METAMORPHISM OF HYDROTHERMALLY ALTERED ROCKS IN A VOLCANOGENIC MASSIVE SULFIDE DEPOSIT: THE PALMEIRÓPOLIS, BRAZIL, EXAMPLE

SYLVIA M. ARAUJO*[1], J. JEFFREY FAWCETT & STEVEN D. SCOTT****

ABSTRACT The PALMEIRÓPOLIS Cu-Zn (Pb) volcanogenic massive sulfide deposit, Brazil, consists of three ore bodies enclosed by hydrothermal alteration zones. The ore bodies and the alteration zones were metamorphosed under amphibolite fades conditions. The Palmeirdpolis alteration zones are characterized by a great diversity of bulk rock composition that originated a wide variety of low variance mineral assemblages. These assemblages are composed of orthoamphiboles (anthophyllite and gedrite), hornblende, biotite, garnet, staurolite, sillimanite, gahnite and, rarer, cordierite. Based on analyses of mineral chemistry aad mineral assemblages, temperatures are estimated to have been 550 - 625°C and pressures 2 - 5.5 kbar. The temperature of metamorphism that prevailed at the Palmeirdpolis deposit is comparable to other amphibolite fades massive sulfide deposits, such as Geco and Linda, Canada; Falun, Sweden; and Bleikvassli, Norway. The mineralogy of the alteration zones is similar in all these deposits even though they were metamorphosed at different pressure conditions, reflected by the crystallization of one of Al_2SiO_5 phase (andalusite, sillimanite or kyanite).

Keywords: volcanogenic deposit, hydrothermal alteration zones, amphibolite fades.

RESUMO METAMORFISMO DE ROCHAS HIDROTERMALMENTE ALTERADAS ASSOCIADAS A DEPÓSITO DE SULFETO MACIÇO VULCANOGÊNICO: O EXEMPLO DE PALMEIRÓPOLIS, BRASIL O depósito de sulfeto MACIÇO a Zn e Cu vulcanogenico de Palmeirdpolis, Brasil, consiste de tres corpos de minério associados a zonas de alteração hidrotermal. Os corpos de minério e as zonas de alteração foram metamorfisados no fades anfibolito. As zonas de alteração do depósito são caracterizadas por uma grande diversidade química que originou uma grande variedade de assembléias mineralógicas. Essas assembléias são compostas por ortoanfibólios (antofilita e gedrita), homblenda, biotita, granada, estaurolita, silimanita, gahnita e, mais raramente, cordierita. Baseado na composição química de diferentes minerals e na associacdes mineralógicas, a temperatura de metamorfismo foi estimada entre 550 e 625°C e a pressão entre 2 e 5,5 kbar. A temperatura de metamorfismo a qual o depósito de Palmeirópolis foi submetido é comparável a de outros depósitos de sulfeto maciço também metamorfisados no fades anfibolito, tais como Geco e Linda, no Canadá; Falun, na Suécia; e Bleikvassli, na Noruega. A mineralogia das zonas de alteração é similar em todos esses depósitos apesar de terem sido submetidos a diferentes condições de pressão, refletidas apenas pela cristalização de um ou outro polimorfo de $A1_2SiO_5$ (andalusita, silimanita ou cianita).

Palavras-chaves: deposito vulcanogênico, zonas de alteração hidrotermal, facies anfibolito.

INTRODUCTION The metamorphosed Zn-Cu (Pb) PALMEIRÓPOLIS massive sulfide deposit is located 200 km north of Brasilia, central Brazil. It contains 4 million metric ton in three ore bodies, C-l, C-2 and C-3, having an average composition of 1.23 percent Cu, 4.64 percent Zn, 0.72 percent Pb and 25.1 g/t Ag (Figueiredo *et al.* 1981). All ore bodies are associated with alteration zones composed of assemblages with anthophyllite, biotite, cordierite, gahnite, sillimanite and staurolite.

In this study, we present data on petrography and mineral chemistry of amphiboles, biotite, garnet, cordierite, staurolite and gahnite from the alteration zones from which we derive the metamorphic conditions that prevailed at the Palmeirdpolis deposit. A comparison is made with alteration zones of other metamorphosed volcanogenic massive sulfide deposits.

GEOLOGICAL SETTING The Palmeirópolis deposit is situated in the Palmeirdpolis volcano-sedimentary sequence (PVSS), part of a 300 km-long major volcano-sedimentary belt that includes the southern Indaianopolis and Juscelandia volcano-sedimentary sequences. This belt is located at the western border of the large granulitic mafic-ultramafic complexes of central Brazil (Cana Brava, Niquelandia and Barro Alto). Together, these form a linear array within Proterozoic fold belts located between the Amazon and São Francisco Cratons. The main geotectonic units present in the region are the Goi£s Massif, the Araf Group and Neoproterozoic sedimentary belts, including the Uruaçu and the Brasilia Belts (Fig. D.

The Goi&s Massif, representing older basement rocks, is a typical TTG-greenstone terrain. This unit was variably affected by the Brasiliano deformation and metamorphism at 550-650 Ma (Marini *et al.* 1984a, b; Fuck *et al.* 1987; Brito Neves and Cordani 1991).

The Araf Group is a Mesoproterozoic continental sedimentary sequence with a thick rhyolitic unit at its base (Marini *et al,* 1984a, b). U-Pb dating of zircon from the rhyolitic flows, as well from associated tin-bearing granites, yield ages of *ca. 1*770 Ma for the magmatism (Pimentel *et al.* 1991).

The Brasilia Belt is located at the western margin of the São Francisco Craton. This belt was deformed during the Brasiliano cycle (Neoproterozoic) and exhibits tectonic and metamorphic vergence towards the craton (Marini *et al* 1984a, b); Polydeformation characterizes the Neoproterozoic Uruac.u Belt. It consists of a pelitic-psammitic sequence with intercalated volcanic rocks, and may represent an internal facies of the Brasilia Belt (Pimentel *et al* 1992).

There is no widely accepted model of the geological setting of the PVSS. Its stratigraphic relationship to the adjacent units is not clear because of limited exposure, faulted contacts and paucity of reliable geochronological data. The PVSS is a bimodal tholeiitic sequence that has been subdivided into

* -Universidade de Brasilia, Institute de GeociSncias, Brasflia, DF, Brazil - Cep: 70.910-900. Fax: 55 - 61 - 347-4062 - Phone: 55 - 61 - 348-2436
** -Department of Geology, University of Toronto, 22 Russell St., Toronto, Ontario, Canada. M5S3B1
Fax: 1 - 416 - 978-3938
Phone: 1 - 416 - 978-5424
1 -corresponding author

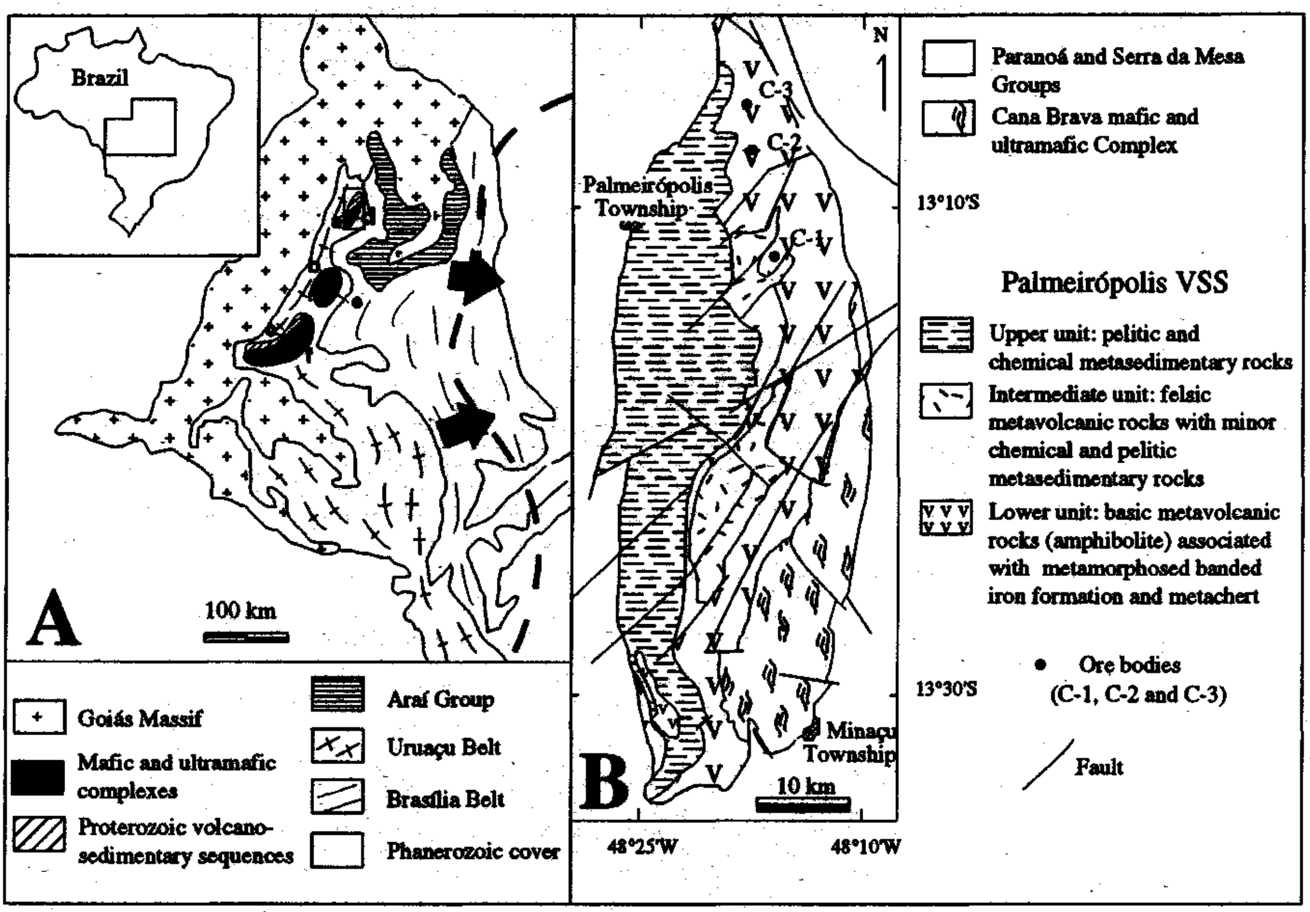

Figure 1 - A. Geological sketch map of central Brazil. Dashed line indicates the limit of the São Francisco Craton. Arrows indicate tectonic vergence of supracrustal rocks. Symbols: a: Palmeirdpolis Sequence, b: Indaianópolis Sequence, c: Juscelândia Sequence; d: Cana Brava Complex, e: Niqueldndia Complex, f: Barro Alto Complex. B. Simplified geological map of the Palmeirópolis volcano-sedimentary sequence (located by small box in A) with the ore bodies heated. Modified from Araujo & Nilson (1988), Danni et al. (1982), Leão Neto & Olivatti (1983),Marinietal. (1984a) and Pimentel et al. (1991).

Figura 1 - A. Mapa geológico esquemático do Brasil central. Liana pontilhada indica o limite do Craton do São Francisco. Setas indicam vergência das rochas supracrustais. Símbolos: a- Sequência Palmeirdpolis, b: Sequência Indaianápolis, c: Sequência Juscelândia; d: Complexo de Cana Brava, e: Complexo de Niquelandia, f: Complexo de Barro Alto, B. Mapa geologico simplificado da sequência vulcano-sedimentar de *Palmerópolis* (localizada por retangulo na figura A). Modificada de Araujo & Nilson (1988), Danni et al. (1982), Leão Neto & Olivatti (1983), Marini et al. (1984a) e Pimentel et al. (1991).

three units (Figueiredo *et al.* 1981) (Figs. 1B, and 2). The lower unit is a large volume of fine-grained amphibolite containing lenses of metamorphosed banded iron formation and metachert. This unit represents an extensive episode of submarine basic volcanism. Related intrusive activity is shown by basic and ultrabasic dykes and granitic bodies that cut this unit.

The PVSS intermediate unit contains metamorphosed felsic volcanic to subvolcanic bodies, represented by quartz-biotite-muscovite-plagioclase schist, quartz-biotite-plagioclase schist and quartz-muscovite schist.

The upper unit of the PVSS contains interbedded chemical and pelitic metasedimentary rocks represented by quartz-muscovite-biotite-titanite schist, quartz-muscovite-biotile-kyaniteschist, quartz-muscovite-garnetschist, quartz-muscovite-staurolite-kyaniteschist, metachertand nmetamorphosed banded iron formation.

Geochronological data based on whole-rock Rb-Sr systematics indicate a Mesoproterozoic age of *ca.* 1300 Ma for the PVSS; some reworking during the Brasiliano cycle is also suggested by the same data (Girardi *et al.* 1978; Drago *et al.* 1981). Pb-Pb dating of galena from the Palmeirópolis deposit suggests an age in the range of 1170 to 1270 Ma (Ralph Thorpe, Geological Survey of Canada, pers. comm.). These data are not conclusive and do not establish the precise age of the PVSS, but they do suggest that the sequence is not older than 1300 Ma.

The geology of the Palmerópolis deposit has been described by Figueiredo *et al.* (1981), Araujo (1986), Araujo and Nilson (1988) and Araujo and Scott (1991). The rocks underwent strong deformation and were metamorphosed under amphibolite facies conditions (regional metamorphism), so many of their original features are obscure. Despite this, the main units may be further divided to show a significant internal succession. The stratigraphic column presented in Figure Prelates the internal stratigraphy at the deposit to that of the Palmeirdpolis volcano-sedimentary sequence. All the Palmerópolis ore bodies are associated with hydrothermally altered rocks of the lower unit of the Palmerópolis sequence.

The ore at Palmeirdpolis is associated with amphibolite and an heterogeneous package of hydrothermally altered rocks that were also metamorphosed under amphibolite facies conditions. These rocks are represented mainly by anthophyllite-biotite assemblages with lenses of amphibolite. Quartz-K feldspar-muscovite schist, metamorphosed subvolcanic bod-

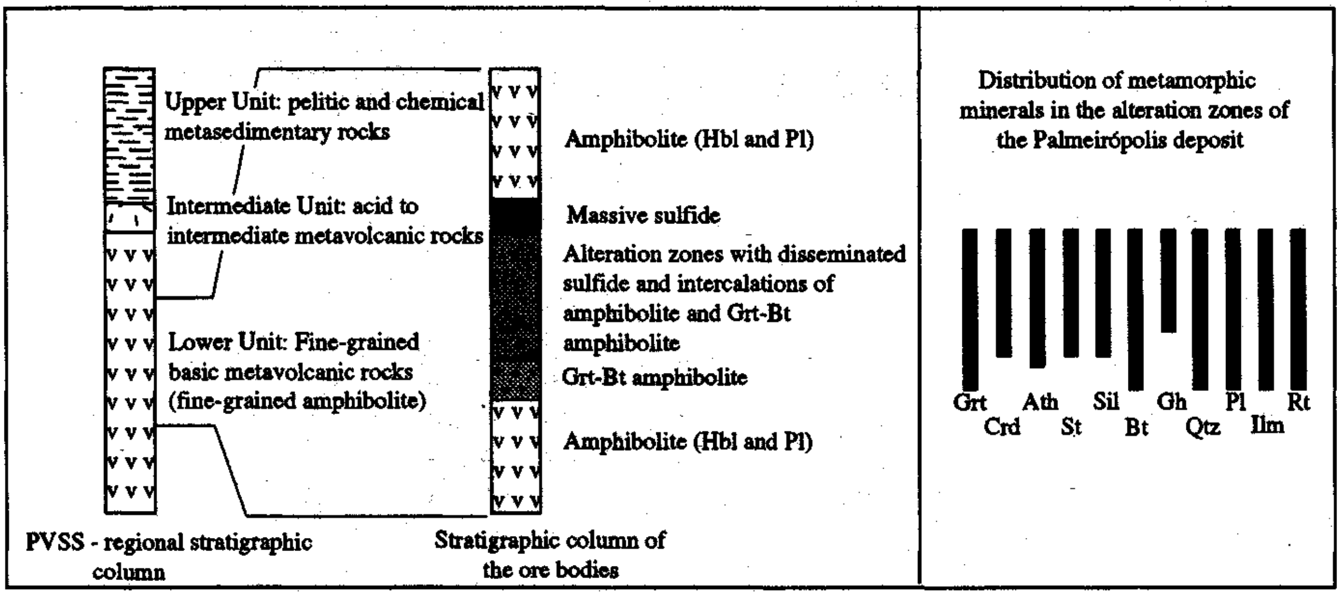

Figure 2 - General stratigraphic column of the Palmeirópolis volcano-sedimentary sequence and the ore bodies illustrating the mineralogy of the alteration zones. Ath: anthophyllite; Bt: biotite; Crd: cordierite; Gh: gahnite; Grt: garnet; Hbl: hornblende; Ilm: ilmenite; Pl: plagioclase; Qtz: quartz; Rt: rutile; Sil: sillimanite; St: staurolite.
Figura 2 - Coluna estratigráfica geral da Sequência vulcano-sediraentar de Palmeirópolis e dos corpos de minerio ilustrando a mineralogia da zonas de alteracao. Ath: antofilita; Bt: biotita; Crd: cordierita; Gh: gahnita; Grt: granada; Hbl: hornblenda; Ilm: ilmenita; PI: plagioclase; Qtz: quartz; Rt: rutile; Sil: sillimanite; St: staurolita.

ies, are also present in the vicinity of the C-l ore body, but no example of this rock is in contact with ore.

The 'ore bodies are located at the contact between the amphibolite and the alteration zone rocks. From top to the bottom the following stratigraphy is observed at the deposit:
- amphibolite with hornblende and plagioclase
- massive sulfide
- disseminated sulfide in alteration zone assemblages
- garnet-biotite amphibolite
- amphibolite with hornblende and plagioclase

The upper contact between the massive sulfide and the amphibolite is sharp. Upper and lower contacts of the alteration zone are gradational over few centimeters to meters.

PETROGRAPHY The dominant metamorphic rocks in the Palmeirdpolis alteration zones are amphibolite and anthophyllite-biotite rocks. The amphibolite is a dark green, fine-grained, well-foliated rock, composed of hornblende and plagioclase (about An_{50}) with lesser quartz, biotite, garnet, titanite, ilmenite and apatite. Diopside and scapolite are scarce and were observed only in the alteration zones of the C-l ore body. Carbonates are observed in fractures. The C-3 ore body is associated with amphibolite that is almost completely chloritized.

The alteration zones of the three ore bodies are not well exposed. All observations are from drill-cores and a shaft at the C-l ore body. The alteration zone rocks are characteristically coarse-grained with a weakly developed foliation, being evident only where the amount of biotite exceeds that of amphibole. Orthoamphibole, mostly artthophyllite, is observed as long prismatic blades and radiating prismatic clusters. Subhedral porphyroblasts of garnet and staurolite are unevenly distributed in the rocks. Sillimanite is present as the fibrous variety, fibrolite. The content of sulfide is highly variable.

Mineral assemblages for the studied samples are shown in Table 1. In thin section, anthophyllite + biotite 4- plagioclase + ilmenite is the most frequently observed assemblage in the metamorphosed alteration zones, although the relative proportions of these minerals vary considerably. Quartz, garnet and staurolite are also widely distributed. Apatite, ilmenite and rutile are accessory phases and are evenly distributed throughout the alteration zones. Sutfides comprise more than 20 volume % of some samples, and are represented by pyrrhotite, pyrite, chalcopyrite, sphalerite and minor galena.

Orthoamphibole occurs as elongated colorless blades, that can reach a few centimeters in length. Anthophyllite and gedrite could not be optically distinguished. This distinction was made with the electron microprobe which showed that both amphiboles coexist in most samples. The textures include discrete grains in some samples and also oriented, bladed intergrowths that are optically continuous. Hornblende was observed in three samples, in discrete subhedral, green crystals, and also intergrowh with anthophyllite.

Garnet porphyroblasts can reach up to 3 cm in diameter. They are characterized by presence of inclusions in their core and clear borders. Garnet in assemblages that also contain sillimanite occurs as typically anhedral poikilitic crystals that grew along the foliation.

Staurolite porphyroblasts are subhedral to anhedral, and poikilitic staurolite crystals are also observed. Inclusion trails in staurolite and garnet suggest some degree of rotation.

Biotite shows strong pleochroism from reddish-brown to colorless. Inclusions of zircon, with its characteristic pleochroic halo, are common. Biotite in the silimanite-bearing assemblages shows pleochroism from almost colorless to green, and the textures suggest replacement of biotite by sillimanite.

Cordierite is rare in the Palmerópolis alteration zones and was observed in only two samples. Cordierite is always altered to pinite along small fractures and commonly shows pleochroic halos around inclusions of zircon.

Table 1 - Mineral assemblages in the studied rocks.
Tabela 1 - Assembléias minerals das rochas estudadas.

Sample	Ath	Ged	Hbl	Bt	Ms	Crd	Grt	St	Sil	Qtz	Pl	Ap	Gh	Zrn	Ilm	Rt	Mag	Sulf	Chl	Ep
31/44.95	X			X				X			X	X	X	X	X	X		X	X	
31/65.20				X			X	X		X	X	X			X	X		X	X	X
31/69.95	X	X		X			X	X				X	X	X	X	X	X	X	X	
31/71.25				X	X		X	X	X	X				X				X	X	
31/75.90	X			X		X	X	X		X	X	X		X	X	X		X	X	
59/52.00	X			X							X	X	X	X		X	X	X	X	
59/52.40	X		X	X						X	X		X			X		X	X	
59/54.20	X		X	X						X	X	X	X	X	X	X		X	X	
61/59.30	X		X	X				X		X	X	X	X		X	X	X	X	X	X
61/60.25	X	X		X		X	X	X		X	X	X	X	X	X	X	X	X	X	X
61/71.25				X			X	X	X	X	X	X		X	X		X	X		
61/115.10	X	X		X			X			X	X	X	X		X	X	X	X		X
61/117.10	X	X		X			X			X	X	X		X	X	X	X	X	X	
61/126.50	X	X		X			X				X	X	X	X	X	X		X		
61/136.15	X			X			X			X	X	X			X	X		X		
84/237.70	X	X		X			X	X		X	X	X		X	X	X				
84/246.80	X	X		X				X			X			X	X	X		X	X	

Abbreviations: Ap: apatite; Ath: anthophyllite; Bt: biotite; Chl: chlorite; Crd: cordierite; Ep: epidote; Ged: gehnite; Grt: garnet; Hbl: hornblende; Ilm: ilmenite; Mag: magnette; Ms: muscovite; PI: plagioclase; Qtz: quatz; Rt: rutile; Sil: sillimanite; St: staurolite; Sulf: sufdites; Zrn: zircon.

Gahnite, the zincian spinel, is disseminated in the alteration zones as green, euhedral to subhedral grains with sulfide (mainly sphalerite) and oxide inclusions.

MINERAL CHEMISTRY

Analytical procedures

Representative samples of the alteration zone assemblages were analysed using a fully automated Cameca-SX50 electron microprobe at the Department of Geology, University of Toronto. Accelerating voltage was 15 kV and beam current 25 to 35 nA. Microbeam size, peak and background time were adjusted for each mineral phase and retained throughout the analyses. Natural and synthetic minerals were used as standards.

Representative analyses of the minerals are given in Tables 2 to 7. For sake of clarity, only selected mineral analyses are shown in the diagrams.

AMPHIBOLES Table 2 gives representative analyses for these minerals. Three different amphiboles have been observed in the Palmeirópolis alteration zones, but only two typically coexist: anthophyllite and gedrite or hornblende and anthophyllite.

Following the nomenclature suggested by Leake (1978) the term anthophyllite is used to describe an orthoamphibole with Si in the standard formula 7.00 and gedrite for Si7.00. Figures 3 and 4 show the miscibility gap between anthophyllite and gedrite, marked by a discontinuity in the A-site occupancy, and in the Al^{IV} and Al_{tot} contents. The width of the gap is very variable and almost nul in some samples. This probably reflects the range in temperature over which these samples equilibrated. This effect can be better observed in Figure 4 that displays compositions of coexisting pairs of amphiboles on portions of the Al-Fe-Mg and Ca-Fe-Mg triangules.

A-site occupancy of cations in anthophyllite ranges from 0.00 to 0.15, and in gedrite from 0.19 to 0.31. Values of Al^{IV} range from 0,13 to 0.97 in anthophyllite and from 1.05 to 1.43 in gedrite. Al^{IV} ranges from 0.29 to 0.96 and from 0.97 to 1.22 in anthophyllite and gedrite, respectively. The effect of pargasite substitution can be observed in Figure 3A from the positive correlation between the A-site occupancy and the Al^{IV} content.

Anthophyllite is always enriched in Mg relative to coexisting gedrite (Fig. 3B). Fetotal content is similar for both amphiboles, and the Al^{IV} content is always enriched in gedrite relative to that of anthophyllite. Gedrite has a tendency to contain more Ti and Ca man coexisting anthophyllite.

Anthophyllite from one-amphibole assemblages displays high Mg/(Mg+Fe) ratios, A-site occupancy near 0.00, and $Si^{IV} \geq 7.61$ (Table 2, sample 59/52.00 is an example of one-amphibole assemblage).

Anthophyllite-hornblende pairs were observed in three of the analysed samples (Tables 1 and 2), coexisting with biotite, plagioclase and quartz, and minor gahnite, rutile and/or ilmenite. Staurolite was observed in one sample. Hornblende is the only calcic amphibole present in these rocks. It has very high Mg/(Mg+Fe) ratios and can be classified as a magnesio-hornblende following the nomenclature of Leake (1978). Anthophyllite in the hornblende-bearing assemblages has higher Mg/(Mg+Fe) ratios when compared to anthophyllite from anthophyllite-gedrite pairs, but their Ca content and A-site occupancy are similar. Figure 4 (C and D) shows the miscibility gap between hornblende and anthophyllite pairs.

Table 2 - Representative electron microprobe analyses of amphiboles.
Tabela 2 - Aná lises por microssonda eletronica representativas dos anfibó lios.

	31/69.95		59/52.0	59/52.40		59/54.20		61/60.25		61/115.10		61/126.50		84/237.70		84.246.80	
	Ath	Ged	Ath	Ath	Hbl	Ath	Hbl	Ath	Ged	Ath	Ged	Ath	Ged	Ath	Ged	Ath	Ged
wt.%																	
SiO2	48,69	45,04	54,72	55,56	48,41	53,72	46,78	52,69	47,91	53,82	46,12	50,92	48,29	49,02	47,98	54,00	46,69
TiO2	0,07	0,10	0,07	0,02	0,35	0,10	0,53	0,13	0,18	0,07	0,17	0,13	0,18	0,18	0,18	0,08	0,18
Al2O3	11,34	15,45	3,72	2,51	11,52	5,01	13,22	6,19	12,39	3,99	15,29	8,60	11,93	10,83	12,06	3,44	14,11
Cr2O3	0,01	0.00	0,02	0,02	0,04	0,06	0,01	0,02	0,07	0,01	0,00	0,02	0,01	0,23	0,03	0,01	0,12
FeO	17,83	18.23	13,38	13.50	8,43	13,12	8.08	15,82	15,68	17,64	16,93	16,12	16,16	18,48	18,57	18,49	17,17
MnO	0,28	0,32	2,00	1,95	0,89	2,44	1,04	1,56	1,65	0,73	0,74	1,28	1,33	0,48	0,49	0,71	0,75
MgO	16,77	15,25	21,58	22,08	15,65	21,00	14,59	18,73	16,80	19,29	15,33	18,14	17,04	16,25	15,91	19,51	16,10
CaO	0,43	0,45	0,53	0,50	9,81	0,63	10,48	0,53	0,66	0,35	0,50	0,54	0,62	0,61	0,57	0,41	0,54
Na2O	1,11	1,54	0,48	0,30	1,69	0,61	1,98	0,54	1,30	0,44	1,98	0,95	1,28	1,01	1,25	0,44	1,59
K2O	0,01	0,02	0,02	0,01	0,11	0,02	0,13	0,01	0,00	0,01	0,00	0,00	0,01	0,00	0,01	0,00	0,00
Total	96,54	96.39	96,51	96,45	96,91	96,72	96,83	96,20	96,64	96,35	97,08	96,70	96,85	97,10	97,04	97,09	97,26
Cations/ 24 O																	
Si	7,03	6,57	7,76	7,87	6,91	7,62	6,71	7,57	6,91	7,75	6,64	7,30	6,95	7,07	6,94	7,75	6,72
Al IV	0,97	1,43	0,24	0,13	1,09	0,38	1,29	0,43	1,09	0,25	1,36	0,70	1,05	0,93	1,06	0,25	1,28
Al VI	0,96	1,22	0,38	0,29	0,85	0,46	0,94	0,62	1,01	0,43	1,24	0,76	0,97	0,91	0,99	0,33	1,11
Ti	0,01	0,01	0,01		0,04	0,01	0,06	0,01	0,02	0,01	0,02	0,01	0,02	0,02	0,02	0,01	0,02
Cr						0,01			0,01					0,03			0,01
Mg	3,61	3,31	4,56	4,66	3,33	4,44	3,12	4,01	3,61	4,14	3,29	3,88	3,65	3,49	3,43	4,17	3,45
Fe	0,42	0,46	0,05	0,04	0,78	0,08	0,88	0,36	0,35	0,43	0,45	0,35	0,36	0,55	0,55	0,48	0,40
Fe	1,74	1,77	1,54	1,56	0,23	1,47	0,09	1,54	1,54	1,70	1,59	1,59	1,59	1,68	1,69	1,74	1,66
Mn	0,03	0,04	0,24	0,23	0,11	0,29	0,13	0,19	0,20	0,09	0,09	0,16	0,16	0,06	0,06	0,09	0,09
Ca	0,07	0,07	0,08	0,08	1,50	0,10	1,61	0,08	0,10	0,05	0,08	0,08	0,10	0,09	0,09	0,06	0,08
Na (M4)	0,16	0,12	0,13	0,08	0,16	0,14	0,17	0,15	0,16	0,12	0,24	0,18	0,16	0,17	0,16	0,11	0,16
Na (A)	0,15	0,31			0,30	0,03	0,38		0,20		0,31	0,09	0,20	0,12	0,19	0,01	0,28
K					0,02		0,02										
Mg/Mg+Fe	0,62	0,59	0,74	0,74	0,77	0,74	0,76	0,68	0,65	0,66	0,62	0,66	0,65	0,61	0,60	0,65	0,63

GARNET Representative garnet analyses are presented in Table 3. Stoichiometric calculations on the basis of 24 O give near ideal 6Si +4A1 per formula unit. Garnet composition has a strong dependency on bulk rock composition. Variations in almandine, pyrope, spessartine and grossular components, and zoning (core to rim) within a porphyroblast are considerable. In any given sample, small crystals are compositionally homogeneous and equivalent to rims of large crystals.

Garnet in parageneses that contain anthophyllite and/or gedrite and biotite has Fe-enriched rim and Mg-enriched core. A slightly Mn-enrichment in the core is also observed (Fig. 5A). Garnet in parageneses that also contain cordierite has Ca- and Mn-enriched rim, and Mg- and Fe-depleted core (Fig. 5B. Garnets in parageneses with green biotite and sillimanite are

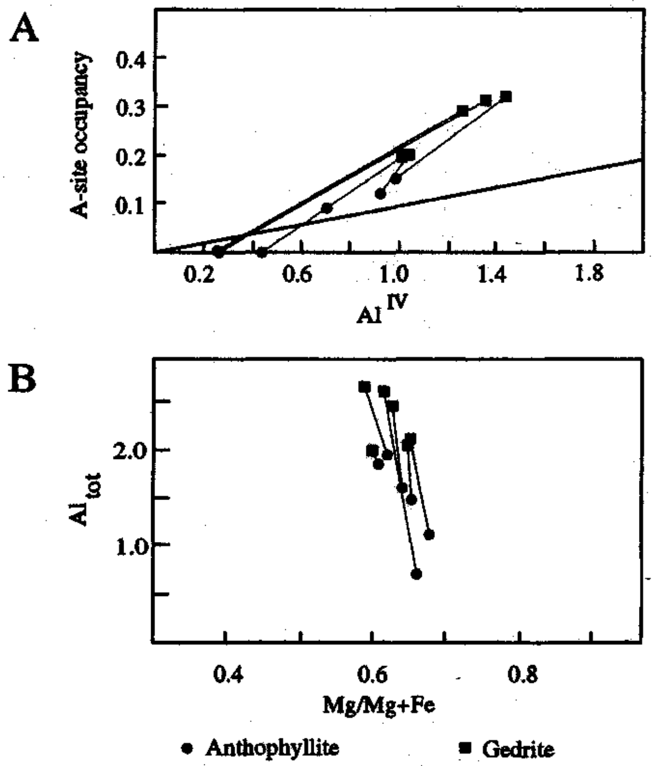

Figure 3 -A. A-site occupancy vs. Al^{IV} for anthophyllite and gedrite. B. Al_{tot} content vs. Mg/Mg+Fe ratios for anthophyllite andgedrite. Coexisting anthophyllite-gedrite pairs are shown by tie lines.

Figura 3 - A. Ocupancia do sitio A vs. Al^{IV} para antofilita e gedrita. B. Conteúdo de Al^{IV} vs. razoes Mg/Mg+Fe para antofilita e gedrita. Pares coexistentes de antofilita e gedrita estao conectados por linhas.

compositionally very homogeneous, with higher Fe and Mn and lower Mg and Ca contents compared to the other garnets (sample 31/71.25, Table 3).

BIOTITE Table 4 presents representative analyses of biotite. All specimens are Ca-poor, have relatively high Al^{VI} and Na content, 0.53 to 1.10 and 0.06 to 0.21 atoms per formula unit, respectively. Fluorine in the hydroxyl site ranges from 0.28 to 0.75 wt. % F. Biotite composition is dependent on the bulk rock composition and is best exemplified by the Mg/Mg+Fe ratios. Biotite in assemblages with hornblende has the highest Mg/Mg+Fe ratio (>0.80), the lowest ratios are found in green biotite from sillimanite and garnet assemblages. TiO_2 content is high (>0.6 wt. %) in all samples, except for the green biotite from sample 31/71.25 (Table 4) in a sillimanite-garnet assemblage which has a TiO_2 content close to 0.4 wt. %.

STAUROLITE Representative microprobe analyses of staurolite are in Table 5. The mineral typically contains more than 1.5 wt. % ZnO. Staurolite in assemblages without gahnite has the lowest ZnO content (sample 31/65.20) . Sample 31/69.95 contains the most Zn-rich staurolite of the analysed set (3.47 - 4.02 wt. % ZnO). Relicts of gahnite within staurolite are observed in this sample. Even though staurolite coexists with sphalerite, relicts of sphalerite within staurolite were not observed.

Zinc is incorporated into the staurolite structure at the expense of both Mg and Fe in approximately equal proportions. Mg/Mg+Fe ratios are similar in all staurolite crystals independent of the ZnO content (Table 5 and Fig. 6).

CORDIERtTE Mieroprobe analyses of cordierite are in Table 6. Due to the extensive pinite alteration, few crystals were analysed. Cordierite has Mg/Mg+Fe ratios around 0.80.

GAHNITE A representative set of gahnite analyses is given in Table 7 and the distribution of Zn, Fe and Mg per formula unit is in Figure 6. Zn is replaced by Mg and Fe in equal proportions in three of the samples. Higher FeO concentrations (sample 31/69.95, Table 7) are restricted to gahnite inclusions within large garnets crystals.

METAMORPHIC CONSTRAINTS Petrographic data show that metamorphic assemblages at the Palmeirópolis deposit and associated alteration zones resulted from a single metamorphic event that reached P and T conditions characteristic of the amphibolite facies. Retrograde metamorphie effects such as chloritization of biotite, garnet and other Fe-Mg phases, alteration of plagioclase and cordierite are always observed.

A large number of geothermobarometers are applied to rocks that underwent metamorphism under amphibolite facies conditions. However, such application to the alteration zones at Palmeirópolis must be done with great caution because the composition of many minerals are different from the normal range for which many of the geothemobarometers were calibrated, the high F content in biotite and the high Zn content in staurolite being good examples. The garnet-biotite thermometer is particularly affected. Many of the analysed garnets contain higher Ga and/or Mn contents than the values used in different calibrations (such as Ferry and Spear 1978), and so the garnet-biotite thermometer cannot be applied to many of these mineral pairs. This is not unique to the PALMEIRÓPOLIS deposit, the same variation has been recognized at other highly metamorphosed volcanogenic massive sulfide deposits, such as the Bleikvassli deposit, Norway (Cook 1993) and Linda deposit, Snow Lake area, Canada (Zaleski *et al.* 1991).

Five garnet-biotite pairs give temperatures in the range of 502 to 587°C at an estimated pressure of 5 kbar (estimated from associated mineral assemblages), using the calibration of Ferry and Spear (1978) with corrections by Hodges and Spear (1982). The lower temperature values are exceptionally low for rocks that contain sillimanite as the only aluminum silicate and may reflect retrograde reequilibration of these minerals. The presence of sillimanite as the only aluminosilicate polimorph phase establishes the minimum temperature of equilibrium for the Palmeirópolis alteration zones at 501°C (Holdaway 1971).

The association hornblende + orthoamphibole is dependent on the bulk-rock Ca/Na ratio. Hornblende is stable only in rocks with high Ca/Na ratios, but the stability of this association is also controlled by temperature. Based on natural assemblages, Spear (1982) suggested that at high temperature (upper garnet grade, ~550°C), the reaction garnet+ chlorite+cummingtonite = hornblende+orthoamphibole can occur, and three different assemblages are possible:

hornblende + orthoamphibole + garnet + cummingtonite
hornblende + orthoamphibole + chlorite + cummingtonite
hornblende + orthoamphibole + garnet + chlorite

The two first assemblages are not present in the Palmeirópolis alteration zones, where cummingtonite was not identified. The third assemblage, with biotite instead of chlorite, is observed. Although this reaction is not well-calibrated (Spear 1993), it places the minimum temperature conditions for the Palmeirópolis metamorphic assemblages around 550°C.

The maximum temperature at which the assemblages equilibrated at Palmeirópolis is constrainted by the coexistence of anthophyllite and gedrite. Based on observed natural

Table 3 -Representative electron microprobe analyses of garnet
Tabela 3 - Análises por microssonda eletrônica representativas das granadas.

	31/69.95		31/71.25		31/75.90		61/115.10		61/117.10		84/237.70	
	C	R*	C	R#	C	R**	C	R*	C	R##	C	R*
wt.%												
SiO_2	38,79	39,06	38,04	37,76	38,69	38,76	38,68	38,68	38,87	38,37	39,05	39,06
TiO_2	0,05	0,04	n.d.	0,01	0,01	n.d.	0,12	0,02	0,12	0,03	0,01	0,02
Al_2O_3	21,92	22,37	21,76	21,67	21,97	22,16	22,10	22,15	22,11	22,07	21,98	22,08
Cr_2O_3	n.d.	n.d.	0,01	n.d.	0,02	0,02	0,01	n.d.	0,02	0,05	0,04	0,04
FeO	31,78	29,92	33,82	33,95	27,39	28,88	26,40	26,91	27,84	30,84	28,17	28,94
MnO	0,15	0,80	2,03	1,74	4,24	2,62	4,95	4,25	4,14	3,04	2,82	2,38
MgO	6,18	8,01	3,75	3,27	5,90	6,75	6,80	6,79	6,10	5,41	6,71	6,21
CaO	2,63	1,59	2,32	2,80	3,65	2,42	2,85	3,01	3,00	2,62	2,63	3,04
Total	101,50	101,79	101,74	101,19	101,87	101,62	101,92	101,81	102,20	102,06	101,40	101,77
Cations/24 O												
Si	6,00	5,97	5,98	5,98	5,97	5,97	5,95	5,95	5,98	5,95	6,02	6,01
Al^{IV}		0,03	0,02	0,02	0,03	0,03	0,05	0,05	0,02	0,05		
Al^{VI}	4,00	4,00	4,01	4,02	3,97	4,00	3,95	3,97	3,98	3,98	3,99	4,00
Ti	0,01						0,01		0,01			
Fe	4,11	3,82	4,45	4,50	3,54	3,72	3,39	3,46	3,58	3,95	3,63	3,72
Mn	0,02	0,10	0,27	0,23	0,55	0,34	0,64	0,55	0,54	0,40	0,37	0,31
Mg	1,43	1,82	0,88	0,77	1,36	1,55	1,56	1,56	1,40	1,25	1,54	1,42
Ca	0,44	0,26	0,39	0,48	0,60	0,40	0,47	0,50	0,49	0,43	0,43	0,50
% end-members												
Almandine	68,60	63,60	74,30	75,30	58,50	61,80	55,80	57,00	59,60	65,40	60,80	62,40
Spessartine	0,30	1,70	4,50	3,80	9,10	5,80	10,60	9,10	9,00	6,60	6,20	5,20
Pyrope	23,90	30,40	14,70	12,90	22,50	25,70	25,80	25,70	23,30	20,80	25,80	23,80
Grossular	7,20	4,30	6,50	8,00	9,90	6,70	7,80	8,20	8,10	7,20	7,20	8,40

** contact withbiotite; -** contact with cordierite; # contact with sillimanite; ## contact with ortkoamphibole. Abbreviations: C, core; R: rim; n.d.: not determined.*

occurences, Spear (1980) suggested that the orthoamphibole solvus closed at approximately 600 to 625°C at ~ 5 kbar. There is a direct correlation between the temperature obtained using the biotite-garnet geothermometry and the width of the A-site occupancy miscibility gap between coexisting orthoamphiboles. The lowest temperature values from the biotite-garnet geothermometry were obtained in samples that show small miscibility gaps.

There are few constraints to allow quantitative estimate of pressure in the Palmeiropoiis alteration zones. The sphalerite geobarometer (Scott 1983) was not sucessfully applied because of paucity of sphalerite-pyrite-pyrrhotite assemblages, where pyrrhotite is typically the only iron sulfide present. Constraints on pressure conditions at Pamerópolis can be based on the rare association cordierite + staurolite. The stability field for this association is restricted to pressures below ~ 5.5 kbar (Spear 1993). The low temperature part of the sillimanite field in the P-T aluminosilicate stability diagram (Holdaway 1971) establishes the minimum pressure for the metamorphic assemblages in the alteration zones at Palmeirópolis,

Figure 7 shows a petrogenetic grid for the alteration zones at the Palmeirópolis deposit. The different metamorphic assemblages of the alteration zones were metamorphosed under amphibolite-facies conditions with temperature in the range 550 to 625°C and intermediate pressure between 2 and about 5.5 kbar.

Table 4 - Representative electron microprobe analyses ofbiotite.
Tabela 4 - Andlises por microssonda eletronica representativas de biotita.

	31/69.95		31/71.25		31.75.90		59/52.40		61/115.10		61/117.10		84/237.70		84/246.80	
	M	G	M	S	C	G	M	A	M	G	M	G	M	G	M	A
wt.%																
SiO_2	38,61	38,74	36,04	36,33	38,92	38,26	40,02	39,64	38,75	38,78	37,72	37,72	39,29	39,18	38,81	38,27
TiO_2	0,99	1,07	0,47	0,40	0,68	1,27	0,89	0,94	1,10	0,92	1,41	1,42	1,16	1,16	1,21	1,16
Al_2O_3	17,48	17,96	19,89	20,84	18,61	18,12	17,12	17,27	17,78	18,02	17,56	17,03	17,77	17,03	17,83	18,13
FeO	9,84	9,79	17,36	16,91	8,62	10,02	7,12	7,11	9,04	8,63	11,71	12,40	10,32	11,31	10,23	10,47
MnO	0,02	0,01	0,02	0,04	0,04	0,06	0,12	0,10	0,02	0,04	0,06	0,06	0,05	0,04	0,05	0,05
MgO	18,04	17,68	11,28	10,94	18,28	17,73	20,40	20,71	18,36	18,80	16,64	16,39	17,45	17,58	17,39	17,24
CaO	n.d.	n.d.	0,01	0,01	0,11	0,02	n.d.	n.d.	n.d.	0,02	n.d.	0,06	n.d.	0,03	0,83	0,05
Na_2O	0,38	0,44	0,28	0,25	0,34	0,32	0,75	0,50	0,52	0,48	0,27	0,19	0,34	0,30	0,55	0,47
K_2O	9,23	9,15	9,75	9,63	9,41	8,97	8,92	8,74	9,18	9,27	9,31	9,74	9,10	9,31	8,98	9,13
F	0,73	0,65	n.d.*	n.d.*	0,32	0,28	0,72	0,66	0,63	0,59	0,57	0,52	0,53	0,58	0,36	0,31
Cl	0,05	0,07	n.d.*	n.d.*	n.d.	0,01	n.d.	n.d.	0,01	n.d.	0,02	0,02	n.d.	0,01	n.d.	0,01
Total	95,06	95,28	95,08	95,37	95,20	94,95	95,76	95,99	95,04	95,29	95,04	95,32	95,79	96,28	95,25	95,15
Cations per 24 (O+OH+F+Cl)																
Si	5,63	5,62	5,43	5,44	5,61	5,56	5,70	5,66	5,61	5,60	5,55	5,57	5,67	5,66	5,63	5,57
Al^{IV}	2,37	2,38	2,57	2,56	2,39	2,44	2,30	2,34	2,39	2,40	2,45	2,43	2,33	2,34	2,37	2,43
Al^{VI}	0,63	0,69	0,97	1,11	0,77	0,66	0,57	0,56	0,65	0,66	0,60	0,53	0,69	0,57	0,67	0,68
Ti	0,11	0,12	0,05	0,05	0,07	0,14	0,10	0,10	0,12	0,10	0,16	0,16	0,13	0,13	0,13	0,13
Fe	1,20	1,19	2,19	2,12	1,04	1,22	0,85	0,85	1,09	1,04	1,44	1,53	1,24	1,37	1,24	1,27
Mn						0,01	0,01	0,01			0,01	0,01	0,01		0,01	0,01
Mg	3,92	3,82	2,54	2,44	3,93	3,84	4,33	4,40	3,96	4,04	3,65	3,61	3,75	3,79	3,76	3,74
Ca					0,02							0,01				0,01
Na	0,11	0,12	0,08	0,07	0,10	0,09	0,21	0,14	0,15	0,13	0,08	0,06	0,10	0,09	0,16	0,13
K	1,71	1,69	1,88	1,84	1,73	1,66	1,62	1,59	1,70	1,71	1,75	1,83	1,67	1,72	1,66	1,69
F	0,34	0,30			0,14	0,13	0,32	0,30	0,29	0,27	0,26	0,24	0,24	0,26	0,17	0,14
Cl	0,01	0,02														
Mg/Mg+Fe	0,76	0,76	0,54	0,53	0,79	0,76	0,83	0,84	0,78	0,79	0,72	0,70	0,75	0,74	0,75	0,75

Abbreviations: M: matrix; A: contact with amphibole; C: contact with cordierite; G: contact with garnet; S: contact with sillimanite; n.d.: not detected; n.d.: not determined.*

COMPARISON WITH OTHER HIGH-GRADE METAMORPHOSED ALTERATION ZONES ASSOCIATED WITH VMS DEPOSITS Metamorphic assemblages from metamorphosed volcanogenic massive sulfide (VMS) deposits similar to those present in the alteration zones of the Palmeirdpolis deposits are found worldwide, but estimates of metamorphic conditions are restricted to a few examples.

The Geco deposit, Canada, is probably one of the most intensely studied metamorphosed volcanogenic massive sulfide deposit (Friesen *et al.* 1982; Petersen and Essene 1982; Petersen and Friesen 1982; Petersen 1984; Pan and Fleet 1992, Schandl *et al* 1995). The ore bodies at Geco are associated with an extensive hydrothermal alteration zone composed of metamorphic assemblages that contain orthoamphiboles, biotite, cordierite, garnet, gahnite and staurolite. Petersen (1984)

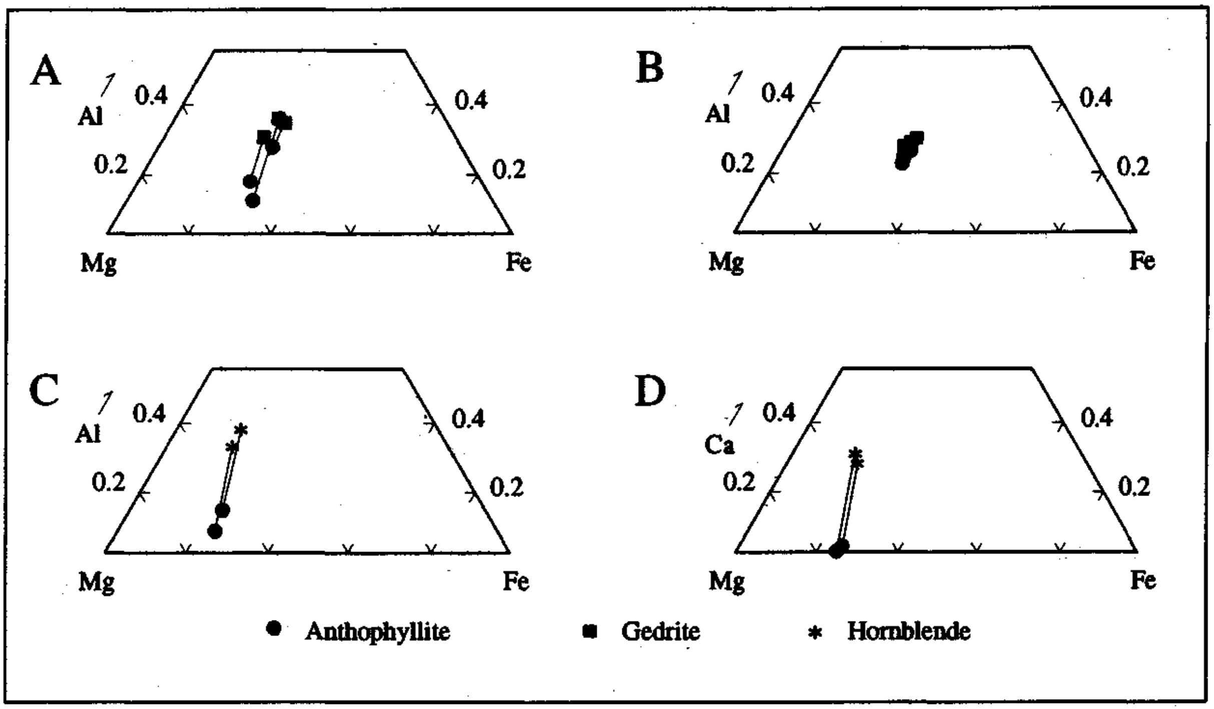

Figure 4-A and B. Portion of the compositional triangle Al-Fe-Mg showing compositions of analysed anthophyllite and gedrite. C. Portion of the compositional triangle Al-Fe-Mg showing compositions of analysed anthophyllite and hornblende. D. Portion of the compositional triangle Ca-Fe-Mg showing compositions of analysed anthophyllite and hornblende. Tie lines connect coexisting phases.

Figura 4 - A e B. Porção do triângulo composicional al-Fe-Mg mostrando composições de antofilita e gedrita analisadas. C. Porção do triângulo composicional Al-Fe-Mg mostrando composições de antofilita e hornblenda analisadas. D. Porção do triângulo composicional Ca-Fe-Mg mostrando composições de antofilita e hornblenda analisadas. Linhas conectam fases coexistences.

Table 5 - Representative electron microprobe analyses of staurolite.

Tabela 5 - Análises por microssonda eletrônica representativas de estaurolita.

	31/65.20		31/69.95		31.75.90		84/237.70		84/246.80	
wt.%										
SiO_2	27,63	27,67	27,67	27,41	27,88	27,80	27,95	28,01	27,95	28,06
TiO_2	0,75	0,59	0,58	0,52	0,60	0,44	0,67	0,63	0,54	0,67
Al_2O_3	53,68	54,73	54,02	54,25	54,80	54,76	53,50	53,08	53,47	54,15
Cr_2O_3	0,05	0,09	0,06	0,17	0,04	0,03	0,27	0,27	0,14	0,17
FeO	12,00	11,12	9,94	10,30	10,36	10,49	10,93	11,78	11,01	10,95
MnO	0,03	0,03	0,07	0,07	0,15	0,13	0,13	0,11	0,21	0,23
MgO	2,77	2,91	2,64	2,64	2,56	2,80	2,78	2,71	2,79	2,79
CaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0,01	n.d.	0,01
ZnO	1,59	1,67	3,84	3,47	1,98	1,93	2,55	2,33	2,62	2,58
Total	98,50	98,80	98,82	98,82	98,36	98,39	98,77	98,94	98,73	99,61
Cations per 48 O										
Si	7,95	7,91	7,96	7,88	7,98	7,96	8,03	8,06	8,04	7,99
Al^{IV}	0,05	0,09	0,04	0,12	0,02	0,04				0,01
Al^{VI}	18,17	18,34	18,27	18,27	18,47	18,44	18,11	18,00	18,12	18,17
Ti	0,16	0,13	0,13	0,11	0,13	0,09	0,14	0,14	0,12	0,14
Cr	0,01	0,02	0,01	0,04	0,01	0,01	0,06	0,06	0,03	0,04
Fe	2,89	2,66	2,39	2,48	2,48	2,51	2,63	2,84	2,65	2,61
Mn	0,01	0,01	0,02	0,02	0,04	0,03	0,03	0,03	0,05	0,06
Mg	1,19	1,24	1,13	1,13	1,09	1,20	1,19	1,16	1,20	1,19
Zn	0,34	0,35	0,81	0,74	0,42	0,41	0,54	0,50	0,56	0,54
Mg/Mg+Fe	0,29	0,32	0,32	0,31	0,30	0,32	0,31	0,29	0,31	0,31

Abreviation: n.d. = not detected

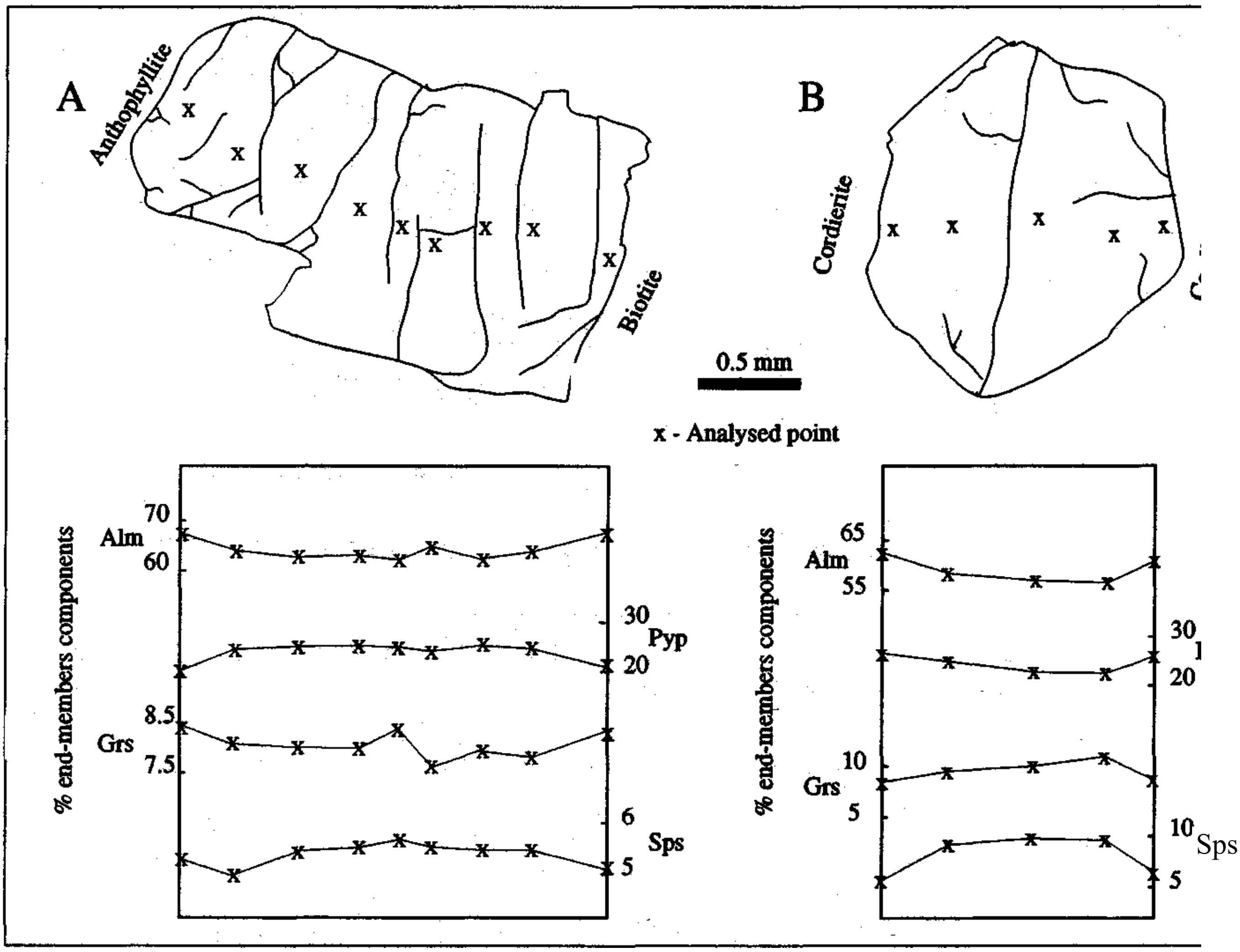

Figure 5 – A. Tuning profile for garnet end-members from a single garnet crystal in an anthophyllite/gedrite-biotite assemblage (sample 84/237.70). B. Zoning profile for garnet end-members from a single garnet crystal in an anthophyllite/gedrite-biotite-cordierite assemblage (sample 31/75.90), Abbreviations: Aim: almandine, Grs: grossular, Pyp: pyrope, Sps: sperssatine.
Figura 5 - A. Distribuicao dos termos finais da granada em um finico cristal de granada numa assembléia a antofilita/gedrita-biotita (amostra 84/237.70). B. Distribuifao dos termos ftnais da granada em um toico cristal numa assemble'ia antofilita/gedrita-biotha-cordierita (amostra 31/75.90). Abreviafdes: Aim: almandina, Grs: grossularita, Pyp: piropo, Sps: espersatita.

estimated the peak metamorphic P-T at 6±1 kbar 650±30°C based on well-calibrated metamorphic reactions and a few geothermobarometers. Pan and Fleet (1992) obtained similar temperature (600 to 650°G) and lower pressure (3 to 6 kbar) conditions for rocks from the alteration zone of the Geco deposit.

Several volcanogenic massive sulfide deposits (Anderson Lake, Stall Lake, Rod, Osborne Lake, Linda) are known in the Snow Lake region of the Flin Flon - Snow Lake volcanic belt, Manitoba, Canada. These deposits are associated with extensive zones of synvolcanic hydrothermal alteration that are characterized by mineral assemblages of the amphibolite fades (cordierite, gedrite, staurolite, garnet, biotite, gahnite). The metamorphic conditions at the Linda deposit were evaluated by Zaleski *et al.* (1991), who suggested metamorphic temperature and pressure of about 550°C and 5 kbar,-respectively.

Cordierite-anthophyllite rocks from the alteration zones of the Falun deposit, Sweden, are characterized by assemblages with cordierite, anthophyllite, garnet, gahnite, quartz, and andalusite. Wolter and Seifert (1984) estimated metamorphic conditions to be 550 ± 50°C and 2.5 ± 1 kbar.

Higher peak pressure (7.5 to 8.5 kbar) and similar temperature (540 to 570°C) were estimated for the alteration lithologies at the Bleikvassli deposit, Norway (Cook, 1993).

Except for Geco, the temperature of metamorphism of the above examples compares well with those at the Palmeir6polis alteration zones but pressure conditions are different (Fig. 7). The stabilities of these nietamorphic assemblages seem to be mainly temperature sensitive, but they are stable over a wide range of pressure. Variations in pressure experienced by metamorphic mineral assemblages are monitored by the presence of different Al_2SiO_5 phase crystallized. Deposits metamorphosed at low pressure are characterized by andalusite (Falun), at intermediate pressure by sillimanite (Palmeirdpolis and Geco) and at high pressure by kyanite (Bleikvassli).

CONCLUSIONS On the basis of mineral chemistry and mineral assemblages in the alteration zones of the Palmeirópolis volcanogenic massive sulfide deposit,

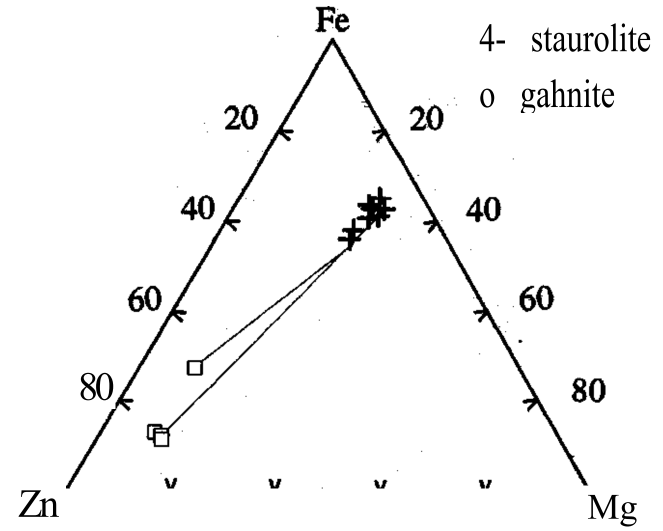

Figure 6 - Distribution of Fe-Mg-Zn per formula unit in analysed staurolite and gahnite. Tie lines connect coexisting phases.
Figura 6 - Distribuição de Fe-Mg-Zn por unidade de fórmula em estaurolita e gahnita analisadas. Linhas conectam fases coexistentes.

Table 6 - Electron microprobe analyses of cordierite.
Tabela 6 - Analises por microssonda eletrônica de cordierita.

	31/75.90		
wt.%			
SiO_2	49,52	49,31	49,28
TiO_2	n.d.	0,01	0,01
Al_2O_3	32,99	32,93	32,76
Cr_2O_3	0,01	n.d.	0,00
FeO	4,26	4,41	4,28
MnO	0,09	0,07	0,05
MgO	10,40	10,27	10,29
CaO	0,01	n.d.	0,02
Total	97,27	96,98	96,70
Cations per 18 O			
Si	5,05	5,05	5,05
Al^{IV}	0,95	0,95	0,95
Al^{VI}	3,01	3,02	3,01
Fe	0,36	0,38	0,37
Mn	0,01	0,01	
Mg	1,58	1,57	1,57
Mg/Mg+Fe	0,81	0,80	0,80

Abreviation: n.d. - not detected

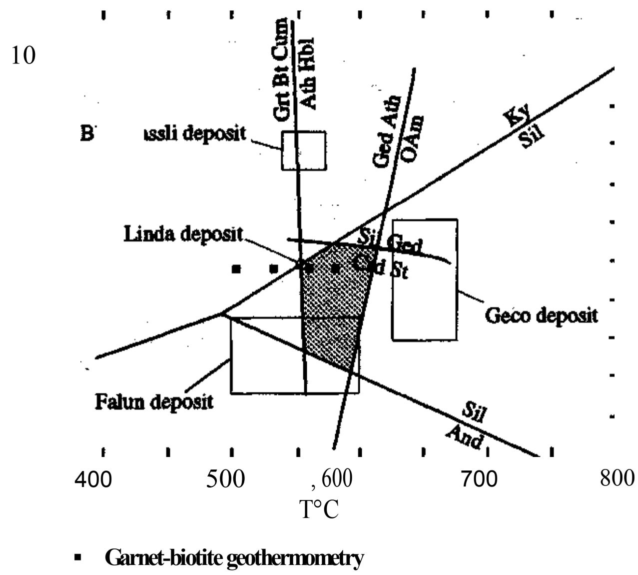

Figure 7 - P-Tpetrogenetic grid (modified from Spear 1993) showing the stability field of mineral parageneses (gray area) and results of garnet-biotite geothermometry fo the Palmeiró polls alteration zones. Aluminosilicate triple point after Holdaway (1971). Pressure and temperature estimates for metamorphic conditions at Bleikvassli (Cook 1993), Falun (Wolter & Seifert 1984), Geco (Pan & Fleet 1992; Petersen 1984) and Linda(Zaleskietal. 1991) deposits are also shown. Formineral abbreviations see Table 1, plus And: andalusite; Cum: cummingtonite; Ky: kyanite; OAm: orthoamphibole.
Figura 7 - Diagrama P-T (modificado de Spear 1993) mostrando o campo de estabilidade de parageneses minerals (area cinza) e resultados do geotermômetro granada-biotita para a zonas de alteração de Palmeirópolis. Ponto tríplice dos alumosilicatos a partir de Holdaway (1971). Condições de pressão e temperatura estimadas nos depósitos de Bleikvassli (Cook 1993), Falun (Wolter & Seifert 1984), Geco (Pan & Fleet 1992; Petersen 1984) and Linda (Zaleski et al. 1991) são também mostradas. Abreviações minerals ver Tabela 1, mais And: andalusita; Cum: cummingtonita; Ky: cianita; OAm: ortoanfibó lio.

Table 7 - Electron microprobe analyses of gahnite.
Tabela 7 - Análises por microssonda eletrônica de gahnita.

	31/69.95	31/75.90	59/52.40	59/61.30
wt.%				
SiO_2	0,01	0,02	0,01	0,04
TiO_2	n.d.	0,01	0,02	0,01
Al_2O_3	57,41	51,90	51,97	51,95
Cr_2O_3	0,05	0,46	0,56	0,14
FeO	11,88	5,56	5,70	6,05
MnO	0,01	0,19	0,09	0,16
MgO	2,20	2,76	2,77	2,43
CaO	n.d.	0,01	0,02	n.d.
ZnO	29,06	38,03	38,04	38,37
Total	100,62	98,95	99,18	99,14
Cations per 4 O				
Al^{IV}	1,99	1,89	1,89	1,90
Cr		0,01	0,01	
Fe	0,29	0,14	0,15	0,16
Mn		0,01		
Mg	0,10	0,13	0,13	0,11
Zn	0,63	0,87	0,87	0,88

Abreviation: n.d. = not detected

metamorphic temperatures and pressures are estimated to have been 550 to 625°C and 2 to 5.5 kbar. Biotite-garnet geothermometry applied to five mineral pairs yields temperatures between 502 and 587°C at an estimated pressure of 5 kbar. The lowest values may reflect retrograde reequilibration of these minerals. Use of other mineralogical geothermobarometers was not possible due to the unusual composition of the minerals in the Palmeirópolis alteration zones, that are different from the normal range for which most geothermobarometers were calibrated. P-T conditions were however reasonably constrained by various mineral assemblages.

Comparison between the Palmeirópolis mineral assemblages, their metamorphic conditions and other amphibolite facies volcanogenic massive sulfide deposits, recrystalized under a large pressure range, shows mat the only major difference in the mineral assemblage is the aluminosilicate polimorph phase present. Deposits metamorphosed at lower pressure conditions are characterized by andalusite, intermediate pressure by sillimanite and higher pressure by kyanite.

Acknowledgments This paper is a part of the senior author's Ph. D. Thesis at the Department of Geology, University of Toronto. We thank Companhia de Pesquisa e Recursos Minerals (CPRM) in Brazil for the facilities which enabled SMA to carry out the field work. We are grateful to Dr. Claudio Cermignani for his assistance with the microprobe operation. The study was supported by Natural Sciences and Engineering Research Council of Canada grants to S. D. Scott, and a CAPES-PADCT (Brazil) scholarship to S. M. Araujo.

REFERENCES

ARAUJO, S.M. 1986. *Petrologia e mineralizacoes sulfetadas da seqiiencia vulcano-sedimentar de PALMEIRÓPOLIS - Golds.* Brasilia. 196 p.(M.Sc. thesis, Universidade de Brasilia).

ARAUJO, S.M. & NILSON, A.A. 1988. Deposito de zinco, cobre e chumbo de PALMEIRÓPOLIS, Goias. In: SCHOBBENHAUSS, C.and COELHO, C.E.S. coords. *Principals Depositos Minerals do Brazil.* Ministeno das Minas e Energia - Departamento Nacional da Produção Mineral -Companhia Vale do Rio Doce. Brasflia. v. 3, p. 171-180.

ARAUJO, S.M. & SCOTT, S.D. 1991. The Palmeirópolis massive sulfide deposit, Brazil. In: GEOL. ASSOC. CANADA-MINERAL. ASSOC. CAN., ANNUAL MEETING, 16. Toronto. 1991, *Program With Abstracts.* Toronto, p. A4.

BRITO NEVES, B.B. & CORDANI, U.G. 1991. Tectonic evolution of South America during the Late Proterozoic. *Precambrlan Res.,* **53**: 23-40.

COOK, N.J. 1993. Conditions of metamorphism estimated from alteration lithologies and ore at the Bleikvassli Zn-Pb-(Cu) deposit, Nordland, Norway. *Norsk Geologisk Tidsskrift,* **73**: 226-233.

DANNI, J.C.M.; FUCK, R.A.; LEONARDOS JR., O.H. 1982. Archean and Lower Proterozoic units in central Brazil. *Geol. Rundschau,* **71**: 291-317.

DRAGO, V.A.; PINTO, A. do C; MONTALV_OS R.M.G. de; SANTOS, R.O.B. dos; SIM_ES, M.A.; OLIVEIRA, F.C; BEZERRA, P.E.L.; PRADO, P.; FERNANDES, C.A.C.; TASSINARI, C.C.G.. 1981. Geologia. In: *Projeto RADAMBRASIL.* Folha SD.22 Goias. Rio de Janeiro, p. 27-300.

FERRY, J.M. & SPEAR, F.S. 1978. Experimental calibration of the partition of Fe and Mg between biotite and garnet. *Contrib. Mineral. Petrol.,* **66**:113-117.

FIGUEIREDO, J.A.; LEAO NETO, R.; VALENTE, C.R. 1981. Depositos de sulfetos macros de Zn, Cu e Pb da região de Palmeirópolis, GO. In: SIMP. GEOL. CENTRO-OESTE, 1. Goiania, 1981. Ata, Goiania, SBG - Nucleos Centro-Oeste and Brasflia. p. 422-441.

FRffiSEN, R. G., PIERCE, G. A.; WEEKS, R. M. 1982. Geology of the Geco base metal deposit: *Geological Association of Canada Special Paper,* **25**: 343-363.

FUCK, R.A.; PIMENTEL, M.M.; BOTELHO, N.F. 1987. Granitoid rocks in west-central Brazil: a review. In: INT. SYMP. GRANITES AND ASSOCIATED MINERALIZATIONS, SGRM - SBG, p. 53-59.

GIRARDI, V.A.V.; KAWASHITA, K.; BASEI, M.A.S.; CORDANI, U.G. 1978. Algumas considerações sobre a evolução geologica da regiao de Cana Brava, a partir de dados geocronológicos. In: CONOR. BRAS. GEOL., 30. Recife, 1978. *Anais...Recife,* SBG. v. 1, p. 337-348.

HODGES, K.V. & SPEAR, F.S. 1982. Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. *Am. Mineral.:* **67**: 1118-1134.

HOLD AW AY, M.J. 1971.Stability of andalusite and the aluminun silicate phase diagram. *Am. J. Sci.:* **271**: 97-131.

LEAKE, B. E.1978. Nomenclature of amphiboles. *Canadian Mineralogist,* **16**: 501 -520.

LEAO NETO, R. & OLIVATTI, O. 1983. *Projeto Palmeirópolis -Etapa Prellmlnar.* Convenio Departamento Nacional da Producao Mineral - Companhia de Pesquisa e Recursos Minerals. Goiania. 29 p. (unpublished report).

MARINI, O.J.; FUCK, R.A.; DARDENNE, M.A.; DANNI, J.C.M. 1984a. Provmcia Tocantins: setores central e sudeste. In: ALMEIDA, F.F.M. DE & HASUI, Y., coords. *O Pre-cambriano do Brasil.* São Paulo, Edgard Blutcher Ltda. p. 205-264.

MARINI, O.J.; FUCK, R.A.; DANNI, J.C.M.; DARDENNE, M.A.; LOGUERCIO, S.O.C.; RAMALHO, R. 1984b. As faixas de dobramentos Brasflia, Uruaçu e Paraguai-Araguaia e o Macifo Mediano de Goias. In: SCHOBBENHAUSS, C., *cootd.Geologia do Brasil.* Ministério das Minas e Energia - Departamento Nacional da Produção Mineral, p. 251-303.

PAN, Y. & FLEET, M.E. 1992. Mineralogy and genesis of the calc-silicates associated with Archean volcanogenic massive sulphide deposits at the Manitouwadge mining camp, Ontario. *Can. J. Earth Sci,* **29**: 1375-1388.

PETERSEN, E.U. & ESSENE, E.J. 1982. Metamorphic zonation of the Geco massive sulfide deposit, Manitouwadge, Ontario, Canada. In: GEOL. SOC. AMERICA, 1982. *Abstracts with Programs,* v. 7, p 586.

PETERSEN, E.U. & FRIESEN, R.G. 1982. Metamorphism of the Geco massive sulfide deposit, Manitouwadge, Ontario. In: GEOL. ASSOC. CANADA-MINERAL. ASSOC. CAN., 1982. *Program with Abstracts,* p. 73.

PETERSEN, E.U. 1984. *Metamorphism and geochemistry of the Geco massive sulfide deposit and its enclosing wall-rocks.* Ann Arbor. 195 p. (Ph. D. thesis, University of Michigan).

PIMENTEL, M.M.; HEAMAN, L.; FUCK, R.A.; MARINI, O.J. 1991. U-Pb geochronology of the Precambrian tin-bearing continental-type acid magmatism in central Brazil. *Precambrian Res.,* 52: 321-335.

PIMENTEL, M.M.; HEAMAN, L.; FUCK, R.A. 1992. Idade do meta-riolito da Seqiiencia Marata, Grupo Araxa\ Goids: estudo geocronoldgico pelos metodos U-Pb em zircao, Rb-Sr e Sm-Nd. *Anais da Academia Brasileira de Ciencias,* **64**: 19-28.

SCHANDL, E.S.; GORTON, M.P.; WASTENEYS, H.A. 1995. Rare earth element geochemistry of the metamorphosed volcanogenic massive sulfide deposits of the Manitouwadge Mining Camp, Superior Province, Canada: a potential exploration tool? *Econ. Geol,* **90**:1217-1236.

SCOTT, S.D. 1973. Experimental calibration of the sphalerite geobarometer. *Econ. Geol.,* **68**: 466-474.

SPEAR, F.S. 1980. The gedrite-anthophyllite solvus and the composition limits of orthoamphibole from Post Pond Volcanics, Vermont. *Am. Mineral.* ,**65**: 1103-1118.

SPEAR, F.S. 1982. Phase equilibria of amphibolites from the Post Pond volcanics, Mt. Cube Quadrangle, Vermont. *J. Petrol,* **23**: 383-426.

SPEAR, F.S. 1993. Metamorphic phase equilibria and pressure-temperature-time paths. *Mineralogical Society of America Monograph Series,* 799 p.

WOLTER, H.U. & SEIFERT, F. 1984. Mineralogy and genesis of cordierite-anthophyllite rocks from the sulfide deposit of Falun, Sweden. *Lithos,* **17**: 147-152.

ZALESKI, E.; FROESE, E.; GORDON, T.M. 1991. Metamorphic petrology of Fe-Zn-Mg-Al alteration at the Linda volcanogenic massive sulfide deposit, Snow Lake, Manitoba. *Can. Mineral.,* **29**: 995-1017

MANUSCRITOA853
Recebido em 23 de setembro de 1996
ReviSão dos Autores em 20 de novembro 1996
ReviSão aceita em 25 de novembro de 1996