ARTICLE

Petrogenesis and tectonic of the Urucum granitic suite, Rio Doce Valley (Minas Gerais – Brazil): an example of syn to late collisional peraluminous magmatism associated with high-angle transcurrent shear zone

Petrogênese e tectônica da suíte granítica Urucum, Vale do Rio Doce (Minas Gerais – Brasil): um exemplo de magmatismo sin- a tardi-colisional associado a zonas de cisalhamento direcionais de alto ângulo

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ABSTRACT: The Urucum suite (582 ± 2 Ma, zircon U-Pb age), situated in the Mid-Rio Doce Valley, eastern part of Minas Gerais State, is characterized by elongated, NW-SE and N-S trending granitic massifs associated with the Conselho Peña-Resplendor high-angle shear zone. It corresponds to a syn to late collisional magmatism that presents dominant solid-state foliation. Four facies are distinguished within the Urucum suite: (i) a porphyritic (Urucum); (ii) a medium- to coarse nequigranular (Palmital); (iii) a tourmaline-bearing; and (iv) a pegmatitic facies. These facies are peraluminous, with alumina saturation index varying from 0.98 to 1.38. SiO_2 contents vary from 70.7 to 73.7 wt%, with K_2O values ranging from 3.5 to 5.7 wt%, Na_2O from 1.9 to 4.4 wt%, MgO from 0.6 to 1.2 wt%, and CaO from 0.3 to 0.9%. Harker-type diagrams show rather continuous trends from the less-evolved Urucum facies to the more evolved tourmaline-bearing and pegmatitic facies. The behavior of several major oxides and trace elements (Fe_2O_3, MgO, MnO, CaO, TiO_2, Al_2O_3, K_2O, Rb and Ba) reflects the role played by fractionation of ferromagnesian minerals, feldspars and accessory minerals. Initial Sr^{87}/Sr^{86} ratios vary from 0.711 to 0.716, with $\varepsilon_{Nd\,(580\,Ma)}$ values between -7.4 and -8.2, and Sm-Nd T_{DM} model ages ranging from 2290 to 1840 Ma.

KEYWORDS: Urucum suite; Geochemistry; Petrogenesis; Araçuaí belt.

RESUMO: *A suíte Urucum (U/Pb em zircão: 582 ± 2 Ma), situada na região do Vale do Médio Rio Doce, leste de Minas Gerais, caracteriza-se por plutons graníticos alongados (NW-SE e N-S) sin a tardi-colisionais associados à Zona de Cisalhamento de Alto Ângulo de Conselho Peña-Resplendor. São rochas foliadas, com predomínio da foliação no estado sólido em relação à foliação magmática. Foram caracterizadas quatro fácies: (i) porfirítica (Urucum), (ii) inequigranular média a grossa, (iii) com turmalina, e (iv) pegmatítica. Essas fácies são peraluminosas, com índice de saturação em alumina entre 0,98 e 1,38. Os teores em SiO_2 variam entre 70,7 e 73,7%, com valores de K_2O entre 3,5 e 5,7%, Na_2O entre 1,9 e 4,4%, MgO entre 0,6 e 1,2%, e CaO entre 0,3 e 0,9%. Em diagramas tipo Harker, os dados químicos mostram trends mais ou menos contínuos desde a fácies menos evoluída (Urucum) até fácies mais evoluídas (turmalina-granitos e pegmatítica). O comportamento de vários elementos maiores e traços (Fe_2O_3, MgO, Mno, CaO, TiO_2, Al_2O_3, K_2O, Rb and Ba) mostram a importância da cristalização fracionada de minerais ferromagnesianos, feldspatos e minerais acessórios. A razão inicial de Sr^{87}/Sr^{86} varia de 0,711 a 0,716, com $\varepsilon_{Nd\,(580\,Ma)}$ entre -7,4 e -8,2, e idades modelo Sm-Nd entre 2290 e 1840 Ma.*

PALAVRAS-CHAVE: *Suíte Urucum; Geoquímica; Petrogênese; Cinturão Araçuaí.*

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INTRODUCTION

Several papers discuss the generation of significant amounts of granites by crustal melting in the late periods of crustal thickening (collision) and also the role of erosion upon the decompression melting and its effect on increasing partial melting (England & Thompson 1984; Hollister 1993; Inger 1994). The crustal thickening is not favorable to generation of a widespread melting (England & Thompson 1984). According to Sylvester (1998), strongly aluminous granites are formed in different types of orogens during the post-collisional phase. During the exhumation episode, which is accompanied by uplift and erosion, partial relaxation of isotherms occurs and widespread amounts of granitic melting are generated in this phase, which comes after collision (Thompson 1981; England & Richardson 1977).

Experimental models show that crustal anatexis of rocks of different compositions is a common process in levels of middle and lower crust (Stevens & Clemens 1993), and it takes place after collision (England & Thompson 1984). They also reveal that widespread amounts of melt can only be generated under H_2O-saturated conditions, situation more common in upper crust. Moreover, under H_2O-undersaturated conditions, appreciable amounts of melt can only be generated as a result of dehydrations involving muscovite, biotite and hornblende (Clemens & Vielzeuf 1987; Vielzeuf & Holloway 198; Patiño Douce & Beard 1995).

The CaO/Na_2O ratios are used to separate pelites-derived strongly peraluminous granites from sandstone-derived ones. The first tends to show values lower than 0.30, while the second one, values higher than 0.30 (Sylvester 1998).

The studied area is located in the Mid-Rio Doce Valley, between Galileia and Conselheiro Peña municipalities, Minas Gerais State – Brazil (Fig. 1A). It belongs to the central segment of the Araçuaí Belt (*sensu* Pedrosa-Soares *et al.* 2001; Pedrosa-Soares & Wiedemann-Leonardos 2000) or Northern Mantiqueira Province (Almeida 1984). In this internal domain (or Eastern Sector, according to Siga Jr. 1986) of the Araçuaí Belt, the regional structures strike between N-S and N-NW, stressing expressive high-angle, ductile shear zones, such as the Resplendor-Conselheiro Peña Shear Zone (Nalini 1997).

The Urucum suite granitoids, focus of this study, correspond to the most expressive peraluminous granitic magmatism of the Rio Doce Valley. They are constituted by two batholiths (of ~120 km² and ~100 km²) and smaller plutons, one of 25 km² and the others of 5 km². The larger bodies are elongated along NW-SE and N-S, and are 17 and 5 km long and 2 and 1.8 km wide, respectively; their emplacement was controlled by the Conselheiro Peña-Resplendor high-angle shear zone (Nalini 1997, Nalini *et al.* 2008).

Their margins and inner parts are characterized by a foliated structure dominated by a solid-state foliation and usually by mylonitic and protomylonitic textures. The contacts with surrounding rocks are tectonic. The granites are leuco- to mesocratic and present a coarse-grained, porphyritic texture. Microcline megacrystals (up to 10 cm-sized) represent, together with plagioclase (oligoclase), 30 to 80% in volume of the rock.

THE REGIONAL CONTEXT OF THE NEOPROTEROZOIC GRANITOIDS

Siga Jr. (1986), using Rb/Sr and U/Pb radiometric data, divided the Neoproterozoic granitoids of the Araçuaí belt in three groups:

1. syn- to late-tectonic (650 – 550 Ma);
2. late- to post-tectonic (550 – 500 Ma), and
3. post-tectonic (500 – 450 Ma).

The results of the 1/100,000 scale *Projeto de Levantamento Geológico Básico* (PLGB – Basic Geologic Survey Project) carried out by CPRM in the Rio Doce Valley led to the classification of the granitoid massifs into three main tectonic groups related to:

1. pre- to syn-regional metamorphism;
2. syn-transcurrent faulting, and
3. post-transcurrent faulting (Féboli *et al.* 1993b).

The most deformed rocks were included in the first group and are concordant with the regional structures. They have expanded composition (tonalite-granodiorite-granite), of calc-alkaline and meta-aluminous geochemical characteristics, having evolved in volcanic-arc and with intraplate settings. The second group is represented by elongated, batholith- showing mylonitic and cataclastic foliation along the borders which varies inwards to an isotropic structure. The geochemical characteristics are very similar to those of the previous group, differing in the peraluminous terms and its post-collisional tectonic. Small plutons are included in the third group. They are ring- and oval-shaped, zoned and concentric, commonly associated with charnockitic, basic, intermediate and ultrabasic rocks (Aimorés, Lagoa Preta, Várzea Alegre massifs, among others). This group is characterized as I-type granites of calc-alkaline and tholeiitic affinities and with intraplate and volcanic-arc settings or related to post-orogenic and post-collisional uplift (Féboli *et al.* 1993, Vieira *et al.* 1993).

In the eastern portion of the studied area, there is located the Brasiliano Rio Doce magmatic arc developed within the 590 – 480 Ma interval (Figueiredo & Campos Neto 1993).

It corresponds to the same magmatic arc described by Wiedemann (1993). Figueiredo & Campos Neto (1993) and Campos Neto & Figueiredo (1995) divided this magmatism in pre-collisional (590 to 570 Ma), syn-collisional (560 to 530 Ma) and post-collisional (520 and 480 Ma), whereas Wiedemann (1993) divided it in syn-orogenic (590 to 580 Ma) and late- to post-orogenic (520 to 450 Ma).

Bilal *et al.* (1998, 2000) divided the Neoproterozoic granitic magmatism of the Rio Doce Valley in four groups:

1. pre-tectonic, represented by the Galileia suite, which yields an U/Pb age of 595 Ma;
2. syn-tectonic, represented by the Urucum suite, of 582 Ma (U/Pb age);
3. late- to post-tectonic, including the intrusive ring complexes such as Aimorés and Ibituba-Itapina, of 537 to 520 Ma; and
4. post-tectonic, represented by the Ibituruna Syenite, which yields a Rb/Sr age of 511 Ma.

Conventional U/Pb zircon ages of 594 Ma and 582 Ma were also obtained respectively for the Galileia suite and the Urucum suite (Nalini 1997; Nalini *et al.* 2000a).

The Neoproterozoic granitic magmatism of the Araçuaí belt was divided by Pedrosa Soares *et al.* (1999) into five suites (G1 to G5), from the oldest to the youngest: G1- syn-tectonic suite, constituting the orogen anatectic core, with I-type gneissic batholiths; G2- calc-alkaline syn-tectonic suite, with S-type granitoids; G3- late-tectonic suite, with S-type peraluminous granites; G4- high-K, calc-alkaline, late- to post-tectonic suite, with I-type granites, including plutons of the charnockitic association (Aimorés, Padre do Paraíso, among others); G5- post-tectonic suite, with predominance of S-type peraluminous granites in zoned plutons, with biotite-granites in the center and two-mica granites or muscovite-garnet granites at the borders. The origin of suite G1 is related to regional anatexis of metasedimentary rocks during crustal thickening, with the generation of suite G3 during the late stage of the process. Suites G2 and G4 are related to the successive stages of a continental magmatic arc evolution. Suite G2 represents the arc root, linked to a subduction zone dipping eastwards (Pedrosa Soares *et al.* 1998, 1999), whereas G4, generated at deep crustal levels, is related to crust/mantle interactions. Suite G5, emplaced at shallower levels (6 to 12 km), was generated in parts of a thickened crust (Pedrosa Soares *et al.* 1987, 1999). Later, Pedrosa Soares and Wiedemann-Leonardos (2000) considered the suite G2 (now named G1) older than suite G1 (now named G2), characterizing the first one as pre-collisional (between 625 and 595 Ma) and the latter as syn-collisional (between 595 and 575 Ma).

The collection of geochronological data is still not sufficient for good interpretations regarding the Araçuaí Belt Brasiliano granites. Pb/Pb dating (of zircon by the evaporation method) carried out for six plutons (and a granitic vein) of suites G1, G2 and G5 defined the following ages: G1/G2- 591 ± 4 Ma (Ataléia); 582 ± 5 Ma (Wolf), 595 ± 3 Ma (Brasilândia); 575 ± 2 Ma (Guarataia); 576 ± 5 Ma (São Vitor/Pescador); G5- 519 ± 2 Ma (Caladão/Padre Paraíso), and 503 ± 9 Ma (granitic veins crosscutting the Caladão Pluton) (Noce *et al.* 1999; Noce *et al.* 2000).

The original scheme of Pedrosa Soares *et al.* (1999) was modified by Pedrosa Soares *et al.* (2001). The granitoids from Araçuaí belt of group 3 were subdivided into G3I and G3S. The first group is characterized by calc-alkaline magma emplaced along oblique to strike-slip shear zones. The second group has peraluminous signature and consists of a series of small coalesced or isoled sillimanite-cordierite-garnet leocogranitic bodies (Pedrosa Soares *et al.* 2001). Later, Pedrosa Soares *et al.* (2008) returned to the groups and, more recently, designated them as supersuites (Pedrosa Soares *et al.* 2011).

THE URUCUM GRANITIC SUITE

Barbosa *et al.* (1964) used for the first time the term "Urucum" to name the two-mica granites of the Urucum ridge, east of Galileia. Later, Silva *et al.* (1987) defined the Urucum suite, including the Urucum Granite, the Palmital Granodiorite (Barbosa *et al.* 1964) and associated pegmatites. They also describe xenoliths of São Tomé Group schists and suggest an origin of this granites by melting epi- to mesozonal of the base of this group and of their lower units (Crenaque Group) and of part of the Pocrane Complex.

The Urucum suite in Minas Gerais occupies about 250 km². It consists of three main plutons:

1. Urucum (porphyritic facies),
2. Palmital (inequigranular facies) and
3. Tourmaline granite (tourmaline-bearing facies).

These plutons are elongated (Palmital) and rounded (Urucum), and oriented in direction NW-SE and N-S. They are foliated, especially at its borders and in the vicinity of shear zones and host rocks. The foliations are steep- to vertical-dipping (Fig. 1b). These plutons are located in the central part of a NW-trending brachyanticlinal structure, located east of Galileia (Moura *et al.* 1978b, Issa Filho *et al.* 1980). Their emplacement is associated with the Conselho Peña-Resplendor Shear corridor (Nalini 1997, Nalini *et al.* 2008).

The rocks of Urucum suite are characterized by the foliations developed in solid and magmatic states, related to
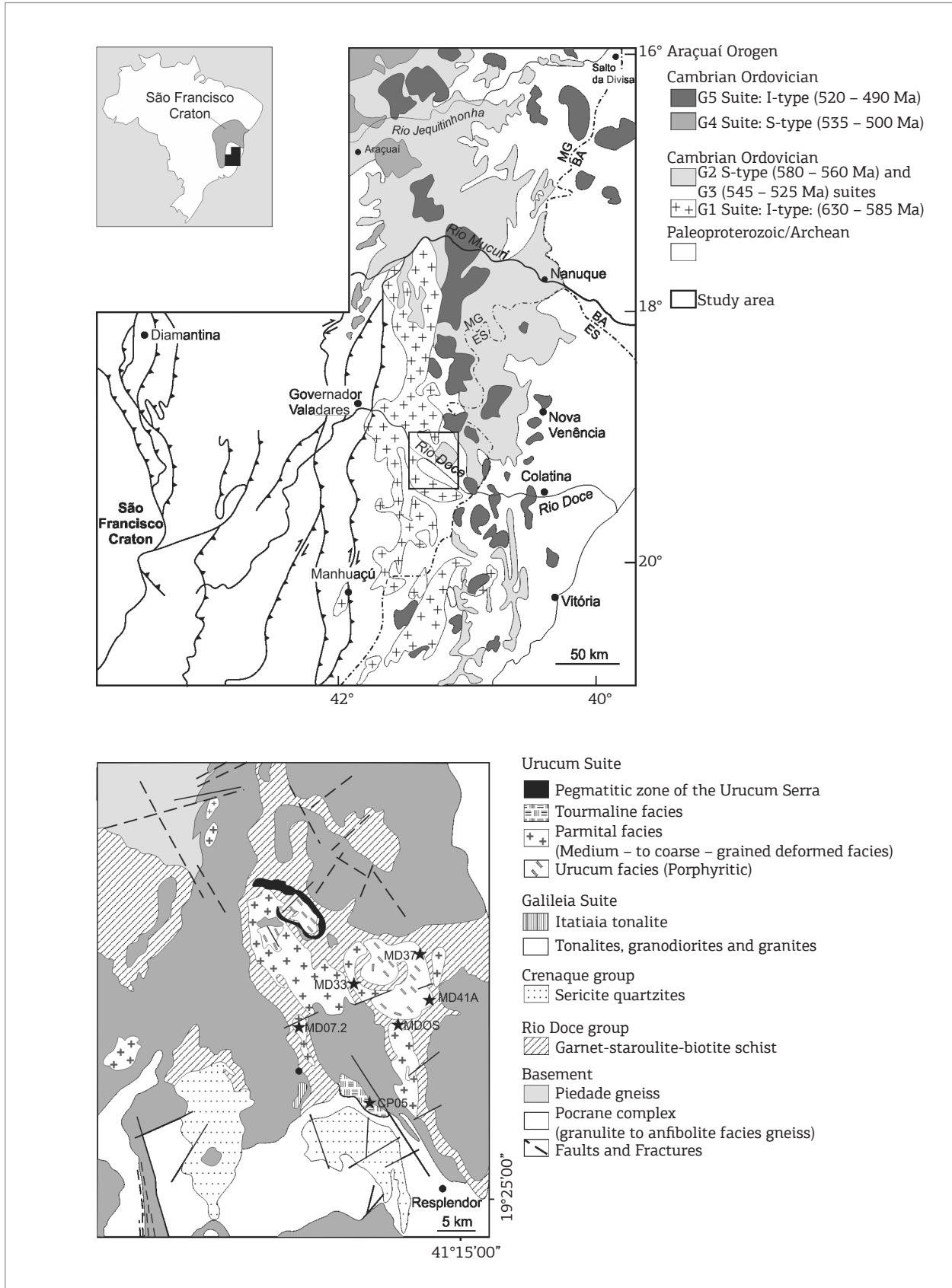
Figure 1. (A) Simplified geological map of the Araçuaí orogen and adjacent regions of the São Francisco Craton (modified from Pedrosa-Soares *et al.* 2007 and 2008). (B) Geologic map of the study area (modified from Silva *et al.* 1987, Barbosa *et al.* 1964 and Nalini 1997).

the first regional deformation phase (D_1). This phase is also recorded in the São Tomé Formation schists (Sn-foliation) (Nalini 1997, Nalini *et al.* 2008). The metamorphic assemblage of these rocks (staurolite and almandine) suggests metamorphism of lower amphibolite-facies, that occurred under the following conditions: P- about 4-5 kbar, and T ranging from 500 to 600ºC (Nalini 1997). In this sense, the emplacement of the Urucum Suite is considered syn-tectonic with respect to D_1- phase, and its generation is related to a regional metamorphic event that affected the above schists and that took place during crustal thickening (Nalini 1997).

In the Rio Doce Valley, peraluminous granites (S-type) are associated with pegmatitic bodies, being well-known the Marilac of Galilelia-Conselheiro Peña pegmatitic fields (Correia Neves *et al.* 1986). The Marilac pegmatitic field, situated northwest of the Governador Valadares city, is 30 – 40 km wide and stretches out for 90 – 100 km along an approximate N-S direction.

The Conselheiro Peña–Galileia pegmatitic field, situated east of Governador Valadares, is 35 – 45 km wide and stretches out for 100 km along an approximate N- direction. These pegmatites are emplaced in garnet- and staurolite mica-schists of the São Tomé Group and in Neoproterozoic granitoids of the Galileia and Urucum suites.

Petrography

The Urucum suite is constituted by four main facies:
1. porphyritic (Urucum facies),
2. medium- to coarse inequigranular (Palmital facies),
3. tourmaline-bearing, and
4. pegmatitic facies.

The predominant facies are the first two (Fig. 1b). The tourmaline-bearing facies can constitute bodies of up to 15 km², as one that occurs in the southeastern region of Conselheiro Peña. These granites are less deformed than those of the Palmital facies and are emplaced in quartzites of the Crenaque Group (Nalini 1997). Their texture is granular, and the rock-forming minerals are biotite, muscovite, potassic feldspar (microcline and orthoclase) and plagioclase. The accessory minerals are apatite, garnet, zircon, monazite and tourmaline.

The Urucum and Palmital facies show transitional contact between them. It is marked by increasing of potassic feldspar megacrystals toward Urucum facies, with the texture passing of inequigranular to porphyritic. Centimeter-sized (6 to 8 cm) potassic feldspar megacrystals (microcline) are common in this facies. Essential minerals are plagioclase and potassic feldspar (50 – 70% of rock volume), with variable quartz, muscovite and biotite contents. Plagioclase crystals rimmed by albite are included in potassic feldspar megacrystals. Frequent accessory minerals are garnet, tourmaline, ilmenite and apatite. Feldspar megacrystals are usually aligned and possibly define

a magmatic foliation. In the vicinity of shear zones occurs solide-state deformation observed under the microscope, being commom protomylonitic texture with potassic feldspar porphyroclasts involved by a finer matrix showing composed of recrystallized quartz, plagioclase, mica and microcline together with an expressive amount of myrmekite.

Two types of plagioclase are distinguished: euhedral to sub-euhedral, poikilitic (millimeter- to centimeter-sized) megacrystals with muscovite, biotite, quartz and microcline inclusions, and sub-euhedral crystals that compose the matrix. Usually, the latter contains mineral inclusions, but in smaller amounts than the first one. The first type of plagioclase also occurs as inclusions or surrounding potassic feldspar megacrystals. An albite reaction rim is also observed, in the subhedral plagioclase grains.

The microcline is more common than orthoclase. It occurs mainly in the matrix, being rare as megacrystal. They are anhedral to sub-euhedral and exhibit characteristic geminations, and contain mica, quartz and albite-rimmed plagioclase inclusions. Microcline usually occurs as interstitial crystals or develops along plagioclase fractures.

Quartz is either strongly recrystallized or occurs as hexagon-shaped, euhedral crystals with triple junctions and also as tear drop-shaped inclusions in micas and feldspars. Euhedral to sub-euhedral, reddish brown biotite crystals present varied sizes and frequently occur in clusters, forming cummulatic textures.

Muscovite occurs in some Urucum suite granites and, with biotite, defines the foliation of the rock. Two types of muscovite are distinguished: primary and secondary. The first type is present as phase essential mineral (5 – 10%) and contains inclusions of quartz, zircon and monazite. The second type is less abundant than first and lies along the cleavage planes of plagioclase (either megacrystals or crystals of the matrix) or potassic feldspar.

Millimeter-sized apatite is the most abundant accessory mineral and commonly occurs as inclusion in biotite.

Geochemistry

Twenty five representative samples of all compositions, textures and grain size of the Urucum suite were selected for whole-rock analysis (major and trace elements), 8 being from the porphyritic (Urucum) facies, 12 from the medium- to coarse inequigranular (Palmital) facies, 2 from the tourmaline-bearing facies, 2 from the pegmatitic facies, and 1 from the aplitic vein that crosscuts the other facies.

The samples were selected so as to represent the whole range of textures, compositions and grain-sizes of each facies. Special attention was given to samples that showed, under the microscope, cummulatic features, defined by both ferromagnesian minerals and feldspars, or even accessory minerals as apatite, zircon etc. Attention was also given to samples that showed some indication of fluid-phase interaction, either

as incipient alteration of feldspars, biotite or amphibole, mainly related to silicification, albitization or greisenization.

The chemical analyses were carried out at the Geochemistry Laboratory of the Saint-Etienne School of Mines, France. The precision of the results was ensured by comparison/control with certified international standards, simultaneously analyzed with each group of samples.

The data were obtained by X-ray fluorescence spectrometry model PW 1404 Philips spectrometer and ICP (Induced Coupled Plasma) emission spectrometry, model JY38PI + JY32P spectrometer.

The major-element analysis carried out by X-ray fluorescence and ICP methods, enabling the comparison between results and/or their use as complementary analytical methods. Major elements are very accurate by ICP and were perfomed for MgO, MnO, CaO and TiO_2, considering that the contents of such components are rather low for the more evolved granites.

Characterization of the Urucum Suite granitoids

The leucogranites of Urucum suite are characterized by plot mainly in the granite and adamellite fields of the chemical-mineralogical diagram of Debon & Le Fort (1983), and follow a trend that approaches the calc-alkaline trend defined by these authors (Fig. 2A).

In Figure 2B, the analyzed samples define two fields in the domain of the peraluminous two-mica granites: one representing the predominance of muscovite over biotite (field I), and another, the predominance of biotite over muscovite (field II). The peraluminous character of these rocks is attested by the alumina saturation diagram (A/CNK vs. A/NK, Fig. 2C); the index values fall in the 0.98 – 1.38 interval, with an average of 1.13. These values are compatible with the interval defined by Chappell & White (1992) for Australian S-type granites (1.01 – 1.39).

The peraluminous character of the Urucum suite granitoids is expressed by the presence of muscovite, garnet and tourmaline as the primary mineral assemblage, as well as by the presence of normative corindon (up to 4.7%).

The CaO/Na_2O ratios of the different facies of studied suite are equal to 0.28. This value is within the range of pelitic-derived sequences post-collisional strongly peraluminous granites (Sylvester 1998).

The behavior of major elements

To study the element behavior during the crystallization process, the sum $Fe_2O_3t + MgO + MnO + TiO_2$ (FMMT), which well discriminates the different facies, was used as a differentiation index.

In general, an increase in SiO_2 occurs with the decrease of FMMT during the differentiation process of the magma (Figs. 2D and 3A). This behavior suggests the fractionation of biotite, tourmaline and garnet. The MgO/TiO_2 ratio varies from 2.14 to 5.33, being higher than that for the I-type granitoids (Galileia suite: varies from 2.25 to 3.45), suggesting that the rocks studied here were originated from melting of metapelitic sequences.

Sample MD 29 (Fig. 2D) has a relatively higher SiO_2 content (73%), despite relatively high MgO (0.75%) and low Na_2O contents (1.8%) (Figs. 3D and 3F). This behavior strongly suggests that changes in composition were resultant from greisenization.

The same diagram shows that one sample of the tourmaline-bearing facies contrast from the others, yielding relatively lower SiO_2 contents (71.9 %). Sample MD07.2 is more Al_2O_3, CaO and Na_2O enriched than CP05A (15.1, 1.6 and 4.3% *versus* 13.7, 1.1 and 3.8%, respectively). One of the samples (CP05A) has significant tourmaline content.

The ternary diagrams, including alkaline and earth alkaline metals, alumina and total ferromagnesian minerals ($CaO-Al_2O_3-FMMT$), show the variation and mobility of these elements (Fig. 3B).

This diagram shows plagioclase enrichment for most of the granite samples of the Palmital facies (Fig. 3B). These samples show depletion of P_2O_5 (< 0.16%) (Fig. 3C) and MnO (Fig. 3D). In general, an increase in $MnO/(MnO+Fe_2O_t)$ values is observed from the Urucum suite granites to the pegmatites (Fig. 3D). This explains the importance of garnet crystallization in the more evolved (pegmatitic and tourmaline-bearing) facies.

The diagram (Fig. 3F) show a wide dispersion of total alkalis contents. This behavior may be explained by wide variation in the content of potassic feldspar megacrystals in the outcrop scale. Al_2O_3 and total alkalis contents increase from the Urucum facies to the pegmatitic facies (Fig. 3B). The Urucum suite leucogranites are relatively more Na_2O enriched than the Himalayan Manaslu leucogranites (Vidal *et al.* 1984) (Fig. 3F).

The behavior of trace elements

The contents of transition elements (Co, V, Zn, Ga, Ni and Cr) decrease with differentiation, exhibiting steeper gradients for V, Co and Ni, but a less steep gradient for Ga (Fig. 4). Most of the tourmaline-bearing samples are depleted in transition elements, which reflect the lower incorporation of such elements.

The dispersion of Rb (between 121 and 262 ppm) and Ba (< 500 ppm) contents results from the crystallization of potassic feldspar megacrystals. On the other hand, the increase of Ba/Sr values (excepting for microgranites) reflects plagioclase crystallization (Fig. 3E).

Despite the dispersion seen in Figure 5A, Th contents decrease with the evolution from the Urucum granite to the pegmatites. Some Palmital (MD60- 22.6 ppm; MD59- 15.7 ppm; MD79- 14.1 ppm) and Urucum (MD56- 20.5 ppm) granite samples are relatively more Th enriched, probably due to their higher monazite content, which explains why they do not plot in main trend. The Th/U ratio, between 0.30 and 4.33,

is relatively low when compared to the usual values (from 3 to 5) yielded by granitic rocks (Fourcade 1981), but are comparable with the values obtained by Cuney *et al.* (1984) for the Himalayan Manaslu leucogranites (0.2 < Th/U < 8). This ratio is controlled by monazite extraction, and the resulting fractionation effect has been used to explain the low values found for the Himalayan leucogranites (Vidal *et al.* 1984).
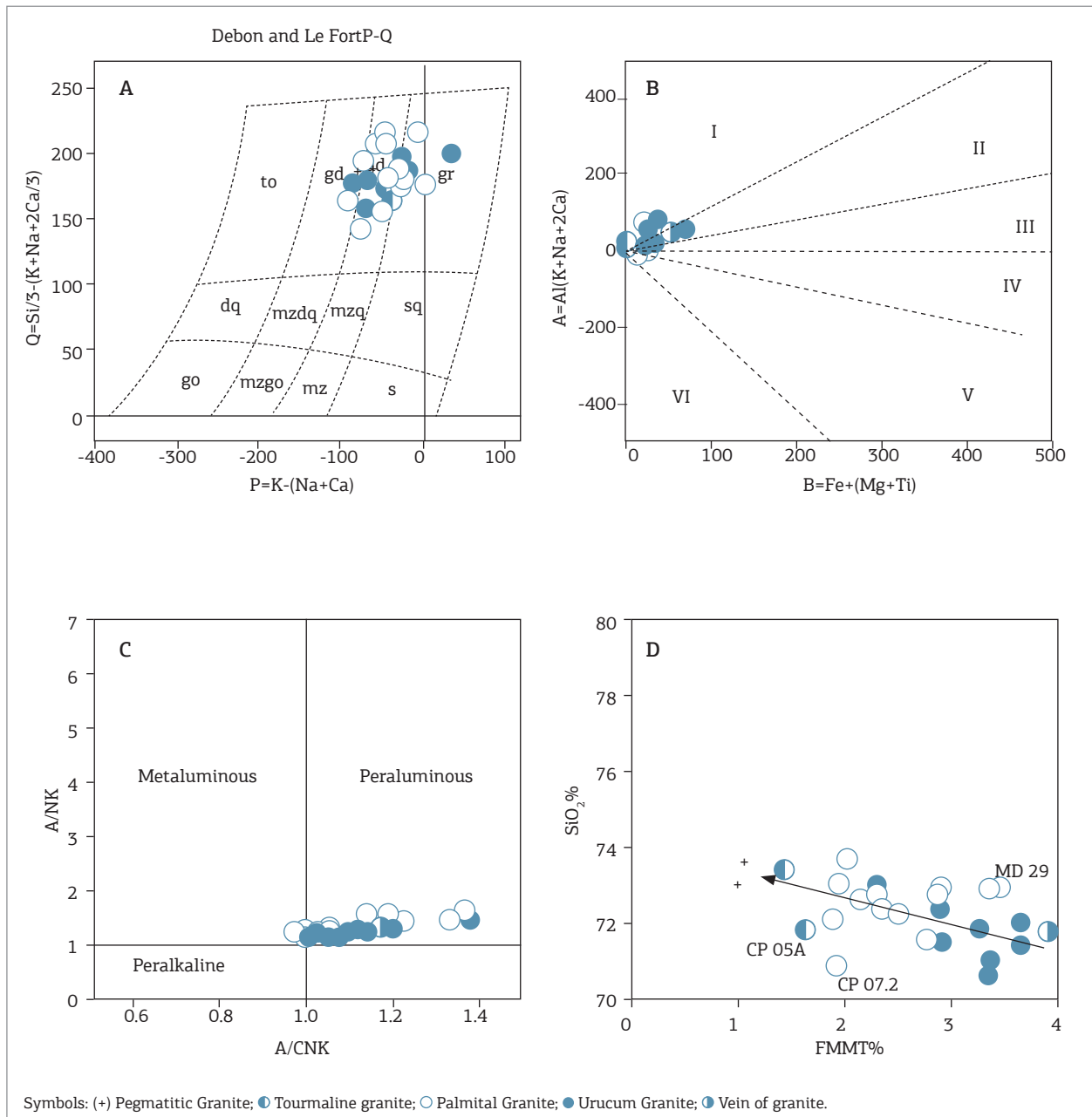

Figure 2. Distribution of granitic facies of Urucum suite based on the diagrams: (A and B) quimical-mineralogical (Q *versus* P) and (A *versus* B) of Debon & Le Fort (1983); with the last classification being divided into the following types of granites: I - peraluminous with two-mica (muscovite > biotite), II - peraluminous with biotite > muscovite, III - peraluminous with biotite; IV - metaluminous with biotite ± amphibole ± ortopyroxene ± clinopyroxene; V - exceptional rocks as carbonatites etc., and VI - leucogranites; (C) Shand's index (Maniar and Piccoli 1989), and (D) the sum $Fe_2O_3^t$ + MgO + MnO + TiO_2 (FMMT) *versus* SiO_2.
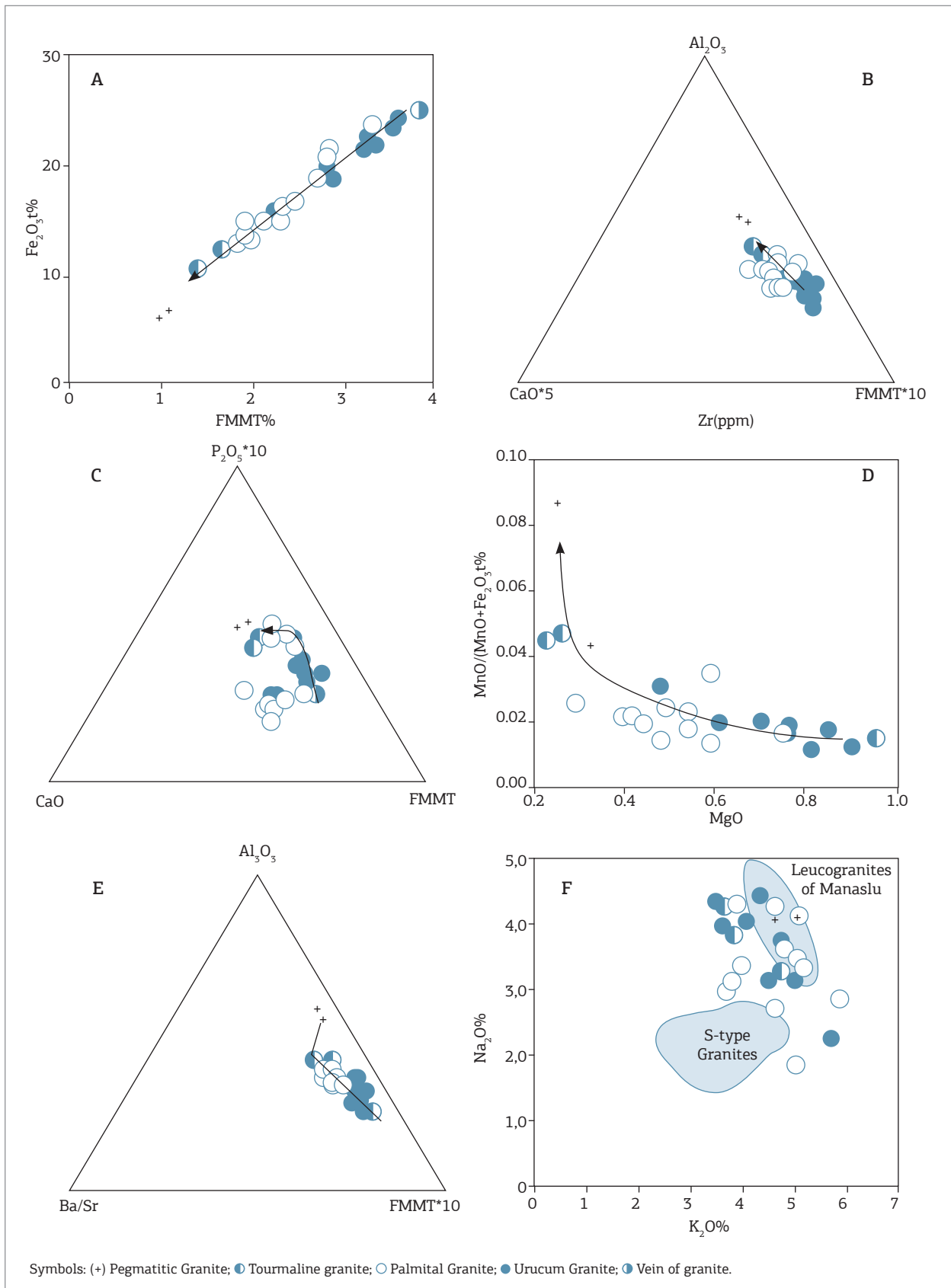
Figure 3. Distribution of granitic facies of Urucum suite based on the diagrams: (A) CaO*5-Al$_2$O$_3$-FMMT*10 (Fe$_2$O$_3$^{t} + MgO + MnO + TiO$_2$), (B) CaO*5-Al$_2$O$_3$-FMMT*10, (C) CaO-P$_2$O$_5$*10-FMMT, (D) MgO *versus* MnO/(MnO + Fe$_2$O$_3$^{t}), (E) Ba/Sr- Al$_2$O$_3$-FMMT*10, (F) K$_2$O *versus* Na$_2$O.

Symbols: (+) Pegmatitic Granite; ◑ Tourmaline granite; ○ Palmital Granite; ● Urucum Granite; ◐ Vein of granite.
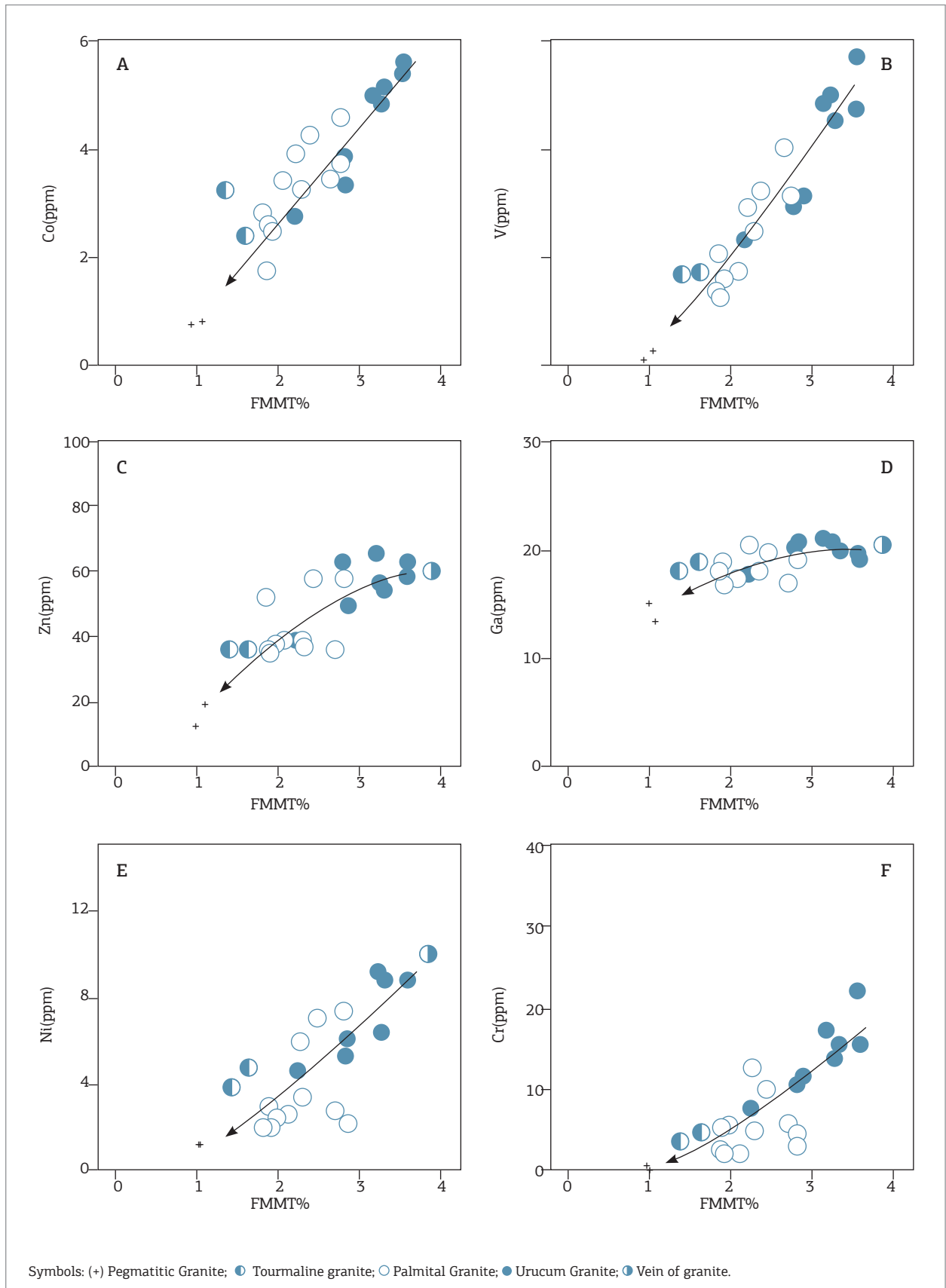
Figure 4. Distribution of granitic facies of Urucum suite based on the diagram with trace elements.
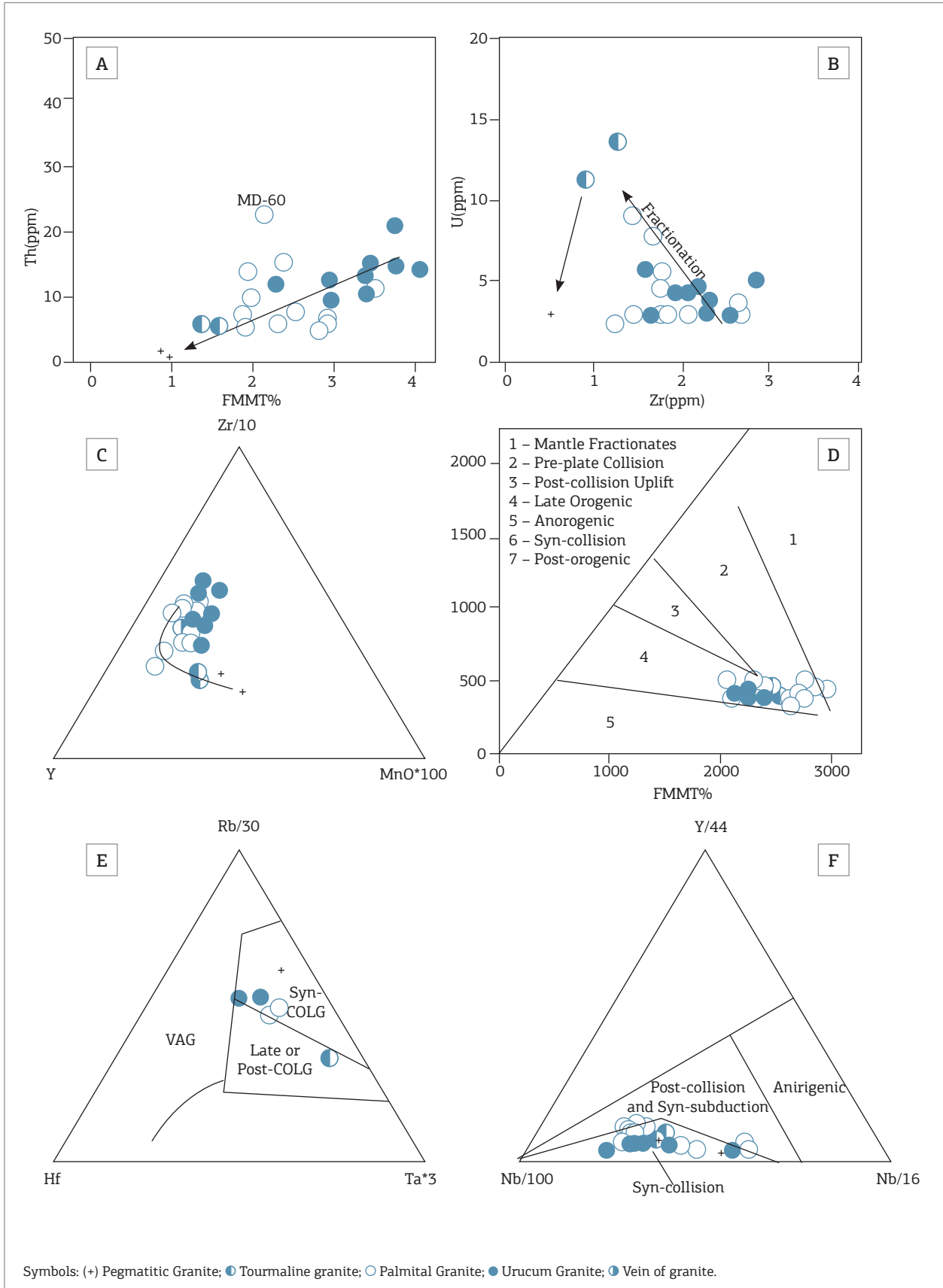
Figure 5. Distribution of granitic facies of Urucum suite based on the diagrams: (A) FMMT-Th, (B) Zr *versus* U), (C) Y-Zr/10-Mn O*^{100}, (D) Batchelor & Bowden (1985), (E) Harris *et al.* (1994) and (F) Thièblemont & Cabanis (1990).
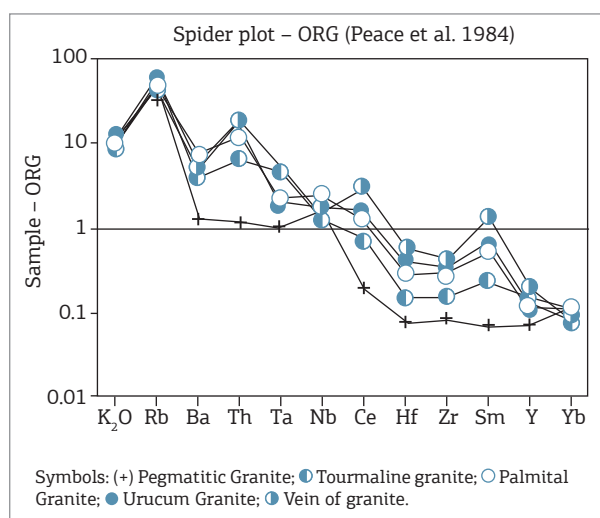
Figure 6. Distribution patterns of the granitic facies of Urucum suite based on the multi- normalized element diagram to mid-oceanic ridge granites of Pearce *et al.* (1984).

In general, the solubility of zircon decreases with temperature, while magma acidity and the peraluminous character increase (Watson 1979; Harrison & Watson 1983; Watson & Harrison 1984). However, the saturation level depends strongly upon molar $(Na_2O+K_2O)/Al_2O_3)$ of the melts, with remarkably little sensitivity to temperature, SiO_2 concentration, or melt Na_2O/K_2O. Watson (1979) experiments show that in peraluminous melts and melts lying in the quartz-orthoclase-albite composition plane, less than 100 ppm Zr is required for zircon saturation. The mains conclusion of author is that any felsic, no-peralkaline magma is likely to contain zircons crystals, because the saturation level is so low for these compositions.

Zr contents decrease with differentiation and show negative correlation with U (except for pegmatites) (Fig.5B), showing that at the last stages of the magmatic crystallization U behaves as an incompatible element, thus leading to U enrichment in the residual liquids, fact confirmed by the presence of U minerals in the pegmatites.

Y contents are controlled by zircon in the less evolved facies (Urucum and Palmital granites) and by garnet in the more evolved facies (tourmaline-bearing granites and pegmatites) (Fig.5C).

Discrimination diagrams for tectonic settings

The composition of the Urucum suite granitoids is comparable to that of syn-collisional granites of Batchelor & Bowden (1985) (Fig. 5D). This observation is confirmed by the Rb/30-Hf-Ta*3 diagram of Harris *et al.* (1994) (Fig. 5E) and the Y/44-Rb/100-Nb/16 diagram of Thiéblemont and Cabanis (1990) (Fig.5F). These parameters indicate

that the composition of Urucum suite is similar to that of syn-collisional granites described by those authors. Ta contents (determined by neutron activation) increase from the Urucum to the tourmaline-bearing facies and then decrease to the pegmatitic granite, indicating that during the crystallization of the latter Ta behaved as an incompatible element. Ta enrichment in the residual pegmatitic liquid is confirmed by the crystallization of niobium tantalates in the pegmatites.

In the multi-element diagrams of Fig. 6 (values normalized to mid-ocean ridge granites of Pearce *et al.* 1984), a similar behavior is observed for the Palmital, Urucum and tourmaline-bearing facies. These facies altogether present enrichment in large-ion lithophile elements (LILE), K_2O, Rb and Ba. Additionally, positive Rb, Th, Nb and Sm anomalies are observed. The relatively high Rb values are typical of syn-collisional granites, implicating an important fluid phase (Pearce *et al.* 1984). The high Rb contents of these granites are in many cases because they are derived from melting of metapelites. Negative anomalies result for Ba, Ta, Hf, Zr and Yb.

The pegmatitic granites behave in a relatively distinct way. These feldspar-rich rocks show positive Rb and Nb anomalies. On the other hand, the values for elements such as Ba, Th and Ta approach those for oceanic-ridge granites, whereas Ce, Hf, Zr, Sm, Y and Yb show values around 0.1 times the normalization values (Fig.6).

DISCUSSION

The Urucum suite is characterized by peraluminous granitoids whose alumina saturation index is comparable to those for the Australian S-type granites (Chappell & White 1974). However, the Urucum suite granites are more Na_2O enriched (average 3.5 *versus* 2.5 %) and more MgO and CaO depleted (average 0.58 and 1.0 % *versus* 1.0 and 1.7%, respectively) than the average S-type granites (Chappell & White 1992). The CaO/Na_2O ratios (0.28) are compatible with derivated-pelitic sequences peraluminous granites (Sylvester 1998). The composition of the Urucum suite granitoids is comparable, nevertheless, to that of the syn-collisional granites (Nalini *et al.* 2000b).

Harker-type diagrams show more or less continuous trends from the (less evolved) Urucum to the (more evolved) tourmaline-bearing and pegmatitic facies, which puts in evidence the fractionation by ferromagnesian minerals, feldspars and accessory minerals during the crystallization of the Urucum suite granitoids. On the other hand, the dispersion illustrated in the alkaline metal diagrams is compatible with crystallization of potassic feldspar as important cummulatic phase, particularly in the pegmatitic facies. Al_2O_3 enrichment also takes place, as suggested by the petrographic observations.

The decrease in transition elements and concentrations (Fig. 4) during magma evolution is due to biotite, tourmaline and garnet fractionation.

Isotopic data available for the Urucum suite (six samples) yield initial Sr^{87}/Sr^{86} ratios in the 0.711 – 0.716 interval, and $\varepsilon_{Nd\,(580\,Ma)}$ values between -7.4 and -8.2, what are compatible with a magma produced by crustal melting of the pelitic sedimentary sequences (Nalini 1997, Nalini *et al.* 2000a). Model ages calculated according to depleted mantle (De Paolo 1981) and obtained for six Urucum suite samples yielded ages in the 1840 – 2290 Ma interval, which is confirmed by inherited zircon U/Pb ages of 2000 ± 300 Ma, suggesting the involvement of Paleoproterozoic protoliths in the origin of the Urucum suite (Nalini *et al.* 2000a).

Geothermometric data were obtained by three methods:

1. apatite and zircon saturation (Watson & Harrison 1984),
2. content of light rare earth in granitic liquids (Montel 1986), and
3. substitution in mica (Monier & Robert 1986).

These results indicate crystallization temperatures in the range of 700 – 750°C for the Urucum and Palmital facies, from 650 – 700°C for the tourmaline-bearing facies, and about 600 – 650°C for the pegmatitic facies (Nalini 1997). As previously mentioned, barometric data suggest minimum pressure conditions around 4 kbar (Nalini 1997).

The comparison of the data presented here with those available in the literature shows that the age for the granitoids of the Urucum suite (582 Ma) falls in the interval of the syn-collisional magmatism of the Araçuaí Orogeny (595 and 575 Ma) and of the Ribeira belt (600 to 590/570 and even 560/540 Ma) in Rio de Janeiro State, respectively (Heilbron *et al.* 1995 and 2004; Machado *et al.* 1996; Machado 1997; Machado & Demange 1998; Trouw *et al.* 2000; Heilbron & Machado 2003; Silva *et al.* 2003; Pedrosa-Soares *et al.* 1999, 2001, 2008; Pedrosa-Soares & Wiedemann-Leonardos 2000), and correspond to the same range of pre-collisional magmatism of the Rio Doce arc/orogeny (Figueiredo & Campos Neto 1993; Campos Neto & Figueiredo 1995).

CONCLUSIONS

During the interpretation of the Urucum suite geochemical data, a strong relation between the evolution of (major and trace) elements and the fractional crystallization of feldspars, ferromagnesian and accessory minerals was stressed out. The accumulation of alkaline feldspar Urucum and pegmatitic facies was not confirmed in the diagrams using K.

As a whole, the different facies define an evolution in the following sequence: Urucum suite granites, Palmital granite,

tourmaline-bearing granite and pegmatitic granites. Thus, the fractional crystallization can be explained on the basis of variations exhibited by the major and trace element variation diagrams, in which the behavior of compatible elements, such as Mg, Ti, Fe, Ba, Zr, Th, Co, V, Zn, Ga, Ni and Cr, is explained by the conspicuous biotite fractionation. On the other hand, alkalies, Mn, P, Li, Ta, U and B show incompatible behavior during magma evolution.

The tourmaline crystallization (tourmaline-bearing facies) is compatible with fractional crystallization of the essential minerals and biotite presents in the magma and progressive B enrichment in the residual magma. However, the crystallization of small quantities of tourmaline as observed in the Urucum suite tourmaline facies (usually < 1 – 2%) is not enough to significantly deplete the residual liquid in B (Pichavant 1981). This fact is confirmed by the extensive presence of tourmaline in the rare element-bearing pegmatites associated with the granites.

Geothermobarometric data available for the Urucum suite suggest crystallization under conditions temperatures varying between 750 (Urucum and Palmital facies) and 600°C (pegmatitic facies), and minimum pressures around 4 – 5 kbar (or 12 – 15 km depths) (Nalini 1997). These data are compatible with the behavior showed by major and trace element diagrams.

Sr and Nd isotopic data available for the Urucum suite granitoids are similar to those obtained for syn-collisional granites (suite G_2 of Pedrosa-Soares & Wiedemann-Leonardos 2000) of the northern portion of the Araçuaí belt (Martins 2000, Martins *et al.* 2004), thus stressing out a strong crustal contribution during the generation of these rocks. The high initial isotopic ratios yielded by the four facies of the Urucum suite (0.7465 – isochron value, or from 0.7114 to 0.7165 – individual samples), which correspond to strongly negative $\varepsilon_{Nd\,(580\,Ma)}$ values (between -7.4 and -8.2), are compatible with a wide partial melting of pelitic sequences to generation of its magmatism. The relative coherence of T_{DM} model ages from 1.8 Ga to 2.3 Ga, obtained for all facies, with the inherited zircon ages around 2.2 Ga, also suggesting melting of sediment derived from Paleoproterozoic rocks as probable sources of magma generation. This interpretation implicates a crustal residence of *ca.* 1.5 Ga for the granite protolith(s).

From the exposed above, the Urucum suite granites (U/Pb age of 582 Ma) are (~30 to 40 Ma) older than the syn-collisional granites (ages between 560 and 530 Ma) of the Rio Doce magmatic arc. Alternatively, they correspond to the syn-collisional magmatism (ages between 591 and 575 Ma) of the Araçuaí belt and also to the syn-collisional magmatism (ages between 600 and 590/570 Ma) of the Ribeira belt in Rio de Janeiro State.

The existence of S-type granites (Urucum suite) with (U-Pb zircon ages of 582 ± 2 Ma (Palmital facies) and 573 ± 4 Ma (megaporphyritic facies) suggests an interval of about 10 Ma between the end of the I-type calc-alkaline magmatism

(Galileia suite, U-Pb age of 594 ±6 Ma) and the beginning of the peraluminous magmatism in the Rio Doce Valley.

Tectonic models of continental collision involving significant crustal thickening (Alpine-Hymalaian type) are compatible with tectonic models proposed for the Araçuaí belt. In this sense, it is assumed in this work that the peraluminous granites from the Urucum suite were generated during late-collisional stage, similarly to what was interpreted for the S-type granites of the Rio de Janeiro state (Machado & Dehler 2002).

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