Anais da Academia Brasileira de Ciências (2007) 79(3): 405-430
(Annals of the Brazilian Academy of Sciences)
ISSN 0001-3765
www.scielo.br/aabc

The Serra da Graciosa A-type Granites and Syenites, southern Brazil. Part 1: Regional setting and geological characterization

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Manuscript received on November 8, 2005; accepted for publication on August 23, 2006; presented by ANTONIO CARLOS ROCHA-CAMPOS

ABSTRACT

The Serra da Graciosa region includes important occurrences of granites and syenites of the Graciosa A-type Province (formerly Serra do Mar Suite), southern Brazil. Using fieldwork, petrography, and remote sensing imagery, we characterize the geology of the plutons in the region. Five individual plutons were recognized. Two correspond to the previously defined Marumbi and Anhangava Plutons. We divide the former "Graciosa Pluton" into three new plutons: Capivari, Órgãos, and Farinha Seca. The plutons are elliptical with northeast-southwest orientation. Two petrographic associations can be recognized: an alkaline association that includes peralkaline and metaluminous hypersolvus alkali-feldspar granites and syenites (Anhangava, Farinha Seca, Órgãos), and an aluminous association composed of metaluminous and weakly peraluminous subsolvus granites (Capivari, Órgãos, Anhangava, Marumbi). Occurrences of each association are limited to one individual pluton or to portions of a pluton, and the age relationships are not well established. Monzodioritic rocks are found marginal to the Órgãos and Farinha Seca Plutons, and interaction with silicic magmas locally produced hybrid quartz syenites (Farinha Seca Pluton). Geothermobarometry indicates emplacement at shallow crustal levels (P = 2 $\pm$ 0.6 kbar), and crystallization temperatures within the interval 900–700°C for the granitic and syenitic rocks, and 1000–750°C for the monzodioritic rocks.

Key words: Serra da Graciosa, A-type granites and syenites, Graciosa Province, Paraná State.

INTRODUCTION

The Serra da Graciosa region, eastern Paraná State, includes some of the most expressive occurrences of granites and syenites of a large A-type province in southern Brazil, originally referred to as the Serra do Mar Suite (Kaul 1984).

This province includes several granitic and syenitic plutons characterized by the coexistence of alkaline and aluminous A-type petrographic associations. The plutons are distributed along an arc that is subparallel to the coast, along the Serra do Mar escarpment, from the northeastern part of Santa Catarina State to the southeastern portion of São Paulo State. The plutons are intrusive mostly in Archean rocks of the Luiz Alves Microplate and in Neoproterozoic rocks of the Curitiba Microplate.

The plutons that outcrop in the Serra da Graciosa region were only subject to reconnaissance studies, and detailed information on the petrographic varieties present, as well as on the genetic relations among them, are completely lacking. The coexistence of alkaline and aluminous associations in post-collisional settings, as is the case of the Serra da Graciosa region, has generated continued interest in the international literature (e.g. King et al. 1997), what makes this region of interest for the understanding of the genetic relationships between these two petrographic associations.

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The purpose of this contribution is to detail the geology of the granitic and syenitic plutons in the Serra da Graciosa region. The results presented here are not only important as a foundation for a more complete petrologic study (Gualda and Vlach 2007a, b), but also lead to an improved understanding of the local geology.

THE GRACIOSA PROVINCE

Nomenclatural Issues

Hasui et al. (1978) were probably the first to recognize that the granitic rocks present along the Serra do Mar escarpment in eastern Paraná and southeastern São Paulo could be grouped into a coherent descriptive unit. They used the name Graciosa Facies for this group of occurrences, after the abundance of these rocks in the Serra da Graciosa region. They describe the Graciosa Facies as being characterized by granites of pronounced alkalinity (alkaline to subalkaline, including sodic amphibole and pyroxene), but also including granodiorites and biotite granites. Kaul et al. (1982) coined the term Serra do Mar Intrusive Suite to describe the series of 28 individual granitic "massifs" that crop out in the region extending from eastern Santa Catarina to southeastern São Paulo States (see also Kaul 1984). Since then, names like Serra do Mar Belt, Serra do Mar Province, and Magmatic Rocks of the Serra do Mar have been used rather informally (Vlach et al. 1991, 1996, Siga Jr et al. 1999, Kaul and Cordani 2000, Passarelli et al. 2004).

Unfortunately, the name Serra do Mar has also been used to describe a group of Mesozoic alkaline rocks in São Paulo State (the Serra do Mar Alkaline Province; Almeida 1983), and the definition of this latter province has precedence over the definition of Kaul (1984). Thus, we suggest the name Graciosa Province for the province of A-type granites and syenites in southern Brazil, following the original name used by Hasui et al. (1978). The name Graciosa has been used to describe one of the granitic occurrences in the Serra da Graciosa region; however, that unit requires redefinition (see below). In accordance with the Brazilian Stratigraphic Code (Petri et al. 1986), we suggest the name Graciosa be used for the Province, a stratigraphic unit of higher rank, while the plutons of the Serra da Graciosa region shall receive distinct names.

We also suggest that volcanic rocks directly associated with the granitic and syenitic rocks (e.g. volcanics in contact with granites in the Morro Redondo Complex; Góis and Machado 1992, Góis 1995) be included in the Graciosa Province.

In most references to date, authors have used the name massif for the individual plutonic units that form the Graciosa Province (e.g. "Anhangava Massif" of Fuck 1966). The term pluton is much preferred (Ulbrich et al. 2001) and should be used instead (e.g. Anhangava Pluton).

Regional Geology

Most plutons of the Graciosa Province are intrusive in rocks of the so-called "Joinville" Massif of Hasui et al. (1975), which is located between the Ribeira Fold Belt to the north and the Dom Feliciano Belt to the south (Figure 1). Both the Ribeira Belt (Hasui et al. 1975) and the Dom Feliciano Belt (Basei et al. 1987) were formed during the Brasiliano/Pan-African cycle, a collage that includes at least two important orogenies: Brasiliano I, with ages around 650–600 Ma, and Rio Doce, more recent, with ages in the interval 600–535 Ma (Campos Neto and Figueiredo 1995).

The term "Joinville Massif" was abandoned by Basei et al. (1992), who defined three independent tectonic units in the area: the Curitiba Microplate to the north, the Luiz Alves Microplate to the south, and the Coastal Granitoid Belt to the east (Figure 1; for details, see Basei et al. 1992, Siga Jr et al. 1993). The Curitiba Microplate is characterized by gneisses and migmatites formed during the Transamazonic Cycle (2.2–1.8 Ga) and migmatized during the Brasiliano (620–550 Ma), and also by deformed granitoids that yield Brasiliano ages (720 Ma U-Pb zircon ages, 580 Ma Rb-Sr ages). The Luiz Alves Microplate is dominated by granulitic gneisses formed during two main periods, one corresponding to the Transamazonic Cycle (2.2–1.8 Ga) and an older cycle with ages in the interval between 2.7 and 2.6 Ga. The Coastal Granitoid Belt is composed mostly of porphyritic monzogranites and two-mica leucogranites formed during the Brasiliano (615–570 Ma). Rocks from the Luiz Alves Microplate yield Transamazonic K-Ar ages, which leads to the conclusion that the block behaved as a craton during the Brasiliano Cycle (Mantovani et al. 1989, Siga Jr et al. 1990).

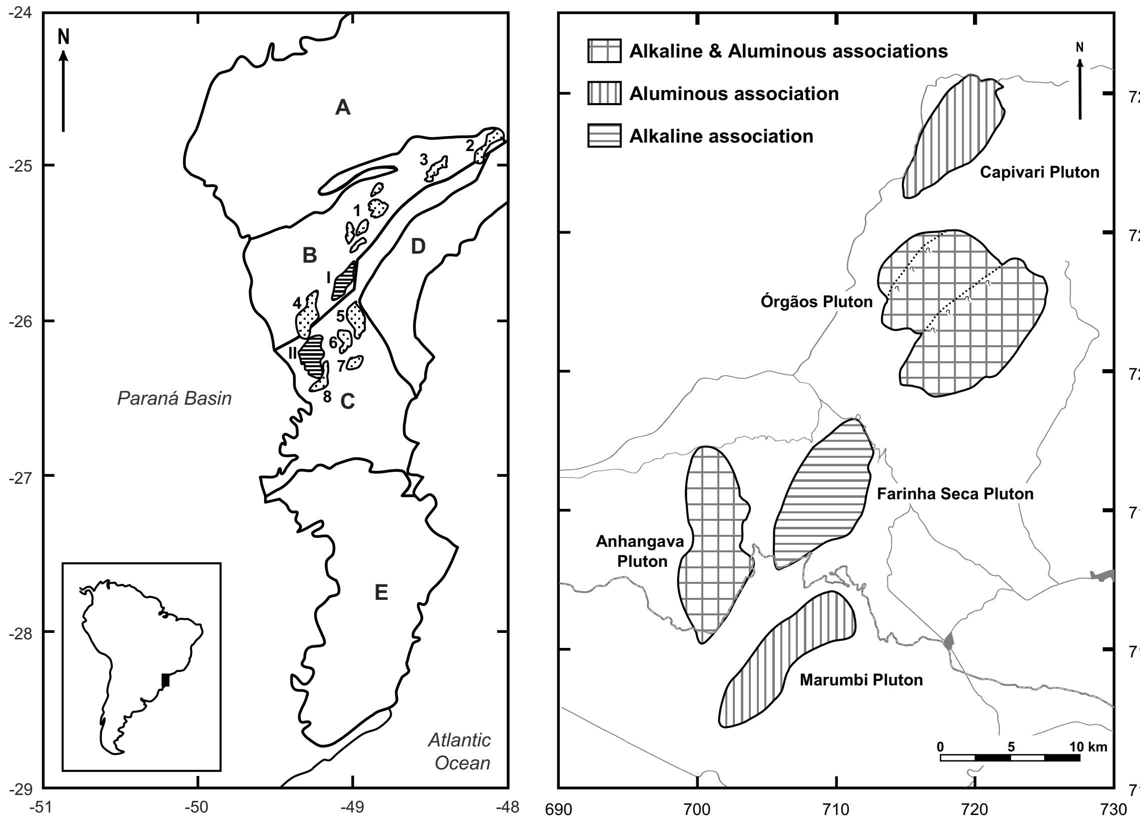

Fig. 1 – The Graciosa Province in southern Brazil (left panel). The main tectonic units in southern Brazil are indicated - A: Ribeira Fold Belt, B: Curitiba Microplate, C: Luiz Alves Microplate, D: Coastal Granitoid Belt, E: Dom Feliciano Belt. Eight main areas of occurrence of granitic rocks are shown – 1: Serra da Graciosa Granites, 2: Guaraú Pluton, 3: Alto Turvo Pluton, 4: Agudos Pluton, 5: Morro Redondo Complex, 6: Dona Francisca Pluton, 7: Piraí Pluton, 8: Corupá Pluton. Also shown are two important volcano-sedimentary basins – I: Guaratubinha Basin, II: Campo Alegre Basin. Notice the distribution of the plutons and volcano-sedimentary basins along an arch approximately parallel to the contact of the Coastal Granitoid Belt and the block formed by the Luiz Alves and Curitiba Microplates. Adapted from Hallinan et al. (1993). Geological sketch showing the outlines of the five individual plutons (right panel). All contacts are mostly inferred based on image analysis, with ground confirmation where possible. Patterns indicate the presence of the alkaline and aluminous associations in each of the plutons. Available data are not sufficient for the delineation of contacts between the areas of occurrence of the two associations in the Órgãos and Anhangava Plutons. In the Órgãos Pluton, the alkaline association is restricted to the northwesternmost portion of the pluton, while in the Anhangava Pluton the alkaline association is present in the northern portion and in the extreme south portion of the pluton. Coordinate values are in kilometers and correspond to local UTM.

The granites and syenites of the Graciosa Province lie approximately parallel to the contact between the Coastal Granitoid Belt and the block formed by the Luiz Alves and the Curitiba Microplates, being intrusive in rocks of this latter block (Kaul 1984, Siga Jr et al. 1993).

GEOLOGIC CHARACTERISTICS

The geology of most plutons in the province is only known at the reconnaissance level (Kaul 1984, 1997, and references therein), and detailed studies are almost completely lacking. One challenging aspect to the study of this group of occurrences is the presence of thick vegetation cover, which strongly limits access and sampling in the area. Hence, a lot of the information available derives from remote sensing data, with little ground check.

The plutons have variable geometry, but subcircular shapes are common. Kaul (1984) and Kaul and Cordani (2000) suggest that directional stresses were relatively unimportant during emplacement of the bodies, a conclusion reinforced by the predominant massive nature of the rock structures. In fact, part of the irregular shapes observed can be explained by deformation due to younger faults. It should be emphasized, however, that deformed rocks are found close to the contacts of some plutons, and indicate local deformation during or soon after emplacement.

The presence of roughly contemporaneous volcano-sedimentary basins in direct contact with many of the plutonic rocks, as well as structural and textural features of the granites and syenites (e.g. presence of miarolitic cavities, bipyramidal quartz, granophyric intergrowths, etc.) indicate shallow levels of emplacement. This conclusion is also supported by the available gravimetric data (Hallinan et al. 1993).

Available Rb-Sr whole-rock ages cluster in the interval 520–600 Ma (Siga Jr et al. 1999, Kaul and Cordani 2000), being somewhat younger than those for the rocks of the Coastal Granitoid Belt (615–570 Ma). U-Pb ages, only available for a few of the plutons, suggest a narrower time interval (575–600 Ma) for the magmatism (Siga Jr et al. 1999, Cordani et al. 2000, Passarelli et al. 2004, Harara et al. 2005). K-Ar ages indicate that rocks of the Graciosa Province experienced short cooling intervals, what is compatible with inferred shallow levels of emplacement (Siga Jr et al. 1994).

All these features suggest that generation of magmas of the Graciosa Province was related to the crustal rearrangement after the collision between the Coastal Granitoid Belt and the Curitiba-Luis Alves block (Siga Jr et al. 1994), in a post-collisional environment as that defined by Liégeois (1998), in which deformation is typically concentrated along faults and little to no deformation takes place in the regions in between the faults.

PETROGRAPHIC CHARACTERISTICS

The plutons in the Graciosa Province have traditionally been described as being composed of granitic and syenitic rocks of alkaline affinity (Fuck et al. 1967, Wernick and Penalva 1978, Hasui et al. 1978, Kaul 1984, Siga Jr et al. 1994, Kaul and Cordani, 2000). This view, however, has to be taken as a simplification given the diversity of rock types present in most of the plutons. Typically peralkaline rocks – with sodic amphibole and/or pyroxene – are ubiquitous, but typically metaluminous and weakly peraluminous rocks are also invariably present, and in fact, may correspond to most (if not all) of the volume present in many of the occurrences.

In general terms, the rocks present can be subdivided into two petrographic associations with contrasted characteristics (Vlach et al. 1991): an alkaline association and an aluminous association. Both associations are characteristic of A-type granites worldwide (see Pitcher 1995).

The alkaline association

An association consisting of hypersolvus alkali-feldspar syenites and alkali-feldspar granites, metaluminous to peralkaline in character, is typical of and is distributed throughout the Graciosa Province (Kaul 1997). They are characteristically leucocratic, medium-grained, equigranular rocks, and occupy the totality of the Corupá Pluton (Garin et al. 2003), as well as significant portions of the Morro Redondo Complex (Góis 1995) and Anhangava Pluton (Gualda 2001). Very differentiated end-members, typically alkali-feldspar granites are found in the Serra da Graciosa region (Gualda 2001) and in the Mandira Pluton (M.C.B. de Oliveira, unpublished data), with the most differentiated varieties being found in the Morro Redondo Complex (F.C.J. Vilalva and S.R.F. Vlach, unpublished data). The least differentiated rocks in this association are metaluminous mafic syenites found in the Corupá Pluton, which include calcic amphibole and clinopyroxene, as well as olivine, in their mineralogy. The more typical syenitic rocks, however, are alkali-feldspar syenites that grade from metaluminous to peralkaline, as indicated by the compositional variations in amphiboles (Gualda and Vlach 2007a, b).

The aluminous association

This association includes mainly subsolvus syenogranites and alkali-feldspar granites, metaluminous to weakly peraluminous, in which biotite and calcic amphibole are the typical mafic minerals. Most rocks are leucocratic, medium to coarse-grained, and display variable texture, from equigranular to porphyritic. This association is important in the Morro Redondo Complex and Anhangava Pluton, and predominates in the Serra da Graciosa region, as well as in the Mandira Pluton.

Gabbro-dioritic rocks

Gabbros and diorites are very rare in the Graciosa Province, despite being common in association with many A-type granites worldwide (e.g. Upton and Emeleus 1987). A single occurrence of biotite hornblende quartz diorites and monzodiorites has been reported by Maack (1961) in the Serra da Graciosa region, in the area surrounding the Paraná Peak. Similar rocks were described in the the Agudos and Corupá Plutons (O.M.M Harara, unpublished data, Garin et al. 2003).

Contemporaneous volcanic rocks

Volcanic rocks contemporaneous to the Graciosa Province magmatism are concentrated in four regions (Figure 1): in the Campo Alegre, Guaratubinha and Corupá volcano-sedimentary basins (Siga Jr et al. 2000), and associated with the plutonic rocks in the Morro Redondo Complex (Góis and Machado 1992). The volcano-sedimentary sequences are characterized by sandstones and conglomerates at the base, followed by basic volcanics, and more rarely silicic volcanic rocks; siltites and arkoses predominate in the intermediate portions of the sequences, while in the upper portions effusive and pyroclastic silicic rocks appear (Ebert 1971, Daitx and Carvalho 1980). The reduction in grain size towards the upper portions of the sequences indicates a progressive stabilization of the basins. Incipient metamorphism is ubiquitous. The most important characteristic to be emphasized, however, is the bimodal nature of the volcanism, with coexisting effusive basic and silicic rocks, while intermediate rocks are rare (Góis and Machado 1992, Góis 1995, Siga Jr et al. 2000).

Geochemical Characteristics

A-type granites and syenites are characterized by high concentrations of alkalis, high field-strength elements (e.g. Zr, Nb, Y), rare earth elements, as well as large enrichment of Fe over Mg, and Ga over Al. Such characteristics can be used to discriminate between A-type rocks and other granitoid rocks (see Whalen et al. 1987, Frost et al. 2001, and references therein).

Kaul and Cordani (2000) show that granites and syenites of the Graciosa Province possess all these characteristics typical of A-type rocks, as illustrated in Figure 2. Also plotted in Figure 2 are data for rocks from the Serra da Graciosa region (Table I). It can be seen that the Serra da Graciosa region includes compositions that span much of the variability observed in the Graciosa Province as a whole. Importantly, Figure 2b nicely illustrates that the alkaline association is characterized by metaluminous to peralkaline rocks, while the aluminous association corresponds to metaluminous to marginally peraluminous rocks, as can be inferred from their mafic mineralogy (Shand 1972).

THE SERRA DA GRACIOSA A-TYPE GRANITES AND SYENITES

The granites and syenites of the Serra da Graciosa region are found within a large area (ca. 500 km^2) in the vicinities of the city of Curitiba, and correspond to one of the largest volumes of granitic rocks in the Graciosa Province.

Natural Characteristics and Location

The Serra do Mar escarpment corresponds to the transition from the Curitiba plateau (formally known as Primeiro Planalto Paranaense) to the west, with average elevation close to 900 m, and the coastal plain (Planície Litorânea) to the east. In the areas where granites are present at this transition, mountains with maximum elevation between 1400 and 2000 m are observed (Figure 3), in sharp contrast with areas where the granites are absent, where no elevation gain is observed next to the escarpment. This makes the recognition of the individual granitic bodies relatively straightforward, especially with the assistance of remote sensing data.

This area is characterized by almost intact Atlantic Forest and, in fact, corresponds to one of the last large remnants of this biome in southern Brazil. The combination of thick vegetation cover and relatively rugged terrain strongly limits access to the area, also because many portions of the area are protected, and commercial exploration and even sampling for scientific activities are very limited. Hence, even in semi-detail work like the one presented here, field coverage is sparse and far less than ideal.

The region in which we focus our attention in this work, here denominated the Serra da Graciosa region, includes a series of mountain ranges (Figure 3) that combined correspond to the Serra do Mar in this area

TABLE I
Whole-rock chemical data for the Serra da Graciosa granites, syenites, and related monzodioritic rocks (oxides: wt.%, trace elements: ppm, LOI: Lost on Ignition, A/CNK and Agpaitic Index defined in Figure 2).

	Alkaline association								
	GRA-14G	GRA-18A	GRA-49	GRA-51	GRA-56	GRA-58	GRA-59A	GRA-70	GRA-74
$SiO_2^†$	76.2	76.6	75.7	74.9	75.1	76.3	73.6	72.0	74.6
$Al_2O_3^†$	11.5	11.9	12.3	12.4	12.5	12.5	13.0	13.8	13.0
$Fe_2O_3^†$	2.72	2.13	2.45	2.35	2.10	1.41	2.72	2.68	2.05
$MgO^†$	0.02	b.d.l.	0.05	0.08	0.09	b.d.l.	0.17	0.09	0.06
$CaO^†$	0.48	0.34	0.17	0.57	0.59	0.47	0.85	0.79	0.54
$Na_2O^†$	3.94	4.16	4.42	4.23	4.05	4.16	4.05	4.30	4.02
$K_2O^†$	4.96	4.69	4.70	4.91	5.02	4.70	5.13	6.09	5.28
$P_2O_5^†$	0.00	0.01	0.01	0.01	0.01	b.d.l.	0.03	0.01	0.01
$MnO^†$	0.08	0.05	0.04	0.05	0.05	0.03	0.06	0.06	0.04
$TiO_2^†$	0.22	0.14	0.18	0.21	0.19	0.11	0.27	0.23	0.20
LOI	0.10	0.25	0.25	0.36	0.41	0.43	0.27	0.22	0.24
Total	100.2	100.2	100.3	100.1	100.2	100.1	100.1	100.2	100.0
H_2O^-	0.04	0.03	0.06	0.09	0.08	0.13	0.13	0.08	0.27
$Ba^†$	19	<10	100	167	165	13	309	180	115
$Be^†$	4	5	5	7	6	5	3	3	3
Ce*	250	133	134	181	170	447	208	340	299
Cl*	303	206	292	235	241	136	209	242	223
Co*	< 1	< 1	< 1	< 1	1	< 1	1	< 1	< 1
Cr*	< 2	8	< 2	< 2	3	< 2	< 2	< 2	< 2
Cu*	< 1	2	< 1	1	1	2	2	2	7
F*	973	2300	1985	2245	2495	3843	849	1234	< 550
Ga*	19	22	24	22	17	21	17	19	22
$La^†$	120	104	78	92	81	219	104	270	136
Nb*	33	50	51	52	33	35	28	21	26
Nd*	102	69	48	82	65	191	77	194	130
Ni*	1	2	1	1	1	2	2	2	7
Pb*	27	18	23	33	22	31	23	20	21
Rb*	126	220	264	220	175	195	125	109	116
S*	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sc*	1	1	1	3	3	1	2	< 1	2
$Sr^†$	11	7	12	31	34	12	54	32	23
Th*	8	17	19	22	14	17	14	14	14
U*	6	4	5	6	5	6	5	5	5
V*	8	< 4	6	11	12	5	10	11	< 4
$Y^†$	56	104	29	82	62	233	68	140	62
$Zn^†$	105	173	189	141	134	139	110	169	87
$Zr^†$	824	487	522	465	505	275	466	528	479
#fe	0.99	1.00	0.98	0.96	0.95	1.00	0.93	0.97	0.97
Na_2O+K_2O	8.89	8.85	9.12	9.14	9.07	8.86	9.18	10.4	9.30
A/CNK	0.90	0.95	0.97	0.94	0.95	0.98	0.95	0.92	0.98
Agpaitic Index	1.03	1.00	1.01	0.99	0.96	0.95	0.94	0.99	0.95
M	1.63	1.47	1.65	1.69	1.64	1.79	2.01	2.02	2.11
Zr+Ce+Y+Nb	1162	774	736	780	770	990	771	1029	865
T_{Zircon} (°C)	940	890	898	880	892	836	880	884	889
$T_{Apatite}$ (°C)	–	–	–	776	–	–	824	730	726

TABLE I (continuation)

	Alkaline association								
	GRA-77	GRA-78A	GRA-78B	GRA-80	GRA-81A	GRA-81B	GRA-81D	GRA-87A	GRA-87B
$SiO_2^{\dagger}$	70.9	69.3	70.1	68.3	63.7	63.9	63.3	66.6	68.2
$Al_2O_3^{\dagger}$	14.8	15.4	14.9	15.1	15.8	15.8	15.7	15.5	14.6
$Fe_2O_3^{\dagger}$	2.38	2.75	2.77	3.90	6.28	6.07	6.86	4.55	4.55
$MgO^{\dagger}$	0.03	0.05	0.10	0.08	0.23	0.23	0.16	0.03	0.11
$CaO^{\dagger}$	0.62	0.67	0.79	1.06	1.77	1.84	2.06	1.48	1.38
$Na_2O^{\dagger}$	5.58	5.71	5.11	5.43	5.44	5.49	5.57	5.46	4.82
$K_2O^{\dagger}$	5.18	5.53	5.55	5.66	6.05	5.97	5.98	5.99	5.66
$P_2O_5^{\dagger}$	b.d.l.	b.d.l.	0.01	0.01	0.07	0.08	0.07	0.01	0.01
$MnO^{\dagger}$	0.05	0.06	0.08	0.12	0.20	0.19	0.23	0.14	0.12
$TiO_2^{\dagger}$	0.16	0.18	0.22	0.24	0.54	0.54	0.55	0.31	0.33
LOI	0.44	0.44	0.33	0.25	0.17	0.08	0.02	0.15	0.13
Total	100.2	100.1	100.0	100.1	100.2	100.3	100.5	100.2	99.9
H_2O^-	0.10	0.17	0.06	0.07	0.12	0.06	0.10	0.18	0.11
$Ba^{\dagger}$	66	47	152	84	121	113	63	15	248
$Be^{\dagger}$	8	6	5	6	3	4	3	5	4
Ce*	245	270	195	306	148	144	171	136	122
Cl*	248	254	372	263	314	260	263	229	376
Co*	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Cr*	< 2	< 2	< 2	< 2	< 2	10	< 2	< 2	6
Cu*	2	1	1	< 1	4	4	4	3	1
F*	3356	2253	2086	2210	981	1075	592	1282	1319
Ga*	26	23	22	23	17	18	18	21	21
$La^{\dagger}$	123	142	102	137	62	57	74	88	44
Nb*	43	46	43	46	36	36	37	31	34
Nd*	100	117	84	112	70	60	61	68	66
Ni*	< 1	< 1	2	1	1	1	1	1	1
Pb*	30	21	23	23	18	15	21	16	27
Rb*	233	200	185	199	118	128	117	170	174
S*	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sc*	4	3	2	1	11	11	7	1	5
$Sr^{\dagger}$	17	17	29	17	14	17	13	17	84
Th*	16	16	13	15	5	5	4	5	7
U*	6	4	7	5	3	6	7	4	< 3
V*	6	< 4	9	5	6	4	4	6	< 4
$Y^{\dagger}$	86	79	62	82	46	43	42	55	68
$Zn^{\dagger}$	114	114	89	139	116	109	120	140	146
$Zr^{\dagger}$	412	421	482	1123	590	531	541	750	995
#fe	0.98	0.98	0.96	0.98	0.96	0.96	0.97	0.99	0.97
Na_2O+K_2O	10.8	11.2	10.7	11.1	11.5	11.5	11.5	11.5	10.5
A/CNK	0.93	0.93	0.94	0.89	0.85	0.84	0.81	0.85	0.88
Agpaitic Index	1.00	1.00	0.97	1.00	0.98	0.98	0.99	1.00	0.96
M	1.91	1.78	1.48	1.53	1.54	1.59	1.41	1.47	1.49
Zr+Ce+Y+Nb	786	815	782	1556	821	754	792	972	1218
T_{Zircon} (°C)	857	856	874	–	–	–	–	–	–
$T_{Apatite}$ (°C)	–	–	730	680	801	812	792	645	711

TABLE I (continuation)

	Aluminous association									
	GRA-11A	GRA-13	GRA-15	GRA-28B	GRA-2A	GRA-2E	GRA-36B	GRA-3B	GRA-40	GRA-76
$SiO_2^†$	73.4	73.0	74.0	71.1	76.4	72.6	73.8	71.3	76.3	75.1
$Al_2O_3^†$	13.6	13.6	12.5	14.2	12.4	13.7	13.4	13.5	12.8	12.6
$Fe_2O_3^†$	2.23	2.14	2.75	2.88	1.44	2.19	1.83	3.65	1.11	1.84
$MgO^†$	0.29	0.15	0.14	0.59	0.06	0.31	0.22	0.13	0.07	0.05
$CaO^†$	1.10	0.88	0.74	1.58	0.50	1.15	1.00	1.10	0.65	0.56
$Na_2O^†$	3.80	4.27	4.01	4.23	3.90	3.60	3.94	3.45	4.17	4.47
$K_2O^†$	5.12	5.14	5.04	4.71	4.82	5.37	5.10	6.11	4.44	4.62
$P_2O_5^†$	0.07	0.03	0.03	0.10	0.01	0.05	0.03	0.02	0.01	b.d.l.
$MnO^†$	0.06	0.05	0.08	0.07	0.03	0.05	0.05	0.09	0.05	0.03
$TiO_2^†$	0.27	0.21	0.29	0.42	0.13	0.25	0.21	0.37	0.10	0.12
LOI	0.38	0.41	0.42	0.50	0.31	0.54	0.51	0.32	0.44	0.46
Total	100.2	99.9	100.0	100.3	100.0	99.9	100.1	100.0	100.1	99.9
H_2O^-	0.05	0.10	0.16	0.07	0.14	0.11	0.08	0.06	0.05	0.14
$Ba^†$	611	291	241	838	137	911	501	244	75	51
$Be^†$	3	3	3	4	1	2	6	1	5	6
Ce*	85	212	631	159	113	187	97	357	52	124
Cl*	146	232	426	167	264	281	141	219	217	197
Co*	2	< 1	< 1	2	< 1	< 1	< 1	< 1	< 1	1
Cr*	10	< 2	< 2	9	< 2	< 2	14	< 2	14	2
Cu*	3	3	1	3	4	3	5	< 1	4	1
F*	1440	1529	2320	3086	570	1123	2386	< 550	2178	4019
Ga*	15	17	17	19	15	15	15	16	17	24
$La^†$	68	79	353	72	86	117	75	198	24	50
Nb*	22	25	31	30	12	20	22	27	28	63
Nd*	44	75	261	48	53	62	40	143	17	44
Ni*	1	1	4	2	1	2	2	3	1	2
Pb*	20	34	31	18	24	27	22	21	38	19
Rb*	182	152	149	177	110	154	207	110	324	275
S*	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Sc*	7	2	< 1	6	5	7	3	5	1	2
$Sr^†$	101	43	44	162	23	165	94	90	22	13
Th*	13	20	17	13	13	18	17	17	21	20
U*	4	6	5	4	3	5	6	5	7	8
V*	14	9	9	22	13	14	16	14	8	7
$Y^†$	35	54	163	56	22	42	35	46	52	93
$Zn^†$	44	68	161	89	38	49	37	100	27	141
$Zr^†$	257	333	679	307	196	289	163	852	99	322
#fe	0.87	0.93	0.95	0.82	0.96	0.86	0.88	0.96	0.93	0.97
Na_2O+K_2O	8.92	9.41	9.05	8.95	8.72	8.96	9.04	9.56	8.61	9.10
A/CNK	0.98	0.96	0.93	0.95	0.99	0.99	0.97	0.94	1.00	0.94
Agpaitic Index	0.87	0.93	0.96	0.85	0.94	0.85	0.90	0.91	0.91	0.98
M	1.58	1.41	1.51	1.49	1.40	1.50	1.58	1.65	1.43	1.53
Zr+Ce+Y+Nb	398	625	1503	552	343	537	317	1281	232	603
T_{Zircon} (°C)	826	847	919	834	806	837	784	941	748	845
$T_{Apatite}$ (°C)	899	821	818	913	–	855	835	791	–	–

TABLE I (continuation)

	Alkaline association							Monzodioritic rocks	
	GRA-7A	GRA-7B	GRA-83	GRA-84A	GRA-85B	GRA-88A	GRA-95	GRA-59D	GRA-59E
$SiO_2^†$	73.0	74.6	72.7	73.2	70.4	76.2	73.3	55.7	54.4
$Al_2O_3^†$	13.6	13.5	13.7	12.9	14.6	12.2	13.4	15.6	15.7
$Fe_2O_3^†$	2.11	1.63	2.29	2.67	2.77	1.51	2.04	9.74	10.2
$MgO^†$	0.33	0.23	0.21	0.10	0.15	0.06	0.13	2.97	3.56
$CaO^†$	1.15	1.05	1.00	0.76	0.98	0.52	0.64	5.56	6.06
$Na_2O^†$	3.96	3.58	4.10	4.44	4.86	3.71	4.00	4.07	3.76
$K_2O^†$	4.91	4.96	5.01	4.92	5.55	5.05	5.84	3.65	3.30
$P_2O_5^†$	0.04	0.02	0.02	0.01	0.02	b.d.l.	b.d.l.	0.92	0.91
$MnO^†$	0.06	0.05	0.06	0.07	0.06	0.04	0.04	0.18	0.16
$TiO_2^†$	0.26	0.19	0.21	0.18	0.22	0.11	0.21	1.76	1.74
LOI	0.51	0.35	0.40	0.48	0.46	0.30	0.34	0.48	0.70
Total	100.0	100.2	99.7	99.7	100.1	99.7	99.9	100.6	100.6
H_2O^-	0.06	0.08	0.07	0.14	0.12	0.09	0.13	0.06	0.17
$Ba^†$	509	482	361	155	192	52	187	1364	1551
$Be^†$	3	3	9	8	7	11	5	3	3
Ce*	115	82	110	169	180	100	109	157	126
Cl*	168	124	193	333	227	471	129	385	365
Co*	< 1	1	< 1	< 1	1	< 1	1	17	21
Cr*	12	12	< 2	9	< 2	11	45	13	19
Cu*	3	4	2	2	1	4	2	13	21
F*	1980	986	2467	4220	3495	2328	2601	959	964
Ga*	16	14	18	22	22	16	18	17	14
$La^†$	80	79	53	86	87	53	106	71	66
Nb*	23	22	32	43	32	27	24	35	21
Nd*	28	27	52	66	68	45	45	78	54
Ni*	1	2	3	2	2	1	2	7	12
Pb*	24	24	18	22	17	50	15	18	14
Rb*	205	218	235	207	254	210	162	90	80
S*	< 20	< 20	< 20	< 20	< 20	< 20	< 20	345	< 20
Sc*	6	5	2	3	4	1	< 1	16	18
$Sr^†$	102	114	74	32	38	14	30	522	633
Th*	19	22	14	16	14	16	9	5	5
U*	5	5	6	6	4	7	4	< 3	< 3
V*	11	16	11	8	10	9	9	149	181
$Y^†$	39	33	51	81	69	41	39	61	38
$Zn^†$	57	37	47	96	94	72	59	135	112
$Zr^†$	215	147	260	426	547	188	275	224	186
#fe	0.85	0.86	0.91	0.96	0.94	0.96	0.93	0.75	0.72
Na_2O+K_2O	8.87	8.54	9.11	9.36	10.4	8.76	9.84	7.72	7.06
A/CNK	0.98	1.02	0.98	0.92	0.93	0.97	0.95	0.75	0.76
Agpaitic Index	0.87	0.84	0.89	0.98	0.96	0.95	0.96	0.68	0.62
M	2.55	2.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr+Ce+Y+Nb	391	283	453	718	827	355	447	477	371
T_{Zircon} (°C)	808	782	825	866	886	801	828	–	–
$T_{Apatite}$ (°C)	842	799	777	751	745	–	–	1026	1007

†Measured by ICP-AES. / *Measured by X-ray fluorescence.

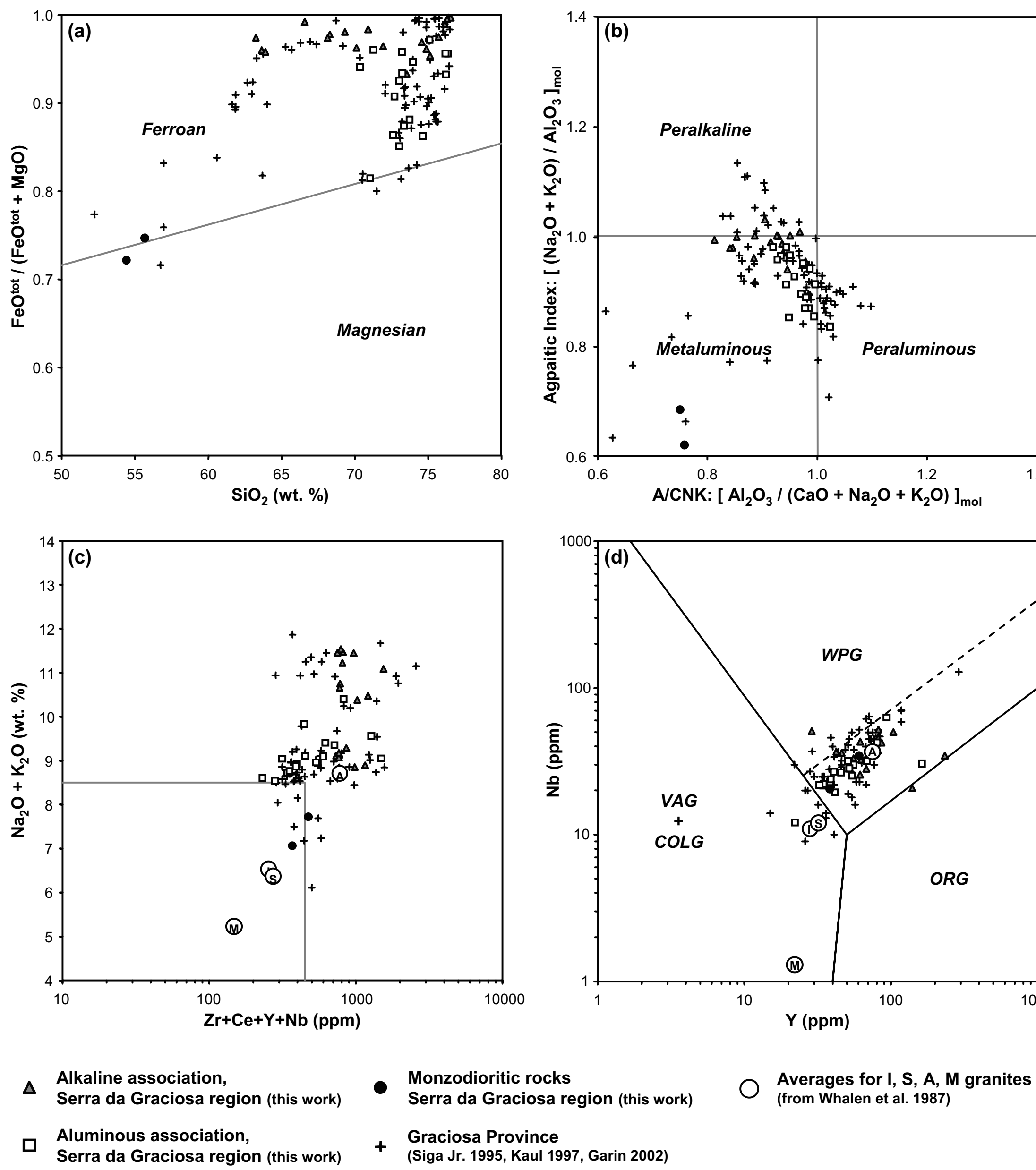

Fig. 2 – Discriminating plots for A-type granites and syenites of the Serra da Graciosa region. (a) SiO_2 versus FeO^{tot} / (FeO^{tot} + MgO) wt.% plot showing the ferroan character of the A-type rocks of the Graciosa Province, in agreement with what is observed elsewhere (see Frost et al. 2001). Notice the distinct trends for the alkaline and aluminous associations. (b) A/CNK versus Agpaitic Index plot showing the degree of alumina saturation. Rocks from the aluminous association are metaluminous to weakly peraluminous, while rocks from the alkaline association are metaluminous to peralkaline. (c) Na_2O + K_2O (wt.%) versus Zr + Ce + Y + Nb (ppm) plot discriminating A-type granites from other types of granites (I, S, and M-type). Field separating A-type granites from the remainder, as well as average compositions for all 4 types of granites, are from Whalen et al. (1987). As expected, rocks from the alkaline association show significantly higher alkali concentrations. (d) Nb versus Y plot for classification in terms of tectonic environment (after Pearce et al. 1984). Most samples fall within the field of within-plate granites (WPG), with only occasional analyses plotting in the other fields (VAG: volcanic arc granites, COLG: collisional granites, ORG: orogenic granites). Field boundaries are from Pearce et al. (1984), and average compositions for A, I, S, and M-type granites are from Whalen et al. (1987).

Fig. 3 – Panoramic view of the Serra da Graciosa region in eastern Paraná State, southern Brazil. The photo was taken from the highway BR-116 in the vicinities of the city of Curitiba. View is to the northeast.

(Serras do Capivari, Órgãos, Graciosa, Farinha Seca, and Marumbi). Also included are the Serra da Baitaca and Serra da Boa Vista, which lie to the west of the Serra do Mar (stricto sensu) and are entirely within the Curitiba plateau. The region is located at approximately 40 km to the east of the city of Curitiba, with dimensions of ca. 50 × 17 km, with major axis oriented along north-northeast-south-southwest.

Historical appraisal of previous work

The identification of granitic rocks of alkaline affinity in the region was pioneered by Maack (1961), who described samples from the Serra dos Órgãos close to the Paraná Peak, from the base of the Serra da Graciosa, and from the Serra do Marumbi. The described rocks are predominantly granites which were classified as alkaline granites (Paraná Peak and Serra da Graciosa) or as granites with alkaline affinity (Serra do Marumbi). Dioritic rocks were identified in the Serra dos Órgãos.

Maack (1961) grouped the granitic rocks of the Serra da Graciosa and of the Serra dos Órgãos under a single name, "*complex of alkaline granites*", but noted that both occurrences are separated by gneissic rocks and dikes of the "*gondwanic volcanism*". The granites of the Serra do Marumbi were mapped as an independent unit, and the presence of "alkaline" granites was inferred in the Serra do Capivari.

Systematic geological mapping of the area is due to Fuck (1966), Cordani and Girardi (1967), and Fuck et al. (1970). Fuck (1966) defined the Anhangava Massif in the Serra da Baitaca and Serra da Boa Vista area; Cordani and Girardi (1967) grouped the occurrences of the Serra do Capivari, Serra dos Órgãos, Serra da Farinha Seca and Serra da Graciosa previously identified by Maack (1961) under the name Graciosa Massif; and Fuck et al. (1970) defined the Marumbi Massif in the Serra do Marumbi area.

More recently, Kaul (1984, 1997), Lopes et al. (1998), Siga Jr et al. (1999, 2000) and Kaul and Cordani (1994, 2000) added new geologic, petrographic and geochemical data. Nevertheless, the distribution of distinct varieties, as well as the field and genetic relations between them, are still very poorly constrained.

MATERIALS AND METHODS

The geological characterization of the granites and syenites in the area was based on the combination of fieldwork, petrography, and interpretation of remote sensing images, also supplemented by laboratory data on magnetic susceptibility of hand-specimens.

Fieldwork

Due to the natural characteristics of the region, fieldwork was mostly limited to profiles along roads and existing trails. Hence, relatively large portions of the area were not visited. Except for the highest peaks in the region, natural outcrops are scarce and usually consist of weathered blocks of up to a few meters in diameter and outcrops along creeks. In some areas on the Serra do Capivari and Serra da Baitaca, small-scale quarries are present, and much better sampling was possible. The quality of the exposures in the area prevented us from observing critical contact relations between the distinct petrographic varieties recognized in the field. Furthermore, given the steepness of the terrain in many areas, movement of blocks of metric to decametric size towards lower portions is probably a common process, such that some of the blocks studied and sampled are probably not in situ. Given all these difficulties, the contacts presented in maps are tentative at best, and strongly dependent on the interpretation of satellite images. We argue, however, that the contacts between granitic rocks and country rocks can be identified with reasonable confidence.

The granitic and syenitic rocks were grouped according to the principles of facies mapping (Ulbrich et al. 2001). Special attention was given to the mafic mineralogy, which is a clear indicator of the alumina saturation (Shand 1972).

Image Processing

In combination with fieldwork, remote sensing images were used, with the main goal of mapping the contacts between the distinct plutons present in the area.

A digital elevation map (Figure 4a) was generated using a regular grid of points, with 500 m spacing, with altitude extracted from topographic sheets at the scale 1:50,000. Data were provided by W. Shukowsky of the Institudo de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo.

TM Landsat 5 images were processed in the Geological Information System Laboratory, at the Instituto de Geociências, Universidade de São Paulo. We used bands 3, 4, 5 and 7 with corrections for atmospheric absorption. Grayscale images of the normalized difference vegetation index (NDVI: normalized difference between bands 3 and 4; Figure 4b), and compositions 457 (4 in red channel, 5 in green channel, and 7 in blue channel) and 347 emphasize the textural (i.e. topographic) characteristics of the imaged area, and were used for this work.

Airborne gamma-ray spectral maps were obtained by interpolation of data acquired as part of the CPRM project Levantamento Aerogeofísico Serra do Mar Sul, executed by GEOFOTO (GEOFOTO 1978). Silva and Mantovani (1994) discuss in detail the data collection methods and the quality of the results. Counts in each of the 3 channels for K, Th (Figure 4c), and U were converted into concentrations by Misener et al. (1997). Maps were generated for each of these 3 channels, for the ratios U/K, U/Th, and Th/K, for the F parameter (F = K*U/Th), as well as for ternary compositions using absolute concentrations and ratios (Gualda et al. 2001).

Magnetic Susceptibility

Magnetic susceptibility measurements were made in laboratory using hand-specimens collected in the field. All measurements were made using a GF Instruments SM-20 portable susceptibilitymeter. Values presented are averages of ca. 10 measurements per sample.

The magnetic susceptibility of a sample is in general directly proportional to the modal abundance of magnetite in the sample (e.g. Sauck 1972). Given the absence of magnetite in most rocks of the alkaline association, and its ubiquitous presence in the aluminous association, the magnetic susceptibility is an important tool for the discrimination of these two associations (Figure 5).

Rock Chemistry

Bulk rock chemical analyses were performed in the Chemistry, ICP and X-Ray Fluorescence Laboratories at the Instituto de Geociências, Universidade de São Paulo. Major, minor and trace elements were analyzed in 37 samples (Table I, Figure 2) representative of the aluminous and alkaline petrographic associations, following the procedures described in Janasi et al. (1996).

GEOLOGICAL OVERVIEW

Fieldwork and image analysis clearly show that the granitic and syenitic rocks in the region give rise to pronounced topographic features, in the form of hills that stand out of the relatively flat areas typical of the portions with underlying country rocks (Figures 3 and 4). Moreover, it is in these areas of rugged terrain where the highest concentrations of incompatible radioactive elements (Th, U, K) are observed. Hence, it becomes relatively easy to delineate the limits of the granitic and syenitic occurrences based on the remote sensing images (Figure 4).

Five individual granitic plutons, fully enclosed by country rocks, were recognized in the area (Figure 1). Two of them correspond to the Marumbi and Anhangava Plutons (Maack 1961, Fuck 1966, Cordani and

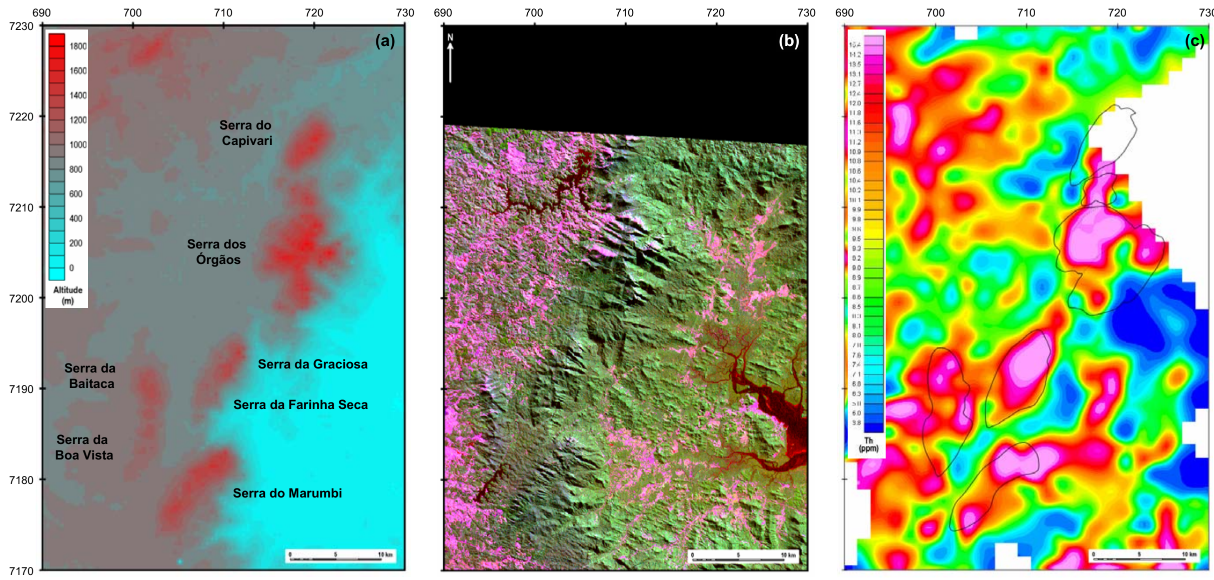

Fig. 4 – Remote sensing images for the Serra da Graciosa region in eastern Paraná State, southern Brazil. (a) Pseudo-color digital elevation map with the main topographic features indicated; (b) TM-Landsat 5 false-color 457 composition (band 4 in red channel, band 5 in green channel, and band 7 in blue channel); note that the hills observed in the field (Figure 3) can be easily recognized, and correspond to the areas of occurrence of granitic and syenitic rocks; (c) Pseudo-color Th map based on airborne gamma-ray spectral data; notice how the areas of high Th abundance – characteristic of granites and syenites – correspond to the areas of high elevation (see text and Gualda et al. 2001 for details); the outlines of the 5 plutons (Figure 1) are shown for reference. Coordinate values are in kilometers and correspond to local UTM.

Girardi 1967). The other three occurrences are within what has so far been called the Graciosa Massif (Cordani and Girardi 1967, Fuck et al. 1970).

The subdivision of the Graciosa Massif into at least two independent plutons is in agreement with the pioneer observations of Maack (1961), who first identified basement rocks separating the occurrences in the Serra da Graciosa from those at the Serra dos Órgãos. The northern portion of the Serra dos Órgãos constitutes a military shooting range, and could not be visited during our field studies. Hence, little information is available for the area between the Serra do Capivari and the Serra dos Órgãos. Nevertheless, analysis of the satellite images, the digital elevation map, the airborne gamma-ray maps, as well as field observations, show that the Serra do Capivari is a separate structure than the Serra dos Órgãos, each one characterized by high concentrations of K, Th, and U. Each of the five units recognized above is separated from each other by areas of relatively low abundances of these elements (Figure 4c), as expected for the basement rocks in the region. It is noteworthy that most A-type plutons worldwide (e.g. Kinnaird and Bowden 1987) and in the Graciosa Province itself (Kaul 1997) are rarely larger than ca. 80–100 km^2; the units suggested here all fall within these limits.

We suggest that the use of the term Graciosa Massif be discontinued in favor to specific names for each of the three new plutons recognized by us, from north to south: Capivari Pluton, Órgãos Pluton, and Farinha Seca Pluton. The suggested nomenclature follows on the tradition within the province to use names based on topographic features. We use the informal name Serra da Graciosa Granites and Syenites to denote the group composed of these three plutons and the previously defined Marumbi and Anhangava Plutons.

The external shapes of these five plutons are presented in Figure 1. These contacts are essentially based on the topography and other terrain characteristics recognizable using the remote sensing tools, but, where possible, were also based on field observations.

The map patterns observed in the gamma-ray maps are broadly in agreement with the subdivision proposed

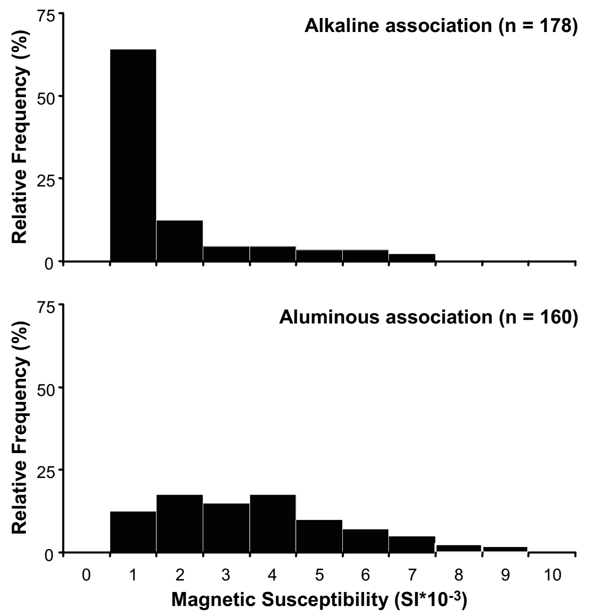

Fig. 5 – Histograms showing the variation in magnetic susceptibility for representative samples of the Serra da Graciosa A-type Granites and Syenites, southern Brazil. N is the total number of individual measurements. Notice the clear difference in magnetic susceptibility between the magnetite-bearing rocks of the aluminous association, when compared to the magnetite-free varieties of the alkaline association.

here. Locally, however, the anomalies in incompatible radioactive elements extend beyond the proposed limits, particularly to the east of the Serra do Mar escarpment. This is probably due to significant down slope movement of metric to decametric blocks (see above) and to migration of radionuclides resulting from weathering of the granitic rocks (Gualda et al. 2001).

In general, the five plutons appear on surface as approximately elliptic features, with major axes oriented along the northeast-southwest direction. The Órgãos Pluton is roughly circular, with reentrants that may indicate internal structures, while the Anhangava Pluton is oriented along the north-south direction. Interestingly, the gamma-ray maps show relatively simple structures for most plutons, the main exception being the Anhangava Pluton.

Kaul (1984, 1997; see also Kaul and Cordani 2000) argues that because the plutons are mostly oriented along a northeast-southwest direction, existing faults with similar orientation probably played an important role during emplacement. The shape of the "Graciosa Massif" as presented by Kaul (1997) is incompatible with this same structural control, and he offers an alternative explanation. Interestingly, the shapes of the three plutons recognized here can be accommodated by the model of a structural control due to prevailing northeast-directed stresses.

In the whole area, but most prominently displayed in the area of the Órgãos Pluton, abundant linear features oriented along northwest-southeast indistinctly cut the granites and the basement rocks (Figure 4). These correspond to basaltic dike swarms related to the Mesozoic reactivation that culminated with the basaltic volcanism in the Paraná Basin (Almeida 1967, Almeida et al. 2000). Accordingly, dikes of centimetric to metric thickness were also identified in the field. Additionally, in many areas, brittle structures with normal displacement were observed, and are interpreted to be a consequence of this event.

GEOLOGY OF THE PLUTONS

The five granitic and syenitic plutons identified here are briefly described below. The main characteristics are summarized in Table II.

CAPIVARI PLUTON

The Capivari Pluton (Figure 6a) is the northernmost of the plutons studied here. The granitic rocks in the area support the Serra do Capivari, whose highest peak sits at 1665 m elevation. Its northern and western portions correspond to the areas with easiest access, due to the proximity to a major highway (BR-116) and to the rudimentary exploration of granitic rocks as building material. The pluton is the smallest of the five plutons, covering a total area of approximately 34 km^2. It has elliptical shape, with major and minor axes measuring 10.5 and 4.5 km respectively. Analysis of the remote sensing images reveals a relatively simple pattern, with no obvious indication of internal structures. Three granitic facies are present (see Petrography section below), all with similar mineralogy, such that all rocks correspond to granites with biotite and minor amphibole. Titanite can be seen in some of the hand specimens.

TABLE II
Main geological and petrographic characteristics of the five plutons in the Serra da Graciosa region.

Pluton	Area (km^2) Size (km) Shape / Orientation	Petrographic associations	Petrographic facies	Main mafic minerals
Capivari	34 10.5 × 4.5 Elliptic / NE	Aluminous	Medium-grained porphyritic granites	Biotite
			Medium-grained inequigranular syenogranites	Biotite
			Medium-grained equigranular syenogranites	Calcic amphibole, biotite
Órgãos	100 12 × 12 Subcircular	Aluminous	Medium-grained porphyritic granites	Biotite
			Medium-grained equigranular syenogranites	Biotite
			Fine-grained equigranular syenogranites	Biotite
		Alkaline	Medium-grained equigranular alkali-feldspar granites	Calcic amphibole
Farinha Seca	46 12 × 6 Elliptic / NE	Alkaline	Fine-grained equigranular alkali-feldspar granites (Na-Ca Amph)	Sodic-calcic amphibole
			Fine-grained porphyritic alkali-feldspar granites (Na Amph)	Sodic amphibole
			Medium-grained equigranular alkali-feldspar granites (Ca Amph – Na Amph)	Calcic to sodic amphibole
Marumbi	34 13 × 4 Elongated / NE	Aluminous	Medium-grained equigranular alkali-feldspar granites	Biotite
Anhangava	51 14 × 4 Elongated / N	Alkaline	Fine-grained inequigranular alkali-feldspar syenites	Olivine, clinopyroxene, calcic amphibole
			Fine-grained equigranular alkali-feldspar syenites	Sodic-calcic amphibole
			Medium-grained equigranular alkali-feldspar syenites with pyroxene and olivine	Clinopyroxene, olivine
			Medium-grained equigranular alkali-feldspar syenites with amphibole	Calcic amphibole
		Aluminous	Medium-grained equigranular syenogranites	Calcic amphibole, biotite
			Medium-grained equigranular alkali-feldspar granites	Biotite

ÓRGÃOS PLUTON

Covering an area of ca. 100 km^2, the Órgãos Pluton (Figure 6b) is the largest of the five plutons. It has a roughly circular shape with 12 km diameter. It sustains the Serra do Órgãos, which includes some of the highest peaks in the whole Paraná State, including the Paraná Peak, at 1922 m. This is the least accessible area in the region, such that sampling was limited to a few trails and roads, mostly on the periphery of the pluton.

The reentrant shape of the pluton is probably indicative of internal complexity within it. The pluton can be divided into two main portions, separated by a northeast-southwest lineament. Both of these portions are approximately elliptical in shape, are oriented along the prevailing northeast-southwest direction, and have sizes similar to those of the other plutons (southeast portion, 34 km^2; northwest portion, 60 km^2). All these features indicate that these two portions might correspond to two individual plutons, with the shape of the contact suggesting that the portion to the southeast could be younger than that to the northwest. On the northwesternmost portion of the Órgãos Pluton, a second lineament – much more subtle than the first one – is observed, which separates an area of rugged terrain to the southeast (characteristic of the two portions described above) from an area of more subdued terrain to the northwest. It is possible that this small area (~ 7 km^2) represents another small independent unit (possibly a stock), especially considering that the alkali-feldspar granites and monzogranites characteristic of this area are quite contrasted when compared to the predominant syenogranites observed in

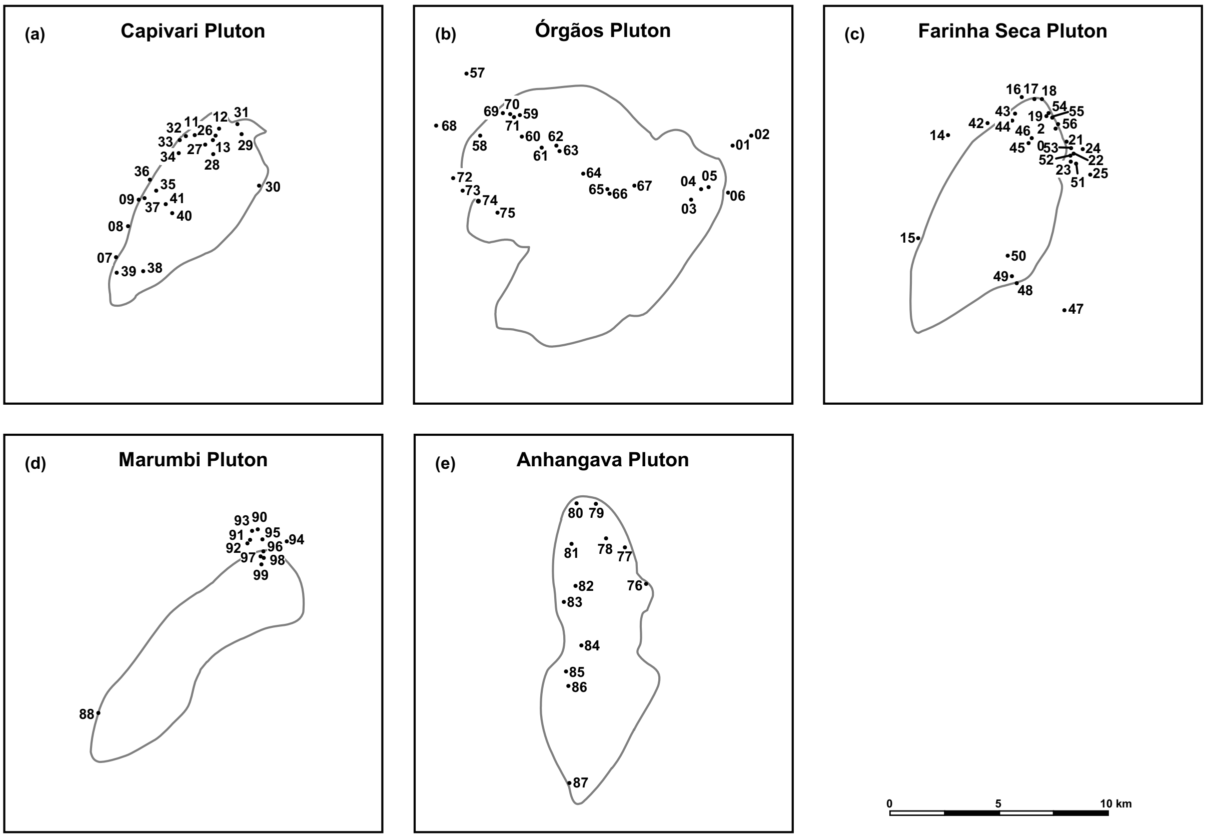

Fig. 6 – Outline of the five individual plutons showing the location of sample collection sites. All plutons are shown at the same scale. Notice that a significant number of points fall outside the traced contact between granites and country rocks; in all cases, these points are on the foothill of steep escarpments of the Serra do Mar, and indicate movement of decametric blocks for large distances (see text for details).

the remainder of the pluton. These interpretations are very tentative at this stage, but, if confirmed, would justify the elevation of the Órgãos Pluton to the status of complex. However, such proposition will have to await further fieldwork in the area.

The gamma-ray maps reveal strong positive anomalies in the central portion of the pluton. In the southeastern portion described above, negative anomalies are seen following one of the main drainages in the area (Figure 4), and suggest the mobilization of radionuclides during weathering of the granitic rocks (cf. Gualda et al. 2001). The main petrographic varieties in the pluton are similar to those found in the Capivari Pluton, with the exception of the northwesternmost portion, which is characterized by alkali-feldspar granites with amphibole and monzodioritic rocks. The occurrence of monzodioritic rocks in this pluton is the only one where basic-intermediate rocks are seen as isolated blocks.

Farinha Seca Pluton

The Farinha Seca Pluton (Figure 6c) crops out to the south of the Órgãos Pluton. The historical Estrada da Graciosa (Graciosa Road) runs along part of the northeastern limit of the pluton, while the Curitiba-Paranaguá Railroad traces the southwestern contact of the pluton. It has elliptical shape with major and minor axes of 12 and 6 km respectively. Access to the interior of the pluton, within the Serra da Graciosa and Serra da Farinha Seca, is only possible using trails and old Jesuit paths. The geophysical maps indicate a homogeneous pluton, with strong positive anomalies of K, U, and Th. In many of the maps, positive anomalies extend to the east of the Serra do Mar escarpment; however, the spectral characteristics in these areas is distinct from those in the pluton, and probably result from weathering (Gualda et al. 2001). This pluton differs from the previous two in that it is dominated by alkali-feldspar granites with amphibole, in part similar to those seen in the northwesternmost portion of the Órgãos Pluton. In an isolated occurrence to the northwest of the pluton, alkali-feldspar granites with amphibole are found, and are texturally distinct from those in the pluton (see Petrography section below). The contact relations of this portion and the main pluton were not observed, but it is possible that this corresponds to a small plug separate from the main pluton. In another isolated occurrence on the northwest portion of the pluton, plagioclase-bearing rocks are seen – namely syenogranites and quartz syenites – and contain mafic enclaves and show textures indicative of magma mingling; the mafic enclaves in these rocks are very similar to the rocks seen in the Órgãos Plutons.

MARUMBI PLUTON

The Marumbi Pluton (Figure 6d) crops out to the southwest of the Curitiba-Paranaguá Railroad. It has irregular shape, elongated along north-south, and dimensions of 13×4 km, yielding a total outcrop area of 37 km^2. Visitation to the northwestern portion of the Serra do Marumbi – which corresponds to a state park – is prohibited, such that fieldwork was limited to the northern and southwestern portions of the pluton. The gamma-ray maps allow the recognition of two main positive anomalies, one on each end of the pluton. Despite the limited sampling, the petrographic facies typical of both portions are very similar to each other. The northeastern portion of the pluton is characterized by vertical walls up to several hundred meters in height; accordingly, movement of blocks towards lower elevations is expected to be significant, and decametric blocks were found at large distances from the inferred (or rarely observed) contact with the country rocks. Interestingly, gamma-ray anomalies are seen at the foothills of these walls, with no significant difference in the spectral characteristics of these portions and the main pluton (Gualda et al. 2001). In all localities visited, a single petrographic facies was recognized, and corresponds to an alkali-feldspar granite with biotite.

ANHANGAVA PLUTON

The Anhangava Pluton (Figure 6e) is oriented along the north-south direction, has dimensions of 14×4 km, is the most easily accessible of the five plutons studied here, and is the only one which has been studied in some detail (Kaul 1997, Lopes et al. 1998). It occupies an area of approximately 51 km^2 in the area of the Serra da Baitaca and Serra da Boa Vista. Its shape is somewhat unusual, with many smaller internal morphological complexities. The contact with the country rocks is not well displayed in the gamma-ray maps, and the spectral characteristics of the anomalies are heterogeneous throughout the pluton (Gualda et al. 2001). The Anhangava Pluton is characterized by a large variety of petrographic facies, but their distribution cannot be easily correlated with the spectral heterogeneities in the gamma-ray maps. The main petrographic varieties are alkali-feldspar syenites with amphibole, clinopyroxene and olivine, alkali-feldspar granites with biotite, and syenogranites with biotite and amphibole (see Petrography section below).

Kaul (1997) suggested a ring structure for the pluton, with three main units: Serra da Baitaca (biotite syenogranites and biotite alkali-feldspar granites), Serra da Boa Vista (riebeckite-biotite and biotite alkali-feldspar granites), and Roça Nova (hornblende and hornblende-clinopyroxene alkali-feldspar syenites and biotite alkali-feldspar granites). Taking into consideration the paragenesis observed, it seems more adequate to group these facies into 3 groups characterized by: (1) fine-grained alkali-feldspar syenites with amphibole and pyroxene, predominant in the northern part of the pluton; (2) syeno/monzogranites and alkali-feldspar granites with biotite usually present in the central part of the pluton; and (3) alkali-feldspar syenites with pyroxene and olivine found in the southernmost portion of the pluton. However, further fieldwork is necessary to properly constrain the distribution and the contacts between these petrographic varieties. In any case, we find no convincing evidence for the presence of a ring structure as that suggested by Kaul (1997).

PETROGRAPHY OF THE PLUTONS

The main petrographic facies found on the five plutons studied are described below. Modal compositions are presented in Gualda and Vlach (2007a).

FINE-GRAINED INEQUIGRANULAR ALKALI-FELDSPAR SYENITES, ANHANGAVA PLUTON

Rocks of this facies are leucocratic (Color Index, CI: 7), medium-fine-grained, and have inequigranular texture;

locally, rocks are porphyritic with a fine-grained matrix. Alkali-feldspar predominates. Amphibole is the prevailing mafic mineral and appears as isolated crystals, which frequently surround partly corroded olivine and euhedral clinopyroxene; more rarely, amphibole appears as interstitial or poikilitic crystals. Clinopyroxene shows characteristic concentric zoning, revealed by colors varying from pinkish in the core, to greenish or colorless close to the rim. Olivine is present in the least differentiated samples. Accessory phases include zircon, apatite and interstitial allanite.

Fine-grained Equigranular Alkali-feldspar Syenites, Anhangava Pluton

This facies comprises predominantly massive, but locally banded, rocks. They are leucocratic (CI: 3-6), have fine-grained equigranular texture. Quartz and mafic minerals are usually interstitial to alkali-feldspar, with infrequent round quartz crystals. Sodic-calcic amphibole is the most abundant mafic mineral and concentric zoning is revealed by variations in the pleochroic patterns, with cores characterized by brown to green shades, and rims in blue and green colors. Pleochroic biotite in shades of brown and deep red (hereafter called red biotite) appears rarely as interstitial crystals of up to 1 mm in size. Clinopyroxene, similar to that seen in the previous variety, is relatively rare, with the exception of some restricted bands in the banded sample. Fluorite, as large ($\sim$1 mm) interstitial crystals, is relatively abundant in the samples with more quartz. Euhedral zircon and chevkinite-perrierite are present, the latter usually included in amphibole crystals.

Fine-grained Equigranular Alkali-feldspar Granites, Farinha Seca Pluton

Rocks from this group are restricted to an isolated occurrence close to the northwestern edge of the Farinha Seca Pluton. It consists of hololeucocratic (CI: 4), massive rocks, with fine-grained equigranular texture. Isolated quartz crystals are observed within an alkali-feldspar framework. Amphibole is typically interstitial to poikilitic. Alkali-feldspar frequently shows “droplet-like” quartz inclusions, resembling granophyric intergrowths. Amphibole, the prevailing mafic mineral, is pleochroic in shades of brown to greenish-blue and deep blue; it grades from sodic-calcic in the cores to sodic in the rims. Rarely, strongly corroded remnants of less-intensely pleochroic greenish amphibole are seen, and correspond to more calcic varieties. Typically sodic amphibole (navy blue in color) develops along fractures in the primary amphibole crystals, and also as isolated needles. Accessories include zircon, apatite and chevkinite-perrierite; fluorite is rare, while ilmenite is the only opaque phase present.

Fine-grained Porphyritic Alkali-feldspar Granites, Farinha Seca Pluton

This variety is found as an isolated outcrop on the southeastern limit of the Farinha Seca Pluton, and corresponds to a massive, hololeucocratic, porphyritic microgranite, characterized by a very-fine-grained equigranular matrix. Its mineralogy is very similar to that of the previous variety. The alkali-feldspar megacrysts are similar to the bigger crystals present in the previous variety, while the quartz crystals are somewhat smaller; bypiramidal quartz crystals are sometimes present. Amphibole is typically sodic and appears isolated as small prisms and needles that are most frequently disseminated throughout the rock, but sometimes form radiated aggregates. Fluorite is relatively more abundant than in the previous variety, while chevkinite-perrierite is scarce. Euhedral cassiterite is very rare.

Medium-grained Equigranular Alkali-feldspar Granites, Farinha Seca and Órgãos Plutons

Rocks from this facies are predominant in the Farinha Seca and are present in areas of the Órgãos Pluton. They are massive, hololeucocratic or leucocratic (CI: 4-6), and have medium-grained, equigranular texture. They consist of a framework of subhedral, mesoperthitic alkali-feldspar, with quartz as clusters of 3-5 round crystals. Amphibole, the most abundant mafic mineral, is usually interstitial and is patchily distributed; compositions are strongly variable, covering the whole spectrum from calcic to sodic amphiboles. Biotite, pleochroic from yellow to light brown (brown biotite), appears partly substituting amphibole (in association with fluorite), or, more rarely, appears as isolated crystals. Chevkinite-perrierite, zircon, fluorite, apatite, ilmenite and minor magnetite are the most common accessory minerals; cassiterite is rare and restricted to the varieties with primary sodic amphibole.

Medium-grained Equigranular Alkali-feldspar Syenites with Pyroxene and Olivine, Anhangava Pluton

Rocks from this facies are leucocratic (CI: 5), with medium-grained equigranular texture. Alkali-feldspar predominates as euhedral perthitic grains, which are always perthitic. Quartz is scarce and always interstitial. Hedenbergitic pyroxene is the prevailing mafic mineral, forming subhedral or interstitial grains. Zoning is indicated by colorless cores in some of the crystals, while the rims are typically dark green, in contrast with those seen in the *fine-grained equigranular alkali-feldspar syenites* of the Anhangava Pluton (see above). Fayalitic olivine is ubiquitous and is usually in close proximity to the clinopyroxene crystals. Accessory minerals include zircon, apatite, chevkinite-perrierite and opaques – mainly ilmenite. These are the only rocks in the alkaline association that lack amphibole.

Medium-grained Equigranular Alkali-feldspar Syenites with Amphibole, Anhangava Pluton

Rocks that compose this facies are massive, leucocratic (CI: 6), with medium-grained equigranular texture. Again, the texture is dominated by subhedral, mesoperthitic alkali-feldspar grains, with interstitial quartz and calcic amphibole homogeneously dispersed throughout the rock. Rarely, deeply corroded pyroxene is found in the cores of the amphibole grains. The main accessory phases are zircon, apatite, opaque minerals (mostly ilmenite), allanite and fluorite.

Medium-grained Porphyritic Granites, Capivari and Órgãos Plutons

Rocks from this facies are the most abundant in the Capivari Pluton, and were observed only locally in the Órgãos Pluton. They are hololeucocratic (CI: 2-3) syenogranites with biotite. The texture is typically porphyritic, with usual 1-2 cm long feldspar megacrysts in a fine-grained, equigranular matrix. Locally, more inequigranular varieties are seen. In rare instances, textural variations are observed within a single block, potentially suggestive of mingling of magmas. The most abundant megacrysts are of alkali-feldspar and plagioclase, with occasional quartz megacrysts. Alkali-feldspar megacrysts are always perthitic, and show abundant inclusions of minute plagioclase and quartz crystals that delineate internal euhedral shapes; these inclusions are particularly common close to the rims of the grains. Plagioclase megacrysts are sometimes present in aggregates of 2-3 grains; they typically display normal zoning (An: 25-12, optical determinations), but only rarely show oscillatory zoning; alkali-feldspar rims around plagioclase are common. Like in the alkali-feldspar megacrysts, quartz inclusions are frequent towards the rims of the bigger crystals, but absent in the central portions. Quartz megacrysts usually form clusters of 2-3 grains. The matrix of these rocks is given by quartz, alkali-feldspar and plagioclase, in this order of abundance. Myrmekitic intergrowths are common in the contacts between plagioclase and alkali-feldspar. Mafic minerals are only found within the matrix; biotite, pleochroic in shades of yellow and brown, predominates among them; amphibole is relatively rare and is frequently corroded, partly replaced by biotite and quartz, and possibly opaques and titanite. Accessory minerals include titanite, allanite, zircon, apatite, fluorite, magnetite and ilmenite.

Medium-grained Inequigranular Syenogranites, Capivari Pluton

Rocks grouped in this facies are found in the extreme north and south portions of the Capivari Pluton. They are hololeucocratic (CI: 3-5), massive rocks, with medium-grained, seriated inequigranular texture. The larger alkali-feldspar crystals are somewhat smaller and more euhedral than the alkali-feldspar megacrysts in the rocks of the previous facies; they sometimes appear in clusters of 3-5 grains. The quartz-rich matrix around this crystals is coarser-grained than in the previous facies, giving rise to the typically inequigranular texture. Otherwise, these rocks are mineralogically similar to those of the previous facies.

Medium-grained Equigranular Syenogranites, Capivari, Órgãos and Anhangava Plutons

These rocks predominate in the northern portion of the Capivari Pluton and in the central portion of the Anhangava Pluton, but are only rarely found in the easternmost portion of the Órgãos Pluton. They are massive, typically hololeucocratic (CI: 2-3), but locally leucocratic (CI: 5), rocks, texturally very distinct from the previous facies. The typical texture is equigranular and medium-grained, characterized by alkali-feldspar and quartz in small clusters. In contrast with the other facies, alkali-feldspar is mesoperthitic; plagioclase is more calcium-rich (An: 30), with concentric zoning only occasionally observed. Biotite, the most abundant mafic mineral, is interstitial and appears mostly within the quartz clusters, but also as isolated grains; it is pleochroic in shades of yellow and brown. Amphibole is present as euhedral grains, in contrast with what happens in the previous facies. Accessory minerals include allanite, zircon, titanite, magnetite, ilmenite and fluorite.

Fine-grained Equigranular Syenogranites, Órgãos Pluton

These rocks are restricted to the extreme east portion of the Órgãos Pluton. They are hololeucocratic (CI: 2-4), with slightly oriented fabric, and fine-grained equigranular texture. Alkali-feldspar is perthitic and its crystals are somewhat larger than those of quartz and plagioclase. Minute inclusions of plagioclase and quartz are common in the bigger alkali-feldspar crystals. Plagioclase and quartz are similar to those found in the previous facies. Brown biotite is the predominant mafic mineral.

Microgranitic Enclaves, Capivari, Órgãos and Anhangava Plutons

Enclaves, from a few to several centimeters in diameter, were observed in all facies of this association, but are especially abundant in the equigranular facies. Rarely, rocks similar to the enclaves are seen as isolated blocks. All studied enclaves are massive, hololeucocratic (CI: 3-5), and have fine to very fine equigranular texture. The matrix is characterized by quartz, alkali-feldspar, plagioclase, biotite and amphibole, all anhedral and with dimensions under 250 m. Occasionally, larger crystals are seen within this matrix; they are frequently corroded, so most likely correspond to xenocrysts incorporated from the host magma. The main mafic mineral is amphibole; biotite and corroded pyroxene are frequently present. The accessory mineralogy includes titanite, zircon, apatite, magnetite and ilmenite.

Medium-grained Equigranular Alkali-feldspar Granites, Marumbi and Anhangava Plutons

Rocks from this facies dominate all of the Marumbi Pluton and appear as somewhat circumscribed occurrences in the central portion of the Anhangava Pluton. Rocks are massive, hololeucocratic (CI: 1-2), and have medium-grained equigranular texture. Perthitic to mesoperthitic alkali-feldspar largely predominates, with quartz and mafic minerals, either as isolated crystals or as clusters of crystals that occupy interstitial positions. Biotite, pleochroic in shades of yellow and green, is the most common mafic mineral. Zircon, ilmenite and magnetite are the most frequent accessory phases.

Monzodioritic Rocks and Enclaves

The monzodiorites are massive, leuco- to mesocratic rocks (CI: 30-35), characterized by equigranular fine-grained texture. These rocks are easily distinguished from the other varieties due to the large quantities of plagioclase and biotite. Plagioclase, calcic amphibole and biotite appear as subhedral crystals, with quartz and alkali-feldspar filling the interstices. Plagioclase invariably shows gradual zoning, and sometimes oscillatory zoning, spanning the compositional range from andesine to oligoclase (An: 40-25). Alkali-feldspar is slightly perthitic, with very thin albite lamellae. Amphibole is the most abundant mafic mineral, typically pleochroic in shades of green, with occasional colorless cores; amphibole is heterogeneously distributed, with local clusters of amphibole crystals. Biotite crystals, somewhat larger than the amphibole ones, show bladed shapes, and are pleochroic in shades of yellow and brown. Apatite is the most abundant accessory phase, followed by titanite, zircon, magnetite and ilmenite.

Medium-grained Equigranular Quartz Syenites and Syenogranites, Farinha Seca Pluton

Rocks from this facies are massive, leucocratic (CI: 10), and have medium-grained equigranular texture. Alkali-feldspar crystals predominate, surrounded by clusters of quartz and mafic minerals. Alkali-feldspar is always perthitic; graphic intergrowths with quartz are frequently present along the margins of the larger grains. Plagioclase (An: 30) is only slightly zoned, and also develops graphic intergrowths with quartz. Quartz appears mostly in the graphic intergrowths, but also as isolated round grains associated with amphibole. The most abundant mafic mineral in these rocks is a green, typically calcic, amphibole. Magnetite and ilmenite are relatively abundant. Interstitial biotite, pleochroic in shades of yellow and brown, is only rarely seen. Zircon, allanite, clinopyroxene and apatite complete the mineralogy of these rocks.

CRYSTALLIZATION CONDITIONS

Geochemical data presented here and mineral chemistry data presented by Gualda and Vlach (2007a) can be combined to assess aspects of the conditions of crystallization of the granites and syenites in the Serra da Graciosa region.

LIQUIDUS TEMPERATURES

Minimum estimates of liquidus temperatures can be obtained using the saturation temperature of early-crystallizing accessory phases as zircon and apatite (Watson and Harrison 1983, Harrison and Watson 1984, Hanchar and Watson 2003). The results obtained for 37 samples are presented in Table I and summarized in Figure 7. The equation used for calculation of Zr saturation temperatures (Watson and Harrison 1983) is applicable to temperatures between 750–1000°C and M ($[(Na+K+2Ca)/(Si*Al)]_{cat}$) in the range 0.9–1.7, while the equation presented by Harrison and Watson (1984) for apatite can be used for SiO_2 concentrations between 45 and 75 wt.%. Compositions and/or temperatures outside these ranges were disregarded.

The liquidus temperature estimates for the granitic and syenitic rocks usually fall in the interval between 750 and 900°C, with T_{Zr} being systematically higher for the alkaline association, and T_{Ap} being systematically higher in the aluminous association, in agreement with the petrographic evidence for early crystallization of zircon in the alkaline association, and early crystallization of apatite in the aluminous association. These data suggest that saturation temperatures for both associations were similar, and close to 850–900°C, comparable to estimates obtained for A-type granites worldwide (Turner et al. 1992, Poitrasson et al. 1995, King et al. 1997). The monzodioritic rocks, typically undersaturated in Zr at liquidus conditions, yield T_{Ap} around 1000°C, probably very close to the liquidus temperatures for these magmas.

SOLIDUS TEMPERATURES AND PRESSURES

Reactions between plagioclase and amphibole are frequently used to obtain solidus temperature estimates for granitic rocks (Holland and Blundy 1994), by employing rim compositions (Anderson 1996). Because the incorporation of Al in hornblende is a function of both temperature and pressure (Hammarstrom and Zen 1986, Hollister et al. 1987, Johnson and Rutherford 1989, Schmidt 1992, Holland and Blundy 1994), a combination of the hornblende-plagioclase geothermometer with the Al-in-hornblende geobarometer allows the simultaneous determination of crystallization temperature and pressure near solidus conditions (Anderson and Smith 1995; see also Anderson 1996). Application of this method is only recommended for amphiboles with mg# > 0.35 and characterized by the paragenesis biotite + hornblende + titanite + Fe-Ti oxide (+ quartz + alkali feldspar + plagioclase), such that no information can be derived for rocks of the alkaline association (Anderson and Smith 1995, Anderson 1996).

The granites of the aluminous association and the monzodioritic rocks yield similar results with equilibration temperatures close to 700–750°C, and these are probably good estimates of the solidus temperatures for these rocks. Pressure estimates for rocks of the aluminous association are variable, between 2 and 4 kbar. Geologic and petrographic evidence suggests that the plu-

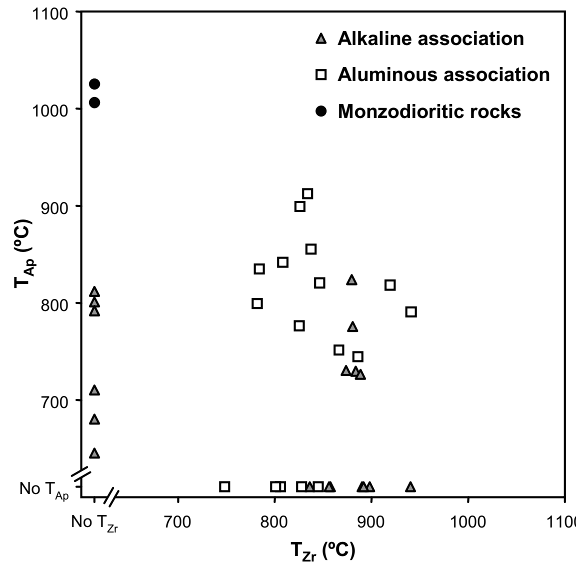

Fig. 7 – Plot of calculated apatite vs zircon saturation temperatures (T_{AP}, T_{Zr}) for granites and syenites of the aluminous and alkaline associations related monzodioritic rocks from the Serra da Graciosa region. Samples outside the ideal ranges of composition or temperature are plotted as No T_{AP} or No T_{Zr}.

tons were emplaced at shallow crustal levels, and it is unlikely that they record final magmatic crystallization under a relatively large pressure gradient as inferred from amphibole and plagioclase compositions. Rather, we believe that the variable results indicate difficulties in the application of the geobarometer for these rocks. Pressure estimates for the monzodioritic rocks are more uniform, and suggest confining pressures of 2.0 ± 0.6 kbar. Given the evidence for interaction between granitic and monzodioritic magmas, this is our best estimate for the emplacement pressures of both monzodioritic and granitic rocks.

REDOX CONDITIONS

The redox conditions under which magmas crystallized in the region are still poorly understood. Preliminary data obtained by Gualda (2001) suggest that the Fe-Ti oxides re-equilibrated under subsolidus conditions. However, a general assessment of the redox conditions can be made based on the available mineralogical data (see also Gualda and Vlach 2007a, b). The paragenesis including quartz, fayalite, and ilmenite as the sole Fe-Ti oxide in most of the alkaline association (particularly in the fine-grained alkali-feldspar syenites and alkali-feldspar granites of the Anhangava and Farinha Seca Plutons – the Alkaline series 1 of Gualda and Vlach 2007a) indicate relatively reducing crystallization conditions, certainly below the QFM buffer. In contrast, the presence of titanite, allanite, and magnetite coexisting with calcic amphibole and ilmenite in the aluminous association, as well as in some metaluminous varieties of the alkaline association (i.e. in the medium-grained equigranular alkali-feldspar granites of the Farinha Seca and Órgãos Plutons – the Alkaline series 2 of Gualda and Vlach 2007a), indicates more oxidizing conditions, close to or buffered at the TMQAI buffer (Wones 1989).

THE PETROGRAPHIC ASSOCIATIONS OF A-TYPE GRANITES

One significant characteristic of many provinces of A-type granites is the coexistence of rocks of contrasted affinity, with rocks of aluminous affinity – metaluminous to marginally peraluminous – being contemporaneous with rocks of alkaline affinity – metaluminous to peralkaline (Lameyre and Bowden 1982, Vlach et al. 1990, 1991, Pitcher 1995, King et al. 1997).

The petrographic facies described here can be ascribed to either of these associations. The subsolvus syeno/monzogranites with biotite and calcic amphibole, typically subsolvus, which predominate in the Capivari and Órgãos Plutons and in the central portion of the Anhangava Pluton, are all part of an aluminous association. The hypersolvus alkali-feldspar granites with biotite present in parts of the Anhangava Pluton and in the Marumbi Pluton are also members of this aluminous association. On the other hand, the alkali-feldspar granites with amphibole of the Farinha Seca Pluton and in the northwesternmost portion of the Órgãos Pluton, and the alkali-feldspar syenites with amphibole, $\pm$ pyroxene, $\pm$ olivine, present in the northern and southern portions of the Anhangava Pluton, all of which are typically hypersolvus, can be grouped into an alkaline association.

As defined here, these two associations characterize two contrasted overarching groups present in the province as a whole and worldwide. Each association certainly includes multiple comagmatic suites, and we detail this aspect elsewhere (Gualda and Vlach 2007a). One important aspect to emphasize here is that, even though rocks from the two associations coexist in a broad sense, occurrences of each association are limited to one individual pluton or to portions of a pluton, and no firm evidence for interaction between magmas of the aluminous and alkaline associations has been found. The referred “coexistence” or “contemporaneity” of the two associations needs to be qualified; the two associations clearly occur in the same general area, and have broadly similar ages. What needs to be defined is whether magmas that formed the alkaline and aluminous association coexisted at the same time and had the opportunity to interact in the magmatic stage. This is not well established, either by field relations or by detailed geochronological data. Given the quality of the exposures and the abundance of distinct petrographic types, the Anhangava Pluton should be the main target for future studies in the area.

The genetic relationship between the monzodioritic and granitic rocks is not yet well understood. It is relevant, however, that the two areas where monzodioritic rocks occur (Farinha Seca and Órgãos Plutons), are also areas of occurrence of alkali-feldspar granites of the alkaline association. Local interaction of these basic-intermediate and silicic magmas seem to have produced the quartz syenites of the Farinha Seca Pluton (Gualda and Vlach 2007a).

CONCLUSIONS

The combination of fieldwork, remote sensing and general petrography led to the definition of five independent plutons in the Serra da Graciosa region. We suggest that the original "Graciosa Pluton" be divided into three independent plutons, the Capivari, Órgãos, and Farinha Seca Plutons. We use the informal denomination Serra da Graciosa Granites and Syenites to the group of occurrences including these three newly defined plutons and the previously defined Anhangava and Marumbi Plutons.

This group of occurrences is one of the most important ones within a large province of A-type granites and syenites in southern Brazil, which extends from northern Santa Catarina State to southern São Paulo State, and is usually referred to as the "Serra do Mar Province" or "Serra do Mar Suite". This same name is also used for a province of Mesozoic alkaline rocks in São Paulo State, but this latter usage has historical precedence. Hence, we suggest that the province of A-type granites in southern Brazil be called the Graciosa Province, following the early usage of the term "Graciosa Facies" (Hasui et al. 1978) to describe the province.

Based on mineralogical and textural petrographic criteria, the facies present can be grouped into two contrasted associations: (1) an aluminous association, including syenogranites with biotite and amphibole of the Capivari, Órgãos and Anhangava Plutons, as well as alkali-feldspar granites with biotite of the Marumbi and Anhangava Plutons; (2) an alkaline association, comprising alkali-feldspar syenites with amphibole (± pyroxene, ± olivine) of the Anhangava Pluton, and also alkali-feldspar granites with amphibole of the Farinha Seca Plutons. Finally, volumetrically unimportant monzodiorites are present in the northwestern portions of the Farinha Seca and Órgãos Pluton, and suggest local mixing and mingling between felsic and mafic magmas.

Further field studies are necessary to clarify the geologic relations within the Anhangava and Órgãos Plutons, which may help constrain the contact and age relations between rocks of the alkaline and aluminous associations, as well as of these with the monzodioritic rocks present in the area.

ACKNOWLEDGMENTS

We are indebted to Francisco J.F. Ferreira, Alexandre C.N. da Silva, Monica Perrotta and George de Barros for assistance with image processing and interpretation. Frederico C.J. Vilalva and Leonardo F.S. Siqueira helped with magnetic susceptibility measurements. We would also like to thank Wladimir Shukowsky, who provided the data used to construct the digital elevation map. During fieldwork, we benefited from the help of many friends and local people in the Serra da Graciosa region. G. Gualda benefited from a M.Sc. scholarship from the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP-98/15656-7). We also thank comments and criticism from two anonymous reviewers.

RESUMO

A região da Serra da Graciosa inclui importantes ocorrências de granitos e sienitos da Província Graciosa de Tipo-A (originalmente chamada de Suite Serra do Mar), Sul do Brasil. Com base em trabalho de campo, petrografia, e imagens de sensoriamento remoto, é feita a caracterização dos plútons da região. Cinco plútons independentes são reconhecidos. Dois deles correspondem a plútons já definidos na região, os Plútons Marumbi e Anhangava; os três restantes derivam da subdivisão do "Maciço Graciosa" em três novos plútons: Capivari, Órgãos e Farinha Seca. Os plútons são elípticos com orientação nordeste-sudoeste. Duas associações petrográficas podem ser reconhecidas: uma associação alcalina que inclui álcali-feldspato granitos e sienitos hipersolvus, peralcalinos a metaluminosos (Anhangava, Farinha Seca, Órgãos), e uma associação aluminosa composta por granitos subsolvus, metaluminosos a marginalmente peraluminosos (Capivari, Órgãos, Anhangava e Marumbi). As ocorrências de cada uma das associações estão limitadas a um dado plúton, ou a porções de um dado plúton, e as idades relativas não são conhecidas. Rochas monzodioríticas são encontradas marginalmente aos Plútons Órgãos e Farinha Seca, e interação localizada com magmas silícicos produziu quartzo sienitos híbridos (Farinha Seca). Geotermobarometria indica colocação em níveis crustais rasos ($P = 2 \pm 0.6$ kbar), e temperaturas de cristalização no intervalo 900–700°C para granitos e sienitos, e entre 1000–700°C para rochas monzodioríticas.

Palavras-chave: Serra da Graciosa, granitos e sienitos de tipo-A, Província Graciosa, Estado do Paraná.

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