ARTICLE

Marins Granite (MG/SP): petrography, geochemistry, geochronology, and geotectonic setting

Granito Marins (MG/SP): petrografia, geoquímica, geocronologia e contexto geotectônico

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ABSTRACT: The Marins Granite forms an ellipsoidal body that crops out along the border between São Paulo and Minas Gerais states. It intrudes meta-sedimentary and meta-igneous rocks of Neoproterozoic age, belonging to the Socorro Nappe and Embu Complex, in the interference zone between the Brasília and Ribeira fold belts. Geochemical analyses indicate a high-K calc-alkaline signature, weakly peraluminous, type I character, poorly differentiated with restricted silica range and similar rare earth element patterns enriched in light rare earth elements. Two lithofacies were defined: (1) Marins facies, predominantly inside the body, isotropic, light gray with inequigranular porphyritic texture containing euhedral to subhedral microcline phenocrysts (< 1 cm), and (2) Mendanha facies, restricted to the border zone of the body, are pinkish with elongated microcline phenocrysts and aligned biotite grains, defining a deformational foliation. Neodymium isotopes point to a crustal signature, revealed by a $\epsilon_{Nd(0.6)}$ of -10.4. T_{DM} ages indicate a paleoproterozoic source. U-Pb LA-ICPMS ages in zircon yielded concordia crystallization ages of 606.9 ± 1.9 Ma for the Mendanha facies and 603.7 ± 4.8 Ma for the Marins facies. These ages are consistent with the interpretation that the Marins Granite is a late to post-collisional body with respect to the collision of the southern Brasília Belt, also reinforced by the location of the granite in the upper plate (Socorro Nappe), a few tens of kilometers away from the suture. The apparent lack of deformation related to collision in the Ribeira Belt (590 – 570 Ma), in the Marins facies, after crystallization of the body, is interpreted as the result of its rheological behavior, more resistant to deformation than the surrounding schists, similar to the behavior of a pre- or syntectonic porphyroblast.

KEYWORDS: post-collisional granitoid; geochemistry; LA-ICP-MS method; Neodymium isotopes

RESUMO: O granito Marins, de forma elipsoidal, aflora ao longo da divisa entre os Estados de São Paulo e Minas Gerais e intrude rochas neoproterozoicas para e ortoderivadas pertencentes à Nappe Socorro e ao Complexo Embu na zona de interferência entre as Faixas Brasília e Ribeira. Esse corpo é cálcio-alcálico de alto K, fracamente peraluminoso de caráter tipo I pouco diferenciado. Apresenta restrita variação de sílica e padrões similares de ETR, enriquecidos em ETRL. Duas litofácies foram definidas: 1) fácies Marins, predominante no interior do corpo, isotrópica, cinza-clara, inequigranular porfírica com fenocristais euédricos a subédricos de microclina (< 1 cm) e 2) fácies Mendanha, restrita à zona de borda do corpo, rosada, com fenocristais alongados de microclina e grãos de biotita alinhados definindo uma foliação deformacional. Isótopos de neodímio apontam assinatura crustal, revelada por valor de $\epsilon_{Nd(0.6)}$ de -10.4 e idade TDM paleoproterozoica. Datações U-Pb LA-ICPMS em zircão forneceram idades concordia de cristalização de $606,9 \pm 1,9$ Ma para a fácies Mendanha e $603,7 \pm 4,8$ Ma para a fácies Marins. Desta forma, o Granito Marins é correlacionado a eventos tardi a pós-colisionais da Faixa Brasília meridional. Tal interpretação é reforçada por sua localização dentro da placa superior (Nappe Socorro), a poucas dezenas de quilômetros da sutura. A aparente ausência de deformação na fácies Marins relacionada à deformação da Faixa Ribeira é interpretada como resultado do seu comportamento reológico mais resistente à deformação. Por essa razão, interpreta-se que a deformação relacionada à colisão na Faixa Ribeira, posterior à cristalização do corpo, está concentrada nas encaixantes e na fácies Mendanha.

PALAVRAS-CHAVE: granito pós-colisional; geoquímica; método LA-ICP-MS; isótopos de Nd.

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Manuscript ID 29863. Received on: 29/11/2012. Approved on: 23/10/2013.

INTRODUCTION

In the Mantiqueira Range, along the border between São Paulo and Minas Gerais states, a porphyritic granite of about 70 km² crops out. Pereira *et al.* (2001) individualized two distinct plutonic bodies, which they called Marins granitoid and Mendanha Granite. New field and petrographic, geochemical, geochronological, and isotopic (Sm-Nd) data allow the presentation of a new geological map in which these two granites are interpreted as two facies of a single body, called Marins Granite.

REGIONAL GEOLOGIC CONTEXT

The area is inserted in the interference zone between the Brasília and Ribeira belts, south and southwest of the São Francisco Craton (Trouw *et al.* 2000; Peternel *et al.* 2005; Fig. 1). Therefore, the region is characterized by overlapping structures, metamorphism, and igneous intrusions related both to the Brasília and to the Ribeira belts.

In the southern segment of the southern Brasília Belt, from west to east, the Socorro-Guaxupé Nappe, the Andrelândia Nappe System, and the (par)autochthonous São Francisco Craton crop out (Campos Neto and Caby 1999, 2000; Campos Neto *et al.* 2004, 2010; Trouw *et al.* 2000; Valeriano *et al.* 2004, 2008). A collisional event between the Paranapanema (western upper plate) and the São Francisco (eastern lower plate) paleocontinents

resulted in nappe structures exhibiting eastern tectonic transport. The age of this collision was estimated at 650 – 605 Ma, becoming younger from north to south (Dardenne 2000; Valeriano *et al.* 2004, 2008; Campos Neto *et al.* 2004, 2010; Trouw, 2008; Reno *et al.* 2009, 2012). In a restricted area within the Socorro Nappe region, at Virginia-MG, the collision was dated at 620 – 605 Ma (Trouw 2008). The Socorro-Guaxupé Nappe is considered the active margin of the Paranapanema paleocontinent, consisting mainly of deformed igneous rocks, interpreted as the root of a magmatic arc with an age of 670 – 615 Ma (Campos Neto *et al.* 2004, 2010). The metamorphism increases from greenschist facies in the São Francisco Craton margin to high-pressure granulite facies in the upper Andrelândia Nappe System (Trouw *et al.* 2000; Campos Neto & Caby 1999, 2000). Within the Socorro-Guaxupé Nappe, the metamorphism decreases from granulite to amphibolite facies upwards.

The evolution of the Ribeira Belt is correlated to the SE subduction of the São Francisco plate and subsequent collision between the São Francisco paleocontinent and the Rio Negro Magmatic Arc (Heilbron *et al.* 2000, 2004, 2008; Heilbron & Machado 2003). The central segment of the Ribeira Belt was subdivided according to Heilbron *et al.* (2000, 2004, 2008) into Occidental Terrane, Oriental Terrane, Cabo Frio Terrane, and Paraíba do Sul Terrane, recording two collisional episodes. The first episode was divided into four tectonic stages. The first stage, pre-collisional, occurred between 630 and 595 Ma (Machado *et al.* 1996) during SE subduction of the São Francisco paleocontinent, producing granitoid plutons of the Rio Negro Magmatic Arc in the upper plate (Tupinambá *et al.* 1998). During the second stage, from 595 to 565 Ma (Machado *et al.* 1996; Heilbron *et al.* 2004), oblique collision occurred between these plates, producing tectonic domains with top to NW tectonic transport. The third stage (late collisional) between 565 and 540 Ma (Machado *et al.* 1996) is recorded by predominantly I-type granitic plutons. The fourth stage (post-collisional) is represented by a compressive phase between 540 and 520 Ma (Machado *et al.* 1996).

The Marins Granite is surrounded by meta-sedimentary rocks of the Embu Complex. The Embu Complex (Hasui *et al.* 1981) contains a set of igneous and meta-sedimentary rocks forming a lens-shaped body on the map, limited by faults and located in the central Ribeira belt. Traditionally this complex makes contact with the Socorro Nappe through the Buquira Shear Zone (Hasui *et al.* 1981), which separates the southern Brasília Belt from the central Ribeira Belt. Recently this relationship was questioned by interpreting the shear zone as being only of local importance and considering the Embu Complex as a continuation of the Socorro Nappe, containing less

Figure 1. Tectonic map of the transition zone between the southern Brasília Belt and the central Ribeira Belt (Trouw *et al.* 2011).

pre-collisional magmatic arc granitoids (Trouw *et al.* 2011). While the Socorro Nappe is composed mainly of the “root” of the magmatic arc (670 – 615 Ma, Campos Neto *et al.* 2011) embedded in meta-sedimentary rocks (Piracaia and Paraisópolis complexes), the Embu Complex is predominantly composed of pelitic meta-sedimentary rocks (Fernandes 1991) with local occurrences of quartzite, paragneiss, calc-silicate rock, marble, amphibolite, and few ultramafic lenses (talc schist). The reinterpretation mentioned above (Trouw *et al.* 2011) proposes that the Socorro Nappe and the Embu Complex have a gradational contact within the Paranapanema plate. Evidence in favor of this interpretation is the occurrence of the Serra do Quebra-Cangalha Granite, dated at *ca* 680 Ma (Janasi *et al.* 2003) intruding the Embu Complex.

The host rocks of the Marins Granite are predominantly paragneisses and schists of the Embu Complex, and locally orthogneisses (Hasui *et al.* 1981; Fernandes 1991). The schists contain biotite, muscovite, quartz, plagioclase, garnet, and staurolite (locally); they are intercalated with layered biotite gneisses. Discontinuous layers of amphibolite with centimetric thickness are locally present. Metric layers of calc-silicate rocks occur subordinately. Talc-schist was observed at one locality. The attitude of the regional foliation is about 160/40, trending NE-SW; it is deflected around the Marins Granite.

The Marins Granite is a body of about 70 km² with porphyritic sieno to monzogranitic varieties. The shape is slightly ellipsoidal with NE-SW direction of the major axis and it presents concordant and discordant contacts with the host rocks (Fig. 2). Sills and dikes of the granite are present in the host rocks with thickness of a few centimeters up to several meters (Fig. 3). The granite sustains a range of mountains more than 2,000 m high, culminating to the east in the Marins Peak (2,421 m) and to the west in the Itaguapé Peak (2,308 m).

PETROGRAPHIC FEATURES

The Marins Granite consists of a hololeucocratic granitic body with color index ranging between 2 and 6% of mafic minerals. It displays a porphyritic texture with phenocrysts of microcline. Two lithofacies were individualized: Marins facies and Mendanha facies.

The prevailing Marins facies is isotropic, light gray, inequigranular porphyritic with euhedral to subhedral microcline phenocrysts of approximately 1 cm (Fig. 4).

Close to the northeastern edge, subhedral microcline phenocrysts have a preferred orientation, possibly as a result of igneous flow foliation. The Marins facies crops out continuously along the ridge that separates the Marins and Itaguapé peaks.

Figure 2. Geological map of the Marins Granite.

The Mendanha facies is present along the southwestern limit of the body; it is characterized by local deformation resulting in preferred orientation of pinkish deformed phenocrysts of microcline and elongated biotite crystals and quartz ribbons (Fig. 5) as a consequence of the presence of a shear zone in this area.

At one site in the core of the body, a subvertical NE-SW shear zone with centimetric thickness and dextral movement was observed.

Figure 3. Dike of Marins Granite.

Figure 4. Microcline phenocrysts in the Marins lithofacies showing random arrangement.

At the microscope, the Marins facies is characterized by microcline phenocrysts up to 1 cm in size. Sparse biotite crystals are present in the fine to medium-grained granitic matrix, which consists mainly of quartz, microcline, plagioclase, and biotite. Apatite, sphene, allanite, zircon, and opaque minerals, usually as inclusions in major phases, represent the accessory minerals. Sericite and chlorite are secondary minerals. The quartz grains are up to 1 cm in size with sinuous contacts and locally exhibit undulose extinction and subgrains. The feldspar grains present serrated contacts and show recrystallization features, like recrystallized borders, wavy extinction, and polygonal contacts. Microcline shows typical “tartan” twinning with perthitic lamellae. Crystals of plagioclase (An_{35}) show polysynthetic twinning, antiperthite, and present alteration to sericite. The biotite is brown, has serrated contacts, and frequently occurs associated with allanite.

The Mendanha facies has similar mineralogical composition as the Marins facies, but differs by having a fine equigranular matrix, showing clusters of recrystallized microcline (Fig. 6).

Figure 5. Deformed microcline with preferential orientation in the Mendanha lithofacies.

Figure 6. Equigranular recrystallized microcline in Marins facies.

The microcline phenocrysts are elongated and some of them exhibit fractures filled with quartz (Fig. 7). Banded quartz with undulose extinction and reduction of size are evidence of recrystallization.

The petrographic classification was based on the location of the studied samples in the QAP diagram (Fig. 8), which deals with both lithofacies. Modal percentages were obtained by point counting of 800 points in each thin section (Tab. 1). The samples are located in the field of monzogranites and along the limit of syenogranites.

LITHOGEOCHEMISTRY

Major and trace elements were measured in the X-ray Fluorescence Laboratory of the Department of Geology, Federal University of Rio de Janeiro, via X-ray fluorescence spectrometer Philips PW2400, with an Rh tube. The loss on ignition was obtained by the weight of the sample before and

Figure 7. Infilling of quartz in fractures of microcline.

after heating at 950°C for half an hour. The major elements were detected by melting 1.2 g of powdered material with lithium tetra borate. The trace elements were determined in 7 g of sample powder, pressed with 1 g of agglutinative wax. The light elements were measured under the following conditions: flow detector, the analyzer crystal PET/Ge and 40 kV – 70 mA power tube. The heavy elements were analyzed with a sealed detector, LIF200/LIF220 crystal analyzers, and a 50 kV to 50 mA power tube. Based on analyses of standards, the relative analytical error was estimated: Si, Al (< 1%), Fe, Mg, Ca (1 – 2%), Ti, Na, K (3 – 5%), and other trace elements ($\leq 6\%$). Calibration curves were obtained from the analyses of the following international standards: NIM-P, 521-84n, GBW07112, GIT-IWG, ANRT, BE-N GIT, PM-S

Figure 8. QAP modal classification diagram for the Marins Granite. Both Marins (circles) and Mendanha Facies (crosses) are plotted.

Table 1. Modal composition (vol.%; 800 points counted in each thin section) of the Marins Granite

	PD-112	PD-35	PD-298	PD-152	PD-91	PD-21	PD-228
Quartz	29.8	28.8	39.4	35.1	31.8	39.3	42.1
Plagioclase	25.3	26.5	21.5	19.3	32.5	18.2	19.7
Biotite	4.9	2	1.5	1.8	4	5.7	4.7
K-feldspar	39.3	38.6	35.1	35.8	28	36.3	32.8
Opaques	0.5	tr	tr	tr	0.2	tr	tr
Zircon	tr	tr	tr	0.1	tr	tr	tr
Apatite	tr	tr	tr	tr	tr	tr	tr
Sericite	0.2	4	2.1	7.6	3.1	0.2	0.5
Allanite	tr	tr	tr	tr	tr	tr	tr
Sphene	tr	tr	tr	tr	tr	tr	tr
Clorite	tr	tr	tr	tr	0.92	tr	tr
Total	100	99.9	99.6	99.7	99.8	99.7	99.8
Q	31.57	30.67	41.04	38.91	34.45	41.9	44.5
A	41.63	41.1	36.56	39.69	30.34	38.7	34.67
P	26.8	28.22	22.4	21.4	35.21	19.4	20.82

Table 2. Results of major (in wt%) and trace elements (in ppm) analyses and geochemical parameters for the Marins Granite samples

	PD-21	PD-112	PD-35	PD-93
SiO ₂	77.06	76.41	73.85	71.83
TiO ₂	0.11	0.13	0.223	0.31
Al ₂ O ₃	12.06	12.54	14.30	15.16
Fe ₂ O _{3T}	1.44	1.55	1.31	2.24
MnO	0.02	0.02	0.02	0.03
MgO	0.04	0.06	0.30	0.42
CaO	0.66	0.63	1.31	1.49
Na ₂ O	2.88	3.01	2.52	3.18
K ₂ O	5.21	5.39	6.16	5.59
P ₂ O ₅	0.00	0.00	0.06	0.06
LOI	0.5	0.33	0.25	0.16
Total	99.99	100.08	100.29	100.46

Cr	42	---	39	58
Ni	38	0.5	38	37
V	16	11	29	41
Zn	49	32	47	70
Rb	309	271.6	179	237
Ba	585	118	1198	1144
Sr	45	31.2	246	243
Nb	32	16.5	27	25
Zr	145	155.9	185	219
Y	33	0.66	25	26
A/CNK	1.04	1.05	1.08	1.08
Mg#	0.05	0.07	0.31	0.27
K/Rb	139.9	164.8	285.8	195.8
Rb/Sr	6.87	8.71	0.73	0.98

La	63.7	78.0	25.3	66.7
Ce	134.4	159.1	54.8	122.5
Pr	15.7	17.88	6.2	13.27
Nd	53.5	67.3	20.6	44.9
Sm	9.59	11.72	3.65	5.87
Eu	0.34	0.38	0.39	1.00
Gd	7.81	8.36	2.61	3.33
Tb	1.24	1.30	0.39	0.36
Dy	6.97	7.46	2.07	1.45
Ho	1.34	1.37	0.38	0.22
Er	3.45	4.22	1.13	0.59
Tm	0.51	0.66	0.16	0.08
Yb	3.37	3.83	1.18	0.49
Lu	0.47	0.63	0.17	0.07
Total ETR	302.39	362.21	119.03	260.83

(Ce/Yb)N	10.32	10.74	12.01	64.67
(Dy/Yb)N	1.34	1.26	1.14	1.92
Eu/Eu*N	0.12	0.11	1.19	0.63

A/CNK: $Al_2O_3 / (Na_2O + CaO + K_2O)$; Mg#: $(MgO/40.3) / [(MgO/40.3) + (Fe_2O_3/159.69) * 2]$; Eu/Eu*N: $(Eu/0.0735) / [(Sm/0.195) + (Gd/0.259) / 2]$; normalized by Boynton (1984).

GIT, CRPG BR, AN-G GIT, GBW07104, GBW07110, GBW07111, AC-E, GS-N, N-MA, and CRPG GH. Trace elements of sample PD-112 and rare earth elements were analyzed in the Acme Analytical Laboratories Ltd. laboratory (Vancouver, Canada) by ICP-MS equipment from the fusion of the sample with 0.5 g of LiBO₂.

Four chemical analyses of major, trace, and rare earth elements were acquired, where two samples represented the Marins lithofacies and the other two represented the Mendanha lithofacies (plotted in black in the figures below). The samples were analyzed together with the results presented by Pereira et al. (2001) (plotted in gray). The circles correspond to Mendanha lithofacies and the crosses to Marins lithofacies.

Tab. 2 presents the chemical analyses of major and trace elements, including the rare earth elements. For the normalization of rare earth element (REE), chondrite of Boynton (1984) was used. The analyzed samples present SiO₂ content between 71 and 77% by weight, characterizing a strongly differentiated granite, with a little expanded sequence of acid character. The Marins facies is more evolved than the Mendanha facies, a fact also observed by Pereira et al. (2001).

Using the QxP diagram of Debon & Le Fort (1983) for classification of plutonic rocks, the samples are located in the granite field (Fig. 9).

In the AFM diagram (Fig. 10), proposed by Irvine & Baragar (1971), samples of the Marins Granite plot in the calc-alkaline field in a sub-parallel array to the AF side of the triangle. In the SiO₂ x K₂O diagram (Peccerillo & Taylor 1976), the Marins Granite samples are located mainly in

Figure 9. QxP geochemistry classification diagram (Debon & Le Fort 1983) for samples of the Marins Granite. Symbols: crosses – Mendanha lithofacies and circles – Marins lithofacies. Samples of Pereira et al. (2001) are plotted in gray color.

the high-K calc-alkaline field (Fig. 11). Despite the fact that some samples plot in the shoshonite series field, their geochemical features do not match with the shoshonite parameters defined by Morisson (1980). The diagrams proposed by Frost et al. (2001) to characterize magmatism show a ferrous character (Fig. 12) and a calc-alkalic to alkali-calcic compositional trend reveals the nature of the magma to be rich in potassium (Fig. 13). The A/CNK ratios are between 1.0 and 1.1, confirming a weakly per-aluminous character (Fig. 14).

Figure 10. AFM diagram for the Marins Granite. Symbology as in Fig. 9.

Figure 12. $\text{FeO}/(\text{FeO}+\text{MgO}) \times \text{SiO}_2$ (Frost et al. 2001) diagram for samples of the Marins Granite. Symbology as in Fig. 9.

Figure 11. $\text{SiO}_2 \times \text{K}_2\text{O}$ diagram for samples of the Marins Granite. Symbology as in Fig. 9.

Figure 13. $(\text{Na}_2\text{O}+\text{K}_2\text{O}) \times \text{SiO}_2$ (Frost et al. 2001) diagram for samples of the Marins Granite. Symbology as in Fig. 9.

Figure 14. A/CNK diagram for samples of the Marins Granite. Symbolology as in Fig. 9.

small. Note that although the modal counting indicates trace content of accessory minerals, the thin section of sample PD-112 shows an increase in concentration of accessory phases.

The pattern of rare earth elements (Fig. 15) shows considerable enrichment in the light rare earth elements ranging from 100 to 500 times chondrite and negative Eu anomaly, suggesting retention of this element in the source or fractionation of plagioclase during magma crystallization. The variation of REE concentrations resulted in a moderately discontinuous pattern, with Ce/Yb_N ratios ranging from 10.32 to 64.67.

Using the parameters devised by Chappell & White (1974) for geochemical classification of granite, the Marins Granite samples show typical I-type granite characteristics (A/CNK < 1.1; moderate Na₂O contents for the range of silica and almost linear variation diagrams). Petrographical aspects such as biotite with pleochroism ranging from pale brown to brown and apatite included preferably in biotite are characteristics of I-type granite, as described by Chappell & White (2001).

Regarding the tectonic environment, the samples are positioned on the diagram $R_1 \times R_2$ (Batchelor & Bowden, 1985), forming a trend from syn to post-col-lisional (Fig. 16).

NEODYMIUM ISOTOPES

Sm-Nd data were obtained for sample PD-21 at the Pará-Iso Isotope Geology Laboratory of the Federal University of Pará (Tab. 3). The results indicate strong fractionation of Sm/Nd, which can be verified by factor

Figure 15. Chondrite-normalized REE diagram (Boynton 1984) for samples of the Marins Granite. Symbols: circles – Mendanha lithofacies and crosses – Marins lithofacies. Samples of Pereira *et al.* (2001) are plotted in gray.

Figure 16. $R_1 \times R_2$ (Batchelor & Bowden, 1985) diagram, with data from the Marins Granite. Symbols: crosses – Mendanha lithofacies and circles – Marins lithofacies. Samples of Pereira *et al.* (2001) are plotted in gray color.

$f_{\text{Sm/Nd}}$ (-0.4). $^{147}\text{Sm}/^{144}\text{Nd}$ isotope ratios ranging from 0.09 to 0.125 are common in most granitoids of the South American Platform, corresponding to $f_{\text{Sm/Nd}}$ between -0.35 and -0.60 (Sato & Siga 2000). The isotopic evolution of Nd for the Marins Granite is shown in Fig. 17. The T_{DM} age of 1.99 Ga indicates a Paleoproterozoic mantle extraction for the granite, a period of significant generation of continental crust (Cordani & Sato 1999). The value of $\epsilon_{\text{Nd}(0.6)}$ is very negative (-10.37), indicating a crustal source for the Marins Granite.

Table 3. Sm-Nd for sample PD-21 (Mendanha Facies) of the Marins Granite

Sample	$^{147}\text{Sm}/^{144}\text{Nd}$	$f_{\text{Sm}/\text{Nd}}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Sm (ppm)	Nd (ppm)	$\epsilon_{\text{Nd}(0)}$	T (Ga)	$\epsilon_{\text{Nd}(0.6)}$	T_{DM} (Ga)
PD-21	0,118068	-0,40	0,511798	9,78	50,08	-16,4	0,6	-10,37	1,99

U-PB ZIRCON GEOCHRONOLOGY

The samples were cleaned with compressed air, crushed, and ground in a disk mill in the Geological Sample Preparation Laboratory (LGPA – UERJ). The heavy minerals were separated by manual panning. After removing the magnetic iron fraction, bromoform separation was carried out and zircon grains were concentrated with a Franz isomagnetic separator. Initially lateral tilting at 10° and frontal slope at 5° were maintained; the amperage was changed to 0.2 A, 0.5 A, 0.75 A, 1.0 A, and 1.5 A. In final Franz, the maximum amperage (1.5 A) with frontal inclination of 5° was maintained, whereas the lateral tilting was changed to 5°, 3°, 1°, and -0.5°, respectively. The zircon grains were selected manually using pincers and a binocular microscope. The grains were glued on a thin section with epoxy resin and polished prior to the isotopic stereomicroscope analyses.

In the geochronology laboratory of Frankfurt University (Goethe Universität Frankfurt), cathodoluminescence images were obtained using an electron microscope (SEM). The U-Th-Pb isotope analyses were performed by LA-ICP-MS using a two-element Thermo-Finnigan coupled to a New Wave Research UP-213 laser system, following the methods detailed in Frei & Gerdes (2009). The diameter of the laser ranged from 20 to 30 microns, with approximately 15 – 20 µm in depth.

Cathodoluminescence images of zircon grains selected in the PD-35 (Marins facies) and PD-112 (Mendanha facies) samples show elongated prismatic shapes with 1x2 ratios between width and length. The grains have well-defined crystal faces, are bi-terminated, and zoned with alternating high and low luminescent domains. Fractures and inclusions were avoided during analysis. Careful study of zircon grains and their zoning, fractures, inclusions, and overgrowth determined the choice of areas for dating the samples (Fig. 18).

The results yield a concordia age of 607 ± 2 Ma for the Mendanha facies (sample PD-112) and a concordia age of 604 ± 5 Ma for the Marins facies crystallization (sample PD-35; Fig. 19). Therefore, considering the error, an age *ca.* 605 Ma is assumed as the crystallization age of the Marins Granite. Ages between 640 and 740 Ma are interpreted as inherited cores. Tables 4 and 5 present laser ablation U/Pb analytical data from samples PD-112 and PD-35, respectively.

Figure 17. ϵ_{Nd} x T(Ga) diagram for sample PD-21 (Mendanha Facies) of the Marins Granite. Symbology as in Fig. 15.

Pereira *et al.* (2001), using the evaporation method (Pb-Pb) in zircon, obtained 592 ± 5 Ma for crystallization of this body and reported the presence of inherited zircon with ages between 793 and 644 Ma.

DISCUSSION AND CONCLUSIONS

Integrating petrographic, geochemical, and geochronological data, the Marins Granite shows a calc-alkaline, I-type character. The very negative epsilon Nd indicates that the granite resulted from partial melting of calc-alkaline Paleoproterozoic crust. This partial melting occurred in the upper plate, the region represented by the Socorro Nappe and the Embu Complex, both interpreted as parts of the Paranapanema paleoplate. The body, with crystallization age of *ca.* 605 Ma, is interpreted as late-collisional with respect to the collision that generated the southern Brasília Belt, dated in this region as 625 – 605 Ma (Trouw 2008). Considering geochronological data of porphyritic calc-alkaline granites of the Central Ribeira Belt, ranging from 585 to 580 Ma, Mendes *et al.* (2006, 2007) associate this time span to the syn-collisional event of the Ribeira Belt. Therefore, despite the geochemical similarity, the Marins Granite (605 Ma) is older than the collision of the Ribeira Belt (590 – 550 Ma, Heilbron *et al.* 2004), different from the suggestion by Pereira *et al.* (2001) who considered the Marins Granite

to be syn-collisional with respect to the Ribeira Belt. Regional mapping around the granite body showed that the region was deformed and metamorphosed by the collisional event of the Ribeira Belt (590 – 550 Ma), which is supported by the deformational style with foliation dipping to the SE and reverse faults with NW vergence. Metamorphic ages around 570 Ma were detected in rims of detrital zircon grains in the country rock (Trouw, 2008 and unpublished data). However, the Marins Granite preserves a characteristic isotropic texture and primary magmatic flow, suggesting that

the body remained resistant to these deformational and metamorphic events subsequent to its formation. The deviation of the foliation of the host rocks around the granite and small shear zones with dextral NE-SW direction within the body testify to this regional deformation related to the Ribeira Belt collision. On a microscopic scale, foliation defined by the preferred orientation of mica and its deviation along the contact of larger and stronger feldspar grains are observed in thin sections of the Mendanha lithofacies, which occurs at the edge of the body.

Figure 18. Zircon grains of Marins Granite.

Table 4. Laser ablation U/Pb analytical data from sample PD-112

spot	²⁰⁷ Pb (cps)	U (ppm)	Pb (ppm)	Th U	²⁰⁶ Pb (%)	²⁰⁶ Pb ²³⁸ U	±2σ	²⁰⁷ Pb (%)	±2σ	²⁰⁷ Pb ²⁰⁶ Pb	±2σ	rho	²⁰⁶ Pb ²³⁸ U	±2σ	²⁰⁷ Pb ²³⁵ U	±2σ	²⁰⁷ Pb ²⁰⁶ Pb	±2σ	conc. (%)
g1	21448	1485	170	0.47	1.23	0.09713	1.7	0.7992	2.8	0.05968	2.2	0.62	598	10	596	13	592	48	101
g3	19983	931	110	0.48	0.67	0.1001	1.6	0.8363	2.9	0.06061	2.4	0.57	615	9	617	13	625	51	98
g4	4784	186	25	0.19	0.11	0.1319	1.5	1.208	2.8	0.06642	2.4	0.53	799	11	804	16	819	49	97
g5	45573	2261	240	0.34	1.23	0.09172	1.8	0.7523	2.9	0.05949	2.3	0.61	566	10	570	13	585	50	97
g6	20967	974	110	0.57	0.06	0.09915	1.7	0.8209	2.1	0.06005	1.2	0.83	609	10	609	10	605	25	101
g7	18611	1909	220	0.67	1.35	0.09805	1.6	0.8117	3.3	0.06004	2.9	0.48	603	9	603	15	605	63	100
g8	4540	562	75	0.74	b.d.	0.1120	1.7	0.9651	2.8	0.06247	2.2	0.60	685	11	686	14	690	48	99
g9	14973	1815	180	0.41	1.34	0.09906	1.7	0.8143	3.0	0.05962	2.4	0.58	609	10	605	14	590	53	103
g10	13466	1611	180	0.47	0.77	0.09865	1.5	0.8228	2.2	0.06049	1.6	0.70	607	9	610	10	621	34	98
g11	11408	1381	160	0.49	0.06	0.09834	1.6	0.8121	2.1	0.05989	1.5	0.73	605	9	604	10	600	31	101
g12	4080	565	71	0.73	0.22	0.09788	1.8	0.8079	2.8	0.05986	2.1	0.64	602	10	601	13	598	46	101
g14	23867	3117	300	0.07	1.02	0.09883	1.7	0.8248	2.5	0.06052	1.8	0.68	608	10	611	11	622	39	98
g15	2317	327	38	0.54	0.07	0.09799	2.4	0.8039	3.6	0.05950	2.6	0.68	603	14	599	16	586	57	103
g18	15252	1853	210	0.37	1.57	0.09851	1.8	0.8096	3.3	0.05961	2.8	0.55	606	11	602	15	589	61	103
g19	6513	910	100	0.48	1.27	0.09563	2.0	0.7881	3.2	0.05977	2.5	0.63	589	11	590	14	595	53	99
g20	2159	238	27	0.51	2.21	0.09678	1.9	0.7931	4.1	0.05943	3.7	0.47	596	11	593	19	583	79	102
g22	11083	1514	180	0.63	1.12	0.09905	1.8	0.8263	3.1	0.06051	2.5	0.59	609	11	612	14	622	53	98
g23	5588	772	88	0.60	0.65	0.09528	1.7	0.7854	2.9	0.05978	2.4	0.58	587	9	589	13	596	51	98
f6	9054	607	66	0.39	0.11	0.09895	1.3	0.8092	2.2	0.05931	1.8	0.58	608	7	602	10	579	38	105
f9	28204	1820	170	0.39	0.11	0.09971	1.4	0.8241	1.8	0.05994	1.2	0.77	613	8	610	8	601	25	102
f10	16323	929	120	0.52	0.42	0.1084	1.4	0.9303	2.2	0.06223	1.7	0.65	664	9	668	11	682	36	97
f11	1060	77	8,7	0.48	b.d.	0.09779	1.5	0.8009	6.0	0.05940	5.8	0.25	601	9	597	28	582	127	103
f14	2594	363	44	0.67	0.60	0.09869	1.3	0.8203	3.6	0.06029	3.4	0.36	607	8	608	17	614	73	99
f16	7934	912	110	0.54	0.08	0.09669	1.4	0.8061	2.2	0.06046	1.7	0.63	595	8	600	10	620	38	96
f17	8983	1081	110	0.15	0.89	0.09987	2.0	0.8348	2.9	0.06062	2.0	0.70	614	12	616	13	626	44	98
f19	1624	105	15	0.72	1.50	0.09985	1.7	0.8276	4.2	0.06011	3.8	0.41	614	10	612	19	608	82	101
f20	1377	171	20	0.50	0.06	0.1010	1.6	0.8195	5.4	0.05886	5.1	0.30	620	9	608	25	562	111	110
f21	24529	1326	150	0.38	0.42	0.09969	1.7	0.8294	2.1	0.06034	1.3	0.80	613	10	613	10	616	28	99
f22	15654	856	85	0.16	b.d.	0.09951	1.3	0.8166	2.1	0.05952	1.6	0.64	612	8	606	10	586	35	104
f24	1483	181	21	0.37	0.59	0.1056	1.6	0.8826	5.0	0.0606	4.7	0.33	647	10	642	24	625	102	104
f26	3394	418	59	1.07	0.21	0.09969	1.7	0.8281	3.9	0.06025	3.5	0.44	613	10	613	18	612	76	100
f28	4219	577	61	0.38	0.15	0.09747	1.3	0.8024	3.6	0.05971	3.3	0.36	600	7	598	16	593	72	101

Figure 19. Marins Granite concordia age of Mendanha lithofacies (PD-112) and Marins lithofacies (PD-35).

Table 5. Laser ablation U/Pb analytical data from sample PD-35

spot	²⁰⁷ Pb (cps)	U (ppm)	Pb (ppm)	Th U	²⁰⁶ Pb (%)	²⁰⁶ Pb ²³⁸ U	±2σ (%)	²⁰⁷ Pb ²³⁵ U	±2σ (%)	²⁰⁷ Pb ²⁰⁶ Pb	±2σ (%)	rho	²⁰⁶ Pb ²³⁸ U	±2σ (Ma)	²⁰⁷ Pb ²³⁵ U	±2σ (Ma)	²⁰⁷ Pb ²⁰⁶ Pb	±2σ (Ma)	conc. (%)
a28	4131	60	11	1.76	1.06	0.1088	2.6	0.9393	5.3	0.06264	4.6	0.49	665	16	672	26	696	98	96
a29	25296	1384	190	0.20	0.00	0.1068	3.2	0.9041	5.3	0.06137	4.2	0.61	654	20	654	26	652	90	100
a30	17783	5608	290	0.06	0.70	0.05464	3.8	0.4028	4.5	0.05347	2.3	0.85	343	13	344	13	349	53	98
a31	6002	284	32	0.55	0.89	0.09735	1.8	0.8076	4.7	0.06017	4.4	0.39	599	11	601	22	610	94	98
a32	3334	140	17	0.57	1.50	0.1037	2.4	0.8712	4.1	0.06094	3.3	0.58	636	14	636	20	637	72	100
a33	28553	477	77	1.53	1.34	0.1030	1.9	0.8615	3.6	0.06067	3.1	0.53	632	12	631	17	628	66	101
a35	28896	1568	190	0.19	1.08	0.1091	2.7	0.9444	4.4	0.06276	3.4	0.63	668	17	675	22	700	73	95
a36	5665	514	63	0.25	1.10	0.1189	1.8	1.056	3.7	0.06442	3.2	0.50	724	12	732	19	755	67	96
a37	1808	303	37	0.27	0.52	0.1162	1.7	0.9941	4.8	0.06205	4.5	0.35	709	11	701	25	676	96	105
a38	21138	2194	220	0.19	0.16	0.102	3.6	0.8567	3.9	0.06094	1.6	0.91	626	21	628	18	637	34	98
a40	9172	703	84	0.28	b.d.	0.1111	2.5	0.9559	3.0	0.06239	1.6	0.84	679	16	681	15	688	35	99
a41	9321	902	100	0.22	0.09	0.1094	3.0	0.9339	3.6	0.06189	2.0	0.83	670	19	670	18	670	44	100
a42	9740	1408	160	0.22	0.44	0.1101	2.9	0.9518	3.5	0.06268	2.0	0.81	674	18	679	18	697	43	97
a44	4495	410	49	0.36	b.d.	0.1129	4.3	0.9677	5.7	0.06217	3.7	0.76	690	28	687	29	680	79	101
a45	3743	320	37	0.34	0.26	0.1077	3.7	0.9138	5.2	0.06156	3.6	0.72	659	23	659	25	659	77	100
a46	17066	1133	170	0.35	0.89	0.1198	3.4	1.052	4.2	0.06370	2.6	0.80	729	23	730	22	732	54	100
a47	18536	810	140	0.35	1.93	0.1223	2.9	1.078	3.6	0.06392	2.1	0.81	744	20	742	19	739	45	101
f31	26410	1256	127	0.16	1.2	0.0983	2.5	0.8168	3.5	0.0603	2.4	0.72	604	15	606	16	613	52	99
f32	42337	2306	237	0.19	2.3	0.0995	5.5	0.8250	6.8	0.0601	4.1	0.80	612	32	611	32	608	88	101
f33	3401	189	21	0.75	b.d.	0.0912	1.7	0.7615	4.8	0.0605	4.5	0.36	563	9	575	21	623	96	90
f34	4943	288	30	0.35	2.3	0.0961	3.0	0.7907	6.3	0.0597	5.5	0.47	592	17	592	29	591	120	100
f35	36198	1516	161	0.21	1.5	0.0978	3.4	0.7944	5.0	0.0589	3.6	0.68	602	19	594	23	563	79	107
f36	12087	671	68	0.22	b.d.	0.0985	2.3	0.8033	3.7	0.0591	3.0	0.61	606	13	599	17	572	64	106
f37	14384	911	99	0.36	b.d.	0.1011	1.6	0.8463	3.3	0.0607	2.9	0.49	621	10	623	16	628	62	99
f38	10283	587	58	0.19	b.d.	0.0977	2.8	0.8039	3.6	0.0597	2.2	0.79	601	16	599	16	592	47	102
f41	3731	164	18	0.94	b.d.	0.0968	2.2	0.7978	5.0	0.0597	4.5	0.45	596	13	596	23	594	97	100
f43	1889	109	12	0.47	b.d.	0.0976	2.3	0.8087	5.0	0.0601	4.5	0.45	601	13	602	23	606	97	99

Figure 20. Schematic drawing suggesting that the Marins Granite behaved like a rigid body during the Ribeira tectonic event.

The schematic sketch (Fig. 20) shows how the granite may have behaved as a rigid body, similar to a porphyroblast in a schist during the tectonic event of the Ribeira Belt. Thus, this event would have been responsible for the strong foliation deviation around the granitic body, yet without changing its isotropic character.

ACKNOWLEDGMENTS

We thank FAPERJ (Foundation for Research Support of Rio de Janeiro), CAPES, and CNPq for financial aid and scholarships. We are also grateful to the reviewers for their careful comments and suggestions.

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