MULTIPLE MAGMA BATCHES IN THE CONSTRUCTION OF THE GRANITE PLUTON, LAVRAS DO SUL INTRUSIVE COMPLEX, SOUTHERN BRAZIL: Sr-Nd ISOTOPIC AND GEOCHEMICAL EVIDENCES.

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The Lavras do Sul intrusive complex-LSIC and coeval trachyandesites are post-collisional to the Dom Feliciano Orogeny (660-550 Ma). They occur in the western portion of the Sul-riograndense Shield composed by the São Gabriel Arc (900-700 Ma). LSIC includes the Tapera monzonite in the north, and a granite pluton in the south (Fig. 1A). Most intrusives formed at the ca. 600 Ma-old event responsible for the construction of the LSIC-framework (Gastal et al., 2005b). A shoshonitic affinity is postulated for these rocks, and metaluminous alkaline granites are subordinate. The latter probably formed in more than one younger magmatic episode (598-586 Ma).

The pluton has approximately a circular shape in plan view (12.0 X 13.5 km), and consists of a reverse zoned granite body (Fig. 1B). Granodiorites and monzogranites are in the core, whereas alkaline syenogranites and perthite granites form semicircular and peripheral stocks. At depth, the pluton is a thin body in which the floor dips gently toward the main roots. The roots indicate magma feeder zones commonly placed below and related to the more evolved facies in composite plutons. Such relationship is more complicated in the LSIC-pluton since most roots may be associated with the less evolved facies. The contact between the nucleus and alkaline granites in the west and south seems to represent fossil conduits for mafic magmas, implying that the reverse zoning resulted from magma recharge episodes.

A multistage emplacement for the LSIC-granite pluton is strongly suggested from geological, geophysical and geochronological data. However, reconciling such idea with the previous petrological models is a hard task. The two contrasting granites were related either by in situ assimilation (Nardi, 1984) or by fractional crystallization-FC process (Vieira Jr. and Soliani Jr., 1989). To evaluate this we present new Sr-Nd isotopes, and major and trace elements on whole-rock (WR) samples of LSIC-granites.

GEOLOGICAL OVERVIEW

The nucleus facies include biotite granodiorites (BG) and amphibole-biotite monzogranites (ABM) that evolve to syenogranites (ABS). ABM-ABS also referred as hybrid terms form semicircular bodies around the core composed by BG (Fig. 1B). Alkaline granites show a polarized occurrence. Perthite granites (PG) predominate in the northwest, and biotite-amphibole syenogranites (BAS) in the south-southeast. All are isotropic facies including Fe-hornblende and Fe-biotite. The main accessories are Ti-magnetite, titanite, zircon and apatite.

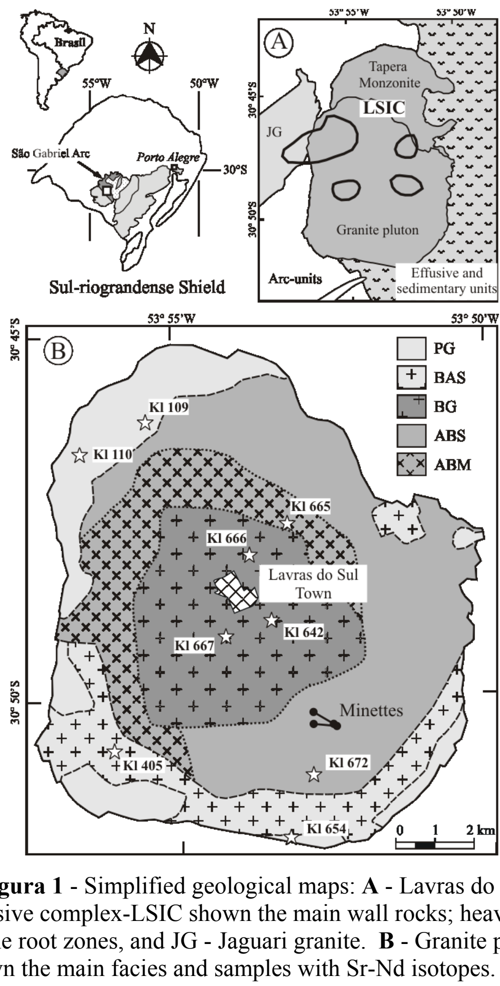

Figura 1 - Simplified geological maps: **A** - Lavras do Sul intrusive complex-LSIC shown the main wall rocks; heavy line for the root zones, and JG - Jaguari granite. **B** - Granite pluton, shown the main facies and samples with Sr-Nd isotopes. PG – perthite granite, BAS – alkaline syenogranite; BG – granodiorite; ABM-ABS – hybrid monzogranite to syenogranite.

Nucleus granites. The two groups of facies (BG and ABM-ABS) are fine to coarse-grained seriate, have similar mineralogical compositions, and the contacts between them are always gradational. They have calcic oligoclase and Fe-hornblende as *liquidi* phases indicating hydrous initial melts. FeO* (=FeO_t/ (FeO_t+MgO)) ratios of amphibole and biotite show moderate values (0.67-0.76), which remain constant or decrease slightly with increasing FeO^*_{WR}. Such behavior more pronounced in BG is attributed to oxidizing conditions during post-magmatic processes. BG contains more calcic plagioclase (An_{20-35}), biotite as the main mafic phase, and common ilmenite. It is texturally varied, including the dominant seriate type (BGS) and a more felsic porphyritic term (BGP) associated with discrete miarolitic cavities. Both, amphibole and titanite are frequent in ABM-ABS, and textural hybrid features are typical of ABM. Titanite has composition close to the end-member in BG-ABM, but it is Nb-Y-rich in ABS. Al-in amphibole geobarometer shows decreasing pressures during the crystallization of these facies from 4 to 2 kbars (Gastal and Lafon, 2005). The crystallization ages are of 601 ± 2 Ma (^{206}Pb-^{238}U) and 603.9 ± 2.2 Ma (^{207}Pb-^{206}Pb) for one sample of each, BGP and ABM respectively (Gastal et al., 2005b). In the two samples, inheritance records are well documented (610-627 Ma), and ages around 592-582 Ma probably related to a younger event also are significant.

Alkaline granites. The contacts between BAS and PG and with the nucleus types are sharp, but without chilling or locally gradational. The two facies have oligoclase/orthoclase as *liquidi* phases, dominant Fe-hornblende and late magmatic Fe-biotite. These features are consistent with more anhydrous, Ca-poor initial melts. $FeO^*_{AMP,\ BT}$ ratios increase regularly (0.76 to 0.96) with increasing FeO^*_{WR}, implying the mineralogical control in the redox path during the differentiation from BAS to PG, also marked by decreasing pressures (2-1 kbar). BAS is medium and coarse-grained heterogranular, and contains common REE-Nb-Y-rich titanite. A wide compositional range in plagioclase (An_{5-32}) suggests some kind of mixing in this facies. The main textural type of PG is medium or coarse-grained equigranular (PGE), in which Fe-hornblende evolves to Fe-barroisite, Fe-rich biotite is *subsolidus* and both fluorite and ilmenite are late-magmatic phases. Along the internal contacts, the PG shows a fine to coarse-grained seriate texture (PGS) and has more frequent oligoclase/albite, Fe-biotite and REE-Nb-Y-rich titanite. The crystallization ages are of 598 ± 3 Ma (^{207}Pb-^{206}Pb) and 586.0 ± 2.8 Ma (^{206}Pb-^{238}U) for respectively one sample of BAS and two of PG (Gastal et al., 2005b). In the latter, the ages around 599 Ma are due to zircons inherited from previous LSIC-events, and ages older than 609 Ma are uncommon.

GEOCHEMISTRY

New chemical analyses on twenty-three WR samples were done by XRF and ICP-MS for major and trace elements respectively. These data together with those from Nardi (1984) show that all facies are mostly metaluminous (ASI ~0.8-1.1, NK/A ~0.6-1.1). Similar values of DI (Σor+ab+q, normative) in the two groups of granites (90-97) suggest the proximity with eutectic compositions. Between the two, the differentiation is marked by the overall decrease of Al_2O_3, MgO and CaO, minor variations of TiO_2 and FeO_t, and increase of alkalis. The nucleus compared with alkaline types show higher contents of Ba and Sr, and lower of Rb, Nb, Y, Zr and REE. The Rb/Sr ratio best discriminates these granites since it distinguishes within the nucleus types, which show SiO_2 contents in a narrow range (Fig. 2).

The less evolved BG-ABM also show similar contents of Al_2O_3, CaO, alkalis, Ba and Sr. BG tends to lower TiO_2 and Rb/Sr, and a pronounced increase of TiO_2 and minor of Rb/Sr marks the transition up to ABM. Both, MgO and FeO_t behave similarly so that it is difficult to explain the chemical trends of BG-ABM through FC. They seem to represent distinct pulses as evidenced in the Rb/Sr *vs.* SiO_2 diagram (Fig. 2). K/Rb and Ba/Rb ratios also discriminate them, and thus BG compared with ABM-ABS would have evolved from a melt with lower Rb/Sr and higher K/Rb and Ba/Rb ratios. In both, Nb and Y concentrations are lower than those of the possible parental trachyandesitic magmas, which suggest incompatible element-poor sources or the amphibole fractionation. They also have low values of Zr and T_{ZR} (< 840°C), being the lowest T_{ZR} in BG (780-760°C). REE patterns marked by increasing LREE and MREE for nearly constant Eu contents are similar in the two. This apparently rules out FC processes, and suggests plagioclase in the residue during partial melting of quartzfeldspatic sources.

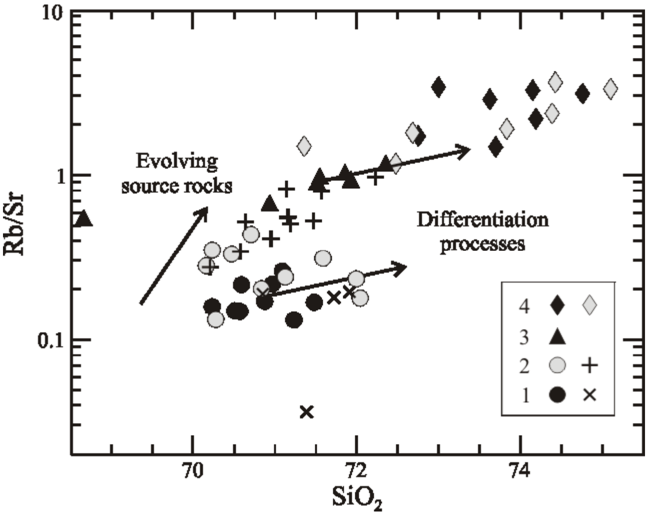

Figura 2 - Rb/Sr *vs*. SiO_2 (wt. %) diagram for LSIC-granites including data from Nardi (1984): 1 - seriate and porphyritic granodiorites (BGS-BGP); 2 - ABM and ABS, hybrid granites; 3 - alkaline syenogranites (BAS); and 4 - equigranular and seriate, perthite granites (PGE-PGS).

Within the hybrid facies (ABM-ABS), the evolution is consistent with FC processes as evidences the decreasing values of Al_2O_3, CaO, MgO, Sr and Ba, and the increase of SiO_2, alkalis and Rb. The variations are minor for TiO_2, FeO_t and REE, but a pronounced increase of Zr, Nb and Y occurs in ABS. It has higher values of T_{ZR} (> 830°C) like those of alkaline types. Such peculiar chemistry suggests the mixture with alkaline granitic melts during the crystallization of ABS. This explains the contrasts between the mafic and accessory phases.

In the alkaline BAS and PG, SiO_2 contents lie in a wider range (69-75 wt. %), and the differentiation trend is consistent with FC (Fig. 2). From BAS to PG, the contents of MgO, FeO_t, CaO, TiO_2, Al_2O_3, Sr, Ba and Eu show regular decrease, and those of alkalis, Nb, Y, Zr and REE increase, despite the scatter in the more evolved PG-samples. T_{ZR} also rises from 840°C to 920°C. The BAS has compositions superposed with ABS. Nevertheless, it shows lower MgO, Sr and Ba, higher alkalis, Rb, Nb and REE, and a less fractionated REE pattern.

Sr-Nd ISOTOPES

Rb-Sr and Sm-Nd WR isotopic analyses were performed according to the routine procedures at Pará-Iso/UFPA. Present day Sm-Nd isotopic ratios for both, DMM and CHUR (Chondritic Uniform Reservoir) are from Goldstein et al. (1984). Analyses were done on nine samples being five of the nucleus and four of alkaline types. Analytical uncertainties are quoted at a 2σ level.

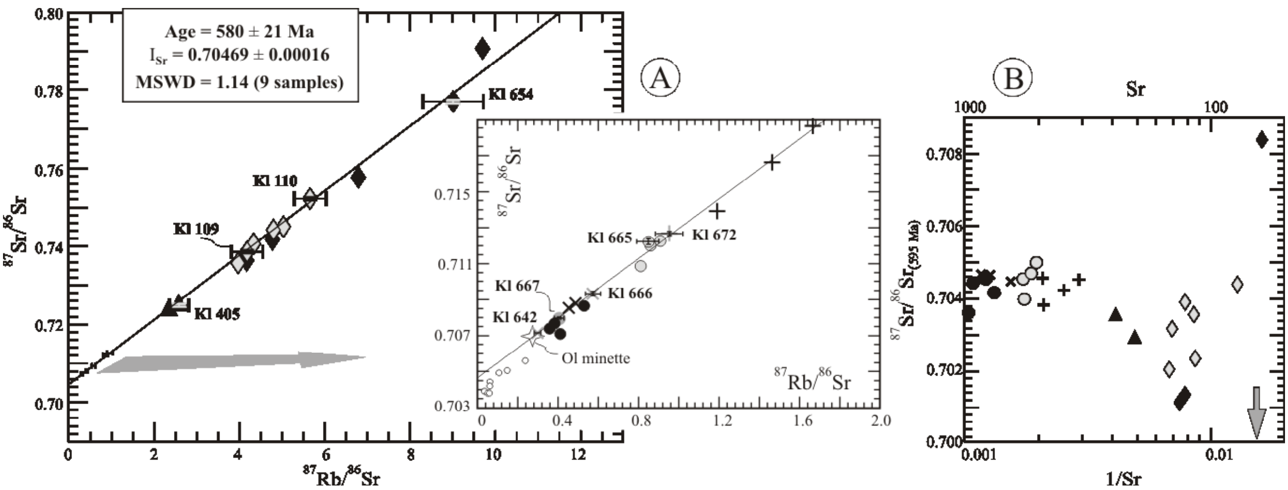

Figura 3 – Sr isotopes for LSIC-granites: (**A**) Rb-Sr isochron diagram shown the age calculated for nine samples. Analytical data for twenty-one samples from Soliani Jr. (1986) are indicated; white star and white small circle, both in the inset for respectively the olivine minette (Gastal and Lafon, 2005) and country granitoids and amphibolites (Leite, 1997); (**B**) $^{87}Sr/^{86}Sr_{(595\ Ma)}$ *vs.* 1/Sr. Arrow indicates two PGE-samples with the lowest $^{87}Sr/^{86}Sr_{(595\ Ma)}$ of ~ 0.68. Symbols as in figure 2.

Rb-Sr data. The regression line for Rb-Sr isotopic ratios of the nine samples define a linear array with some scatter of data yielding an age of 580 ± 21 Ma (MSWD of 1.1) (Fig. 3A). These data together with those from Soliani Jr. (1986) totaling thirty samples provide a result roughly similar (~573 Ma, MSWD of 2.4). The progressive rising in $^{87}Rb/^{86}Sr$ ratios allows distinguishing within the nucleus facies, and also between ABS and BAS. Seventeen samples of nucleus types yield an age of 594 ± 40 Ma (MSWD of 3.1), while an age of 606 ± 42 Ma (MSWD of 1.5) is obtained for thirteen samples from alkaline facies. Excluding one sample with the highest radiogenic ratio, the regression line for the latter yields an age of 574 ± 32 Ma (MSWD of 0.97). Most samples of the nucleus types show similar I_{Sr} ratios of ~0.7045, as also shown in the $^{87}Sr/^{86}Sr_{(595\ Ma)}$ *vs.* 1/Sr diagram (Fig. 3B). In BGS and ABM, however, some samples deviate (Fig. 3A). They have minor I_{Sr} (≤ 0.704) and hence the participation of older country rocks with a low I_{Sr} in their genesis is a viable explanation. For alkaline granites, I_{Sr} ratios are slightly lower (~0.7035 for BAS) and decrease with the differentiation towards PGE, but they tend to higher values in PGS (Fig. 3B). The largest variations of I_{Sr} in PGE are indicating disturbances in the isotopic system during late-magmatic processes.

The small difference in I_{Sr} (0.7045-0.7035) apparently points to similar source materials for the two groups of LSIC-granites. However, I_{Sr} show a slight negative correlation with common lead ratios (I_{Pb}), obtained on feldspar, from nucleus to alkaline types (Gastal and Lafon, 2005). This suggests the involvement of distinct sources providing an alternative for their genesis. Analogous mantle-derived parental magmas were progressively less contaminated by crustal sources during the formation of the pluton occurred in increments. The olivine minette that occurs as a dyke in LSIC is one of the best candidate for the parental magma. It has I_{Sr} of 0.7047, close to that of nucleus facies but higher I_{Pb} like the alkaline types (Gastal and Lafon, 2005).

Sm-Nd data. Isotopic ratios for the nine samples together with two from Babinski et al. (1996) define a poor-correlated array with a positive slope in the Sm-Nd isochron diagram. Regression for these data provides Meso to Paleoproterozoic ages (~2.0-1.2 Ga), reflecting mixtures of either crustal or mantle sources. Accordingly all facies show old T_{DM} ages (1.62-1.33 Ga) and negative

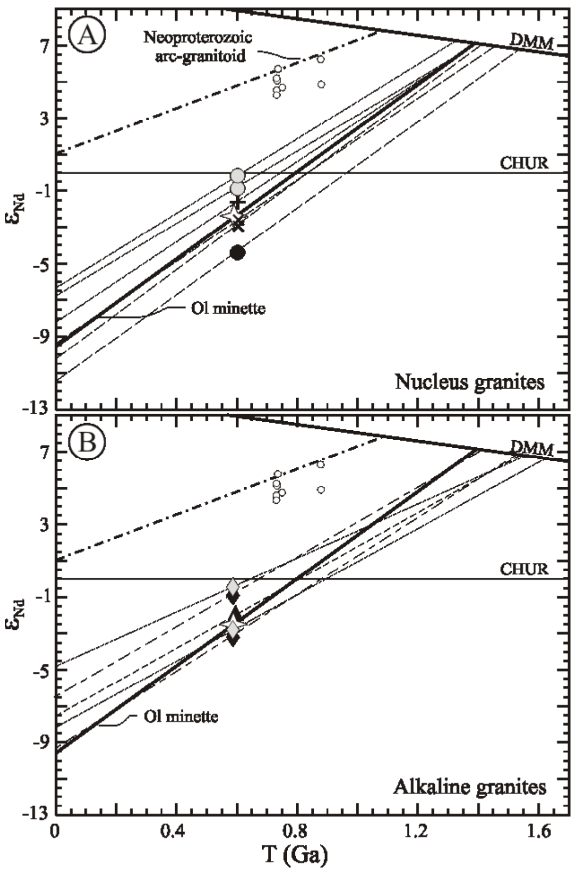

Figura 4 – Nd isotopic evolutionary diagrams for the nucleus (**A**) and alkaline (**B**) LSIC-granites, including also two samples from Babinski et al. (1996). Symbols as in figures 2 and 3.

ε_{Nd}(t), but the values of both are superposed for nucleus and alkaline granites suggesting that the two derived from a similar mixture (Fig. 4). However, the two show distinct values of $f_{Sm/Nd}$ reflected by different slopes in ε_{Nd}-growth lines, and this indicates differences in the generation processes or source materials. Nucleus facies show $f_{Sm/Nd}$ close to olivine minette, while a smaller fractionation is required for the genesis of alkaline types.

Further, the Nd isotopes unequivocally discriminate within the nucleus types (Fig. 4A). BG has lower ε_{Nd}(t)-values (-4.37 to -2.65) and older T_{DM} ages (1.54-1.42 Ga), and the increase of ε_{Nd}(t) marks the BGS-BGP evolution. ABM-ABS show higher ε_{Nd}(t)-values (-1.56 to -0.18), and younger T_{DM} (1.40-1.33 Ga), and the reverse occurs with differentiation. The more evolved terms of both have Nd isotopic ratios close to that of olivine minette. Such behavior then suggests mixing of this mantle magma with different crustal sources, whose records would be better preserved in the less evolved and restite-rich terms (BGS-ABM). ε_{Nd}–growth lines in the two groups are consistent with the modeling for binary mixing of source materials presented by Gastal et al. (2005a – Fig. 9), in which one end-member is a REE-enriched mantle-derived magma like the olivine minette. In such case, the small variations of ε_{Nd}-values in BGS and ABM may represent mixing of this magma with up to 70-80% of crustal rocks, including an older source in the genesis of BG and younger in ABM. The former would be similar to the lower crust in the region and the latter to Neoproterozoic country rocks (900-700 Ma), so this difference may explain the contrast in some trace element ratios (Rb/Sr, Ba/Rb and K/Rb).

Within alkaline granites, BAS-PGE show minor variations in T_{DM} (1.52 - 1.40 Ga) and ε_{Nd}(t) (-2.97 to -0.73), but PGS has older T_{DM} (1.62-1.56 Ga) for similar ε_{Nd}(t). Despite most samples have ε_{Nd}(t)-values like the olivine minette, all tend to older T_{DM} ages and have lower $f_{Sm/Nd}$ (Fig. 4B). This suggests that the alkaline granites derived from a distinct parental magma, or that their genesis also involved mixing with melts produced from a refractory crust residue.

FINAL CONSIDERATIONS

Sr-Nd isotopes and geochemical data allow improving the discrimination among the three groups of LSIC-granites. Despite the compositional similarity of the two nucleus types BG and ABM-ABS, trace elements and Nd isotopes show they represent distinct magma pulses. They formed probably through contamination of a mantle-derived magma like the olivine minette with a heterogeneous crust. The two show Pb inheritance and also low T_{ZR} (840-760°C) for M values (=Na+K+ 2Ca/Al*Si, cation fractions) in the same range than that of alkaline granites (~1.4-1.6). This classifies the two nucleus groups as cold, inheritance-rich granites (Miller et al., 2003), reinforcing that this type of granites results in some measure from melting of quartzfeldspatic rocks as argued by Chappell et al. (1998). FC processes may explain the ABM-ABS evolution, but some kind of mixture with alkaline granitic melts would have occurred at the emplacement level. The alkaline BAS and PG are hot, inheritance-poor granites (T_{ZR} > 840°C) according to Miller et al. (2003), and can represent the extreme fractionation at deeper levels of a mantle-derived magma like the olivine minette. However, the differences in Nd isotopes suggest a distinct parental magma or re-melting of crust residues. The latter also is consistent with the hot and inheritance-poor nature of alkaline LSIC-granites, and would be expected resulting from the latest events of magma recharge. In any case, it is possible to conclude that the LSIC-pluton formed through several episodes of recharge with roughly similar basic magmas and that the major crustal contribution apparently occurred in the less evolved facies placed above most roof zones. This suggests that during the initial events forming the pluton the emplacement occurred by cantilever-like mechanisms (Cruden and McCaffrey, 2001), and that the alkaline types were emplaced probably through incremental intrusions and widening along uncollapsed ring faults.

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RESUMO

São apresentados dados geoquímicos e isotópicos Sr-Nd para os granitos do complexo intrusivo Lavras do Sul-CILS, no sul do Brasil. Eles formam *pluton* concêntrico que inclui (núcleo-borda): granodioritos (BG), monzogranitos a sienogranitos híbridos (ABM-ABS), sienogranitos alcalinos (BAS) e pertita granitos (PG). Os dois primeiros estão no núcleo e foram formados durante os episódios iniciais (~605-601 Ma), e os últimos são alcalinos e formados em mais de um evento mais jovem (~598 a 586 Ma). Todos são metaluminosos e exibem conteúdos similares de elementos maiores, e as diferenças se referem aos traços. Os termos do núcleo exibem maior Ba e Sr, e menor HFSE, ETR e Rb. Os *trends* de diferenciação tanto entre os dois grupos contrastantes, como entre os tipos do núcleo não são consistentes com cristalização fracionada e sugerem pulsos de magma distintos. Todos tem I_{Sr} similar (0,7045-0,7035), T_{DM} mais antiga (1,62-1,33 Ga), e $\varepsilon_{Nd}(t)$ negativo (-4,37 to –0,18). Valores estes próximos daqueles do olivina minete que ocorre como dique, e que melhor representa o magma parental derivado de um manto rico em ETR. Maior participação crustal ocorreu nos tipos do núcleo classificados como granitos frios e ricos em herança (T_{ZR} 830°-760°C). Estes exibem valores de $f_{Sm/Nd}$ similar ao do olivina minete, e as diferenças nos isótopos de Nd sugerem que o BG e ABM resultaram da mistura deste magma com segmentos crustais diversos. Os alcalinos são granitos quentes e com pouca herança (T_{ZR} > 840°C). Eles exibem menor $f_{Sm/Nd}$, o que sugere magma parental distinto ou refusão de resíduos crustais.