Journal of the Virtual Explorer, 2004
Volume 17
Paper 3
http://virtualexplorer.com.au/

The lithospheric mantle as a source of magmas during orogenic processes: insights from high-K diorites in the Borborema Province and implications for continental dynamics

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Keywords: diorite, shoshonite, Borborema, Tibet, lithosphere

Abstract: Incompatible-element-rich dioritic rocks are common in several Brasiliano/Pan-African belts. In the Borborema Province, northeastern Brazil, these rocks were emplaced in an intracontinental setting during regional deformation and intruded high-grade metamorphic rocks. The diorites have relatively high MgO (up to 7 wt %), FeOt (up to 10.6 wt %) and CaO (up to 8 wt %) together with high K_2O (up to 5.8 wt %) and large ion lithophile elements (LILE) (e.g., 700-3000 ppm Ba, 30-150 ppm La), and are characterized isotopically by negative $\varepsilon_{Nd_{(t)}}$ values (-6.9 to -14.9) and high initial $^{87}Sr/^{86}Sr$ ratios (0.7058 - 0.7102). These geochemical and isotopic features are similar to those of shoshonites erupted in the Tibetan plateau in the advanced stages of the India/Asia collision, for which a subcontinental lithospheric mantle source is attributed. The diorites can thus be considered as intrusive analogs of modern shoshonites, pointing to a significant role of the mantle lithosphere as a magma source.

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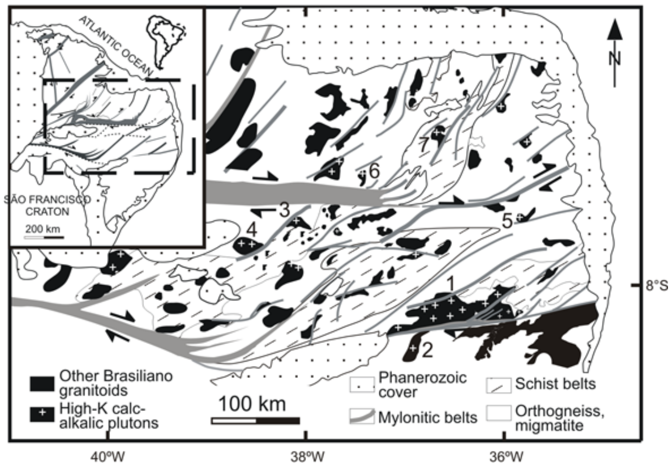
Introduction

Shoshonitic magmas, such as those erupted in the Tibetan plateau, characterize advanced stages of collision in young continental orogens and are attributed to partial melting of subcontinental mantle lithosphere (Turner et al., 1992; 1996; Miller et al., 1999; Schaefer et al., 2000). Although commonly dubbed "post-orogenic" (Turner et al., 1992; Schaefer et al., 2000), they were emplaced during active convergence between major crustal blocks, and are broadly contemporaneous with, or may even precede the, emplacement of "syncollisional" leucogranites (Chung et al., 1998; Miller et al., 1999). In older orogens, where deeper crustal levels are exposed, this kind of magmatism can be represented by mafic/intermediate plutonic rocks rich in K and other mantle-incompatible elements. Dioritic rocks with these characteristics are widespread in several Neoproterozoic belts (e.g. Nigeria Province, Dada et al., 1995; East African Orogen in Sudan, Küster & Harms, 1998; Damara, Jung et al., 2002; Kaoko, van de Flierdt et al., 2003). In this paper, we focus on diorites from the Brasiliano/Pan-African Borborema Province, northeastern Brazil (Figure 1). Based on a compilation of previously published work, their geochemical characteristics are reviewed and compared to Tibetan shoshonites. It is deduced that the diorites preserve source-inherited features, despite modification caused by mixing with felsic magmas and by small degrees of fractional crystallization and/or assimilation of country rocks. The source is interpreted as ancient, metasomatized continental mantle lithosphere, akin to that inferred for modern shoshonites (Turner et al., 1996; Chung et al., 1998). Possible mechanisms responsible for partial melting, along with implications for continental dynamics and crustal stabilization, are discussed.

Figure 1. Location of Borborema Province



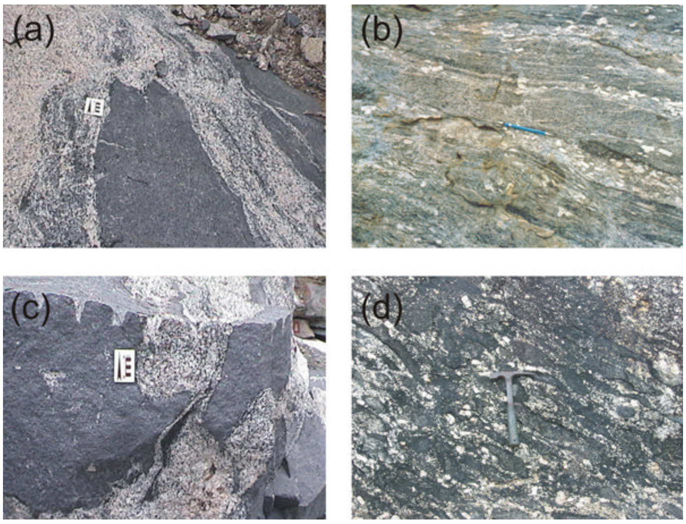
Insert: Location of Borborema Province relative to South America and sketch showing main shear zones. Enlarged area: Simplified geological map of eastern Borborema Province. Plutons with available geochemical data used in this study:

1. Caruaru-Arcoverde (Neves & Vauchez, 1995; Neves et al., 2000);
2. Alagoinhas (Mariano et al., 2001, and unpublished data);
3. Itaporanga (Mariano & Sial, 1990; Mariano et al., 1996; Mariano et al., 2001);
4. Serra da Lagoinha (Mariano et al., 2001);
5. Campina Grande (Almeida et al., 2002);
6. Espinharas (Campos et al., 2002);
7. Acari (Jardim de Sá, 1994; Hollanda et al., 2003).

Borborema Province high-K diorites

Dioritic rocks in the Borborema Province are characterized petrographically by the presence of biotite as a main mafic phase, commonly associated with sub-equal amounts of amphibole, and rare clinopyroxene. Most modal compositions plot in the quartz-diorite and quartz-monzodiorite fields. These rocks are associated with coarse-grained, porphyritic high-K calc-alkalic quartz monzonites to granites that form numerous composite plutons up to 2000 km^2 in area in the central and northeastern portions of the province (Figure 1 ; Mariano & Sial, 1990; Jardim de Sá, 1994; Neves & Mariano, 1997; Ferreira et al., 1998; Neves et al., 2000). Commingling features are widespread, indicating that dioritic and granitic magmas coexisted. The main features are: gradational contacts (Figure 2a), locally characterized by alternation of felsic and mafic bands giving rise to net-veined complexes which resemble stromatic structures of migmatites (Figure 2b); lobate and cuspate contacts (Figure 2c); and the frequent entrapment of K-feldspar megacrysts by diorites (Figure 2a and b). Abundant aligned elongated dioritic enclaves may represent disrupted syn-plutonic dikes (Figure 2d). Late fracture-controlled dioritic dikes free of K-feldspar megacrysts attest to recurrence of dioritic magmatism. The diorites generally represents 5 to10 % of the outcrop area of the plutons, but in a few cases they may reach up to 40 %.

Figure 2. Field relationships



Field relationships between felsic porphyritic quartz monzonite to granite and diorites in the Borborema Province.

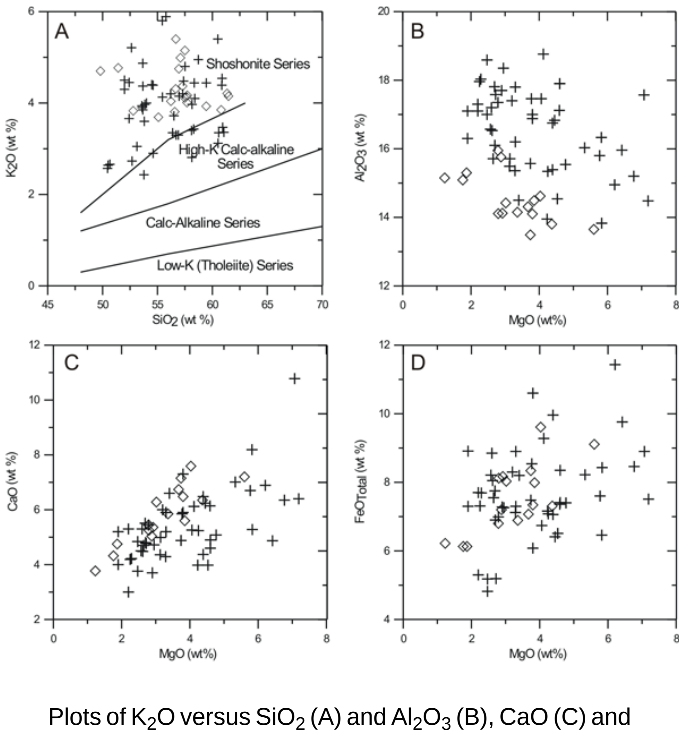
a. Gradational contact between large dioritic enclaves and granite developing hybrid bands;
b. net-veined complex similar to stromatic structures of migmatites;
c. three-dimensional view of irregular lobate and cuspate contacts indicating coexistence in magmatic stage; and
d. swarm of aligned elongated dioritic enclaves, suggesting disrupted syn-plutonic dikes.

Plutons of the diorite-granite association intrude low- to medium-pressure, high-temperature metamorphic rocks and are associated with transcurrent shear zones (Figure 1 ; Vauchez et al., 1995; Neves et al., 1996; Archanjo et al., 2002; Weinberg et al., 2004). Available zircon U-Pb and ^{206}Pb-^{207}Pb ages range from 592 to 579 Ma (Leterrier et al., 1994; Guimarães et al., 1998; Almeida et al., 2002; Brito Neves et al., 2003; Neves et al., 2004). Intrusion occurred when the Brasiliano orogeny was well-advanced, post-dating its beginning by 40-60 Ma (see review in Neves, 2003), indicating the intracontinental nature of plutons and associated shear zones.

Comparison with Tibetan lavas

Ranges and means of major-elements and selected trace-element compositions of diorites (Mariano & Sial, 1990; Jardim de Sá, 1994; Neves & Vauchez, 1995; Mariano et al., 1996; Neves & Mariano, 1997; Neves et al., 2000; Mariano et al., 2001; Almeida et al., 2002; Campos et al., 2002; Hollanda et al., 2003) are compared to shoshonites from eastern Tibet (Turner et al., 1996) in Table 1. Selected major- and trace-element compositions for the diorites are presented in Table 2 . The only noticeable differences in the major-element chemistry are that the shoshonites have slightly higher K_2O (Figure 3a) and lower Al_2O_3 (Figure 3b). In both datasets, MgO ranges mainly from 2 to 5 wt%, but may reach up to 7 wt%. CaO and FeO correlate positively with MgO, respectively, reaching up to 8.0 and 10.6 wt%, in the Borborema Province, and 11 and 12 wt% in the shoshonites (Figure 3c and d). In the Peccerillo & Taylor (1976) diagram, the dioritic samples plot in the shoshonitic field and transitional between the high-K calc-alkalic and shoshonitic fields (Figure 3a). Selected trace element (Figure 4) show superposition of fields for diorites and shoshonites with the main difference due to the Rb enrichment (Figure 4a) of most of the shoshonitic samples.

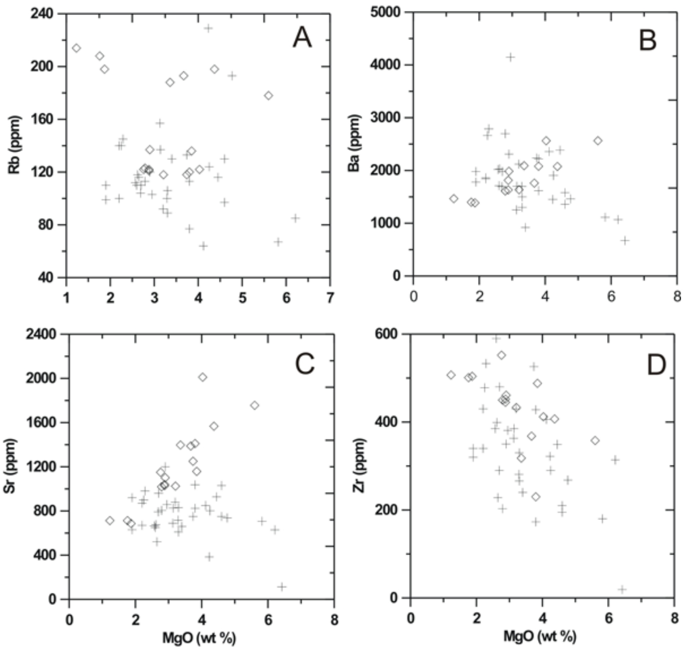
Figure 3. Plots of K_2O versus SiO_2



Plots of K_2O versus SiO_2 (A) and Al_2O_3 (B), CaO (C) and FeO (D) versus MgO for samples of diorites from Borborema Province (crosses) and shoshonites from

Tibetan plateau (open diamonds). The shoshonitic, high-K calc-alkalic and calc-alkalic and fields in (a) are from Peccerillo & Taylor (1976). See text and Fig. 1 for sources of data.

Figure 4. Selected trace element

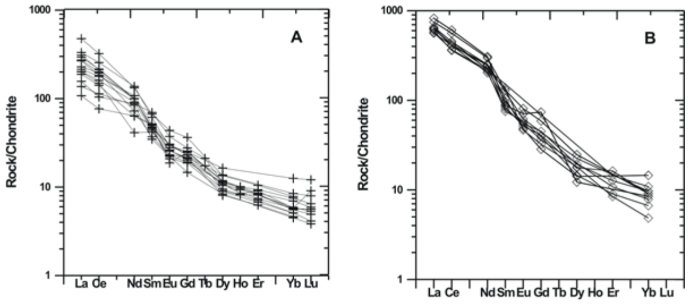


Selected trace element vs. MgO diagrams for samples of diorites from the Borborema Province (crosses) and shoshonites from Tibetan plateau (open diamonds).

The Borborema diorites and Tibetan shoshonites show comparable LILE and high-field strength elements (HFSE) concentrations, Sr, La and Nb, which are more abundant in the shoshonites (Table 1 ; Figure 5). The diorites have high light rare earth element (LREE) contents, with La/Yb ratios varying from 16 to 90, and negligible Eu anomalies. This results in fractionated REE patterns (Figure 5a), better marked from La to Dy, and with the heavy REEs showing a much flatter slope. These REE patterns are similar to those of Tibetan shoshonites (Figure 5b) except for their more fractionated patterns characterized by La/Yb ratios varying from 56 to 129.

The diorites are characterized by negative ε_{Nd} values (-6.9 to -14.9), high initial $^{87}Sr/^{86}Sr$ ratios (0.7058-07102), and intermediate $\delta^{18}O$ whole-rock values (between 7.5 and 8.2 ‰). Unradiogenic Nd and radiogenic Sr isotopic values are also characteristic of Tibetan shoshonites (Table 1).

Figure 5. Selected REE-patterns



Selected REE-patterns for dioritic rocks from Borborema Province (A) and shoshonites from Tibetan plateau (B). Normalizing factors from Evensen et al. (1978). See text and Fig. 1 for sources of data.

Petrogenesis

Interaction between mafic and felsic melts are reported in all studied plutons in the Borborema Province (Mariano & Sial, 1990; Neves & Vauchez, 1995; Neves & Mariano, 1997; Campos et al., 2002). Absence of cumulates, relatively constant K_2O with increasing SiO_2 (Figure 3a), linear trends in major- (e.g., Figure 3c and d) and trace-elements (e.g. Figure 4c and d) against MgO diagrams, and lack of negative Eu anomalies in REE diagrams (Figure 5a), indicate that samples with higher SiO_2 reflect mixing with granitic melts rather than fractional crystallization. The relatively low δO18 whole-rock values (< 8.2 %), although higher than typical mantle values of 5-6 %, indicate that assimilation of high δO18 crustal rocks was minor if at all.

Given the relatively high MgO and low SiO_2 in most dioritic samples, mafic or ultramafic sources are required. Since geochemical and isotopic characteristics are not compatible with an origin by partial melting of normal mantle peridotitic sources, other possibilities include mafic lower continental crust, oceanic crust, mantle wedge above subducting oceanic plate, and subcontinental lithospheric mantle.

Partial melting of mafic protoliths appears unlikely because most dehydration-melting experiments of metabasalts have produced tonalitic to granitic melts rather than dioritic ones (e.g. Rushmer, 1991; Patiño-Douce & Beard, 1995). Wolf & Wyllie (1994) and Rapp & Watson (1995) report experimental melts produced at temperatures above 1000°C with SiO_2 contents similar to those of the studied diorites. However, their TiO_2 and MgO contents are lower and Na_2O/K_2O ratios much higher (>> 2-3) than in the

Borborema Province diorites (Table 1). Also, the high temperatures required to produce the low- SiO_2 experimental melts are hard to attain at crustal pressures, even by repeated injections of basaltic magmas at the Moho, the most efficient mechanism to heat up the lower crust (Petford & Gallagher, 2001; Annen & Sparks, 2002). Mafic components within the subcontinental mantle, rather than in the lower continental crust, could be considered as an alternative. However, partial melting of eclogites, the stable mafic rock type at upper mantle conditions, produces melts strongly depleted in heavy REEs and Y due to partitioning of these elements into garnet (Green, 1994; Rapp & Watson, 1995; Rapp et al., 2003). This is inconsistent with the observed REE patterns and concentration of HREE (ca. 5-10 times chondritic values) (Figure 5). Similar reasoning can be applied against partial melts from subducted oceanic crust, from which they can also be distinguished by negative $\varepsilon_{Nd_{(t)}}$ values.

The major-element chemistry of our most primitive dioritic samples, except for their high K_2O content, are similar to: (a) mid-ocean ridge basalt (MORB) from a segment of the southwestern Indian ridge characterized by high Na_2O (3.3-4.0 wt%) and Al_2O_3 (16.1-18.3 wt%), low TiO_2 (1.2-1.5 wt%), and low CaO/Al_2O_3 (0.56-0.66) (Meyzen et al., 2003); (b) experimental melts produced by partial melting of lherzolite under water-undersaturated conditions (0.5 and 0.9 wt% H_2O added) at 1100°C and 1 GPa (Hirose and Kawamoto, 1995). The unusual MORB compositions have been attributed by Meyzen et al. (2003) to partial melting of a mantle depleted in clinopyroxene, due to earlier melting events. This explanation can also account for the higher CaO content of the experimental melts as compared with the Borborema diorites (Table 1). Thus, a refractory source appears to be involved in the genesis of the diorites. This source could only be subcontinental lithospheric mantle, depleted due to early melt extraction of continental crust. Because the high contents of incompatible elements cannot be explained by interaction with granitic magmas (e.g., Ba is higher in the diorites than in the coexisting granites; Figure 4b ; Neves et al., 2000), metasomatic enrichment of the source following melt depletion is required. Calculated compositions produced by dehydration melting experiments of phlogopite-bearing peridotite at 1075°C and 1GPa under water-undersaturated condition (Conceição & Green, 2004) are similar to the Borborema diorites, except for lower FeO and higher MgO and CaO (Table 1). This represents a strong argument favorable to the genesis of the diorites by small degree partial melting (5-8 %; Conceição & Green, 2004) of a metasomatized mantle source.

Nd model ages of diorites suggest that the metasomatic event occurred in the Paleoproterozoic (Table 1), during which much of continental crust in Borborema Province was produced (Van Schmus et al., 1995; Brito Neves et al., 2000, Neves, 2003 and references therein). The possibility that the old T_{DM} ages reflect crustal contamination through assimilation of supracrustal rocks can be ruled out because these rocks have lower T_{DM} ages than the diorites (typically 1.0-1.3Ga; Van Schmus et al., 1995; 2003)

The source proposed for Tibetan shoshonites is also lithospheric mantle metasomatized well before (0.9-1.3 Ga; Turner et al., 1996; Chung et al., 1998) the partial melting event. Higher alumina contents in the Borborema diorites (Figure 3b) might reflect higher degrees of partial melting from a source with similar composition and/or an alumina-poorer source for the shoshonites. The first possibility is consistent with higher LILE contents of the shoshonites.

Discussion and conclusion

Dioritic rocks with characteristics akin to those discussed here are found in several other Neoproterozoic belts, such as the Nigerian Province (Dada et al., 1995), the East African Orogen in Sudan (Küster & Harms, 1998), and the Damara (Jung et al., 2002) and Kaoko (van de Flierdt et al., 2003) belts in Namibia. This indicates that partial melting of subcontinental mantle lithosphere is a common process during orogenic events. Although the volume fraction of diorites is generally not large, the presently exposed outcrop surface places only a lower bound on the amount of magmas produced. Due to their low viscosities, mafic magmas tend to extrude at the surface and can normally only be arrested during ascent if they found some rheological trap, such as partial melting zones or felsic magma chambers or if they reach their neutral buoyancy level. It is thus possible that large granitic batholiths are floored by diorites, as observed in several upper-crustal silicic magma chambers (e.g., Wiebe, 1993), and that granitoids contain a significant fraction of mantle-derived material due to their interaction with dioritic melts (e.g. Neves et al., 2000).

The widespread distribution of dioritic rocks in Borborema Province requires a regionally extensive heat source. Mechanisms commonly invoked for production of lithosphere-derived magmas are delamination or convective removal of the lower part of lithospheric mantle (Kay & Kay, 1993; Platt & England, 1994). These processes prompt high rates of uplift, denudation, subsequent extension and cooling, and thus appear to be inappropriate in the case of Borborema Province, where evidence for large-scale post-orogenic extension have not been reported in any of the studies conducted so far. The delamination model owes its popularity to the perceived intrinsic gravitational instability of post-Archean as compared with Archean continental lithosphere. Buoyancy of Archean mantle lithosphere results from its highly depleted nature, while high Fe/Mg ratios is responsible for a greater density of younger lithosphere (e.g. Griffin et al., 2003). However, thermal effects can counter compositional ones and inhibit delamination of post-Archean continental lithosphere, as discussed below.

In metasomatically enriched mantle, as that inferred below Borborema Province during the Proterozoic, the contents of U, Th and K can be high enough to result in significant heat production (O'Reilly & Green, 2000; Neves & Mariano, 2004). This aspect has not been taken into account in models of continental deformation, and can strongly influence the thermal structure and evolution of the lithosphere. Hot (and thus weak) continental lithosphere can be easily deformed when affected by relatively small tectonic forces. So, large-scale remobilization of HPE and other icompatible element-enriched Proterozoic lithosphere during orogenesis may be a natural consequence of its intrinsic greater fertility and smaller strength as compared with depleted Archean lithosphere (Pollack, 1986). During contractional deformation, the compositionally defined lithosphere, i.e. the portion of the mantle with trace element and isotopic concentrations distinct from the convecting asthenosphere (e.g., McDonough, 1990), will increase in thickness to accommodate the imposed horizontal shortening. The thermal lithosphere, given by the depth of the 1280°C isotherm (e.g., McKenzie & Bickle, 1988), will also increase in thickness, but the ratio of thermal to chemical lithospheric thickness is expected to decrease with root thickness due to lateral and basal heating by the asthenosphere. The base of an already hot chemical lithosphere submitted to increased depths and temperatures may result in the "asthenospherization" (i.e. attainment of temperatures greater than 1280°C) of its lower part. Because temperature decreases rock density, the developing root may thus never attain negative buoyancy or, if it does, its magnitude may not be enough to prompt delamination.

Increased temperature in the chemical lithosphere may ultimately lead to partial melting. If temperatures are not high enough to surpass the dry peridotite solidus, only regions capable of underwent dehydration melting or fluid-present melting will be affected. This is consistent with geochemical arguments suggesting that potassic magmas with the characteristics discussed here are derived from low degree partial melting of phlogopite bearing peridotite (Turner et al., 1996), a view reinforced by recent experimental work on model rocks with this composition (Conceição et al., 2004). Once volatiles or water-bearing phases are depleted by melt extraction, a shift toward the dry peridotite melting relation will occur, resulting in short-lived magmatism. This inference is consistent with the relatively narrow range of U-Pb ages (590-580 Ma) of plutons of the granite/diorite association in Borborema Province (Leterrier et al., 1994; Guimarães et al., 1998; Almeida et al., 2002; Brito Neves et al., 2003; Neves et al., 2004). A viscosity increase produced by complete dehydration explains how originally hot mantle can eventually be stabilized after their fusible components are removed by melting (Neves et al., 2000).

The occurrence of shoshonites in zones of thickened crust and their spatial association with strike-slip shear zones in Boborema Province suggest a genetic link between melt flow and mantle deformation during continued convergence of lithospheric blocks in an intracontinental setting. In this setting, zones of localized deformation might reflect heterogeneous degrees of mantle metasomatism, with the parts more strongly affected being more prone to deformation and partial melting. The presence of melt could enhance recrystallization rates in these zones, leading to faster deformation and, eventually, to the development of shear zones.

Acknowledgments

The authors acknowledge support by the Brazilian agency Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Constructive comments by Roberto Weinberg, Bruce Schaefer, and Geordie Mark helped improved the manuscript.

References

Almeida, C.N., Guimarães, I.P. and Da Silva Filho, A.F., 2002. Petrogênese de rochas plutônicas félsicas e máficas na Província Borborema, NE do Brasil: o complexo cálcio-alcalino de alto-K de Campina Grande. Revista Brasileira de Geociências, 32: 205-216.

Annen, C. and Sparks, R.S.L., 2002. Effects of repetitive emplacement of basaltic intrusions on thermal evolution and melt generation in the crust. Earth and Planetary Science Letters, 203: 937-955.

Archanjo, C.J., Trindade, R.I.F., Bouchez, J.L. and Ernesto, M., 2002. Granite fabrics and regional-scale strain partitioning in the Seridó Belt (Borborema Province, NE Brazil). Tectonics, 21, doi: 10.1029/2000TC001269.

Brito Neves, B.B., Santos, E.J. and Van Schmuss, W.R., 2000. Tectonic history of the Borborema Province, in Cordani, U.G., Milani, E.J., Thomaz Filho, A. and Campos, D.A. (Editors), Tectonic evolution of South America: 31st International Geological Congress, Rio de Janeiro, pp. 151-182.

Brito Neves, B.B., Passarelli, C.R., Basei, M.A.S. and Santos, E.J., 2003. Idades U-Pb em zircão de alguns granitos clássicos da Província Borborema. Geologia USP, Série Científica, 3: 25-38.

Campos, T.F.C., Neiva, A.M.R. and Nardi, L.V.S., 2002. Geochemistry of the Espinharas hybrid complex, northeastern Brazil, Lithos, 64: 131-153.

Chung, S.-L., Lo, C.-H., Lee, T.-Y., Zhang, Y., Xie, Y., Li, X., Wang, K.-L. and Wang, P.-L., 1998. Diachronous uplift of the Tibetan plateau starting 40 Myr ago, Nature, 394: 769-773.

Conceição, R.V. and Green, D.H., 2004. Derivation of potassic (shoshonitic) magmas by decompression melting of phlogopite+pargasite lherzolite. Lithos, 72: 209-229.

Dada, S.S., Briqueu, L., Harms, U., Lancelot, J.R. and Matheis, G., 1995. Charnockitic and monzonitic Pan-African series from north-central Nigeria: trace-element and Nd, Sr, Pb isotope constraints in their petrogenesis. Chemical Geology, 124: 233-252.

Evense, N.M., Hamilton, P.J. and O´Nions, R.K., 1978. Rare earth elements abundances in chondrite meteorites. Geochemica et Cosmochimica Acta., 42: 1199-1212.

Ferreira, V.P., Sial, A.N. and Jardim de Sá, E.F., 1998. Geochemical and isotopic signatures of Proterozoic granitoids in terranes of the Borborema structural province, northeastern Brazil. Journal of South American Earth Sciences, 11: 439-455.

Green, T.H., 1994. Experimental studies of trace-element partitioning applicable to igneous petrogenesis-Sedona 16 yars later. Chemical Geology, 117: 1-36.

Griffin, W.L., O'Reilly, S.Y., Abe, N., Aulbach, S., Davies, R.M., Pearson, N.J., Doyle, B.J. and Kivi, K., 2003. The origin and evolution of Archean lithospheric mantle. Precambrian Research, 127: 19-41.

Guimarães, I.P., Da Silva Filho, A.F., Almeida, C.N., Araújo, J.M.M., Sales, A. and Melo, S.C., 1998. The Brasiliano granitoids from the Pajeú Paraíba belt and Teixeira High: Sm-Nd isotope geochemistry and U/Pb in zircon ages: Anais XL Congresso Brasileiro de Geologia, Belo Horizonte, Anais, p. 48.

Hirose, K. and Kawamoto, T., 1995. Hydrous partial melting of lherzolite at 1 GPa: The effect of H_2O on the genesis of basaltic magmas. Earth and Planetary Science Letters, 133: 463-473.

Hollanda, M.H.B.M., Pimentel, M.M. and Jardim de Sá, E.F., 2003. Paleoproterozoic subduction-related metasomatic signatures in the lithospheric mantle beneath NE Brazil: inferences from trace element and Sr-Nd-Pb isotopic compositions of Neoproterozoic high-K igneous rocks. Journal of South American Earth Sciences, 15: 885-900.

Jardim de Sá, E.F., 1994. A Faixa Seridó (Província Borborema, NE do Brasil) e seu significado geodinâmico na cadeia Brasiliana/Pan-Africana. PhD thesis, Universidade de Brasília, Brazil.

Jung, S., Hoernes, S. and Mezger, K., 2002. Synorogenic melting of mafic lower crust: constraints from geochronology, petrology and Sr, Nd, Pb and O isotope geochemistry of quartz diorites (Damara orogen, Namibia). Contributions to Mineralogy and Petrology, 143: 551-566.

Kay, R.W. and Kay, S.M., 1993. Delamination and delamination magmatism. Tectonophysics, 219: 177-189.

Küster, D. and Harms, U., 1998. Post-collisional potassic granitoids from the southern and northwestern parts of the Late Neoproterozoic East African Orogen: a review. Lithos, 45: 177-195.

Leterrier, J., Jardim de Sá, E.F., Bertrand, J.-M. and Pin, C., 1994. Ages U-Pb sur Zincon de granitoides brasilianos de la ceinture du Serido (Province Borborema, NE Brésil). Comptes Rendus de l'Academie des Sciences Paris, 318: 1505-1511.

Mariano, G. and Sial, A.N., 1990. Coexistence and mixing of magmas in the Late Precambrian Itaporanga batholith, state of Paraíba, northeastern Brazil. Revista Brasileira de Geociências, 20:101-110.

Mariano, G., Sial, A.N., Cruz, M.J.M. and Conceiçao, H., 1996. The potassic calc-alkalic Itaporanga Batholith, northeastern Brazil: mineral chemistry and oxygen-isotope data. International Geology Review, 38: 74-86.

Mariano, G., Neves, S.P., Da Silva Filho, A.F. and Guimarães, I.P., 2001. Diorites of the high-K calc-alkalic association: Geochemistry and Sm-Nd data and implications for the evolution of the Borborema Province, Northeast Brazil. International Geology Review, 43: 921-929.

McDonough, W.F., 1990. Constraints on the composition of the continental lithospheric mantle: Earth and Planetary Science Letters, 101: 1-18.

McKenzie, D., and Bickle, 1988 The volume and composition of melt generated by extension of the lithsophere. Journal of Petrology, 29: 625-679.

Meyzen, C.M., Toplis, M.J., Humler, E., Ludden, J.N. and Mével, C., 2003. A discontinuity in mantle composition beneath the southwest Indian ridge. Nature, 421: 731-733.

Miller, C., Schuster, R., Klötzli, U., Frank, W. and Purtscheller, F., 1999. Post-collisional potassic and ultrapotassic magmatism in SW Tibet: geochemical and Sr-Nd-Pb-O isotopic constraints for mantle source characteristics and petrogenesis. Journal of Petrology, 40: 1399-1424.

Neves, S.P., 2003. Proterozoic history of the Borborema Province (NE Brazil): correlations with neighboring cratons and Pan-African belts, and implications for the evolution of Western Gondwana. Tectonics, 32, doi:10.1029/2001TC001352.

Neves, S.P. and Vauchez, A., 1995. Successive mixing and mingling of magmas in a plutonic complex of Northeast Brazil. Lithos, 34: 275-299.

Neves, S.P. and Mariano, G., 1997. High-K calc-alkalic plutons in NE Brazil: origin of the biotite diorite/quartz monzonite to granite association and implications for the evolution of the Borborema Province. International Geology Review, 39: 621-638.

Neves, S.P. and Mariano, G., 2004. Heat-producing elements-enriched continental mantle lithosphere and Proterozoic intracontinental deformation: insights from Brasiliano/Pan-African belts: Gondwana Research, 7: 427-436.

Neves, S.P., Vauchez, A. and Archanjo, C.J., 1996. Shear-zone controlled magma emplacement or magma-assisted nucleation of shear zones? Insights from Northeast Brazil. Tectonophysics, 262: 349-365.

Neves, S.P., Mariano, G., Guimarães, I.P., Da Silva Filho and A.F. and Melo, S.C., 2000, Intralithospheric differentiation and crustal growth: evidence from the Borborema Province, northeastern Brazil. Geology, 28: 519-522.

Neves, S.P., Melo, S.C., Moura, C.A.V., Mariano, G. and Silva, J.M.R., 2004. Zircon Pb-Pb geochronology of the Caruaru area, northeastern Brazil: temporal constraints on the Proterozoic evolution of Borborema Province. International Geology Review, 46: 52-63.

O'Reilly, S.Y. and Griffin, W.L., 2000. Apatite in the mantle: implications for metasomatic processes and high heat production in Phanerozoic mantle. Lithos, 53: 217-232.

Patiño Douce, A.E. and Beard, J.S., 1995. Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar. Journal of Petrology, 36: 707-738.

Peccerillo, R. and Taylor, S.R., 1976. Geochemistry of Eocene cal-alkaline volcanic rocks from the Kastamonu area, northern Turkey. Contributions to Mineralogy and Petrology, 58: 63-81.

Petford, N., and Gallagher, K., 2001, Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma. Earth and Planetary Science Letters, 193: 483-499.

Platt, J.P. and England, P.C., 1994. Convective removal of lithosphere beneath mountain belts: Thermal and mechanical consequences. American Journal of Sciences, 294: 307-336.

Pollack, H.N., 1986. Cratonization and thermal evolution of the mantle. Earth and Planetary Science Letters, 80: 175-182.

Rapp, R.P. and Watson, E.B., 1995. Dehydration melting of metabasalt at 8-32 kbar: Implications for continental growth and crust-mantle recycling. Journal of Petrology, 36: 891-931.

Rapp, R.P., Schimizu, N. Norman, M.D., 2003. Growth of early continental crust by partial melting of eclogite. Nature, 426: 605-609.

Rushmer, T., 1991. Partial melting of two amphibolites: contrasting experimental results under fluid-absent conditions. Contributions to Mineralogy and Petrology, 107: 41-59.

Schaefer, B.F., Turner, S.P., Rogers, N.W., Hawkesworth, C.J., Williams, H.M., Pearson, D.G. and Nowell, G.M., 2000. Re-Os isotope characteristics of post-orogenic lavas: implications for the nature of young lithospheric mantle and its contribution to basaltic magmas. Geology, 28: 563-566.

Turner, S., Arnaud, N., Liu, J., Rogers, N., Hawkesworth, G., Harris, N., Kelley, S., Van Calsteren, P. and Deng, M., 1996. Post-collision, shoshonitic volcanism on the Tibetan Plateau: implications for convective thinning of the lithosphere and the source of ocean island basalts. Journal of Petrology, 37: 45-71.

Turner, S., Sandiford, M. and Foden, J., 1992. Some geodynamic and compositional constraints on "postorogenic" magmatism. Geology, 20: 931-934.

van de Flierdt, T., Hoernes, S., Jung, S., Masberg, P., Hoffer, E., Schaltegger, U., and Friedrichsen, H., 2003, Lower crustal melting and the role of open-system processes in the genesis of syn-orogenic quartz diorite-granite-leucogranite associations: constraints from Sr-Nd-O isotopes from the Bandombaai Complex, Namibia. Lithos, 67: 205-226.

Van Schmus, W.R., Brito Neves, B.B., Hackspacher, P., and Babinski, M., 1995, U/Pb and Sm/Nd geochronologic studies of the eastern Borborema Province, northeastern Brazil: initial conclusions. Journal of South American Earth Sciences, 8: 267-288.

Van Schmus, W.R., Brito Neves, B.B., Williams, I. S., Hackspacher, P., Fetter, A. H., Dantas, E. L. and Babinski, M., 2003. The Seridó Group of NE Brazil, a late Neoproterozoic pre- to syn-collisional basin in West Gondwana: insights from SHRIMP U-Pb detrital zircon ages and Sm-Nd crustal residence (T_{DM}) ages. Precambrian Research, 127: 287-327.

Vauchez, A., Neves, S.P., Caby, R., Corsini, M., Egydio-Silva, M., Arthaud, M.H. and Amaro, V., 1995. The Borborema shear zone system, NE Brazil. Journal of South American Earth Sciences, 8: 247-266.

Weinberg, R.F., Sial, A.N. and Mariano, G., 2004. Close spatial relationship between plutons and shear zones. Geology, 32: 377-380.

Wiebe, R.A., 1993, Basaltic injections into floored silicic magma chambers: EOS, 74: 1-3.

Wolf, M.B. and Wyllie, P.J., 1994. Dehydration-melting of amphibolite at 10 kbar: the effects of temperature and time. Contributions to Mineralogy and Petrology, 115: 369-383.

A. Tables

Table A.1. Synthesis of geochemical and isotopic data

	SiO_2 (wt%)	TiO_2 (wt%)	Al_2O_3 (wt%)	FeO* (wt%)	MgO (wt%)	CaO (wt%)	Na_2O (wt%)	K_2O (wt%)	Na_2O/K_2O	Ba (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Nb (ppm)	La (ppm)	Yb (ppm)	Th (ppm)	(La/Yb)N (ppm)	ε_{Nd} (i)	T_{DM} (Ga)	$^{87}Sr/^{86}Sr$	$\delta^{18}O$ (permil)
Borborema	51-61(57)	0.8-2.0(1.4)	14.5-18.8(16.9)	5.4-10.6(7.8)	1.9-7.0(3.6)	3.0-8.0(5.4)	2.9-5.2(3.8)	2.4-5.8(3.8)	0.9-1.2	920-2788(1840)	64-229(118)	384-1200(790)	173-590(336)	14-53(28)	35-156(73)	1.0-2.8(1.46)	8-22(15)	16-90(51)	-6.9--14.9	1.4-2.0	0.7058-0.71002	7.5-8.2
Tibet	46-63(56)	0.4-2.3(1.6)	12.4-19.5(14.4)	4.3-11.0(8.0)	0.4-8.0(3.6)	2.1-12(6.2)	2.6-4.6(3.6)	1.2-7.7(4.6)	0.5-1.1	1270-25600(17667)	56-515(162)	635-4810(1397)	115-695(416)	26-44(37)	82-390(173)	0.8-2.4(1.4)	8-50(23)	56-129(78)	-5.42--8.13	0.8-1.0	0.7076-0.7105	#
RW	52-75(	0.1-1	14.4-11	2.3-11	0.5-4	1.7-8	3.5-6	0.2-1	2.3-19													

Table A.2. Selected chemical data of diorites from the borborema province

	SiO_2 (wt%)	TiO_2 (wt%)	Al_2O_3 (wt%)	FeO* (wt%)	MgO (wt%)	CaO (wt%)	Na_2O (wt%)	K_2O (wt%)	Na_2O/K_2O	Ba (ppm)	Rb (ppm)	Sr (ppm)	Zr (ppm)	Nb (ppm)
Itaporanga	57.3	1.3	17.7	7.3	2.9	3.7	3.5	4.2	0.75	2310	120	1200	350	30
Serra da Lagoi-nha	58.1	1.6	16.1	6.9	2.7	4.8	3.9	3.4	0.64	1980	110	960	480	26
Caruaru-Arcoverde	56.4	1.3	17.8	7.7	2.7	5.5	3.9	3.3	0.35	1694	104	792	290	25
Acari	58.3	1.0	16.6	8.2	2.5	4.5	3,6	4.4	0.44	2019	112	665	385	#
Espinharas	57.4	1.3	15.6	4.2	3.7	4.9	3.4	4.5	0.51	2236	133	750	526	#
Alagoi-nhas	58.3	1.45	15.5	7.8	3.1	4.4	3.6	3.4	0.57	1253	157	689	363	30

Note

Selected major elements and trace elements