GEOCHEMISTRY AND Nd ISOTOPIC EVIDENCE OF THE PENSAMIENTO GRANITOID COMPLEX, RONDONIAN-SAN IGNACIO PROVINCE, EASTERN PRECAMBRIAN SHIELD OF BOLIVIA: PETROGENETIC CONSTRAINTS FOR A PLUTONIC ARC

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INTRODUCTION

The Pensamiento Granitoid Complex (PGC) forms a large volume of gneisses and granites in the Bolivian departments of Santa Cruz and Beni and represents important area of the Rondonian- San Ignacio Province (RSIP) formed at 1,55 to 1,30 Ga, in the SW part of the Amazonian craton. The Rondonian- San Ignacio Province is characterized by a continental collision with a moderately large microcontinent, made up by a relatively thick continental crust, an accretionary regime very different to eastern neighbors Ventuari-Tapajós and Rio Negro Juruena provinces, which are tipified by a regime with soft-collision stacking of oceanic features (Teixeira *et al*. 2006; Cordani and Teixeira 2007).

The Pensamiento Granitoid Complex is made up of plutonic and subvolcanic granites, with subordinate syenites, granodiorites, tonalites, trondhjemites and diorites. The metamorphic basement consists of gneisses and granulites of the Lomas Maneches complex occurring in the southern border of our study area. The present work, of reconnaissance scale, was made along the road that joints Santa Rosa de la Roca and Piso Firme localities, covering a 330 km transverse in a large area of exposure of the PGC. This work aims to determine the Precambrian tectonic evolution of Eastern Bolivia and its relationship to Mesoproterozoic evolution of SW Amazonian craton. In this paper we present petrography and geochemistry evidence coupled with Sr-Nd isotopic results that contribute to the geologic knowledge of the area, and further to the tectonic evolution.

REGIONAL GEOLOGY

Before the SHRIMP U-Pb geochronological investigation reported by Boger *et al*. (2005), the classical knowledge of Bolivian Precambrian Metamorphic Basement comprised three units: the Lomas Maneches Granulitic Complex, the Chiquitania Gneissic Complex and the San Ignácio Schist Group.

Two tectonic events have been distinguished within the PGC: syn- to late kinematics granitoids and late to post –kinematics granitoids (Litherland *et al.* 1986). The syn- to late- kinematics granitoids are the La Junta and San Martin granites. The late- to post-kinematics granitoids were designed as San Cristóbal, Porvenir, and Diamantina granites. In this group we have included the Piso Firme Granophyre, although Litherland *et al*. (1986) classified the granophyres as syn/late tectonics. Similar syn, late and post-tectonic granites intruding the Colorado Complex are described by Rizzotto and Quadros (2007) in southeastern of Rondônia. In the PGC region the Metamorphic Basement is present in the southern contact between the Puerto Alegre/La Junta Granite. In this work, these rocks we recognized as Lomas Maneches Complex.

SHRIMP zircon U-Pb dating in the PGC yielded crystallization age of 1,34 Ga for the Diamantina Granite, 1,35 Ga for La Junta Granite and 1,37 Ga for San Martin Granite (Matos *et al*., in preparation). The recent SHRIMP zircon U-Pb analyses from the Pensamiento Complex are temporally related but different setting to the emplacement of rapakivi granites of Santo Antonio, Teotonio, and Alto Candeais suites in northern Rondonia (Teixeira *et al*. 2006). Up to now, the Bolivian Precambrian area remains at reconnaissance scale; ages, structures, and composition of rocks units and orogenic events in Bolivia are still poorly known.

METHODS

Thirteen samples were selected for major, minor and trace elements chemistry at Chemical Laboratory of Institute of Geosciences (University of São Paulo). The analytical routine of the laboratory comprises X-ray fluorescence spectrometry for the analysis of the major, minor and some trace elements. ICP-MS for the analysis of REE and some trace elements. Thirteen samples were analyzed by Sm-Nd whole-rock technique at the Geochronological Research Center (CPGeo) of the University of São Paulo, Brazil. The Sm and Nd concentrations were determined by isotope dilution with a combined spike tracer, using the two-column technique. The isotope ratios were measured on VG-354 multi-collector mass spectrometer. In addition, thirteen Rb-Sr whole rock analyses were carried out using isotope dilution technique, at the Geochronological Research Center (CPGeo) of the University of São Paulo, Brazil. Isotope ratios were measured on VG-354 multicollector and single collector mass spectrometers.

RESULTS

MAJOR AND TRACE ELEMENTS

Syn- to late-kinematic granitoids

Four samples of the La Junta Granite and one of the San Martin Granite show SiO_2 content from 69 to 77 %. Major oxides display regular trends of decreasing Al_2O_3, MgO, CaO and Fe_2O_{3Tot} with increasing SiO_2 content suggesting a general fractional crystallization process. Variation diagrams of Zr, Ba and Sr against SiO_2 show roughly decreasing of the trace elements with increasing SiO_2 probably due to zircon, feldspar and plagioclase separation from the evolving melts. The plot of Rb/Sr versus Sr/Ba shows a linear tendency for rocks suggesting again fractional crystallization. All samples are subalkaline and fall in the calc-alkaline field of the AFM diagram. The samples plot in the high-K calc-alkaline field with SiO_2 content higher than 69 %. The REE patterns of the La Junta and the San Martin granitoid samples are moderately fractioned in terms of LREE/HREE with a slightly negative Eu anomaly. One sample presents very different signature with no negative Eu anomaly, suggesting depleted source in REE, or fractionation with amphibole and/or allanite in the residue. The spider diagram presents steep patterns because the high LILE contents of these rocks. Negative peaks of Sr, P, and Ti suggest fractionation of feldspars apatite, and titano–magnetite and sphene, respectively.

Late- to post -kinematics granitoids

Major and trace elements data in eight samples display negative correlations for Al_2O_3, MgO, CaO and Fe_2O_{3Tot} with increasing SiO_2 content suggesting a general fractional crystallization process. All samples are subalkaline and fall in the calc-alkaline field of the AFM diagram. The Piso Firme Granophyre, Porvenir and San Cristobal granitoids have narrow range in the SiO_2 contents (from 74 to 76 %) whilst the samples plot in the high-K field. The Piso Firme Granophyre has metaluminous composition and the Porvenir and San Cristobal granitoid rocks are peraluminous. Regarding the REE patterns the Piso Firme, Porvenir and San Cristobal samples show low LREE fractionation, and subhorizontal tendency of HREE with negative Eu anomaly, probably reflecting plagioclase and/or feldspar fractionation process. They are slightly less enriched in LILE compared to the syn- to late-kinematic granitoids, and also have deeper negative peaks of Sr, P and Ti reflecting fractional crystallization. The Diamantina Granite shows SiO_2 content that ranges from 72 to 75 % and are plotted again in the high-K field and are placed on the peraluminous composition. In the REE patterns two different signatures can be distinguished: *i*) three samples show steep patterns compared with the Piso Firme, San Cristobal and Porvenir granitoid rocks, which is related with the high contents of LREE and depletion in HREE, probably reflecting amphibole fractionation and/or allanite. *ii*) One sample shows "gull wing-shaped" REE patterns with moderate negative Eu anomaly. In the multielement diagrams, the negative peaks of Sr, P, and Ti can be interpreted as fractionation of mica, feldspar, apatite, and Ti phases.

Nd-Sr ISOTOPES

Sm-Nd whole rock data of the syn- to late-kinematic San Martin and La Junta granitoid rocks yielded "normal" crustal differentiation $f_{Sm/Nd}$ ratios (-0,28 to -0,50), and the T_{DM} model ages are 1,68 Ga and between 1,87 to 2,04 Ga, respectively. The $\varepsilon_{Nd(1.33Ga)}$ was considered as a reference age according with the SHRIMP U/Pb zircon age for the San Rafael Granite (Boger *et al*. 2005). The $\varepsilon_{Nd(1.33Ga)}$ value for the San Martin Granite is +1,8 whereas the La Junta Granite shows a contrasting source given by the negative values between -2,9 to -4,3. The late- to post-kinematic San Cristobal, Porvenir and Piso Firme plutons show $f_{Sm/Nd}$ ratios between -0,31 and-0,25, T_{DM} model ages from 1,58 to 1,74 Ga, and positive $\varepsilon_{Nd(1.33Ga)}$ values of +2,7 to +1,5. In a similar way the Sm-Nd data of the Diamantina Granite displays T_{DM} model ages between 1,65 and 1,92 Ga ($f_{Sm/Nd}$ ratios between -0,50 and -0,25), and $\varepsilon_{Nd(1.33Ga)}$ values from +0,4 to -1,2. From the above the PGC rocks display Nd signatures compatible with mixing of mantle derived and short crustal residence components in the petrogenetic process. The plot of Nd (ppm) contents versus the $\varepsilon_{Nd(1.33Ga)}$ clearly discriminate three different isotopic fields: *i*) the syn- to late kinematic La Junta samples have Nd (ppm) contents from 22 to 100 and $\varepsilon_{Nd(t)}$ values from -2,9 to -4,3, implying crustal derivation. In contrast, the San Martin sample has Nd value of 108 ppm and $\varepsilon_{Nd(t)}$ of +1,8; *ii*) the late- to post-kinematic samples suggest a predominant juvenile derivation given by the positive $\varepsilon_{Nd(t)}$ values from +2,7 to +1,5 and Nd from 30 to 80; *iii*) the Diamantina Granite yielded a Nd content between 23 to 78 ppm and $\varepsilon_{Nd(t)}$ values from +0,4 to -1,2 indicating the role of mantle component but minor crustal contribution in the petrogenetic process. All the $^{87}Sr/^{86}Sr$ ratios have been similarly calculated for the $\varepsilon_{Nd(1.33Ga)}$reference age (Boger *et al*. 2005). The data indicate a mantle component in their genesis, and crustal mixing for the Diamantina granite. The syn- to late-kinematic La Junta and San Martin samples yield roughly comparable $^{87}Sr/^{86}Sr_i$ ratios from 0,7039 to 0,7061 but contrasting $\varepsilon_{Nd(t)}$ values implying derivation from mixing sources, as previously stated. The late- to post kinematic plutons (including the Diamantina pluton) show a larger variation in $^{87}Sr/^{86}Sr_t$ ratios from 0,7017 to 0,7066 and mostly positive $\varepsilon_{Nd(t)}$ values. This reinforces the important role of Mesoproterozoic mantle source in the magma genesis of these rocks.

DISCUSSION AND FINAL REMARKS

The PGC comprises rocks that have been distinguished as syn- to late-kinematic and late- to post-kinematic granitoid rocks. The San Martín Granite yielded crystallization age of 1.373 ± 20 Ma; La Junta Granite yielded 1.347.±.21 Ma and the Diamantina Granite yielded 1.340. ±.20 Ma. As already seen, the PGC rocks display Nd-Sr isotopic features suggestive that different sources contributed to the magma genesis, which is consistent with the trace element compositions. The La Junta Granite has $^{87}Sr/^{86}Sr_i$ ratios of 0,704 to 0,706, older T_{DM} ages (1,87 to 2,04 Ga) and negative ε_{Ndt} values (-2,9 to -4,3) favoring a significant contribution from crustal material corroborated by the recognized negative Nb and Ta anomalies in the spidergram. However, the syn- to late-kinematic San Martin pluton has initial $^{87}Sr/^{86}Sr$ ratio of 0,704, T_{DM} age of 1,68 Ga and $\varepsilon_{Ndt)}$ value of +1,8 that indicates significant mantle contribution in the genesis. The Diamantine Granite shows initial $^{87}Sr/^{86}Sr$ ratios that range between 0,702 and 0,704, T_{DM} ages from 1,6 to 1,9 Ga and ε_{Ndt} values of +0,4 to -1,2 indicating an origin by mixture of magmas derived from depleted mantle and homogeneous crustal source. These isotopic features agrees well with the scenario of island arcs culminating with continental collision at *ca* 1,33 Ga against the RNJP, as recently proposed for the Rondonian-San Ignacio province by Cordani and Teixeira (2007).

The PGC rocks show a general fractional crystallization trend. The subordinate intermediate compositions as tonalites, diorites in the PGC can be raised to support fractionation model. In contrast the peraluminous, silica-rich compositions and isotope data of some PGC rocks would be explained by partial melting of the lower crust, in agreement with the Nd evidence. On the basis of integrated geological, geochemical and isotopic data we are able to consider the La Junta plutons (syn- to late kinematic) as I-Caledonian type granites, represented by batholiths related to infracrustal melts linked with subduction of oceanic lithosphere beneath the tectonically stable foreland. Nevertheless most of the investigated late- to post-kinematic rocks originated from juvenile sources as suggested by the Nd/Sr signatures.The syn- to late- kinematic San Martin and La Junta granitoids (1.373 ± 20 to 1.347 ± 21 Ma) display similar patterns in terms of geochemistry, petrography, structure and U/Pb age with the granite intrusions (1.340 ± 5 Ma) genetically associated with gabbros, amphibolites of the Colorado Complex (Rizzotto and Quadros 2007), in Rondônia state, constraining the major magmatic and metamorphic event of the Rondonian-San Ignacio province. Both felsic rocks are calc-alkaline, high-K, metaluminous to peraluminous. Whereas the Nd isotopic features of the Colorado felsic-mafic intrusions (Teixeira *et al*. 2006; Rizzotto and Quadros 2007). T_{DM} model ages between 1,51 to 1,58 Ga and $\varepsilon_{Nd(t)}$ value of +2,3 comparable well with that of the San Martin granitoid; they are distinct from the La Junta isotopic features. The late- to post-kinematic Porvenir, San Cristobal, Piso Firme and Diamantina granitoid (1.340 ± 20 Ma) are comparable in age with the Alto Candeais Intrusive Suite (U-Pb age 1.346 Ma; 1.338 Ma) (Bettencourt *et al*. 1999; Payolla *et al*. 2002). According with three scenarios for collisional orogenies envisaged by Condie (1997) we can consider for the PGC the final collision of two continents the Paraguá block with the RNJP that originate the Rondonian-San Ignácio orogeny (Cordani and Teixeira, 2007).

In summary, the evidence indicates that the late- to post-kinematic granitoids including the Diamantina Granite (Sm-Nd T_{DM} age of 1,58 to 1,92 Ga) show juvenile like Nd signatures, this strongly support a plutonic arc setting in which a "fertilized" mantle would be expected as a matter of fact. If this is correct, the Porvenir, San Cristobal, Diamantine and Piso Firme granitoids bear the most primitive signature of such plutonic episodes among the plutons investigated. As such the San Ignacio orogeny in Bolivia is roughly comparable with the tectonic and magmatic events named as Rondonian-San Ignacio orogeny, as recognized in the Brazilian counterpart. Finally, we consider that the Bolivian Precambrian shield plays a role in any effort to better understand not only the Rondonian-San Ignacio but also the Sunsas-Aguapei provinces, and thus we strongly recommend and encourage further geochronological and chemical studies in the r*egion.*

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