Gravimetric, radiometric, and magnetic susceptibility study of the Paleoproterozoic Redenc¸a˜o and Bannach plutons, eastern Amazonian Craton, Brazil: Implications for architecture and zoning of A-type granites

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Abstract

The 1.88 Ga, anorogenic, A-type Redenc¸a˜o 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 in northern Brazil. Petrographic and geochemical aspects associated with magnetic susceptibility and gamma-ray spectrometry data show that the Redenc¸a˜o and the northern part of Bannach plutons are normally zoned. They 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; and (2) a second, slightly younger magma pulse, 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 Redenc¸a˜o and Bannach plutons are sheeted-like composite intrusions, approximately 6 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 resulted from 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 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 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 can be explained by magma transport via dikes.

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1. Introduction

During the past two decades, Proterozoic, A-type granites, dominantly rapakivi, have been described from many Precambrian shield areas, such as North America (Anderson and Bender, 1989; Emslie, 1991; Barnes et al., 2002; Anderson and Morrison, 2005), Fennoscandia (Haapala and Rämö, 1990; Rämö and Haapala, 1995; Kosunen, 2004), and the Amazonian Craton (Bettencourt et al., 1999; Dall’Agnol et al., 1999a, 2005). In the Amazonian Craton, felsic volcanic rocks and mafic and charnockitic plutonic rocks are also associated with rapakivi granites (Bettencourt et al., 1999; Dall’Agnol et al., 1999a; Fraga, 2002).
A-type, rapakivi granites show a pronounced peak in the Proterozoic (~1.88–1.0 Ga) and a bimodal mafic-felsic magmatic association (Ramö, 1991; Ramö and Haapala, 1995). The Proterozoic A-type granites also reveal large variation in their redox behavior, ranging from reduced to oxidized (Haapala and Ramö, 1990; Frost and Frost, 1997; Frost et al., 1999; Elliott, 2001; Anderson and Morrison, 2005; Dall’Agnol and Oliveira, 2007) and thus show evidence of substantial variation in crystallization conditions and source composition.

The tectonic setting of the Proterozoic A-type, rapakivi granites has remained an issue of controversy. The classic Proterozoic rapakivi granites are associated with mafic dike swarms, listric shear zones, and thinned crust (Ramö and Haapala, 1995). They were intruded into a crust that predates them by some hundred million years (e.g., Ramö and Haapala, 1995; Ramö et al., 2002; Dall’Agnol et al., 2005) and are found as discordant multiple plutons, which indicates an extensional tectonic setting and anorogenic origin (lack of direct association to convergent processes and resulting mountain building; Haapala and Ramö, 1999). However, other authors suggest that rapakivi granites could be related to distal orogenesis (Ahäll et al., 2000). Rapakivi granites and related “anorogenic” granites have become important tools for modeling Precambrian intra-plate crustal processes and global-scale lithospheric evolution. An origin associated with crustal anatexis promoted by magmatic underplating is generally admitted (Huppert and Sparks, 1988; Ramö and Haapala, 1995; Dall’Agnol et al., 1999a).

Another common feature of the A-type granite plutons is their internal compositional zoning (Paradella et al., 1998; Costi et al., 2000; Rajesh, 2000; Teruiya, 2002; Richardson, 2004); generally, they are more mafic at the margins and grade inward, with or without discontinuities, to more felsic zones (near normal zoning). Reverse zoning (more mafic core than outer zones) may also be observed (Ceci and Frederick, 2002) but is most common in calc-alkaline granitoïd plutons (Zorpi et al., 1989; Paterson and Vernon, 1995). Generally, the zoned plutons are interpreted as having been intruded in a continuous series of magmatic pulses, leading to in situ growing of the pluton (Bateman and Chappel, 1979; Pitcher, 1979; Zorpi et al., 1989; Petford, 1996). Their cores formed by subsequently emplaced, more mobile, differentiated rocks. In the case of anorogenic granites, neither the mechanisms nor the timing for zoning development are entirely understood.

Deep seismic sounding studies in the classical Wiborg rapakivi batholith indicate that it is a shallow, sheeted-like intrusion with associated mafic intrusions in deeper crustal levels (Ramö et al., 1994). The common occurrence of granite intrusions as sheet-shaped bodies is now recognized (Rocchi et al., 2002; Aranguren et al., 2003; Pons et al., 2006), and models of the formation of such intrusions have been discussed (Román-Berdiel et al., 1995). The classic diapiric models for granite intrusion (Ramberg, 1970; Weinberg, 1996) have been criticized, and the role of dikes in the ascent of felsic magmas was emphasized (Clemens and Mawer, 1992; Petford et al., 1994; Petford, 1996).

Proterozoic A-type granites have been described from the Archean Rio Maria region in the eastern Amazonian Craton in Brazil (Dall’Agnol et al., 1999b, 2005). The Jamon Paleoproterozoic A-type granite suite has been dated at 1.88 Ga and was intruded into an approximately 3 Ga old crust characterized by greenstone belts and granitoid rocks. The Archean crust remained stable until the 1.88 Ga granite magmatism commenced. The Jamon suite is formed by the Redencão, Bannach, Jamon, Musa, Marajoara, Manda Sata, Seringa, São João, and Gradaus plutons (Fig. 1b). These granites are usually undeformed, shallow-level plutons associated with bimodal dyke swarms, locally forming composite mafic-felsic dikes. They are high-K granites with subalkaline A-type chemistry, show a pronounced oxidized character (Dall’Agnol et al., 2005; Dall’Agnol and Oliveira, 2007), and display many characteristics of the oxidized, mid-Proterozoic A-type granites of the western United States (Anderson and Bender, 1989; Barnes et al., 2002; Anderson and Morrison, 2005).

The mineralogy, geochemistry, and petrology of the Jamon suite granites are relatively well studied (Dall’Agnol et al., 1999b, 2005; Almeida, 2005). However, the internal zoning, tridimensional shape, and emplacement history of its plutons needs additional investigation. Airborne magnetic and radarsat image analysis provide an integrated view of the regional geological features of the area of the Redencão and Bannach plutons. Aeroradio-metric (gamma ray) surveys and magnetic susceptibility data are associated with field, petrographic, and geochemical data to clarify their internal zoning. In parallel, a gravity survey on the mentioned plutons is conducted. Tridimensional modeling provides an estimate of the mass distribution at depth and allows estimation of the shape and thickening of the plutons. The new geophysical data acquired in the Redencão and Bannach plutons enable a reinterpretation of the magmatic evolution and serves as a basis for an initial discussion about the mechanisms of their emplacement.

2. Geologic setting

The Jamon suite is situated in the Carajás province of the eastern Amazonian Craton (Dall’Agnol et al., 2005). The Carajás province, included in the Central Amazonian province (Tassinari and Macambira, 2004; Fig. 1a), is dominated by Archean terrains intruded by Paleoproterozoic anorogenic granites. To the west, it is limited by a terrane dominated by Proterozoic granitoids and Uatuma volcano-pyroclastic assemblages; to the east, by the Neoproterozoic Araguaia Belt, whose evolution is associated with the Brasiliano (Pan-African) cycle that did not significantly affect the Amazonian Craton; and to the north, by the Maroni-Itacauínas province, formed during the 2.2–2.1 Ga Trans-Amazonian event (Fig. 1a).
The Carajás province was cratonised at the end of the Archean and remained stable until the emplacement of A-type granites at approximately 1.88 Ga (Machado et al., 1991; Macambira and Lafon, 1995; Dall’Agnol et al., 1999a,b, 2005; Teixeira et al., 2002), as a direct response of the extensional tectonic regime that involved underplating of mafic magmas in a continental lithosphere. In the Rio Maria terrane, the occurrence of dike swarms coeval with the granites that include mafic-felsic composite dikes are interpreted as indirect evidence of these processes (Dall’Agnol et al., 2005). In the adjacent provinces, orogenic events are significantly older (e.g., Trans-Amazonian event in the north) or younger (e.g., Brasiliano event in the east) than these granites. Lamario et al. (2002) and Dall’Agnol et al. (2005) suggest that the A-type granite magmatism of the Carajás province was related to a continental event that marks the beginning of the breakup of the Paleoproterozoic continent formed at the end of the Trans-Amazonian orogenic cycle.

The Carajás province is divided into two Archean tectonic domains, the 3.0–2.86 Ga Rio Maria Granite-Greenstone Terrane (Macambira and Lafon, 1995; Dall’Agnol et al., 2006) and the rift-related Carajás Basin, dominantly composed of 2.76–2.55 Ga metavolcanic rocks, banded iron formations, and granitoids (Machado et al., 1991; Macambira and Lafon, 1995; Sardinha et al., 2006). The granite plutons of the Jamon suite are intrusive in Archean granitoids and greenstone belts of the Rio Maria Granite-Greenstone Terrane, which corresponds to the southern part of the Carajás metallogenic province (Fig. 1b). The greenstone belts (Andorinhas Supergroup) are composed dominantly of komatiites and tholeiitic basalts (Dall’Agnol et al., 2006). Four principal groups of Archean granitoids have been distinguished (Macambira and Lafon, 1995; Dall’Agnol et al., 2006): (1) older tonalitic-trondhjemitic series (TTG) represented by the Arco Verde and Caracol tonalites (~2.97–2.93 Ga); (2) 2.87 Ga sanukitoid Rio Maria granodiorite and associated rocks, intrusive into the greenstone sequence; (3) younger TTG series, represented by the Mogno and Água Fria trondhjemites (2.87 Ga); and (4) potassic leucogranites of calc-alkaline affinity, represented by the Xinguara, Mata Surrao, Guarantã, and similar granites (~2.86-Ga).
### 3. General aspects of the studied plutons

The Redenc¸a˜o and Bannach plutons are unfoliated, and their 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. 2a and b). The Bannach pluton was interpreted as composed of at least three independent near-circular intrusions, migrating from north to south (Almeida, 2005). External contacts are sharp, and angular xenoliths of Archean rocks are commonly observed near the margin of the plutons, indicating a high viscosity contrast between the magmas and the Archean bedrock. The country rocks are strongly affected by contact metamorphism. Hornblende hornfels contact aureoles around the 1.88 Ga plutons are well developed in both granitoids and greenstones (Dall’Agnol et al., 1999b). Al-in-hornblende barometers and mineral assemblages developed in the contact aureole suggest that the plutons of the Jamon suite were emplaced at shallow crustal levels (~1–3 kbar; Dall’Agnol et al., 1999b, 2005). The felsic dikes associated with the Jamon Suite yield Pb–Pb zircon ages of 1885 ± 4 and 1885 ± 2 Ma (Oliveira, unpublished data). One of these dikes, rhyolite porphyry, shows evidence of mingling with an associated mafic dike (Dall’Agnol et al., 2005), demonstrating that the mafic and felsic magmas were contemporaneous. Therefore, as indicated by dike swarms coeval with the granitic magma, the granite plutons were emplaced in an extensional tectonic regime. The Redenc¸o and other Jamon suite plutons are disposed nearly parallel to NW–SE faults in the basement, consistent with magma ascent along preexisting deep fault lineaments, as well as with the dominant WNW–ESE to NNW–SSE trends of Paleoproterozoic dikes. It indicates that extensional stress disposed along a NNE–SSW to ENE–WSW direction strongly controlled the Jamon suite emplacement.

### 4. Zoning of the plutons

#### 4.1. Petrographic and geochemical data

The petrography and magmatic evolution of the Redenc¸o and Bnnach granites were discussed by Oliveira et al. (2005) and Almeida (2005), respectively. Both granites are very similar in textures and mineralogy. These plutons consist of several intrusive phases disposed in near-concentric zones and cut by syenogranite dikes. They are formed essentially of coarse-grained, equigranular to porphyritic, or coarse- to medium-grained seriated monzogranites with subordinate medium, even-grained...
types. All facies are leucocratic with contents of mafic minerals normally between 15% and 6%; in the less evolved facies, they reach more than 25% and but are less than 5% in the differentiated leucogranites. Biotite is the dominant mafic mineral, found in all granite varieties; amphibole, sometimes with relics of clinopyroxene, is abundant only in the less evolved facies. The assemblage of accessory minerals includes zircon, apatite, iron-titanium oxides (magnetite/ilmenite), sulphide phases (pyrite/chalcopyrite), allanite, titanite, and, in the more evolved facies, fluorite. Subsolidus processes were limited to alteration of plagioclase and mafic phases; epidote, sericite, and chlorite are alteration products.

The distribution of the different facies is relatively well ordered in the granite plutons (Fig. 3a and b). In the Redencão 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 toward the interior of the pluton to dominantly coarse-grained, equigranular, seriated, or porphyritic biotite monzogranites. The seriated and porphyritic biotite monzogranite facies configure annular structures in the central and southern areas of the pluton. In the central part of the pluton, evolved leucogranites define a small circular structure (Fig. 3a). Field relationships show that the seriated and porphyritic biotite monzogranite facies are intrusive in the coarse, even-grained (hornblende) biotite monzogranite. Aplitic dikes are common and coincide in orientation with the main NE-SW and NW–SE faulting system.

In the Jamon Suite, except locally in composite dikes, evidence of magma mingling between mafic and felsic magmas has not been reported (Dall’Agnol et al., 2005). However, in the Redencão and Bannach plutons, evidence of “mingling” of the coarse porphyritic facies with other felsic magmas is frequently observed. In these mingled rocks, plagioclase-mantled K-feldspar megacrysts are common, but typical wiborgitic and pyterlitic rapakivi textures are absent (cf. Râmô and Haapala, 1995).

The internal zoning of the northern intrusion of Bannach (Fig. 3b) is similar to that of the Redencão pluton. However, in the Bannach pluton, some significant differences are worthwhile noting: The (clinopyroxene)-amphibole-bearing, less evolved monzogranites are more abundant and show a regular distribution along all pluton margins; the coarse-equigranular and medium- to coarse-grained seriated biotite monzogranites are not found; four pulses of leucogranites, situated generally near 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; and felsic granitic dikes are systematically associated with the porphyritic monzogranites (Fig. 3b).

The magnetic zoning is marked in both plutons by the systematic decrease of modal mafic mineral content, plagioclase/potassium feldspar and amphibole/biotite ratios, and anorthite content of plagioclase \((\text{An}_{32-15})\) from the (clinopyroxene)+amphibole+biotite monzogranite near the leucogranites. However, the abundance of alkali feldspar and quartz increases toward the inner zone. \(\text{TiO}_2, \text{MgO}, \text{FeO}_\text{O}, \text{CaO}, \text{P}_2\text{O}_5, \text{Ba}, \text{Sr}, \text{and Zr decrease, and SiO}_2, \text{K}_2\text{O, 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. Oliveira (2001) proposes that fractional crystallization was the dominant process of magmatic evolution of the Redencão pluton. Nevertheless, magma mingling processes influence the evolution of this granitic pluton, as suggested by the relationships between porphyritic biotite granites and leucogranites. Similar magmatic processes have been proposed to explain the zoning of the Bannach pluton (Almeida, 2005). The leucogranite facies of both plutons is interpreted as probably late, independent injections of evolved, felsic magmas (Oliveira, 2001; Almeida, 2005).

4.2. Magnetic susceptibility data

In the Redencão and Bannach plutons, the bulk magnetic susceptibility (K) shows similar values, varying between \(1.05 \times 10^{-3}\) and \(54.72 \times 10^{-3}\) SI, with an average of \(11.55 \times 10^{-3}\) SI, in the Redencão 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). K has a unimodal and bimodal distribution in the Redencão and Bannach plutons, respectively (Fig. 4a and b). Magnetite is always dominant over ilmenite, and modal contents of Fe-Ti oxide minerals vary between 3.5% and 0.4% in the Redencão 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). Magnetic susceptibility (MS) essentially reflects variations in the magnetite content of different granitic facies.

Average MS values decrease from the (clinopyroxene)-amphibole-biotite monzogranites to the biotite monzogranites, attaining the lowest value in the leucomonzogranites. In other words, magnetic susceptibility decreases from the facies with higher modal contents of mafic minerals to the leucogranites. In Bannach, this trend implies a decrease of MS from the border to the center of the pluton with a normal and concentric zoning (Fig. 4b; Almeida, 2005); in the Redencão pluton, the highest MS values are concentrated in the southern part of the pluton, decreasing to the NE and mid-central domains, and the lowest MS values are found in the center of the intrusion (Fig. 4a; Oliveira et al., 2002). The MS behavior is consistent with the pattern indicated by petrographic and geochemical data, such that MS decreases from less evolved to more evolved granites and can be used as a magmatic differentiation index (Oliveira et al., 2002).
Fig. 3. Sketch geological maps showing the areal distribution of granite facies in the (a) Redenção pluton and (b) northern and central parts of the Bannach pluton. Insets in (a) and (b) show SRTM/gamma thorium integrated product showing the internal zoning in the Redenção and Bannach plutons. SRTM (Shutter Radar Topography Mission–NASA).
4.3. Remote sensing and aerogamma spectrometry

The sources of natural gamma radiation are associated with common rock-forming minerals (feldspars, micas, and clays) in the case of K and accessory minerals (e.g., zircon, monazite) for U and Th. The Total Count channel (CT), with a broad spectrum that includes the contribution of K, U, and Th radiations, presents higher intensity and is statistically more reliable for the discrimination of rock units (Paradella et al., 1998). However, U and Th channels are indicated for rock type identification and detection of hydrothermal/metasomatic processes (Vasconcellos et al., 1994; Richardson, 2004). It is worth recalling that U behaves geochemically as a mobile element, whereas Th is generally immobile or less mobile during secondary processes.

As mentioned by Paradella et al. (1998), in interpreting the results of this integration, certain factors that could have affected the measured values must be considered (e.g., variation in the vegetation cover). Interpretations based on the K-channel should be treated with caution due to the possibility of false responses induced by the vegetation. This caution is not crucial for U and Th channels (Pereira and Nordemann, 1983). The more important effect is the spatial correlation of higher gamma responses with the geomorphology of the area.

In the Redenção granite, the SRTM (Shutter Radar Topography Mission)/gamma products reveal a strong correlation between gamma ray anomalies and higher topographic levels (Fig. 3a). Results from Bannach pluton obtained with orbital remote sensing and gamma integration also show that the strongest gamma responses relate mainly to high and moderate relief areas within the pluton (Fig. 3b).

In the interior of the studied plutons, the SRTM/U product shows higher gamma U activities in the central areas of the intrusions compared with at the borders. Similar positive gamma anomalies are indicated by Th in the central parts of the massifs (Fig. 3a and b). The analysis of the airborne and SRTM/gamma TC products reinforces
the results obtained through the RADAR/U-Th products. The gamma anomalies in the plutons are coincident with the distribution of their more evolved, generally leucogranitic facies. These rocks are enriched in K, Th, and U, which explains their radiometric contrast with the more mafic biotite-amphibole monzogranites, dominant in the border of the plutons (Fig. 3a and b). Thus, aerogamma spectrometry offers useful information for understanding internal magmatic zoning in the plutons.

Whole-rock geochemical data on the Redenção and Bannach plutons (Almeida, 2005; Oliveira, 2006) demonstrate that K contents are higher toward the central sector of the plutons compared with the borders, but the K contribution alone would not be able to determine the main gamma patterns recorded in the whole intrusions. U and Th also increase during magmatic differentiation, explaining the observed gamma U and Th behaviors (Fig. 3a and b). The same evolution trends and general radiometric features are observed in the Musa, Jamon, and Marajoara plutons of the Jamon suite. A similar magmatic evolution is assumed for the Paleoproterozoic, tin-mineralized Antônio Vicente pluton (west of Carajás Province), in which more evolved facies are enriched in U and Th (Teixeira et al., 2002).

5. Gravity method

5.1. Gravity survey and corrections

5.1.1. Bannach area

Given the importance of altimetric information and the absence of reference base stations in the Bannach region for the gravity survey on the Bannach pluton, it was necessary to define a new altimetric base in that area. To this end, a new reference base-station has been transferred from the Brazilian Fundamental Gravity Net (Escobar, 1980), taking as altimetric reference an IBGE base located in Rio Maria (985 L; 7°16’18”S/50°05’48” W), with a g value in the system GRS-67 of 978044.87 (Carvalho, 1988). The new gravimetric base-station, with a g value of 978010.49, was located in Bannach town and named Hotel Catarinense (7°20’52” S/50°24’39” W). Gravity was measured at 147 stations following approximately N–S- and E–W-trending traverses on the Bannach pluton and its neighboring country rocks. Distances between gravity stations are approximately 500 and 1000 m in the border and the center of the pluton, respectively. The gravity measurements are referred to the international gravity net (IGSN 1971) at the new Bannach gravimetric base.

A Lacoste-Romberg Model G gravity meter, with precision of ±0.01 mGal, was employed for measurements. Geographic coordinates and elevations were obtained using a Magellan Pro Mark X differential GPS, with average precision of approximately 10 and 0.4 m in the horizontal and vertical directions, respectively. The altitudes relative to the sea level were obtained with a Paulin altimeter accurate to the meter. Instrument drift, latitude, free-air, and Bouguer corrections were applied to the observed data. A reduction density of 2.67 g/cm³ was used to perform the Bouguer corrections. If necessary, the gravity response of a regional field, approximated by a first-order polynomial, has been removed from the data along each traverse to produce an anomaly that reaches zero at both ends of the profile.

5.1.2. Redenção area

The results of the gravity survey of the Redenção pluton presented here constitute part of a larger-scale gravity exploration campaign accomplished by Mineração Jenipapo (Western Mining Company; WMC) in an area covering the border between the eastern Amazonian Craton and the Brasiliano Araguaia Belt. In this area, Archean units of the Rio Maria Granite–Greenstone Terrane are exposed and intruded by Paleoproterozoic A-type granites and low grade metasedimentary rocks of the Araguaia Belt.

Between 1999 and 2000, 135 observations were collected along roads crossing the Redenção pluton and adjacent country rocks, with a constant spacing of 1 km between stations. The reference base station is located in the city of Redenção. The gravity meter was a Scintrex CG3 Autograv Meter with a precision of 0.01 mGal. The positioning was carried out with a Trimble Geodetic Base Station System 4700 with an accuracy of 5–10 cm. Latitude, free-air, Bouguer, topographic, tide, and instrument drift corrections were applied to the data. For the Bouguer and topographic corrections, a reference density of 2.67 g/cm³ has been assumed. The gravity response of a regional field, approximated by a first-order polynomial, is removed from the data along the traverses if necessary to produce an anomaly that falls off to zero at both ends of the profile.

5.2. Density measurements

Density measurements were carried out on selected samples considered representative of both the different granite varieties and the surrounding country rocks. In the Redenção and Bannach plutons, the average density values of each facies generally decrease from the border to the center. The biotite monzogranites and leucogranites have density less than 2.66 g/cm³, whereas the clinopyroxene-bearing, cumulatic monzogranites and the biotite-amphibole monzogranites density is greater than 2.70 g/cm³ (Table 1). These plutons are composed of approximately 80% biotite ±amphibole monzogranite (ρ = 2.64–2.65 g/cm³). The denser facies occur locally as enclaves or along the borders of the plutons. The leucogranites are less dense (ρ = 2.61 g/cm³) than other varieties and occur as either stocks in the center of the intrusions or dikes. Despite the internal density variations, in both plutons, the density distribution is uniform enough to justify the adoption of a unique average density of 2.64 g/cm³.

Density of the country rocks of the studied plutons is quite variable, decreasing from the mafic greenstone belts (ρ = 2.97 g/cm³) to the Rio Maria granodiorite and associ-
ated monzonites ($\rho = 2.74–2.85$ g/cm$^3$), and then attaining the lowest values in the tonalites and leucomonzogranites ($\rho = 2.65–2.63$ g/cm$^3$). For a simplified, integrated modeling, taking into account the overall dominance of granitoids, an average density of 2.73 g/cm$^3$ is assumed for the country rocks. An average density contrast of $0.09 \pm 0.01$ g/cm$^3$ between the country rocks and the Paleoproterozoic granites therefore is assumed for the gravity inversion of the anomalies produced by both plutons.

5.3. Inversion methodology

The mathematical details of the gravity inversion method are presented in Silva and Barbosa (2006). Here, we present an overview of the method’s rationale. Let $S$ be a 2D gravity source with arbitrary shape and arbitrary density contrast distribution, and assume that an outline of this source may be defined by a combination of geometric elements consisting of axes and points ($e_1$ and $e_2$; Silva and Barbosa, 2006). We discretize the subsurface region, containing the sources, into a grid of 2D rectangular cells (Fig. 5) and assign different density contrasts to each cell to approximate the continuous distribution of density contrasts with a discrete one. The purpose of the method is to estimate density contrasts for all cells, which fit the observations and present non-null estimates close to the geometric elements. To this end, the interpreter specifies a set of line segments and points, which presumably outlines the true sources, and assigns to each geometric element a target density contrast. The method then estimates the shapes of the sources by estimating the density contrast of each cell of the grid and thus generates a discrete distribution of density contrast that produces the best fit to the observed anomaly and concentrates the non-null estimated density contrasts around the specified geometric elements.

Fig. 5. Outline of a 2D gravity source ($S$) defined by a combination of geometric elements consisting of axes and points ($e_1$ and $e_2$; Silva and Barbosa, 2006).

The estimated density contrasts of the cells about a given geometric element tend to be close to the target density contrast assigned to the geometric element. The user may then accept the solution or modify the target, densities, and/or the number and position of the geometric elements and start a new inversion, then repeat this interactive procedure until reaching a satisfactory solution. Because the interpretation model consists of a grid of prisms with different density contrasts, this technique allows for lateral facies changes. This interpretation method has been implemented in a user-friendly environment by means of suitable graphical interfaces, allowing fast and efficient interactivity.

5.4. Results

The Bouguer anomalies of the Redenção and Bannach plutons along six traverses are presented in Figs. 6 and 7, respectively. Both plutons produce gravity lows, typical behavior of most granite plutons due to their lower density relative to the surrounding rocks (Aranguren, 1997; Singh et al., 2004).

Each gravity profile has been inverted using the interactive inversion procedure described in the previous section and assuming that each pluton may be outlined by a single axis at surface (Figs. 6 and 7b), then assigning a density contrast of 0.09 g/cm$^3$ to each axis. Because the Redenção and Bannach plutons are exposed, the feature of interest, which will be extracted from the gravity data, is the spatial variation of the plutons’ thickness. The results of the inversion of the gravity anomaly along the traverses appear in Figs. 6 and 7b for Redenção and Bannach, respectively. A remarkable feature of both plutons, disclosed by the gravity inversion, is that they exhibit a lateral extension

Table 1  
Mean density values estimated for the Redenção and Bannach granite varieties and country rocks

<table>
<thead>
<tr>
<th>Density, g/cm$^3$</th>
<th>Redenção and Bannach plutons</th>
<th>Country rocks (Redenção pluton)</th>
<th>Country rocks (Bannach pluton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinopyroxene–hornblende–biotite monzogranite</td>
<td>2.77 ± 0.03</td>
<td>Rio Maria Granodiorite</td>
<td>2.74 ± 0.01</td>
</tr>
<tr>
<td>Biotite-hornblende monzogranite</td>
<td>2.70 ± 0.01</td>
<td>K-leucomonzogranite</td>
<td>2.72 ± 0.02</td>
</tr>
<tr>
<td>Hornblende-biotite monzogranite</td>
<td>2.65 ± 0.01</td>
<td>Arco Verde Tonalite</td>
<td>2.65 ± 0.02</td>
</tr>
<tr>
<td>Biotite monzogranite</td>
<td>2.63 ± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leucomonzogranite</td>
<td>2.61 ± 0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Density, g/cm$^3$</th>
<th>Greenstone Belts</th>
<th>Mafic Rocks/Monzonites</th>
<th>Rio Maria Granodiorite</th>
<th>K-leucogranite</th>
<th>Arco Verde Tonalite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.97 ± 0.03</td>
<td>2.85 ± 0.02</td>
<td>2.74 ± 0.01</td>
<td>2.63 ± 0.02</td>
<td>2.65 ± 0.02</td>
</tr>
</tbody>
</table>
substantially larger than the vertical one, outlining a sheeted geometry. An approximate N–S cross-section (A–A₀ in Fig. 6 a and b₁) through the strongest negative residual anomaly over the Redenc¸a˜o intrusion, for example, indicates that a maximum deepening of the granite’s floor to 5.6 km is necessary to explain the gravity anomaly, according to the assumed density contrast between the granite and its country rocks. Similar results are obtained along the B–B’ and C–C’ cross-sections (Fig. 6 a, b₂, and b₃). The estimates of the plutons’ depth to the bottom indicates a progressive thinning from the center to the borders and maximum thickness values of 5.6 and 2.2 km, respectively, for the Redenc¸a˜o and Bannach plutons (Figs. 6 and 7 b, c, and d). 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. Because 2D gravity inversion has been performed on data produced by 3D sources, the maximum depths of the plutons may be slightly greater than the estimated figures of 5 and 2 km. The plutons’ original thicknesses are also larger than their respective estimated floor depths, because they are exposed in surface and their roofs were partially eroded.

A contour map of the Redenc¸a˜o massif’s depth to the bottom was drawn from the gravity anomalies modeling using the method of Silva and Barbosa (2006). (d) Cross-sections through the Redenc¸a˜o pluton showing its morphology with depth; all sections obtained from 2D gravity inversion. All sections are shown at the same horizontal and vertical scales with no vertical exaggeration. The profiles are indicated in Fig. 8a and c. Depths are in kilometers. A density of 2.64 g/cm³ was employed for the granite varieties of the Redenc¸a˜o pluton and 2.73 g/cm³ for the country rocks.

Fig. 6. Redenc¸a˜o pluton. (a) Bouguer anomaly map showing the gravity stations (crosses) and contours in 1.0 mgal. (b) Observed gravity (squares) and calculated Bouguer anomaly (continuous lines) obtained from the modeling of the residual anomalies associated with the modeled geometry of the pluton. Gravity inversion profiles with the regional field removed as computed by 2D modeling. (b₁) A–A’, approximate N–S profile; (b₂) B–B’, approximate SW–NE profile; (b₃) C–C’, approximate W–E profile. (c) Contour map of the Redenc¸a˜o pluton depth drawn from gravity anomalies modeling using the method of Silva and Barbosa (2006). (d) Cross-sections through the Redenc¸a˜o pluton showing its morphology with depth; all sections obtained from 2D gravity inversion. All sections are shown at the same horizontal and vertical scales with no vertical exaggeration. The profiles are indicated in Fig. 8a and c. Depths are in kilometers. A density of 2.64 g/cm³ was employed for the granite varieties of the Redenc¸a˜o pluton and 2.73 g/cm³ for the country rocks.
Almeida (2005) proposes that the Bannach pluton consists of three successive near-circular intrusions that grow younger from the north to the south. The resulting picture looks similar to that presented for the Sara-Fier Complex of the Nigerian Younger Granite province (Bowden and Turner, 1974; Bowden and Kinnaird, 1984). In the Bannach pluton, the gravity survey was restricted to its northern and central parts, which correspond to the first intrusion and part of the second intrusion (Almeida, 2005). The different gravimetric cross-sections suggest that the pluton is also a sheeted intrusion. However, it differs from the Redencção because of its smaller thickness; it is only locally thicker than 2 km. In addition, the gravity data reveal 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, which reinforces the hypothesis of a pluton origin by multiple sequential intrusions, evolving from north to south. The steep increase of the gravity response in the limit between the first and second intrusions, also observed in the western border of the first intrusion, is strong evidence of a shallow contact between the granite and the country rocks in the mentioned areas (Fig. 7d; C–C profile). Thus, the general shape of the Bannach pluton is similar to that of the Redencção pluton, but they differ in thickness. The origin by sequential multiple center intrusion is also a distinct aspect of the Bannach pluton not observed at Redencção, though it may be present in the Musa pluton of the Jamon suite (Dall’Agnol et al., 1999b).

6. Discussion

6.1. Tridimensional shape of the plutons

A remarkable feature of the Redencção pluton and the northern intrusion of the Bannach pluton is that they
exhibit a lateral extent greater than their vertical one, outlining a sheeted geometry. They are near-circular bodies with approximate diameters of 25 and 20 km, respectively, extending to a maximum depth of 5.6 km in the case of Redencão and of 2.2 km for Bannach (Fig. 8a and b). The original thicknesses of these plutons should be greater than their estimated floor depths, but it is improbable that they were significantly thicker, because geological evidence, including common occurrence of microgranites and granophryic textures, points to a near-roof level of exposition presently. Several granite plutons display sheeted-like geometries with fractal thickness/length ratios (McCaffrey and Petford, 1997). The average thickness/length ratios of the studied plutons are similar to those indicated by the general power law for laccolith dimension (McCaffrey and Petford, 1997; Rocchi et al., 2002) and those observed in classical rapakivi granite batholiths (Vigneresse, 2005): Wiborg (350 km $\times$ 200 km $\times$ 5 km) from Finland; Åland (110 km $\times$ 90 km $\times$ 8 km) and Nordingrå (50 km $\times$ 20 km $\times$ 5 km) from Sweden; and Korosten (125 km $\times$ 100 km $\times$ 0.5–3 km) from Ukraine.

In general, the global shape of rapakivi granites strongly differs from that of other massifs (Vigneresse, 2005). The L/W vs. W/T diagram discriminates the three-dimensional characteristics of intrusive plutons (Améglio et al., 1997; McCaffrey and Petford, 1997). The relation between the length/width (L/W) and width/thickness (W/T) ratios clearly separates wedge-shaped plutons from flat-floored ones and reflects the control of the emplacement mechanism and shape of the plutons by regional tectonics (Fig. 9). In this respect, the rapakivi granites are characterized by a very large W/T ratio, whereas the L/W ratio remains close to 1, reflecting a semi-circular shape at the surface. This finding indicates the anisotropic character of the crust at the time of emplacement (Hogan et al., 1998; Vigneresse et al., 1999).

The Bannach pluton reaches at its greatest extension a length of 45 km in the NW–SE direction (Fig. 2b). However, this pluton is a composite intrusion formed by at least three coalescent plutons (Almeida, 2005; Figs. 2, 3, 7b3, c, and d; cross-section C–C$^c$). Gravity data reinforce the hypothesis that the growth of the northern part of the Bannach pluton results from the amalgamation of smaller, sheeted-like plutons that intruded in sequence from northwest to southeast.

The occurrence of thin-sheeted intrusions, rarely more than 5 km thick, rather than thick plutons, would be expected in an extensional tectonic setting. The results of gravity inversion in the Redencão and Bannach plutons indicate that their three-dimensional shape agrees with this model. This conclusion can be extrapolated to the entire Jamon suite.

### 6.2. Tectonic setting and emplacement of the studied plutons

The extensive A-type, rapakivi magmatism developed during the end of the Paleoproterozoic and, remarkably, along the entire Mesoproterozoic appears to be a very spe-
specific, worldwide event. This magmatism has been recognized in most old cratonic blocks, especially in North America, Baltic, and Amazonia (Rämö and Haapala, 1995). It generally has been associated with the breakup of a supercontinent formed in the late Paleoproterozoic or early Mesoproterozoic (Hoffmann, 1989; Windley, 1993, 1995; Brito Neves, 1999; Frost et al., 1999; Condie, 2002; Lamarão et al., 2002; Zhao et al., 2004; Dall’Agnol et al., 2005; Vigneresse, 2005). The origin of rapakivi granites and associated rocks is considered typical of anorogenic, extensional settings, which are not associated with major episodes of large-scale deformation that would mark any model of local plate convergence. However, they could represent the reflex in stabilized areas of distal orogenic events (cf. Ahäll et al., 2000; Zhao et al., 2004).

In the Amazonian Craton, the emplacement of the Jamon suite granites takes place approximately 200 Ma after the latest peak of convergence of the Transamazonian event during the Paleoproterozoic. Moreover, the A-type plutons of Carajás province are approximately 1.0 Ga younger than their Archean country rocks (Macambira and Lafon, 1995; Rämö et al., 2002; Dall’Agnol et al., 2005). The development of this extensive granite magmatism is considered associated with the fragmentation of an approximately 2.0 Ga, Paleoproterozoic supercontinent and postdates the Archean crust of the Carajás province by one billion years (Dall’Agnol et al., 2005).

The generation of the A-type rapakivi granites of the Carajás province is admittedly linked to asthenosphere upwelling and magma production in the mantle, followed by partial melting of the lower continental crust triggered by the heat provided by the underplating of mantle magmas (Dall’Agnol et al., 2005). The resulting anatectic liquids ascend in the crust and are emplaced as high-level granite complexes. In this model, extension is associated with mantle upwelling and indicated by the occurrence of diabase and granite porphyry dikes swarms coeval with the Jamon suite. The dikes follow WNW–ESE to NNW–SSE trends, demonstrating that the tectonic extensional stress was oriented approximately NNE–SSW to ENE–WSW. The 1.88 Ga A-type granite plutons and stocks of Carajás are also disposed along a belt extending from the border between the Amazonian Craton and the Arauáia belt in the east, to the Xingu region domain in the west. This belt also follows the general trend defined by the dikes (Fig. 1b).

A wealth of geological evidence argues in favor of an emplacement of the Jamon suite in an extensional setting. In this context, dikes are the most efficient way to feed upper crustal plutons (Petford, 1996; Petford et al., 2000). Moreover, important information on the emplacement mechanism of granitic magmas is preserved in the 3D shape of the plutons. The inferred tabular geometry of the studied plutons, similar to that assumed for rapakivi complexes, is not predicted by diapirc models (Cruden, 1990), though it is consistent with expectations in the case of granitic magma transport via a series of dike feeder channels (Petford, 1996).

Assuming a dike-like ascent model, two stages during the construction of the Bannach and Redenção plutons can be recognized. The relationships of the Jamon suite plutons with coeval, NW–SE-trending dike swarms indicate that in a first stage, the ascent of magma took place through similarly orientated fracture zones, perpendicular to the principal extensional stress. Mingling structures, locally found in the composite dike, indicate the ascent of mafic and felsic magmas through the same fissures and the contemporaneous character of these magmas. The second stage corresponds to the switch from upward flow to lateral spread of magma at upper crustal levels and is responsible for the sheet-like shape of the plutons. The high viscosity contrast and absence of deformation aureole within the country rocks suggest that the lateral spreading of the plutos was not the main mechanism for space creation during emplacement; rather space was created mostly by the vertical displacement of country rock. On a regional scale, the Redenção and Bannach plutons are aligned nearly parallel to NNW–SSE faults in the Archean basement, consistent with magma ascent along preexisting deep fault lineaments. Deep faults served as channels for the magma upwelling, and tectonic discontinuities represented weaker zones that favored magma emplacement at shallow crustal level.

6.3. Internal zoning of the plutons

All studied plutons of the Jamon suite display normal zoning (see also Dall’Agnol et al., 2005). A common explanation for this feature is magmatic evolution by fractional crystallization, with gradual differentiation from the margins to the center of the plutons (Bateman and Chappell, 1979). Zorpi et al. (1989) and Richardson (2004) discuss hypotheses to explain this type of zoning and mention that granite plutons are more commonly formed of a series of
continuous pulses of magmas differentiated elsewhere. They emphasize the role of magma mingling processes in the origin of normal-zoned, calc-alkaline plutons and conclude that in situ, fractional crystallization should be ruled out as the dominant mechanism for zoning development. They admit that zoning was inherited from an earlier stage of the pluton’s evolution. Despite the geochemical contrasts between the calc-alkaline granites and those of the Jamon suite (Dall’Agnol and Oliveira, 2007), the general conclusions of Zorpi et al. (1989) are probably also applicable for the Redenção and Bannach plutons, with the important difference that mingling processes in the latter are restricted to felsic, porphyritic granites, without evidence of any involvement of mafic magmas except in local composite dikes.

The geochemical characteristics of the Redenção and Bannach granite varieties indicate that the leucogranites of both plutons are not derived directly by fractional crystallization of the less evolved amphibole-biotite-bearing facies (Oliveira, 2001; Almeida, 2005). They were interpreted as late-emplaced varieties of more evolved magmas derived from similar sources and processes but not necessarily from the same magma. This interpretation is consistent with the general features observed in these plutons and could partially explain their normal zoning. The coarse biotite monzogranites should be derived from the amphibole-biotite monzogranites by fractional crystallization. The gradual compositional transition between these facies, associated with the late emplacement of leucogranite magmas, could explain the general zoning of the plutons. Local occurrences of clinopyroxene-bearing, mafic mineral–enriched monzogranites relate to cumulus processes that involve the less evolved rocks.

7. Conclusions

Near the end of the Paleoproterozoic (~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 show that the Redenção and northern part of Bannach plutons are normally zoned. They 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; and a slightly younger pulse, located at the center of the plutons, composed of even-grained leucogranites.

Composite 2D gravity inversions along profiles indicate the approximate 3D geometry of these massifs that correspond to sheet-shaped intrusions (Rocchi et al., 2002; Aranguren et al., 2003). The studied plutons follow the general power law for laccolith dimension or sheeted-like geometry (McCaffrey and Petford, 1997; Rocchi et al., 2002; Cruden, in press), 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 from the amalgamation of smaller, sheeted-like plutons that intruded in sequence from northwest to southeast. This suggestion is consistent with evidence that the Bannach pluton is a composite intrusion formed of at least three coalescent plutons (Almeida, 2005).

The occurrence of diabase and granite porphyry dike swarms, striking NW–ESE to NNW–SSE and coeval with the Jamon suite, demonstrates that at that time, the tectonic extensional stress was oriented approximately 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 high contrast of viscosity between the granites and their Archean country rocks are not consistent with diapiric or ballooning models (Castro, 1987; Cruden, 1990, in press) but can be explained by magma transport via dikes (Petford, 1996).

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References


