Isotopic Signatures of Neoproterozoic to Cambrian Ultrapotassic Syenitic Magmas, Northeastern Brazil: Evidence for an Enriched Mantle Source

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Abstract

Neoproterozoic to Cambrian ultrapotassic (K₂O up to 13 wt%) peralkaline alkali-feldspar–rich syenitic plutons were emplaced along the boundary between the Cachoeirinha-Salgueiro and Alto Pajeú tectonostratigraphic terranes of the Borborema structural province, northeastern Brazil. Syenite and alkaline pyroxenitic magmas coexisted in these plutons, which locally carry mica pyroxenite xenoliths. In the Triunfo batholith, the largest peralkaline pluton in the region, syenites and alkali pyroxenites have high pyroxene-corrected δ¹⁸O values (+8.1 to +8.5‰), high δ³⁴S (+12.3‰ in syenite and +11.2‰ in alkali pyroxenite), high initial ⁸⁷Sr/⁸⁶Sr ratios (0.7098, syenite and alkali pyroxenite data lying on the same Rb-Sr isochron), and low εNd (-15.3 to -17.2 in syenite and -16.1 in pyroxenite). Whole-rock δ¹⁸OSMOW for mica pyroxenite xenoliths varies from +7.5 to +8.0‰SMOW. Syenite, alkali pyroxenite, and xenoliths all are enriched in large-ion lithophile elements (LILE). These geochemical and isotopic signatures suggest that the magmas were derived from an incompatible-element–enriched mantle source; this protolith probably resulted from hybridization by addition of crustal material via subduction at ~2.4 Ga, as estimated from Nd model ages. Partial melting of metasomatized material and magma emplacement at a late stage of the Brasiliano Orogeny (566 Ma) were controlled by mantle-deep shear zones during the amalgamation of the Cachoeirinha-Salgueiro and Alto Pajeú terranes.

Introduction

MANTLE-DEEP SHEAR ZONES are known to provide access for mantle-derived magma to migrate upward into the crust (e.g., Hutton, 1992); thus the geochemical study of magmas associated with shear zones can provide a way to probe the mantle beneath stable regions. An enormous volume of granitic and syenitic plutons was emplaced along the Borborema shear zone system of northeastern Brazil. In this paper, we describe the geochemistry and isotopic characteristics of mantle-derived Neoproterozoic to Cambrian ultrapotassic peralkaline syenites in this setting, indicative of an old LILE-enriched mantle source.

General Geology

The Borborema structural province of northeastern Brazil is divided into domains by a complex network of shear zones that resulted from a terrane amalgamation process (Santos and Brito Neves, 1993), involving belts and massifs as defined by Brito Neves (1984). Its major characteristics developed during the late Mesoproterozoic to Neoproterozoic (Brasiliano Orogeny). Two of the shear zones, the E-trending dextral strike-slip Pernambuco (PSZ) and Patos (PTSZ) zones, are notable because of their great length (>500 km). Dextral displacement was transferred from one shear zone to another via a series of subsidiary NE-trending shear zones (Davison et al., 1995).
Several lines of evidence indicate that partial melting occurred during the major shear event (Davison et al., 1995; Silva and Vauchez, 1992). The enormous volume of syn- to late-kinematic granites of Neoproterozoic age also attests to the fact that the Brasiliano Orogeny was the major tectonothermal event in the Borborema structural province (Sial and Ferreira, 1990).

Numerous and voluminous fault-controlled syenitic, monzonitic, and granitic intrusions of an alkalic to calc-alkalic nature occur in the region between the PSZ and PTSZ. Peralkallic syenitic and granitic rocks occur as elongate, aligned plutons, dike sets, and ring structures, or were intruded along shear zones, within terranes or along their boundaries, in the region between the PSZ and PTSZ (Fig. 1). Two major pluton alignments occur: (1) along the PSZ, concentrated in its central and eastern portion, extending for 300 km, and (2) along the boundary between the Cachoeirinha-Salgueiro and the Alto Pajeú terranes (Fig. 1), forming a "syenitoid line" that extends for 200 km, as described by Ferreira and Sial (1986).

This magmatism appears to stitch the two terranes together. Those authors recognized two major groups among the peralkallic rocks—silica-oversaturated potassic and silica-saturated ultrapotassic syenites and granites. Plutons along line (1) are mostly granitic in composition, and along line (2) they are mostly syenitic.

**Ultrapotassic Peralkallic Plutons**

Ultrapotassic peralkallic plutons along line (2) are predominantly equigranular, medium-grained leucocratic alkali-feldspar syenites composed of perthitic microcline and aegirine-augite with variable abundances of quartz, titanite, apatite, richterite (formed at the expense of pyroxene), and magnetite. Tiny, brown mica flakes are present in some places. These rocks have up to 13 wt% K₂O and are ultrapotassic, according to the Foley et al. (1987) classification.

Numerous inclusions or syn-plutonic or late-stage dikes of alkali pyroxenite occur within all of the syenitic plutons. In most cases, inclu-
sions are more or less elongate and oval-shaped, with sharp contacts but smooth perimeters. Alkaline pyroxenite has about the same grain size as host syenite and consists mostly of euhedral to subhedral aegirine-augite, titanite, apatite, and rare blue amphibole replacing pyroxene, microcline, and interstitial quartz—i.e., basically the same modal phases found in host syenite, but present in different proportions.

In the largest pluton, the Triunfo batholith, field evidence indicates that the syenite and its alkaline pyroxenitic inclusions both were in magmatic stages when brought into mutual contact, under thermal equilibrium conditions; several lines of geochemical evidence point to chemical equilibration between them. Recognition of this thermal-chemical equilibrium led Ferreira et al. (1994) to propose that the syenite and alkaline pyroxenite were isolated through a large-scale liquid immiscibility process. Inclusions of syenitic and alkaline pyroxenitic material with a mutually interstitial emulsion-like texture, interpreted by those authors as part of the original composition, are present in the Triunfo pluton.

Sporadic mica pyroxenite inclusions consist mainly of diopside-salite (>80% of the bulk inclusion), with variable, subordinate amounts of F-rich phlogopite, calcite, hyalophane, titanite, and apatite, as well as traces of barite. Corroded pyroxene is observed in the vicinity of these late space-filling minerals. These late-stage minerals were precipitated from a metamorphic fluid that corroded the early-crystallized pyroxene.

Geochemistry

Analytical techniques

Oxygen-isotope analyses were performed at the Stable Isotope Laboratory, Department of Geology, University of Georgia, Athens (UGA) and at the Federal University of Pernambuco, Brazil (UFPE) using fluorine as the decomposition reagent. 18O/16O ratios of syenite and pyroxenite were measured on a Finnigan MAT Delta E mass spectrometer in UGA and a VG Isotech SIRA II in UFPE, and were reported relative to the SMOW standard, with a precision of ±0.1‰. 87Sr/86Sr ratios were measured on a Finnigan MAT 261 solid-source mass spectrometer at the Department of Geological Sciences, University of Texas at Austin; Sr and Rb concentrations were determined by isotope dilution. 143Nd/144Nd ratios and Sm and Nd concentrations were measured at the University of Blaise Pascal, Clermont-Ferrand, France by isotope dilution using a mixed 149Sm, 150Nd tracer, on a VG 54 E mass spectrometer. Chemical procedures are described in Pin and Carme (1987), except that Sm and Nd were separated from one another and from the other lanthanides using the extraction chromatography method of Richard et al. (1976). Initial 143Nd/144Nd and εNd were computed assuming an age of 566 Ma, based on the results of Rb-Sr isochron analysis. Isotope analyses in various laboratories were of aliquots of the same materials. Major- and minor-element analyses are presented in Table 1; isotopic data are listed in Table 2.

Results

Figure 2 illustrates values of selected trace, minor, and major elements for peralkaline plutons along the syenitoid line normalized against concentrations of these elements in primitive mantle. The syenite and alkaline pyroxenite, except for Rb and K in the latter, exhibit high relative enrichment in the selected elements, especially the most incompatible ones (left side of figure). Significant negative anomalies are apparent for Nb, P, and Ti, with an incipient one for Sr. These patterns resemble those for the Italian ultrapotassic lavas, which Foley et al. (1987) classified as typical Group-III ultrapotassic magmas and to which a subduction-related origin has been ascribed (Rogers et al., 1985).

Whole-rock δ18O values in the syenites range broadly between +1.8 and +9.6‰, and δ18O values of feldspar (a major component) vary from −1.2 to +9.5‰. The variability indicates that these are not primary values. δ18O values of pyroxene are much more uniform than whole-rock values, ranging from +8 to +8.3‰. Assuming a pyroxene-whole rock fractionation of +0.25‰, as recommended by Taylor et al. (1984) for Italian ultrapotassic rocks, remarkably uniform and high corrected whole-rock δ18O values are obtained for the Triunfo rocks, ranging from +8.1 to +8.5‰, which differs markedly in some samples from the measured bulk-rock value (Fig. 3).
Table 1. Selected Major- and Minor-Element Analyses of the Ultrapotassic Triunfo Pluton and Other Bodies along the Syenitoid Line, Northeastern Brazil

<table>
<thead>
<tr>
<th></th>
<th>TRF-02</th>
<th>TRF-11</th>
<th>PTR-28a</th>
<th>TN-2</th>
<th>BN-1</th>
<th>SDI-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>60.50</td>
<td>59.60</td>
<td>50.60</td>
<td>59.10</td>
<td>62.10</td>
<td>59.60</td>
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<tr>
<td>TiO₂</td>
<td>0.68</td>
<td>0.46</td>
<td>1.00</td>
<td>0.86</td>
<td>0.68</td>
<td>0.43</td>
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<tr>
<td>Al₂O₃</td>
<td>14.70</td>
<td>14.90</td>
<td>0.33</td>
<td>13.80</td>
<td>15.80</td>
<td>12.70</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.40</td>
<td>3.10</td>
<td>10.70</td>
<td>1.80</td>
<td>1.40</td>
<td>2.20</td>
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<tr>
<td>FeO</td>
<td>1.30</td>
<td>1.15</td>
<td>4.50</td>
<td>4.60</td>
<td>0.74</td>
<td>1.70</td>
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<tr>
<td>MgO</td>
<td>1.40</td>
<td>1.10</td>
<td>7.40</td>
<td>3.40</td>
<td>1.40</td>
<td>4.70</td>
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<tr>
<td>CaO</td>
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<td>2.60</td>
<td>17.60</td>
<td>5.20</td>
<td>2.30</td>
<td>4.00</td>
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<tr>
<td>Na₂O</td>
<td>2.80</td>
<td>3.80</td>
<td>4.60</td>
<td>3.60</td>
<td>1.40</td>
<td>2.70</td>
</tr>
<tr>
<td>K₂O</td>
<td>12.20</td>
<td>11.60</td>
<td>0.13</td>
<td>5.60</td>
<td>12.40</td>
<td>10.00</td>
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<tr>
<td>BaO</td>
<td>0.41</td>
<td>0.51</td>
<td>1.90</td>
<td>0.53</td>
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<td>0.85</td>
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<td>P₂O₅</td>
<td>0.26</td>
<td>0.28</td>
<td>0.13</td>
<td>0.17</td>
<td>0.79</td>
<td>0.60</td>
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<tr>
<td>CO₂</td>
<td>0.05</td>
<td>0.05</td>
<td>0.50</td>
<td>0.41</td>
<td>0.88</td>
<td>0.20</td>
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<td>H₂O</td>
<td>0.09</td>
<td>0.15</td>
<td>0.06</td>
<td>0.50</td>
<td>0.25</td>
<td>0.05</td>
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<tr>
<td>Total</td>
<td>99.95</td>
<td>99.78</td>
<td>99.48</td>
<td>99.79</td>
<td>100.08</td>
<td>99.94</td>
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<table>
<thead>
<tr>
<th></th>
<th>Nb</th>
<th>Y</th>
<th>Rb</th>
<th>Sr</th>
<th>Zr</th>
<th>La</th>
<th>Ce</th>
<th>Nd</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd</th>
<th>Dy</th>
<th>Ho</th>
<th>Er</th>
<th>Yb</th>
<th>Lu</th>
<th>ΣREE</th>
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<tr>
<td>ppm</td>
<td>&lt; 20</td>
<td>&lt; 20</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>20</td>
<td>22</td>
<td>&lt; 20</td>
<td>&lt; 20</td>
<td>&lt; 10</td>
<td>&lt; 20</td>
<td>22</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: TRF = Triunfo syenite; PTR = Triunfo alkalic pyroxenite; TN = Serra do Livramento; BN = Bom Nome; SDI = Serra de Duas Irmãs.

These high δ¹⁸O magmas cannot have been derived by partial melting of a "normal" upper-mantle reservoir, believed to have uniform δ¹⁸O values between +5.5 to +6‰ (Taylor, 1980). In principle, contamination could explain these values, but ¹⁸O values for country rocks, possible contaminant candidates, are not very high. Host rocks of the Triunfo pluton have values of approximately +14.0‰ (biotite schists), +15.0‰ (phylmites), and +10.5‰ (porphyritic granodiorite in contact with the pluton on its southern side). Large-scale interaction with these country rocks is unlikely to have produced large volumes of magmas with uniform δ¹⁸O values and ultrapotassic chemical compositions.

Values of δ³⁴S of bulk sulfur for syenite and alkalic pyroxenite all are positive, ranging from +8.3 to +12.3‰cdt (average: +10.4‰). These values are higher than those for ocean-floor basalts (average +0.3‰) (Sakai et al., 1978) and alkali basalts (average +2.6 ± 1.4‰) (Ueda and Sakai, 1984). For comparison, we analyzed three typical samples from the Roman ultrapotassic province, Italy, which yielded δ³⁴S values from +2.7 to +3.2‰cdt. High δ³⁴S for the studied ultrapotassic magmas suggest either a source that is different from upper-mantle material parental to normal mafic magmas, or that some process has increased the abundance of heavy sulfur.
Table 2. Rb/Sr and Sm/Nd Isotopic Data for the Triunfo Ultrapotassic Pluton, Northeastern Brazil

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{87}\text{Rb}/^{86}\text{Sr}$</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>Nd, ppm</th>
<th>Sm, ppm</th>
<th>$^{143}\text{Nd}/^{144}\text{Nd}$</th>
<th>$^{147}\text{Sm}/^{144}\text{Nd}$</th>
<th>$\varepsilon\text{Nd}(0)$</th>
<th>$t_{\text{DM}}$(Ma)</th>
<th>Nd($t_{\text{DM}}$)</th>
<th>$f$(Sm/Nd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRF-22</td>
<td>0.4915</td>
<td>0.71380</td>
<td>108.40</td>
<td>20.900</td>
<td>0.511524</td>
<td>0.1165</td>
<td>-21.7</td>
<td>2376</td>
<td>2.8</td>
<td>-0.41</td>
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<tr>
<td>TRF-31</td>
<td>0.5551</td>
<td>0.71394</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRF-25</td>
<td>0.8256</td>
<td>0.71651</td>
<td>63.00</td>
<td>12.000</td>
<td>0.511440</td>
<td>0.1151</td>
<td>-23.4</td>
<td>2474</td>
<td>2.6</td>
<td>-0.41</td>
</tr>
<tr>
<td>TRF-11</td>
<td>0.9740</td>
<td>0.71781</td>
<td>25.30</td>
<td>4.800</td>
<td>0.511504</td>
<td>0.1147</td>
<td>-22.1</td>
<td>2362</td>
<td>2.8</td>
<td>-0.42</td>
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<tr>
<td>TRF-12</td>
<td>1.2085</td>
<td>0.71960</td>
<td>40.30</td>
<td>7.950</td>
<td>0.511454</td>
<td>0.1192</td>
<td>-23.1</td>
<td>2562</td>
<td>2.5</td>
<td>-0.39</td>
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<tr>
<td>TRF-64</td>
<td>1.3285</td>
<td>0.72027</td>
<td></td>
<td></td>
<td>-</td>
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<tr>
<td>TRF-13</td>
<td>1.4363</td>
<td>0.72141</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
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<tr>
<td>TRF-14</td>
<td>1.6597</td>
<td>0.72355</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>TRF-02</td>
<td>1.9120</td>
<td>0.72437</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PTR-54</td>
<td>0.0064</td>
<td>0.71014</td>
<td>62.80</td>
<td>13.200</td>
<td>0.511538</td>
<td>0.1270</td>
<td>-21.5</td>
<td>2649</td>
<td>2.3</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

Abbreviations: TRF = syenite; PTR = alkaline pyroxenite.
Fig. 2. Primitive mantle–normalized element-concentration-envelope surfaces for the Triunfo syenites (light pattern), alkalic pyroxenites (dark pattern), and other bodies along the syenitoid line (no pattern). Normalizing values are from Wood (1979), except for Nd, which is from Nelson et al. (1986).

Regression of 10 whole-rock Rb-Sr data points for the Triunfo pluton corresponds to an age of 545 ± 5 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.71007 ± 0.00003 (Fig. 4). The lowest data point, which pertains to an alkalic pyroxenite inclusion, lies approximately on the isochron. A calculation omitting this datum provides $t$ = 566 ± 10 Ma and initial $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.7098 ± 0.0001, which are acceptably similar values considering the scatter of data evident in Figure 4; these values suggest that the Triunfo syenite and its alkalic pyroxenite inclusions are contemporaneous with the same initial Sr ratio.

Values of $\varepsilon$Nd are strongly negative (−15 to −18) for all bodies along the syenitoid line (Table 2, Fig. 5), implying the presence of an old, LREE-enriched source. Sm/Nd ratios are quite uniform (−0.19), lower than in CHUR (0.31) (DePaolo, 1988) and compatible with a LILE-enriched source.

Data of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\varepsilon$Nd for the Triunfo pluton (Fig. 6) group tightly in the enriched source area of the plot, close to a projection of the mantle array. These data suggest an old LREE- and LILE (Rb)-enriched component in the source of these magmas.

**Discussion and Conclusions**

Several lines of evidence point to an LREE- and LILE-enriched mantle source as the best explanation for the chemical and isotopic signatures of the syenitic rocks studied here. Among them is the presence of mica pyroxenite xenoliths, characterized by high concentrations of Ba, La, K, Ce, Nd, Sm, Sr, and Ti, compared to mantle concentrations, and by $\delta^{18}$O (+7.5 to +8.0‰SMOW) (Ferreira and Sial, 1993). The petrography and mineral chemistry of the calcite- and phlogopite-bearing pyroxenite inclusions in the syenite suggest invasion by CO$_2$-saturated fluid or melt. Ferreira et al. (1995) inferred that these xenoliths are products of metasomatism in the mantle source area and are the source for ultrapotassic magmas, inasmuch as partial melting of a material with these chemical characteristics could explain the incompatible-element enrichment observed in the Triunfo batholith.

Most sulfur in mafic and granitic rocks occurs as sulfides (Ueda and Sakai, 1984), and the sulfate/sulfide ratio in magmas always is less than unity (Katsura and Nagashima, 1974) but increases with increasing oxygen fugacity (Faure, 1986). Degassed magma may be enriched in $\delta^{34}$S under a high $f$(O$_2$), but as
Fig. 4. Rb-Sr isochron for Triunfo pluton. Alkaline pyroxenite datum is on the Y-axis (not included in the isochron calculation).

Fig. 5. εNd-age evolution curves for the Triunfo ultrapotassic magma, with tDM model ages ranging from 2.4 to 2.6 Ga.

pointed out by Ueda and Sakai (1984), natural magmas generally do not have sufficiently high oxygen fugacity values for such enrichment. Studies conducted by Sakai (1968) indicate that at magmatic temperatures, isotope fractionation between sulfur species is not expected to exceed $5\%$. An unreasonably large amount of light sulfide would have to have been fractionated in order to raise the value of $\delta^{34}S$ in Triunfo magma to $+12\%$. Host-rock sulfur was not likely imbibed into the magmas because whole-rock $\delta^{34}S$ values are similar in all syenite plutons along the syenitoid line, whereas sulfur in different host rocks (shoshonitic syenites, biotite schists, gneisses, and migmatises—see Figure 1) is expected to have varied in terms of $\delta^{34}S$.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ vs $1/\text{Sr}$ for syenite and alkaline pyroxenite along the syenitoid line defines an approximately horizontal trend (Fig. 7), thus ruling out simple two-component mixing between sources with distinctively different $^{87}\text{Sr}/^{86}\text{Sr}$. High but relatively uniform initial $^{87}\text{Sr}/^{86}\text{Sr}$, including that of high-Sr alkaline pyroxenite, which has the most mantle-like composition, argues that these values (0.709 to 0.710) are primary.

Depleted-mantle (DM) Nd model ages for plutons of the syenitoid line indicate $t_{DM}$ values ranging from 2362 to 2562 Ma (average 2443 Ma) (Table 2). If the hypothesis of a continental-crustal source for these magmas can be ruled out, an alternative possibility—a continental lithospheric mantle source—is strengthened. These ages suggest ancient LREE enrichment of the source, perhaps by addition of subducted continental crust. Van Schmus et al. (1995) interpreted similar model ages to indicate derivation from isolated older fragments of Mesoproterozoic crust that is a major feature of the Borborema structural province. It is noteworthy that a 2.4-Ga Nd model age corresponds to a prominent interval of continental crust formation in this part of northeastern Brazil (Cordani et al., 1988). Relations are illustrated schematically in Figure 8.

Possible interactions between mantle peridotite and hydrous silicic melts derived from subducted crust were examined by Sekine and Wyllie (1982) and Wyllie and Sekine (1982). In this process of "mantle hybridization," ascending silicic melt reacts with olivine in overlying
mantle peridotite to produce hybrid rocks that are rich in phlogopite and pyroxene ± quartz. A liberated H₂O-rich fluid phase converts the original peridotite into olivine-absent phlogopite pyroxenite. Blocks of phlogopite pyroxenite rise diapirically into continental lithosphere, providing a K-rich source from which potassic magmas can be derived by subsequent partial melting. Geochemical signatures of the magmas would be ascribed to mantle metasomatism (Wyllie and Sekine, 1982).

This model adequately explains the isotopic patterns and presence of pyroxenite xenoliths in the Triunfo magma. Syenitic and granitic magmas, mostly peralkaline, were emplaced along upper mantle–deep shear zones, especially in the middle parts of the E-W Pernambuco shear zone and its subsidiary NE-trending shear zones (Ferreira and Sial, 1993). Deep shear zones thus could have acted as pathways for emplacement of magma during a late stage of the Brasiliano Orogeny.

A metasomatic event was proposed to explain LILE-enriched mantle-derived rocks for other areas in this part of Brazil. Guimarães et al. (1993) described incompatible-element–enriched shoshonitic syenites and monzonites intruding the Alto Pajeú terrane, which he interpreted as being derived from a metasomatized lithospheric mantle source and emplaced along faults. Likewise, Neoproterozoic peralkaline granitoids in the Seridó fold belt and syenites in the Riacho do Pontal fold belt (Fig. 1) also are enriched in most incompatible elements. Nevertheless, all these rocks exhibit low Nb (<20 ppm), which seems to be a characteristic for peralkaline magmas in the Borborema structural province.
Fig. 8. Sm/Nd two-stage model for the Triunfo ultrapotassic magma.

Indications of an enriched source also are present in Mesozoic tholeiitic diabases and Tertiary alkali basalts, which have high Ba, K, Rb, Sr, and Pb, and peridotite nodules having up to 600 ppm Ba (Sial et al., 1991). Presumably the enriched zone is not in the asthenosphere or it would have been swept away by mantle convection currents. Rather, an anomalously isolated LILE-enriched lithospheric mantle area has survived a long interval since early Proterozoic times.

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