Intralithospheric differentiation and crustal growth: Evidence from the Borborema province, northeastern Brazil

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ABSTRACT

Thousands of cubic kilometers of high-K calc-alkalic magmas intruded the Borborema Province (northeastern Brazil) during the Neoproterozoic Brasiliano orogeny. They make up large batholiths in which mantle-derived mafic to intermediate rocks coexist with a larger amount of granitoids. The relatively low silica contents (61–70 wt% SiO_2) and moderate to high compatible element concentrations (0.3–3.5 wt% MgO, 1.5–3.8 wt% CaO, as much as 150 ppm of Cr) of the granitoids indicate that they contain an appreciable mantle component. The similar trace element geochemical (high contents of incompatible trace elements) and isotopic (strongly negative ε_{Nd} values) signatures of mafic and felsic rocks combined with geochemical modeling suggest that (1) the mafic and felsic rocks are genetically linked, (2) the granitic magmas were produced by 20%–30% partial melting from a source having geochemical characteristics similar to the mafic rocks, and (3) mingling and mixing of felsic magmas with subsequent batches of mafic magmas yielded the silica-poor granitoids. Isotopic data preclude involvement of the asthenosphere in the genesis of the mafic melts and instead indicate their derivation from an old, enriched lithospheric mantle. Therefore, addition of mantle material to the crust occurred through internal lithospheric differentiation, in contrast with conventional crustal-growth models.

Keywords: high-K, calc-alkalic, geochemistry, Nd isotopes, Proterozoic crustal growth.

INTRODUCTION

Conventional crustal-growth models involve addition of juvenile mantle material to the continental crust in subduction-zone environments. In particular, crustal growth via granitoid magmatism is accomplished by the production of tonalites, trondhjemites, and granodiorites by partial melting either of the subducted slab or of mafic rocks that underplate the crust and are themselves the products of partial melting of the mantle wedge (e.g., Martin, 1986; Atherton, 1990; Tarney and Jones, 1994). The contribution of high-K calc-alkalic granitoids, abundant in post-Archean orogenic belts, to crustal growth is less certain. Roberts and Clemens (1993) and Clemens (1999) concluded on the basis of experimental data that most high-K calc-alkalic granitoids were generated from mantle-derived metaigneous mafic to intermediate sources. It is thus clear that these granitoids may also have a large mantle component. However, they will contribute to crustal growth only if their sources were formed shortly before the partial-melting event. If their protoliths were already part of the continental crust, partial melting will only result in intracrustal differentiation.

High-K calc-alkalic batholiths occur in some subduction-zone environments, but are more characteristic of postcollisional settings formed after basin closure and continental collision (Pitcher, 1987; Liégeois, 1998; Barbarin, 1999). These batholiths are common in orogenic belts of all ages and are particularly ubiquitous in the Pan-African-Brasiliano belt that extends from northeastern Brazil to Hoggar, Africa (Caby et al., 1991; Liégeois et al., 1998). In the Tuareg shield (in Mali and Niger), isotope data indicate that the source of these magmas was the lithospheric mantle, K enrichment occurring shortly before magma generation, probably during a previous subduction event (Liégeois et al., 1998). For high-K calc-alkalic magmas in the Borborema province, northeastern Brazil (Fig. 1), we propose here a derivation from old lithospheric sources. In both cases, crustal growth results from intralithospheric differentiation, not from addition of juvenile material from the mantle, unlike normal calc-alkalic magmatism. Thus, crustal growth models must take into consideration contributions given by the subcontinental lithospheric mantle.

The Borborema province consists of basement rocks of Paleoproterozoic age, small Archean nuclei, and Paleoproterozoic to Neoproterozoic volcano-sedimentary belts (Caby et al., 1991; Van Schmus et al., 1995; Dantas et al., 1998 and references therein). The absence of suture zones of Brasiliano age in the interior of the Borborema province indicates that it constituted a large continental mass during the late Neoproterozoic. In this area (Fig. 1), the Brasiliano event is characterized by (1) large shear zones mainly developed under low-pressure, high-temperature conditions (Vauchez et al., 1995), and (2) intrusion of numerous granitoid and syenitic batholiths (Neves and Mariano, 1997; Ferreira et al., 1998; Guimarães and Silva Filho, 1998; Sial et al., 1999) occurring far away (>300–600 km depending on pluton location) from the boundary zones with the adjoining cratons, indicating that the magmatism was not subduction related.

HIGH-K CALC-ALKALIC ASSOCIATION OF NORTHEASTERN BRAZIL

Petrography, Geochemistry, and Sm-Nd Isotopes

Most granitoid bodies of the high-K calc-alkalic association in northeastern Brazil have large outcrop areas, usually greater than 200 km^2. They consist predominantly of coarse-grained to porphyritic quartz monzonites, quartz syenites, and granites closely associated with quartz diorites and quartz monzodiorites, the proportion of which ranges from less than a few percent to as much as 40% (Neves and Mariano, 1997). The mafic rocks occur as isolated bodies, as enclaves, or as dike swarms and show common commingling textures with the granitoids. Mafic and felsic rocks have biotite, amphibole, plagioclase, K-feldspar, and quartz as their main mineral phases. From a geochemical point of view, they are characterized by high K_2O/Na_2O ratios (generally >1 even in the more mafic samples) while displaying other features similar to most calc-alkalic magmas worldwide (Neves and Mariano, 1997). The 588 Ma (zircon U-Pb; Guimarães et al., 1998) Caruaru-Arcoverde batholith is the largest body of the high-K calc-alkalic association (outcrop area >2000 km^2) and is the main concern of this paper. However, the similarities between it and the other high-K calc-alkalic plutons allow the main conclusions reached here to be applied to other bodies.

Granitoids represent more than 90% of the Caruaru-Arcoverde batholith. They are metaluminous, relatively SiO_2 poor (61–70 wt%), and relatively CaO (1.5–3.8 wt%), FeO_{total} (3.5–6.5 wt%), and MgO rich (0.3–3.5 wt%) compared with crustal melts derived from metasedimentary or metaigneous sources (e.g., Skjerlie and Johnston, 1992; McCarthy and

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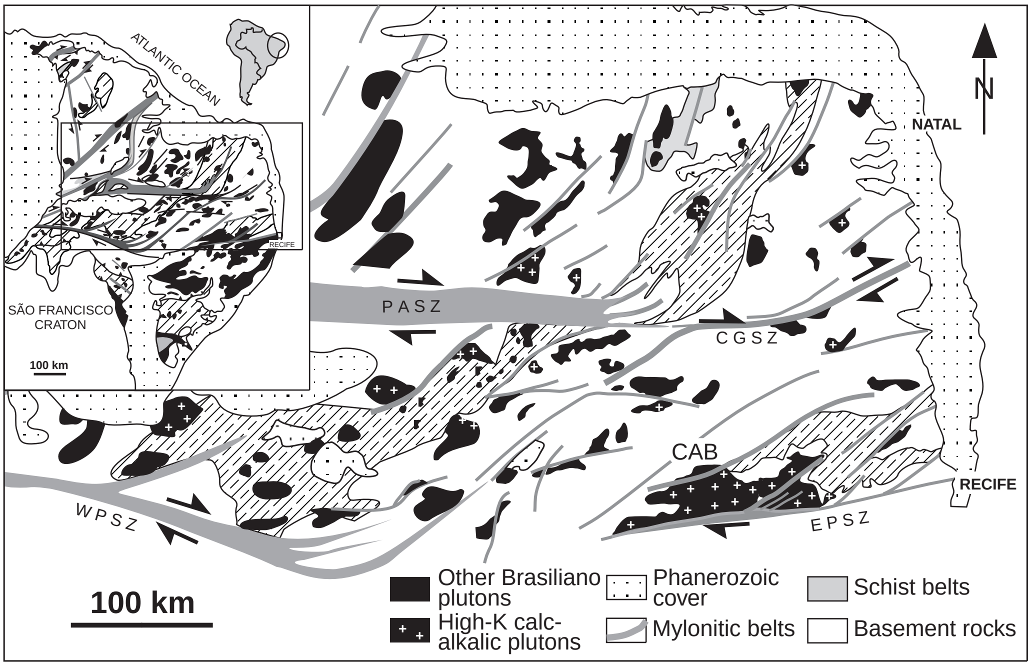

Figure 1. Generalized geologic map of central sector of Borborema province (location in insert) showing main bodies of high-K calc-alkalic association. Shear zones: PASZ—Patos, CGSZ—Campina Grande, WPSZ—West Pernambuco, EPSZ—East Pernambuco. CAB—Caruaru-Arcoverde batholith.

Patiño Douce, 1997); typically, they have ~5 wt% K_2O (Table A[1]; Fig. 2). Their main trace element characteristics are relatively high Sr (normally 250–400 ppm), Ba (>900 ppm), and Cr (as high as 180 ppm) contents and a relatively low Rb content (generally 120–200 ppm) (Table A [see footnote 1]; Fig. 2). The granitoids show light REE (rare earth element) enrichment and small to insignificant negative Eu anomalies (Fig. 3A). Dioritic rocks have relatively high contents of compatible (as high as 6 wt% MgO and 300 ppm Cr) as well as incompatible (K, Ba, light REE) elements (Fig. 2; Table A [see footnote 1]) and display fractionated REE patterns (Fig. 3B). Major and trace elements typically display rectilinear trends from the silica-poorest dioritic sample to the silica-richest granitic sample in Harker diagrams, although large dispersions are observed for some trace elements (Fig. 2).

Sm-Nd isotope analyses of four granitoid and three diorite samples were performed at the Isotope Geochemistry Laboratory (University of Kansas) (Table 1).The ε_{Nd} (600 Ma) values are extremely negative, ranging from –13 to –16, and T_{DM} (depleted mantle age) Sm-Nd is mainly in the range 1.8–2.0 Ga; granitoids and diorites display overlapping isotope ratios.

Petrogenesis

The high MgO, CaO, and compatible trace element contents of the quartz diorites point to an origin in the upper mantle. Although assimilation of supracrustal rocks by juvenile magmas could be postulated as responsible for their high contents of incompatible elements and Paleoproterozoic Nd model ages, petrological considerations limit the amount of crustal contamination that is reasonable. Sm-Nd studies show that supracrustal belts in the central domain of the Borborema province have considerably lower T_{DM} ages (typically 1.0–1.3 Ga; Van Schmus et al., 1995) than the quartz diorites. Lack of correlation between silica content and isotopic composition (Tables A [see footnote 1] and 1) indicates that assimilation was not important. The observed geochemical and isotopic signatures of the studied rocks exclude asthenospheric or plume sources (Hart et al., 1992), being only approached by those of lithosphere-derived magmas (Menzies, 1990; Daley and DePaolo, 1992; Dodson et al., 1998). The parental magmas of the quartz diorites are therefore interpreted as derived from an old (>1.8 Ga), incompatible element–enriched, subcontinental lithospheric mantle.

The granitoids and quartz diorites share many mineral, geochemical, and isotope characteristics but cannot be related by fractional crystallization. Linear trends in Harker diagrams, high contents of compatible elements, and absence of significant Eu anomalies in the granitoids are inconsistent with this process, and attempts to model it quantitatively have failed. In order to obtain a 10 wt% increase in SiO_2 from typical diorite (56 wt%), 60%–70% fractional crystallization would be necessary, resulting in K_2O (6.0–7.5 wt%) and incompatible elements (e.g., >1500–2000 ppm Ba) contents considerably higher than those observed in the granitoids. As is the case with the quartz diorites, the lack of correlation between silica content and Nd isotopic composition (Tables A [see footnote 1] and 1) indicates that assimilation of metasedimentary rocks cannot have been important.

Even the granitoids with highest SiO_2 contents (65–70 wt%) are too rich in compatible elements to represent partial melts of typical crustal rocks (Skjerlie and Johnston, 1992; McCarthy and Patiño Douce, 1997), requiring mafic to intermediate metaigneous protoliths (Roberts and Clemens, 1993). Geochemical modeling (Fig. 3C) shows that 20%–30% batch melting of a source similar in composition to the quartz diorites (e.g., high-K amphibolites) satisfactorily reproduces the trace element geochemistry of the granitoids. The relatively high degrees of partial melting involved explain the large volumes of granitic magmas produced and their high Sr and Ba contents. Subsequent mixing between mafic and felsic magmas to produce the more mafic granitoids is consistent with field and geochemical data, as previously discussed by Neves and Vauchez (1995) and Neves and Mariano (1997).

DISCUSSION

The high contents of compatible elements in quartz diorites and granitoids of the high-K calc-alkalic association indicate a dominantly mantle contribution to the magmatism. In contrast, the incompatible element contents and negative ε_{Nd} values are more typical of crust-derived melts. In addition, granites and quartz diorites have trace element signatures characteristic of subduction-zone environments (e.g., low Nb contents; Table A [see footnote 1]), for which there is no evidence in the study area. The apparent contradiction expressed in the geochemical and isotopic data may be explained by metasomatic enrichment of the lithospheric mantle during the Paleoproterozoic, when much of the present crust of the Borborema province was produced (Caby et al., 1991; Van Schmus et al., 1995; Dantas et al., 1998, and references therein). The incompatible element enrichment and subduction signature may have been inherited from subduction events associated with crust generation. Remobilization of this lithospheric mantle during the Brasiliano

[1]GSA Data Repository item 200059, major and trace element analyses of granite and diorite samples, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

orogeny can account for the genesis and spatial association of quartz diorites and granites in the following sequence. (1) A thermal anomaly induced partial melting of enriched parts of the continental mantle lithosphere. The origin of the heat source is not yet clear but could involve conductive heating of the lithosphere by upwelling of the asthenosphere (Neves et al., 2000). (2) The resulting mafic magmas underplated the continental crust; they produced differentiated melts and gabbroic and ultramafic cumulates. (3) Part of the differentiates crystallized at depth; these rocks were converted to amphibolites under the action of the prevailing high geothermal gradient. These newly formed, warm mafic lower crustal amphibolites would have been more prone to partial melting than the preexisting lower crustal rocks, thus producing granitic magmas. The absence of inherited zircons in the granitoids (Guimarães et al., 1998) supports this scenario. Because mafic rocks retain almost the same isotopic characteristics of their source, the mantle signature is transmitted to the felsic magmas. (4) Granitic magmas formed magma chambers in the middle crust that acted as barriers to the ascent of subsequently differentiated mantle melts; therefore, mixing and mingling of later melts with the earlier emplaced magma was favored. The processes of magma extraction from the lithosphere, formation of young mafic lower crust, and its partial melting shortly afterward to produce granitic magmas imply transfer of material from the mantle to the crust and, thus, result in crustal growth.

Enriched isotopic and geochemical signatures are not restricted to the high-K calc-alkalic association in northeastern Brazil. Metaluminous and ultrapotassic syenitic plutons may display still more extreme isotopic and incompatible trace element compositions. Metaluminous syenites have high MgO, Cr, and Ni contents and ε_{Nd} values of –14 to –10 (at 600 Ma) (Guimarães and Silva Filho, 1998); thus they appear to be derived from the same mantle reservoir as the diorites. Ultrapotassic syenites contain xenoliths of phlogopite-bearing clinopyroxenite, interpreted as derived from their mantle source (Ferreira and Sial, 1993); strongly negative ε_{Nd} values (–18 to –15 at 600 Ma) imply that this source is ancient (ca. 2.1 Ga) continental mantle lithosphere (Ferreira et al., 1994). Taking into account the combined area of high-K calc-alkalic and syenitic plutons (>10 000 km^2), it is safe to assume that several thousands of cubic kilometers of lithosphere-derived magmas were emplaced into the Borborema province during the Brasiliano orogeny.

CONCLUSIONS

Granitoids of the high-K calc-alkalic association in northeastern Brazil have geochemical characteristics indicative of derivation from mafic sources, whereas high incompatible trace element contents in mafic rocks indicate an origin in the lithospheric mantle. The low ε_{Nd} value of the granitoids suggests that their source could be mafic lower crust of Paleoproterozoic age. However, because mafic and felsic rocks share many trace element geochemical and Nd isotope signatures, derivation of granitoids from new crust formed by partial melting of old lithospheric mantle is more consistent with the data. In the present case, (1) granitoid magmatism was not a simple intracrustal dif-

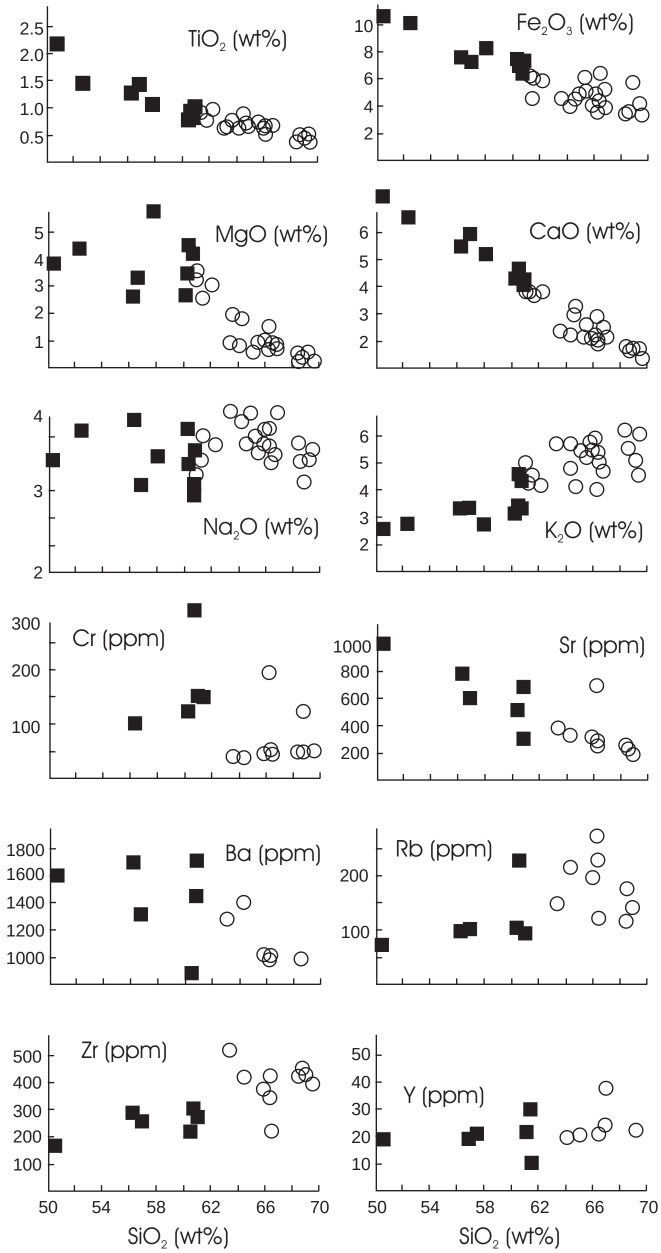

Figure 2. Selected major and trace element Harker diagrams for granitoids (circles) and quartz diorites to monzodiorites (squares) of Caruaru-Arcoverde batholith.

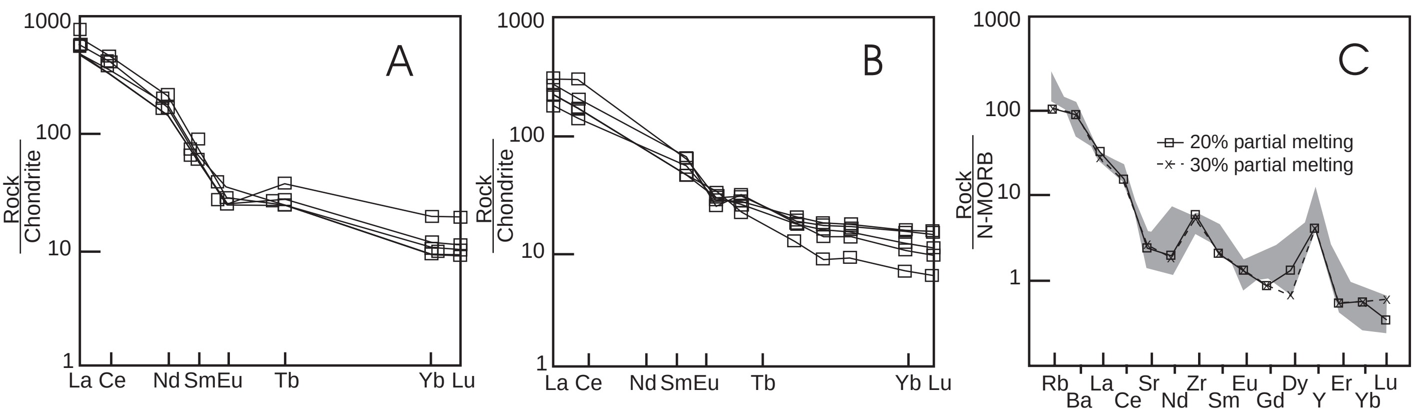

Figure 3. A and B: Rare earth element patterns for (A) granitoids and (B) quartz diorites. C: Comparison of calculated trace element concentrations for partial melts of quartz diorite (56 wt% SiO_2; $Pl_{41}Bi_{25}Amph_{22}Qz_6KF_3Ap_{0.5}Others_{2.5}$) with observed abundances in granitoids (gray). MORB—mid-ocean ridge basalt. Partition coefficients used are from Hanson (1980), Green (1994), Sisson (1994), Ewart and Griffin (1994), and references therein.

TABLE 1. Sm-Nd ISOTOPIC DATA FOR THE CARUARU-ARCOVERDE BATHOLITH

Sample number	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	ε_{Nd}(600 Ma)	T_{DM} (Ma)
Granitoids						
BEZ-9	95.52	14.06	0.08900	0.511398 ± 15	-15.95	2013
TQ-131A	49.95	8.08	0.09775	0.511546 ± 19	-13.74	1969
BEZ24	105.45	13.46	0.07717	0.511367 ± 14	-15.66	1872
TQ-177	78.45	12.56	0.09676	0.511707 ± 19	-10.52	1741
Quartz diorites						
TQ-265	48.48	8.14	0.10154	0.511642 ± 14	-12.15	1904
FN-52A	54.49	8.35	0.09270	0.511470 ± 15	-14.83	1983
FN-228B	38.61	7.08	0.11090	0.511680 ± 13	-12.12	2022

ferentiation process but involved redistribution of mass vertically within the lithosphere; (2) crustal growth took place at the expense of old lithospheric mantle, not from juvenile mantle material; and (3) partial melting occurred in a postcollisional setting and was unrelated to subduction. Internal lithospheric differentiation may therefore be an important mechanism, albeit subordinate, by which continental growth can take place. Because high-K calc-alkalic granitoids are abundant in post-Archean time and their contribution for continental growth is not accounted for by current models of crustal evolution, Proterozoic crustal growth rates may be underestimated.

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