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# Gravimetric, radiometric, and magnetic susceptibility study of the paleoproterozoic Redenção and Bannach plutons: implications for architecture and zoning of A-type granites

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**Abstract** The 1.88 Ga, anorogenic, A-type Redenção and Bannach granites, representative of the Jamon suite, and associated dikes, are intrusive in Archean granitoids of the Rio Maria Granite-Greenstone Terrane in the eastern Amazonian craton. The Redenção and the northern part of Bannach plutons are normally zoned and were formed by two magmatic pulses: (1) a first magma pulse was fractionated in situ after emplacement at shallow crustal level generating a series of coarse, even-grained monzogranites with variable modal proportions of biotite and hornblende; (2) a second, slightly younger, located to the center of the plutons, was composed of a more evolved liquid from which even-grained leucogranites derived. Gravity modeling indicates that the Redenção and Bannach plutons are sheeted-like composite laccolithic intrusions, ~6 km and ~2 km thick, respectively. These plutons follow the general power law for laccolith dimension and are similar in this respect to classical rapakivi granite plutons. Gravity data suggest that the growth of the northern part of the Bannach pluton results of the amalgamation of smaller sheeted-like plutons that intruded in sequence from northwest to southeast. The Jamon suite plutons were emplaced in an extensional tectonic setting and the stress was oriented approximately along NNE-SSW to ENE-WSW, as indicated by the occurrence of diabase and granite porphyry dyke swarms, orientated WNW-ESE to NNW-SSE and coeval with the Jamon suite. The inferred tabular geometry of the studied plutons and the high contrast of viscosity between the granites and their Achaean country rocks can be explained by magma transport via dikes.

*Keywords*: Gravity; magmatic zoning; laccolith; anorogenic; Amazonian craton.

**INTRODUCTION** The 1.88 Redenção and Bannach plutons are magnetite-bearing, A-type granites of Paleoproterozoic age. They intrude the Archean rocks of the Rio Maria Granite-Greenstone Terrane in the eastern part of the Amazonian craton in northern Brazil. The Archean crust remained stable until 1.88 Ga when an episode of distension and underplating led to the generation and emplacement of A-type granites (Jamon Suite) and associated mafic and felsic (Dall'Agnol *et al.* 1999). The mineralogy, geochemistry, and petrology of the Jamon suite granites are relatively well studied (Dall'Agnol *et al.* 1999, 2005, Dall'Agnol & Oliveira submitted). However the internal zoning, tridimensional shape and emplacement history of its plutons needed additional investigation. Aeroradiometric (gamma ray) surveys and magnetic susceptibility data were associated with field, petrographic, and geochemical data to put in evidence their internal zoning. In parallel, it was carried out a gravity survey on the mentioned plutons. Tridimensional modeling provided an estimate of the mass distribution at depth and allowed estimation of the shape and thickening of the plutons. The new geophysical data acquired in the Redenção and Bannach plutons enable a re-interpretation of their magmatic evolution and is employed as a basis for an initial discussion about the mechanisms of their emplacement.

**GENERAL ASPECTS OF THE STUDIED PLUTONS** The Redenção and Bannach plutons are unfoliated and deformational structures are practically restricted to fracturing and faulting. Magmatic foliation is only locally developed on the border. Both granite intrusions are subcircular and remarkably discordant cross-cutting the E-W or NW-SE earlier structural trends of the Archean country rocks (Fig. 1a, b). The Bannach pluton was interpreted as composed of at least three independent near-circular intrusions, migrating from north to south (Almeida 2005). Angular xenoliths of Achaean rocks are commonly observed near the margin of the plutons, indicating a high viscosity contrast between the magmas and the Achaean bedrock. The country rocks are strongly affected by hornblende hornfels contact metamorphism and suggest that these plutons were emplaced at shallow crustal levels (~1 to 3 kbar, Dall'Agnol *et al.* 2005). Swarms of mafic, intermediate, and felsic dykes are associated with the Jamon Suite.

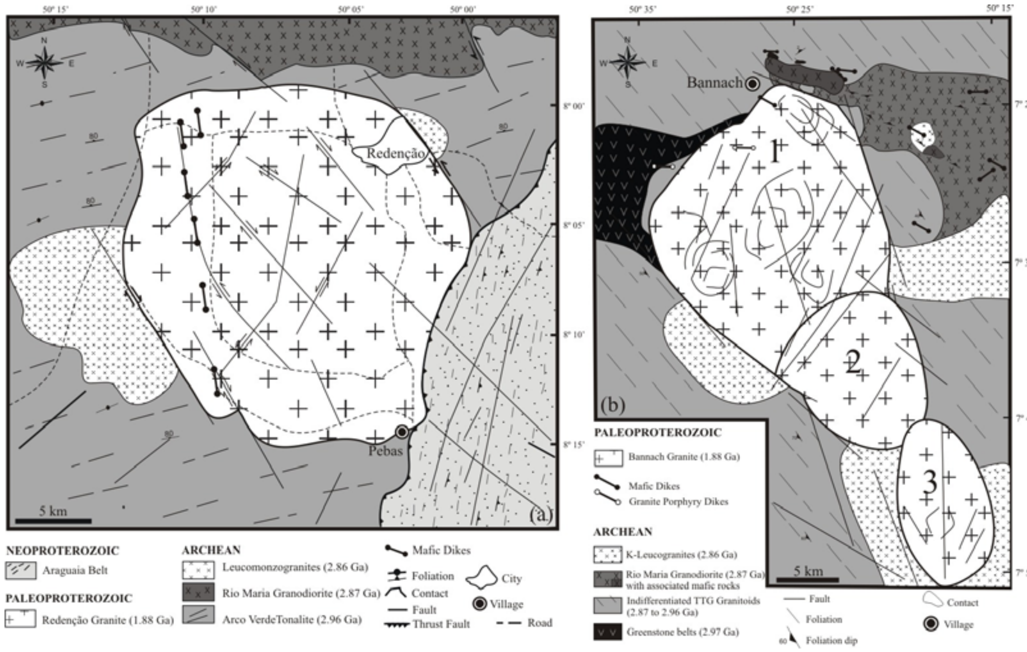


*Figure 1. Detailed geological map of the (a) Redenção (Oliveira, 2001) and (b) Bannach (Almeida, 2005) plutons. 1, 2, and 3 indicate the successive intrusions of the Bannach pluton*

A composite mafic-felsic dike cutting Archean sanukitoid granodiorites was described (Dall'Agnol *et al.* 2005). In this composite dike, a rhyolite porphyry shows evidence of mingling with an associated mafic dike, demonstrating that the mafic and felsic magmas were contemporaneous. The felsic dikes yielded Pb-Pb zircon ages of 1885±4 Ma and are coeval with the granitic plutons, demonstrating that the latter were emplaced in an extensional tectonic regime.

**ZONING OF THE PLUTONS Petrographic and geochemical data** The petrography and the magmatic evolution of the Redenção and Bannach granites were discussed by Oliveira *et al.* (in press) and Almeida (2005), respectively. These plutons consist of several intrusive phases disposed in near-concentric zones and cut by syenogranite dikes. In the Redenção granite, the less evolved rocks are even-grained, coarse biotite+hornblende monzogranites, locally enriched in cumulatic amphibole ± clinopyroxene, which occurs in the southern part of the pluton. They grade to the interior of the pluton to dominantly coarse-grained, equigranular, seriated or porphyritic biotite monzogranites. The seriated and porphyritic biotite monzogranite facies are intrusive in the coarse- even-grained (hornblende)-biotite monzogranite and configure annular structures in the central and southern areas of the pluton. In the central part of the pluton, evolved leucogranites define small circular structures (Fig. 2a). Aplitic dikes are common and coincide in orientation with the main NE-SW and NW-SE faulting system.

The internal zoning of the northern intrusion of Bannach (Fig. 2b) is similar to that of the Redenção pluton. However, in the Bannach pluton, some significant differences are worthwhile: the (clinopyroxene)-amphibole-bearing, less evolved monzogranites are more abundant and show a regular distribution occurring along all pluton margins; the coarse-equigranular and the medium- to coarse-grained seriated biotite monzogranites are not found; four pulses of leucogranites, situated generally towards the central parts of the pluton, have been identified; the porphyritic biotite monzogranites are disposed as NE-SW elongated discordant bodies, cutting the other facies; felsic granitic dikes are systematically associated with the porphyritic monzogranites (Fig. 2b).

The magmatic zoning is marked in both plutons by the systematic decrease of modal mafic mineral content (25% to < 5%), plagioclase/potassium feldspar and amphibole/biotite ratios and anorthite content of plagioclase ($An_{32-15}$) from the (clinopyroxene) + amphibole + biotite monzogranite toward the leucogranites. On the other hand, the abundance of alkali feldspar and quartz increases towards the inner zone. $TiO_2$, MgO, $FeO_t$, CaO, $P_2O_5$, Ba, Sr, and Zr decrease, and $SiO_2$, $K_2O$, and Rb increase in the same way. Magmatic differentiation was controlled by fractionation of early crystallized phases, including amphibole ± clinopyroxene, andesine to calcic oligoclase, ilmenite, magnetite, apatite, and zircon. Negative Eu anomalies increased with differentiation.

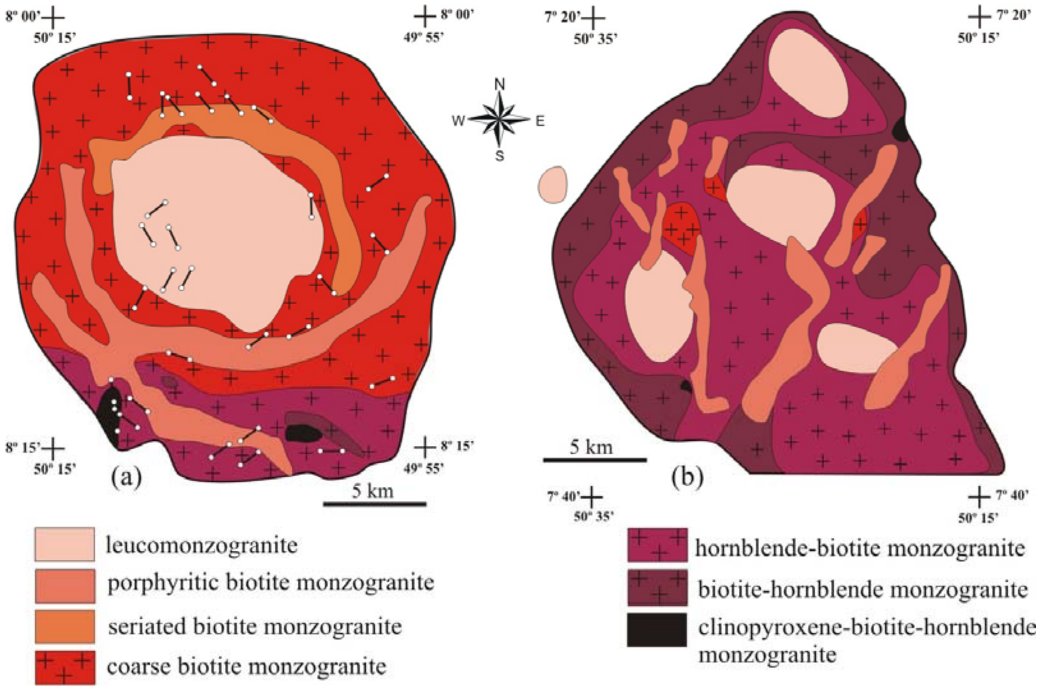


*Figure 2. Sketch geological map of the (a) Redenção (Oliveira, 2001) and (b) Bannach (Almeida, 2005) plutons showing the areal distribution of granitic facies*

Fractional crystallization was the dominant process of magmatic evolution of the plutons. Nevertheless, magma mingling processes had also influenced the evolution of this granitic pluton. The leucogranite facies of both plutons were interpreted as probable late, independent injections of evolved, felsic magmas (Oliveira 2001, Almeida 2005).

**Magnetic susceptibility data** In the Redenção and Bannach plutons, the bulk magnetic susceptibility (K) shows similar values, varying between $1.05 \times 10^{-3}$ and $54.72 \times 10^{-3}$ SIv with an average of $11.55 \times 10^{-3}$ SI in the Redenção pluton (Oliveira *et al.* 2002), and between $1.07 \times 10^{-3}$ and $72.74 \times 10^{-3}$ with an average of $9.26 \times 10^{-3}$ in the Bannach pluton (Almeida 2005). Magnetite is always dominant over ilmenite and modal contents of Fe-Ti oxide minerals vary between 3.5 and 0.4 % in the Redenção, and between 3.8 and ~0.1% in the Bannach pluton. Both granites are typical magnetite series ferromagnetic granites (Ishihara 1981, Ferré *et al.* 2002). Average MS values decrease from the (clinopyroxene)-amphibole-biotite monzogranites to the biotite monzogranites, attaining the lowest value in the leucomonzogranites. In Bannach, this implies decrease of MS from the border to the center of the pluton with a normal and concentric zoning (Fig. 5b; Almeida 2005); in the Redenção pluton, the highest MS values are concentrated in the southern part of the pluton, decreasing to the NE and mid-central domains, the lowest MS values being found in the center of the intrusion (Oliveira *et al.* 2002). The MS behavior is consistent with the pattern indicated by petrographic and geochemical data.

**Remote sensing and aerogamma spectrometry** In the interior of the studied plutons, the SRTM/U product showed clearly higher gamma U activities in the central areas of the intrusions compared to their borders. Similar positive gamma anomalies are also indicated by Th in the central parts of the massifs (Oliveira *et al.* submitted). The gamma anomalies in the plutons are coincident with the area distribution of their more evolved, generally leucogranitic facies. These rocks are enriched in K, Th, and U, explaining their radiometric contrast with the more mafic biotite-amphibole monzogranites, dominant in the border of the plutons. Thus, the aerogamma spectrometry gives useful information for the understanding of the internal magmatic zoning in the plutons.

**GRAVITY METHOD Gravity survey** In the Bannach area, gravity was measured at 147 stations following approximately north-south and east-west trending traverses on the Bannach pluton and its neighboring country rocks. The distance between gravity stations are about 500 m and 1000 m, in the border and in the center of the pluton, respectively. A Lacoste-Romberg Model G gravity meter, with a precision of ±0.01 mGal, was employed for measurements. A reduction density of 2.67 g/cm$^3$, was used to perform the Bouguer corrections. The gravity response a regional field, approximated by a first-order polynomial has been removed from the data along each traverse, where necessary, in order to produce an anomaly falling off to zero at both ends of the profile. The results of gravity surveying of the Redenção pluton presented here constitute part of a larger scale gravity exploration campaign accomplished by Mineração Jenipapo (Western Mining Company – WMC) on an area covering the border between the eastern Amazonian craton and the Brasiliano Araguaia Belt. 135 observations were collected along roads crossing the Redenção pluton and adjacent country rocks, with a constant spacing of 1 km between the stations. The gravity meter was a Scintrex CG3 Autograv Meter with a precision of 0.01 mGal.

**Tri-dimensional shape of the plutons** The mathematical details of the gravity inversion method are presented in Silva and Barbosa (2006) and details of the gravity modeling are described in Oliveira et al. (submitted). A remarkable feature of both plutons, disclosed by the gravity inversion, is that they exhibit a lateral extension substantially larger than vertical one, outlining a sheeted geometry (Fig. 3). According to the assumed density contrast between the granites and their country rocks (- 0.09 ± 1 g/cm$^3$), a maximum thickness values of 5.6 km and 2.2 km, respectively, for the Redenção and Bannach plutons, with a progressive thinning from the center to the borders, is necessary to explain the gravity anomaly. In the former, the main concentration of granitic mass is situated in the central to northeastern part of the intrusion. In the latter, it is located in the central-northern and southern areas of the intrusion (Fig. 3).

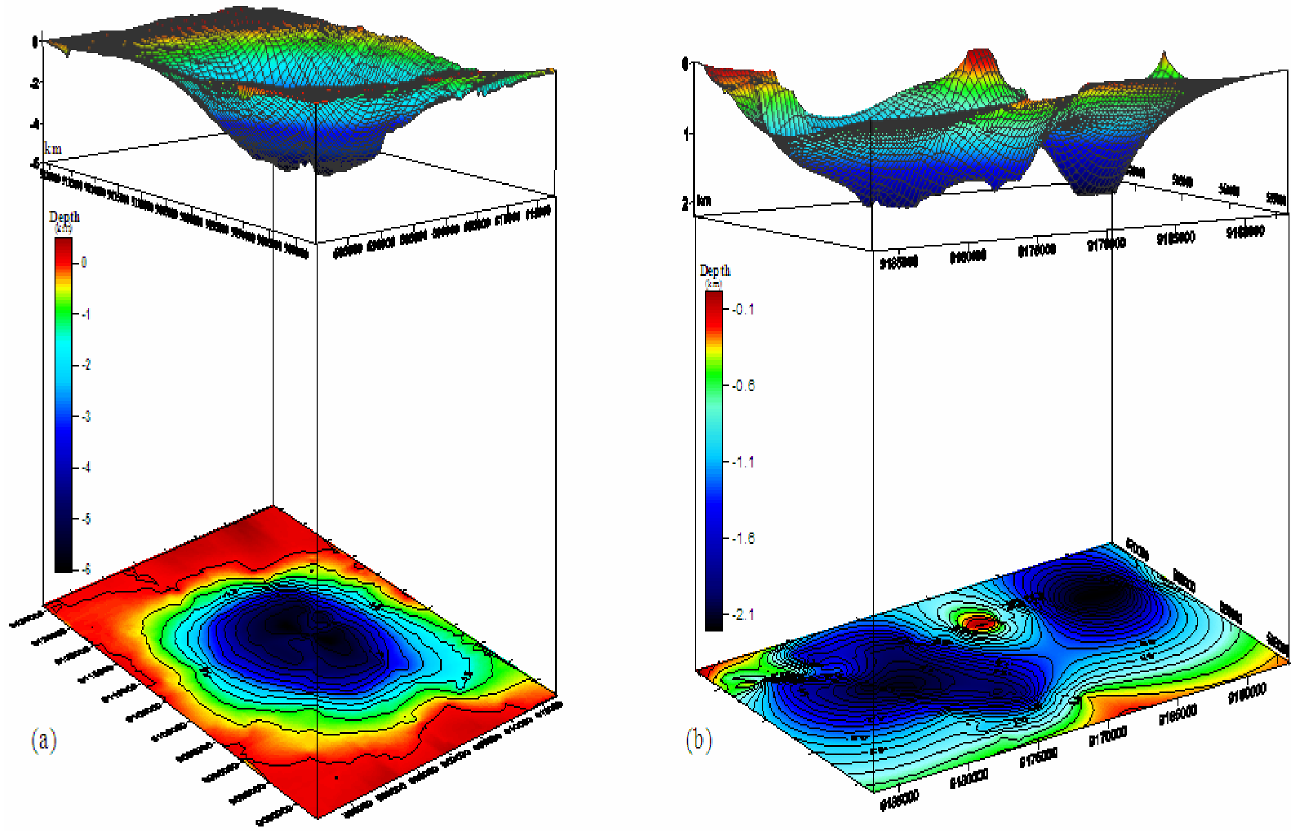


*Figure 3. Perspective views of the three-dimensional geometry of the Redenção and Bannach plutons through gravity data analysis associated with depth maps (in km) (a) Redenção pluton. View from SW to NE. (b) Bannach pluton. View from WNW to ESE*

From the contour map of the Redenção massif's depth, draw from the gravity inversion (Fig. 3a), it can be seen that the overall trend is a progressive deepening of the floor of the pluton from its border to its center. Gravity data provides, therefore, strong evidence that the Redenção intrusion has a laccolithic shape (Fig. 3a). In the Bannach pluton, the gravity survey was restricted to its northern and central parts that correspond to the first intrusion and to part of the second intrusion that compose the pluton (Almeida 2005). The different gravimetric cross sections suggest that the pluton is also a laccolith. However, it differs from the Redenção because of its smaller thickness, being only locally thicker than 2 km (Fig. 3b). Besides, the gravity data revealed the existence of a gravity high, approximately coinciding with the limit between the first and second intrusions. A gravity high is also identified along the western border of the first intrusion. It reinforces the hypothesis of an origin of the pluton by multiple sequential intrusions, evolving from the north to the south. The steep increase of the gravity response is a strong evidence of a shallow contact between the granite and the country rocks in the mentioned areas. It is concluded that the general shape of the Bannach pluton is similar to that of the Redenção pluton, but they differ in thickness (Fig. 3). The origin by sequential multiple center intrusion is also a distinct aspect of the Bannach pluton not observed at Redenção.

**CONCLUSIONS** At the end of Paleoproterozoic times (~1.88 Ga), the Amazonian Craton recorded a tectonothermal event that resulted in major lithospheric reorganization associated with mantle upwelling, mafic underplating, crustal extension, and emplacement of "anorogenic", A-type granites. Petrographic and geochemical aspects associated with magnetic susceptibility and gamma-ray spectrometry data showed that the Redenção and the northern part of Bannach plutons are normally zoned. They were formed by two magmatic pulses: a first pulse, resulting in a fractionation series of coarse, even-grained monzogranites with variable modal proportions of biotite and hornblende; a slightly younger pulse, located to the center of the plutons, composed of even-grained leucogranites.

Composite 2-D gravity inversions along profiles allowed us to determine the approximate 3-D geometry of these massifs that correspond to sheet-shaped laccolithic intrusions (Rocchi *et al.* 2002, Araguren *et al.* 2003). The studied plutons follow the general power law for laccolith dimension (Mcffrey & Petford 1997, Cruden 2005), and their dimensional ratios are similar to those observed in classical rapakivi granite batholiths (Vigneresse 2005). Gravity data suggest that the growth of the northern part of the Bannach pluton results of the amalgamation of smaller sheeted-like plutons that intruded in sequence from northwest to southeast. This is consistent with evidence that the Bannach pluton is a composite intrusion formed by at least three coalescent plutons (Almeida 2005).

The occurrence of diabase and granite porphyry dyke swarms, orientated WNW-ESE to NNW-SSE and coeval with the Jamon suite, demonstrates that, at that time, the tectonic extensional stress was oriented approximately along NNE-SSW to ENE-WSW. The 1.88 Ga A-type granite plutons and stocks of Carajás are disposed along a belt that follows the general trend defined by the dikes. The inferred tabular geometry of the studied plutons and the high contrast of viscosity between the granites and their Archean country rocks are not consistent with diapiric or ballooning models (Castro *et al.* 1987, Cruden 1990, 2005, Barros *et al.* 2001), but can be explained by magma transport via dikes (Petford 1996).

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