Geologia Série Científica USP
Revista do Instituto de Geociências - USP
Geol. USP, Sér. cient., São Paulo, v. 10, n. 3, p. 3-18, outubro 2010

Relationships Between Shearing and Granitic Magma Emplacement: the Remígio-Pocinhos Shear Zone in the São José do Campestre Massif, NE Brazil

Relação Entre Cisalhamento e Alojamento de Magmas Graníticos: Zona de Cisalhamento Remígio-Pocinhos, Maciço São José do Campestre, NE do Brasil

Rielva Solimairy Campelo do Nascimento[1] (rielva@ufam.edu.br), Ian McReath[2] (ianmcr@usp.br), Antônio Carlos Galindo[3] (galindo@geologia.ufrn.br)
[1]Departamento de Geociências - Instituto de Ciências Exatas - UFAM
Av. General Rodrigo Octávio Jordão Ramos 3.000, CEP 69077-000, Manaus, AM, BR
[2]Departamento de Mineralogia e Geotectônica - Instituto de Geociências - USP, São Paulo, SP, BR
[3]Departamento de Geologia - Instituto de Ciências Exatas - UFRN, Natal, RN, BR

Received 14 August 2009; accepted 19 May 2010

ABSTRACT

Based on mineralogical, geochemical and textural characteristics, a variety of granite types was identified amongst the intrusions emplaced during the tectonic activity along the Remígio-Pocinhos shear zone in NE Brazil during the latest stages of the Brasiliano orogeny. They include peraluminous granites with I-type mineralogical compositions as well as transitional-to-alkaline geochemical characteristics. These granites contain mafic to intermediate microgranular enclaves. Overall, they are very similar to many other Brasiliano-age plutons in the extreme NE of Brazil. Metaluminous alkaline granites with aegirine-augite usually contain andradite as a minor phase, and titanite as an important accessory mineral. Several aspects of their trace element geochemistry repeat features of syn to late- tectonic alkaline granites in other parts of NE Brazil and in the rest of the world. The shear zone has deep roots, and the heat flow during granite genesis was probably high. A variety of lower crustal source rocks was probably involved in the genesis of these granites.

Keywords: Seridó region; Shear zones; Emplacement of granite magmas; Diversity of granite types; Transitional granite types.

RESUMO

Com base em características mineralógicas, geoquímicas e texturais foram identificados vários tipos graníticos entre os plútons intrudidos durante atividade tectônica ao longo da zona de cisalhamento de Remígio - Pocinhos, relacionada à última fase da orogenia brasiliana. Os tipos incluem granitos peraluminosos com composições mineralógicas do tipo I, e características químicas na transição de subalcalina a alcalina. Este tipo porta encraves microgranulares máficos a intermediários. De modo geral assemelham-se a muitos outros plútons brasilianos no extremo nordeste do Brasil. Granitos alcalinos metaluminosos, portadores de aegirina-augita, muitas vezes contêm como fase menor a andradita, enquanto a titanita é fase acessória importante. Vários aspectos de suas composições geoquímicas repetem os de granitos alcalinos sin a tardi-tectônicos encontrados em outras partes do Brasil nordestino, tal como em outras partes do mundo. As raízes da zona de cisalhamento são profundas, e é provável que o fluxo de calor durante a gênese dos granitos fosse alto. Portanto, várias rochas da crosta inferior são possíveis fontes dos magmas.

Palavras-chave: Região do Seridó; Zonas de cisalhamento; Colocação de magmas graníticos; Diversidade de tipos graníticos; Tipos de granitos transicionais.

INTRODUCTION

In Brazil, as in other parts of the world, granite plutons have been used as structural and geochronological markers of orogenic events (e.g., Jardim de Sá et al., 1987; Hollanda et al., 1999; Guimarães et al., 2004). When coupled with studies of petrogenesis, this information has led to significant advances in the understanding of the geodynamic evolution of orogenic belts, including those of northeastern Brazil.

In the Borborema Province, granite plutons are found in the neighborhood of transcurrent shear zones, which were active during the Brasiliano orogenesis (e.g., Jardim de Sá et al., 1987; Caby et al., 1991; Neves and Vauchez, 1995; Nascimento et al., 2000; McReath, Galindo, Dall´Agnol, 2002). An example of the relationships between shearing and granite emplacement is found in the Remígio-Pocinhos shear zone (RPSZ) in the eastern part of the province, where transtensional shearing together with high heat flow led to the formation of elongated granite bodies parallel to the shear zone direction (Trindade et al., 1993; Souza and Jardim de Sá, 1993; Jardim de Sá et al., 1997; Nascimento et al., 1997; Nascimento, 1998).

The presence of a variety of granite types in a relatively small area around the RPSZ invites a study of their petrogenesis, especially the identification of the different source rocks involved in their genesis and the role of shearing on melt extraction and emplacement.

THE REMÍGIO-POCINHOS SHEAR ZONE

The RPSZ is an example of the SW-NE oriented Brasiliano-age transcurrent faults which cross Paraíba State (Figure 1). One of the eastern branches of the Patos Lineament, the RPSZ extends over more than 150 km to the Potiguar shore line, where it is covered by the Barreiras Group sediments (Jardim de Sá et al., 1993; Trindade et al., 1993; Trindade et al., 1995a, 1995b). The structure was responsible for the re-working of the older gneiss-migmatite basement complex, as well as the younger meta-sedimentary unit which form parallel E-W and NE-SW oriented belts, sometimes reduced to isolated blocks surrounded by mylonite to ultramylonite zones. Various granitoid bodies were intruded during the shearing. The shear zone is a focus for negative gravity anomalies, which show that the RPSZ has lithospheric scale and that crustal thinning also occurred (Lins et al., 1993).

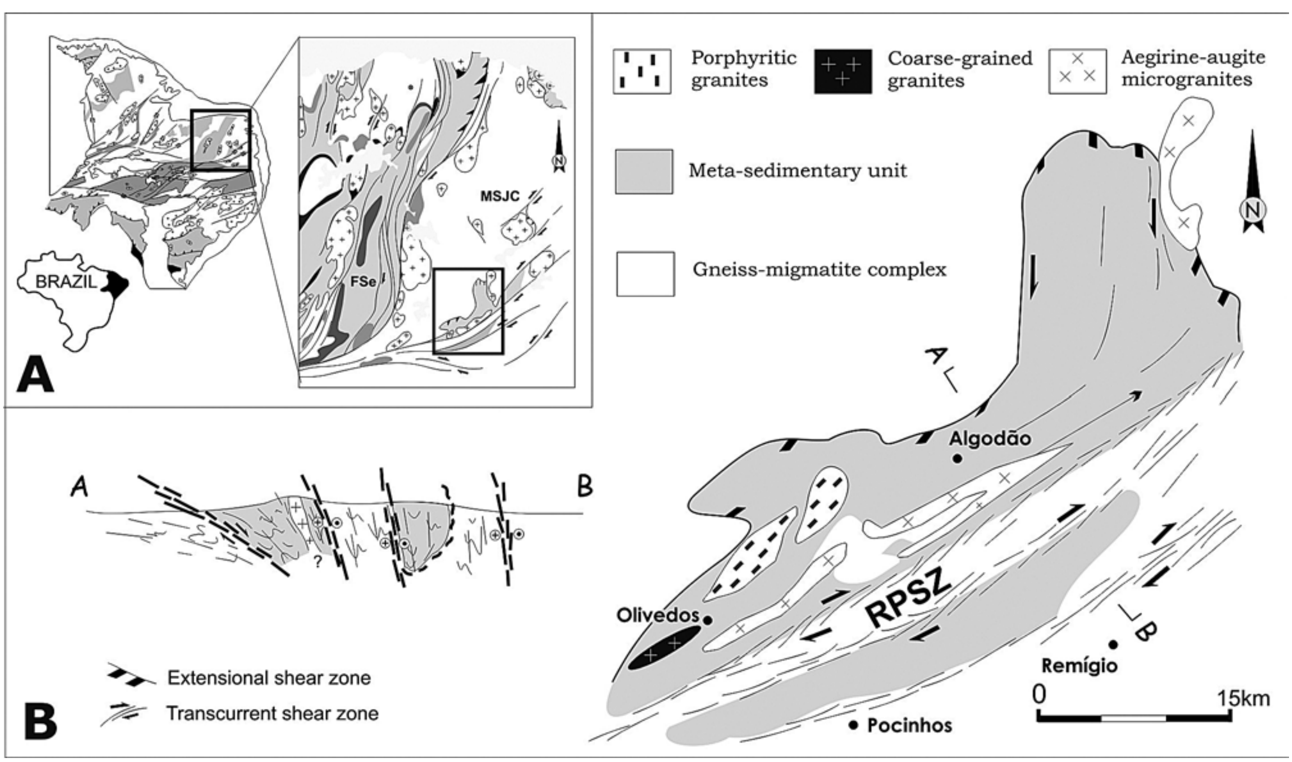

Figure 1. A. Location of the RPSZ relative to the Seridó meta-sedimentary belt (FSe) and the gneiss-migmatite basement of the São José do Campestre massif. Modified from Jardim de Sá (1994). **B.** Geological sketch map showing section A - B which is about 26 km long and crosses the RPSZ. Modified from Souza and Jardim de Sá (1993).

The gneiss-migmatite basement complex is composed of meta-granitic to meta-tonalitic rocks, which underwent gneissification, migmatization and, less frequently, granulitization. It was intruded by pegmatite dykes, granites and, less frequently, basic dykes, which are now amphibolites. The meta-sedimentary unit is mainly composed of mica-schists with subordinate paragneisses and lenses of marble and calc-silicate rocks. Both the basement and supracrustal rocks exhibit a shallow angle fabric, whose dip becomes steeper, and finally vertical, towards the higher strain zones in the south (Figure 2A). This structural evolution is accompanied by an increase in metamorphic grade. The mica-schists become migmatized with the formation of millimeter to centimeter-wide bands of granitic leucosomes parallel the schistosity. Garnet-bearing leucogranitic sheets, probably formed by partial melting of meta-sediments, are also concordant with the foliation. They form boudins with mylonitic fabrics (Figure 2B).

Kinematic indicators in the mica-schists include sigmoidal boudins, S-C foliations, and asymmetry of pressure shadows in andalusite, garnet and cordierite porphyroblasts, which demonstrates extensional movement with top to SSW (Trindade et al., 1993; Trindade, 1995). This sector is termed “extensional domain” (Figure 2B). This extension is also seen in the gneiss-migmatite basement complex through the presence of granite boudins and the asymmetry of feldspar augen. The foliation becomes progressively steeper southwards and adopts the direction N65ºE with a deflected, shallow rake stretching lineament in the centre of the structure (Figure 2A).

In the central zone, basement orthogneisses and anatectic products in the mica-schists have kinematic indicators appropriate to dextral movements (Figure 2B). There is kinematic continuity between the northern and central zones. The overall presence of syn-kinematic granitic sheets and high-temperature low-pressure metamorphic mineral assemblages also points to this continuity (Trindade et al., 1995a).

The mylonite zones are more widely spaced in the northern part of the RPSZ, whereas in the transcurrent sector, they form a 8 km-wide belt which controls the contacts between basement and meta-sediment slices. Large-scale folds with axial planes parallel to the neighboring mylonites occur north and south of the system, while folds with oblique axial planes are present in the transcurrent sector. The folds developed together with, or after the shearing (Trindade et al., 1995a).

Brasiliano-age granites in the RPSZ are syn-kinematic, and were emplaced parallel to its structural trend (Figure 3). The syn-kinematic character of the intrusions is indicated by their sigmoid form, which is concordant with the dextral kinematics of the shearing, and by the development of a solid state PFC fabric (Hutton, 1988), which evolved from a SPD magmatic fabric. Preferred magmatic orientations such as the stacking of feldspar phenocrystals are observed inside the plutons and coincide with the orientations of feldspar

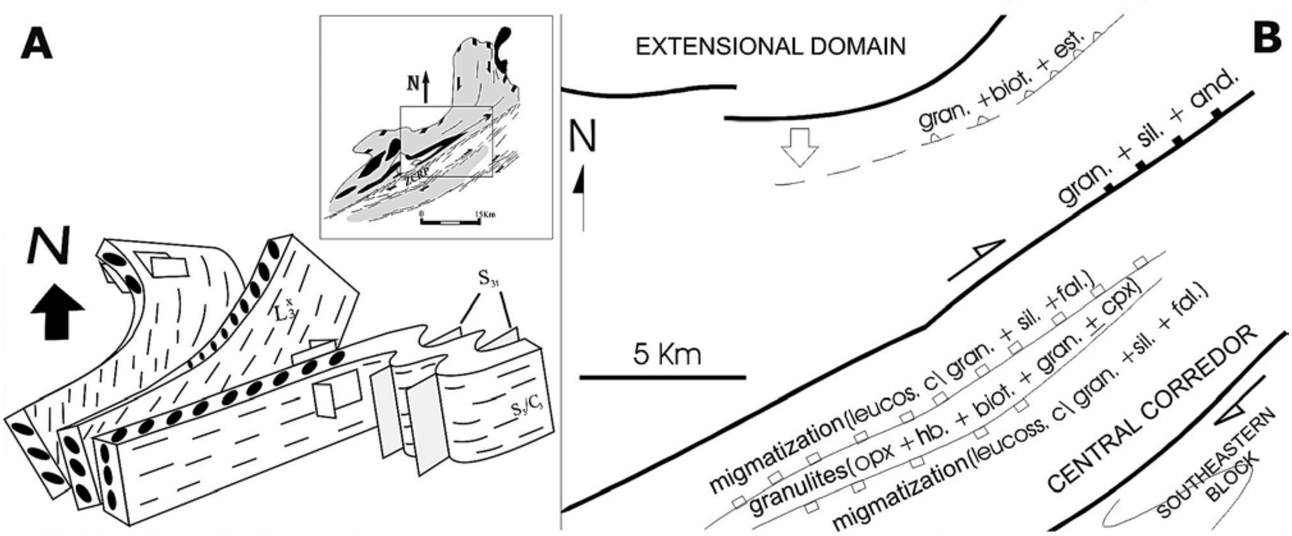

Figure 2. A. Geometry and kinematics of the RPSZ. Note the northern extensional component, which evolved in the south to trancurrent with progressive steepening of the shears together with shallower stretching lineations (after Trindade, 1995). **B.** variation of metamorphic parageneses in the RPSZ according to Trindade (1995): **gran** = garnet; **sil** = sillimanite; **est** = staurolite; **biot** = biotite; **and** = andaluzite; **fal** = alkaline feldspar; **opx** = orthopyroxene; **hb** = hornblend; **cpx** = clinopyroxene.

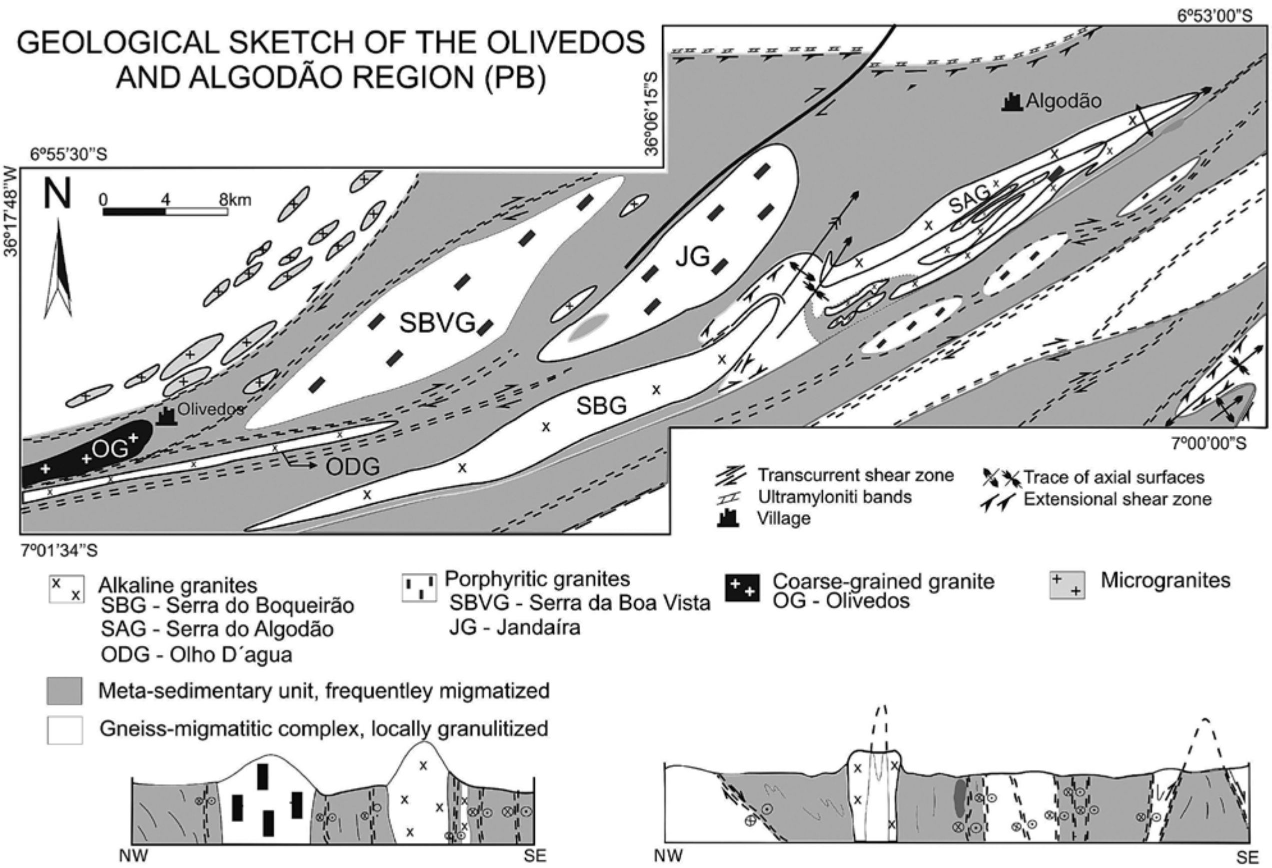

Figure 3. Granites associated with the RPSZ, modified from Trindade (1995) and Araújo (1995). The left-hand section is about 22 km long and cuts the Serra da Boa Vista and Serra do Boqueirão granites. The right hand section is about 32 km long and passes through Algodão village.

porphyroblasts at the borders, as well as the orientation of those present in the anatectic material from the host rocks. The fabrics are concordant with the foliation in the host rocks (Trindade et al., 1995b).

GRANITES ASSOCIATED WITH THE RPSZ

The syn-shear granites are elongated along the NE-SW direction and crop out individually over less than 30 km^2. They may be divided petrographically into five groups: porphyritic titanite-biotite granite, coarse-grained biotite granite, biotite microgranite, alkaline granite, and aluminous granite (Figure 3). We found no field evidence to establish a relative chronology of intrusion. For the following descriptions, modal compositions were obtained by conventional point counting, while feldspar and pyroxene compositions were analysed by electron microprobe at the *Universidade de Brasília*.

The porphyritic titanite-biotite granite *sensu lato* occurs in the Serra da Boa Vista (SBVG) and near Jandaíra (JG). Both granites intrude the metasedimentary unit. An imprecise Rb-Sr whole rock isochron age of about 550 Ma was obtained by Nascimento (1998). The outcrop pattern of SBVG is sigmoid, whereas that of JG is *en cornue*. In both cases, the outcrop shape is coherent with the inferred direction of movement along the shear zone. A number of sheets of this granite type with metric to decametric widths are also found in the central part of the shear zone (Figure 3).

Apart from slightly porphyritic types with feldspar phenocrystals that reach lengths of 1.5 cm, the textures of the SBVG also include coarse equigranular versions. Compositions range from quartz monzodiorite to more differentiated monzogranite. The composition of plagioclases in the SBVG is more calcic ($An_{29\text{-}24\%}$) than that in the JG, while the alkali feldspar compositions are practically identical ($Or_{>92\%}$). The mafic mineral content varies from 4 to 20 vol.% (Figure 4). In the JG, grey to pink monzogranite with mafic mineral content between 9 and 15 vol.% is the major rock type. The length of the feldspar phenocrystals reach 3 cm. The plagioclase composition is $An_{22-17\%}$.

In both intrusions, biotite, titanite and magnetite are the major mafic phases, while amphibole, zoned allanite, zircon and apatite are accessories. Alteration products are white mica, carbonate minerals and chlorite.

Both the SBVG and JG have fabrics developed in the viscous state during intrusion, as well as during solid state deformation, when continuous mylonitic zones were formed inside the intrusions. In the zones with N40°E direction, subhorizontal lineations of mafic minerals and stretched quartz and feldspar porphyroclasts/blasts are present. The sheets which occur south of the Serra do Boqueirão alkaline intrusion are highly deformed, and are now augen mylonites or ultramylonites (Figure 5A).

The SBVG contains mega-xenoliths of the gneissic host rocks, while the JG has mega-xenoliths of the surrounding mica-schists. Circular to ellipsoidal microgranular mafic enclaves with contacts that are mainly diffuse sometimes incorporate feldspar phenocrystals from the surrounding granite, giving rise to mingling textures or structures (Figure 5B). Examination of the whole population of enclaves reveals color differences that range from light to dark, as well as different abundances of incorporated feldspar phenocrysts, which suggests that different degrees of mixing occurred, resulting in the formation of intermediate-composition rocks.

The Olivedos intrusion (OG), which is located at the western extremity of the studied area near the homonymous city, is composed of coarse-grained biotite granite. Its outcrop pattern is *en cornue*, and its southern contact is delimited by a shear zone. An imprecise Rb-Sr whole rock isochron age of about 525 Ma has been obtained by Nascimento (1998). Like the porphyritic intrusions, the OG hosts elongated mafic microgranular enclaves (Figure 5C), which sometimes repeat the mingling textures and structures already described. The OG rocks are light grey or off-white, leucocratic with mafic mineral content between 4 and 10 vol.%, medium to coarse-grained, inequigranular but without great overall difference. Most rocks are monzogranite, but one granodiorite sample was encountered (Figure 4). The plagioclase composition is oligoclase $An_{17-18\%}$, while the alkali feldspar is $Or_{>93\%}$. Accessory minerals are biotite, ilmenite, allanite, zircon and apatite, while white mica, carbonate minerals, epidote, and chlorite are alteration products. Although preferred mineral orientations were imposed in the viscous state, most orientations are due to solid state deformation which led to the development of a sub-vertical N76°E foliation with a sub-horizontal lineation. The kinematic indicators present inside the pluton include conjugate S-C foliations, asymmetric feldspar porphyroclasts and enclaves, and indicate dextral movements concordant with the RPSZ. Granite dykes and pegmatite veins cut the structures.

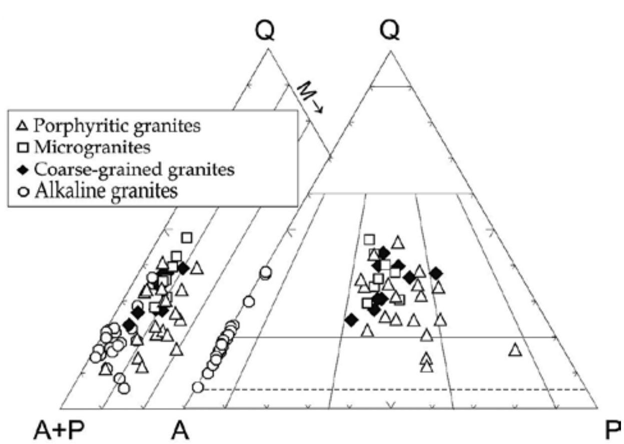

Figure 4. Modal compositions of granites in the RPSZ according to the classification of Streckeisen (1976).

Biotite microgranite forms small sheets in the NW extremity of the area near Olivedos town (Figure 3). Their orientation is N45°E, and they mainly intrude the basement rocks, although some are found in the meta-sedimentary unit. The rocks are very homogeneous, light grey leucocratic, fine-grained monzogranite (Figure 4) with small amounts of mafic mineral, including biotite, undifferentiated opaque oxide minerals and titanite. Allanite, zircon and apatite are other accessory minerals, and the usual alteration products are also present.

Stretched quartz grains and oriented mafic minerals define a sub-horizontal lineation contained within the sub-vertical foliation which is quite penetrative in the intrusion. The kinematic indicators conform to the overall kinematic features of the RPSZ.

In the southern part of the study area, small sheets of aluminous granite cut both the meta-sedimentary and basement units. The fine to medium-grained monzogranites or granodiorites contain two micas and sometimes garnet and sillimanite as well. They are believed to be products of anatexis of meta-sediments during the shearing episode, and were strongly deformed by folding or boudinage. They could not be shown at the scale of Figure 3 due to their small size and were not studied in greater detail due to their restricted volume.

Aegirine-augite microgranite forms the Serra do Boqueirão granite (SBG) in the central-southern part of the area, and the Serra do Algodão granite (SAG) in the east part (Figure 3). The high total alkalis content (see later) is a classic sign of alkalinity (Tomkieff, 1983), but does not

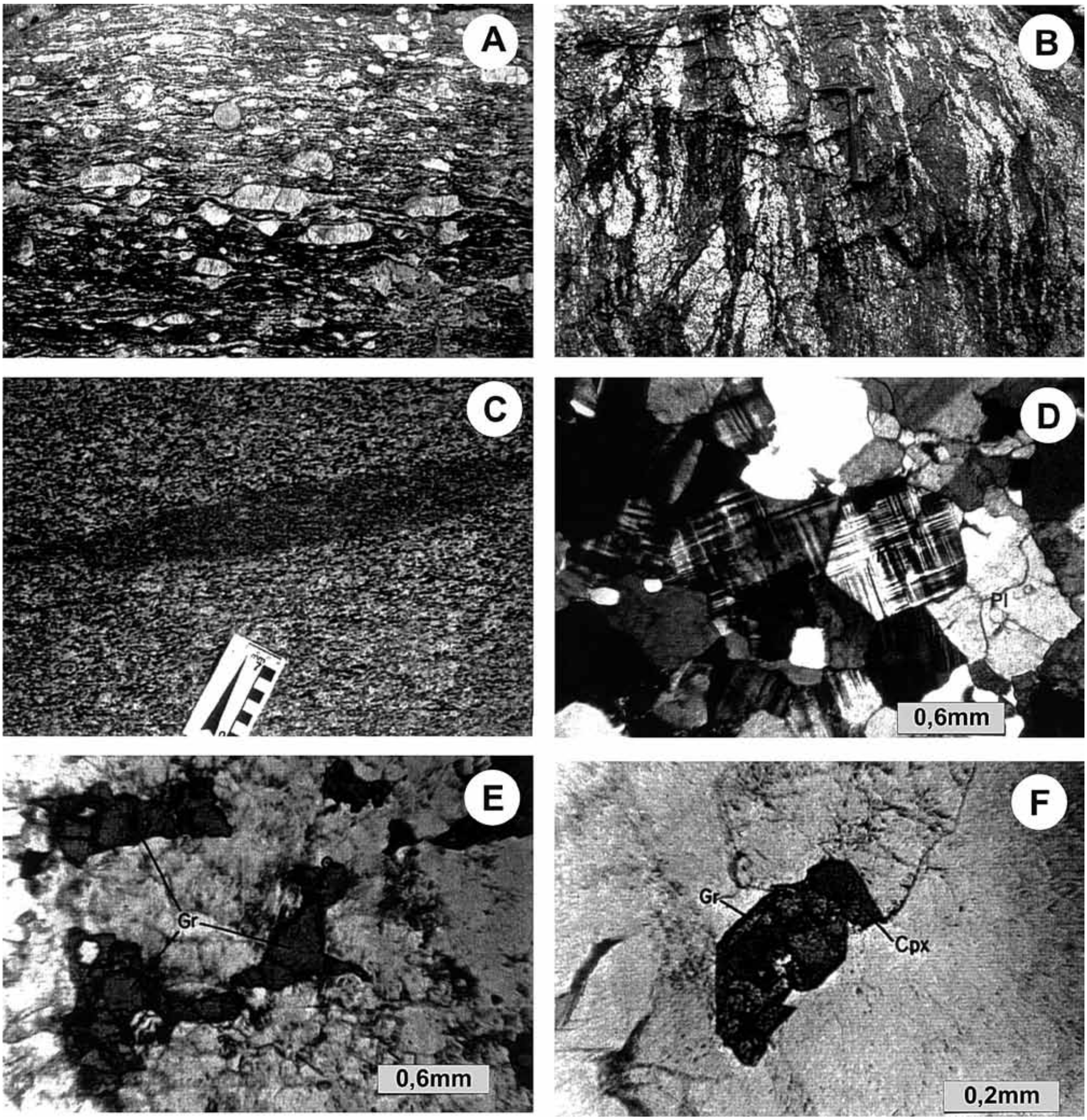

Figure 5. A. Mylonitic porphyritic granite from a sheet located south of the Serra da Boa Vista with augen and recrystallized K-feldspar phenocrystals about 3 cm long, whose geometry indicates dextral movements. **B.** Mechanical mixing of magmas with superposed transcurrent shear deformation at the eastern contact of the JG. The width of the outcrop is about 3 m. **C.** Field aspects of the OG at the northeastern contact, showing an elongated mafic enclave along the S plane, which indicates dextral movement. **D.** Polygonal K-feldspar crystals from the SAG. **E.** Late-stage interstitial skeletal garnet from the SAG. **F.** Hypidiomorphic garnet surrounding clinopyroxene in an arrangement which suggests a peritectic reaction (SBG).

mean that they are alkaline granites in the traditional sense of the term, which usually implies a peralkaline character. An imprecise Rb-Sr whole rock isochron age of 530 Ma has been obtained by Nascimento (1998). The intrusions are elongated and parallel to the shear zones, which define the limits of the northern extensional segment and the southern trancurrent segment. The SAG has an isoclinal antiform structure (Trindade et al., 1995a, 1995b). Alkaline granites also form sheets emplaced within the shear zones, of which the most important is the 8 km long Olho d´Água granite (OAG) located at the south-western extremity of the area. The alkaline intrusions mainly cut the meta-sedimentary unit, although some cut the basement. Mylonitic xenoliths of the two host-rock types are sometimes encountered.

The rocks usually have a sub-vertical foliation, which is present in the borders of the larger bodies and contains a sub-horizontal lineation defined by mafic minerals and stretched quartz grains. Quartz veins injected parallel to the C plane have an internal foliation parallel to the S plane, thus defining dextral kinematics concordant with that found in the RPSZ.

The rocks of the SAG, SBG and OAG are very similar. They are leucocratic, off-white, equigranular, fine to medium-grained, and contain albite ($An_{<1}$ in SAG and $An_{1.8\text{-}4.6}$ in SBG) and orthoclase $Or_{>92}$ (Figure 5D). Their compositions range from alkali-feldspar quartz syenite to alkali-feldspar granite. Important minor phases are clinopyroxene, of which most crystals were identified optically and by electron microprobe analysis as aegirine-augite, with Q (Wo + En + Fs) approximately 67%, Ae ($NaFe^{3+}Si_2O_6$) approximately 33%, and insignificant Jd ($NaAlSi_2O_6$) contents, when not accompanied by andradite (Figure 5E). Where andradite is present, the clinopyroxene is hedenbergite or (sub-calcic) augite (Figure 5F). Titanite and undifferentiated opaque oxide minerals are also minor phases, while accessory minerals are hornblende, allanite, apatite and zircon. Optical signs of compositional zoning of the major, minor and accessory silicate minerals are usually not seen. Dark minerals comprise less than 13 vol.% (Figure 4).

GEOCHEMISTRY OF THE GRANITES

In order to reinforce the grouping of the granites, which was based on field relationships and petrographic features, 40 samples selected from the four major types - porphyritic granite, coarse-grained granite, microgranite and alkaline granite - were analyzed for major and trace elements (Table 1), and 11 of these were also analyzed for rare earth element (REE) contents (Table 2). Major and most trace elements were analyzed by X-ray fluorescence at the *Laboratoire de Petrologie et Tectonique* of the *Université Claude Bernard*, Lyon, France, while the REE were analyzed at the *Centre de Recherches Pétrographiques et Géochimiques-CRPG/CNRS,* Vandoeuvre, France.

Chemical typology of the granites

Harker diagrams (Figure 6) reveal the separate groupings and trends of the different granite types. The trend of the alkaline granites is different from those of the other groups, and the latter may show different trends according to the elements chosen to demonstrate the variation. The microgranites and coarse-grained granites both show positive correlations between Na_2O and SiO_2 and negative correlations between K_2O and SiO_2, when their concentrations of Rb and Nb are higher. These two granite types are very similar, although the coarse-grained type is richer in Nb and Y, and poorer in Zr (Figure 6).

The coarse-grained granites and microgranites are slightly peraluminous, with alumina saturation indices between 1.0 and 1.1, largely because CaO contents are very low (Figure 7A). The porphyritic granites are similar, although one sample, with a higher-than-normal modal content of hornblende (1.85 vol.%), possibly as a result of more accumulation of heavy minerals in the magma chamber, which results in a CaO content of 3.62%), is metaluminous. The alkaline granites are slightly peraluminous (molar $Al_2O_3/(CaO + Na_2O + K_2O) \leq 1.1$) or metaluminous, although one sample, with a total alkalis content of about 15%, is peralkaline.

TAS and R_1-R_2 diagrams (Figure 7C and 7D) are very effective in showing up the differences between the groups. The separation between evolved alkaline and sub-alkaline granites is best shown in the TAS diagram using the limit defined by Middlemost (1985) on the basis of the chemical analysis of rocks with accompanying petrographic analyses. This limit coincides with the trend proposed by Lameyre (1987) for silica-saturated alkaline suites. Rocks from the SAG, SBG and OAG are clearly alkaline (alc). The others are subalkaline and display a monzonitic trend (mz). In the R_1-R_2 diagram, the SAG, SBG and OAG rocks are alkaline and highly evolved, while the others also show monzonitic affinities in this diagram.

Petrogenetic aspects

The amount of data for the microgranites and the OG is limited, and consequently these types will not be discussed here.

Harker diagrams show that Rb is incompatible, while V is compatible (Figure 6). In both cases, precise results are available. The logarithmic-scale diagrams (Figure 8) of Rb and V, and Rb and Sr for porphyritic granites

Table 1. Major and trace element analyses of selected samples of granites from the RPSZ. Intrusion codes: see text; **MicroG** = microgranite; Major and minor elements in weight %, traces in p.p.m. * Total includes between about 0.1% and 0.8% LOI, or between 0.07% and 0.18% H_2O^-.

Intrusion	OG	SBVG			JG		MicroG	SBG			SAG			
Sample	RN 13B	RN 29A	RN 27	RN 32	RN 38A	RN 39	RN 19	RN 03C	RN 08	RN 11	RN 40	RB 41	RN 42	RN 45A
SiO_2	74.89	60.59	66.20	74.25	69.08	71.65	73.2	70.31	72.31	72.29	69.20	71.50	70.38	71.76
TiO_2	0.16	0.81	0.44	0.22	0.46	0.37	0.19	0.08	0.07	0.07	0.08	0.06	0.09	0.07
Al_2O_3	13.17	18.38	17.06	12.83	15.61	13.59	13.63	15.94	15.14	15.07	15.05	15.62	14.86	14.76
Fe_2O_3t	1.73	5.I0	3.15	2.07	3.10	3.06	2.01	0.83	0.91	0.94	1.01	0.75	1.24	1.05
MnO	0.04	0.07	0.04	0.03	0.05	0.05	0.04	0.02	0.01	0.03	0.02	0.03	0.02	0.03
MgO	0.27	1.55	0.95	0.28	0.91	0.55	0.24	0.08	0.09	0.08	0.14	0.12	0.15	0.05
CaO	1.04	3.42	2.16	0.60	1.66	1.30	1.23	0.43	0.47	0.27	0.30	0.24	0.32	0.43
Na_2O	3.42	4.67	4.18	3.17	3.84	3.27	3.12	4.48	4.50	5.15	3.48	5.20	3.75	4.96
K_2O	4.66	4.22	4.72	5.38	4.53	4.79	5.29	6.60	5.35	5.14	10.42	5.53	7.03	5.29
P_2O_5	0.04	0.31	0.26	0.06	0.21	0.10	0.05	0.20	0.08	0.03	0;05	0.02	0.12	0.02
Total *	99.56	99.25	99.27	99.02	99.55	98.84	99.11	99.12	99.08	99.15	99.83	99.23	98.37	98.84
Rb	394	81	155	118	118	101	215	222	139	154	177	99	172	133
Sr	106	936	523	59	505	168	180	1205	1126	940	956	1394	866	724
Ba	386	3503	1743	234	1261	464	702	3980	3599	3036	7916	2732	4476	2582
V	23	67	46	22	44	28	24	27	29	25	44	n.d.	n.d.	n.d.
Zr	140	331	277	231	251	345	175	10.8	146	27.8	196	24	167	230
Nb	35.5	16.2	11.5	10.9	9.2	14.6	10.5	11.0	20.2	15.9	12.2	14.3	25.3	10.2
Ta	n.d.	0.45	0.49	n.d.	0.64	0.72	n.d.	1.26	0.99	0.95	1.19	1.12	2.12	0.69
Th	n.d.	2.65	12.3	n.d.	6.16	17.8	n.d.	0.36	7.37	5.12	2.95	0.97	8.41	2.13
U	n.d.	2.15	2.27	n.d.	0.95	10.9	n.d.	0.49	1.77	2.59	1.28	0.52	3.23	1.06

Table 2. Y and rare earth elements.

	SBVG		JG		SBG			SAG			
	RN 27	RN 29A	RN 38A	RN 39	RN 03C	RN 08	RN 11	RN 40	RN 41	RN 42	RN 45A
Y	13.7	18.2	9.1	16.5	4.2	8.9	11.8	7.2	n.d.	n.d.	n.d.
La	59.85	37.94	147.8	60.65	3.74	8.7	12.22	11.74	5.97	19.73	10.56
Ce	100.1	75.52	240.8	109.8	8.45	15.04	21.84	19.95	8.56	32.13	18.10
Pr	11.56	8.61	25.49	11.86	1.20	12.71	2.52	2.12	1.10	3.40	1.89
Nd	41.33	33.74	82.30	43.52	4.74	5.92	8.82	6.78	4.59	12.10	6.55
Sm	7.03	6.20	8.49	7.00	1.12	1.17	1.79	1.12	0.86	2.13	1.16
Eu	1.96	2.36	1.19	1.34	0.85	0.84	0.95	0.81	0.81	1.34	0.75
Gd	4.59	4.34	4.95	5.42	0.80	0.80	1.33	1.01	0.82	1.72	0.97
Tb	0.58	0.59	0.67	0.65	0.14	0.15	0.24	0.14	0.13	0.25	0.14
Dy	2.62	3.02	2.93	3.22	0.77	0.88	1.50	0.85	0.70	1.40	0.73
Ho	0.43	0.55	0.44	0.58	0.14	0.16	0.31	0.16	0.13	0.29	0.13
Er	1.00	1.48	1.23	1.62	0.35	0.48	0.85	0.50	0.31	0.81	0.41
Tm	0.095	0.20	0.15	0.21	0.047	0.091	0.15	0.079	0.037	0.13	0.076
Yb	0.57	1.46	1.08	1.29	0.36	0.62	1.21	9.54	0.35	0.88	0.59
Lu	-.093	0.22	0.18	0.23	0.086	0.11	0.18	0.086	0.045	0.13	0.11

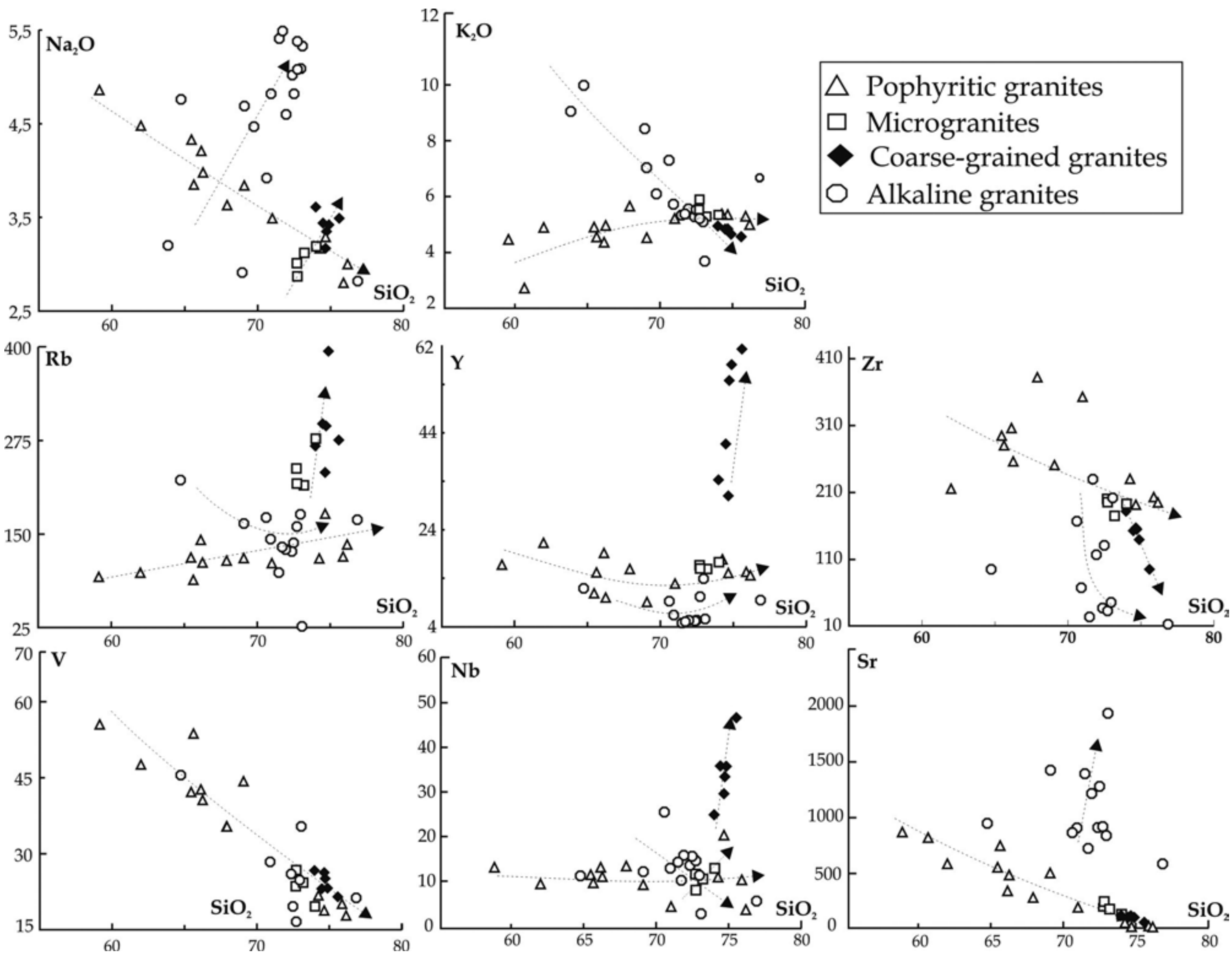

Figure 6. Harker variation diagrams for some major and trace elements in granites of the RPSZ.

show vertical trends suggestive of dominant fractional crystallization during magmatic differentiation, the former controlled by ferromagnesian minerals, the latter involving plagioclase and perhaps apatite.

Using the analytical data (Table 2), Harker diagrams (Figure 6) and spidergrams (Figures 9 and 10), it is possible to evaluate the nature of the fractionated mineral phases. Apatite fractionation is shown by the dramatic reduction of P_2O_5 concentrations with increasing SiO_2 content in the SBVG, SBG and JG. Using similar reasoning for Ti, Fe and Mg, it is probable that amphibole, biotite and titanite were also fractionated. Zr shows a behavior compatible with early zircon undersaturation, followed by compatible behavior when the zircon saturation point is reached at a SiO_2 content of approximately 70%.

Chondrite-normalized REE patterns for the porphyritic granites have light REE enrichment relative to heavy REE which have a more horizontal slope (Figure 9A). The light REE enrichment may have been caused by the practically constant presence of titanite and allanite in the rocks. Eu anomalies range from slightly positive (Eu/Eu* = 1.3) to moderately negative (Eu/Eu* = 0.5), suggesting that variable accumulation or fractionation of feldspars occurred.

Chondrite-normalized spidergrams for the porphyritic rocks show positive anomalies for La, Ce, Nd and Zr, and negative anomalies for Nb, Ta, P, Ti (the last two, very pronounced), and, in some samples, for Sr as well (Figure 9B). While the positive anomalies can be reconciled with the presence of minerals which concentrate light REE, and most of the negative anomalies reflect crystal fractionation already discussed here, the negative Nb and Ta anomalies may reflect the influence of an essentially supra-subduction environment.

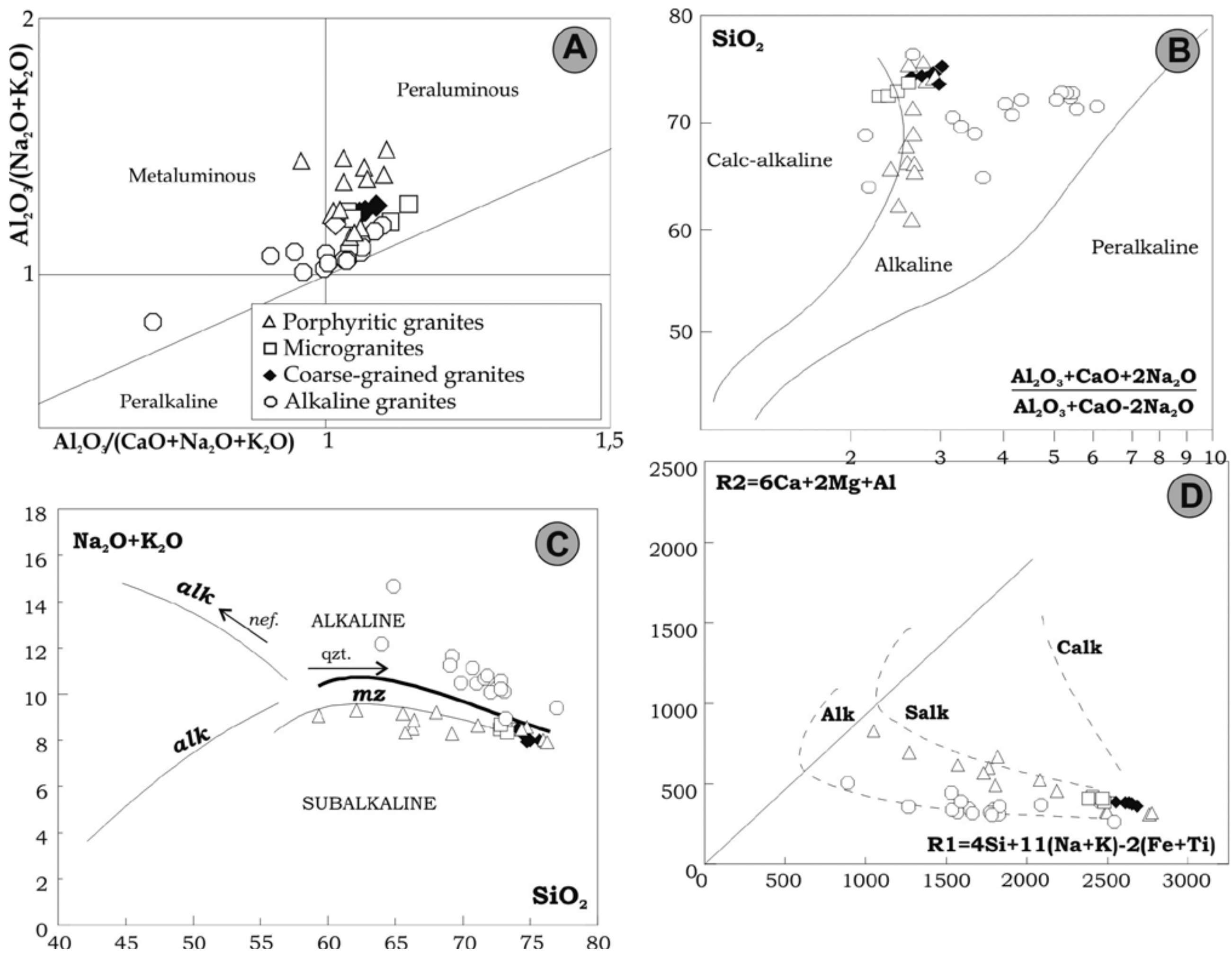

Figure 7. A. Alumina saturation (Shand) index with fields suggested by Maniar and Piccoli (1989). **B.** Alkalinity *vs.* SiO_2 after Wright (1969), showing the transitional character of some of the porphyritic granites. **C.** TAS diagram. See text for discussion of divisions and trends. **D.** R_1-R_2 diagram according to La Roche et al. (1980).

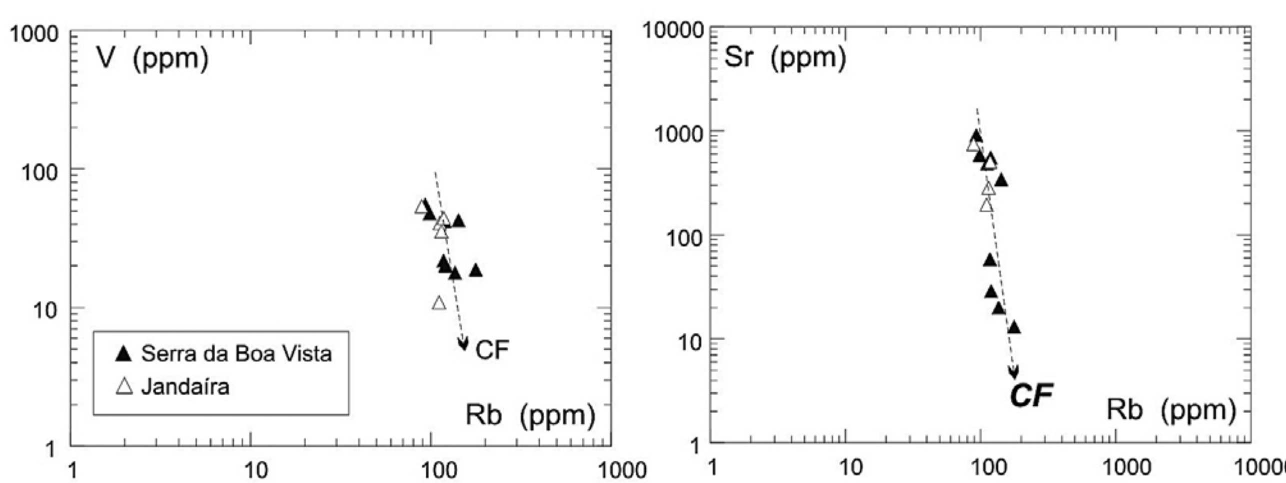

Figure 8. Logarithmic-scale diagrams of incompatible element Rb *vs.* compatible elements V and Sr for the porphyritic granites.

REE patterns for the alkaline granites are enriched in light REE relative to heavy REE and have strong positive Eu anomalies with Eu/Eu* between 1.8 and 2.9 (Figure 10A), the latter probably due to the predominance of feldspars in the modes as a result of accumulation during magmatic differentiation. Chondrite-normalized spidergrams confirm the accumulation of feldspars by the strong relative enrichment of Sr, while Ti and P depletion indicate that Ti-bearing minerals and apatite were either retained in the refractory residue during partial melting or fractionated during crystallization (Figure 10B).

Crystallization conditions

Schmidt´s calibration (1992) of the relationship between the pressure of crystallization and the aluminium content in hornblende shows that the porphyritic granites solidified under pressures of approximately 6 kbar (Nascimento, 1998). The temperature of crystallization calculated using the partition of Al^{IV} between hornblende and plagioclase (Blundy and Holland, 1990) is approximately 750ºC, while values found using the zircon saturation geothermometer (Watson and Harrison, 1984) are in the range of 810ºC - 850ºC. The divergence between the two estimates may be due to slight zircon accumulation in the analysed porphyritic granites. The zircon saturation geothermometer indicates temperatures between 750º and 800ºC for the coarse-grained granite, and between 600º and 800ºC for the alkaline granites.

No geobarometers were available to estimate the pressure of crystallization of the coarse-grained and alkaline granites. The presence of relatively un-resorbed epidote implies that crystallization started at pressures around REF.

Using the obtained pressure and temperature, the calculation proposed by Wones (1989) shows that the titanite + magnetite + quartz paragenesis present in the porphyritic granites crystallized at $\log fO_2$ around - 14.5.

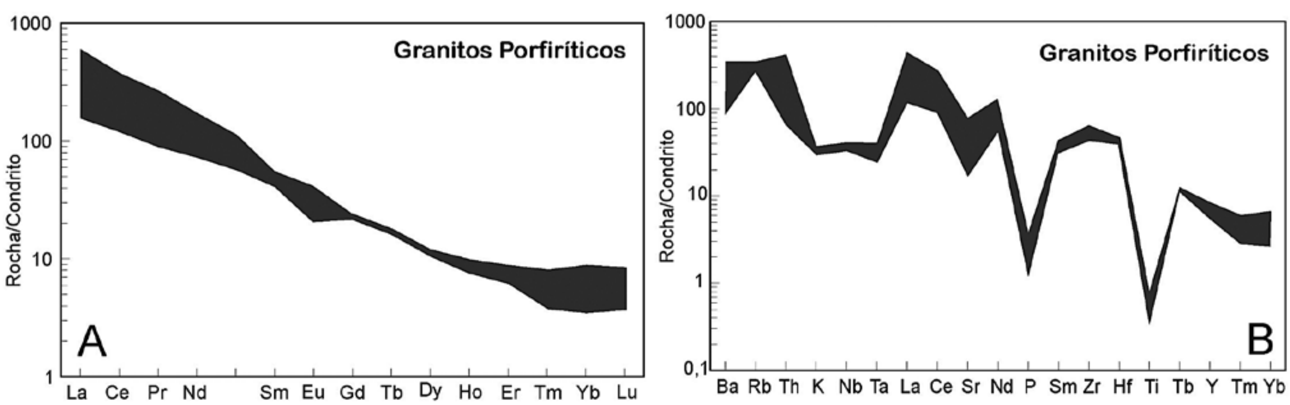

Figure 9. A. Chondrite normalized (Evensen, Hamilton, O´Nions, 1978) REE diagram for the SBVG and JG. **B.** Spidergram for porphyritic rocks using the chondrite composition of Thompson (1982).

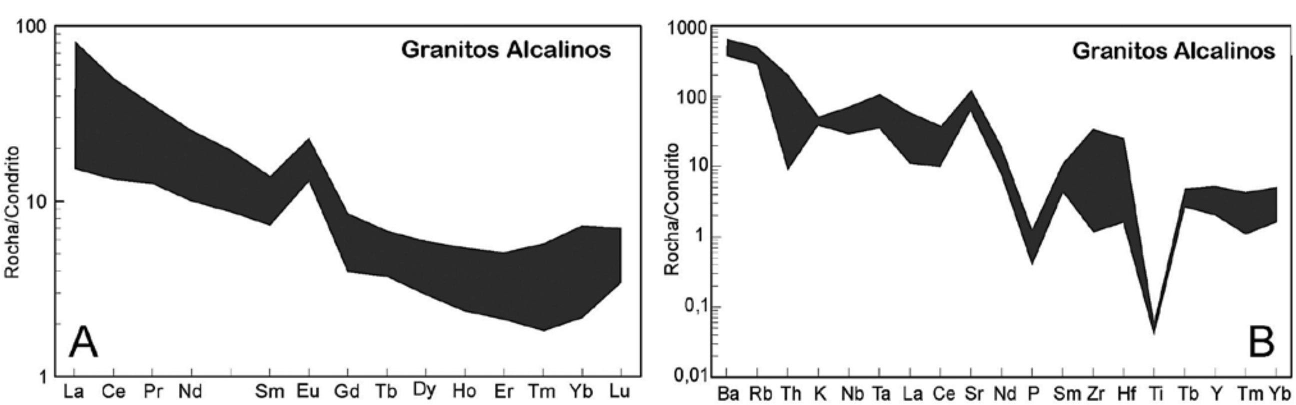

Figure 10. A. Chondrite-normalized (Evensen, Hamilton, O´Nions, 1978) REE patterns for the alkaline granites. **B.** Chondrite-normalized (Thompson, 1982) spidergrams for the alkaline granites.

DISCUSSION AND CONCLUSIONS

The schemes presented by Chappel and White (1974), Loiselle and Wones (1979), and White (1979) which related granite types to the nature of their source rocks are well-known, and the limitations of the I, S, A and M "letter soup" system have been emphasized by many critics. The facts point to the important participation of magma differentiation processes in determining the variety of quartz-feldspathic rocks distinguished by the nature of the ferromagnesian minerals present (Frost et al., 2001; Bonin, 2007). Nevertheless, the typology schemes are still quite useful in the case of the granites associated with the RPSZ.

The SAG, SBG and OAG alkaline rocks have anhydrous mineral assemblages, high Fe/Mg ratios, low CaO and MgO contents, and high concentrations of Ga and Nb, features which are rather typical of A-type granites (White and Chappel, 1983; Whalen, Currie, Chappel, 1987). As far as this denomination is concerned, the "A" used for the studied granites only signifies alkaline. Although the granites may have been intruded during early extensional phases of shear zone development, they have obviously been affected by orogenic processes. On the other hand, the high Sr and Ba contents were not previously seen to be typical of this granite type, although Bonin (1990, 2007) demonstrated that syn to late-tectonic A-type granites are relatively enriched in these elements when compared to the anorogenic types.

Apart from Bonin´s recent contribution (2007), Eby (1990, 1992), Dall´Ágnol et al. (1999) and Dall´Agnoll and Oliveira (2007) also noted chemical complexities in the A-type. Eby used the Zr/4-Y-Nb diagram to characterize the mantle or crustal source of the alkaline rocks. The separation is defined by the Y/Nb ratio = 1.2. In our rocks from the SBG (9 samples) and SAG (1 sample), the concentrations of Zr and Y are relatively low, while the Nb concentrations probably depend mainly on the modal proportion of titanite, a phase that concentrates Nb. These concentrations vary from nearly zero (recorded as not determined) to trace quantities up to 1.22 vol.%. In rocks with traces or practically no titanite, TiO_2 contents vary from 0.03 to 0.15 wt.%, while Nb concentrations range from 2.7 to 5.5 p.p.m., whereas in rocks with larger quantities of titanite, TiO_2 contents are up to 11 - 15 p.p.m. (Table 3). We are unable to identify the cause of the exceptions, although it is obvious that the precision of determination of low modal proportions of accessory minerals and TiO_2 concentrations close to the limits for quantitative analysis must have some effect. Eby´s criteria are therefore not very useful to identify the possible source rocks.

When comparisons are made between the alkaline granites of the RPSZ and other A-type granites in the Seridó, it is seen that, in the eastern part of the belt, the Sr and Ba contents of the syn-orogenic rocks of Japi (Hollanda, 1998) and Caxexa (Nascimento, 2000) are similar, while in the western part of the belt (Umarizal: Galindo, 1993; Galindo et al., 1995; McReath, Galindo, Dall´Agnol, 2002) they are different. It is also worth noting that in the Transverse Zone of the Borborema Province, the rocks of the syn-orogenic A-type granite of Catingueira (Galindo and Sá, 2000) also have Sr and Ba contents similar to those of the RPSZ A-type rocks.

As already noted, the porphyritic rocks of the SBVG and JG, the rocks of the OG and the microgranites are peraluminous due to low CaO contents rather than to high Al_2O_3 contents. This is a reflection of the mineralogical compositions, in which biotite is the main mafic mineral and amphibole is absent from the OG and the microgranites. In the SBVG, JG and OG, mafic microgranular enclaves are encountered. Ilmenite is present in the OG.

In spite of their aluminous character, which might be taken to indicate a meta-sedimentary source, the mineralogical and chemical compositions are closer to those of I-type granites, though different from the Cordilheira I-type in their high total alkalis content, which suggests a character transitional towards the A-type (see also Figure 7B). Transitional characteristics are also found in the rock suites present in Acari, Totoró, São José de Espinharas, Tourão-Caraúbas and Monte das Gameleiras in the Seridó belt, in which porphyritic granite is a dominant member (Jardim de Sá, 1994; Galindo et al., 1995; Antunes et al., 2000).

Table 3. Relationships between the Y/Nb ratios, the modal titanite contents and the TiO_2 concentrations in some alkaline granites from the RPSZ.

Sample	Y/Nb	Titanite, vol.%	TiO_2, wt.%
SBG			
RN-02A	1.06	1.22	0.15
RN-03C	0.38	0.14	0.08
RN-06	2.07	n.d.	0.06
RN-07	0.50	0.20	0.07
RN-08	0.44	0.10	0.07
RN-09B	1.73	trace	0.03
RN-10	0.39	0.90	0.07
RN-11	0.74	0.82	0.07
RN-16	1.23	n.d.	0.06
SAG			
RN-40	0.59	0.46	0.27

Petrogenetic aspects

We were unable to undertake a detailed study of the mafic to intermediate enclaves found in the porphyritic granites in order to test the possible role of mixing in their petrogenesis and their relationships with the porphyritic granites. In other porphyritic suites which contain mafic enclaves, the mafic and felsic end members were derived from different sources (Jardim de Sá, 1994; Neves and Vauchez, 1995; Antunes et al., 2000; Medeiros et al., 2008).

Although Loiselle and Wones (1979) believed that alkaline granites are the products of the differentiation of alkali basalt magmas, there is often little geological or geochemical evidence for the presence of basic rocks or possible differentiates. A number of authors (e.g., Barker et al., 1975; Bailey, 1978; Collins et al., 1982; Clements, Holloway, White, 1986) therefore proposed that alkaline granites are the products of partial melting of a relatively anhydrous source rock in the lower crust. Barker et al. (1975) proposed that basalt underplating provided the heat source necessary for the partial melting of granulite and produced hypersolvus peralkaline and subalkaline granites. Harris and Marrimer (1980) believed that mantle-derived, volatile-rich halogen-bearing fluids, which would promote the partial melting of the lower crust, would supply the high concentrations of alkali and high field strength trace elements that are frequently found in these rocks. Collins et al. (1982) and experimental studies of Clements, Holloway and White (1986) suggest that A-type granites are the products of high temperature partial melting of lower crustal rocks which were previously depleted of some elements by the extraction of I-type magmas.

Petrographic and geochemical features already presented for the alkaline rocks do not suggest that extensive differentiation was involved in the generation of these rocks, which is especially important if a mantle source is contemplated. In many ways, the RPSZ alkaline rocks are similar to those present in the Lachlan fold belt, Australia: metaluminous character, relatively high concentrations of Rb, Sr, Eu and Ba, and so on, which led King et al. (1996) to propose a lower crustal source.

For the RPSZ alkaline rocks, paleoproterozoic amphibolite-facies granodioritic to tonalitic gneiss-migmatites are hosts to many of the granites, and are locally granulitized in the shear zone. It is highly probable that granulitic equivalents of these rocks are present at depth, and their partial melting could produce the alkaline granites. The possibility that the sub-alkaline granitoids represent the products of previous extraction of I-type magmas before the melting of the granulitic residue remains to be tested by isotope studies and thermal modeling of the evolution of the shear zones, which almost certainly have deep roots reaching to mantle depths, thus providing access of mafic magmas and/or volatile-rich solutions to at least the lower crust.

ACKNOWLEDGEMENTS

The authors thank João Maria Martins Araújo for his help with the field work and useful discussions about the geology of the studied area. Drs. Emanuel Ferraz Jardim de Sá (UFRN) and Ricardo Ivan F. da Trindade (USP) also contributed with discussions and suggestions during the elaboration of the Masters dissertation of the first author. We would also like to thank Dr. V. P. Ferreira and an anonymous reviewer for the careful reading and helpful comments that helped to improve the manuscript.

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