THE MAUÁ GRANITIC MASSIF, CENTRAL RIBEIRA BELT, SÃO PAULO: PETROGRAPHY, GEOCHEMISTRY AND U-PB DATING

MARCELO FILIPOV¹ & VALDECIR DE ASSIS JANASI²

ABSTRACT The Mauá granitic massif is an elongated body dominated by a porphyritic biotite monzogranite which grades, in its southwestern extremity, to lighter equigranular granite and greisenized (tourmaline)-biotite-muscovite leucogranite. Abundant enclaves can be divided in three types: grey *microgranular enclaves*, with rounded shapes and igneous textures, are compositionally similar to the enclosing porphyritic granites; dark, rounded, *micaceous enclaves* have high K/Na, and may correspond to highly assimilated metasedimentary xenoliths; and angular *gneiss xenoliths* seem to be fragments of an unexposed type of country rock.

The primitive magmas that formed the massif were Zr, P and LREE-saturated, and became progressively enriched in U, Cs, Y, HREE, F and possibly Ta.

Geochemical data show that most of the observed compositional variation can be a reflection of crystal fractionation at the level of emplacement. However, other processes such as magma mixing, contamination and post-magmatic alteration seem to respond for local chemical variations. U-Pb monazite dating point to a crystallization age of 588 ± 2 Ma which is ca. 20 myr. younger than those of nearby crust-derived syn-orogenic granites.

Keywords: granite, enclave, geochemistry, monazite, U-Pb geochronology, Ribeira Belt

RESUMO O maciço granítico Mauá é um corpo alongado dominado por um biotita monzogranito porfirítico que grada, em seu extremo sudoeste, para um granito equigranular mais claro e para um (turmalina)-biotita-muscovita leucogranito greisenizado. Enclaves são abundantes, e de três tipos: *enclaves microgranulares* graníticos, com formas arredondadas e texturas ígneas, são similares composicionalmente aos granitos porfiríticos que os contêm; *enclaves micáceas* escuros, arredondados, têm alto K/Na, e devem corresponder a xenólitos metassedimentares bastante assimilados; e *xenólitos gnáissicos* angulosos devem ser fragmentos de um tipo não-exposto de rocha encaixante.

Os magmas primitivos que formaram o maciço eram saturados em Zr, P e ETRL, e se tornaram progressivamente mais ricos em U, Cs, Y, ETRP, F e possivelmente Ta. Os dados geoquímicos mostram que a principal variação composicional observada no maciço pode refletir cristalização fracionada ao nível de colocação. Outros processos, como mistura de magmas, contaminação e alteração hidrotermal podem responder por variações químicas locais. Datação U-Pb em monazita indica uma idade de cristalização de 588 ± 2 Ma que é ca. 20 milhões de anos mais nova que a de granitos sin-orogênicos de derivação crustal vizinhos.

Palavras-chave: granito, enclave, geoquímica, monazita, geocronologia U-Pb, Cinturão Ribeira

INTRODUCTION A series of elongated, small to medium-sized granite massifs intrude the Ribeira Belt south of the São Paulo city. Although some general field and petrographic characteristics of these occurrences are known from mapping reports (Coutinho 1972, Theodorovicz *et al.* 1990) and academic thesis (Alves 1975, Motidome 1992), none was the subject of more detailed work with emphasis on petrological aspects (cf. Janasi & Ulbrich 1992 for data available for these occurrences in the early 1990s). Mauá is one of the largest massifs in the region, and probably the best exposed, since it has been exhaustively exploited as dimension stone during the last decades. Its main petrographic facies is well-known in the dimension stone market as "granito cinza Mauá" (grey Mauá granite).

Taking advantage of the excellent exposures (even though mostly restricted to boulders cut for exploitation), several samples of this granite were collected and subjected to petrographic, geochemical and geochronological studies. We present here these data in an integrated way, as a contribution to the petrogenesis of the granite magmatism in this portion of the Ribeira Belt.

GEOLOGICAL SETTING The Neoproterozoic Ribeira Fold Belt (RFB) extends for ca. 1500 km in the NE-SW direction along the coastal areas of Southeastern Brazil (Fig. 1, inset). Its central and northern segments separated, in pre-drift reconstructions, the São Francisco (SFC) and Congo Cratons. The southern segment of the RFB is covered to the north by the Paleozoic and younger volcano-sedimentary sequences of the Paraná Basin. These possibly overlie another stable area (the Paraná Craton of some authors) which was juxtaposed to the São Francisco Craton immediately prior to the development of the RFB (e.g., Ribeiro *et al.* 1995).

The depositional age of various metasedimentary sequences described in the RFB is still a matter of debate. Both Mesoproterozoic and Neoproterozoic sequences appear to be present but, in the absence of reliable direct determinations, many estimates remain highly

speculative. A dominantly gneissic-migmatitic basement, of Paleoproterozoic and older age, has been recognized in several areas (e.g., Machado *et al.* 1996) within the RFB, including nuclei cropping out some tens of kilometers to the E of the Mauá granite (Tassinari 1988, Fernandes 1991).

Neoproterozoic granites are abundant throughout the entire RFB, in part as huge strike-parallel batholiths. Several granite types or suites have been recognized based on their petrographic affinities and structural relationships (Hasui *et al.* 1978; Janasi & Ulbrich 1991; Machado & Demange 1996). Recent U-Pb data have shown that the "syn-orogenic" granitic magmatism was diachronous throughout the RFB. Older ages (610-600 Ma) are reported for high-K calc-alkaline and peraluminous leucogranites in the Agudos Grandes and Três Córregos batholiths in the State of São Paulo (Janasi *et al.* 2001, Gimenez Filho *et al.* 2000), while ages in the 590-565 Ma range are typical of similar rocks in the northeastern portion of the belt in the States of Rio de Janeiro and Espírito Santo (Söllner *et al.* 1987, Campos Neto & Figueiredo 1995, Machado *et al.* 1996, Tupinambá 1999).

The Mauá granite is one of several smaller biotite-only or biotite + muscovite-granite bodies appearing along an extensive belt south and east of the São Paulo city (Fig. 1) within the so-called Embu Domain. No precise age determinations are available for these granites, which are thought to be mostly derived from crustal protoliths (Wernick *et al.* 1985, Wernick & Galembeck 1987, Janasi & Ulbrich 1991).

GEOLOGY OF THE MAUÁ MASSIF **Local geology** The Mauá massif occurs as an elongated body oriented N45E (22 x 2-2.5 km; ca. 45 km²) intruding low- to medium-grade metasedimentary rocks (Fig. 2). Low-grade sericite phyllites and fine-grained ($\pm$ garnet) muscovite-biotite schists are the country rocks of the N and NE portions of the Mauá massif, while ($\pm$ garnet $\pm$ kyanite)-sillimanite-muscovite-biotite schists with local variations to fine-grained gneisses predominate in its southern half (Theodorovicz *et al.* 1990, Silva

¹ filipov@usp.br. Pós-Graduação, Departamento de Engenharia de Minas, Escola Politécnica, Universidade de São Paulo, CEP 05508-900, São Paulo, SP, Brasil.

² vajanasi@usp.br. Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562 (Cidade Universitária), CEP 05508-900, São Paulo, SP, Brasil

1992). Although uncommon in the neighborhood of the Mauá massif, a variety of orthogneisses are recognized in this portion of the Embu Domain; those with well-developed migmatitic structures are interpreted as Paleoproterozoic or older basement sequences (e.g., Sadowski 1977), while more homogeneous bodies may correspond to early Neoproterozoic intrusions (e.g., Coutinho 1972, Fernandes 1991).

Other granite massifs occurring in this portion of the Embu Domain are as yet known only in their general petrographic features. Contrary to the Mauá massif (see below), most of these occurrences are made up of granites with a conspicuous solid-state foliation, and are interpreted as syn-orogenic. No hornblende-bearing, typically metaluminous, granites are recognized within these massifs. The main variations are from less fractionated porphyritic biotite granites (e.g., the predominant rock type in the Itapeti massif, Morais 1995) to equigranular two-mica ($\pm$ garnet, tourmaline) granites (e.g., Santa Branca, Iupeba, Guacuri massifs; Alves 1975, Silva 1992, Wernick et al. 1985) and associated ($\pm$ muscovite $\pm$ garnet) tourmaline pegmatites.

Field aspects of the main granite facies Early maps (Coutinho 1972) show the Mauá massif to be made up of a single granite type (a grey porphyritic biotite granite), and surrounded by a thin gneissic envelope corresponding to a more deformed border facies. In the more detailed work of Theodorovicz et al. (1990), a small leucogranite body was mapped in the southwesternmost portion of the massif, and described as transitional into the main porphyritic facies.

A *porphyritic biotite granite* is the predominant rock type over most of the massif. It corresponds to the "Mauá grey granite", exploited as a dimension stone in several quarries, and employed in many buildings (e.g., some subway stations, in the city of São Paulo). The rock usually exhibits a flow foliation, defined by the orientation of the white, tabular, 2-3 cm long K-feldspar megacrysts, of the abundant

enclaves (see below) and, to a lesser extent, of the biotite from the medium-grained groundmass.

Modal analyses performed on 150-300 cm² polished surfaces stained with sodium cobaltinitrite point to monzogranite compositions with a slight predominance of plagioclase over alkali feldspar (25 Qtz: 40 Pl: 35 Af when recalculated to 100%) and color indices of 7 to 10 (corresponding almost essentially to the biotite content).

The *leucogranites* forming the SW portion of the massif are part of a shallow-level cupola that was moderately affected by hydrothermal processes. The rock is a white to light-grey equigranular biotite-muscovite monzogranite with color index under 5, and is usually deeply weathered. Centimeter-sized irregular-shaped pegmatites with miarolitic cavities (Fig. 3a) and decimeter-sized ball-shaped mica-quartz greisens were identified in fracture zones in some exposures of fresh rock within an area of former sand extraction from the granite-derived saprolite (point 5, Fig. 2). One to two meter-wide dikes of medium-grained tourmaline granite locally cut the biotite-muscovite leucogranite. Veins of tourmalinite with some cm-sized tourmaline crystals may appear in fracture planes.

There is an apparently continuous transition from the biotite-muscovite leucogranite to the porphyritic biotite granite through an inequigranular facies with intermediate color indices which predominates in the area between the SW corner and the eastern half of the massif (points 8, 12 and 13; Fig. 2).

Enclaves The presence and abundance of enclaves is a conspicuous feature in the Mauá massif. The most abundant type of enclave is usually a grey, fine-grained rock with igneous texture and felsic ("granitic") composition. It appears as rounded, decimeter- to centimeter-sized bodies elongated parallel to the flow foliation of the porphyritic granites (Fig. 3b); a typical feature is the development of a remarkable concentration of white feldspar megacrysts similar to those of the country granites surrounding the enclaves, a feature attributable to flow differentiation (Fig. 3c). The presence of such

Figure 1. Geological sketch map of the central Ribeira Belt in the State of São Paulo, Brazil (simplified from Campos Neto 2000). 1= Phanerozoic cover and intrusive rocks; 2= late- and post-orogenic granites (Ita Province); 3= peraluminous, (garnet)-(muscovite)-biotite granites; 4= porphyritic biotite granites; 5= porphyritic hornblende-biotite granites; 6= Socorro-Guaxupé Nappe (mostly garnet-bearing migmatites); 7= São Roque Group (mostly low-grade metapelites and metapsammities); 8= Serra do Itaberaba Group (medium-grade metavolcanosedimentary sequences); 9= Embu and Pilar do Sul complexes (respectively, medium and low-grade metapsupracrustals); 10= Paleoproterozoic and older gneissic basement to the Embu Complex; 11= Costeiro Complex (ortho- and para-derived migmatites); 12= faults, some with directional movement indicated. Inset: main tectonic provinces of Brazil. SFC= São Francisco craton; RFB= Ribeira Fold Belt.

megacrysts, often of slightly smaller size and mantled by plagioclase, within the fine-grained enclaves is an indication that some kind of interaction between these two magmas (grossly of similar composition) took place in a plastic state.

A second type of enclave, less abundant and of smaller size (usually

Figure 2. Main geologic units of the 1:50,000 Mauá sheet (simplified from Theodorovicz et al. 1990 and Silva 1992). 1 to 4: Embu Complex; 1= paragneisses and feldspathic schists; 2= migmatitic gneisses, mostly paraderived; 3= Sillimanite-kyanite-mica schists; 4= low- to medium-grade metapelites and metapsammities; 5= orthogneisses and migmatites (Costeiro Complex); 6= syn-orogenic granitic massifs (mostly muscovite-biotite equigranular granite); 7= late-orogenic Mauá granitic massif; 8= Tertiary-Quaternary sediments (São Paulo Basin); 9= Quaternary alluvionary sediments; 10= main roads; 11= main cities; 12= location of samples.

Figure 3. Field photographs of the Mauá granite massif. A) Mirolitic cavities partly filled with a muscovite pegmatite in the most differentiated facies of the Mauá massif, a muscovite-biotite leucogranite (point MAU-5); B) Rounded and elongated grey, 15 cm-long microgranitic enclave within the porphyritic biotite granite; note a single large white K-feldspar megacryst within the enclave and biotite-rich spots in the granite (point MAU-9); C) Flow-parallel concentration of K-feldspar megacrysts surrounding an oval-shaped microgranitic enclave (point MAU-2); D) A 2 cm rounded biotite-rich enclave within the porphyritic biotite granite (point MAU-9); E) Small biotite-rich enclaves grading to spots in the porphyritic biotite granite (point MAU-2); F) Sharp contact between gneiss xenolith and inequigranular biotite granite from point MAU-8. Pen in photographs A to E is 12 cm long; label in photograph F is 4 cm long.

centimetric), is a dark, biotite-rich enclave that also appears within the porphyritic biotite granite in most of the quarries visited (Fig. 3d). These enclaves look like schist xenoliths in an advanced stage of assimilation, as suggested by their rounded shapes and small sizes, and sometimes seem grade into the granite groundmass (Fig. 3e).

A third type of enclave was found only in point 8, where the inequigranular granite hosts a meter-sized xenolith of greyish medium-grained biotite gneiss. The contact is sharp and angular (Fig. 3f).

MICROSCOPIC PETROGRAPHY **Porphyritic biotite monzogranite** The microcline megacrysts show Carlsbad and well-developed tartan twinning; string perthite usually occurs in small amounts. Randomly-oriented inclusions of biotite and tabular plagioclase showing thin albite rims are common. The borders of the megacrysts are often corroded by myrmecite.

Plagioclase (An₂₇₋₂₄) predominates over xenomorphic microcline and quartz in the groundmass; it is usually subidiomorphic, shows both Carlsbad and polysynthetic twinning, and has a discrete zoning enhanced by the saussuritization of the cores.

Quartz appears as mosaic aggregates derived from originally xenomorphic crystals with interstitial to curved contacts with the feldspars, suggestive that it was the last felsic mineral to start crystallization.

Reddish-brown biotite is subidiomorphic to xenomorphic, and is locally interstitial to plagioclase.

Apatite is a relatively abundant, early-formed accessory mineral found as inclusions in both feldspars and in the biotite. Small crystals of zircon occur mostly as inclusions in biotite, developing wide pleochroic haloes. Prismatic bluish tourmaline is identified in some samples, in part as inclusions in biotite. Titanite is xenomorphic and always associated to the biotite borders (Fig. 4a); epidote may appear in a similar manner. Allanite occurs in most samples as zoned, prismatic, strongly metamictic crystals with sizes up to 2 mm, in part rimmed by epidote, and occasionally including prismatic apatite (Fig. 4b). Monazite is present in most samples, but is invariably corroded and mantled by allanite or an allanite-apatite intergrowth, except when included in the larger biotite crystals. These features, illustrated in Figs. 4c and 4d, suggest that the monazite was brought to the magma as inclusions in biotite xenocrysts, many of which also are clearly corroded. The opaque mineral is mostly ilmenite; magnetite is rare or absent, as reflected in the low total magnetic susceptibility of the rock (ca. 0.2×10^{-3} SI).

Secondary minerals are the products of subsolidus reactions involving biotite (chlorite + titanite + opaques) and the cores of plagioclase (epidote + calcite + sericite).

Biotite-muscovite leucogranite The more felsic leucogranite sample (MAU-5) is mostly composed of subidiomorphic oligoclase with cores partly replaced by muscovite aggregates and weakly perthitic xenomorphic microcline bearing small inclusions of rounded quartz, the latter mainly forming polygonal aggregates derived from the recrystallization of larger (up to 3 mm) grains. Reddish-brown biotite is xenomorphic, shows rare zircon and monazite inclusions, and is often strongly altered to chlorite + titanite or to aggregates of small titanite and opaque mineral. Muscovite is to a large extent clearly secondary, replacing plagioclase and biotite, but some interstitial, primary crystals can be identified. Apatite is rare and allanite is absent. Fluorite is a common alteration product in the cores of plagioclase. Fe-Ti oxides are rare and restricted to ilmenite, as attested by the extremely low total magnetic susceptibility of the rock ($0.01\text{--}0.03 \times 10^{-3}$ SI).

Inequigranular biotite monzogranite Inequigranular granites intermediate between the porphyritic monzogranite and the leucogranite in terms of color index, texture and mineralogy occur east of Mauá (points 8 and 12, Fig. 2). Muscovite is present, but in minor proportions, and is clearly secondary. Allanite, epidote and titanite occur, but in lesser proportions as compared to the porphyritic monzogranites.

Felsic microgranular enclaves The modal composition of the felsic microgranular enclaves is similar to that of the host porphyritic biotite granites. The textures are subvolcanic, and the preservation of some delicate features attests that the crystallization occurred at a shallow-level, with no important concomitant deformation. Zoning in subidiomorphic plagioclase crystals is here more pronounced, with a clear optical distinction between andesine (An_{32}) cores and oligoclase (An_{66}) borders. A granophyric (alkali feldspar-subrounded quartz) intergrowth is common, and mantles some early-crystallized feldspars (Fig. 4e). Some larger quartz crystals seem to have been corroded. The reddish-brown biotite is subidiomorphic to xenomorphic and rich in accessory mineral inclusions.

The accessory minerals are the same present in the host porphyritic granites: prismatic apatite with up to 1 mm; prismatic, zoned allanite

with epidote rims; zircon and monazite, both mostly as inclusions developing pleochroic haloes in biotite; and prismatic blue tourmaline. Some small (0.2–0.3 mm) titanite crystals appear in the groundmass, and may be of magmatic origin.

Mica-rich enclaves The texture of these enclaves is typically metamorphic, granolepidoblastic, with a mosaic of reddish-brown biotite (up to 30% of the mode) and quartz + feldspar (microcline >> plagioclase) defining a thin foliation sometimes tightly folded in a microscope scale (Fig. 4f). Accessory minerals are mostly small crystals of zircon, titanite and rare blue tourmaline.

Gneissic enclave The gneissic enclave (sample MAU-6a) is a biotite gneiss of granitic composition showing a seriated texture with clear signs of solid-state recrystallization, such as a widespread microgranulation surrounding the larger, xenomorphic grains of quartz and feldspars, and the irregular, contorted shapes of the greenish-brown biotite. Accessory minerals are apatite, allanite, opaques and titanite, besides xenomorphic epidote crystals rich in quartz inclusions, and traces of garnet.

GEOCHEMISTRY Analytical techniques Major and some trace elements (Ba, Sr, Zr, Y, V) were analysed by ICP-AES at the ICP Laboratory, Instituto de Geociências, Universidade de São Paulo (USP), Brazil, on representative powdered samples dissolved after alkali fusion following the procedures described in Janasi *et al.* (1995). For three samples, identified in Table 1, the major elements contents were determined by ICP-AES while those of a large set of trace elements were obtained by ICP-MS at Activation Laboratories, Ancaster Canada. Trace elements additional to those analysed by ICP-AES at USP were determined in some samples by INAA at Activation Laboratories and by FRX at USP; these cases are noted in Table 1. Additional trace elements on sample MAU-11a were analysed at the Plasma Analytical Laboratory, University of Kansas, USA, by ICP-MS; for procedure details, see Janasi (1999).

Chemical affinities and evolution of the granites and felsic enclaves The granite samples from the Mauá massif show a small SiO_2 range (70–76 wt%) (note that data plotted in Fig. 5 were recalculated to 100% on an anhydrous basis, which raises the oxide contents of some samples with lower totals in Table 1). Additionally, silica contents decrease in the more extremely fractionated facies

Figure 4. Photomicrographies of selected textural features of the Mauá granite massif: a) Xenomorphic titanite occurring as inclusions and in the borders of subidiomorphic biotite crystals (porphyritic granite MAU-13a); b) Zoned, subidiomorphic allanite with apatite inclusion (MAU-13a); c) A monazite crystal at the border of a corroded biotite crystal is mantled by an intergrowth of allanite and apatite; note a pleochroic halo in the biotite (porphyritic granite MAU-14a); d) another monazite grain corroded and mantled by allanite + apatite. This seems to be a more advanced stage of the process shown in the previous photo (see text for discussion); the inclusions in the biotite crystal, clearly much more corroded here, are zircon and monazite (microgranite MAU-14b); e) granophyric intergrowth around an oligoclase crystal (microgranite MAU-2a); f) folded foliation of a biotite schist enclave (sample MAU-10a). Bar size = 1 mm.

(Fig. 5); because of this, we use another oxide (CaO) as a differentiation marker in binary variation diagrams.

The porphyritic granite typical of the massif has low **mg#** (ca. 20) and a slightly peraluminous character ($ASI = 1.01-1.03$); a sharp increase in **ASI** and decrease in **mg#** is observed in the more differentiated leucogranite sample ($ASI = 1.11$; **mg#** = 10; Table 1).

The felsic microgranular enclaves are chemically very similar to the host porphyritic biotite granites. The two rock types cluster together in the least fractionated portion (1.5-1.8 wt% CaO; 70-72 wt% SiO_2) of most diagrams; a slightly higher MgO content in the enclaves seems to be the only systematic chemical difference between them (Fig. 5). The microgranular enclave MAU-11b is the only outlier, and is depleted in alkali feldspar-resident elements (K, Na, Al, Ba, Sr).

Samples from outcrop MAU-14, a quarry located at the SE border of the massif (Fig. 2), show some slight, but perceptible, contrasts with similar rocks from other outcrops; more evident are the higher K and Al and lower Si contents of both the porphyritic granite and the microgranular enclave, in accordance with the presence of primary muscovite in these rocks.

Smooth trends can be traced in binary variation diagrams for all major and trace elements (Fig. 5), and seem consistent with crystal fractionation as the main mechanism of differentiation. The fractionation of the early-crystallized minerals plagioclase, biotite, Fe-Ti oxide, apatite, zircon and monazite can account for the decrease in

Ca, Fe, Mg, Ti, Ba, Sr, P, Zr and LREE. The passage to the more differentiated leucogranite sample MAU-5 is marked by an increase in Na and Al and a decrease in Si. This should be a result of the shift of the granite minimum towards more Ab-rich and Qtz-poor compositions at the final stages of differentiation, probably reflecting the increase in the a(HF), mineralogically evidenced by the appearance of fluorite as a late mineral in this sample.

The REE patterns of the granites and microgranular enclaves are shown in Fig. 6. Once again the similarity between the microgranular enclaves and their host porphyritic granites is evident. Both rock types show moderately fractionated REE patterns $[(La/Yb)_N = 12-16]$ with well-delineated negative Eu anomalies ($Eu/Eu^* = 0.5-0.6$), and a more pronounced LREE fractionation ($(La/Sm)_N = 4$ to 5)) as compared to that of the HREE $[(Tb/Yb)_N = ca. 1.5]$. The inequigranular granite (sample MAU-8a) owes its less fractionated REE pattern $[(La/Yb)_N = 10]$ to a greater increase in the HREE as compared to the LREE, suggestive that a mineral phase bearing the latter begins to be extracted from the magma at this stage. This tendency is more pronounced with further differentiation; additionally, the leucogranites show deep negative Eu anomalies, and the more fractionated sample (MAU-5) exhibits a typical "seagull wing" REE pattern (Fig. 6).

As usual, Y follows the HREE, and behaves as an incompatible element in the Mauá massif (Table 1). A few other trace-elements show a tendency to increase in the more felsic granites; these are U, Cs, Mn

Table 1. Results of geochemical analyses for granites and enclaves from the Mauá massif. Oxides in wt%; trace-elements in ppm. Numbers in italics refer to analyses done by XRF. For analytical methods used for other elements, refer to text. **Mg#** = molar $MgO/(MgO + FeO)$; **ASI** = molar $Al_2O_3/(CaO + K_2O + Na_2O)$; $T(Zrn\ sat)$ = zircon saturation temperature; $T(Mnz\ sat)1$ and 2 = monazite saturation temperatures, calculated with 3.5 wt% and 8 wt% water in the magma, respectively; $T(Ap\ sat)$ = apatite saturation temperature; all temperatures in degrees centigrade. * Samples analysed at Actlabs, Canada.

Rock Type	Porphyritic granite					Inequigr. granite	Leucogranite		Felsic microgranular enclave			Mica-rich enclave			Gneiss enclave
Sample	MAU-1A*	MAU-4	MAU-9	MAU-11A	MAU-14A	MAU-8A	MAU-6B	MAU-5	MAU-2A*	MAU-3B*	MAU-11B	MAU-14B	MAU-10B	MAU-16A1	MAU-6A
SiO ₂	71.52	68.39	69.96	70.38	69.69	71.82	74.23	73.91	71.18	70.45	72.12	68.98	56.47	59.31	64.92
TiO ₂	0.34	0.44	0.38	0.42	0.31	0.26	0.15	0.08	0.43	0.43	0.57	0.34	0.89	0.80	0.78
Al ₂ O ₃	14.04	13.67	13.41	14.04	14.12	12.78	12.73	13.42	14.14	14.36	11.54	14.19	16.35	15.71	14.87
Fe ₂ O ₃	3.26	4.00	3.27	3.62	3.18	2.55	1.62	1.24	3.72	4.04	5.07	3.39	9.57	9.46	4.98
MnO	0.06	0.07	0.07	0.07	0.06	0.06	0.06	0.14	0.06	0.06	0.09	0.06	0.17	0.16	0.10
MgO	0.42	0.52	0.37	0.48	0.39	0.30	0.13	0.07	0.56	0.60	0.67	0.42	2.23	1.77	2.25
CaO	1.58	1.71	1.64	1.68	1.43	1.24	0.83	0.30	1.62	1.81	1.58	1.39	0.90	0.66	3.54
Na ₂ O	3.39	3.10	3.38	3.23	3.20	3.07	3.38	3.96	3.10	3.23	2.63	3.14	2.15	2.05	1.84
K ₂ O	4.98	4.73	4.28	4.98	5.19	4.86	4.81	4.64	5.12	5.01	3.72	5.19	8.85	8.15	5.13
P ₂ O ₅	0.18	0.19	0.15	0.17	0.15	0.09	0.02	0.01	0.17	0.19	0.22	0.16	0.10	0.06	0.24
LOI	0.65	nd	nd	nd	nd	nd	nd	nd	0.29	0.39	nd	nd	nd	Nd	Nd
Total	100.42	96.82	96.91	99.07	97.72	97.03	97.96	97.77	100.39	100.57	98.21	97.26	97.68	98.13	98.65
Ni	21		4	3.84		3	2	2	25	20			40		17
Co	4								5	6					
Sc			8	5.92		4	<2	3					11		13
V	25		18	16		10	10	<4	14	22		10	148	122	101
Sn	5.0			6.54					3.0	3.0					
W	1.7								1.3	0.6					
Mo	4.3			1.38					4.8	4.7					
Rb	226		191	204		223	254	337	205	231			503		295
Cs	8.9			7.54		7.9	6.8	9.6	4.4	3.8			16.1		
Ba	717	1069	686	888	817	408	149	59	885	636	371	472	717	681	876
Sr	162	178	147	167	135	102	44	19	166	150	105	102	126	112	315
Ga	21		18	19		16	18	19	22	23			19		16
Ta	2.03								1.51	1.51			(1.40)		
Nb	15.4		17	20.36		18	16	17	16.0	20.3			16		15
Hf	5.8			7.22		7.2	4.7	3.8	6.0	6.0			3.8		
Zr	230	292	207	237	212	168	78	52	218	236	318	218	130	181	332
Y	38	34	33	33.81	32	42	34	63	31	36	39	32	52	16	30
Th	16.06		15	14.78		21.0	21.5	15.3	15.10	13.76			9.40		18
U	8.69		3.80	4.80		9.2	9.4	14.2	3.90	3.41					
La	60.70		55	56.00		63	35	22	52.00	64.00	75	76.94	31	38	36
Ce	106.80		109	114.89		126	66	36	127.20	122.80			64		132
Pr	12.37			12.76					14.38	13.70					
Nd	41.00		50	46.51		52	33	17	47.70	44.20			26		61
Sm	7.90			8.75		8.79	6.59	4.86	8.90	8.30			4.83		
Eu	1.33			1.18		1.2	0.5	0.4	1.24	1.21			1.2		
Gd	6.30			6.41					7.30	6.40					
Tb	1.00			1.15		1.5	1.9	1.7	1.10	1.00			1.7		
Dy	4.90			6.09					5.50	4.70					
Ho	1.00			1.21					1.20	1.10					
Er	3.10			3.23					3.40	3.30					
Tm	0.47								0.53	0.48					
Yb	2.90					4.2	3.7	6.7	2.90	2.70			5.30		
Lu	0.42			0.39		0.56	0.49	0.92	0.43	0.41			0.87		
F			1520	1460		1950	1040	1460					4160		1880
Mg#	20.33	20.47	18.31	20.80	19.54	18.90	13.71	10.06	22.97	22.73	20.74	19.70	31.58	27.04	47.22
A/CNK	1.01	1.03	1.02	1.02	1.05	1.02	1.04	1.11	1.04	1.02	1.03	1.07	1.11	1.17	0.99
T(Zrn sat)	817	839	809	819	812	793	733	707	814	818	854	816			
T(Mnz sat)1	802			808		818	778	749	816	811					
T(Mnz sat)2	771			774		786	746	719	784	779					
T(Ap sat)	982	957	946	964	943	911	803	748	972	978	1010	944

Figure 5. Binary variation diagrams using CaO as a differentiation index for rocks of the Mauá granitic massif.

and probably Rb, Ta, Nb and F (elements not analysed or analysed for only a few samples). This behavior is typical of many other fractionated granites, mostly those of peraluminous affinities (e.g., Chappell 1999). Contrary to the observed in some S-type granites, however, P clearly does not show a tendency to increase in the more fractionated facies of the Mauá massif, a behavior that can be attributed to the moderate ASI (< 1.1) of the magmas, preventing the formation of the AlPO_4 molecules that seem to cause P to remain dissolved in those magmas.

Mechanisms of magmatic fractionation other than simple closed-system fractionation (e.g., assimilation with crystal fractionation, ACF) or open-system (metasomatic) processes operating in the more fractionated (cupola) granites can also potentially respond for the geochemical behavior observed in the Mauá massif. A detailed mass balance modelling of the process of magmatic differentiation in the massif awaits isotope and mineral chemistry data, as well as more data on some of the trace-elements mentioned above, and will be presented

in the future.

The origin of the metamorphic enclaves High K_2O (8-9 wt%), K/Na (ca. 2.5) and Ba/Sr (ca. 6), besides low CaO are chemical features of the micaceous dark microgranular enclaves that could be consistent with a pelitic protolith. However, the ASI is relatively low (1.1-1.2), in agreement with the absence of strongly peraluminous minerals in these rocks. The REE pattern of sample MAU-10b (Fig. 6b) is weakly fractionated $[(\text{La}/\text{Yb})_N = 4]$ and shows a moderately negative Eu anomaly.

The gneissic enclave MAU-6a is also characterized by anomalously high K/Na, but its non-peraluminous character (ASI=0.99), as well as significantly higher mg#, CaO and Sr clearly indicates a non-pelitic protolith. It also contrasts sharply with the chemistry of the Mauá granites, and is interpreted as a fragment brought from deeper parts of the terrane; it could correspond to a fragment of a basement association or to an older orthogneiss.

Figure 6. REE patterns normalized to chondrite (Boynton 1984) for selected granites (a) and enclaves (b) from the Mauá granitic massif.

Magmatic temperatures The behavior of Zr, P and LREE (Fig. 5) shows that the magmas giving origin to the Mauá granites must have been saturated in zircon, apatite and monazite over most of their histories. As such, saturation temperatures calculated from the models of Watson & Harrison (1983), Harrison & Watson (1984) and Montel (1993) can be used to estimate their *liquidus*, assuming that the rock compositions approach those of the melts. This assumption, always loaded with large uncertainties in the case of plutonic rocks, receives some support in the case under study from the near-identical compositions shown by fine-grained, igneous-textured microgranular enclaves and host granites, and by the apparently minimum-melt compositions of the leucogranites.

Zr analyses are available for all samples, and as such zircon saturation temperatures were obtained using the Watson & Harrison (1983) calibration for the whole compositional spectrum seen in the Mauá massif. The zircon saturation temperatures of the least fractionated rocks, for which a greater number of analyses is available, have a distinct peak ($N=7$) at 810–820°C (Table 1), with only two higher values at 840–850°C. A continuous drop in temperature with fractionation, down to 707°C in leucogranite MAU-5, is consistent with the observed in the massif and with the expected from experimental studies in similar rocks.

As shown by petrography, monazite is the main LREE-bearing mineral only in the most fractionated granites of the Mauá massif; when present in the porphyritic granites, it is always corroded and mantled, a feature suggestive of reaction with the magma (see above). As such, meaningful monazite saturation temperatures could only be obtained for leucogranite samples for which complete REE analyses were available. Differently from zircon, the monazite solubility is strongly dependent on the H_2O contents of the granitic magmas (Montel 1993); as such, a range of monazite saturation temperatures is obtained for each sample if no constraints can be placed on this

variable. We calculated temperatures for two extreme H_2O contents, 3.5 wt% (a typical value expected in crustal magmas generated by biotite dehydration melt; see Thompson 1996) and 8 wt%, a maximum content in H_2O -saturated melts crystallizing at low (near-surface) pressures (Holtz & Johannes 1994). A temperature drop with fractionation is also evident in the monazite data; note however that, to be compatible with the zircon data, a raise in the H_2O contents of the more fractionated magmas is required, which is in accordance with the petrographic and experimental constraints.

The apatite saturation temperatures are higher than those obtained from the other two saturation thermometers by ca. 100–150°C, and are clearly exaggerated (Table 1). No reasons were found to justify such discrepancy, except that the literature shows that the Harrison & Watson (1984) calibration fails to yield reliable results in peraluminous rocks (e.g., Pichavant et al. 1992).

U-Pb GEOCHRONOLOGY Analytical procedures

Sample MAU-11a, a porphyritic monzogranite from the center of the Mauá massif, was crushed in a steel jaw-crusher and then in a disk mill. The heavy minerals were concentrated from the <100 mesh fraction at the Instituto de Geociências e Ciências Exatas, UNESP, at Rio Claro, SP, using a mechanical “panner”. Monazites were separated and dissolved, and Pb and U were extracted and analysed at the Isotope Geochemistry Laboratory (IGL), University of Kansas, USA, following the methods described in Janasi et al. (2001). Decay constants used were $0.155125 \times 10^{-9} \text{ year}^{-1}$ for ^{238}U and $0.98485 \times 10^{-9} \text{ year}^{-1}$ for ^{235}U . Data were regressed using the ISOPLOT program of Ludwig (1993); uncertainties are given at the 2-sigma confidence level.

Results Two monazite crystals were analysed. A 4 µg crystal from the least magnetic fraction m(0.7 A) is concordant at $588.2 \pm 2.2 \text{ Ma}$ (Table 2). This age is interpreted as dating the magmatic crystallization of the massif, since it derived from a low-temperature melt that intruded rocks metamorphosed to temperatures below T_c for monazite. The other crystal, from fraction m(0.6 A), is slightly discordant, but has an identical $^{207}\text{Pb}/^{206}\text{Pb}$ age, within error ($592.5 \pm 4.1 \text{ Ma}$), so that a regression forced to zero yields an age indistinguishable from that of the concordant crystal.

CONCLUSIONS The Mauá granite is a $588 \pm 2 \text{ Ma}$ (U-Pb, monazite) elongated massif dominated by a slightly peraluminous porphyritic biotite granite ($ASI=1.01\text{--}1.04$) rich in igneous-textured felsic microgranular and, to a lesser extent, in mica-rich metamorphic enclaves. The first enclaves are compositionally nearly identical to the host granites, and could correspond to blobs of granitic magma intruded as thin syn-plutonic dikes which chilled and were disrupted within the main body of solidifying granite. The origin of the second enclave type is more enigmatic. It could correspond to restites or to highly-digested xenoliths; however, aluminous minerals typical of pelite-derived metamorphic rocks are not present in any of the samples examined. Some porphyritic granites show large corroded biotite crystals with monazite inclusions; the latter, when in contact with the rest of the rock, are also corroded and mantled by allanite. This suggests that both the biotite and its monazite inclusions were out of the equilibrium with the magma and probably of foreign origin. It is noted, however, that monazite is also uncommon in the mica-rich enclaves.

Liquidus temperatures in the 800–820°C range, estimated from zircon and monazite saturation thermometry in the granite samples, are within the range, or slightly lower than those estimated experimentally for biotite dehydration-melting from metagreywacke-like sources (e.g., Montel & Vielzeuf 1997).

A compositional zoning is present in the SW half of the massif, with the main porphyritic facies giving way to progressively lighter

Table 2. U-Pb analytical data.

fraction	Size (mg)	Pb (ppm)	U (ppm)	observed			ages (Ma)			Rho	ages (Ma)			+/- (Ma)
				206Pb/204Pb	206Pb/238U	%error	207Pb/235U	%error	207Pb/206Pb		206Pb/238U	207Pb/235U	207Pb/206Pb	
M(0.6 A)	0.008	2214.0	10502	2879	0.09329	1.40	0.76784	1.40	0.05969	0.99116	574.9	578.5	592.5	4.1
M(0.7 A)	0.004	2772.6	8166.9	3279	0.09556	0.55	0.78495	0.56	0.05958	0.98387	588.3	588.3	588.2	2.2

and more even-grained granites. This zoning culminates with the occurrence, at the SW end of the massif, of a white two-mica leucogranite affected by hydrothermalism, as evidenced by the presence of fracture-controlled pegmatites with miarolitic cavities, quartz-mica greisen, tourmaline granites and tourmalinites.

The geochemical expression of the faciological variation are smooth compositional trends seen in the behavior of all major and trace-elements, which qualitatively imply the fractionation of an assemblage dominated by plagioclase and biotite, besides accessory Fe-Ti oxide, apatite, zircon and monazite (or allanite). A few elements such as Cs, U, HREE, Y and possibly F, Rb and Nd keep an incompatible behavior up to the more fractionated leucogranites. Both closed-system and open-system crystal fractionation seem consistent with the geochemical behavior observed; both models can be more carefully tested when mineral chemistry and isotopic data are available.

Also, the more pronounced enrichment and depletion in some elements seen in the passage to the more felsic leucogranite sample can simply result from a protracted fractionation process, but the possibility that part of the chemical variation is an effect of metasomatic (hydrothermal) processes has to be tested.

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REFERENCES

- Alves F.R. 1975. *Contribuição à geologia da região de Salesópolis-Guararema, SP*. Master in Science Dissertation, Instituto de Geociências, USP, São Paulo, 138 pp. (unpublished).
- Boynton W.V. 1984. Cosmochemistry of the rare-earth elements: meteorite studies. In: P. Handerson (Ed.): *Rare-earth elements geochemistry*. Elsevier, Amsterdam, p. 63-114.
- Campos Neto M.C. 2000. Orogenic systems from Southwestern Gondwana: An approach to Brasiliano-Pan-African cycle and orogenic collage in Southeastern Brazil. In: U.G. Cordani, E.J. Milani, A. Thomaz Filho & D.A. Campos (Eds.): *Tectonic Evolution of South America*. 31st International Geological Congress, Rio de Janeiro, p. 335-365.
- Campos Neto M.C. & Figueiredo M.C.H. 1995. The Rio Doce orogeny, Southeastern Brazil. *Journal of South American Earth Sciences*, 8(2):143-162.
- Chappell B.W. 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos*, 46:535-551.
- Coutinho J.M.V. 1972. Petrologia do pré-Cambriano em São Paulo e arredores. *Boletim IGA-USP*, 3:5-99.
- Dantas E.L., Hackspacher P.C., Fetter A.H., Sato K., Pimentel M.M. & Godoy A.M. 2000. Nd isotope systematics related to Proterozoic evolution of the Central Ribeira Belt in the State of São Paulo, SE Brazil. *Revista Brasileira de Geociências*, 30 (1-3):140-143.
- Gimenez Filho A., Janasi V.A., Campanha G.A.C., Teixeira W. & Trevizoli Júnior L.E. 2000. U-Pb dating and Rb-Sr isotope geochemistry of the eastern portion of the Três Córregos batholith, Ribeira Fold Belt, São Paulo. *Revista Brasileira de Geociências*, 30(1-3):45-50.
- Fernandes A.J. 1991. *O Complexo Embu na leste do Estado de São Paulo- contribuição ao conhecimento da litostratigrafia e da evolução estrutural e metamórfica*. Master in Science Dissertation, Instituto de Geociências, Universidade de São Paulo, 120 pp. (unpublished).
- Harrison T.M. & Watson E.B. 1984. The behavior of apatite during crustal anatexis: Equilibrium and kinetic considerations. *Geochimica et Cosmochimica Acta*, 48:1468-1477.
- Hasui Y., Carneiro C.D.R., Bistrichi C.A. 1978. Os granitos e granitóides da região de dobramentos sudeste nos Estados de São Paulo e Paraná. In: Congresso Brasileiro de Geologia, 30, Recife-PE, SBG-Núcleo Nordeste. *Anais*, 6:2594-2608.
- Holtz F. & Johannes W. 1994. Maximum and minimum water contents of granitic melts: implications for chemical and physical properties of ascending magmas. *Lithos*, 32: 149-159.
- Janasi V.A. 1999. *Petrogênese de granitos crustais na Nappe de Empurrão Socorro-Guaxupé (SP-MG): uma contribuição da geoquímica elemental e isotópica*. Post-Doctor Thesis, Instituto de Geociências, Universidade de São Paulo, 304 pp. (unpublished).
- Janasi V.A. & Ulbrich H.H.G.J. 1991. Late Proterozoic granitoid magmatism in the State of São Paulo, southeastern Brazil. *Precambrian Research*, 51:351-374.
- Janasi V.A. & Ulbrich H.H.G.J. 1992. Inventário bibliográfico de granitos do Estado de São Paulo. *Boletim IG-USP, Série Especial*, 11, 253 p., mapas, anexos.
- Janasi V.A., Andrade S. & Ulbrich H.H.G.J. 1995. A correção do drift instrumental em ICP-AES com espectrômetro sequencial e a análise de elementos maiores, menores e traços em rochas. *Boletim IG-USP, Série Científica*, 26:45-58.
- Janasi V.A., Leite R.J. & van Schmus W.R. 2001. U-Pb chronostratigraphy of the granitic magmatism in the Agudos Grandes Batholith (W of São Paulo, Brazil)—implications for the evolution of the Ribeira Belt. *Journal of South American Earth Sciences*, 14:363-376.
- Ludwig K.R. 1993. ISOPLOT- A plotting and regression program for radiogenic isotope data. Version 2.70. June 9, 1993 Revision of U.S.G.S. Open-File Report 91-445, 42 pp.
- Machado N., Valladares C., Heilbron M., Valeriano C. 1996. U-Pb geochronology of the central Ribeira belt (Brazil) and implications for the evolution of the Brazilian Orogeny. *Precambrian Research*, 79(3/4):347-361.
- Machado R. & Demange M. 1996. Classificação estrutural e tectônica dos granitóides neoproterozóicos do Cinturão Paraíba do Sul no Estado do Rio de Janeiro. *Boletim IG-USP, Série Científica*, 25:81-96.
- Montel J.-M. 1993. A model for monazite/melt equilibrium and application to the generation of granitic magmas. *Chemical Geology*, 110(1/3):127-146.
- Montel J.-M. & Vielzeuf D. 1997. Partial melting of metagreywackes, Part II. Compositions of minerals and melts. *Contributions to Mineralogy and Petrology*, 128:176-196.
- Moraes S.M. 1995. *Granito Itapeti, SP: petrografia, litoquímica e tipologia de zircão*. Master in Science Dissertation, Instituto de Geociências e Ciências Exatas, UNESP, Rio Claro-SP, 130 pp. (unpublished).
- Motidome M.J. 1992. Geologia do Complexo Embu na região entre Santa Isabel e Biritiba-Mirim, SP. Master in Science Dissertation, Instituto de Geociências, USP, São Paulo, 172 pp. (unpublished).
- Pichavant M., Montel J. M. & Richard L. R. 1992. Apatite solubility in peraluminous liquids: Experimental data and an extension of the Harrison-Watson model. *Geochimica et Cosmochimica Acta*, 56:3855-3861.
- Ribeiro A., Trouw R.A.J., Andreis R.R., Paciullo F.V.P., Valença J.G. 1995. Evolução das bacias Proterozóicas e o termo-tectonismo brasileiro na margem sul do Cráton São Francisco. *Revista Brasileira de Geociências*, 25(4):235-248.
- Sadowski G.R. 1977. Reativação do embasamento na Faixa de Dobramento Ribeira na região da Serra do Cubatão. *Boletim do Instituto de Geociências, USP*, 8: 67-76.
- Sato K. 1998. *Evolução crustal da Plataforma Sul-Americana com base na geoquímica isotópica Sm-Nd*. Doctor in Sciences Thesis, Instituto de Geociências, Universidade de São Paulo (unpublished).
- Silva P.C.S. 1992. *O Complexo Embu na porção sudeste da Folha Mauá (SF-23-Y-D-IV-I)*. Master in Science Dissertation, Instituto de Geociências, USP, 107 pp.
- Söllner F., Lammerer B. & Weber-Diefenbach K. 1987. The Brasiliano orogenesis: age determination (Rb-Sr and U-Pb) in the coastal mountain region of Espírito Santo, Brazil. *Zentralblatt für Geologie und Paläontologie*, 1987, p. 729-741.
- Tassinari C.C.G., 1988. *As idades das rochas e dos eventos metamórficos da porção sudeste do Estado de São Paulo e sua evolução crustal*. Doctor in Sciences Thesis, Instituto de Geociências, Universidade de São Paulo, 236 pp. (unpublished).
- Thompson A.B. 1996. Fertility of crustal rocks during anatexis. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 87:1-10.
- Theodorovitz A., Yamato A.A., Takahashi A.T., Vasconcelos C.S.; Santarém P.C. & Silva V.A. 1990. Projeto Santa Isabel/Mogi das Cruzes/Mauá. Relatório Final, CPRM-Pró-Minério, 194 pp.
- Tupinambá M. 1999. *Evolução tectônica e magmática da Faixa Ribeira na região serrana do Estado do Rio de Janeiro*. Doctor in Sciences Thesis, Instituto de Geociências, Universidade de São Paulo 221 pp. (unpublished).
- Watson E.B. & Harrison T.M. 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters*, 64:295-304.
- Wernick E. & Galembeck T.M.B. 1987. Evolução geotectônica durante o Proterozóico Superior no Estado de São Paulo: uma contribuição através da análise do magmatismo granitóide. In: Simpósio Regional de Geologia, 6, Rio Claro-SP, Atas, 1:191-204.
- Wernick E., Weber-Diefenbach K. & Soave L.A. 1985. Dados químicos e tipologia de zircão em granitos (Três Lagos e Guacuri) e tonalitos (Parelheiros) dos arredores de São Paulo: uma interpretação preliminar. In: Simpósio Regional de Geologia, 5, São Paulo, SBG- Núcleo São Paulo, Atas, 1:35-48.

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