedimentary host rocks (Salobo, Pojuca, Grão-Pará and Rio Novo groups). Metamorphic recrystallization in the contact aureole around the Estrela Granite Complex reached hornblende and pyroxene hornfels facies. The aureole is characterized by the local presence of schists containing abundant snowball garnet porphyroblasts indicating a top to south movement related to emplacement of the Estrela Granite Complex. It is suggested that occurrences of garnet-bearing schists, near Salobo and Pojuca areas, may represent tectono-metamorphic aureole around other Late-Archean syntectonic granite bodies.

Keywords:

INTRODUCTION The Carajás Mining Province (Northern Brazil) is well known by its important Au, Fe, Mn, Ag, Mo and Cu deposits which are hosted in Archean metavolcano-sedimentary sequences (Salobo, Pojuca, Bahia, Rio Novo groups; Docegeo 1988). Geochronological data and field relationships reveal that a granitic basement (2,81 Ga) underlies these 2,76 Ga supracrustal rocks (Olszelwski *et al.* 1989, Machado *et al.* 1991). Successive pulses of granites intruded these supracrustals at ~2,75 Ga (Huhn *et al.* 1999), ~2,56 Ga (Machado *et al.* 1991, Lindenmayer *et al.* 1994) and ~1,88 Ga (Olszelwski *et al.* 1989, Machado *et al.* 1991, Dall'Agnol *et al.* 1994).

The presence of garnet-bearing schists in Carajás has first been documented by Beisiegel *et al.* (1973) and later by Docegeo (1988), Lindenmayer (1990), Winter (1994), Melo and Villas (1997) and others.

Here we discuss the metamorphic and tectonic meaning of the garnet–bearing rocks of the contact aureole around the Estrela Granite Complex, an Archean alkaline A-type massif (Barros 1997, Barros and Barbey 1998). The granite complex is situated to the east from Carajás Range, in the vicinity of the Curionópolis and Parauapebas (Fig. 1). Our conclusions are then extended to the north of the Carajás Range and some implications for the lithostratigraphy of the supracrustal series in the Carajás area are discussed.

Silicates were analyzed by transmission electronic microprobe (10A, 15kV, 10s) at the Université Henri Poincaré (Service de Microanalise). The garnet-bearing rock chemical analysis was obtained by ICP-MS at the CRPG laboratories, Vandoeuvre-lès-Nancy, France.

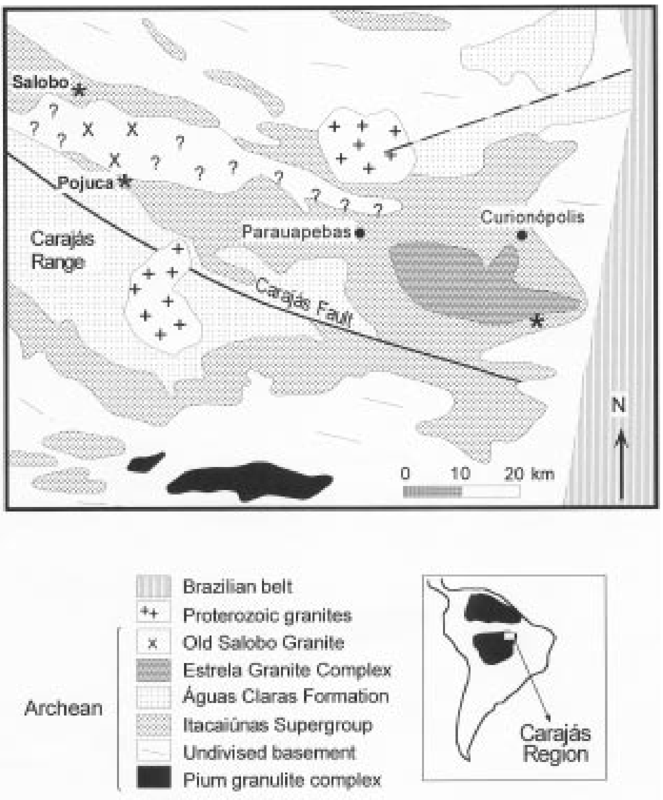

Figure 1 - Schematic geological map of the Carajás region (modified from Docegeo 1988 and Araújo et al. 1988). *** *indicates garnet-bearing rocks.*

WHOLE-ROCK MINERALOGY AND CHEMISTRY Garnet-bearing schists outcrop near the southeastern contact of the Estrela Granite Complex (Fig. 2). They consist of garnet porphyroblasts within a matrix composed of biotite (31%), hornblende (23%), plagioclase (An_{52-45}; 22%), quartz (21%) and minor ilmenite (2%), epidote, zircon, apatite and tourmaline (0.5%). Proportions of garnet porphyroblasts are variable but may reach 30% of the whole rock volume (Fig. 3a).

Amphibole is pale yellow-green and bluish green ferrotschermakite (cf. Leake *et al.* 1997), with high contents of Al_2O_3 (15.50 – 16.60 %), FeO (19.30 – 20.80 %), Na_2O (1.50 – 1.32 %), relatively low values of TiO_2 (0.30 – 0.50) and low #Mg (0.36 - 0.39) values (Tab. 1).

Biotite is chemically (Table 1) homogeneous (FeO = 19.3 – 20.0%; MgO = 10.7 – 11.0%; TiO_2 = 1.7 – 2.0%).

Garnets have relatively homogenous compositions (Table 1) with Almandine (0.73-0.75%) predominating largely over the other components (Pyrope = 0.11-0.14%; Spessartine = 0.02-0.07%; Grossular = 0.09%). Slight decreasing of MnO from the core (3.15%) to the margin (2.32%) of the crystals evidences a discrete zoning.

Whole rock composition displays high FeO (15.73%) and Al_2O_3 (14.81%) values and moderate MgO (4.63%), CaO (4.46%), K_2O (1.81%) and Na_2O (1.58%) contents. REE pattern reveals a slight LREE fractionation [$(La/Sm)_N$=4.05] and flat HREE [$(Gd/Yb)_N$=1.42] and no Eu anomaly. In the Total Alkalis vs. Silica diagram (Le Maitre 1989), this rock plots in the andesite-basalt composition. However a possible sedimentary derivation cannot be discarded (i.e. graywacke).

STRUCTURE AND METAMORPHISM The rock has a continuous subvertical schistosity parallel to the contact of the granite (Fig. 2) and given by the preferred orientation of biotite, amphibole (nematoblastic texture), plagioclase and quartz ribbons. Quartz occurs as neoblasts aggregates, strongly oriented along the schistosity. Neoblasts are polygonal and show, only very locally, undulose extinction and subgrain, suggesting significant recrystallization.

Two morphological types of garnet-porphyroblasts (Figs. 3a and 3c) occur in these rocks: snowball and tabular. Both are in general centimeter-sized, asymmetric and contain abundant inclusions of quartz, ferromagnesian minerals and ilmenite. The helicitic structures

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are consistent with the stretching lineation indicating a top to the south movement. Tabular garnet porphyroblasts may be decimeter long (up to 20 cm; Fig. 3b) and may envelope the snowball ones. Occurrence of garnet is limited to mafic schists from the inner aureole (Fig. 2). According to Cooper (1972), porphyroblasts are more frequent in middle and higher conditions of the oligoclase zone, mainly in iron-rich mafic rocks.

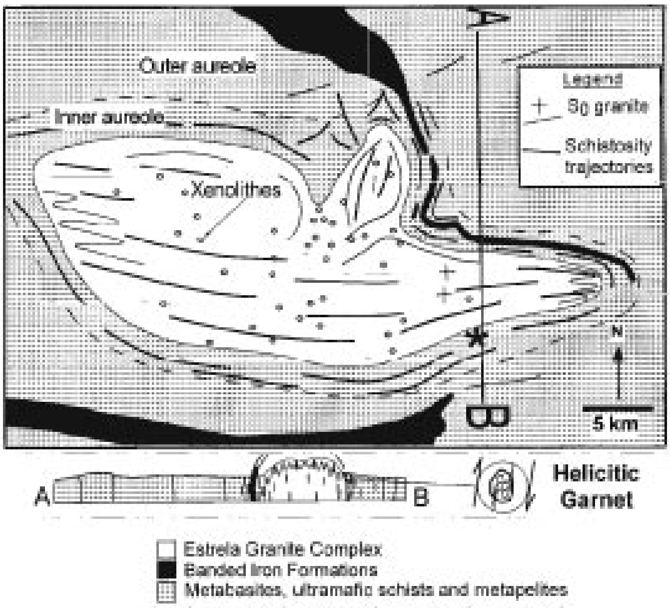

*Figure 2. Geological map pf the Estrela Granite Complex (Barros 1997). * indicates garnet-bearing rocks.*

Quartz-veins millimeter wide and meter to decimeter long (Fig. 3a), locally with tourmaline, are common. They are generally conformable with the schistosity, but may cut across. In the latter case, veins are moderately to strongly fold. Quartz veins are frequently associated to garnet-enriched domains. Tourmaline needles are oriented along stretching lineation and commonly microboudinage (Fig. 3d).

The coexistence of garnet with calcic plagioclase (An_{52-45}), biotite and ferrotschermakite indicates medium to high-grade facies conditions (Winkler 1979, Spear 1995). Normal zoning shown by regularly decreasing of MnO from the core (3.15%) to the margin (0.79%) suggests increasing temperatures during garnet growing (cf. Harte and Graham 1975, Miyashiro 1994). Estimates of P-T conditions in the contact aureole (Barros 1997) using garnet-hornblende and biotite-garnet geothermometers (Graham and Powel 1984, Ferry and Spear 1978) yielded temperatures between 520° and 612°C which is comparable to temperatures (550°-650°C) estimated from the pair ferropargasite-calcic plagioclase of amphibolites from the inner aureole. Pressures are estimated within 2.5 to 3.5 kbar range (Barros 1997).

DISCUSSION Significance of garnet porphyroblasts in the Estrela Granite Complex The inner part of the contact aureole around the Estrela Granite Complex is characterized by the presence of syntectonic garnet porphyroblasts. This observation is consistent with structural data about the Estrela Granite Complex that shows its syntectonic emplacement. Barros (1997) describes that this emplacement occurred in two successive stages: (i) an inflation stage controlled by magma driving pressure intrusion accompanied by ballooning, followed by (ii) a passive stage of deflation controlled by regional stress. The direction and sense of rotation of the snowball garnets and the stretching lineation (inverse top to the south movement) are consistent with ascent of the granites.

Porphyroblasts growth is controlled by several processes: material dissolution, solution transfer, nucleation and growth (Bell *et al.* 1986,

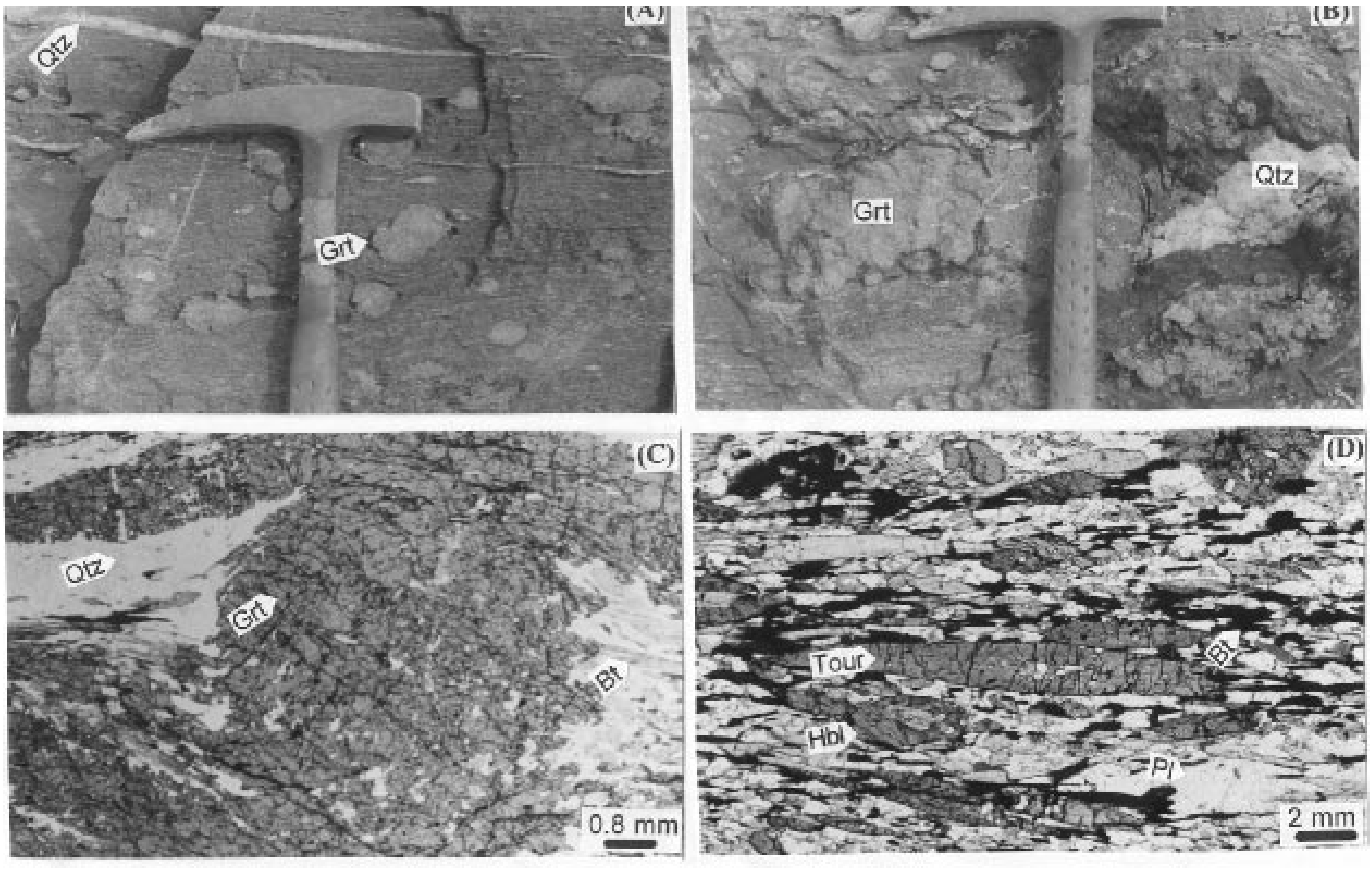

Figure 3 (a) Garnet-bearing mafic schist. Note the presence of snowball garnet porphyroblasts and of quartz veins conformable with the schistosity. (b). Detail of mafic schist showing a decimeter long tabular garnet porphyroblast and associated quartz domains. (c) Photomicrograph of mafic schist showing a snowball garnet with helicitic ilmenite inclusions. Note that tabular garnet envelops the snowball porphyroblast. (d) Photomicrograph of mafic schist showing microboudinage of tourmaline crystals.

Table 1. Representative mineral-chemistry data of the garnet-bearing metabasite from the inner aureole around the Estrela Granite Complex.

Garnet			Hornblende			Biotite			Plagioclase		
SiO_2	37.67	37.21	SiO_2	39.98	40.66	SiO_2	35.40	35.73	SiO_2	57.24	55.98
Al_2O_3	20.74	20.80	Al_2O_3	16.21	16.10	Al_2O_3	16.66	16.70	Al_2O_3	27.24	28.07
TiO_2	0.002	0.05	TiO_2	0.47	0.34	TiO_2	2.02	1.80	TiO_2	0.04	0.00
FeO	33.54	33.33	FeO	20.75	20.06	FeO	19.83	19.95	FeO	0.04	0.00
MnO	2.316	3.15	MnO	0.16	0.04	MnO	0.00	0.00	MnO	0.06	0.00
MgO	2.959	2.82	MgO	6.47	6.58	MgO	10.97	10.67	MgO	0.00	0.00
CaO	3.011	3.13	CaO	10.58	10.57	CaO	0.00	0.00	CaO	9.22	10.71
Cr_2O_3	0.002	0.00	Cr_2O_3	0.00	0.03	Cr_2O_3	0.00	0.05	Cr_2O_3	0.00	0.00
NiO	0.002	0.00	NiO	0.00	0.01	NiO	0.00	0.00	NiO	0.05	0.06
Na_2O	0.053	0.00	Na_2O	1.50	1.32	Na_2O	0.40	0.43	Na_2O	5.95	5.40
K_2O	0.001	0.00	K_2O	0.27	0.34	K_2O	8.38	8.36	K_2O	0.08	0.07
Total	100.30	100.50	Total	96.39	96.05	Total	93.38	93.69	Total	99.92	100.29
Al^{VI}	3.917	3.890	Al^{VI}	1.052	1.141	Al^{IV}	2.514	2.468	Si	2.565	2.511
Ti	0.000	0.006	Fe^{3+}	0.216	0.083	Z	8.000	8.000	Al	1.439	1.484
Fe^{3+}	0.030	0.138	Ti	0.054	0.039	Al^{VI}	0.529	0.580	Fe	0.001	0.000
Cr	0.000	0.000	Cr	0.000	0.004	Cr	0.000	0.006	Ca	0.443	0.515
R^{3+}	3.947	4.034	Ni	0.000	0.001	Fe	2.570	2.583	Na	0.517	0.470
Fe^{2+}	4.464	4.328	Mg	1.477	1.503	Ni	0.000	0.000	K	0.005	0.004
Mg	0.707	0.672	Fe^{2+}	2.443	2.489	Mg	2.534	2.462	Sum	4.969	4.982
Mn	0.314	0.428	Mn	0.021	0.005	Mn	0.000	0.000			
Ca	0.517	0.537	C	5.263	5.265	Ti	0.235	0.210	% An	45.91	52.08
R^{2+}	6.001	0.000	Ca	1.737	1.736	Y	5.869	5.841	% Ab	53.61	47.52
Total	15.983	15.999	Na(M4)	0.263	0.264	Ca	0.000	0.000	% Or	0.47	0.41
Alm.	0.744	0.726	B	2.000	2.000	Na	0.120	0.129			
Pyrope	0.118	0.113	Na(A)	0.182	0.128	K	1.657	1.651			
Spess.	0.052	0.072	K	0.053	0.066	X	1.777	1.780			
Gross.	0.086	0.090	A	0.235	0.195	XYZ	15.64	15.622			
Fe^{2+} calc.	33.319	32.302	Fe^{2+} calc.	19.065	19.412	XFe	0.504	0.512			
Fe^{3+} calc.	0.248	1.141	Fe^{3+} calc.	1.872	0.720						
			#Mg	0.357	0.369						

Silicates were analized by electron microprobe, CAMECA-SX-50 (10A, 15kV, 10s), at the Université Henri Poincaré (Service de Microanalyse).

Bell and Cuff 1989). According to these authors, strain partitioning can promote porphyroblasts growth within flattening strain domains. Otherwise, porphyroblasts dissolution is more facilitated in shear strain domains. Fluid production, fundamental during porphyroblast formation, is controlled by dehydration (Bell *et al.* 1986, Bell and Cuff 1989), which are very common within thermal aureoles, and mainly when flattening stresses are imposed by intrusions (Bateman 1985). The close spatial relationship between garnet porphyroblasts and abundance of tourmaline-bearing quartz veins supports the role of a fluid phase during garnet growth (dissolution/transfer/precipitation).

The two morphologically distinct types of garnet and their relative growth chronology could reflect distinct growth conditions. Snowball garnet probably formed under differential vertical movement between the granite body and the country rocks, whereas tabular garnet is mainly due to flattening of the contact aureole. This can be tentatively related to the two-stage emplacement of the granite complex. The subvertical lineation and garnet rotation microstructures may express accommodation of differential movements between the granites and the host-rocks during the first stage of granite emplacement (inflation), whereas the tabular morphology of the subsequent garnet porphyroblasts may result mainly from flattening (deflation).

Significance of garnet-bearing schists in the Itacaiúnas Supergroup In the Salobo and Pojuca domains the presence of garnet-bearing schists has been reported by several authors, and interpreted as corresponding to more ancient higher grade sequences (Salobo and Pojuca) than the regional greenschist facies sequences (Grão-Pará). We believe that these garnet-bearing rocks may also result from thermal metamorphism around granite plutons. First, the extend of the Archean alkaline granite magmatism has been underestimated in the Carajás Mining Province. For instance, to the north of the Carajás Range, between the Igarapé Salobo and Igarapé Pojuca groups, widespread quartzo-feldspathic rocks were interpreted as belonging to the basement assemblage (Xingu Complex). This is far from being certain, and should be re-assessed. Then, the Estrela Granite Complex is not the only Archean alkaline granite in the Carajás area, but has many similarities with the 2,56 Ga Old Salobo Granite (Machado et al. 1991, Lindenmayer et al. 1994) as well as with the 2,75 Ga Planalto Granite (Huhn *et al.* 1999). Lastly, there seems to be a correlation between the location of the garnet-bearing rocks and the quartzo-feldspathic domains. For instance, Lindenmayer and Fyfe (1992) suggest that the Igarapé Salobo and Igarapé Pojuca groups correspond to higher metamorphosed lateral variations of the Grão-Pará Group, metamorphosed under greenschist facies. Moreover, Olszewsky *et al.* (1989) and Matta and Teixeira (1990) report an increase in the metamorphic degree and schistosity intensity in metabasites toward the crystalline rocks (north and northeast of the Carajas Range). These data and the presence of the garnet-bearing rocks suggest, by comparison with the Estrela Granite Complex, that the size of the Old Salobo granite or of other earlier alkaline granite (ca. 2,7 Ga) may have been underestimated, and that the local increase in the metamorphic grade may correspond to unreported contact aureoles.

The above discussion corroborates the comparison made by Lindenmayer and Fyfe (1992) who have demonstrated that the Grão-Pará (low grade) and Salobo-Pojuca (medium to high-grade) sequences are contemporaneous and belong to the same lithostratigraphic unit.

CONCLUSIONS Late-Archean metamorphic and tectonic evolution of the Carajás Mining Province was controlled by syntectonic intrusions of relatively hot alkaline granites at 2,75 Ga (Estrela Granite Complex). These granites emplaced in high crustal levels (2.5 – 3.5 kbar) within volcano-sedimentary sequences previously metamorphosed under greenschist conditions (Barros 1997, Barros and Barbey 1998). Mafic schists containing syntectonic garnet porphyroblasts are locally found around the Estrela Granite Complex. These garnet-bearing schists are part of the contact aureole and are considered to result from the thermal and mechanical effects of pluton emplacement. It is suggested that other garnet-bearing rocks found in higher grade areas of the Carajás terrane close to crystalline domains, could also represent the contact aureole around unreported Late-Archean granite bodies.

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