Geochemical and isotopic evidence for the petrogenesis and emplacement tectonics of the Serra dos Orgaos batholith in the Ribeira belt, Rio de Janeiro, Brazil

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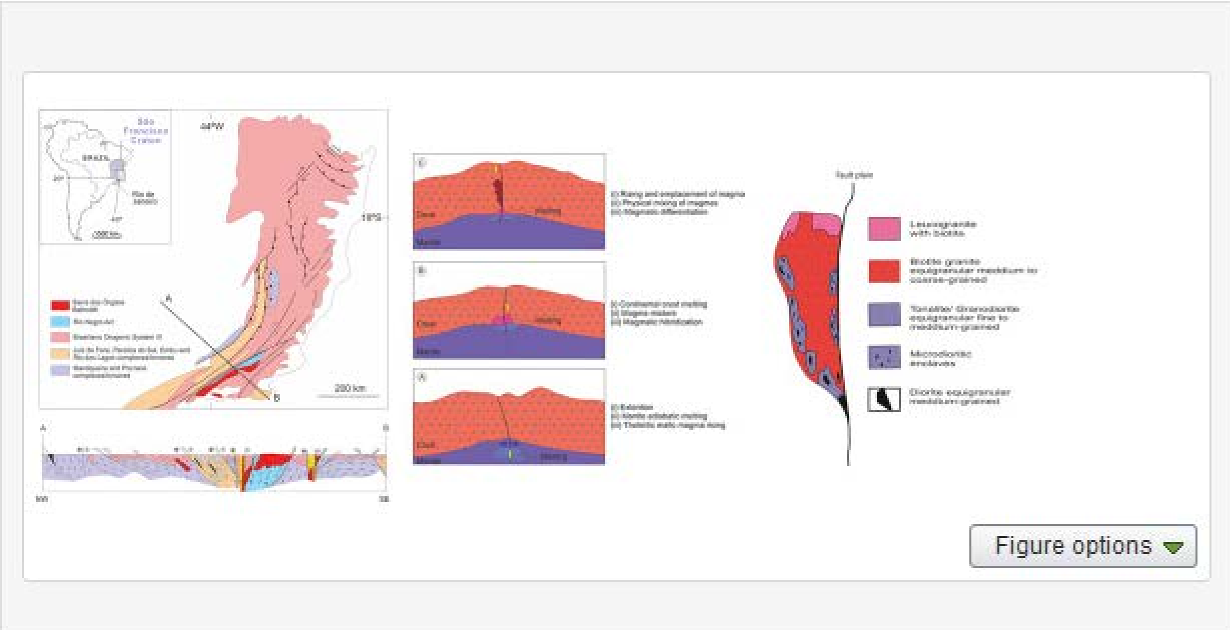
Abstract

The Serra dos Órgãos batholith in the State of Rio de Janeiro (Brazil) is a NE-SW-trending elongated body that occupies *ca*. 5,000 km^2 in plan view. It is a foliated intrusion, especially at its borders and is crosscut by syn-magmatic shear zones, with foliations that are moderately- to steeply-dipping to the northwest and moderately- to shallow-dipping in the center and to the southeast, in a configuration of a large laccolith. It was emplaced between 560 to 570 Ma, during an extensional episode that was part of a series of events that comprise the Brasiliano Orogeny in SE Brazil, and which includes deformation, metamorphism and granite intrusion during the interval between 630 and 480 Ma. The two main rock types in the batholith are biotite-hornblende monzogranite, and biotite leucogranite, with subordinate tonalite, granodiorite, diorite, quartz diorite (enclaves), aplite and pegmatite. Harker-type diagrams help show two rock groups with similar trends of evolution: a dioritic and a granitic. The first one is tholeiitic, whereas the second is calc-alkaline, with medium- to high-K calc-alkaline affinity and metaluminous to slightly peraluminous character. In both groups strong decrease in Al_2O_3, MgO, FeOT and CaO relative to silica contents are observed, which is compatible with trends of fractional crystallization involving clinopyroxene and/or hornblende, plagioclase, opaque minerals, apatite, microcline and biotite. The Sr and Nd isotopic data suggest recycling of a Paleoproterozoic crust as an important petrological process to generate the batholith rocks. Geothermometry (amphibole composition) and geobarometry (saturation in zircon and apatite) indicate that most of the batholith solidified at mid to lower crustal levels at about 750°C and between 5 and 5.5 kbar. We consider that Serra dos Órgãos crustal protoliths underwent melting caused by the interaction with hotter mafic magma at the base of the crust. These two magmas, with distinct initial compositions and rheology, probably underwent mixing and mingling. This process continued during the rise of the magma

through the crust, which was accompanied by magmatic diffentiation. The main feature that characterizes the post-collisional Serra dos Órgãos granite magmatism is the connection with high angle ductile shear zones of continental scale and presence to a greater or lesser extent of mafic magmas.

Key-Words: Ribeira Belt, Serra dos Órgãos Batholith, Petrogenesis, Tectonic

Graphical abstract



1. Introduction

The Neoproterozoic/Cambrian granitic magmatism in the central part of the Ribeira belt was developed during an orogenic system newer in Southeastern Brazil, named Rio Doce Orogeny and best characterized in the Serra do Mar microplate, which represents the accretionary event that was active between 590 and 480 Ma (Campos Neto and Figueiredo, 1995). The authors separated this event into three tectonic stages: (i) pre-collisional (590-570 Ma), syn-collisional (560-530 Ma) and post-collisional (520-480 Ma). Further works, supported by geological mapping, tectonic analysis, geochemistry date and new geochronological and isotopic data, have characterized oldest magmatic arcs and described as Andean-type These arcs are referred to as Rio Paraíba do Sul - ≥ 620/600 Ma (Machado and Demange, 1998; Machado et al., 2000), Rio Negro - 640-600 Ma (Tupinambá, 1999; Tupinambá et al., 2000) or 790-620/610/590 (Heilbron and Machado 2003, Tupinambá et al., 2007, 2012; Heilbron et al., 2004) and Serra da Bolívia – 650-590 Ma (Heilbron et al., 2013).

The generation of large granitic batholiths is associated primarily with magmatic arcs related to active subduction environments or collisional environments linked to high-grade metamorphism. In Neoproterozoic orogenic belts that occur in Brazil, the main magmatism presents a post-collisional nature, with the syn-collisional granite having a very subordinate volume. The post-collisional granite magmatism have common characteristics were their connection with ductile shear zones of continental scale and presence to a greater or lesser extent of mafic magmas. These magmas, generally dioritic composition, underwent a physical and chemical mixing process with granitic magmas, generating hybridization structures at high temperatures and physical structural relationships based on crystallization conditions.

The Serra dos Órgãos batholith, the subject of this article, crops out in the central hill ranges of the Rio de Janeiro State. It is the largest batholith, forming a tabular body about 165 km long and 30 km wide, concordant with the tectonic regional structure. Here we present a review of previous work on the Neoproterozoic tectonic evolution of the region, on the granitoids of Rio de Janeiro, and on the Serra do Órgãos batholith. There follows a brief description of samples present in the batholith, together with a presentation of new geochemical data on whole rocks and minerals.

We discuss implications for the petrogenesis of the batholith, its tectonic environment and intrusion depth, based in detailed petrographic observations, structural data, and new isotopic (Sr and Nd), geochemical and geothermobarometric data.

2. Materials and Methods

In the present study, approximately sixty samples from 3 traverses of the batholith were studied. Analyses of these samples were obtained on an Philips PW 1404 X-ray fluorescence spectrometer, or on Jobin JY-38Pi and JY32P atomic emission ICP spectrometers at the geochemical laboratory of the Saint Etienne School of Mines, France, after appropriate sample preparation. Chemical classifications of the rocks using the TAS (Le Bas et al., 1986) and the R1-R2 of La Roche et al., (1980) schemes (not shown) are usually in good agreement with the semi-quantitative modal classification. In cases where a major discrepancy between petrographic and chemical classifications was found (e.g. monzogranite versus tonalite, or quartz diorite versus granodiorite) priority was given to the petrographically assigned name.

Strontium isotope analyses of six rock samples were performed at the Geochemistry Laboratory of Clermont-Ferrand University, and two rock samples were analyzed for neodymium isotopes in the Geochronology Laboratory of Rennes University, France. In both cases the same rock samples were used for analyses and they were selected based on previously obtained petrographic and geochemical data.

Other data geochronological were obtained by U/Pb method in multi-crystal zircon fractions, Pb/Pb in mono-crystal zircon by evaporation and Rb/Sr whole rock isochron (Cordani et al., 1973;

Machado et al., 1996, Porto et al., 1996; Machado, 1997; Tupinambá, 1999). More recently, one sample of batholith was dated by U/Pb SHRIMP method yielding an age of 569 ± 6 Ma (Silva et al., 2003).

3. Tectonic Context

3.1 *The Ribeira Belt*

The Ribeira belt (Almeida et al., 1973) is part of the central segment of the Mantiqueira Province and extends for more than 1,400 km along the southeastern coast of Brazil (Fig. 1), which is continuous along the strike of belt, with NE structural trend between the states of Paraná and Rio de Janeiro that changes to NS between the Espírito Santo and Minas Gerais (Almeida et al., 1981; Hasui and Oliveira, 1984; Trouw et al., 2000; Heibron et al., 2004). The NE-SW to NNE-SSW oriented Ribeira belt has neoproterozoic ages and was developed by amalgamation of the São Francisco and Congo cratons and involved a complex history of collision and accretion/collage of terranes, microcontinents and island arcs (Campos Neto and Figueiredo, 1995; Brito Neves et al., 1999; Trouw et al., 2000; Heilbron et al., 2000, 2004, 2013, 2015; Heilbron and Machado, 2003; Silva et al., 2003).

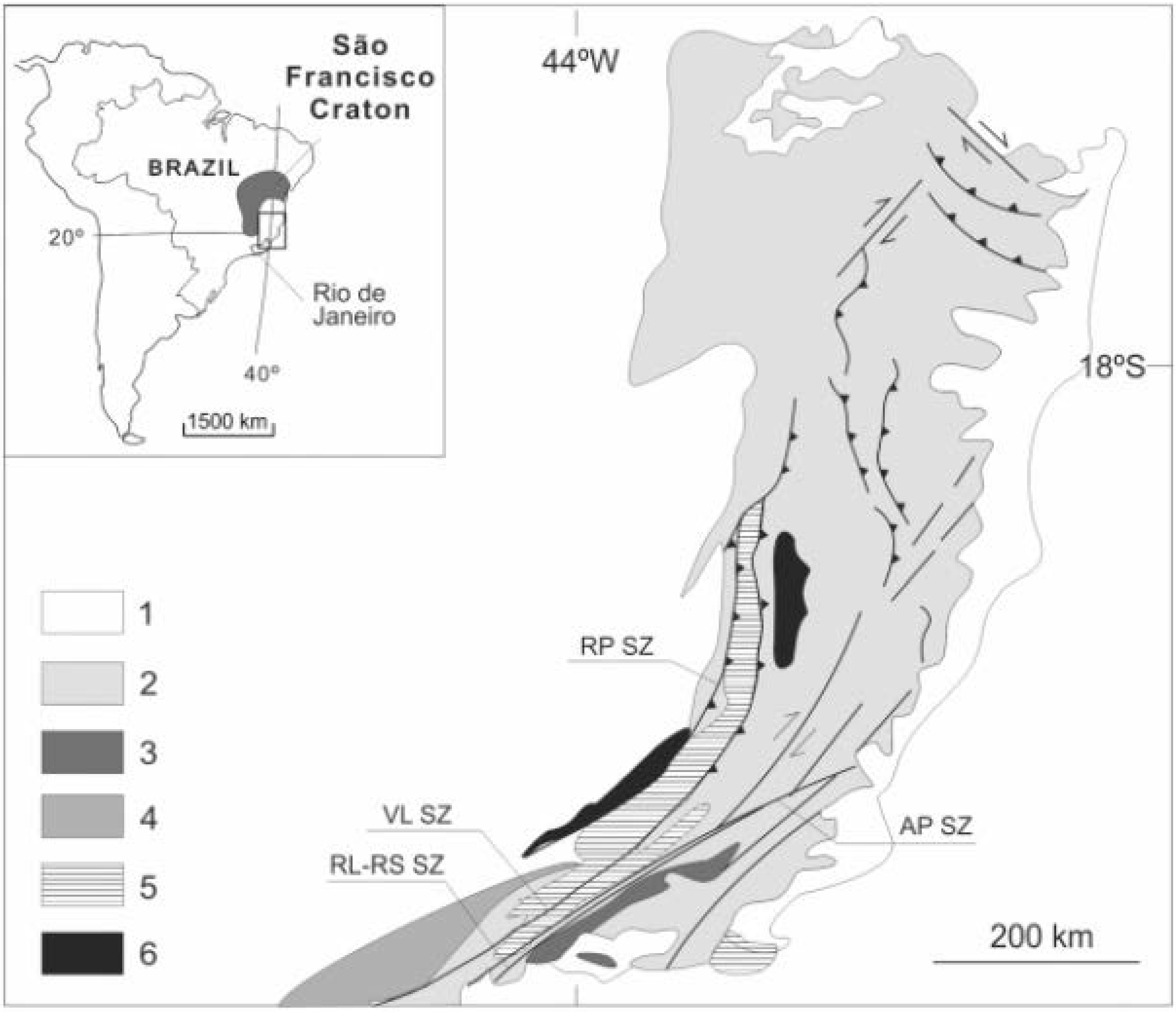


Fig. 1.
Simplified map tectonic of the Ribeira belt. Adapted from Bizzi et al. (2003). 1 = Quaternary sediments; 2 = Brasiliano Orogenic System III; 3 = Serra dos Órgãos Batholith; 4 = Embu Terrane; 5 = Juz de Fora Complex; 6 = Mantiqueira and Pocrane complexes. SZ = Shear Zones: RP = Rio Preto, VL = Valença, AP = Além-Paraíba, RL-RS = Ribeirão das Lajes-Rio Santana.

Two orogenic systems are described by Campos Neto and Figueiredo (1995) in the central and northern segments of the Ribeira belt: an older, orogeny named 'Brasiliano I', which was of the collision type or controlled by ocean plate subduction, and occurred between 700 and 600 Ma; and another, younger, the Rio Doce Orogeny, with batholithic calc-alkaline plutonism indicating northwestern subduction, best characterized in the Serra do Mar Microplate by a magmatic arc, active between 590 and 570 Ma, with collisional stage between 560-530 Ma. In the final stage of the "Brasiliano I' orogeny in the Apiaí-Guaxupé Microplate, occurred an alkali-calcic plutonism at 610 Ma that graded to rapakivi-like Fe-Hastingsite-biotite granites genesis with 600-580 Ma, marking the post-orogenic phase of this orogeny, which is synchronous with the establishment of a new magmatic arc. According to Hasui (2010), the collisional processes began in the Brasiliano I (900-700 Ma), but were mainly developed during the Brasiliano II (670-530 Ma) and ended in the Brasiliano III (580-490 Ma), resulting the orogenic systems Mantiqueira and Tocantins.

Pioneer studies (Rosier, 1957, 1965) suggested the presence of Alpine-style nappes in the Rio de Janeiro region. Subsequent studies have attempted to related the geological features to the tectonic evolution of destructive plate margins. (e.g. Demange et al., 1991; Wiedemann, 1993; Figueiredo and Campos Neto, 1993; Campos Neto and Figueiredo, 1995; Trouw et al., 2000; Tupinambá et al., 2012; Heibron et al., 2000, 2004, 2013, 2015; Heilbron and Machado, 2003).

The Rio Paraiba do Sul positive flower structure associated with ductile shear zones of high angle corresponds to the main structural framework of the core of the Ribeira belt in Rio de Janeiro (Machado and Endo, 1993; Dehler, et al., 2006). This structure, recognized since the 1960s, consists of oppositely dipping foliations to NW in its southern limb, and to SE in northwestern limb, and was initially described as fan-like structure (Ebert, 1968).

The Ribeira belt (RB) involves to the Serra do Mar microplate and Paraíba do Sul and Juiz de Fora terranes (Campos Neto and Figueiredo, 1995). The Serra do Mar microplates that consists of three middle-high grade metamorphosed terranes – *granulite-granite-migmatite, gneiss-migmatite* and *supracrustal* – has been accreted the Paraiba do Sul and Juiz de Fora terranes during the Cambrian collisional event of this sector of Gondwana (Campos Neto and Figueiredo, 1995). According to such authors, in the Búzios region, located in the eastern portion of the RB in Rio de Janeiro, there occurs an exotic terrane, known as the Cabo Frio terrane, composed of a paragneiss-quartzite sequence and high grade metamorphic ortogneisses of the Ryacian (2.2-2.0 Ga), that was affected by a tectono-metamorphic event that occurred in the Cambrian (~520 Ma), which has been attributed to Buzios Orogeny (Schmitt, 2001; Schmitt et al., 2004). In this event, occurred accretion of the younger terrane in the eastern part of the RB in Rio de Janeiro and it is considered an exotic terrain in the belt (Campos Neto and Figueiredo, 1995; Schmitt et al., 2004).

The RB in the Rio de Janeiro State has been divided in four tectonic domains which are separated by ductile shear zones whose direction is parallel to the regional structures with predominantly horizontal slip. From SE to NW the domains are: Litorâneo, divided into northern and southern segments; Serra dos Órgãos, Paraíba do Sul (also divided into northern and southern segments) and Juiz de Fora (Fig. 2a).The domains represent megaslices or terranes, successively stacked against the southern and southeastern borders of the São Francisco Craton and reworking its margin (Heilbron and Machado, 2003; Heilbron et al., 2003). The collision(s) were responsible for the transcurrences and tectonic transport/flow parallel (tectonic escape) and oblique to the belt, considering the São Francisco Craton as a reference (Vauchez et al., 1992, 1994; Dehler and Machado, 2002; Dehler et al., 2006; Vicente et al., 2007; Karniol et al., 2008). An oblique collision model involving the Vitória, São Paulo and Brasília plates was proposed to account for the development of transpressional tectonics with strong strain partitioning between contractional and strike-slip structures (Ebert and Hasui, 1998).

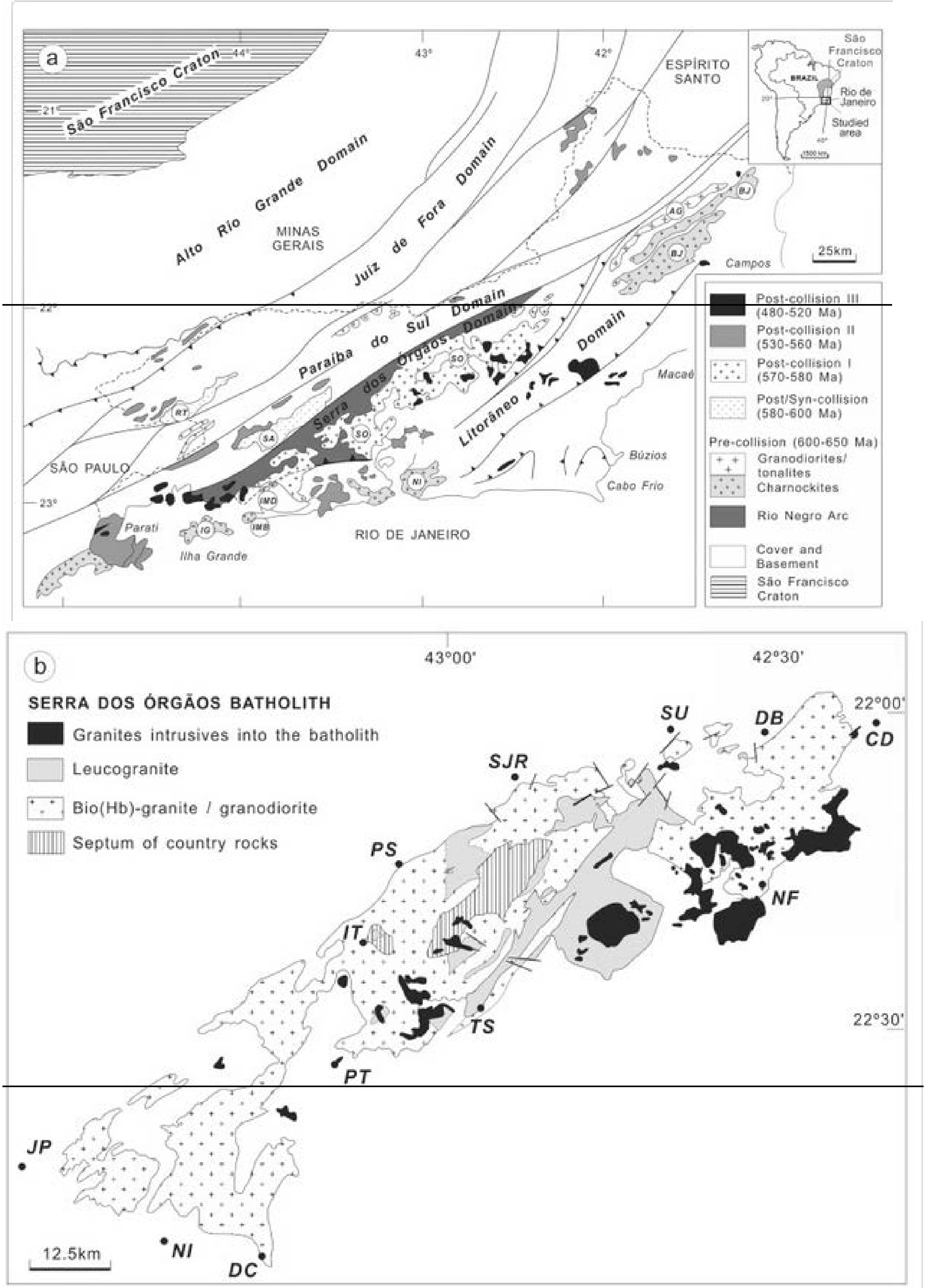


Fig. 2.

(a) The Ribeira belt belt from eastern São Paulo State to southern Espírito Santo State. Tectonic domains and Pre-, syn-, late-, late/post- and post-collisional granitoids mentioned in the text: BJ = Bela Joana; NI = Niteroí; IG = Ilha Grande; IMD = Ilha de Madeira; SO = Serra do Órgãos; AG = Angelim; SA = Serra das Araras; RT = Rio Turvo (modified from Machado et al., 2000); (b) The Serra dos Órgãos batholith and later granites in the Serra dos Órgãos domain. Major and minor towns in the area are shown: PS = Posse, IT = Itaipava, SJR = São José do Ribeirão, SU = Sumidouro, DB = Duas Barras, CD = Cordeiro, JP = Japeri, CV = Cava, NI = Nova Iguaçú, DC = Duque de Caxias, NF = Nova Friburgo, TS = Teresópolis, PT = Petrópolis.

More recently, the RB in Rio de Janeiro was divided into four major tectonic units: (a) Occidental terrane, at northwest, regarded as the reworked margin of the craton of San Francisco, (b) the klippe of the Paraíba do Sul; (c) Oriental terrane or Serra do Mar microplate (*sensu* Campos Neto and Figueiredo, 1995), comprising an association of the three magmatic arcs (Rio Negro, Bolivia and Serra da Prata), and (d) Cabo Frio terrane (Heilbron et al., 2003, 2013). The Occidental terrane represents the reworked margin of the São Francisco Craton (Heilbron et al., 2003, 2013). The Paraíba do Sul klippe is considered a synformal structure overlying the Juiz de Fora domain. The Oriental terrane has been divided in three tectonic domains: (a) Cambuci domain; (b) Costeiro domain, and (c) Italva klippe.

The researchers who have focused their attention on the tectonic model of RB suggest an older tectonic of low-angle-tectonism that predates the tectonic of high-angle tectonism (Heilbron, 1993; Heilbron et al. 1994, 1995, 2004), whereas others consider only one tectonic event, which was responsible for the formation of the coeval structures (low- and high-angle) related to oblique collision in continental-scale (Ebert and Hasui, 1998; Dehler, 2002; Dehler et al. 2007). This regional oblique collision, related to an E-W convergence trend, is considered the event that triggered a transpressional tectonic regime in the belt, which was responsible for dextral strike-slip movement parallel to the orogenic trend. It has been described by several authors (Machado and Endo, 1993; Ebert and Hasui, 1998; Dehler et al. 2007).

In the central and northern parts of RB, two groups of the extensional settings were recently characterized: an older one, between 610 and 570 Ma, related to Serra do Azeite shear zone, constituting mylonites with deformation that began in amphibolite facies conditions and progressed to greenschist facies, preserving a well-developed mylonitic fabric (Dehler et al. 2007), that has been identified in other belt segments (Dehler and Machado, 2002; Karniol and Machado, 2007); and a younger one, dating between 520 and 500/480 Ma, interpreted as result of the orogenic collapse and which was related to the emplacement of the post-collisional granites with age between 520 and 480 Ma (Trouw et al. 2000; Heilbron et al. 2004), although structural data are still not available. This orogenic collapse has been also described in the Araçuaí belt and postdates the regional contraction strain (Pedrosa Soares et al. 2000, 2009, 2011; Heilbron et al. 2004).

The older extensional structures have been described in the north of Rio de Janeiro State, between Muriaé and Itaperuna (Karniol et al., 2007; Machado et al., 2001), and in the eastern portion of the *Quadrilátero Ferrífero*, in the Furquin, Acaiaca and Dom Silvério regions (Endo, 1997). In this region, mylonitic quartzites of the Rio das Velhas Supergroup occur over a wide area in the contact of basement rocks belonging to the Mantiqueira complex. This wide area composed of mylonites is associated with the Furquim shear zone, whose kinematic indicators (S-C and S-C-C’ foliations, asymmetric structures and shear-bands) suggest top-to-ESE shearing (Endo, 1997). This same kinematic context has been reported in several regions of the Ribeira belt, and its development is considered coeval with a phase of regional stretching, sub-parallel to the belt (Dehler and Silva, 2000; Dehler et al., 2006, 2007; Karniol et al., 2007, 2008). According to these authors, this phase is related to the transtensional regime responsible for the tectonic extrusion and uplift of crustal slices. $^{40}Ar/^{39}Ar$ ages obtained for amphiboles and micas from Serra do Azeite mylonites and pegmatites cluster between 600 and 570 Ma (Campagnoli, 1996), and suggest that the extensional event operated in this period (Machado et al., 2001; Dehler et al., 2007).

3.2 *The Rio de Janeiro Neoproterozoic/Cambrian Granitoids*

Reviews on the Neoproterozoic/Cambrian granites were done in the Ribeira belt in the State of Rio de Janeiro by Penha (1984), Penha and Wiedemann (1984), Junho et al. (1987), Wiedemann et al., (1987), Junho (1991, 1993, 1998), Machado and Peloggia (1987), Machado and Demange (1994a, 1998), Heilbron (1995), Heilbron et al. (1995, 2004, 2005), Heilbron and Machado (2003), Machado (1997), Machado et al. (2000), Tupinambá et al. (2000, 2012). Geochronological data and tectonic classification of these granitoids have been presented by several authors (Machado et al., 1996; Machado, 1997; Tupinambá, 1999; Pereira et al., 2002; Heilbron and Machado, 2003; Heilbron et al., 2004, 2013; Tupinambá et al., 2000, 2012; Silva et al., 2003, 2008; Valeriano et al., 2011).

Three groups of Neoproterozoic/Cambrian granites are recognized in the Ribeira belt. The oldest group is foliated or gneissic batholiths whose internal structures are concordant with the tectonic regional structure. These pre- or syn-collisional plutons are considered to be pre- or syn- tectonic in relation to the second phase of folding F_2 which affected the regionally host rocks of these plutons (Machado and Demange, 1994a). They were intruded under deep conditions corresponding to the amphibolite or granulite facies into middle or lower crust.

Three types of plutons are found in the first group. The first type is represented by Bela Joana pluton, which is constituted exclusively by charnockitoid rocks. The second type is represented by the Niterói, Ilha Grande, Ilha da Marambaia and Ilha de Madeira plutons, in which charnockitoids are associated with granitoids. In the third type, the charnockitoids are absent (Rio Negro, Serra do Órgãos, Angelim, Serra das Araras and Rio Turvo plutons).

The first two types are composed of I-type granites, while the third includes both I- and S-types, with the latter being represented by the Serra das Araras and Rio Turvo plutons. The I-type associations form linear batholiths that have tectonic, transitional and intrusive contacts with the host rocks. They have a wide compositional variation between tonalite and granite, and contain mafic microgranular enclaves and diorite bodies (Machado and Demange, 1994; Machado, 1997). Migmatitic or gneissic granites predominate in the S-type association, but granodiorites are also present. These plutons form elongated bodies whose contacts with the host rocks are transitional. Enclaves are of metasedimentary rocks. This association has been described both in the southern part of the Paraíba and Costeiro domains (Fig. 2a). The third type is composed mainly of strongly foliated tonalite and granodiorite to diorite and quartz diorites enclaves (Rio Negro and Angelim plutons) and granodiorites and syenogranites with enclaves similar to the previous (Serra dos Órgãos batholith).

The Serra dos Órgãos batholith is the largest granitic body of the Ribeira belt in Rio de Janeiro State. It corresponds to the remarkable linear structure with concordant contacts with regional country rocks. Unlike of the rocks of other granitic bodies related to first group, the rocks of the batholith generally present a well-preserved magmatic fabric in scale of outcrop and rarely exhibit gneissic structure. The batholith is structurally homogeneous and was emplaced in crustal levels corresponding to middle crust. On the other hand, the other bodies of the same group (I-type and S-type), particularly the Angelim, Bela Joana, Serra das Araras and Rio Turvo batholiths, are strongly deformed and display a remarkably linear structure with ductile deformation and recrystallization of quartz, feldspars, garnet, amphibole and pyroxene in the charnockitic rocks. These bodies were emplaced in deeper crustal levels compatible with lower crust. Post-tectonic granites with clearly intrusive contacts and dated around ca. 485 Ma (U-Pb in zircon) are described by many authors in several parts of the batholith (Junho et al., 1987; Wiedemann et al., 1987; Junho, 1998; Valeriano et al., 2011).

The second group of granitoids in the Ribeira belt is composed of smaller massifs, such as stocks or small tabular or elongated batholith associated with regional, high-angle ductile shear zones (Nummer, 2001; Nummer et al., 2007). The plutons are foliated, with solid-state deformation especially at the borders and igneous flow structures in the nuclei. Contacts are often tectonically deformed and transposed to be concordant with host rock structures. I-type granites or granodiorites predominate, but S-type granites are also found.

Finally, the third group is composed of small circular plutons intruded into shallow crustal levels, with sharp contacts. Textures are isotropic to flow-oriented, and equigranular to porphyritic are found. Granites predominate over granodiorites, and are commonly accompanied by pegmatites. Dioritic microgranular enclaves are common. These late- to post-tectonic plutons have received most of the attention dedicated to granites in Rio de Janeiro (e.g. Wiedemann et al., 1987; Junho et al., 1987; Junho, 1991, 1993; Valeriano et al., 2011). Recently, this group of granites was separated in two magmatic pulses: the first one occurred at 512 Ma (Pedra Branca, Suruí and Buarana plutons) and the second occurred at ca. 486 Ma (Mangaratiba, Favela, Andorinha, Frades, Nova Friburgo and Sana granites) (Valeriano et al., 2011). According to authors, this first pulse post-dates the end of the last and main collisional phase by 35 Ma, and also post-dates the onset of the second collisional by 20 Ma.

Three Neoproterozoic magmatic arcs have been recognized in the Ribeira belt in Rio de Janeiro: an intraoceanic arc (Rio Negro) with age between 790-620/600 Ma and two Cordilheran arcs (Bolívia and Serra da Prata or Italva) developed between 650-590 Ma (Tupinambá, 1999; Tupinambá et al., 2000, 2007, 2012; Heilbron et al., 2013). According to these authors, these arcs were progressively amalgamated during the main collision event of the Brasiliano collage, occurred between

620-580 Ma, and also during the last collision event that took place ~ 520 Ma (Trouw et al., 2000; Schmitt et al., 2004). The Rio Negro arc, with εNd(t) ratios from −14 to +5 and 87Sr/86Sr initial ratios between 0.704 to 0.719 and also values between 0.727 to 0.736 (Table 2, p. 432), is considered the most primitive arc among them (Tupinambá et al., 2012). Samples from this arc yield Sm-Nd model ages ranging from 2.47 Ga to 0.99 Ga and exhibit three important modes at 1.0, 1.3 and 1.8 Ga, the latter one being the most expressive. These model ages are interpreted as mixing between juvenile and basement with different isotopic compositions, whereas the older, at 1.8 Ga, is considered as the age of basement rocks that contaminated the juvenile magmatic arc rocks (Tupinambá et al., 2013). On the other hand, Sm/Nd isotopic data of the Cordilheran-type arcs indicate T_{DM} values between 1.72 Ga and 2.04 Ga, except for three samples, which display Mesoproterozoic model ages. The εNd(605) between -8 and -12, indicates participation of older basement in the generation of these arcs (Heilbron et al., 2013).

. In the northern portion of the Rio de Janeiro State, in the Araçuaí Orogen, there are records of widespread magmatic activities of granite generation related to the Rio Doce arc, developed from 630 to 480 Ma (Pedrosa-Soares and Wiedemann-Leonardos, 2000; Silva et al., 2008; Pedrosa-Soares et al., 2011; Gonçalves et al., 2014; Peixoto et al., 2015). These authors divided this magmatism in six suites (G1, G2, G3S, G3I, G4 and G5), from the oldest to the youngest: G1- pre-collisional, ranging predominantly from 625 and 595 Ma; G2- syn-collisional, with ages in the 580 Ma to 560 Ma interval, and peak around 575 Ma, G3-I and G3-S– late to post-collisional, representing pulses of calc-alkaline magma intruded mainly along oblique to strike-slip shear zones, with ranging ages from 560 Ma to 530 Ma; G4 and G5 suites are late- to post-tectonic suite (post-collisional), with ages between 530 to 500 Ma and 500 to 480 Ma, respectively.

A syn- to post-collisional event related to evolution tectonic of the 'Brasiliano I' Orogeny (> 600 Ma) and best characterized in the Apiaí-Guaxupé microplate was described in the southern and southwestern parts of the Rio de Janeiro State by Campos Neto and Figueiredo (1995). This event also resulted in the accretion of granitic belt of the Embu terrane which was intruded by voluminous peraluminous plutonism between 750 and 700 Ma, as well as by other younger S-type plutons associated with metaluminous porphyritic granites with late-collisional characteristics (Vieira and Tassinari, 1988). The southern portion of the Serra do Mar microplate of the Rio Doce orogeny (younger) contains alongated I-type plutons of hornblende-biotite monzonite-granites, frequently associated with charnockites with syn- to late-collisional characteristics and age at about 550-540 Ma (1995). Recently published U-Pb geochronological data, obtained from zircon and monazite crystals from the nine granite plutons of the Embu terrane (Caucaia, Itapeti, Sabaúna, Santa Branca, Santa Catarina, Mauá, Guacurí, Quebra-Cangalha and Lagoinha), show that the ages are concentrated in a narrow interval around 590 to 580 Ma and a minor part is concentrated in the range between 660 and 620 Ma (Quebra Cangalha batholith and Santa Catarina Granite), indicating a long history of crustal reworking and magma generation (Alves et al. 2013). According to these authors, the data confirm that granite magmatism is at least some 10-15 m.y. younger in the central Ribeira belt when compared to the neighboring domains to the north (i.e. the Apiaí-Guaxupé terrane), where the ‘synorogenic’ granites were mostly formed in the interval 630 to 600 Ma and the ‘post-orogenic’ granites were divided in two groups with different ages (~585 and 565 Ma), interpreted as a result of crustal melting (Leite et al., 2007a, b).

3.3 The Serra dos Órgãos Batholith

This batholith is one of the largest in southeastern Brazil, and in size is comparable to many of the Andean batholiths of the western coast of South America. It has approximately 165 km of extension for about 25 km wide. The first reference (Lamego, 1938) refers to a large granitic batholith in the Serra do Mar which also occupies parts of the lowlands near the city of Rio de Janeiro and of the Paraíba do Sul river valley (Fig. 2b). The body was considered to be a typical batholith intruded into Archaean crust, with an envelope of migmatites, gneisses and granites. Rosier (1957, 1965) described the batholith as gneissic granitoids and considered it to form part of the Serra dos Órgãos nappe. Other denominations were used by a number of authors, while Barbosa and Sad (1985) were the first to designate it as a batholith.

Calc-alkaline orthognaisses and migmatites, which have been designated as the Rio Negro, Santo Aleixo and Bingen units (Barbosa and Sad, 1985) form an approximately 3-5 km wide envelope around the batholith. They mark the position of major regional high-angle ductile shear zones, the Ribeirão das Lajes – Miguel Pereira shear to the northwest, and the Niterói shear to the southeast. These gneisses are considered as products of an earlier intrusive episode, and are not further discussed here.

The Serra dos Órgãos batholith is foliated, especially at its borders and in the vicinity of the ductile shear zones, with foliations which are moderately- to steeply-dipping in the northwest, and moderately- to shallow-dipping in the centre and southeast. The foliations define smooth open folds with southward-directed asymmetries.

The first proposal of a stratigraphic sequence in the Serra dos Órgãos rocks was made by Leonardos Jr. (1973), who distinguished eight facies, in order of decreasing age: (i) granitic migmatite; (ii) tonalitic gneiss; (iii) hornblende adamelite; (iv) coarse-grained granite; (v) fine-grained foliated quartz diorite; (vi) fine-grained granodiorite; (vii) fine to medium-grained grey granite; and (viii) pink aplitic granite. Barbosa and Sad (1985) separated two principal facies in the batholith: monzogranite and granodiorite with hypidiomorphic-granular textures, and leucogranite with granular textures. The latter rocks are described as intrusive into the former. Quartz gabbro, quartz diorite and orthoamphibolite occur locally.

The calc-alkaline character of the intrusion is supported by chemical data from several outher studies (Machado Filho et al., 1983; Machado, 1997; Machado and Demange 1994b; Sanchez et al., 1995; Porto Jr. et al., 1996; Tupinambá, 1999).

Machado and Demange (1994b, 1998) consider that the rocks of the batholith are tholeiitic or transitional to calc-alkaline. They noted that the analyzed samples have high Fe_2O_3 contents (average of 6.3% for granodiorite and tonalite, and 2.5% for granite). The rocks are metaluminous to peraluminous, and the Peacock index of the association is 58 (Calc-alkaline serie, not shown). The rocks are mantle fractionates or pre-collisional according to the Batchelor and Bowden (1985) classification or volcanic arc to within-plate in the discriminant diagrams of Pearce et al. (1984).

Tupinambá (1999) studied rocks from four main areas within the batholith. Their modal compositions vary between tonalite and monzogranite, mainly medium- to high-K calc-alkaline and metaluminous.

Geochronological data obtained by Delhal et al. (1969) and Cordani et al. (1973) for the rocks of the batholith revealed U/Pb ages in multi-crystal zircon fractions of 620 Ma, considered as the age of migmatization and formation of the batholith granitoids, and also of the earlier orogeny in the region. Delhal et al. (1969) observed that the zircon grains have inherited core, whereas Tupinambá (1999) noted that some of the analysed zircon samples were in fact from the Rio Negro orthogneiss unit which surrounds the batholith.

Tupinambá (1999) obtained younger U/Pb multi-crystal zircon ages of 560 ± 4 Ma and 546 ± 11 Ma, and confirmed that some zircon populations have a predominantly inherited composition. He also reported a Pb/Pb mono-crystal zircon evaporation age of 580 ± 17 Ma, and a Rb/Sr whole rock isochron age of 579 ± 16 Ma (initial Sr ratio = 0.70925) from eight samples, with a sample with initial $^{87}Sr/^{86}Sr$ ratio of 0.7085. According to this author, the available U/Pb data (mostly determined in multicrystal zircon fractions with few of the morphological and other controls which have since become common practice) can be grouped in two age intervals: 620 - 590 Ma, during which the migmatization and leucogranite crystallization occurred, and 550 - 480 Ma, when post-collision granites were intruded. Sm/Nd isotopic data indicate T_{DM} values between 1.7 and 1.5 Ga, and $\varepsilon_{Nd(600)}$ between -5,9 and -4.2 (Tupinambá, 1999).

Geochronological data obtained in zircon by U-Pb SHRIMP and Conventional yielded ages of 569 ± 6 Ma and 560 ± 3.8 Ma, respectively (Silva et al., 2003; Tupinambá, 1999). The sample dated by Silva et al. (2003) is a porphyritic granodiorite with solid-state fabrics overprinting, and the age was interpreted by them as the crystallization age of the granodioritic magma. The age obtained by Tupinambá (1999) was in another facies of the batholith.

The available Rb/Sr whole rock data does not yield consistent results, since ages between 560 and 624 Ma have been obtained (Cordani et al., 1973; Machado et al., 1996; Porto et al., 1996; Machado, 1997; Tupinambá, 1999). Metamorphism at around 520-530 Ma may have had a variable effect on the rocks of the batholith (Tupinambá, 1999), but the main reason for the divergences is probably found in initial heterogeneity of the Sr isotopic composition. $(^{87}Sr/^{86}Sr)_{600}$ values mostly cluster in the range 0.708 - 0.710, but outlying values of ~0.705 are found.

3.3.1 Petrography

Our study of the batholith has identified in this work two main mapping facies by semi-quantitative modal analysis; the monzogranite and the leucogranite. Smaller amounts of tonalites and diorites are associated with the latter group. The main difference between them is in the content of mafic minerals and the percentage of plagioclase and K-feldspar. The monzogranite containing biotite with compositions between annite and siderophyllite, and ferrohastingsite. These rocks have granular, hypidiomorphic textures, and are intruded by biotite leucogranites which sometimes contain amphibole. The accessory minerals usually include apatite, zircon, allanite and Fe-Ti oxide minerals, as well as titanite, garnet and muscovite. Contacts between granite facies vary from sharp, clearly igneous, through irregular to transitional, and may also be fault-related. The leucogranites locally show a concordant coarse-grained to pegmatitic facies. Pegmatitic leucogranites also form a discordant generation. These rocks are leucocratic, coarse- to medium-grained and display clear magmatic features, including syn-magmatic shear zones, which were locally preserved of the deformation posterior to the emplacement of batholith. Alignment of K-feldspar and biotite defines a magmatic foliation at the outcrop scale.

As already noted by Barbosa and Sad (1985), the mapped units should be thought of as associations in which either one or the other facies predominates in each mapped areas. Transitions between biotite-amphibole granites and leucogranites are registered in which large variation in the proportion of mafic minerals (e.g. from 15-20% to ~5% biotite) may occur at outcrop scale.

The K-feldspar (pink) and plagioclase (white and grey) are euhedral, while the quartz is anhedral, and sometimes elongate and deformed. The biotite is euhedral and generally occurs in aggregates.

Plagioclase, K-feldspar and quartz are essential minerals. Biotite and amphibole occur in quantities generally less than 5%, except in diorites, where they make up about 20%. Plagioclase occurs both in the matrix (~1.0 mm) as larger crystals (~3.2 mm). It occurs in grouped crystals with granular texture. The crystals are locally altered to sericite and present undulatory extinction. Biotite, zircon, apatite and opaque minerals are found as inclusions.

K-feldspar occurs as larger crystals (~4 mm) and in the matrix (~1.2 mm), and as interstitial crystals. It occurs as microcline and perthitic crystals displaying undulatory extinction and containing plagioclase and quartz as inclusions.

Quartz occurs as ameboid and irregular crystals elongate, with undulatory extinction and display strongly recrystallized grains. Amphibole, K-feldspar, plagioclase, allanite and zircon occur as inclusions.

Biotite is euhedral to anhedral and occurs as oriented and aggregated crystals defining the foliation of the rock. It occurs associated with amphibole, allanite and carbonate, and contains inclusions of apatite and opaque minerals. It is locally transformed (partial or totally) to chlorite and muscovite. Amphibole is strongly pleochroic and occurs as aligned crystals often transformed to biotite defining the foliation of the rock. Quartz, apatite, opaque minerals and plagioclase are found as inclusions.

Apatite is the most abundant accessory mineral, followed by zircon, and opaque minerals, while titanite, garnet and monazite are more rarely found. Chlorite, muscovite, sericite and carbonates are the alteration minerals.

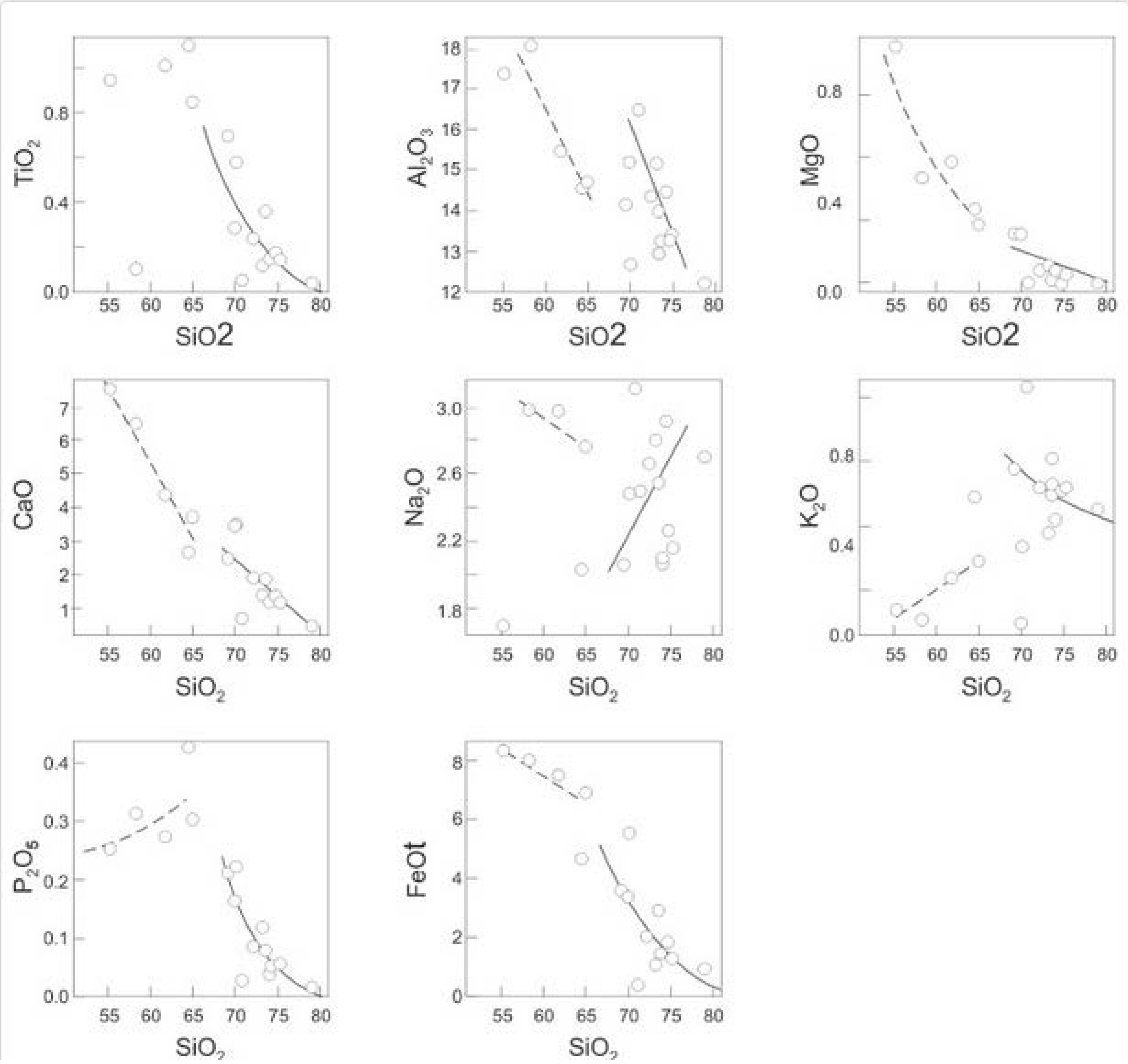
4. Results

4.1 Geochemistry

Thirty samples of granites (monzo and syenogranites), granodiorites, quartz diorites and diorites were selected for geochemical analyses. Selected compositions are given in Table 1. As mentioned previously, the chemical classification is in good agreement with the semi-quantitative modal classification. When differences occurred, the petrographic classification was used and the chemical data discussed in terms of possible hydrothermal alteration.

The samples that yielded SiO_2 contents between 69.3 and 79% correspond to granodiorites, monzogranites and syenogranites (Table 1). The dioritic magmatism is represented by gabbroic diorites, diorites and quartz diorites, with SiO_2 contents between 55.3 and 61.8%. High Al_2O_3 contents (18.1 to 14.5%) were observed for the dioritic rocks, the Al_2O_3 contents for the granitic rocks (15.1 to 12.2%) are compatible with I- and S-type granites of metaluminous and peraluminous character, respectively. The dioritic rocks present normative hypersthene, suggesting a tholeiitic affinity, whereas for the granitic rocks, low normative corundum were obtained (1.2 to 2.4), which are comparable to those observed in peraluminous granites generated from partial melting of the pelitic to psammitic and quartz-feldspatic (granitic) sources.

In Harker diagrams, the major elements (Fig. 3) show two distinct trends: one corresponding to the dioritic rocks and another to the granitic rocks. The first one is marked by decreasing Al_2O_3, MgO, FeO_T and CaO and increasing TiO_2, P_2O_5 and K_2O contents with increasing SiO_2. This behavior is compatible with a magmatic evolution influenced by differentiation mechanisms, such as fractional crystallization of clinopyroxene and/or hornblende and plagioclase. On the other hand, the second trend is characterized by a smooth decrease in MgO and CaO (and apparentely in TiO_2 and P_2O_5) with strong dispersion in Na_2O and increasing in K_2O, suggesting that the magmatic differentiation of these rocks was controlled by fractional crystallization of biotite, plagioclase, apatite, K-feldspar and opaque minerals. K_2O/Na_2O ratios increase with differentiation in dioritic rocks (0.8 to 2.1), whereas in granites rocks, this ratio ranges especially between 1.4 and 3.3.



The trace elements (Fig. 4) present a regular behavior, showing well-defined trends that suggest that metamorphism did not affected significantly the composition of the Serra dos Órgãos rocks. Both granitic and dioritic rocks show negative correlation of Sr and V and positive correlation of Nb, Y, Ba, U and Th with SiO_2, confirming the fractionation of plagioclase, biotite and zircon. Low Zr contents and gradual decrease during differentiation are compatible with granitic magmas produced by partial melting of crustal rocks (Patiño-Douce and Johnston, 1991; Patiño-Douce and Harris 1998; Patiño-Douce, 1999).

A TAS diagram (Cox et al., 1979) shows the subalkaline character for the studied samples, highlighting the dioritic composition of dioritic rocks and the granitic composition of the felsic rocks (Fig. 5a). A Shand diagram modified by Villaseca et al. (1998) shows the slightly peraluminous character of the dioritic rocks whereas the granitic rocks are more peraluminous (Fig. 5 b). The AFM diagram (Irvine and Baragar, 1971) characterizes the tholeiitic affinity of the dioritic rocks and calc-alkaline affinity of the granitic rocks (Fig. 6). The Le Maitre (1989) diagram classifies the granite magmatism as high-K calc-alkaline evolving to shoshonitic (Fig. 7).

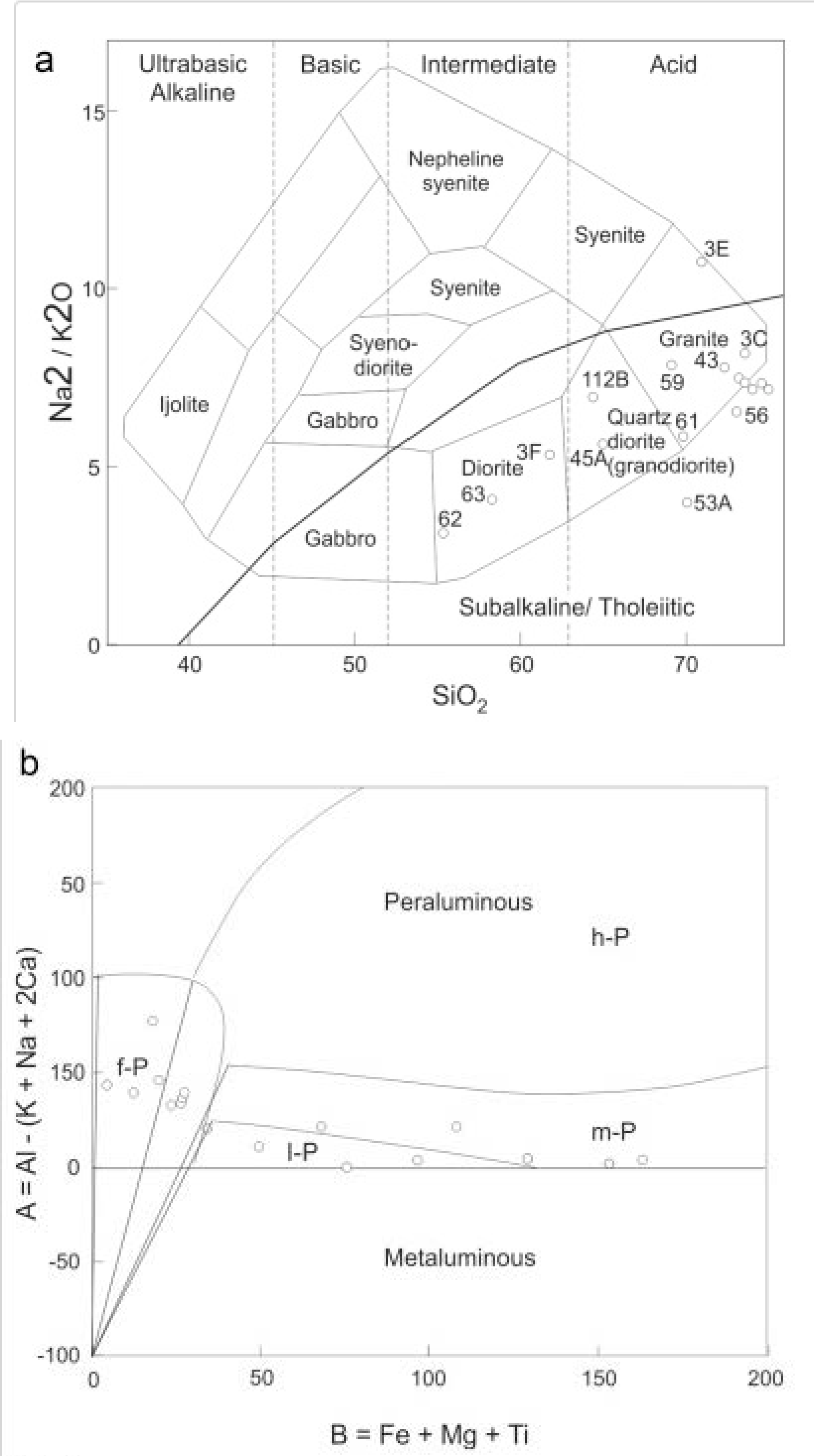


Fig. 5.
(a) TAS diagram with fields after Cox et al. (1979); (b) Shand diagram modified by Villaseca et al. (1998).

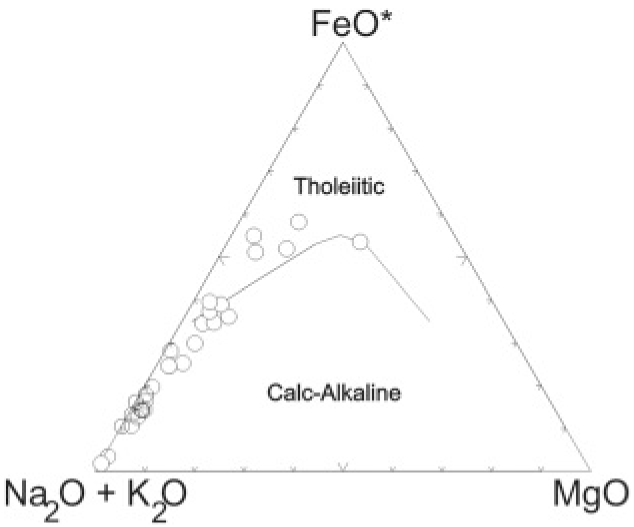


Fig. 6.
FMA diagram with fields after Irvine and Baragar (1971).

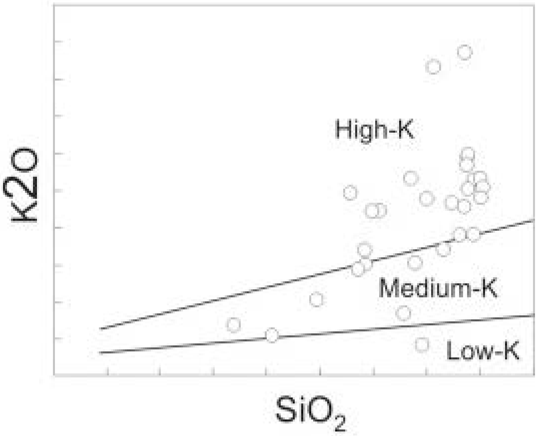


Fig. 7.
K2O vs. SiO2, with fields after Le Maître (1989).

Chondrite normalized values show a similar evolution for the two rock groups, suggesting that they are cogenetic. However, there are differences between them. Two dioritic rock samples exhibit similar patterns to those of granites with strong LREE fractionation relative to the HREE, and negative Eu anomalies (Fig. 8a and b). The other dioritic samples yield less differentiated patterns with a slight LREE enrichment and no Eu anomalies (Fig. 8a). The granitic rocks are characterized by higher ∑LREE and lower ∑HREE contents and negative Eu anomalies, which is compatible with calc-alkaline series (Fig. 8 b).

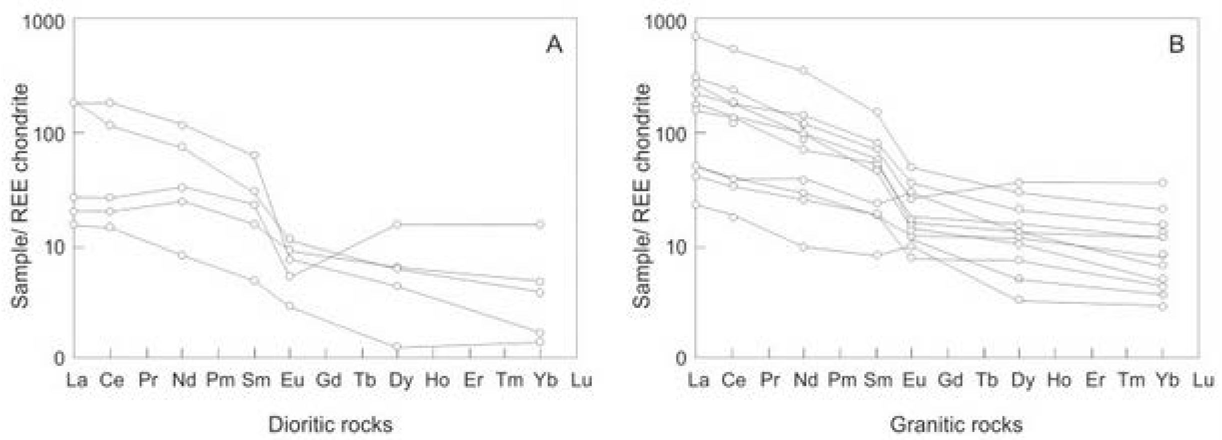


Fig. 8.
Chondrite-normalized rare earth elements according to Sun and McDonough (1989).

Multi-element, ORG normalized (Pearce et al., 1984) patterns are similar for the two rock groups, differing by higher Rb and Ba contents in dioritic rocks and higher Th contents in granitic rocks (Fig. 9c and d). Negative Ta and Zr anomalies are present in both groups, showing that the patterns are similar but the concentration are quite distinct. In the Rb *versus* (Y + Nb) and Nb *versus* Y diagrams (Pearce *et al.*, 1984; Pearce, 1996), most samples plot in the fields intra-plate (WPG) and volcanic arc (VAG) granites, and one sample in the syn-collision field (syn-COLG) in Pearce et al. (1984) diagrams **(**Fig. 10 a and b**)** or plot mainly on post-collisional field in Pearce (1996) diagram **(**Fig. 10 a**)**. The R_1-R_2 diagram (Batchelor and Bowden, 1985) suggests a similarity of the granitic rocks with magmatism generated from crustal melting (syn-collision), and of the dioritic rocks with pre-collision magmatism (Fig. 11).

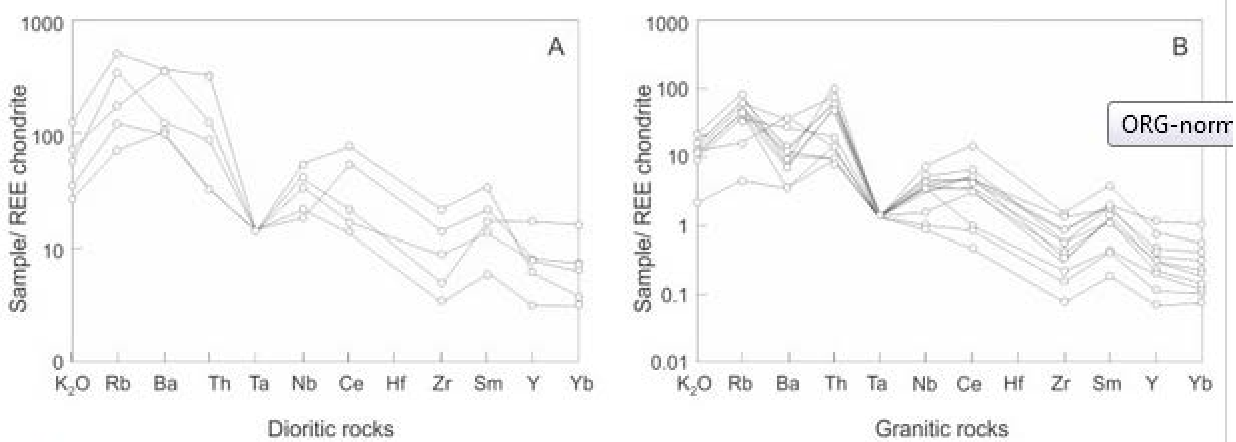


Fig. 9.
ORG-normalized multi-element variation diagrams according to Pearce et al. (1984).

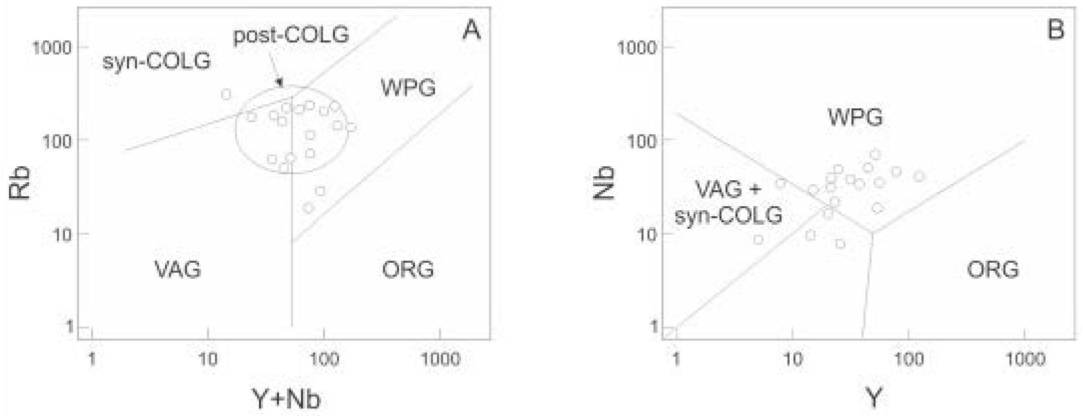


Fig. 10.
Rb versus (Y + Nb) and Nb versus Y diagrams (Pearce et al., 1984 and Pearce, 1996).

4.2 *Geothermometry and Geobarometry*

Since the compositions of many of the granites of the Serra dos Órgãos batholith are rather calcic, the positions of minima or eutectics in the Qz-Or-Ab diagram are displaced upwards and to the right of those of the Ca-free systems. For this reason, the experimental results can only be used as a very rough guide to possible conditions prevailing during magmatic crystallization. The quartz diorites, granodiorites and tonalite cluster close to low-pressure quartz-albite cotectics of the haplogranite system. The pattern of overall K and Rb enrichment for this trend is compatible with the absence of important K-felspar fractionation during this part of the evolution. The more mafic granites and diorites plots near low pressure, water-saturated minima.

The apatite and zircon saturation geothermometers (Watson and Harrison, 1984) yield similar temperature, differences are usually < 5% relative to the mean value for about one half of the analyzed samples, and differences of < 10% are recorded in the remaining values (Table 2). Excluding the anomalously P- and Zr-rich samples, whose temperatures would necessarily be higher by at least 50°C, the temperature ranges (R) and average temperature (T) registered for the different rock types are: granite R = 687-856°C, T = 748°C; granodiorite and tonalite, R = 867 – 924°C, T = 897 °C; quartz diorite, R = 849 – 896°C, T = 873 °C. Most of the obtained temperatures for granites are concordant at 798 ± 20 and 805 ± 34 ^{o}C.

Amphibole compositions determined by electron microprobe analysis at the laboratory of the School of Mines, Fontainebleau, France, range from magnesian hastingsite in the quartz diorites to hastingsite in the granites. Mean Al_{tot} values in atomic formulae based on 23 O vary between about 2.05 (hornblendes from a granodiorite and three granites) to about 2.32 (tonalite) and 2.47 (quartz diorite). In each sample, very little between-grain and within-grain variation was detected. The temperatures deduced from the saturation geothermometers are closer to those used by Johnson and Rutherford (1989) in their calibration of the Al-in-hornblende geobarometer (JR89), and most but not all samples contain all the essential buffer minerals. Pressure estimates using JR89 vary from 5.1-5.5 kbar (granodiorite and three granites) to 6.4 kbar (tonalite) and 7.0 kbar (quartz diorite) (Table 2). For comparison, results using Schmidt's (1992) calibration (S92) and the average of JR89 and S92 results are also given.

Calculated minimum and maximum solidification pressures for the Serra dos Órgãos rocks are probably different, because the composition of the quartz diorite is different from that used in the calibration of geobarometry, and the calculated pressure may be unreal. These results suggest that initial crystallization of the amphiboles occurred in the lower or middle crust. More work is needed to check whether differentiation was accompanied by a consistent decrease in the amphibole crystallization pressure.

The P-T estimates obtained here are similar to those deduced by Rego (1989) for the Angelim (tonalite) (P = 5 kbar) Bela Joana (charnockite) plutons, respectively, P= 2 to 6,6 kbar and T = 787 to 869^{o} C , and P = 5.8 kbar and T = ~738^{o} C.

4.3 *Isotopic geology*

New results obtained at the isotope geology laboratory of Rennes University, France, for two granodiorite samples from the Serra dos Órgãos batholith indicate Nd T_{DM} model ages of 2.0 and 1.5 Ga. For a model age of 600 Ma, $\varepsilon_{Nd(600)}$ values are –7.7 and –6.2, while for $(^{87}Sr/^{86}Sr)_{600}$ values are 0.717 and 0.707, a range wider than the one found in previous studies. These results attest to a strong, and in the case of Sr, a very heterogeneous crustal contribution (Table 3).

Two samples from monzogranites have $(^{87}Sr/^{86}Sr)_{600}$ between 0.7090 and 0.7100 calculated from results reported by Machado (1997) obtained at the Geochemistry Laboratory of Clermont-Ferrand University, France), but four samples from the granodiorites to diorites show a much wider range of $(^{87}Sr/^{86}Sr)_{600}$ values, between 0.7070 and 0.7100. Only one sample from monzogranite was previously analyzed, and it is amongst the more radiogenic types with $(^{87}Sr/^{86}Sr)_{600}$ between 0.7090 and 0.7100.

5. Discussion

The new isotopic results reported here indicate that the granites present an isotopically heterogeneous source. The granites probably represent a product derived of partial melting of the continental crust, whereas diorites result from mantle-derived source. The more mafic granites involve contributions from different isotopic sources and are associated with mixture of dioritic and granitic magmas. The granites probably represent a series of products derived from a relatively homogeneous magma which progressively differentiate during its rise in the crust, whereas the more mafic granites to diorites, involves contributions from sources of different isotopic compositions.

The compositional variations of the Serra dos Órgãos batholith are consistent with an evolution associated with magmas generated from partial melting of crustal rocks, triggered by underplating of mafic magmas. The compositions and temperatures of these magmas were initially very different. They probably have undergone magma mixing and mingling, followed by magmatic differentiation. Granitoids with these characteristics are commonly generated in orogenic belts formed by continental collision. Magmas that represent this type of tectonic setting can be produced during the climax of a collisional event or later – late or post-collision events that are related to uplift and post-orogenic relaxation or extension (England and Thompson, 1986; McClay et al., 1986; Malavieille, 1993; Liegeois, 1998; Patiño-Douce and McCarthy, 1998; Barbarin, 1999; Philipp and Machado, 2005).

Larger volumes of mafic material derived from enriched mantle were intruded in other areas of the Ribeira belt during the Brasiliano orogeny (Ludka et al., 1998; Ludka and Wiedemann-Leonardos, 2000). The isotopic evidence for the origin of the granitic batholiths found in the Ribeira belt points to an important, even dominant, role of recycling of older (Paleo/Mesoproterozoic) crustal material, and this picture is repeated for many of the Neoproterozoic granites intruded in the region during different phases of the Brasiliano orogeny (Machado et al., 2000). In fact, in the entire Brasiliano cycle in southern and southeastern Brazil (Araçuaí and Ribeira belts and Embu terrane), the quantity of juvenile material identified so far is limited and extensive crustal recycling seems to be the general rule (*see* Sato, 1996; Nalini, 1997; Cordani and Sato, 1999; Nalini et al., 2000; Wiedemann et al., 2004; Leite et al., 2007b; Pedrosa Soares et al., 2011; Tupinambá et al., 2012; Heilbron et al., 2013; Alves et al., 2013).

Based on the Ribeira belt structural framework in Rio de Janeiro, it is suggested that the emplacement of the Serra dos Órgãos Batholith occurred in the contact between the Serra do Mar microplate and Paraíba do Sul terrane (*sensu* Campos Neto and Figueiredo, 1995) or between Occidental and Oriental terranes – Central Tectonic Boundary (*sensu* Almeida et al., 1998). This limit (Fig. 12), located in the southern limb of the positive flower structure of the Paraiba do Sul River (Machado and Endo, 1993), corresponds to the high-angle Rio Santana-Ribeirão das Lajes shear zone (Machado, 1984). This shear zone developed under high-temperature conditions and in the presence of granitic melts (Dehler and Machado, 2002; Dehler et al., 2006). It evolved in two stages: an earlier stage with top-to-SSW/SW sinistral thrusting and orogen-parallel tangential motion, and a later stage, with top-down to NNE/NNE transtensional deformation (Dehler et al., 2006). These two shear movements took place under or close to anatectic conditions. The first movement is certainly older than the emplacement of the Serra dos Órgãos batholith, and was coeval with crustal anatexis and the main metamorphic event (M_1) in the Juiz de Fora and Paraíba domains that occurred at around 580 Ma (Machado et al., 1996). The second movement is extensional and may have deformed the solid-state fabric of the syn-collisional peraluminous granitoids of the Serra das Araras, here interpreted as late-collisional, and also controlled the emplacement of granitic bodies (Dehler et al., 2006).

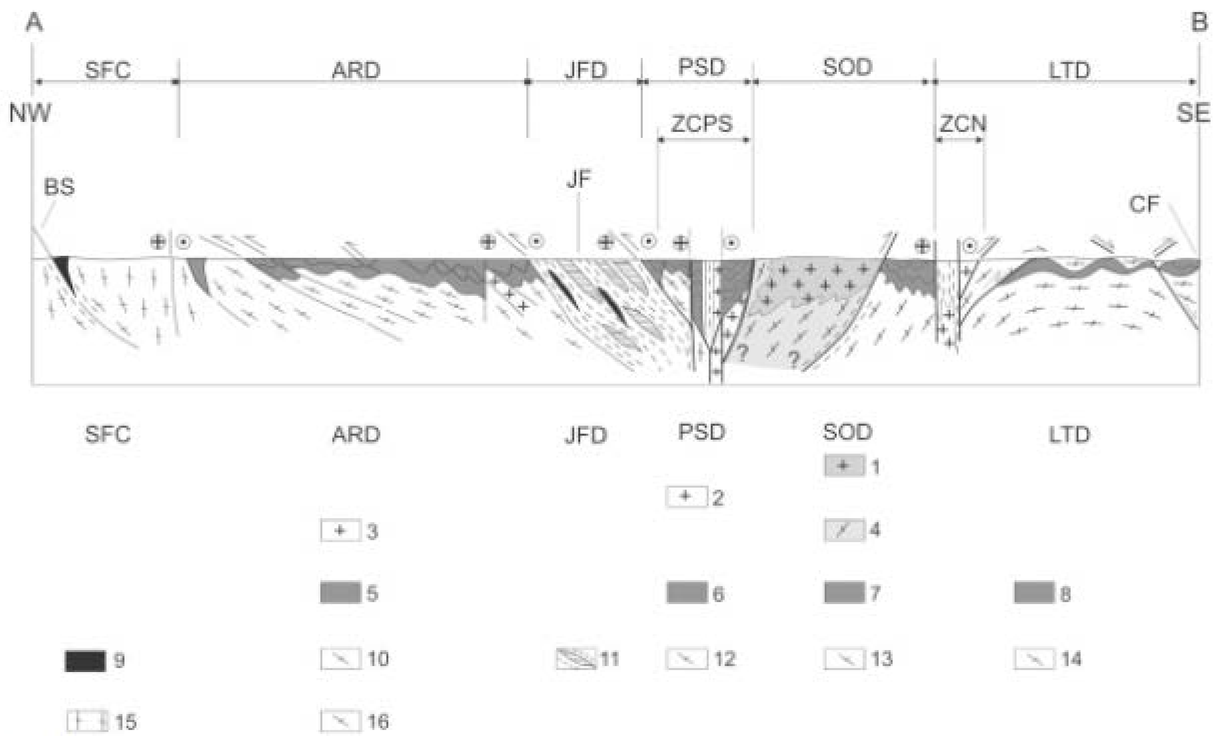


Fig. 12.

NW-SE geological section of the Central Ribeira belt showing the positive-flower structure and tectonic contacts between the main terranes of the belt (adapted from Machado and Endo, 1993). Legend: 1 = Serra dos Órgãos batholith; 2 = Serra das Araras; 3 = Serra do Lagarto pluton; 4 = Rio Negro arc; 5 = Andrelândia Group; 6 = Supracrustal Paraíba do Sul; 7 = Santo Eduardo/Itaocara/Italva Formation/Group; 8 = Búzios Sequence; 9 = Bom Sucesso mafic-ultramaphic sequence; 10 = Piedade Complex; 11 = Juiz de Fora Complex; 12 = Quirino Complex; 13 and 14 = Rio dos Lagos Complex; 15 and 16 = Mantiqueira and Barbacena complexes.

The pressure release caused by the extensional movement of the shear zone causes adiabatic partial melting of the mantle and generation of mafic magma (Fig. 13). The rise and emplacement of mafic magma caused the increase of geothermal gradient and the partial melting of the lower continental crust (Fig. 14). In conditions of high temperature may have occurred the mixture between mafic and felsic melts.

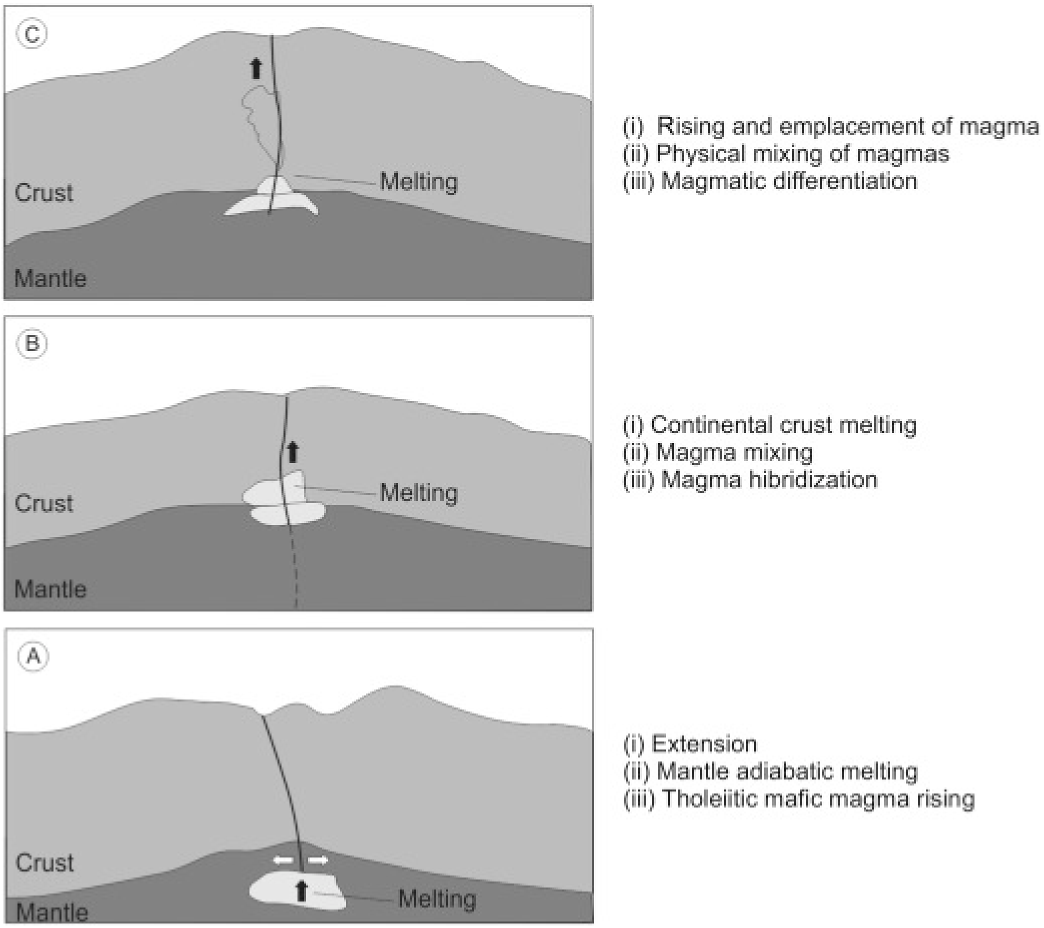


Fig. 13.

Schematic model of the crust showing the generation of the Serra dos Órgãos Batholith: (a) Ductile shear zone reaching deep conditions and causing adiabatic melting of the mantle and generating a mafic magma; (b) Rise of mafic magma with increased of geothermal gradient in lower crust and partial melting of the rocks from the base of the continental crust; (c) Magma mixing with partial chemical interaction generating hybrid granitoids and areas rich in dioritic enclaves showing textural variation, highlighting the lips in the

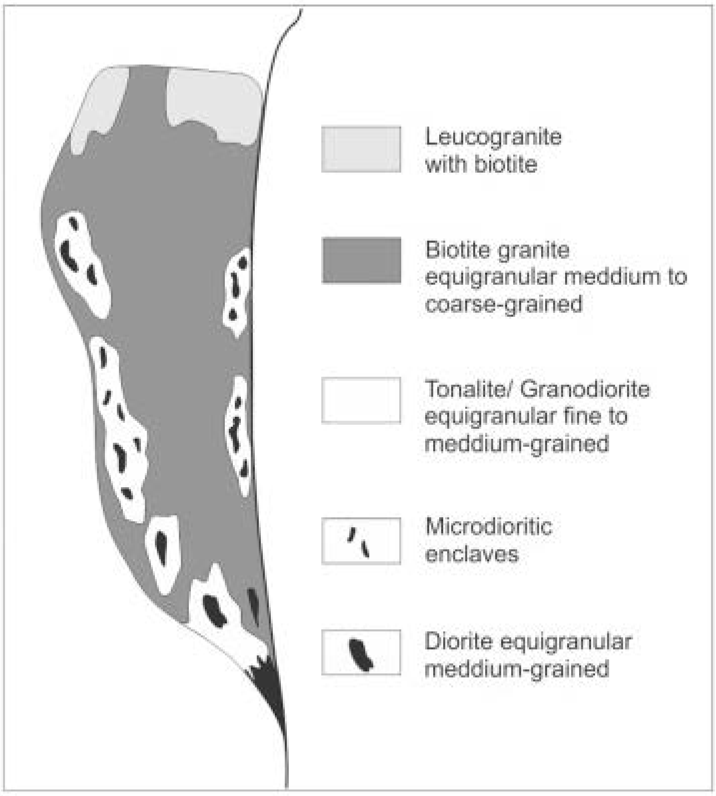


Fig. 14.
Textural variation of the batholith, highlighting the lips in the basal portion rich in microdioritic enclaves and mafic minerals with finer texture than the dominant granite.

Extensional structures older than the orogenic collapse have been recognized in several segments of the Ribeira belt: in the southern portion of the State of São Paulo (Serra do Azeite), and north of the State of Rio de Janeiro, between Muriaé and Itaperuna (Machado et al., 2001; Dehler et al., 2007; Karniol et al., 2007). They are also described in the eastern portion of the *Quadrilátero Ferrífero*, in the Furquin, Acaiaca and Dom Silvério regions (Endo, 1997). In this region, mylonitic quartzites of the Rio das Velhas Supergroup occur as a wide range in the contact on basement rocks belonging to the Mantiqueira complex. This wide mylonite range is associated with the Furquim shear zone, whose kinematic indicators (S-C and S-C-C' foliations, asymmetric structures and shear-bands) suggest top-to-ESE shearing (Endo, 1997). This same kinematic context has been reported in several regions of the Ribeira belt, and its development is considered coeval with a phase of regional stretching, sub-parallel to the belt, which is related to the transtensional regime responsible for the tectonic extrusion and uplift of crustal slices (Dehler and Silva, 2000; Dehler et al., 2006, 2007; Karniol et al., 2007). $^{40}Ar/^{39}Ar$ ages obtained for amphiboles and micas from Serra do Azeite mylonites and pegmatites confirm the K/Ar ages obtained by Campagnoli (1996), and suggest that the extensional event operated between 600 and 580/570 Ma (Machado et al., 2001, 2007; Dehler et al., 2007).

We consider these extensional structures as related to truly orogenic collapse of the Ribeira and Araçuaí orogens, and not to post-tectonic granites of these belts with ages at around 500 Ma, as systematically considered by the majority of the authors.

The results discussed in this work, although spanning a short time range of about 10 Ma (Tupinambá, 2000; Silva et al., 2003), make a comparison, in terms of age, possible between the magmatism related to G3-I suite (580 to 560 Ma) of the Araçuaí Orogen and the younger plutons of the Embu domain (~580 Ma), and further with the younger subgroup of post-orogenic granites (~ 565 Ma) associated with Apiaí domain (Pedrosa-Soares et al., 2001, 2011; Alves et al., 2017; Leite et al., 2007 a, b, among others). Sr and Nd isotopic signature of these granites supports an origin involving crustal melting of an essentially Paleo/Mesoproterozoic basement, caused by input of hotter mafic magma from the mantle at the base of the crust undergoing thinning under extensional regime. This caused the raise of lithospheric mantle and promoted the adiabatic decompression which was accompanied by melting of rocks of basic composition.

6. Conclusions

We consider that Serra dos Órgãos batholith was generated from melting of crustal rocks, caused by the interaction with hotter mafic magmas at the base of the crust. These two magmas, initially of different composition and rheology, were probably subjected to strong interaction, which continued during the ascension of the magmas in the crust, accompanied initially by fractional crystallization of clinopyroxene and/or hornblende, plagioclase, apatite, opaque minerals, and, then, biotite and potassic feldspar.

The P-T conditions inferred for the Serra dos Órgãos rocks (P= 5.1-7.0 Kbar, T= 748-897^{o} C) are similar to those obtained for the Angelim (P= 2 to 6.6 kbar and T = 787 to 869^{o} C; Rego, 1989) and Bela Joana (P = 5.8 kbar and T = ~738^{o} C; Rego, 1989) syn-tectonic plutons in the Ribeira belt in the State of Rio de Janeiro. The emplacement and crystallization of all these plutons occurred under conditions corresponding to the amphibolite or granulite facies in the mid or lower crust.

Some of the ages obtained for the Serra dos Órgãos batholith are coincident with the extensional episode identified by several authors in the Ribeira belt. The batholith was emplaced synchronously with such extensional episode (~580 Ma) during the Brasiliano orogeny. It is still not clear whether the batholith was emplaced in an essentially continuous fashion over a short time interval, or resulted from a sequence of separated intrusive pulses over a longer time interval.

The batholith was emplaced along of the Ribeirão das Lajes-Rio Santana shear zone, a large crustal discontinuity that separates the Serra do Mar Microplate from the Paraiba do Sul terrane, which is the same structure that separates the Oriental from the Occidental terranes. This limit, located in the southern limb of the positive flower structure of the Paraiba do Sul River, corresponds to the structure mentioned above, which was developed under high-temperature conditions and in the presence of granitic melts. The regional foliation in the southern limb of the positive flower structure is sub-parallel to the shear zone, and the ductile shearing was coeval with the ductile flow parallel to the orogen.

The isotopic evidence for the origin of the Serra dos Órgãos batholith is consistent with those available for other batholiths in the southeastern and southern regions of Brazil, including the Brasiliano/Cambrian granites of the Araçuaí and Dom Feliciano Orogens (Pedrosa-Soares et al., 2001, 2011; Siva et al., 2008; Peixoto et al., 2015; Philipp and Machado, 2005; Philipp et al., 2007), suggesting that the dominant petrological process was the recycling of a Paleoproterozoic crust, and that this context is repeated for many Neoproterozoic granites emplaced in the region during different events of the Brasiliano cycle.

Another important aspect of the generation and emplacement of Brasiliano granitic bodies in the Ribeira belt, and probably in other Neoproterozoic belts of the South American Platform, is the role played by high-angle transcurrent ductile shear zones. These events were probably responsible for the syntectonic characteristics of these rocks, including solid-state deformation and tectonic foliation, particularly at the borders of the plutons, which are sometimes so strongly oriented that they can be mistaken for banded gneisses, similarly to what occurs with many foliated granites in the Espírito Santo and Rio de Janeiro states, which were mapped as orthogneisses and diatexites, respectively.

These shear zones were apparently developed early during the geological history of the belts, and controlled subsequent granite plutonism. Their presence exerted a fundamental role in the geodynamic evolution of the belts, and may explain some of the magmatic and tectonic differences between Neoproterozoic and younger belts.

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