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Alkaline Ultrapotassic A-Type Granites Derived from Ultrapotassic Syenite Magmas Generated from Metasomatized Mantle

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Abstract

Ultrapotassic Neoproterozoic granites crop out in southern and northeastern Brazil, associated with syenitic suites. The granites occur as small circular bodies and dikes hosted by the syenitic rocks. The southern intrusions reflect post-collisional magmatism, whereas the northeastern granites were emplaced in mobile belts produced during intraplate continental collision. Systematic mineralogical differences of the granites reflect higher K_2O/Na_2O ratios in the northeastern assemblages. Bulk-rock compositions of the ultrapotassic granites show very high alkalis (mainly K_2O) and LIL elements, with significant depletions of Nb, Y, Zr, Hf, Ga, and REE relative to anorogenic granites. These are typical characteristics of ultrapotassic, silica-saturated alkaline rocks from post-collisional settings. Trace- and rare-earth–element patterns suggest derivation by fractional crystallization from syenitic parental magmas. Geochemical and mineralogical characteristics of these granites are completely different from within-plate alkaline granites. Most compositional data are comparable to those of shoshonitic granitoids, suggesting a probable mantle source modified by subducted-slab dehydration. In spite of this, the geochemical composition of the analyzed ultrapotassic granites is also quite different from shoshonitic and calc-alkaline granitoids in collisional settings, defining a silica-saturated ultrapotassic rock series.

Introduction

EXCEPT FOR anatetic granites of mantle provenance, most granitoids reflect less differentiated magmatism, as presently recognized by most authors (e.g., Patiño Douce, 1999; Clemens, 2003). Therefore, granitoids must be considered in terms of magmatic series (e.g., Tauson, 1983; Lameyre and Bowden, 1982; Lameyre and Bonin, 1991).

The silica-saturated alkaline series as defined in the TAS diagram (Le Maitre, 1989) can be sodic, potassic or shoshonitic, and ultrapotassic when K_2O/Na_2O ratios are higher than 2.0 (Plá Cid et al., 2000). Granites of the sodic series are generally referred to as metaluminous or peralkaline granites of alkaline affinity, whereas those of potassic affinity are termed shoshonitic or monzonitic (e.g., Pagel and Leterrier, 1980; Tauson, 1983; Nardi, 1986). The term ultrapotassic has been used mainly for basic and intermediate rocks (Foley et al., 1987); nevertheless, Plá Cid et al. (2000) suggested use of this term for silicic rocks with K_2O/Na_2O ratios higher than 2. In this paper, ultrapotassic granites are characterized and considered as representative of the most differentiated magmas of the silica-saturated ultrapotassic series.

Neoproterozoic granites from northeastern Brazil, which are genetically related to silica-saturated ultrapotassic syenites, have been described by Da Silva Filho et al. (1987, 1993), Ferreira (1991), and Plá Cid et al. (1999, 2000). In southern Brazil, Stabel et al. (2001) described granites associated with ultrapotassic syenites of Neoproterozoic age (~611 Ma), related to post-collisional stages of the Brasiliano-Pan-African cycle.

Ultrapotassic syenitic magmatism associated with collisional settings is usually related to mantle sources previously modified by melting/dehydration of subducted oceanic plates (Thompson and Fowler, 1986; Corriveau and Gorton, 1993; Ferreira et al.,

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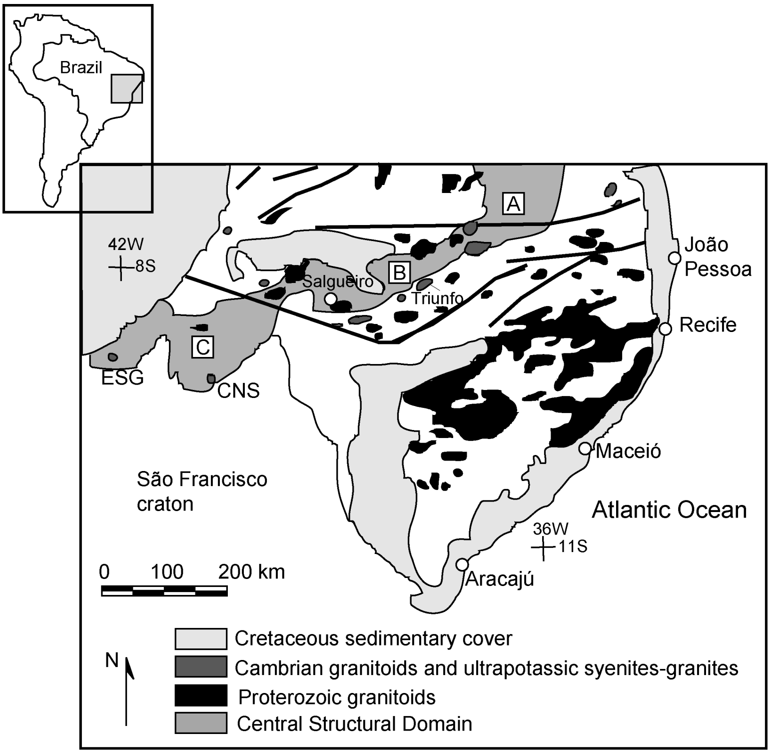

FIG. 1. Borborema Province, northeast Brazil, its lithologies and structural domains (modified from Sial and Ferreira, 1988). Central Structural Domain (light grey area): A = Seridó fold belt; B = Cachoeirinha–Salgueiro fold belt; C = Riacho do Pontal fold belt. Ultrapotassic granites presented in this study correspond to occurrences associated with the Engraçadinha syenitic–granitic suite (ESG) and Casa Nova syenitic suite (CSN). Some data are presented from granitic samples associated with ultrapotassic syenites occurring close to the Triunfo intrusion.

1994; Plá Cid et al., 1999, 2003). An earlier subduction in southern Brazil occurred at about 760–700 Ma, and its signature is ubiquitous in the post-collisional magmatism (Bittencourt and Nardi, 2000). In northeastern Brazil, subduction occurred during the Paleoproterozoic, and the Neoproterozoic ultrapotassic magmatism reflects this much older mantle metasomatism, as suggested by Ferreira et al. (1994) and Jardim de Sá (1994) for other granitoids in this same region.

Geologic Context of Ultrapotassic Granites

Ultrapotassic granites from northeastern Brazil (Fig. 1) are located along a series of northeast-trending Neoproterozoic fold belts, which constitute the Borborema Province structural domain (Fig. 1). The ultrapotassic granites are emplaced in metamorphic terrains (Figuerôa and Silva Filho, 1990; Plá Cid et al., 1999), which have Paleoproterozoic and Archean ages (Barbosa and Dominguez, 1996). These metamorphic units belong to the Riacho do Pontal fold belt, close to the structural limit with the São Francisco craton (Fig. 1), and sometimes occur as xenoliths in the ultrapotassic syenite-granite bodies. According to several authors (Ferreira, 1991; Da Silva Filho et al., 1993; Jardim de Sá, 1994; Guimarães and Da Silva Filho, 1998) these fold belts were developed during the Neoproterozoic by a series of intracontinental collisions, with intense crustal reworking and accretion of mafic and felsic magmatism with mantle origin, but without evidence of contemporaneous subduction. However, a previous Paleoproterozoic subduction has been frequently admitted by several authors (Ferreira et al., 1994; Plá Cid et al., 1999, and references therein).

Shield areas in southern Brazil (Fig. 2) are composed mostly of magmatic rocks related to the

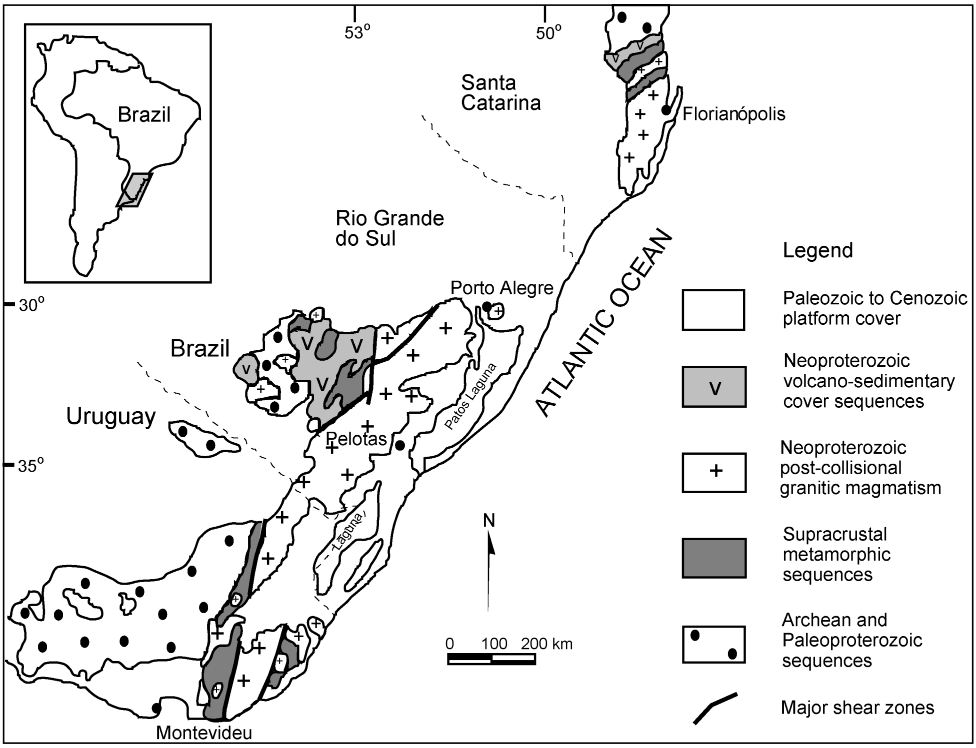

FIG. 2. Simplified geological map of the Sulriograndense shield area, southern Brazil.

Brasiliano–Pan African cycle (Brito Neves and Cordani, 1991) emplaced in a Paleoproterozoic metamorphic basement (Hartmann et al., 2000). The Brasiliano–Pan African cycle is marked by arc magmatism with ages between 760 and 700 Ma (Fernandes et al., 1992; Babinski et al., 1996; Chemale Jr. et al., 1997) and a widespread post-collisional magmatism, in the sense of Liégeois et al. (1998), with ages from 650 up to 550 Ma (Bitencourt and Nardi, 2000). The southern Brazilian post-collisional magmatism comprises syn-transcurrent, high-K, sub-alkaline granitoids and leucocratic peraluminous granites, evolving to granitoids of shoshonitic affinity and eventually to late-transcurrent, dominantly metaluminous alkaline granites. All this granitic magmatism, with the exception of the peraluminous rocks, is associated with basic magmas represented by mafic microgranular enclaves, synplutonic dikes, and mafic components in mixed systems. The western and northwestern portions of the Sulriograndense shield represent less deformed areas, with volcano-sedimentary sequences deposed in strike-slip basins developed during this time gap and intruded by plutonic associations. This magmatism shows the same geochemical evolution present in the eastern part. High-K, sub-alkaline granitoids, shoshonitic plutonic-volcanic associations, and silica-saturated, alkaline to continental tholeiitic plutonic-volcanic sequences are in the range of 650 to 580 Ma. The age of the ultrapotassic magmatism is about 610 Ma and is coeval with the shoshonitic series, represented by the Lavras do Sul Shoshonitic Association (Lima and Nardi, 1998).

Ultrapotassic granites from northeast Brazil are undeformed, with mineral orientation and segregations promoted by magmatic flow during crystallization. Granites occur as dikes, with thickness around a few meters, some with composite syenite-granite compositions crosscutting or parallel to the magmatic flow structure of the host syenitic rocks (Plá Cid et al., 2000). In a few cases, they form isolated circular bodies, or gradational facies in the syenitic intrusions. Most of the granites are fine to medium-grained, equigranular, leucocratic rocks, without mafic enclaves or significant textural variations. The composite dikes consist of coarse-grained syenites

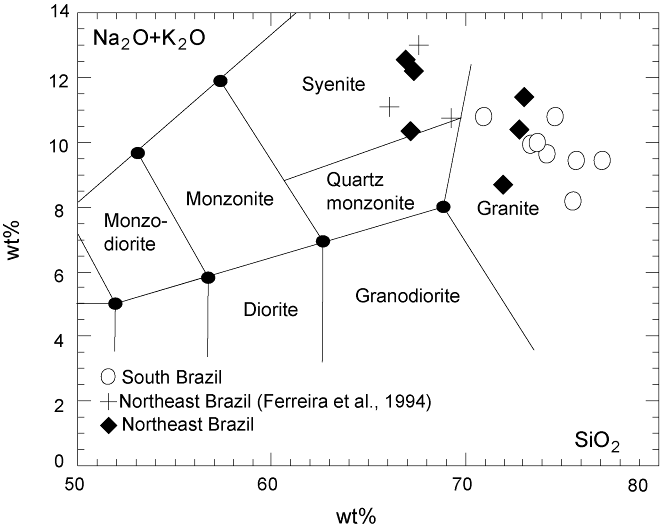

FIG. 3. Total alkalis vs. Silica (TAS) diagram with samples plotted in the silica-saturated alkaline field, compositionally corresponding to trachytes and rhyolites.

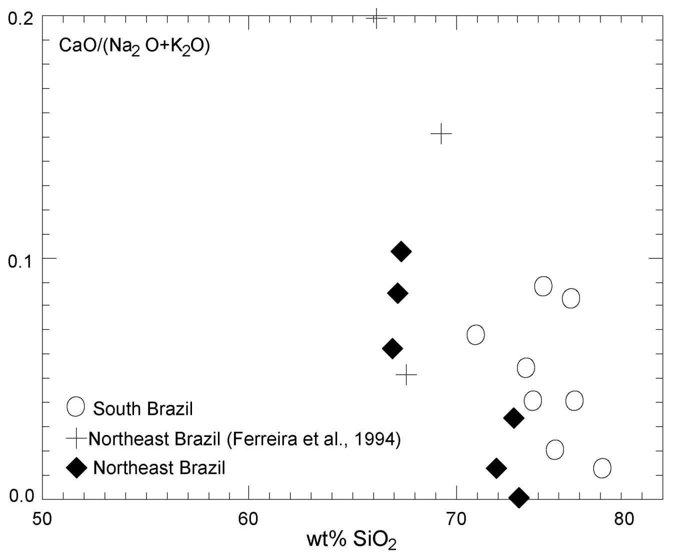

FIG. 4. $CaO/(Na_2O+K_2O)$ vs. silica diagram, showing the low values of this ratio in most samples, as typically observed in alkaline metaluminous granites.

forming the outer portion, in sharp contact with the host syenite, and fine-grained granitic compositions in the central part. The magmatic orientation of minerals is roughly parallel in both syenites and granites, and also in the regional metamorphic units, which demonstrates that such magmas crystallized under the influence of late-tectonic movements. This is corroborated by a whole-rock Rb-Sr isochron

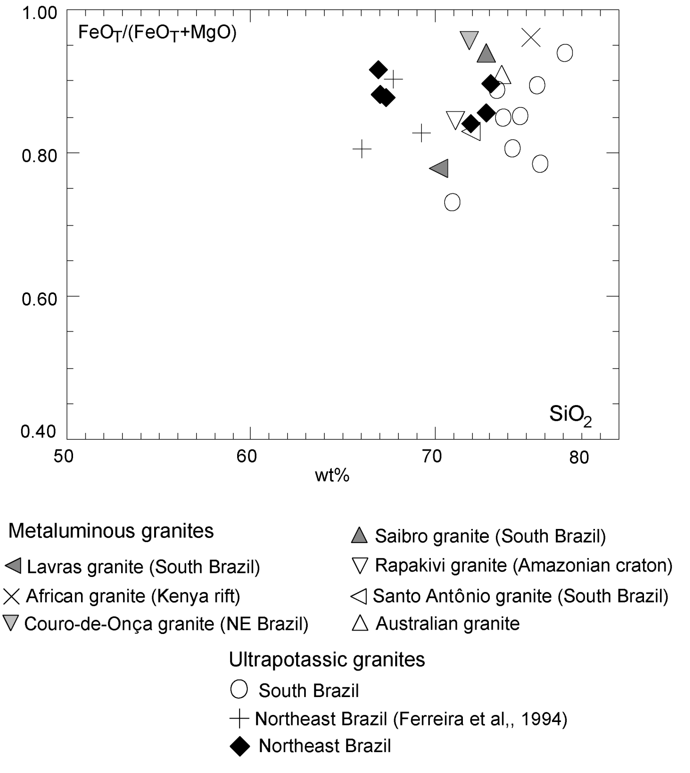

FIG. 5. FeOT/(FeOT + MgO) vs. silica diagram (after Nardi and Bonin, 1991) showing the similarity between ultrapotassic and alkaline metaluminous granites. Data for the metaluminous rocks are: Rapakivi Amazonian granites (Dall'Agnol et al., 1999); Santo Antônio Granite (Barros and Nardi, 1994); A-type Australian granites (Collins et al., 1982); Saibro Suite (Nardi and Bonin, 1991), Kenya Rift granites (MacDonald et al., 1987), Lavras Granite (Nardi, 1984), Couro-de-Onça Granites (Plá Cid et al, 2000).

obtained for the syenites that yielded an age of 555 ± 10 Ma, with $Sr_i = 0.7068$ (Jardim de Sá, 1994; Plá Cid et al., 1999).

Southern Brazil ultrapotassic granites are associated with the Piquiri Syenite (Vieira Jr. et al., 1989; Stabel et al., 2001). The granites are fine- to coarse-grained, leucocratic, and occur mainly as centimeter-to meter-thick dikes crosscutting the host syenite. Their textures are generally hypidiomorphic, equigranular, and inequigranular, with alkali feldspars oriented by magmatic flow. The contacts with the host syenite are commonly gradational, suggesting their co-magmatic character.

Petrographic Features

Felsic rocks of silica-saturated ultrapotassic series are quartz-alkali feldspar syenites and alkali feldspar granites, according to the modal nomenclature proposed by Streckeisen (1976). The ultrapotassic granites are compositional and texturally very homogeneous. Their mineralogy is dominated by alkali feldspar, quartz, plagioclase, pyroxene, calcic amphibole, biotite, titanite, magnetite, with minor amounts of blue amphibole, apatite, albite, zircon, and carbonate. Most granitic rocks are slightly inequigranular, in a few cases porphyritic, with alkali feldspar phenocrysts. The main petrographic variation between syenites and granites is the modal proportion of quartz.

In the northeast Brazil occurrences, alkali feldspar is the dominant mineral phase, and it occurs as subhedral crystals, generally homogeneous or with very thin perthites. Quartz is mostly interstitial, in some cases forming aggregates where the crystals exhibit wavy extinction and rare polygonal (120º) contacts. Quartz grains occur also as inclusions in alkali feldspar, mostly in the granites *strictu sensu.*

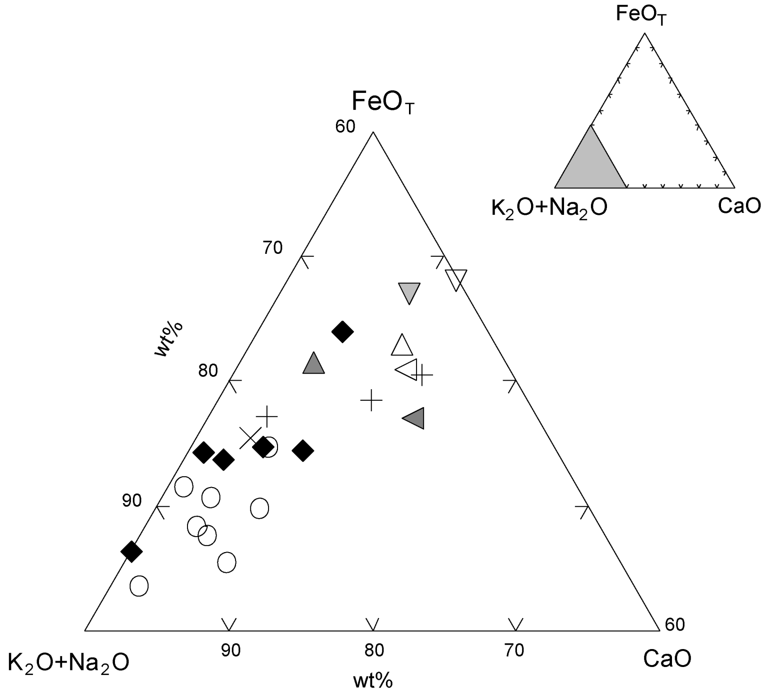

FIG. 6. Calcium × iron × alkalis triangular diagram proposed for discriminating between ultrapotassic, alkaline, and shoshonitic granitoids. The legend is the same as in Figure 5.

Pyroxene is green to pale green, euhedral to subhedral, and occurs as agglomerates with titanite, and uncommonly with magnetite. Some euhedral crystals occur as inclusions in alkali feldspar grains. The quartz syenitic rocks contain greater amounts of pyroxene than do the granites. Titanite is euhedral and characteristically associated with magnetite ± pyroxene in the agglomerates. Apatite and zircon are the main accessory phases and occur as euhedral inclusions in alkali feldspar. Some late-magmatic blue amphibole is related to the subsolidus transformation of pyroxene. Albite is rare, but some grains are present interstitially in the alkali feldspar mosaic. Textural relations indicate that principal and accessory minerals crystallized simultaneously, although titanite and magnetite are possibly later than other phases such as quartz, alkali feldspar, apatite, and pyroxene (Plá Cid et al., 1999, 2000).

Two different types of ultrapotassic granites occur in southern Brazil. (1) Perthite granites are hypidiomorphic rocks, constituted mainly by interstitial quartz, euhedral alkali feldspar grains with Ab-component around 20–30%, and including euhedral pyroxene and partially resorbed plagioclase. Amphibole is rare, and is considered as a late-magmatic transformation of pyroxene. Titanite euhedral crystals are abundant. Textural relationships indicate that crystallization started with pyroxene, apatite, and zircon, followed by plagioclase, which was later partly resorbed. The late-magmatic mineralogy is formed by quartz, alkali feldspar, biotite, amphibole, magnetite, and titanite. In a few cases, albite micro-crystals surround alkali feldspar. (2) Two-feldspar granites (syenogranites) are hypidiomorphic rocks, locally with inequigranular texture due to the presence of phenocrysts of plagioclase and alkali feldspar. Early-crystallized plagioclase is partially resorbed. Alkali feldspar shows a variable amount (~10%) of fine perthite. The principal mafic phases are amphibole and biotite, with small amounts of preserved pyroxene. Titanite occurs as rare euhedral grains. Zircon and apatite are typical accessory phases. The textural relationship of feldspar and quartz in the perthite granites classify them

TABLE 1. Representative Chemical Data of Ultrapotassic Granites from Northeast and Southern Brazil

Sample:	Southern Brazil								Northeast Brazil							
	A06b	A12	FPQ 15	FPQ 26	FPQ 27	FPQ 30	FPQ 37	FPQ 38	CN60B	CN7A	ENG31	ENG32	ENG52	ENG53	TN-1	UDS-95
SiO_2	75.71	77.04	74.23	75.55	70.92	74.68	73.4	73.68	72.82	73.02	67.36	66.90	71.93	67.21	69.31	66.11
Al_2O_3	12.7	12.08	12.82	12.76	13.91	13.57	14.46	13.02	14.13	13.60	14.66	14.80	17.47	15.97	13.93	13.42
FeOt	1.17	1.25	1.13	0.51	1.99	0.40	0.87	0.95	1.71	0.77	2.27	2.31	1.47	3.54	2.80	3.43
Fe_2O_3	1.31	1.40	1.27	0.57	2.24	0.45	0.98	1.07	1.92	0.87	2.55	2.59	1.65	3.98	3.14	3.85
MnO	0.01	0.01	0.02	0.01	0.02	0.00	0.01	0.01	0.03	0.01	0.05	0.06	0.02	0.06	0.08	0.08
MgO	0.32	0.08	0.27	0.06	0.73	0.07	0.11	0.17	0.29	0.09	0.32	0.21	0.28	0.48	0.58	0.84
CaO	0.39	0.12	0.85	0.68	0.74	0.23	0.54	0.41	0.35	0.01	1.25	0.78	0.11	0.88	1.62	2.22
Na_2O	3.74	3.08	3.07	4.92	3.31	2.74	4.48	2.79	0.72	1.55	2.73	2.48	1.46	0.50	2.67	1.71
K_2O	5.71	6.36	6.54	3.26	7.50	8.07	5.47	7.21	9.65	9.85	9.47	10.07	7.20	9.83	8.05	9.4
TiO_2	0.17	0.16	0.10	0.10	0.32	0.08	0.06	0.11	0.32	0.06	0.19	0.19	0.20	0.42	0.26	0.37
P_2O_5	0.1	0.03	0.17	0.02	0.05	0.03	0.02	0.04	0.11	0.09	0.09	0.11	0.06	0.08	0.16	0.24
LOI	0.5	0.53	0.34	0.25	0.42	0.37	0.39	0.38	0.44	0.46	0.44	0.52	0.54	0.51	0.04	0.18
Total	100.66	100.89	99.68	98.18	100.16	100.29	99.92	98.88	100.78	99.61	99.11	98.71	100.92	99.92	99.84	98.42
Ag. index	0.97	0.99	0.95	0.91	0.98	0.98	0.92	0.95	0.82	0.97	1.01	1.01	0.58	0.72	0.94	0.97
Ba	1616	1147	1530	497	2954	2022	1830	2660	1318	2407	4846	5403	5233	5613	4290	5055
Rb	300	303	231	209	325	305	259	283	209	278	264	272	265	282	238	314
Sr	646	364	691	404	947	933	955	994	117	38	463	475	224	152	786	594
Cs	23	9	7	10	9	6	7	6	n.d.	1	5	4	n.d.	n.d.	n.d.	n.d.
Ga	24	22	14	23	n.d.[1]	n.d.	23	14	26	20	17	17	16	14	n.d.	n.d.
Ta	13	9	2	6	2	1	3	2	n.d.	1	1	1	n.d.	n.d.	1	1
Nb	31	79	19	36	32	9	14	10	32	6	8	8	15	12	n.d.	n.d.
Hf	8	11	3	6	9	2	4	8	n.d.	2	4	3	n.d.	n.d.	10	7
Zr	464	248	63	122	203	72	63	238	87	44	158	144	117	142	251	108
Y	19	11	12	12	4	3	4	5	16	2	13	16	43	72	n.d.	n.d.
Th	60	138	18	64	43	14	27	181	3	2	10	10	9	8	34	6
Cr	15	5	10	10	13	2	10	10	n.d.	2	3	2	n.d.	n.d.	10	16
Ni	5	5	10	29	1	1	10	10	17	2	4	2	19	17	n.d.	23
Cu	5	11	62	5	3	10	5	5	74	4	3	4	58	37	n.d.	8
Pb	95	45	34	29	29	24	37	22	4	11	25	15	13	5	n.d.	n.d.

La	22.9	45.7	15.4	56.7	23.9	9.7	3.1	13.6	26.60	5.99	20.49	26.49	91.80	66.60	45	55
Ce	33	94.70	25.60	87.30	43	19	5.80	25.90	81.70	15.28	42.18	49.40	200.30	132.90	97.00	132
Pr	5.02	7.83	2.61	6.46	n.d.	n.d.	0.74	2.91	8.43	1.93	5.07	6.52	20.09	19.47	n.d.	n.d.
Nd	19.3	23.50	9.00	18.20	16.00	9	3.10	10.50	40.70	7.13	19.58	24.22	87.70	92.00	37.00	56
Sm	3.61	4.06	1.90	2.70	2.20	1.6	0.80	1.80	8.30	1.34	4.09	4.77	15.40	17.60	7.60	9.7
Eu	0.92	0.99	0.75	0.38	1.00	0.6	0.30	0.57	2.18	0.77	2.06	2.40	3.46	4.44	2.20	2.5
Gd	2.47	2.41	1.80	1.7	n.d.	n.d.	0.70	1.20	6.50	1.01	2.94	3.76	13.40	15.40	n.d.	n.d.
Tb	0.35	0.41	0.40	0.40	0.25	0.25	0.10	0.20	0.80	0.14	0.43	0.50	1.80	2.20	0.6	0.7
Dy	1.75	2.07	2.20	2.10	n.d.	n.d.	0.80	0.90	3.50	0.55	2.15	2.80	8.40	11.40	n.d.	n.d.
Ho	0.3	0.36	0.40	0.40	n.d.	n.d.	0.10	0.20	0.50	0.10	0.40	0.50	1.40	2.00	n.d.	n.d.
Er	0.97	1.14	1.30	1.20	n.d.	n.d.	0.40	0.40	1.30	0.22	1.02	1.30	3.90	6.00	n.d.	n.d.
Tm	0.16	0.19	0.19	0.20	n.d.	n.d.	0.06	0.07	0.13	0.03	0.16	0.19	0.41	0.62	n.d.	n.d.
Yb	1.06	1.23	1.10	1.20	0.7	0.5	0.40	0.50	0.80	0.15	1.09	1.22	2.80	4.00	2.70	1.2
Lu	0.17	0.17	0.17	0.17	0.11	0.08	0.06	0.08	0.11	0.03	0.16	0.18	0.39	0.66	0.30	0.2

[1]n.d. = not determined.

as hypersolvus granites, whereas the syenogranites are transsolvus granites as defined by Martin and Bonin (1976).

Ultrapotassic perthite granites from southern and northeastern Brazil are mineralogically different, mainly due to the different K_2O/Na_2O ratio and H_2O-contents of magma (see geochemistry section). Similarly, both types show high modal proportions of titanite.

Mineralogic Compositions

Pyroxenes in the ultrapotassic granitoids from southern Brazil are diopside and Ca-rich augite, normally replaced by later magmatic Mg-hornblende or actinolite. In the northeastern occurrences, the pyroxene is aegirine-augite, with up to 62% of acmite component in the granites and 40% in the quartz syenites. Mg-riebeckite has been identified in some ultrapotassic granites as a late-magmatic transformation of aegirine-augite.

Biotite occurs mainly in southern Brazil ultrapotassic granitoids and shows the same Fe/(Fe+Mg) ratios determined for the actinolites, between 0.4 and 0.5, which are also similar to those of Mg-hornblende and biotite from less differentiated co-magmatic syenites and quartz-syenites. According to the classification proposed by Nachit et al. (1985), they plot in the field of biotite from shoshonitic rocks. Fe/(Fe+Mg) ratios in amphibole and biotite are much lower than in syenites, which is consistent with the relatively large abundance of Fe-Ti oxides and with increasing oxidation during the syenitic magma differentiation (Stabel et al., 2001).

Ultrapotassic granites in southern Brazil are transsolvus granites with albite-oligoclase (An_{0-15}) and alkali feldspar (Or_{90-99}), and hypersolvus granites where perthitic feldspar has up to 30% in volume of Ab-component. In the northeastern granitoids, the alkali feldspar is quite homogeneous, with orthoclase contents varying from 90% in quartz syenites to 96% in granites. Quartz syenite alkali feldspars are also richer in BaO (1.0 wt% on average), whereas in the granitic dikes they show lower values, close to the detection limit. The lack of early-crystallized plagioclase is certainly caused by the very high K/Na ratio in the magma, promoting early alkali feldspar crystallization, out of the plagioclase stability field and close to the Or end-member, as discussed by Neksvasil (1990) based upon experimental data. Apatite crystals show high Sr (up to 1.0 wt%) and LREE ($La_2O_3 + Ce_2O_3 > 0.8$

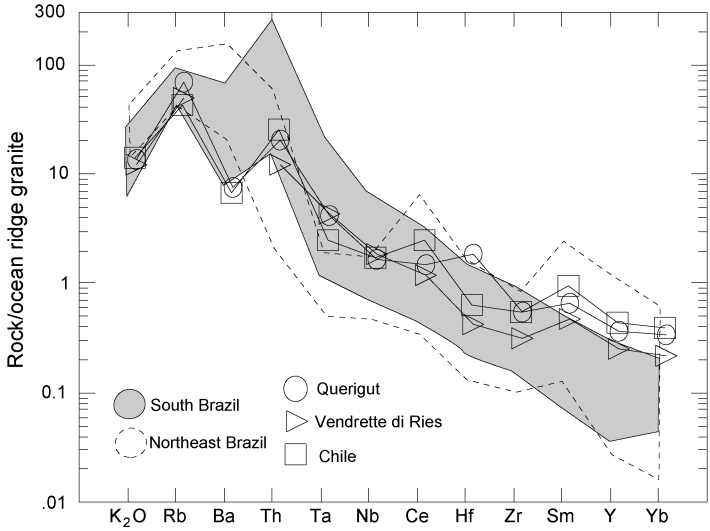

FIG. 7. Spidergrams normalized to ocean-ridge granites (Pearce et al., 1984) and compared with typical post-collision and collisional shoshonitic granites from the Pyrenees and the Andes. The strong similarity between ultrapotassic granites and shoshonitic rocks associated with sources affected by subduction zones is evident.

wt%) contents in the quartz syenites, whereas in apatites from granites these elements are below the detection limit (< 0.1 wt%).

Geochemistry of Ultrapotassic Granitoids

Representative geochemical data of ultrapotassic granites and quartz syenites are presented in Table 1. In the TAS diagram (Fig. 3), these rocks plot in the syenite and granite fields, belonging to the silica-saturated alkaline series. $Na_2O + K_2O$ concentrations vary from 8.6 to 12.5 wt% and the higher amounts are in the northeastern Brazil granites. In the R1R2 diagram (De La Roche et al., 1980), the ultrapotassic granitoids plot in the syenite and quartz syenite fields, which is caused by the strong influence of K_2O on the calculation of R1-parameter, whereas most alkaline metaluminous (Nardi and Bonin, 1991) and peralkaline granites plot in the granite fields, with R1 higher than 2000. The $CaO/(Na_2O + K_2O)$ ratio in most samples is below 0.1, like the metaluminous granites of alkaline affinity (Fig. 4). The $FeO_T/(FeO_T + MgO)$ ratio is moderate to high, varying from 0.60 to 0.85 (Fig. 5), with most samples showing values around 0.8, as observed in typical metaluminous granites of alkaline associations (Nardi and Bonin, 1991). These values are lower than those observed in granitic and rhyolitic rocks from anorogenic settings, where values of over 0.9 predominate (Whalen et al., 1987; Ewart, 1981; Nardi, 1991). Most ultrapotassic granites have a metaluminous character, indicated by the presence of normative diopside, and lack of normative acmite or corundum, as well as by Shand's index generally varying from 0.90 to 1.00. According to major-element evidence, these granites are classified as metaluminous, belonging to alkaline ultrapotassic associations, generally with potassic character defined by K_2O/Na_2O ratios higher than 2, and $Na_2O + K_2O$ contents over 9 wt%. Based on major-element compositions, ultrapotassic granites can be clearly distinguished from other metaluminous alkaline or shoshonitic granites on a CaO-FeOt-(Na_2O+K_2O) diagram (Fig. 6).

Sr contents in ultrapotassic granites are moderate to high, and variable, generally from 200 to 900 ppm, and seem to be controlled mainly by alkali feldspar fractionation. Ba contents are also affected by magmatic differentiation (Plá Cid et al., 2000). However, the enriched character of these magmas is demonstrated by Ba contents around 2000–5000 ppm in most granitoids, and in some cases by higher values in less-evolved rocks. Moderate to high contents of Rb, around 200–300 ppm, indicate the

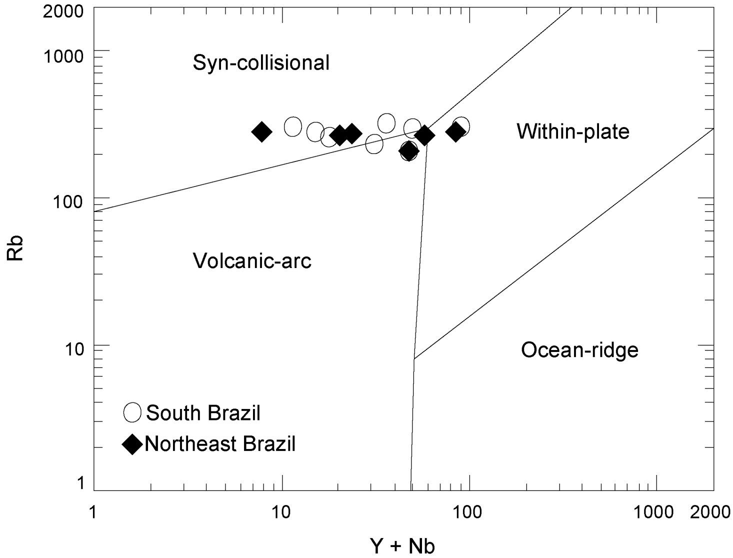

FIG. 8. Rb vs. Y+Nb tectonic diagram (after Pearce et al., 1984) applied to the ultrapotassic granites. These data confirm those observed in Figure 6, associating this magmatism with sources modified by subduction.

evolved character of granitic liquids and are in agreement with the extreme LILE enrichment characteristic of these magmas.

HFSE contents that are typically enriched in granites of silica-saturated alkaline series from anorogenic settings, mainly in peralkaline types (Whalen et al., 1987) such as Nb, Y, Ce, and Zr, are relatively low in ultrapotassic granites. The total contents of these elements is normally below 400 ppm, whereas Whalen et al. suggested values above 350 ppm for the alkaline, metaluminous, and peralkaline anorogenic granites. In the same way, the 1000*(Ga/Al) ratio is lower than typically reported for granitoids of alkaline affinity. In the ultrapotassic granites, this ratio ranges between 1.5 and 3.5, whereas the alkaline granites exhibit values between 2.5 and 5.

Spidergrams for selected trace elements normalized to ocean-ridge granites (ORG; Pearce et al., 1984) show that the ultrapotassic granites have patterns close to those of shoshonitic granites from Chile, and from Quérigut and Vedrettte di Ries referred to by Pearce et al. (1984); all of them are examples of magmatism related to sources affected by subduction (Fig. 7). The heavy rare-earth elements (HREE) and Y concentrations are lower than those of the granite groups cited by Pearce et al. (1984).

In the (Nb + Y) *vs.* Rb diagram (Fig. 8), ultrapotassic granites plot close to the boundary between syn-collisional and volcanic-arc granite fields, which, according to Pearce (1996), defines the field of post-collisional granites. Considering the diagrams for discrimination of tectonic settings based upon trace elements, such as Rb/10 vs. Hf vs. Ta*3 and Ta vs. Nb, both referred to by Harris et al. (1986), the ultrapotassic granites plot generally along the boundaries of fields related to magma sources affected by subduction (Fig. 9), confirming the similarity observed in spidergrams (Fig. 7) of ultrapotassic and shoshonitic granites.

REE patterns normalized to chondritic values (Evensen et al., 1978) show La_N/Yb_N values between 10 and 30 (Fig. 10). The observed patterns generally show Eu-negative and -positive anomalies. The REE contents are typically lower than those observed in granites of metaluminous alkaline and peralkaline associations. Positive Eu anomalies are not due to feldspar accumulations, as reflected in their Sr, Ba, Pb, and Al_2O_3 contents, which are similar to those of rocks without Eu anomalies. Those anomalies can be produced by fractionation and segregation of phases that concentrate preferentially the trivalent REE, such as apatite and titanite (Pla Cid et al., 1999).

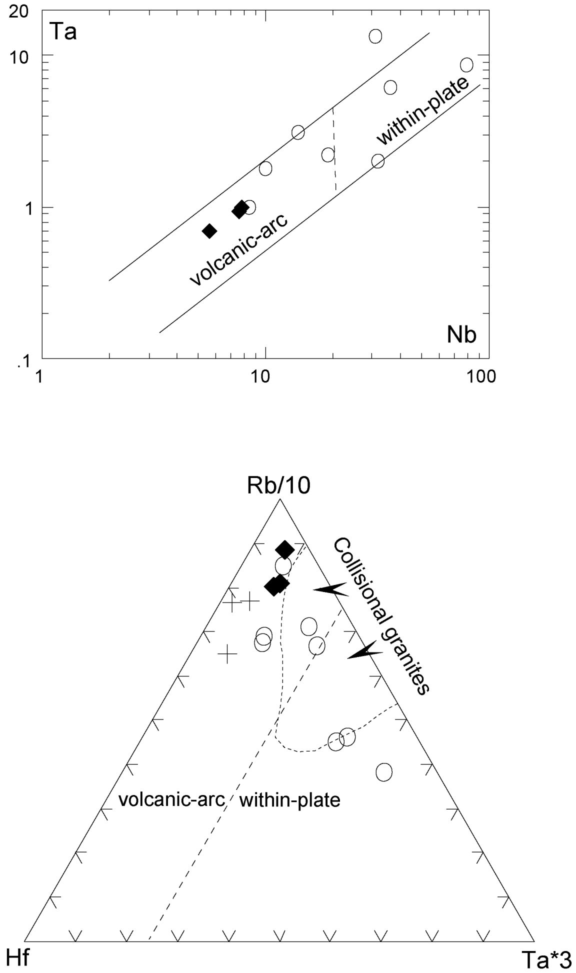

FIG. 9. Ta vs. Nb and Ta*3 vs. Rb/10 vs. Hf tectonic diagrams (after Harris et al., 1986), showing that ultrapotassic granites plot preferentially in the field of volcanic-arc and collisional granitoids. The symbols are the same as in Figure 5.

Petrogenetic Considerations

Ultrapotassic granites have the highest alkali ($Na_2O + K_2O$) contents among all granitoids of alkaline association. Their average is around 10 wt%, with maximum concentrations reaching up to 11.5 wt%. The triangular diagram (Fig. 6) is proposed for discriminating the ultrapotassic granites from the other types. Compared to rapakivi and shoshonitic granites (Nardi, 1986; Rämö, 1991; Dall'Agnol et al., 1999), the ultrapotassic ones are richer in alkalis and Ba, and poorer in CaO and TiO_2.

Sodic alkaline metaluminous and rapakivi-type granites generally exhibit HREE fractionated patterns, with large Eu negative anomalies. Ultrapotassic granites present HREE fractionated patterns, and a tendency for Eu positive anomalies in some samples. Shoshonitic granites have REE patterns (Nardi, 1986) comparable to those of ultrapotassic granitoids; the REE patterns of high-SiO_2 shoshonitic granites, however, have negative Eu anomalies.

Granitoids associated with potassic/ultrapotassic syenitic magmatism have been described by Laflèche et al. (1991) and Bourne and L'Heureux (1991) in the Abitibi greenstone belt, Canada. The granites of these associations, the so-called nordmarkites, in contrast to the ultrapotassic granitic rocks from Brazil, have K_2O/Na_2O ratios lower than

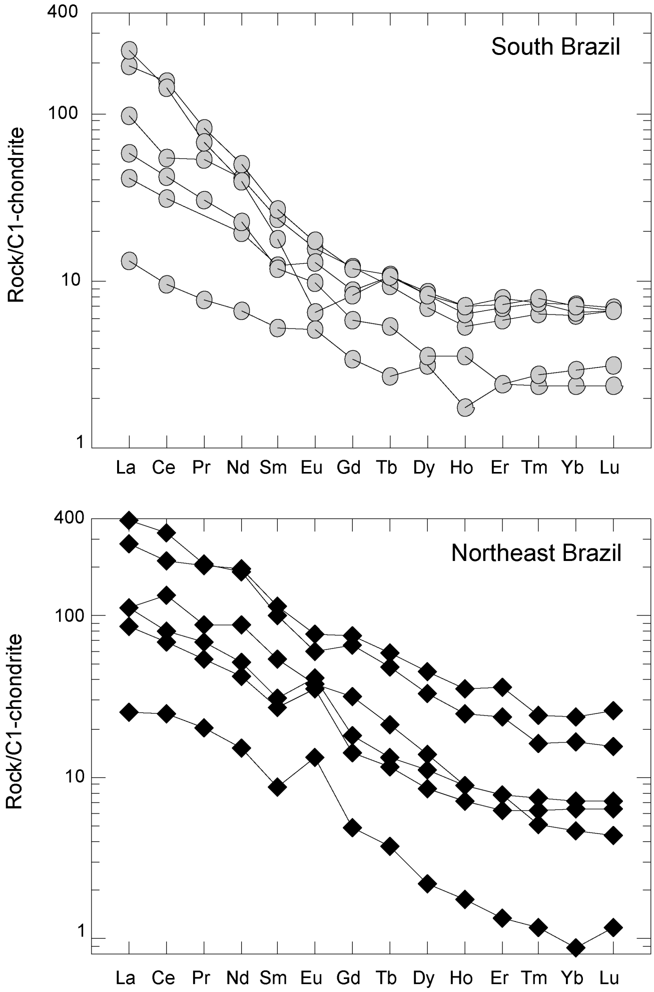

FIG. 10. REE paterns of ultrapotassic granites from Brazil normalized to the C1-chondritic values of Evensen et al. (1978).

1, and their genesis was related to crustal melting and contamination.

The granites referred to as ultrapotassic in this study are clearly associated with ultrapotassic syenite magmatism. Ultrapotassic granite bodies, dikes, and layers generally show gradational contacts with the syenite host, and the same igneous orientations generated by magmatic flow, which indicates simultaneous crystallization. The compositional coherence between syenites and granites observed for accessory and major minerals, as well as for whole-rock compositions, suggests their co-magmatic character. The geochemical trends from syenites to granites are close to those expected for differentiation controlled by mineral segregation due to magmatic flow, as previously discussed by Plá Cid et al. (1999, 2000) and Stabel et al. (2001). Differences in rare-earth patterns are explained by fractionation of mineral phases, such as titanite, zircon, and apatite.

Ultrapotassic granites are characterized by their high total alkalis, as well as by high K_2O/Na_2O ratios, reflecting the composition of the parental syenitic magma. The high contents of LIL elements, particularly Ba and Rb, are also a consequence of their derivation. The relatively low contents of some HFS elements (e.g., Nb, Ta, Zr, and Hf) in ultrapotassic syenites and granites are features that point to a mantle source previously modified by subduction-related metasomatism.

Major-element mass balances suggest that ultrapotassic granites could represent liquids derived from syenitic parental magmas by mineral fractionation and segregation controlled by magmatic flow. The major-element variation from syenite to granite is explained by fractionation of about 50% alkali feldspar + pyroxene + apatite ± mica ± plagioclase paragenesis in southern Brazil, and 80% alkali feldspar + pyroxene ± apatite ± titanite in the northeastern suites. The high modal proportions of fractionated minerals in syenitic magmas necessary to produce the ultrapotassic granitic liquids are compatible with their occurrence as small bodies, dikes, or layers.

Mineralogical and geochemical differences in ultrapotassic granites from southern and northeastern Brazil are ascribed to the original composition of syenitic parental magmas. The extremely high K_2O/Na_2O original ratio of the parental magma in the Borborema Province magmatism led to early crystallization of potassic feldspar. The water-undersaturated character of this magma prevented the formation of hydrous minerals as micas or amphiboles. Fractional crystallization makes late-stage liquids relatively enriched in Na, and the stable pyroxene under such conditions is aegirine-augite, despite the low total amounts of sodium in the parental magma. On the other hand, southern Brazil ultrapotassic granites were derived from syenitic magmas with lower K_2O/Na_2O ratios, and higher water activity, which leads to plagioclase early crystallization. Amphibole replaces calcic pyroxene due to increasing water activity caused by early crystallization of anhydrous phases. Other differences in some trace and rare-earth elements were inherited from the syenitic parental magmas, and may reflect heterogeneity in the composition of mantle-source, and/or differences during the initial stages of differentiation from parental magma.

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REFERENCES

Babinski, M., Chemale, J. R. F., Hartmann L. A., Van Schmus, W. R., and Silva L. C., 1996, Juvenile accretion at 750–700 Ma in southern Brazil: Geology, v. 24, p. 439–442.

Barbosa, J. S. F., and Dominguez, J. M. L., 1996, Mapa geológico do Estado da Bahia. Texto explicativo: Salvador, Brazil, Secretaria da Indústria, Comércio e Mineração do Estado da Bahia, PPPG-UFBA.

Barros, C. E., and Nardi, L. V. S., 1994, O Maciço Granítico Santo Antônio, RS: Magmatismo Neoproterozoico de afinidade shoshonítica: Anais da Academia Brasileira de Ciência, v. 66, no. 4, p. 441–465.

Bittencourt, M. F., and Nardi, L. V. S., 2000, Tectonic setting and sources of magmatism related to the Southern Brazilian shear belt: Revista Brasileira de Geociências, v. 30, p. 184–187.

Bourne, J. H., and L'Heureux, M., 1991, The petrography and geochemistry of the Clericy Pluton: An ultrapotassic pyroxenite-syenite suite of late Archaean age from Abitibi region, Quebec: Precambrian Research, v. 52, p. 37–51.

Brito Neves, B. B., and Cordani, U., 1991, Tectonic evolution of South America during the Late Proterozoic: Precambrian Research, v. 53, p. 23–40.

Chemale Jr., F., Babinski, M., Van Schmus, W. R., Wildner, W., and Lima, E. F., 1997, U-Pb and Sm-Nd isotopic studies of Neoproterozoic to early Paleozoic belts in southern Brazil [abs.], *in* Proceedings of South American Symposium on Isotope Geology, Campos do Jordão, São Paulo, p. 71.

Clemens, J. D., 2003, S-type granitic magmas—petrogenetic issues, models, and evidence: Earth Science Reviews, v. 61, p. 1–18.

Collins, W. J., Beams, S. D., White, A. J., and Chappell, B. W., 1982, Nature and origin of A-type granites with particular reference to southeastern Australia: Contributions to Mineralogy and Petrology, v. 80, p. 189–200.

Corriveau, L., and Gorton, M. P., 1993, Coexisting K-rich alkaline and shoshonitic magmatism of arc affinities in the Proterozoic: A reassessment of syenitic stocks in the southwestern Greenville Province: Contributions to Mineralogy and Petrology, v. 113, p. 262–279.

Dall'Agnol, R., Costi, H. T., Leite, A. A. da S., Magalhães, M. S., and Teixeira, N. P., 1999, Rapakivi granites from Brazil and adjacent areas: Precambrian Research, v. 95, nos. 1–2, p. 9–39.

Da Silva Filho, A. F., Guimarães, I. P., and Thompson, R. N., 1993, Shoshonitic and ultrapotassic Proterozoic intrusive suites in the Cachoeirinha-Salgueiro belt, NE Brazil: A transition from collisional to post-collisional magmatism: Precambrian Research, v. 62, p. 323–342.

Da Silva Filho, A. F., Thompson, R. N., and Leat, P., 1987, Petrology of the Terra Nova pluton, Brazil and associated ultrapotassic dikes: Revista Brasileira de Geociências, v. 17, p. 481–487.

De La Roche, H., Leterrier, J., Grande Claude, P., and Marchal, M., 1980, A classification of volcanic and plutonic rocks using R1-R2 diagrams and major element analysis—its relationship and current nomenclature: Chemical Geology, v. 29, p. 183–210.

Evensen, N. M., Hamilton, P. J., and O'Nions, R. K., 1978, Rare earth abundances in chondritic meteorites: Geochimica et Cosmochimica Acta, v. 42, p. 1199–1212.

Ewart, A., 1981, The mineralogy and chemistry of the anorogenic Tertiary silicic volcanics of S.E. Queensland and N.E. New South Wales, Australia: Journal of Geophysics Research, v. 86(B11), p. 10,242–10,250.

Fernandes, L. A. D., Tommasi, A., and Porcher, C. C., 1992, Deformation patterns in the southern Brazilian branch of the Dom Feliciano Belt: A reappraisal: Journal of South American Earth Sciences, v. 5, p. 77–96.

Ferreira, V. P., 1991, Petrology and geochemistry of the late Precambrian ultrapotassic peralkaline Triunfo pluton and related dikes, State of Pernambuco, Northeast Brazil: Unpubl. Ph.D. thesis, University of Georgia, Athens.

Ferreira, V. P., Sial, A. N., and Whitney, J. A., 1994, Large scale silicate immiscibility: A possible example from northeast Brazil: Lithos, v. 33, p. 285–302.

Figuerôa, I., and Silva Filho, I., 1990, Geologia da folha Petrolina, *in* DNPM/CPRM, Programa de Levantamentos Geológicos Básicos do Brasil (PLGBB), Folha SC.24-V-C-III Petrolina: Rio de Janeiro, Brazil.

Foley, S. F., Venturelli, G., Green, D. H., and Toscani, L., 1987, The ultrapotassic rocks: Characteristics, classification, and constraints for petrogenetic models: Earth Science Reviews, v. 24, p. 81–134.

Guimarães, I. P., and Da Silva Filho, A. F., 1998, Nd- and Sr-Isotopic and U-Pb geochronologic constraints for evolution of the shoshonitic Brasiliano Bom Jardim and Toritama complexes: Evidence for a trans-Amazonian enriched mantle under Borborema tectonic province, Brazil: International Geology Review, v. 40, p. 500–527.

Harris, N. W. B., Pearce, J. A., and Tindle, A. G., 1986, Geochemical characteristics of collision-zone magmatism, *in* Coward, M. P., and Ries, A. C., eds., Collision tectonics: Geological Society of America Special Publication, v. 19, p. 67–82.

Hartmann, L. A., Piñeyro, D., Bossi, J., Leite, J. A. D., and Mcnaughton, N. J., 2000, Zircon U/Pb SHRIMP dating of Paleoproterozoic Isla Mala granitic magmatism in the Rio de la Plata craton, Uruguay: Journal of South American Earth Sciences, v. 13, p. 105–113.

Jardim de Sá, E. F., 1994, A faixa Seridó (Província Borborema, NE do Brasil) e o seu significado geodinâmico na cadeia Brasiliana/Pan-Africana: Unpubl. tese de Doutorado, Universidade de Brasília, Brasília, Brazil.

Laflèche, M. R., Dupuy, C., and Dostal, J., 1991, Archaean orogenic ultrapotassic magmatism: An example from the southern Abitibi greenstone belt: Precambrian Research, v. 52, p. 71–96.

Lameyre, J., and Bonin, B., 1991, Granites in the main plutonic series, *in* Didier, J., and Barbarin, B., eds., Enclaves and granite petrology: Amsterdam, The Netherlands, Elsevier, p. 3–17.

Lameyre, J., and Bowden, P., 1982, Plutonic rock type series: Discrimination of various granitoid series and related rocks: Journal of Volcanology and Geothermal Research, v. 14, p. 169–186.

Le Maitre, R. W., 1989, A classification of igneous rocks and glossary of terms. Oxford, UK, Blackwell Scientific Publications, 193 p.

Liégeois, J-P., Navez, J., Hertogen, J., and Black, R., 1998, Contrasting origin of post-collisional high-K calc-alkaline versus alkaline and peralkaline granitoids. The use of sliding normalization: Lithos, v. 45, p. 1–28.

Lima, E. F., and Nardi, L. V. S., 1998, The Lavras do Sul shoshonitic association: Implications for the origin and evolution of Neoproterozoic shoshonitic magmatism in southernmost Brazil: Journal of South American Earth Sciences, v. 11, no. 1, p. 67–78.

MacDonald, R., Davies, G. R., Bliss, C. M., Leat, P. T., Bailey, D. K., and Smith, R. L. 1987, Geochemistry of high-silica peralkaline rhyolites, Naivasha, Kenya Rift Valley: Journal of Petrology, v. 28, p. 979–1008.

Martin, R. F., and Bonin, B., 1976, Water and magma genesis: The association hypersolvus granite–subsolvus granite: The Canadian Mineralogist, v. 14, p. 228–237.

Nachit, A., Razafimahefa, N., Stussi, J., and Carron, J., 1985, Composition chimique des biotites et typologie magmatique des granitoids: Compte Rendus de l'Academie des Sciences de Paris, v. 301, no. 11, p. 813–818.

Nardi, L. V. S., 1984, Geochemistry and petrology of the Lavras Granite Complex, RS, Brazil. Unpubl. doctoral thesis, University of London, England, 268 p.

Nardi, L. V. S., 1986, As rochas granitóides da série shoshonítica: Revista Brasileira de Geociências, v. 16, p. 3–10.

Nardi, L. V. S., 1991, Caracterização petrográfica e geoquímica dos granitos metaluminosos da série alcalina: Revisão: Pesquisas, v. 18, no. 1, p. 44–57.

Nardi, L. V. S. and Bonin, B., 1991, Post-orogenic and non-orogenic alkaline granite associations: The Saibro intrusive suite, southern Brazil—a case study: Chemical Geology, v. 92, p. 197–212.

Neksvasil, H., 1990, Reaction relations in the granite system: Implications for trachytic and syenitic magmas: The American Mineralogist, v. 75, p. 560–571.

Pagel, M., and Leterrier, J., 1980, The subalkaline potassic magmatism of the Ballons massif (southern Vosges, France): Shoshonitic affinity: Lithos, v. 13, p. 1–10.

Patiño Douce, A. E., 1999, What do experiments tell us about the relative contribution of crust and mantle to the origin of granitic magmas?, *in* Castro, A., Fernández, C., and Vigneresse, J.- L., eds., Understanding granites: Integrating new and classical techniques: Special Publications Geological Society of London, v. 168, p. 55–75.

Pearce, J. A., 1996, A user's guide to basalt discrimination diagrams, *in* Wyman, D. A., ed., Trace element geochemistry of volcanic rocks: Applications for massive sulphide exploration: Geological Association of Canada, Short Course Notes, v. 12, p. 79–113.

Pearce, J. A., Harris, N. B. W., and Tindle, A. G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 956–983.

Plá Cid, J., Nardi, L. V. S., Conceição, H., and Bonin, B., 1999, Petrogenesis of the Neoproterozoic alkaline ultrapotassic suites of Northeastern Brazil: Major- and trace-element evidence from pyroxene chemistry and numerical modeling: International Geology Review, v. 41, p. 1005–1028.

Plá Cid, J., Nardi, L. V. S., Conceição, H., Bonin, B., and Jardim de Sá, E. F., 2000, The alkaline silica-saturated ultrapotassic magmatism of the Riacho do Pontal fold belt, NE Brazil: An example of syenite-granite Neoproterozoic association: Journal of South American Earth Sciences, v. 13, p. 661–683.

Plá Cid, J., Nardi, L. V. S., Stabel, L. Z., Conceição, R. V., and Balzaretti, N. M., 2003, High-pressure minerals in mafic microgranular enclaves: Evidences for co-mingling between lamprophyric and syenitic magmas at mantle conditions: Contributions to Mineralogy and Petrology, v. 145, p. 444–459.

Rämö, O. T., 1991, Petrogenesis of the Proterozoic rapakivi granites and related basic rocks of southeastern Fennoscandia: Nd and Pb isotopic and general geochemical constraints: Bulletin of the Geological Survey of Finland, v. 355, 161 p.

Sial, A. N., and Ferreira V. P., 1988, Brasiliano age peralkaline plutonic rocks of the Central Structural Domain, northeast Brazil: Rendicontti della Societá Italiana di Mineralogia e Petrologia, v. 43, no. 2, p. 307–342.

Stabel, L. Z., Nardi, L. V. S., and Plá Cid, J., 2001, Química mineral e evolução petrológica do Sienito Piquiri: Magmatismo shoshonítico, neoproterozóico, pós-colisional no sul do Brasil: Revista Brasileira de Geociências, v. 31, no. 2, p. 211–222.

Streckeisen, A., 1976, To each plutonic rock its proper name: Earth Science Reviews, v. 12, p. 1–33.

Tauson, L. V., 1983, Geochemistry and metallogeny of the latitic series: International Geology Review, v. 25, p. 125–135.

Thompson, R. N., and Fowler, M. B., 1986, Subduction-related shoshonitic and ultrapotassic magmatism: A study of Siluro-Ordovician syenites from the Scottish Caledonides: Contributions to Mineralogy and Petrology, v. 103, p. 470–492.

Vieira Jr., N., Fernandes, L. A. D., Koester, E., and Sherer, C. S., 1989, Enclaves microgranulares do maciço Sienítico de Piquiri–RS: Acta Geológica Leopoldense, v. 29, p. 185–206.

Whalen, J. B., Currie, K. L., and Chappell, B. W., 1987, A-type granites: Geochemical characteristics, discrimination, and petrogénesis: Contributions to Mineralogy and Petrology, v. 95, p. 407–419.