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Structural and Compositional Evolution of Cr-Spinels and Hornblendes, Palma Group, Rio Grande do Sul, Brazil

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Abstract - One amphibolite facies metamorphic event is registered in chromites and hornblendes from the Palma Group serpentinites and meta-andesites, Brazil's southernmost Rio Grande do Sul State. Metamorphism was apparently caused by syntectonic injection of voluminous Cambaí Group meta-granitoids and not by post-tectonic Jaguari Granite intrusion. Regional metamorphic hornblendes are in direct contact with magmatic pargasites, which indicates that it was the first metamorphic event in the area. Both hornblendes in Campestre Formation and Cr-spinels in Cerro da Cruz Formation are little zoned, an indication that only one metamorphic event was of regional extent. Recrystallization to chlorite + epidote greenschist facies parageneses is restricted to shear zones and volumetrically small.

Keywords - Cr-spinel, hornblende, electron microprobe, backscattered electrons

INTRODUCTION

The internal structure and chemical composition of minerals establish fundamental constraints on the origin and evolution of the rock associations in which they occur. Minerals which present extensive solid solutions are even more useful as indicators of geological processes. The zoning of chromian spinels and hornblendes is a key to the correct unravelling of complex geological histories. We made use of these characteristics in Cr-spinel and hornblende to unravel the metamorphic evolution of the Palma Group serpentinites and andesites in the Palma region south of São Gabriel, State of Rio Grande do Sul, Brazil.

Chromian spinel texture and composition are good indicators of the tectonic environment of formation of the spinels (Irvine, 1965, 1967; Dick & Bullen, 1984; Sack & Giorso, 1991). Mantellic chromites in ophiolites display ductile deformation, whereas crustal crystals respond mostly in a brittle manner to deformation (Strieder & Nilson, 1992). The spinel solid-solution series has been much studied, due to its tectonic, petrologic, and economic importance. The chemistry of Cr-spinels is constrained by many factors, including the magmatic or metamorphic (either mantellic or crustal) setting of formation; the chemistry can be usually disciminated among magmatic, metamorphic and mantellic compositions (see Suita & Strieder, 1996, for a review).

The spinel group of minerals, including chromite, is highly reactive in the presence of metamorphic fluids and tends to re-equilibrate or newly-crystallize as P, T, X conditions change. This has been widely applied to unravelling how the rocks are affected by progressive regional or contact metamorphism (Matthes, 1971; Oliver *et al.*, 1972; Trommsdorf & Evans, 1972; Springer, 1974; Evans & Trommsdorf, 1974; Evans & Frost, 1975; Arai, 1975; Irving & Ashley, 1976; Evans, 1977; Hietanen, 1977; Turner, 1981; Naumann & Hartmann, 1984; Suita, 1996; Suita & Hartmann, 1997). Internal parts of crystals may be armoured by newly-deposited or recrystallized rims, and thus preserve the chemical record of older events. The central parts of thick (>10 m) massive chromitites tend to preserve older compositions better than thin chromitites, whereas disseminated grains in a silicate matrix are usually re-equilibrated by superimposed younger events. Heat and fluids from intrusive granites may cause recrystallization of spinels, making this mineral group significant for the study of contact aureoles.

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Calcic amphiboles are common indicators of metamorphic conditions in deformed segments of the crust. Their chemistry is sensitive to varying P, T, X conditions, e. g. actinolite indicates greenschist facies and hornblende amphibolite facies (Bucher & Fry, 1994). Calcic amphiboles in low-pressure metamorphic belts have overall lower contents of Ti and Na when compared with medium-pressure belts (Laird & Albee, 1981; Hartmann *et al.*, 1990). When subjected to stress during crystallization, the prisms are aligned along the foliation and may generate a lineation. In low-stress or contact metamorphism, the crystals tend to become poiquiloblastic without preferential alignment. Polimetamorphism may cause diffusional zoning in amphiboles. These characteristics were used for unravelling the metamorphic evolution of volcanoclastic rocks and integrated with the Cr-spinel studies from associated serpentinites.

Disseminated Cr-spinels are common in serpentinites and olivine+talc meta-serpentinites in southern Brazil and thus are useful for the identification of tectonic and petrologic environment of formation (Hartmann & Remus, 1999). They are common in the Vila Nova Terrane of Western Rio Grande do Sul State in southern Brazil, identified by Babinski *et al.* (1996), Leite (1997) and Leite *et al.* (1998) as juvenile accretion in the Neoproterozoic. The Cerro Mantiqueiras Ophiolite has been characterized by Leite (1997) and occurs only 30 km to the SE of the study area. The NS-trending, western border of the Dom Feliciano Belt of crustal reworking (Babinski *et al.*, 1997; Silva *et al.*, 1999) is positioned only 55 Km to the east. On the other hand, Remus *et al.* (1993) identified komatiitic chemistry in the ultramafic schists located 35 Km to the north. These three contrasting neighbours may indicate that the VNT contains septa of older basement in the juvenile terrane. Therefore, the crust in the Palma region could be very complex. Hence studies of chromian spinels were carried out in association with the andesitic hornblendes to determine the origin and evolution of the Palma Group.

The Palma region has been the focus of geological interest for decades (Jost, 1966; Villwock & Jost, 1966). Its evolution is related to the complex geology of southern Brazil. Current models call either for a Neoproterozoic ophiolitic crust or an Archean greenstone belt, or else a tectonic mixture of the two rock associations, invaded by voluminous syn- to post-tectonic granites. Questions that require answer are the regional or contact metamorphic nature of the serpentinites and schists and the number of geological events registered in the minerals.

Additionally, the Cr-spinels could contain structural and chemical information regarding a mantellic or crustal origin, including the possible wide aureoles of crustal contact metamorphism. How can these Cr-spinels in the serpentinites and the hornblendes in the meta-andesites be used to constrain these questions?

GEOLOGY AND SAMPLES

The Palma region (~30 × 30 km) is situated in the riverhead of the Rio Vacacaí, south of the town of São Gabriel in Brazil's southernmost State of Rio Grande do Sul (Fig. 1). Geological mapping was undertaken by many authors for two decades (Szubert *et al.*, 1977; Kirchner & Grazia, 1978; Szubert, 1978; Garcia & Hartmann, 1981; Kirchner & Andriotti, 1981; Chemale, 1982; Naumann *et al.*, 1984; Santos *et al.*, 1990), with reviews by Hartmann & Nardi (1983), Jost & Hartmann (1984) and Chemale *et al.* (1995). First geological studies in

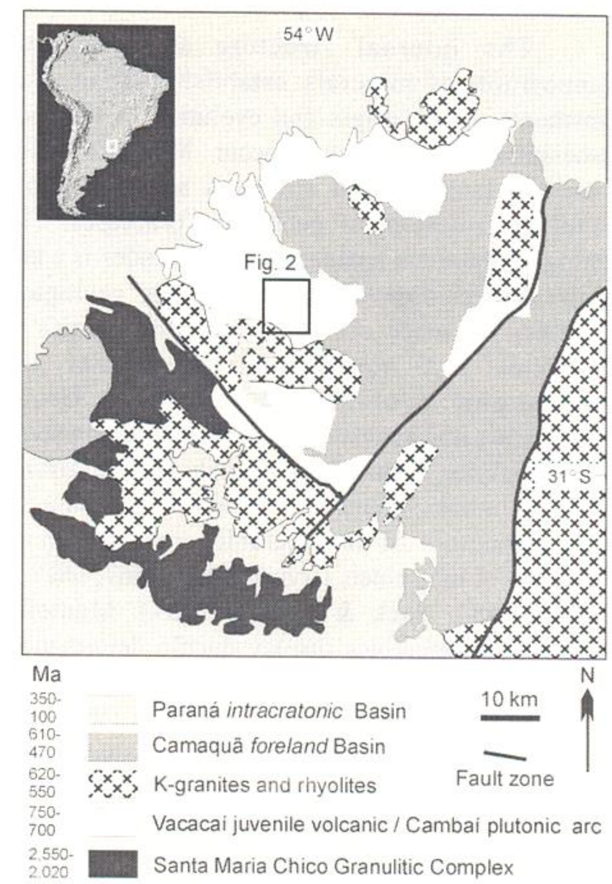

Figure 1 - Geological map of São Gabriel Block (Hartmann *et al.*, 1999) in Rio Grande do Sul shield.

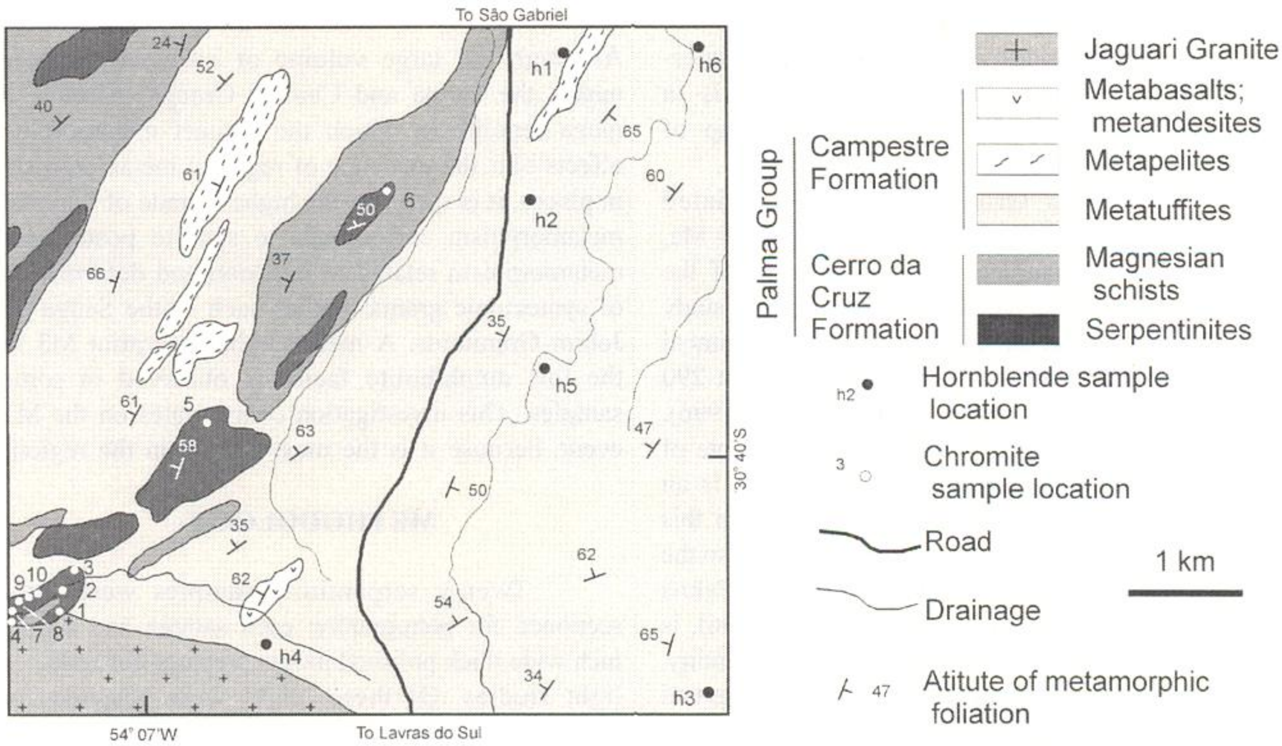

Figure 2 - Geological map of the investigated portion of the Palma Group and intrusive Jaguari Granite. Studied samples indicated by circles (white = serpentinites; black = andesites).

the area were done by Leinz (1943), Goñi *et al.* (1962) and Jost (1966). Senior undergraduates of UFRGS (1966, 1967, 1985) and UNISINOS (1981) mapped the region at the 1:50,000 scale. More recently, UFRGS (1996) senior undergraduates mapped the area during 30 days and sampled and thin sectioned 300 ultramafic, mafic and intermediate metamorphic rocks.

The ultramafic and andesitic rocks collected for this study are located close to coordinates 30°40'S, 54°07'W (Fig. 2). The ultramafics are strongly magnesian and most have a jackstraw texture (Snoke & Calk, 1978; Nesbitt & Hartmann, 1986) of interlocking one mm-long prisms of olivine and one mm-wide triangular portions of fine-grained interlocking blades of talc (Fig. 3). The arrangement of these crystals is approximately random, as observed on different scales, including hand samples sawed in three perpendicular directions. The olivine blades are almost entirely serpentinized, but they survive in few small patches, where the elongation sign is negative, a property of metamorphic olivines (Trommsdorf & Evans, 1972; Hartmann, 1982; Hartmann *et al.*, 1987). All samples closer than 600 m from the granite have a jackstraw-texture whereas those farther away do not. Samples between 1,500 and 5,000 m from the granite have an interlocking arrangement of fine-grained serpentine and talc (or magnesite). Radiating bundles of tremolite (identified with the optical microscope and by EDS on the electron probe) are present in the matrix of the jackstraw-textured meta-serpentinites to a distance of 600 m from the contact, but are not seen farther away.

These rocks were collected from the Cerro da Cruz Formation serpentinites of the Palma Group, which also contains metabasalts, metandesites, metapelites, metatuffites and magnesian schists (Fig. 2). The ultramafic rocks of the Palma Group are varied in composition, containing serpentinites,

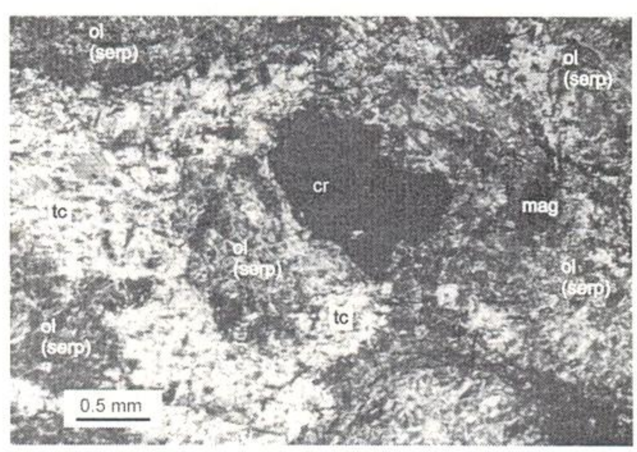

Figure 3 - Photomicrography of Cr-spinel crystal (black) in jackstraw-textured serpentinite; ol = olivine (now serpentine); tc = talc; mag = magnetite.

ultramafic schists rich in talc, chlorite and tremolite. The studied meta-andesites are part of the Campestre Formation of this Palma Group which is in concordant contact with the Cambaí Group of gneissic diorites, tonalites, and granodiorites.

The Palma Group has not been dated radiometrically, but its minimum age is 700-750 Ma, which is the conventional U-Pb zircon age of the Campestre Formation dated to the north of the study area by Machado *et al.* (1990) and of the Cambaí Group gneisses dated in an outcrop along Br-290 about 50 km to the north by Babinski *et al.* (1996). The Palma Group may contain unidentified septa of older paleoproterozoic sequences. Hence here is an intriguing problem that remains to be solved in this area, and is more important due to the proximity to the westernmost border of Gondwanaland. The Palma Shear Zone (PSZ), as defined by UFRGS (1996), is a major Neoproterozoic crustal-scale discontinuity, along which a clockwise movement is imprinted on all the lithological units, under transitional upper greenschist/amphibolite facies conditions.

Intrusive granites are volumetrically abundant in the region, including the Santa Rita Monzogranite, the São Manoel Granite, and the Jaguari Granite.These granites were intruded in the Palma and Cambai Groups at ca. 590-550 Ma (Gastal *et al.*, 1992). They cause significant contact aureoles on the older sequences, such as in the southern part of the Santa Rita Monzogranite (Naumann & Hartmann, 1984). The aureole on the Palma Group in general, and in the northern part of the Jaguari Granite in particular, is investigated in this work for the first time.

The Jaguari Granite is rounded in shape and has 20 km in diameter (Gastal *et al.*, 1992). A large contact aureole is to be expected, for Turner (1981) illustrates that the thermal effect of the igneous body tends to extend to a distance comparable to the diameter of the intrusion. The intensity of recrystallization of the Palma Group is expected to be attenuated by the low amphibolite facies parageneses already present before the intrusion of the granite.

Regional metamorphism was superposed in the Palma Group by the intense contact metamorphism of the postectonic granites; this makes very difficult the discrimination of the two metamorphic events, regional and contact. The regional metamorphsim occurred in the greenschist to amphibolite facies transition, and is characterized in this investigation as M1. Greenschist facies M2 metamorphism is observed along shear zones. Although the large volume of intrusive granites makes the Palma and Cambai Groups resemble a mega-xenolith in which the contact metamorphic effects blur the evidence of regional metamorphism in places, it is seen that the highest grade of regional metamorphism corresponds to syn- to postectonic metamorphism related to intrusion and deformation of syntectonic granite bodies such as the Sanga do Jobim Granitoids. A metamorphic overprint M3 in the low amphibolite facies is observed in some samples. This investigation concentrates on the M1 event, because it is the most intense in the region.

METHODOLOGY

Twenty serpentinite samples were thin-sectioned for petrography; each sample had a one-inch wide thick polished mount prepared for reflected light studies. Of these, eight were selected for electron microprobe analyses and imaging because they cover a fairly large distance away from the granite contact and have well developped Cr-spinel grains. Samples extend from 100 m near the contact of the Jaguari Granite to 5,000 m north of it. Six samples of meta-andesites from the Campestre Formation were selected for further studies out of 100 thin-sectioned, because they are located at increasing distances from the Jaguary Granite contact. This was done in order to test the hypothesis of contact metamorphism caused by intrusion of the Jaguary Granite into the Campestre Formation.

The Cr-spinels and hornblendes were investigated in the CAMECA SX-50 electron microprobe laboratory of Centro de Estudos em Petrologia e Geoquímica, Instituto de Geociências, Universidade Federal do Rio Grande do Sul. Ten Cr-spinel images were made in the backscattered electron (BSE) mode using Polaroid 55 film. In sequence, twelve WDS quantitative scans were performed on the Cr-spinel crystals with the electron microprobe (EPMA). Backscattered electron (BSE) images were made with the electron microprobe on Polaroid 55 film and scanned. Oxides of the following elements were analysed with 10% accuracy and precision: Mg, Al, Cr, Mn, Ti, Fe, Si; ferrous and ferric iron were calculated by charge balance.

Several spots were analysed on each studied hornblende crystal in the six samples; accuracy and precision are within 10%. Analytical data were retrieved in an electronic file and treated with

Microcal Origin 4.0 and CorelDraw 8. The analytical data were calculated and plotted with MinPet 2.0.

EVOLUTION OF Cr-SPINELS

The Cr-spinel crystals (Fig. 3) are euhedral to subhedral, 1-2 mm large and equant, and some are bordered by small grains of chromian magnetite, which are also abundant in seams in the crystal or dispersed in its matrix. Mg-chlorite occurs as rare 0.5 mm-large crystals in a few of the samples.

The BSE images (Figs. 4 and 5) reveal rather homogeneous crystals, without significant variations in average atomic numbers in the same grain. Nevertheless, some variation is present in Figs. 4a, 4e, 5c, 5d and 5e as darker and brighter areas. Brighter bands cut across the grains along fractures (e.g. Figs. 4a, 4e, 5d and 5e) and rims, and bright small grains are also present in the matrix.

Twelve traverses were made on the eleven studied Cr-spinels. Position of chemical traverses on the crystals are displayed in Figs. 4 and 5. Graphs in Figs. 6 and 7 and Table 1 demonstrate the rather homogeneous composition of the Cr-spinels. They are mostly chromites (35 wt% Cr_2O_3), but samples 7 and 8 (Figs. 4c and 4d) correspond to Cr-magnetites. Chemical zoning is very weak or absent, and only present in the rims, which trend towards slightly more iron-rich compositions. MgO and Al_2O_3 remain below 10 wt%. Contents of TiO_2 are extremely low, except in Cr-magnetites.

Inhomogeneous parts of crystals are located mostly along fractures, as observed in the BSE images, and are invariably impoverished in Cr_2O_3 and enriched in Fe_2O_3. Sample 5 (Fig. 5d) is an exception, because Al_2O_3 may reach 42 wt% in parts of the crystal.

Optical and BSE observations show no evidence of ductile deformation – such as subgrains, dynamically-recrystallized smaller grains, or crystal stretching – more common in grains of crustal derivation. The mineral chemistry, particularly the low TiO_2 content, might indicate mantellic composition, but Figure 8 confirms that the crystals are not mantle-derived, for they plot entirely outside the ophiolitic field. They also plot outside the magmatic field, and therefore this possibility is rejected.

A solid-state crustal origin is indicated by the chemistry of the crystals, because all compositions fall in the metamorphic field. The grade of metamorphism shown by the composition of the spinels (Fig. 8) varies from upper greenschist to lower amphibolite facies. No regular chemical variation is observed with distance from the Jaguari Granite contact, as can be seen by comparing field location (Fig. 2) with composition of crystal (Figs. 4, 5, 6 and 7). This is due to thorough recrystallization of the spinels in the regional metamorphic event, before intrusion of the granite. The thermal effect was only observed in the formation of picotite and radiating bundles of tremolite in the matrix of serpentinites very close to the granite contact; recrystallization of the Cr-spinels to Cr-magnetite along fractures may also be due to this event.

HORNBLENDES

Rock types are rather varied in the Palma Group, but the Campestre Formation meta-volcano-clastics are abundant and contain the studied hornblendes. The low amphibolite facies metamorphism and deformation were intense, but the dominant quartz-feldspar-amphibole mineralogy of the meta-andesites (Fig. 9, Table 2) makes them massive and weakly banded S and L tectonites, in general. Amphiboles are very common. An igneous amphibole (Table 2) is present regionally in the Palma Group in peridotites, pyroxenites, gabbros, anorthosites, basalts and andesites. In all these rock types, the amphibole is of late-igneous crystallization, brown to reddish brown in color, large 2V (+), extinction angle = 30°. These amphiboles are descriptively classified as basaltic hornblendes (Deer *et al.*, 1966), and were correctly considered pargasites by Garcia & Hartmann (1981), Chemale (1982) and Oliveira (1982). Amphiboles from the Campestre Formation were studied in this project in ca. 100 thin-sections, and in additional 300 thin-sections from previous studies (Garcia & Hartmann, 1981; Chemale, 1982; Oliveira, 1982).

Calcic amphiboles with appreciable Al content may be called hornblendes, according to Deer *et al.* (1992, p. 226) and these are the predominant amphiboles in the Campestre Formation. They are light green under the microscope and tend to be optically unzoned, indicating that only one metamorphic event occurred in the region or two events in very similar metamorphic conditions. Some are partially to completely altered to either chlorite or epidote, but some thin-sections both alteration minerals are present.

Chemical anayses of the amphiboles (Table 3, Figs. 10 and 11) are of calcic amphiboles with predominance of tschermakitic hornblendes. Most

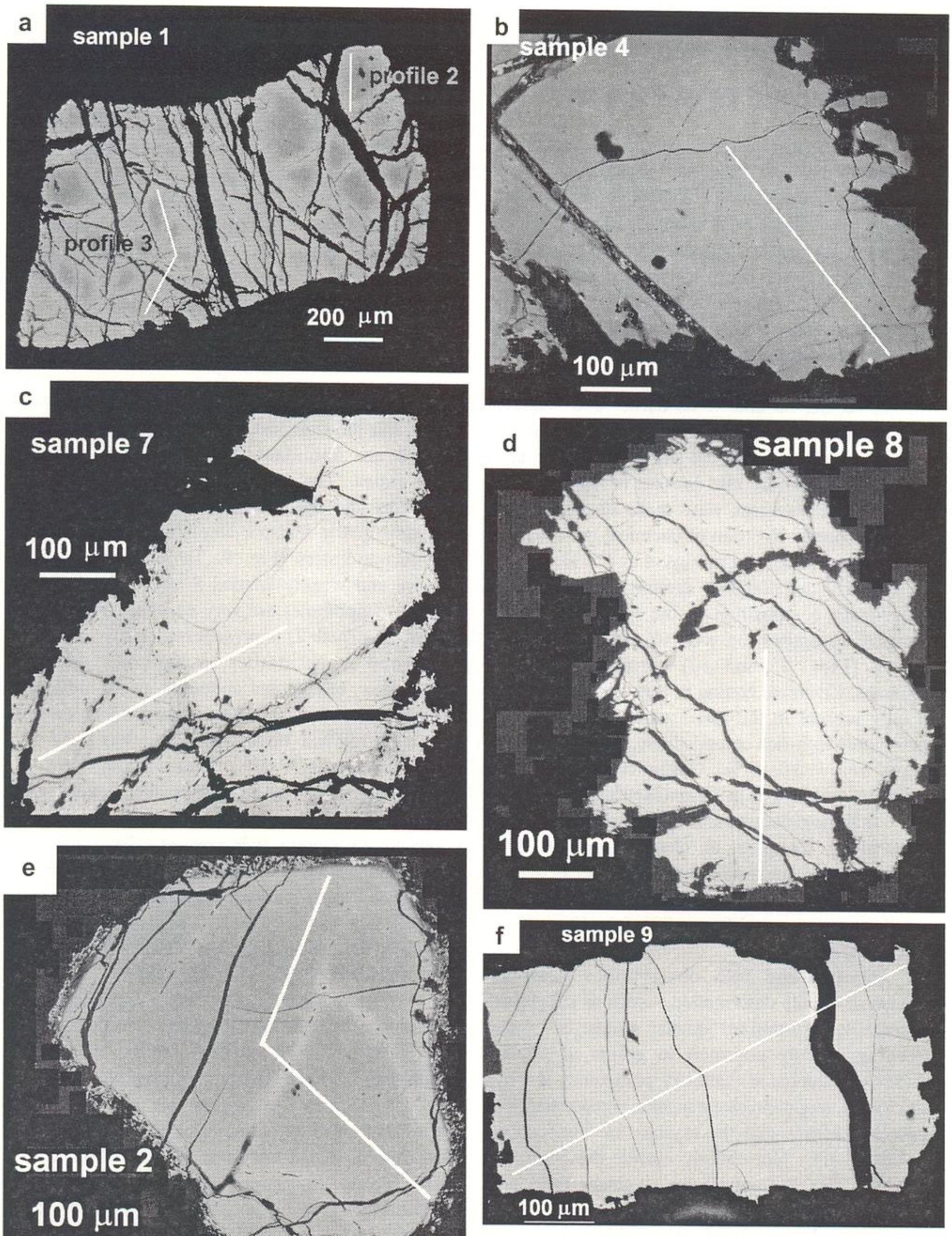

Figure 4 - Backscattered electron images of Palma Group Cr-spinels. EPMA scans indicated by white lines.

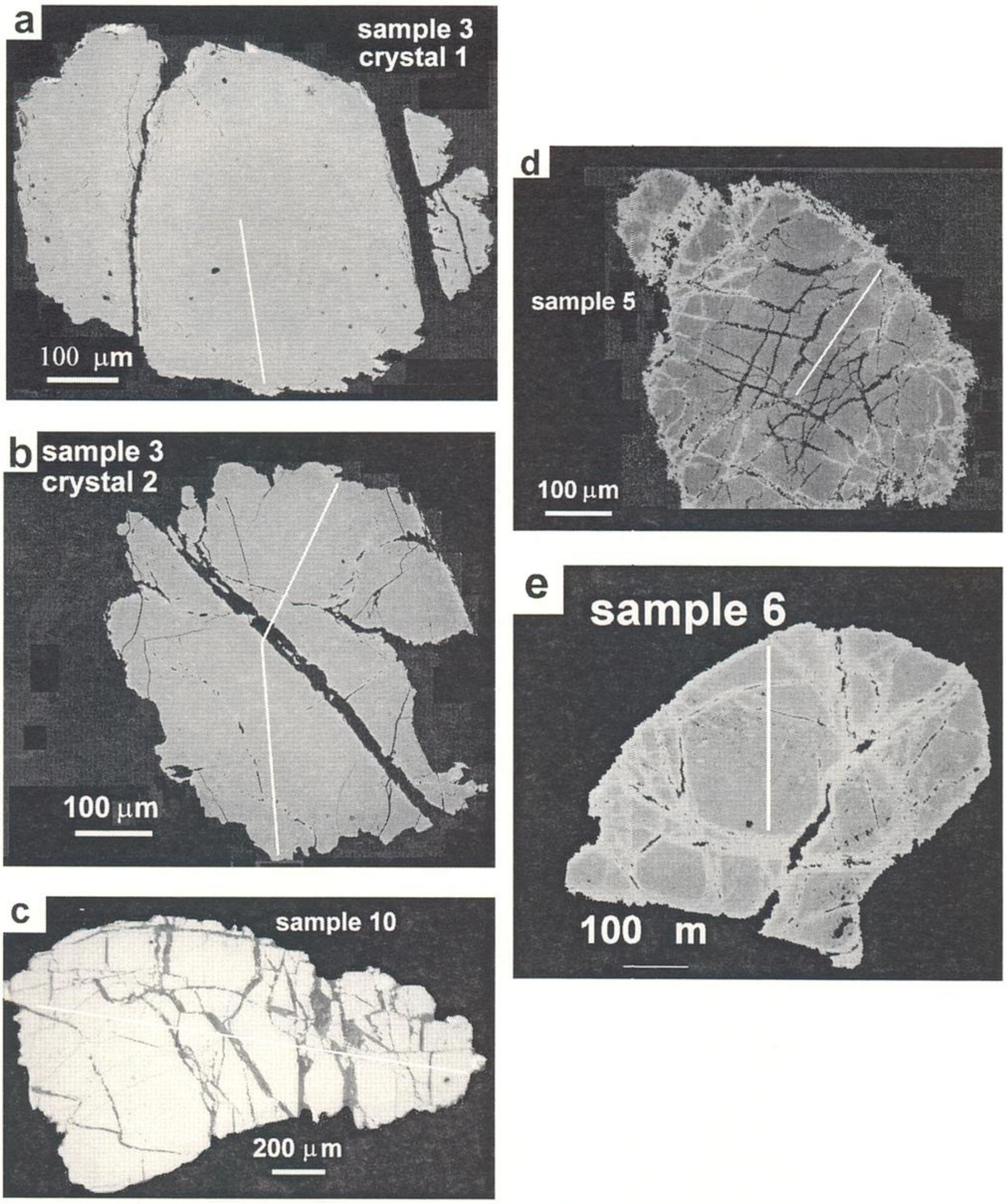

Figure 5 - Backscattered electron images of Palma Group Cr-spinels. EPMA scans indicated by white lines.

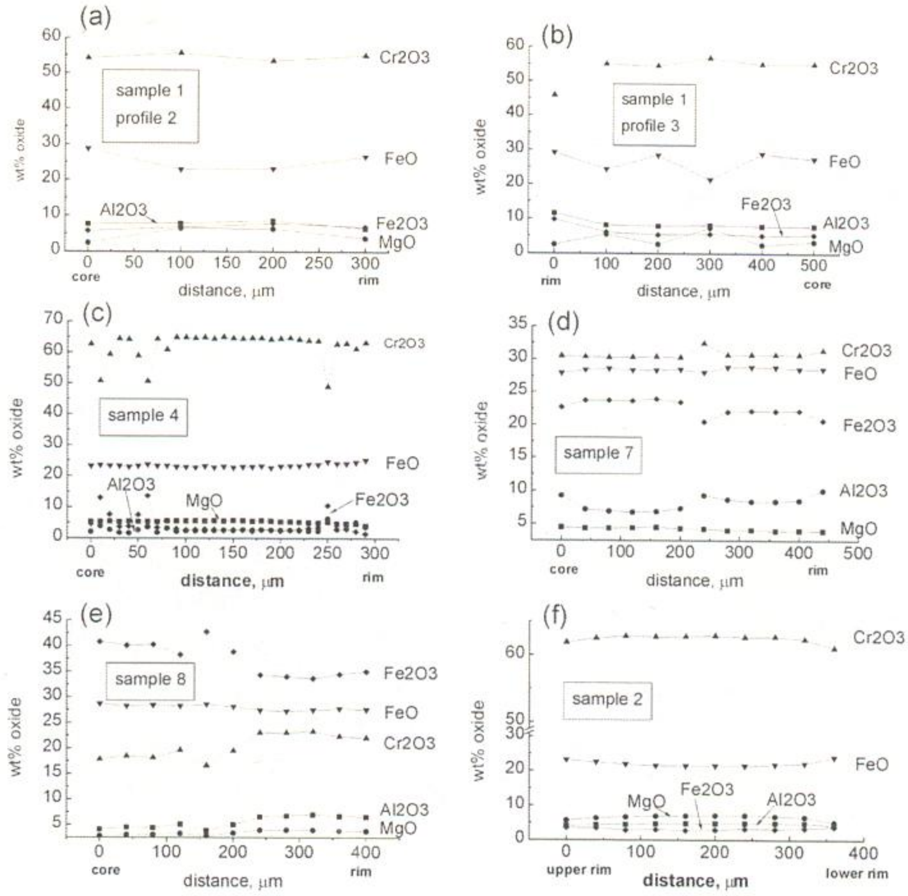

Figure 6 - Distance-composition diagrams of several Cr-spinel crystals have very little zoning.

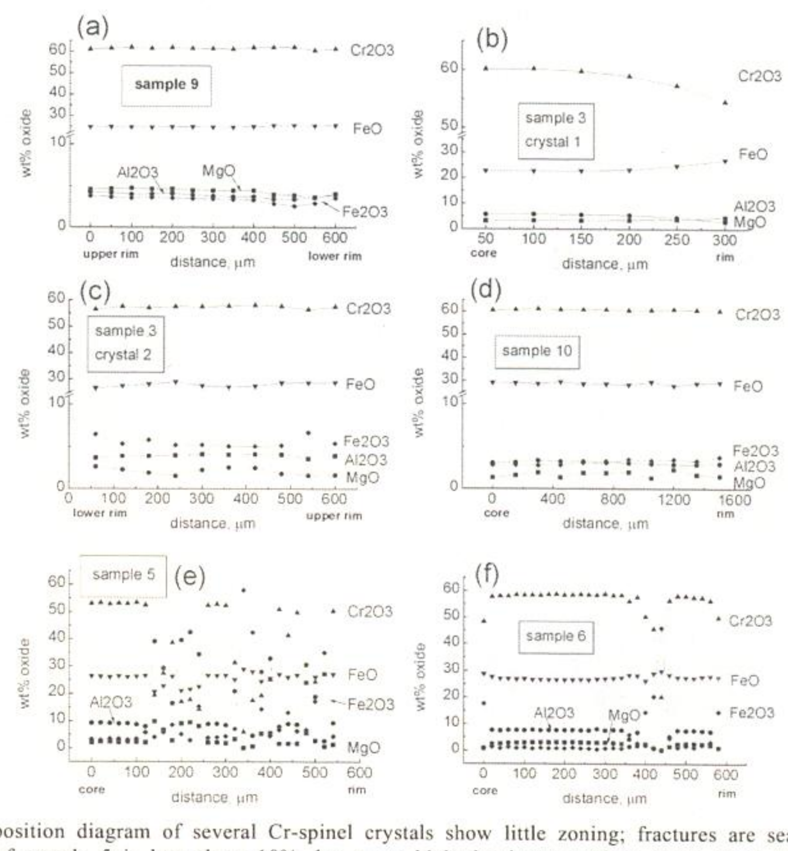

Figure 7 - Distance-composition diagram of several Cr-spinel crystals show little zoning; fractures are sealed by Cr-magnetite (e.g. *e* and *f*). Al_2O_3 content of sample 5 is low about 10%, but some high-aluminum portions reach about 40%.

Table 1 - Representative electron microprobe chemical analyses (wt %) of studied Cr-spinels. One spot analysis selected from homogeneous crystals, two spot analyses from zoned crystals. - below detection limit.

	1	2	3		4		5		6		7		8		9	10
			a	b	a	b	a	b	a	b	a	b	a	b		
SiO_2	–	–	–	–	–	0.42	–	1.29	–	0.28	–	–	–	–	–	–
TiO_2	–	–	–	–	0.11	1.29	–	0.40	–	0.36	3.90	3.45	2.32	2.15	0.07	–
$Al2O_3$	7.93	4.69	3.27	4.49	1.78	6.38	9.11	39.14	7.69	0.16	6.85	8.63	4.49	6.97	4.15	2.91
Cr_2O_3	55.23	62.70	60.18	54.57	64.32	49.07	53.18	19.33	57.96	20.09	30.34	30.61	18.46	23.97	61.45	60.59
Fe_2O_3	6.33	3.02	6.21	8.51	3.38	10.49	3.54	4.09	1.28	45.90	23.96	21.97	40.07	33.70	3.66	3.31
FeO	22.58	21.48	22.74	26.97	23.16	24.52	26.33	20.48	26.85	29.78	28.30	28.78	28.24	27.45	24.74	28.70
MgO	6.39	6.87	5.74	2.95	5.30	5.28	2.27	9.93	2.84	0.27	4.50	4.02	3.06	3.93	4.65	1.65
MnO	0.57	0.57	0.64	0.64	0.76	0.79	2.73	1.08	1.47	0.64	0.64	0.69	0.40	0.48	0.70	0.54
Total	99.03	99.33	98.78	98.13	98.81	98.21	97.16	95.74	98.06	97.48	98.49	98.15	97.04	98.65	99.42	97.70

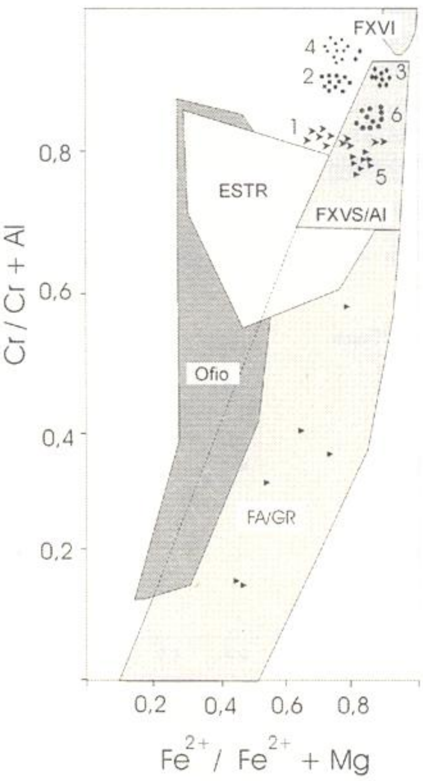

Figure 8 - Selected compositions of six analysed crystals plotted on discriminant diagram (Irvine, 1965). All samples plot in the upper greenschist/lower amphibolite facies (UG/LAF) field; a few of the sample 5 compositions plot in the upper amphibolite/granulite facies (UA/GF) field. None of the samples plots in the ophiolite/upper mantle (OPH) or igneous stratiform (STR) fields. Retrogressive Cr-magnetite compositions in the lower greenschist facies (LGF) were not plotted for clarity.

grains show very weak or no zoning at all. Basaltic hornblende of magmatic origin was analyzed in one crystal of sample 7, and yielded a high TiO_2 (ca. 3 wt%) pargasite composition. The associated widespread metamorphic green hornblendes present only ca. 0.3 wt% TiO_2. The magmatic pargasite is more silica-deficient (~40.6 wt% SiO_2) than the metamorphic hornblendes (~42-45 wt% SiO_2). Only sample 3 hornblende has a more siliceous composition and plots outside the compositional field of the other hornblendes for all analysed cations; it is contained in a biotite-rich (~22 vol.%) rock and this is the reason for the different composition of the hornblende.

Low amphibolite facies metamorphism is predominant in the regional metamorphic event in the studied samples. Al_2O_3 content is high, varying from 11 to 16 wt%. This can be extended to most of the Palma Group because the hornblendes are optically similar as seen under the petrographic microscope. Greenschist facies parageneses containing chlorite and epidote are restricted to shear zones and are not widespread in the volcanoclastic sequence.

What is the nature of the metamorphic event responsible for the latest, dominant recrystallization of the hornblendes and Cr-spinels? The relation between Ti × Al in the M_1 hornblendes (Fig. 12) is similar to the Cambaizinho Sequence 30 km north of

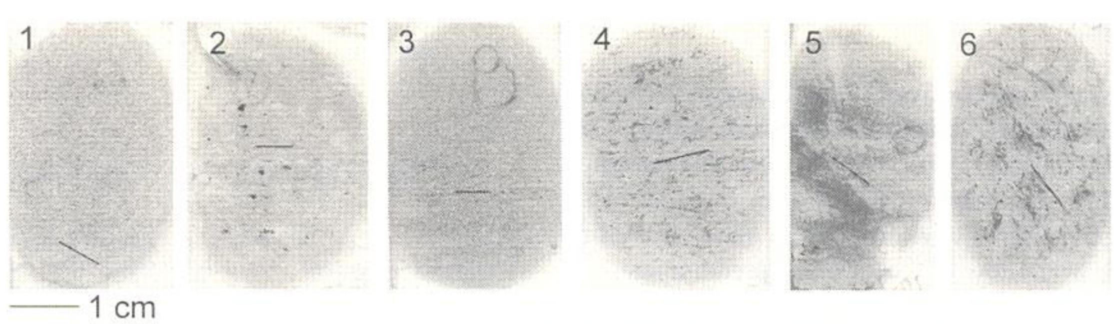

Figure 9. Scanned thin-sections of andesites (samples 1-6) used in this investigation. Metamorphic foliation indicated by black lines.

Table 2 - Rock and hornblende characteristics in studied meta-andesites from the Campestre Formation, Palma Group.

Sample	Mineralogy	Texture	M1 hb pleochroism
1	Ig = plag, qz M1 = bio, gar, epi, tit, hb M2 = carb, chlo, epi	M1 matrix weakly granoblastic; porphyroblastic M2 Nematoblastic	Ng = bluish green Nm = intense green Np = light yellow
2	Ig = plag, qz M1 = hb, zo, bio, op M2 = chlo	M1 matrix weakly granoblastic; porpyroblastic M2 Lepidoblastic	Ng = bluish green Nm = intense green Np = pale yellowish green
3	Ig = plag, qz, kf, op, zir, tit M1 = bio, anf M2 = chlo, carb	Matrix weakly granoblastic M1 porphyroblastic M2 granoblastic decussate	Ng = intense green Nm = intense green Np = pale yellow
4	Ig = plag, qz M1 = hb, epi, op, carb. M2 = chlo	M1 matrix granoblastic M2 weakly nematoblastic M3 granoblastic decussate	Ng = bluish green Nm = intense green Np = golden yellow
5	Ig = plag, qz M1 = epi, hb, op M2 = epi, ser	M1 incipient granoblastic and porphyroblastic M2 incipient nematoblastic	Ng = green Nm = bluish green Np = golden yellow
6	Ig = plag, qz M1 = hb, epi, carb, op M2 = chlo	M1 matrix weakly granoblastic; porphyroblastic M2 lepidoblastic	Ng = bluish green Nm = intense green Np = pale golden yellow

Obs.: plag = plagioclase, qz = quartz, bio = biotite, gar = garnet, epi = epidote, tit = titanite, hb = hornblende, carb = carbonate, chlo = chlorite, zo = zoisite, op = opaque mineral, kf = K-feldspar, zir = zircon, ser = sericite. M1= oldest regional metamorphism, low-amphibolite facies; M2 = shear zone metamorphism, greenschist facies; M3 = latest metamorphism, low-amphibolite facies.

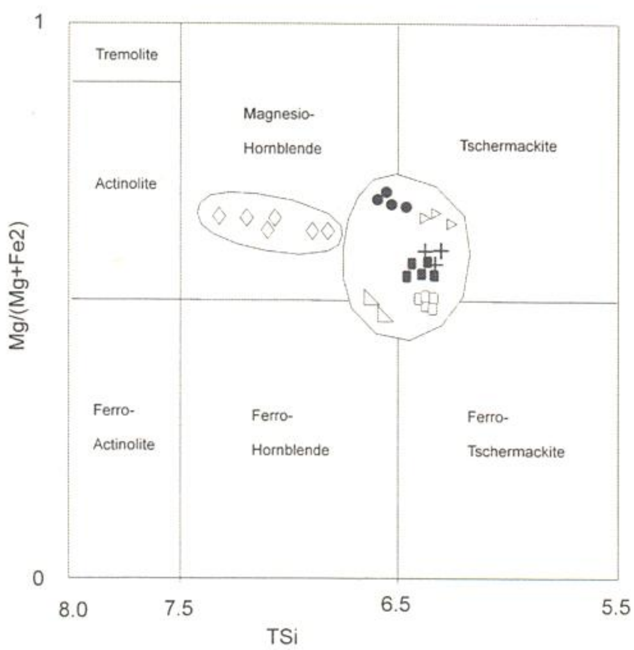

Figure 10 - Hornblende compositions from meta-andesites define a narrow compositional field in the Leake *et al.* (1997) diagram. Each symbol corresponds to analyses of hornblendes from one thin section.

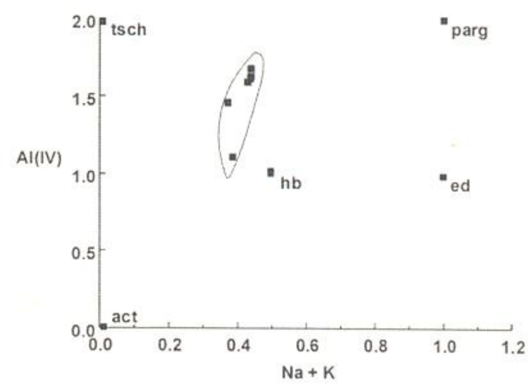

Figure 11 - Chemical composition of analyzed hornblendes has a tschermackitic trend. In this diagram, only the average composition of analyzed amphiboles is shown for each sample.

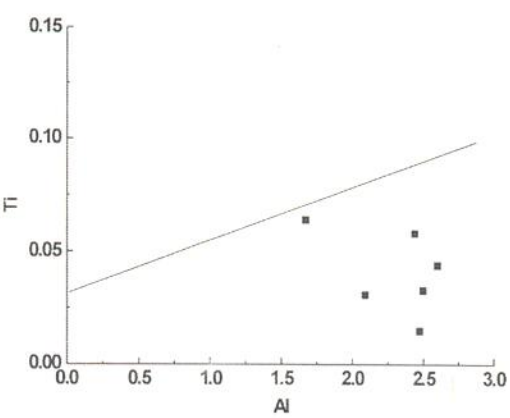

Figure 12 - Low-Ti content of analyzed hornblendes, as commonly observed in hornblendes from medium P/T metamorphic belts. Low P/T hornblendes from other terrains straddle the inclined line. In this diagram, only the average composition of analyzed amphiboles is shown for each sample.

Palma, and is indicative of crystallization in medium P/T metamorphic conditions (Laird & Albee, 1981; Hartmann *et al.*, 1990). Heat flow in this island-arc sequence was therefore lower than in some of the younger volcanic environments in other parts of the world, where low P/T conditions predominate.

Observation of Figure 2 indicates that metamorphic pressures were fairly high, for there is

Table 3 - Representative electron microprobe analyses of hornblendes from the Campestre Formation. One metamorphic (low TiO_2) and one magmatic (high TiO_2) analysis in sample 7 hornblendes.

Sample	1	2	3	4	5	6	7	7
SiO_2	43.05	41.96	47.95	42.34	43.09	44.68	43.41	40.60
TiO_2	0.21	0.36	0.38	0.35	0.30	0.23	0.46	2.63
Al_2O_3	15.02	13.93	7.66	12.89	14.35	13.55	12.82	14.48
FeO	17.08	16.57	14.40	17.24	14.74	16.05	17.56	18.03
Cr_2O_3	0.00	0.02	0.06	0.00	0.00	0.00	0.02	0.07
MnO	0.42	0.53	0.52	0.42	0.34	0.55	0.22	0.22
MgO	8.49	9.37	12.19	9.26	10.51	10.75	8.63	7.70
CaO	11.19	11.48	12.17	10.94	11.52	11.23	11.27	11.32
Na_2O	1.20	1.35	0.67	1.36	1.33	1.27	1.24	1.36
K_2O	0.30	0.39	0.59	0.36	0.30	0.30	0.30	0.71
F	0.01	0.04	0.09	0.00	0.00	0.06	0.15	0.00
H_2O	2.00	1.95	1.97	1.95	1.95	2.02	1.90	1.90
Total	98.97	97.95	98.65	97.11	98.43	100.69	97.90	99.02

an absence of correlation between amphibole composition and distance from the Jaguary Granite contact. Figure 10 shows that there is little variation in amphibole chemistry with distance from granite contact. This shallow intrusion is therefore not the cause of the regional metamorphic event.

Because the hornblende textures are indicative of syn- to postectonic metamorphism, the source of heat may be found in the sum of the several foliated granitic intrusions in the area. The Palma Group resembles a mega-xenolith contained in the syn- to postectonic magmas. The rocks were probably subjected to intense circulation of fluids (and advecting heat) from the crystallizing granites.

The regional syn- to postectonic M1 event generated parageneses nearly in thermal equilibrium with the intruding postectonic granites; hornblendes remained stable, without generation of zoning to lower-grade amphiboles. This is the geological explanation for the textural and compositional observations on the amphiboles.

CONCLUSIONS

Cr-spinels in the northern aureole of the Jaguari Granite were formed as accessory minerals during regional metamorphism of ultramafic rocks; serpentinites and jackstraw-textured meta-serpentinites were formed during this event. Hornblendes in meta-andesites were formed in this same regional metamorphism, which is well preserved throughout the entire Palma Group. Grade of metamorphism varies from epidote-amphibolite to lower amphibolite facies, whereas the contact effect is only observed as lower grade recrystallization in the matrix of serpentinites or in fractures, the crystals modifying their chemistry accordingly from chromite to chromian magnetite; epidote and chlorite are formed in the meta-andesites. Lack of zoning of amphibole crystals indicates that the low-grade event of chlorite and epidote formation remained restricted to narrow shear zones because the amphiboles did not recrystallize during this event. This seems a low-grade shear-zone metamorphism. Older chromian spinels are mostly chromites but chromian magnetites also occur; these minerals show weak chemical zoning. Late inhomogeneities occur along fractures in the Cr-spinels where they tend to be poor in Cr_2O_3 and rich in Fe_2O_3. Low TiO_2 in studied chromites may be caused by regional crustal metamorphism, and does not seem to be related to a mantellic origin.The source of heat for metamorphism may be the nearly simultaneous intrusion of several granitic plutons, affecting the Palma basement as a mega-xenolith.

No indication is obtained from the Campestre Formation hornblendes or Cerro da Cruz Formation Cr-spinels for decreasing conditions of contact metamorphism with increasing distance from the Jaguary Granite contact. Low Ti and Na of the M_1 hornblendes characterizes the Campestre Formation as a medium P/T metamorphic belt comparable to the Cambaizinho belt 50 km to the north.

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REFERENCES

Arai, S. 1975. Contact metamorphosed dunite-harzburgite complex in the Chugoku District, Western Japan. **Contributions to Mineralogy and Petrology, 52**: 1-16.

Babinski, M.; Chemale Jr., F.; Hartmann, L. A.; Van Schmus, W. R. & Silva, L. C. 1996. Juvenile accretion at 750-700 Ma in southern Brazil. **Geology, 24**: 439-442.

Babinski, M.; Chemale Jr., F.; Van Schmus, W. R.; Hartmann, L. A. & Silva, L. C. 1997. U-Pb and Sm-Nd geochronology of the Neoproterozoic granitic-gneissic Dom Feliciano Belt, Southern Brazil. **Journal of South American Earth Sciences, 10**: 263-274.

Bucher, K. & Fry, M. 1994. *Petrogenesis of Metamorphic Rocks*. Complete Revision of Winkler's Textbook. Berlin, Springer-Verlag, 318 p.

Chemale Jr., F. 1982. **Geologia da região de Palma, São Gabriel, Rio Grande do Sul**. Porto Alegre. 136 p. MS Dissertation, Curso de Pós-Graduação em Geociências/UFRGS.

Chemale Jr., F.; Hartmann, L. A. & Silva, L. C. da. 1995. Stratigraphy and tectonism of the Brasiliano Cycle in southern Brazil. **Communications Geological Survey of Namibia, 10**:151-166.

Deer, W. A.; Howie, R. A. & Zussman, J. 1966. **An introduction to the rock-forming minerals**. London, Longman Scientific & Technical.

Deer, W. A.; Howie, R. A. & Zussman, J. 1992. **An introduction to the rock-forming minerals**. London, Longman Scientific & Technical. 696 p.

Dick, J. B. & Bullen, T. 1984. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. **Contributions to Mineralogy and Petrology, 86**: 54-76.

Evans, B. W. 1977. Metamorphism of alpine peridotite and serpentinite. **Annual Reviews of Earth and Planettary Sciences, 5**: 397-447.

Evans, B. W. & Frost, B. R. 1975. Chrome-spinel in progressive metamorphism: A preliminary analysis. **Geochimica et Cosmochimica Acta, 39**: 959-972.

Evans, B. W. & Trommsdorf, V. 1974. On elongate olivine of metamorphic origin. **Geology, 2**: 131-132.

Garcia, M. A. M. & Hartmann, L. A. 1981. Petrologia do Complexo Palma, RS. **Acta Geologica Leopoldensia, 13**: 51-119.

Gastal, M. C. P.; Schmitt, R. S. & Nardi, L. V. S. 1992. Granitóides da parte centro/sudoeste do Escudo Sul-riograndense. Novos dados e discussões sobre a gênese e tipologia do magmatismo alcalino. **Pesquisas, 19**: 174-182.

Goñi, J. C. 1962. Origine des roches ultrabasiques et serpentineuses du precambrien de Rio Grande do Sul (Brésil): mode de gisement et minéralisations. **Boletim da Escola de Geologia da UFRGS, 12**: 1-91.

Goñi, J. C.; Goso, H. & Issler, R. S. 1962. Estratigrafia e Geologia Econômica do Pré-Cambriano e Eo-Paleozóico Uruguaio e Sul-Riograndense. **Avulso da Escola de Geologia da UFRGS, 3**: 1-105.

Hartmann, L. A. 1982. Textura metamórfica de olivina em talco serpentinitos da região de Mata Grande (RS). **Acta Geologica Leopoldensia, 17**: 179-188.

Hartmann, L. A.; Leite, J. A. D.; McNaughton, N. J. & Santos, J. O. S. 1999. Deepest crust of Brazil – SHRIMP establishes three events. **Geology, 27**(10):947-950.

Hartmann, L. A. & Nardi, L. V. S. 1983. Contribuição à geologia da região oeste do Escudo Sul-riograndense. In: SIMPÓSIO SUL-BRASILEIRO DE GEOLOGIA, 1., 1983, Porto Alegre. **Anais**... Porto Alegre, SBG. p. 9-18.

Hartmann, L. A. & Remus, M. V. D. 1999. Origem e evolução das rochas ultramáficas do Rio Grande do Sul desde o Arqueano até o Cambriano. In: Holz, M. & Ros, L. F. de (eds.). **Geologia do Rio Grande do Sul**, Editora UFRGS (no prelo).

Hartmann, L. A.; Remus, M. V. D. & Koppe, J. C. 1987. Distinção entre textura spinifex e arranjos de olivina metamórfica. **Revista Brasileira de Geociências, 17**: 302-305.

Hartmann, L. A.; Tindle, A. & Bitencourt, M. F. 1990. O metamorfismo de fácies anfibolito no Complexo Metamórfico Passo Feio, RS, com base em química dos minerais. **Pesquisas, 17**(1-2): 62-71.

Hietanen, A. 1977. Blades of olivine in ultramafic rocks from Northern Sierra Nevada, California. **Journal of Research of the US Geological Survey, 5**: 217-219.

Irvine, T. N. 1965. Chromian spinel as a petrogenetic indicator. Part 1: theory. **Canadian Jouranl of Earth Sciences, 2**(4): 648-672.

Irvine, T. N. 1967. Chromian spinel as a petrogenetic indicator. Part 2: petrological application. **Canadian Journal of Earth Sciences, 4**: 71-103.

Irving, A. J. & Ashley, P. M. 1976. Amphibole-olivine-spinel, cordierite-anthophyllite and related hornfelses associated with metamorphosed serpentinites in the Goobarragandra District, near Tumut, New South Wales. **Journal of the Geological Society of Australia, 23**: 19-43.

Jost, H. 1966. Complexos Básico-ultrabásicos do Alto Rio Vacacaí, São Gabriel - Rio Grande do Sul - Brasil. **Notas e Estudos da Escola de Geologia da UFRGS, 1**: 55-61.

Jost, H. 1970. Esboço geológico da folha "Cabeceiras do Rio Vacacaí", São Gabriel, R.G.S. **Boletim da Escola de Geologia da UFRGS, 16**: 1-47.

Jost, H. & Hartmann, L. A. (1984) Província Mantiqueira - Setor Meridional. In: Almeida, F. F. M. and Hasui, Y. (eds). **O Pré-Cambriano do Brasil.** São Paulo, Edgard Blucher. p. 345-367.

Jost, H. & Villwock, J. A. 1966. Contribuição à Estratigrafia do Pré-Cambriano do Rio Grande do Sul. **Notas e Estudos da Escola de Geologia da UFRGS, 1**: 13-26.

Kirchner, C. A. & Andriotti, J. L. S. (1981) Prospecção geoquímica de detalhe na associação máfico-ultramáfica de Palma, RS. **Acta Geologica Leopoldensia, 9**: 11-24.

Kirchner, C. A. & Grazia, C. A. 1978. Prospecção geoquímica de detalhe na associação ofiolítica de Palma, São Gabriel, RS. CONGRESSO BRASILEIRO DE GEOLOGIA, 30., 1978, Recife. **Anais**... Recife, SBG, v. 5, p. 2102-2111.

Leake, B. E. *et al.* 1997. Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. **American Mineralogist, 82**:1019-1037.

Leinz, V. 1943. Calcário de Vacacaí. **Mineração e Metalurgia, 7**: 1-29.

Leite, J. A. D. 1997. **A origem dos hazburgitos da Sequência Cerro Mantiqueiras e implicações tectônicas para o desenvolvimento do Neoproterozóico na porção Oeste do Escudo Sul-riograndense**. Porto Alegre. 224 p. Doctoral Thesis, Curso de Pós-Graduação em Geociências da UFRGS.

Laird, J. & Albee, A. L. 1981. Pressure, temperature, and time indicators in mafic schist: their application to reconstructing the polymetamorphic history of Vermont. **American Journal of Science, 281**:127-175.

Leite, J. A. D.; Hartmann, L. A.; McNaughton, N. J. & Chemale Jr., F. 1998. SHRIMP U/Pb zircon geochronology of Neoproterozoic juvenile and crustal-reworked terranes in southernmost Brazil. **International Geology Review, 40**:688-705.

Machado, N.; Koppe, J. C. & Hartmann, L. A. 1990. Upper Proterozoic U-Pb age for the Bossoroca Belt, Rio Grande do Sul, Brazil. **Journal of South American Earth Sciences, 3**: 87-90.

Matthes, W. 1971. Die ultramafischen Hornfelse, insbesondere ihre Phasenpetrologie. **Fortschreitungen Mineralogischen, 48**: 109-127.

Naumann, M. P. & Hartmann, L. A. 1984. Cornubianitos ultramáficos e metassomatitos associados da região do Arroio Corticeira, Ibaré, RS. CONGRESSO BRASILEIRO DE GEOLOGIA, 33., 1984, Rio de Janeiro. **Anais**... Rio de Janeiro, SBG, p. 4279-4290.

Naumann, M. P.; Hartmann, L. A.; Koppe, J. C. & Chemale Jr., F. 1984. Sequências supracrustais, gnaisses graníticos, granulitos e granitos intrusivos na região de Ibaré-Palma, RS – geologia, aspectos estratigráficos e considerações geotectônicas. CONGRESSO BRASILEIRO DE GEOLOGIA, 33., 1984, Rio de Janeiro. **Anais**... Rio de Janeiro, SBG, p. 2417-2424.

Nesbitt, R. W. & Hartmann, L. A. 1986. Comments on 'A peridotitic komatiite from the Dalradian of Shetland' by D. Flinn and D.T. Moffat. **Geological Journal, 21**: 201-205.

Oliveira, M. T. G. 1982. Petrologia do Maciço Máfico-Ultramáfico Passo do Ivo, São Gabriel, Rio Grande do Sul. **Acta Geologica Leopoldensia, 11**: 131-218.

Oliver, R. L.; Nesbitt, R. W.; Hansen, D. M. & Franzen, N. 1972. Metamorphic olivine in ultramafic rocks from Western Australia. **Contributions to Mineralogy and Petrology, 36**: 335-342.

Remus, M. V. D.; Hartmann, L. A. & Formoso, M. L. L. 1993. Os padrões de elementos terras raras e a afinidade geoquímica komatiítica dos xistos magnesianos e rochas associadas do Complexo Cambaizinho, São Gabriel, RS. **Revista Brasileira de Geociências, 23**: 370-387.

Sack, R. O. & Ghiorso, M. S. 1991. Chromian spinels as petrogenetic indicators: thermodynamics and petrological applications. **American Mineralogist, 76**: 827-847.
Santos, E. L.; Azevedo, G. C.; Remus, M. V. D.; Maciel, L. A. C. & Mossmann, R. 1990. Mapeamento geológico das Sequências Metavulcano-sedimentares do oeste do Escudo Sul-riograndense, RS. CONGRESSO BRASILEIRO DE GEOLOGIA, 36., 1990, Natal, **Anais**... Natal, SBG, p. 2976-2990.
Snoke, A. W. & Calk, L. C. 1978. Jackstraw-textured talc-olivine rocks, Preston Peak area, Klamath Mountain, California. **Geological Society of America Bulletin, 89**: 223-230.
Silva, L. C. da, Hartmann, L. A., McNaughton, N. J. & Fletcher, I. R. 1999. SHRIMP U/Pb zircon timing of Neoproterozoic granitic magmatism and deformation in the Pelotas Batholith in southernmost Brazil. **International Geology Review** (in press).
Springer, R. K. 1974. Contact metamorphosed ultramafic rocks in the Western Sierra Nevada Foothills, California. **Journal of Petrology, 15**: 160-195.
Strieder, A. & Nilson, A. 1992. Estudo petrológico de alguns fragmentos da melange ofiolítica em Abadiânia (GO): II - as cromitas primárias e as suas transformações metamórficas. **Revista Brasileira de Geociências, 22**: 353-362.
Suita, M. T. F. 1996. **Metalogenia e geoquímica de platinóides em complexos máfico-ultramáficos do Brasil: alguns critérios e guias, com ênfase no Complexo Máfico-ultramáfico de Barro Alto (Goiás, Brasil Central)**. Porto Alegre. 525 p. Doctoral Thesis, Curso de Pós-Graduação em Geociências, UFRGS.
Suita, M. T. F. & Hartmann, L. A. 1997. Controle das transformações nos padrões de EGP pelo estudo da geoquímica da cromita. **Revista Brasileira de Geociências, 2**: 185-192.
Suita, M. T. F. & Strieder, A. J. 1996. Cr-spinels from Brazilian mafic-ultramafic complexes: metamorphic modifications. **International Geology Review, 38**: 245-267.
Szubert, E. C. 1978. Uma associação ofiolítica completa, Palma, São Gabriel, RS. Geologia e questões estratigráficas. CONGRESSO BRASILEIRO DE GEOLOGIA, 33., Recife. **Anais**...Recife, SBG, v. 1, p. 467-476.
Szubert, E. C. 1979. Depósitos de ouro e as rochas ultramáficas da faixa ofiolítica de Palma, São Gabriel, RS. **Mineração Metalurgia, 7**: 14-19.
Szubert, E. C.; Kirchner, C. A.; Grazia, C. A.; Andriotti, J. L. S. & Shintaku, I. 1977. **Projeto cobre nos corpos básico-ultrabásicos e efusivas do Rio Grande do Sul**. Final Report, Convênio DNPM/CPRM, Porto Alegre, 2 v., 113 p. (unpubl.).
Trommsdorf, V. & Evans, B. W. 1972. Alpine metamorphism of peridotitic rocks, **Schweiz. Mineralogische und Petrographische Mitteilungen, 54**: 333-352.
Turner, F. J. 1981. **Metamorphic petrology - mineralogical, field and tectonic aspects**. New York, McGraw-Hill Book Co., 524 p.
Villwock, J. A. & Jost, H. 1966. Mineralizações de cobre, molibdênio e ouro das cabeceiras do Rio Vacacaí, São Gabriel, RS. CONGRESSO BRASILEIRO DE GEOLOGIA, 21., 1966, Curitiba. **Anais**...Curitiba, SBG, p. 80-102.