Abstract
A comprehensive tectonic evolution of Proterozoic to Cambrian rocks that integrate the crystalline basement of Rio de Janeiro State, based on the new geological map, is presented. The map combines detailed geological data integrated to a 1:400,000 scale and new geochemical and geochronology data to characterize the distinct terranes amalgamated during three pulses of the Brasiliano orogeny. The Occidental terrane comprises the Tonian to Late Cryogenean passive margin of the São Francisco paleocontinent, including reworked cratonic basement. At the same period, two magmatic arc systems were developed outboard: The Continental Inner arc system represented by the dismembered terranes (Paraíba do Sul, Embú, and Cambuci domain) integrated now in the Central Superterrane: and the Intra-oceanic Outer Arc System, the Oriental Terrane, developed from 860 to 620 Ma. Related active basins were detected in association with the two arc systems that collided at ca. 620 – 595 and 605 – 550 Ma against the São Francisco passive margin. A later collision episode at ca. 535 to 510 Ma brought the Cabo Frio Terrane (Angola tip) and closed the Búzios back-arc basin. Finally, the collapse of the orogenic belt, probably related to slab detachment and asthenosphere upwelling marks transition to Gondwana stabilization.

KEYWORDS: Ribeira belt; Gondwana; Accretionary orogen; continental margin; Brasiliano orogeny.

INTRODUCTION
The recently published Geological and Mineral Resources Map of Rio de Janeiro State — 1: 400,000 scale (Heilbron et al. 2017) — comprises an extensive geologic and cartographic compilation of the state’s onshore area. The publication, in Brazilian Portuguese language, resulted from a cooperation between the Geological Survey of Brazil (Companhia de Pesquisa de Recursos Minerais — CPRM) — National Geology Program (Programa Geologia do Brasil — PRONAGEO) — and Universidade Estadual do Rio de Janeiro (UERJ).

The complete geological dataset of the Rio de Janeiro State is the result of 25 years of field survey and laboratory research developed by the TEKTOS Geotectonic Research Group (Geology Institute, UERJ) in collaboration with other research groups from UERJ, the Department of Mineral Resources of Rio de Janeiro State (DRM-RJ) and the Federal University of Rio de Janeiro.

The new Geological and Mineral Resources Map of Rio de Janeiro State integrates 1:50,000 and 1:100,000 scale geologic quadrangles and maps, as well as data from structural, petrographic, lithogeochemical, geochronological and isotopic analyses of igneous and metamorphic rocks of the onshore bedrock and Cenozoic sedimentary cover. The final version of the map was prepared in Geographic Information System platform. Under PRONAGEO Mapping Program, a total of fifteen 1:100,000 scale geological sheets were published by UERJ and one by the DRM-RJ. The lithostratigraphic nomenclature, outcrop description, and analytical data are all available in the CPRM’s GeoSGB database (http://geosgb.cprm.gov.br/).

The bedrock geology of Rio de Janeiro State is largely constituted of high-grade metamorphic rocks and granitoid bodies belonging to the Ribeira orogenic belt, which developed in the context of amalgamation of the Gondwana supercontinent, through Neoproterozoic to Cambrian diachronic convergence of several tectonic blocks, referred to as the Brasiliano Orogeny (Heilbron et al. 2000, 2004, 2008, Silva et al. 2002).
Following the Ordovician tectonic transition to relatively stable Gondwana supercontinent, a protracted period of tectonic quiescence lasted until the tectonic reactivations in the Lower Cretaceous. Mafic dike swarms (Almeida et al. 2013) were emplaced prior to the break-up of Western Gondwana, the opening of the South Atlantic Ocean and the development of the offshore Campos and Santos sedimentary basins. An important Late Cretaceous to Paleogene tectonic episode resulted in the development of the Southeast-Brazil Rift System, associated to the emplacement of numerous intrusive-sub-volcanic alkaline complexes. Finally, Neogene to Holocene sedimentation complete the geological record of Rio de Janeiro State.

In this contribution, a synthesis of the lithology, age, and tectonic setting of the Proterozoic to Ordovician units of the onshore area of Rio de Janeiro State is presented. Based on an integrated interpretation of these rock units and analytical data, a tectonic evolutionary model is presented in the context of the Ribeira orogen. The geology of post-Ordovician igneous and sedimentary units, although integrating the published Rio de Janeiro State map, does not belong to the scope of this article, and thus will not be discussed.

This contribution is specially intended to integrate the special volume of the Brazilian Journal of Geology in honor of Prof. Dr. Edilton Santos, the late eminent geologist who dedicated his life to the scientific advancement of the knowledge of the Brazilian bedrock geology and who inspired many of his colleagues and students.

**TECTONIC ORGANIZATION OF RIO DE JANEIRO STATE**

The southeastern region of Brazil is part of the Mantiqueira Province, a Neo-proterozoic orogenic system originally defined by Almeida et al. (1981), which extends broadly parallel to the coast. In Rio de Janeiro, the Mantiqueira province is represented by the Ribeira belt, which extends for ~500 km, merging with the Araçuaí Belt to the north (Alkmim et al. 2017). The Ribeira belt truncates the southernmost segment of the NW-trending Brasilia belt and, to the south, it is adjacent to the Luis Alves craton and Dom Feliciano belt in Southern Brazil (Heilbron et al. 2004).

The Ribeira Belt resulted from the collision between the São Francisco and Congo paleocontinents and the tip of the Angola Craton, also involving two intervening magmatic arc systems (Trouw et al. 2000, Heilbron et al. 2008, 2017). The belt was developed during several Ediacaran to Cambrian episodes of convergence in the context of the Brasiliano-Panafrikan Orogeny. The transition to stable the Gondwana supercontinent regime was marked by voluminous Late Cambrian to Early Ordovician post-collisional granite-gabbro magmatism interpreted as related to subducted lithospheric slab detachment and gravitational collapse of the resulting over-thickened continental crust (Heilbron & Machado 2003, Valeriano et al. 2011).

The tectonic organization of the Ribeira Belt (Fig. 1) comprises four tectonostratigraphic terranes (Howell 1989) bounded by major thrusts and subvertical dextral shear zones. From northwest to southeast they are:

- the Occidental Terrane, regarded as the reworked passive margin of the São Francisco Craton (SFC);
- the Central Superterrane, which comprises minor tectonic units known as Paraíba do Sul-Embú Terrane and Cambuci Domain, which might represent an Inner Continental Magmatic Arc System collided at ca. 620 – 595 Ma;
- the Oriental Terrane interpreted as the Outer Magmatic Arc System, with juvenile intra-oceanic docked at ca. 595 – 565 Ma;
- the Cabo Frio Terrane (tip of the Angola craton) collided at ca. 535 – 510 Ma (Heilbron & Machado 2003, Schmitt et al. 2004, Heilbron et al. 2017).

The transition from the central to the northern segment of the Ribeira and Araçuaí belts to the north is marked by the change of structural trend of the orogen, from ENE-WSW to N-S, along with a transition from transpressional deformation regime in the former, to frontal contraction in the latter.

**PROTEROZOIC STRATIGRAPHIC OUTLINE OF RIO DE JANEIRO STATE**

In this section, the Paleoproterozoic basement, the pre-collisional supra-crustal units, and the magmatic arc rocks of Rio de Janeiro State are briefly described in stratigraphic (age) order, regardless of which tectonic terrane they belong to. Table 1 stresses the differences between the four terranes concerning the Paleoproterozoic basement units, the Neoproterozoic deformed cover (passive or active margin settings), and the main collision episode detected. The sin-collisional magmatic rocks are described in the following section in the context of terrane amalgamation.

**Paleoproterozoic basement units**

The Paleoproterozoic basement rocks (Fig. 2) comprise ca. 13% of the Rio de Janeiro territory and occur in almost all tectonic terranes of the belt, except in the Oriental Terrane, where only Neoproterozoic to Ordovician rocks occurred (Heilbron et al. 2010). The basement units are represented by four lithologic complexes, namely, Mantiqueira, Juiz de Fora, Quirino, and Região dos Lagos complexes, briefly described below.

**Mantiqueira Complex**

The Mantiqueira Complex is the basement unit of the lowerrmost structural domain of the Occidental Terrane, only outcropping in the southwestern region of the state, north of the city of Resende (Fig. 2). The complex comprises tonalitic to granitic hornblende-bearing orthogneisses. Migmatitic structures are common with leucosomes characterized by the presence of centimetric hornblende crystals. Amphibolite enclaves and metric lenses are present in almost all visited outcrops. Their protoliths are diorites, quartz-diorites, and gabros. Porphyritic granite occurs locally, with pink K-feldspar megacrysts and matrix composed of plagioclase, quartz, hornblende, and biotite. Light gray and pink granitic to granodioritic gneiss lenses and/or metric layers intrude the above-mentioned rocks (Fig. 3A and B).
All the available geochemical and geochronological data of the Mantiqueira complex were obtained in the nearby Minas Gerais State. Element compositions (Figueiredo & Teixeira 1996) point to several magmatic suites of continental magmatic arc setting. Geochronological data indicate crystallization from 2.2 to 2.08 Ga (Heilbron et al. 2010, Degler et al. 2017, Kuribara et al. 2019, Cutts et al. 2018), with Archean inheritance, and a metamorphic event at ca. 2.04 Ga (Heilbron et al. 2010, Machado et al. 1996, Silva et al. 2002).

Juiz de Fora Complex

The Juiz de Fora Complex (JFC) is the basement association of the uppermost thrust sheet of the Occidental Terrane. The tectonic style of this structural domain is the tight tectonic intercalation between the JFC and Neoproterozoic metasedimentary rocks of the Raposos and Andrelândia Groups.

The JFC is represented by orthogranulites and orthogneisses (Fig. 3) with varying degrees of deformation and retrogressive alteration. Where preserved from retrogressive alteration, the JFC rocks typically display a greenish or caramel color with

Figure 1. Tectonic map of the Rio de Janeiro State, modified from Heilbron et al. (2017).

Table 1. Main lithological units of the tectonostratigraphic terranes of the Ribeira belt.

| Terrane                          | Occidental | Central                  | Oriental | Cabo Frio           |
|----------------------------------|------------|--------------------------|----------|---------------------|
|                                  | Lower Thrust System | Upper Thrust System |          |                     |
| Neoproterozoic Cover Unit        | Andrelândia (proximal passive margin) | Raposos (distal passive margin) | Paraíba do Sul, Embú and Bom Jesus de Itapoa | Italva, São Fidelis (fore arc and back arc) | Búzios (accretionary wedge) |
| Basement Unit                    | Mantiqueira | Juiz de Fora             | Quirino and equivalents | - | Região do Lagos     |
| Crystallization Ages (Ga)        | 2.2 – 2.1  | 2.40 – 2.07 | 2.30 – 2.19 | - | 2.0 – 1.94          |
| Inheritance (Ga)                 | 2.75 – 2.60 | - | 3.28 – 2.80 | - | 2.60 – 2.50          |
| Paleoproterozoic Metamorphism    | 2.06 – 2.05 Ga | - | - | - | - |
| Main Collision Episode (Ma)      | 620 – 585 | 620 – 585 | 620 – 585 | 605 – 550 | 535 – 510 |
massive igneous texture. As they become more mylonitic, they turn to white and pink colors with enclaves and centimeter lenses of black mafic granulite relics. The orthogranulites compositions range from noritic through enderbitic and charno-enderbitic to charnockitic. Enderbitic granulites predominate and commonly occur interleaved with charnoenderbitic to charnockitic varieties. Lenticular bands of noritic rocks occur in association with enderbites and, more rarely, with charno-enderbites and charnockites. Injections and bands of pink, medium to coarse grained charnockitic rock of Neoproterozoic age are common (Fig. 3 C and D).

Geochemical data are available for selected regions in the state and the nearby Minas Gerais State (Duarte et al. 1997, Heilbron et al. 1998, 2013, Duarte et al. 2004, Fernandes André et al. 2009). The felsic rocks comprise two of intermediate to high-K calcalkaline compositional groups, mostly with juvenile magmatic arc signatures (Duarte et al. 1997, Heilbron et al. 1998). Low TiO$_2$-P$_2$O$_5$ tholeiites with Normal- to Enriched-MORB or Island Arc Tholeiite (IAT) signatures predominate in the basic rocks. Together with (high TiO$_2$) transitional to alkaline basic rocks, they are indicative of extensional or continental intra-plate environments. LA-ICP-MS U-Pb geochronological U-Pb zircon and with Sm-Nd isotope data is available (Machado et al. 1996, Heilbron et al. 2010, Fernandes André et al. 2009, Silva et al. 2002, Ragatky et al. 1999, Noce et al. 2007, Degler et al. 2017). Altogether, the results indicate:

- ca. 2.4 Ga age for tholeiitic basic rocks;
- calcalkaline felsic rocks of ca. 2.14 to 2.09 Ga, with juvenile Nd signatures;
- ca. 1.7 to 1.6 Ga for alkaline basic and felsic rocks.

The latter age interval is correlated to the Statherian Taphrogenesis recorded in much of the São Francisco paleocontinent, following the Rhyacian Orogeny (Brito Neves et al. 2014). The combination of geochemical and geochronological data suggests that the JFC represents a juvenile or intra-oceanic magmatic arc, with Siderian to Rhyacian Sm-Nd depleted mantle model (T$_{DM}$) ages, and positive initial εNd values (Ragatky et al. 1999, Fernandes André et al. 2009). The occurrence of MORB-like basic rocks of ca. 2.4 Ga, represent the oldest oceanic associations identified in the JFC. Fernandes et al. (2018) recently reported Archean ages for the southernmost JFC, suggesting that a microcontinent might have been present at that time. Nevertheless, it is not clear whether Archean zircons are interpreted as crystallization ages or (most likely) as inheritance.

**Quirino Complex**

The Quirino Complex (Valladares et al. 2002) and its equivalents in the southernmost part of the state, the Campinho and Taquaral complexes (Heilbron et al. 2017), represent the basement association of the Paraíba do Sul-Embú Terrane (Fig. 2). These complexes comprise mesocratic tonalitic to granitic biotite- and hornblende-bearing orthogneisses, with abundant ultramafic (tremolitic), mafic (amphibolite), and calc-silicate enclaves (Fig. 3E and F). Leucogranite lenses are frequent. Near the contact with the Occidental terrane, the orthogneisses are highly deformed with unequivocal top-to-NW kinematic indicators (Figs. 2 and 3).

**Figure 2.** Map of the Paleoproterozoic basement units in the Rio de Janeiro State.
Figure 3. Selected field examples of the Paleoproterozoic basement units of the Rio de Janeiro state: (A) Orthogneiss with amphibolite lenses and (B) Hornblende-biotite orthogneiss with migmatitic texture of the Mantiqueira Complex (Occidental Terrane); (C) Intercalation of enderbitic and basic orthogranulites and (D) orthopyroxene orthogranulite of the Juiz de Fora Complex (Occidental Terrane); (E) banded migmatitic orthogneiss with mafic rocks enclaves and, (F) Orthogneiss of the Quirino Complex (Central Terrane); (G) banded orthogneiss and (H) hornblende orthogneiss with amphibolite lenses of the Região dos Lagos Complex (Cabo Frio Terrane).
The available lithogeochemical data indicates two arc-related calcalkaline suites, one is a tonalitic to granodioritic intermediate-K suite, and the other a high-K granodioritic to granitic suite (Valladares et al. 1997). U-Pb zircon data indicate crystallization ages of ca. 2.3 to 2.1 Ga with Neoarchean inheritance. The available Sm-Nd data suggest that the high-K group has a juvenile signature with Paleoproterozoic TDM model ages close to the crystallization ages (Machado et al. 1996, Valladares et al. 2002).

Região do Lagos Complex

The Região dos Lagos Complex (RLC) occurs in easternmost Rio de Janeiro State between the cities of Araruama, Cabo Frio, and Macaé (Fig. 2). The RLC comprises tonalitic to granodioritic orthogneisses with diorite and amphibolite lenses and enclaves (Fig. 3). Porphyritic foliated biotite-bearing granodiorites to granites are common nearby Araruama. When highly deformed, as in the Búzios Cape region, the contacts with Neoproterozoic metasedimentary rocks of the Búzios and São Fidélis groups are transformed into banded hornblende-bearing gneisses.

Amphibolites occur as decametric to centimeter tabular bodies or boudinated lenses (Fig. 3G and H). The contact relationships are always sharp which, together with body geometry, suggest that the basic rocks represent dikes and sills within the enclosing orthogneisses. Its mineralogy comprises plagioclase and hornblende, as well as diopside, titanite, apatite, zircon, and opaque minerals. In the Macaé region, a meta-gabbro stock of undetermined age is composed of augite, plagioclase, and accessory minerals. Viana et al. (2008) presented geochemical data for the orthogneisses of the Região do Lagos Complex. They belong to the calcalkaline series and display metaluminous to weakly peraluminous character, subdivided into intermediate- and high-K compositional groups. U-Pb geochronological data (Schmitt et al. 2004) indicate crystallization ages between ca. 2.09 to 1.95 Ga, Nd TDM model ages of 2.65 – 2.56 Ga with initial εNd -3.6 and -10, suggestive of Archean inheritance.

Neoproterozoic units of the São Francisco paleocontinent passive margin: Andrelândia and Raposos groups

The passive margin of the São Francisco paleocontinent is represented by the Andrelândia group and its distal equivalent, the Raposos group. Both occur in the structural domains of the Occidental Terrane (Fig. 4).

In the lowermost structural domain, two rock units of the Andrelândia Group were mapped. The first one consists of banded biotite gneisses composed of quartz, plagioclase, biotite, and minor garnet. A centimeter- to decimeter-thick compositional banding with graded contacts between bands of different compositions suggests sedimentary bedding. Migmatitic textures are frequent, where leucosomes veins bordered by biotite-rich domains (melanosomes) are suggestive of in situ anatexis. Intercalations of quartzites, sillimanite-garnet-biotite gneisses, and of minor calc-silicate rock and amphibolite are frequent. The second lithological association comprises sillimanite-garnet-biotite gneisses with metamorphic variations to K-feldspar-kyanite gneisses. The gneisses contain frequent centimetric to decimetric intercalations of calc-silicate rocks, manganese formation (gondite) and amphibolite lenses and

Figure 4. Metasedimentary rock units in the Rio de Janeiro State.
boudins. Muscovite-sillimanite feldspathic quartzite layers complete the lithology of this association (Fig. 5). Locally late granitic veins with blue cordierite porphyroblasts crosscut the (sillimanite)-garnet-biotite gneiss.

The Raposos Group is regarded as the distal segment of the same passive margin and occurs in the uppermost thrust sheet of the Occidental Terrane (Fig. 4). The Raposos Group rocks typically display a mylonitic fabric, occurring as tectonic intercalation within the Paleoproterozoic JFC orthogranulites.

Similarly, two units were mapped: biotite banded paragneisses with thick quartzite layers; and sillimanite garnet K-Feldspar gneisses with intercalations of Mn-rich rocks (gondites), quartzites, sillimanite schist, and amphibolites (Fig. 5).

Detrital zircon studies indicate that the source of both the proximal and distal units, in Rio de Janeiro State, is the São Francisco paleocontinent (Valladares et al. 2004, 2008). The depositional age’s lower limit for metamorphic overprint if of ca. 620 to 570 Ma. The youngest detrital zircons of ca. 0.9 Ga within the metasedimentary rocks and TDM model ages of the amphibolites indicate a Neoproterozoic depositional age.

Neoproterozoic Magmatic Arcs

In the last decade, orthogneisses with magmatic arc geochemical and isotopic signatures have been described in Rio de Janeiro State (Heilbron & Machado 2003, Tupinambá et al. 2012, Heilbron et al. 2000, 2008, 2017, 2019, Tedeschi et al. 2016, Peixoto et al. 2017).

Figure 5. Selected outcrops of the Andrelândia and Raposos Groups, Occidental Terrane: (A) Biotite banded gneisses; (B) Detailed of the mylonitic texture nearby the contact with the Oriental terrane; (C) Decametric feldspathic quartzitic layer and calcilicate boudin with top to W kinematic indicate; (D) Pure quartzite layer with oblique stretching lineation; (E) Folded calcilatic layer; (F) Stretched amphibolite boudin within the garnet gneisses at the Paraíba do Sul shear zone.
Corrales et al. (2019), Heilbron et al. (2019) grouped the magmatic arcs of the Ribeira belt in Rio de Janeiro State into an inner arc system that crops out as dismembered inliers close to Minas Gerais State and continue northward into the Rio Doce Arc in the Araquai orogen, an Outer arc system, comprising juvenile orthogneisses in the Serra dos Órgãos mountain range and Rio de Janeiro city, extending onto coastal Angra dos Reis and Paraty towns to southwest. The arc magmatic rocks occupy ca. 13% of the state’s territory (Fig. 6).

The Inner Magmatic Arc System
The Inner Magmatic Arc System has continental geochemical signatures and it is represented by stocks embedded within high-grade metasedimentary units and the orthogneisses of the Quirino complex and equivalents (Fig. 6). It is represented by the Serra da Bolívia (Heilbron et al. 2013) and by the Marceleza and Leopoldina Stocks (Corrales et al. 2019). All units are greenish and contain orthopyroxene-bearing charnockitic rocks (Fig. 7). Geochemical data indicate several magmatic series, ranging from tholeiitic, calcalkaline (intermediate- and high-K) and shoshonitic, all with high Ba-Sr signatures pointing to continental magmatic arc settings (Heilbron et al. 2013, Tedeschi et al. 2016, Corrales et al. 2019). The geochronological data published by these authors reveal crystallization ages between 650 and 595 Ma, with older Tonian inherited grains and/or autocrysts. Coeval enriched intraplate meta-gabbros and meta-diorites were recently described, suggesting roll back and slab window tectonic processes during subduction.

The Outer Magmatic Arc System
The magmatic rocks of the Outer Magmatic Arc System occur in the Oriental Terrane (Fig. 6), comprising the older, the juvenile Serra da Prata (Peixoto et al. 2017), and the Rio Negro magmatic arcs (Tupinambá et al. 2012). The Serra da Prata Arc comprises tonalitic, granodioritic, and dioritic orthogneisses. The plutonic character of the unit was highlighted by Peixoto & Heilbron (2010) and Peixoto et al. (2017). The Serra da Prata Arc comprises mesocratic quartz-dioritic, tonalitic, and granodioritic hornblende-biotite gneiss, containing 40% of biotite and hornblende (Fig. 8). Stripes of intrusive biotite leucogneisses, amphibolite enclaves, and lenses are locally found.

Geochemical data point out to arc settings, that together with the older Tonian ages and primitive Nd and Sr isotopic signatures made the Serra da Prata arc the representative unit of the older and initial stage of the subduction detected at the Ribeira belt (Heilbron & Machado 2003, Peixoto et al. 2017). The age of metamorphism was calculated at 601 ± 2.5 Ma, overlapping the metamorphic age obtained for the Italva Group by Heilbron & Machado (2003).

The Rio Negro complex represents the largest magmatic arc in Rio de Janeiro (Fig. 6), comprising a group of plutonic foliated to homogeneous orthogneisses with dioritic to granodioritic compositions, porphyritic gneisses, and leucogneisses (Fig. 8). Meta-gabbroic rocks occur as isolated bodies within the complex.

Three magmatic series with distinct Sr and Nd isotopic signatures have been identified within the plutonic rocks of the Rio Negro Complex: the intermediate-K, the high-K, and the shoshonitic series (Tupinambá et al. 2012). As pointed out by these authors, the geochemical data also indicates a clear geographic polarity with the more primitive and intermediate-K granitoids located westward, while the high-K and shoshonitic rocks predominate eastward.

Figure 6. Magmatic arc units in the Rio de Janeiro State.
The intermediate-K series comprises tonalites, granodiorites, diorites, and thronjémites with isotopic signature defined by low (< 0.705) $^{87}\text{Rb}/^{86}\text{Sr}$ ratios predominating over crustal values. The juvenile character of the series is also observed in $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, with positive to weakly negative $\varepsilon\text{Nd}(t)$ values (Tupinambá et al. 2012).

The rocks of the high-K series contain higher contents of $\text{K}_2\text{O}$, $\text{TiO}_2$, $\text{P}_2\text{O}_5$, $\text{MgO}$, high field strength elements (HSFE) elements (Y, Nb), U, Th, and Zr. They have higher Zr/Nb and La/Yb ratios than the intermediate- to low-K series rocks. The distribution of the rare earth elements shows a high degree of fractionation and a weakly negative europium anomaly. The isotopes signature of the rocks is more evolved, with large variation on the $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ initial ratios, indicating different degrees of crustal contamination (Tupinambá et al. 2012).

The U-Pb zircon data indicates crystallization ages of ca. 790 and 640 – 610 Ma (Heilbron & Machado 2003, Tupinambá et al. 2012).

Neoproterozoic arc-related metasedimentary units

Paraiba do Sul and Embú groups: transition from passive to active margin in the Inner Arc System

The Paraiba do Sul and Embú groups (Fig. 4) represent the supracrustal sequence of the Paraiba do Sul and Embú terranes (Heilbron et al. 2000), now integrated into the Central Superterrane. The unit comprises banded biotite gneisses and sillimanite-garnet-biotite gneisses, with intercalations of calcitic and dolomitic marbles, calcisilicate rocks, gondites, amphibolites, and quartzites/metacherts (Fig. 9A to C). Lithogeochemical data indicate that the amphibolites are tholeiitic rocks with signatures pointing to continental basalts (WPB) and E-MORB related to the development of the passive margin.

The Embu Group in Rio de Janeiro State is made up of sillimanite-muscovite-biotite gneiss/schist (Fig. 9D), sometimes with garnet and/or tourmaline, biotite gneiss fine, both with frequent intercalations of lenses calcisilicate rocks, micaceous

Figure 7. Selected outcrops of the Inner continental magmatic arc system: (A) Overview of the Serra da Bolivia Range nearby Itaocara town; (B) foliated meta-gabbro and (C) Foliated tonalite with diorite enclave of the Serra da Bolivia Complex; (D) Foliated monzodiorite cut by porphyritic granites of the Marceleza Complex; (E) detail of the contact; (F) Hand sample of the meta-gabbro of Marceleza Complex.
quartzites and, more locally, lenses of marbles, amphibolites, gondites, fine hornblende-biotite garnet gneiss, and rare shale tremolite lenses. The mica-rich gneisses of this unit include several concordant centimeter levels of quartz-rich turmalinites that suggest a volcano-sedimentary contribution. The partial melting of the Embu Group schistose gneisses generated several concordant levels of leucogranites with muscovite, garnet and tourmaline, as well as porphyroblastic granite/ gneisses (Eirado Silva et al. 2006).

Provenance studies for the Embú group with the LA-ICPMS technique are restricted to São Paulo State. The available results indicate provenance from older than 1.8 Ga basement rocks, Mesoproterozoic and Neoproterozoic sources, suggesting that the Inner Magmatic Arc System rocks had contributed with detritus to sedimentary basin (Duffles et al. 2016, Vinagre et al. 2014). Tonian metamorphic ages constrain the sedimentation age of the Embú group in São Paulo and Paraná States (Vlach et al. 2011, Cordani et al. 2002, Campanha et al. 2019).

**Bom Jesus do Itabapoana Group: the fore-arc basin**

The Bom Jesus do Itabapoana Group occurs in the north-western region of Rio de Janeiro (Fig. 4). The predominant rock type is the (orthopyroxene)-(sillimanite)-garnet-biotite gneiss, usually migmatitic (Fig. 10A). The medium to coarse-grained granitic to granodioritic leucosomes contain garnet and biotite and/or orthopyroxene (Tupinambá et al. 2007). The gneisses comprise centimetric to metric layers of dolomitic olivine marble, gondites, calc-silicate rocks, amphibolites, and meta-ultramafic rocks. The dolomitic marble layers comprise phlogopite, olivine, diopside, talc, titanite, spinel, and apatite. Amphibolite and gondite bodies up to 200m thick are common. Meta-pyroxenites (diopside) and hornblendites are the ultramafic types.

U-Pb detrital zircon data (Heilbron & Machado 2003, Lobato et al. 2015) point to provenance from the Neoproterozoic Serra da Bolivia and Rio Doce arcs and from older sources.

**Italva Group: the early back-arc basin**

The Italva Group (Peixoto & Heilbron 2010, Peixoto et al. 2017, Sad & Dutra 1988) crops out in a NE-SW belt at the western part of Rio de Janeiro State, in the cities of Cantagalo and Italva (Fig. 4). It consists of gneisses intercalated with marbles and amphibolites, associated with the development of the Serra da Prata Tonian magmatic arc (Peixoto et al. 2017). Peixoto and Heilbron (2010) and Peixoto et al. (2017) redefined the units of this domain by subdividing it into three units, namely, Euclidelândia, São Joaquim, and Macuco.

The Euclidelândia Unit occurs at the bottom of the pile and consists of muscovite biotite schistose gneisses (granite to tonalitic composition), locally with garnet and sillimanite. The São Joaquim Unit encloses thick layers of marbles that are explored for the cement industry of Rio de Janeiro State. The presence of graphite and sulfides (mostly pyrite) either disperse or as centimetric layers are common features (Fig. 10B, C and D).

Figure 8. Selected outcrops of the magmatic arc rocks of the Serra da Prata and Rio Negro complexes (the Outer arc system): (A) Mesocratic foliated tonalite with diorite enclaves and granodiorite veins and (B) Hornblende porphyroid tonalite with folded granodiorite veins of the Tonian Serra da Prata Complex, (C) Foliated orthogneisses and (D) Grey foliated tonalite cut by dioritic veins of the Rio Negro Complex.
The most impure marbles are foliated and contain granoblastic quartz and diopside, tremolite and zircon, biotite gneisses and amphibolite centimetric to metric layers occur within the marbles. The Macuco Unit comprises foliated coarse-grained (garnet)-biotite leucogneisses (with granitic to tonalitic composition), locally with sillimanite.

Amphibolites are associated with all units of the Italva group (Fig. 10C), including marbles and gneisses. They have mostly sharp contacts, but when in contact with the marbles they present a narrow zone with amphibole, carbonate, and garnet, characterizing an older metamorphosed contact aureole, as also described for the marbles of Espirito Santo State by Mesquita et al. (2017).

Tonian U-Pb ages (ca.-860 – 840 Ma) indicate that the Euclidelândia and São Joaquim units are coeval with the development of the Serra da Prata Arc (Heilbron & Machado 2003, Peixoto et al. 2017).

São Fidélis Group: the late back-arc basin

The São Fidélis Group emerges in a range between the Serra do Mar escarpment and the coastal plain, from the city of Rio de Janeiro to the north, crossing the border with the state of Espírito Santo (Fig. 5). It represents the other supracrustal sequence of the Oriental Terrane, associated with the magmatic rocks of the Rio Negro Magmatic Arc.

The São Fidelis group (Fig. 11) comprises high-grade metapelite paragneisses with lenses of quartzites and calcsilicate rocks (Tupinambá et al. 2007). It was subdivided into two units in the new geological map of Rio de Janeiro State. The basal one consists predominantly of kinzigitic gneiss (Kühn et al. 2004, Tupinambá et al. 2012) composed by migmatitic (sillimanite)-biotite-garnet gneisses locally with cordierite and graphite. The leucosomes contain beautiful examples of peritectic garnet (Fig. 11A and B) and cordierite. The top unit is made of banded gneisses, also with garnet and sillimanite, but with sillimanite biotite gneissic layers, besides lenses and boudins of calcsilicate rock (Fig. 11 C and D), amphibolite and pure or feldspathic quartzites. The quartzites could reach thick layers (ten to hundred meters), with internal compositional layering.

The provenance studies, based on U-Pb geochronology yielded interesting results pointing out to a double verging provenance, from the Rio Negro and Serra da Prata arcs, located western wards and older zircons that come from the Cabo Frio-Angola side eastern wards (Lobato et al. 2015, Schmitt et al. 2004, Capestrano et al. 2017). Lobato et al. (2015) highlighted the predominance of Mesoproterozoic to ca. 1.9 Ga Paleoproterozoic ages in the source area of the precursor sediments, a typical signature of Angola Craton rocks.

Búzios Group

The Búzios Group (Heilbron et al. 1982) is overthrust by the orthogneisses of the Região do Lagos Complex and crops out as scattered outcrops at the easternmost segment of the Rio de Janeiro State. The unit is made up of pelitic metasedimentary
Figure 10. Selected examples of the rocks of the Bom Jesus do Itabapoana and Italva groups. (A) Garnet opx gneisses and (B) olivine dolomitic marble layers of the Bom Jesus do Itabapoana Group, (C) and (D) calcitic marbles and layers of amphibolites of the Italva Group. Figure 11C display a structure similar to modern trombolites.

Figure 11. Selected examples of the rocks of the São Fidelis Group, Oriental Terrane. (A) Folded kinzigitic gneisses at the Rio the Janeiro town; (B) detail of the mineralogy of the paragneisses, with peritectic garnet within a leucossomatic vein; (C) banded quartzite layer within the paragneisses; (D) detail of the mineralogy of a coarse grain feldspathic quartzite with centimetric sillimanite porphyroblasts.
high-grade gneisses (metapelites) with frequent intercalations of calc-silicate rock boudins and layers, mica rich schistose gneisses, and amphibolite bodies (Fig. 12).

The predominant rock type of the Búzios group is a migmatitic banded (kyanite)-sillimanite-K-feldspar-garnet-biotite gneiss (Heilbron et al. 1982). Stromatic migmatitic textures are represented by elongated granitic to granodioritic leuco-somes bordered by melanosome rich in biotite, plagioclase, garnet, sillimanite, and kyanite (Fig 12A and B).

Calc-silicate rocks are very common and occur either as centimetric to metric boudins, to decametric layers at the top of the sequence. The calc-silicate rocks are granoblastic, with light green to grey colors and are composed of plagioclase, diopside, quartz, K-feldspar, scapolite, hornblende, and biotite (Fig. 12C).

Amphibolites (mafic granulites) are most common at the base of the sequence, nearby the contact with the overthrust orthogneisses of the Região do Lagos Complex. They are black coarse-grained rocks, with granoblastic textures and display a planar (primary?) compositional layering, alternating the contents of pyroxenes, plagioclase, and amphibole. The essential mineralogy consists of made by diopside, hornblende, plagioclase, garnet, quartz, besides traces of apatite, and opaque minerals. (Fig. 12D)

The U-Pb provenance studies pointed out similar signatures as the São Fidelis group, with Neoproterozoic, Mesoproterozoic, and Archean/Paleoproterozoic (2.6 and 1.9 Ga) sources (Fernandes et al. 2015), except by the Ediacaran zircons that are clearly metamorphic overgrowths in the latter group (Lobato et al. 2015). The younger zircon of ca. 570 Ma and the Cambrian (ca. 525 – 510 Ma) metamorphic overprint (Schmitt et al. 2004) bracket the deposition, suggesting that the São Fidelis group together with syn-collisional granitoids contributed for the provenance of the Búzios group. Lu-Hf data reveals juvenile sources (Fernandes et al. 2015).

**THE NEOPROTEROZOIC COLLISIONAL EPISODES: DEFORMATION AND MAGMATISM**

The closure of all oceanic spaces resulted in diachronous collisions of different terranes against the São Francisco-Congo (SFC) paleocontinent. The subduction of the passive margin of the SFC underneath the Central Terrane is considered the oldest Neoproterozoic collision episode detected in Ribeira Belt within Rio de Janeiro State. Intermediate- to high-pressure metamorphism of ca. 630 to 595 Ma, recorded only in Minas Gerais State, is coeval to the main deformation episode that resulted in the NW-verging dextral transpressive thrust system. Syn-collisional granitoids (I to S type and hybrids) testify the crustal shortening and melting, and multiple and varied granitoid generation accompanied this hot collision episode.

The collisional stage was followed by docking of the Outer Magmatic Arc System (Oriental Terrane) at ca. 605 – 595 Ma, resulting in high-temperature metamorphism and progressive deformation. In Rio de Janeiro State, due to the current erosion level,
the record of foreland and succession basins are missing but occur close to suture at the Mantiqueira Range, in Minas Gerais State. Finally, between ca. 535 to 510 Ma, the back-arc space between the outer arc and the outboard Angola paleocontinent was closed, resulting in the late orogeny and docking of the Cabo Frio terrane. This episode of subduction-collision and exhumation was fast enough to preserve the high-pressure kyanite bearing granulites in the Búzios Cape. Deformation overprinted the previously docked terranes, resulting in regional normal folding and discrete dextral shear zones.

**Deformational evolution**

The tectonic vergence of the Ribeira belt is directed NW toward the SFC. However, since the collision was oblique, it resulted in the partitioning of the deformation between shortening accommodated by major low-angle thrusts and folds and dextral sub-vertical shear zones (Fig. 13). The major suture zones are complexly folded, a consequence of the multiple collision stages and the extensional collapse of the belt.

The region encompassed by the state of Rio de Janeiro was fully covered by structural analysis, from direct field data. Data distribution is virtually homogeneous, except for areas covered by Cenozoic sediments. The maximum attitude of the main foliation, from density stereoplots, is 145/41 (azimuth of dip direction/dip angle). This N55-60E strike of the foliation is ubiquitous, especially in the southern and central sectors of the state, while subordinate N30-40E strikes become very common in the northern part of the state. Within the Oriental and Cabo Frio terranes, the foliation is subhorizontal. The stretching lineations are preferably oriented NE-SW, at a maximum at 038/17 with some dispersion to the NW and SW quadrants.

The overall set of foliations is arranged in the form of a girdle, whose pole plunging to N55E represents the axis of the late regional D3 folds. Two major late folds are highlighted by their axial planes in the integrated structural map (Fig. 13). One is the Paraíba do Sul synform, which roughly coincides with the present position of the Paraíba do Sul River. The other is the Rio de Janeiro antiform, which extends from the city of Rio de Janeiro toward NE. These large-scale folds resulted in the folding of the main foliation and associated stretching lineation.

Other structures of regional relevance are the ductile shear zones that crosed the entire state from SW to NE (Fig. 13), including the Além Paraíba shear zone (Campanha 1981).

**Deformation within the Occidental Terrane**

The Occidental Terrane is the lowermost tectonic unit. It appears along both limbs of the Paraíba do Sul synform (Fig. 13), and at a tightly folded zone within the Além Paraíba shear zone. The stereoplots of Figure 14A show this synformal structure that refolds the main foliation.

The main foliation and tight to isoclinal overturned folds are the result of the main deformation event, which includes the progressive transpressional deformational phases D1 + D2. Two major structural domains were separated within the Occidental Terrane (Heilbron et al. 2000):

![Figure 13. Simplified structural map of the Rio de Janeiro State, with the main suture zones and regional folds associated with late shear zones.](image)
Figure 14. Stereographic projections of the main foliation (poles) and stretching lineation within the terranes of the belt (lower hemisphere projection).
• the lowermost thrust sheet (Andrelândia Thrust System) is characterized by more sub-horizontal folds and thrusts that involves the basement rocks (nappe style), better seen at Minas Gerais;
• the upper Juiz de Fora thrust system that has a different tectonic style, with the widespread development of a mylonitic foliation, disrupted isoclinal folds, and high strain partitioning between moderate dipping fold zones and zones with the predominance of steep foliation with a dextral lateral component.

There is an intense tectonic imbrication between the deformed Neoproterozoic cover and the basement units that are clearly seen in the geological map.

The main S2 foliation is a coarse crenulation cleavage or schistosity, subparallel to S1, more clearly seen in D2 fold hinges or under the microscope. The predominance of S2 foliation is due to the coeval development of D2 deformation and M1 main metamorphic thermal peak (Machado et al. 1996, Heilbron et al. 2000). The main deformation is concomitant with high-grade metamorphism leading to the generation of high-temperature mylonites with intense static recrystallization. The D2 folds are asymmetrical, tight to isoclinal, with axis parallel to the stretching lineation, with vergence to NW (Fig. 15).

The main stretching lineation presents complex patterns accompanying the partitioning of the deformation, divided into zones of high and low rake values, independent of the dip of foliation. In high-dipping regions, foliation is mandatory to use the rake values, not the trend of lineation in order to evaluate the obliquity of lineation on the foliation planes. Indeed, the lineation varies from high rake positions, with kinematic indicators pointing to NW tectonic transport, to low rake positions, with increasing dextral strike-slip component. The asymmetrical folds and kinematic indicators are best observed on a NW-SE cross-section, which is considered the vorticity profile plane (VPP, Robin & Cruden 1994) although the stretching lineation is NE-SW, characterizing a typical transpressional tectonic regime (Passchier 1998).

The late deformation D3 is responsible for refolding the D1+D2 structures resulting in normal outcrop and regional scale open to tight folds, frequently associated to shear zones. The most important D3 structures affecting both the Occidental Terrane and the Central Terrane (Paráába do Sul-Embú and Cambuci) are the Paráába do Sul synform and the Além Paraíba shear zone (Fig. 13). Within the latter shear zone, the older mylonitic S1+S2 deformation is transposed, re-oriented to S3, and recrystallized.

Deformation within Central Terrane

In the last 5 years, a dismembered terrane was envisaged, in consequence of the discovery of a continental magmatic arc in both the Paraíba do Sul-Embú Terrane (Corrales et al. 2019, Campanha et al. 2019) and the Cambuci Domain (Heilbron et al. 2013). The Central Terrane, as defined here, encompasses both tectonic units mentioned above. It crops out as discontinuous lenses and klipen structures in the map due to the late D3 folding (Figs. 1 and 13).

The main deformation phases are also defined as D1+D2. The foliation is a coarse grain schistosity (S1) folded by tight to isoclinal D2 folds, better visualized within the metasedimentary units of this terrane (Fig. 15). The schistosity became tighter and sometimes mylonitic at the basal contacts of the terrane, where top to NW kinematic indicators are present (Fig. 3). The main foliation is folded, changing from moderate dips to SE, in the northern limb of the mega synform, to steep dips to NW in its southern limb, close to the Além Paraíba shear zone. D2 folds are usually asymmetric with vergence to NW. The stereogram of foliation pole (Fig. 14C) shows a girdle-like vertical distribution with an axis of attitude of 055/01, parallel to the axis of the regional D3 folds and indicative of NW-SE compression (N35W) from the sum of D1 to D3 phases. The stretching lineation stereoplot shows concentration in the NE and SE quadrants, with variations to N and NW, with high plunges, a compatible pattern with the obliquity variation over the foliation planes.

As described for the Occidental Terrane, the D3 folding is represented by normal to inclined folds with NE-SW subhorizontal axis and steep axial planes. Folds turn from open to tight as they get closer to the D3 shear zones (Fig. 13). The D3 deformation style developed from E-W flattening with NE-orientated stretching shear zones, with a vertical clockwise vorticity axis.

Deformation within the Oriental Terrane

The main deformation in the Oriental terrane is defined by D1 and D2 deformational phases. D1 is represented by a coarse-grained foliation, parallel to leucosome veins and coeval with thermal metamorphic peak. D2 folds are recumbent and some large-scale examples can be seen at the cliffs of Rio de Janeiro State. Differently from other terranes, the development of a penetrative S2 foliation is not common within the Oriental Terrane, except in micaceous metasedimentary rocks, where a crenulation foliation is observed under the microscope. The foliation stereoplot of Figure 14E

| Time       | Stage                               | Occidental Terrane | Paráába do Sul-Embú Terrane | Oriental Terrane | Cabo Frio Terrane |
|------------|-------------------------------------|---------------------|-----------------------------|------------------|-------------------|
| 510 – 480 Ma | Slab detachment and collapse        |                     | D1 transtensional phase with open folds and shear zones, better developed at the Oriental and Cabo Frio terranes |
| 535 – 510 Ma | Docking of Cabo Frio Terrane       | D1 open folds and dextral subvertical late shear zones | D1+D2 phases |
| 595 – 565 Ma | Docking of the Oriental Terrane     | Late D2             | Late D2                     | D1+D2            |
| 620 – 595 Ma | Docking of the PSul-Embú Terrane   | D1+D2               | D1+D2                       |

Table 2. Correspondence of the deformational phases between the tectonic terranes of the Ribeira belt.
shows moderate dip to SE and a very dispersed pattern of the stretching lineation is probably related to the superposition of the D3 and D4 structures. Few shear zones parallel to the S1+S2 foliation were mapped and are associated with the reverse limbs of the large D2 folds (Fig. 16). The late D3 deformation is represented in map-scale as normal open folds, such as the Paraíba do Sul synform and the Rio de Janeiro antiform.

Figure 15. Main Deformation Structures from Occidental terrane: (A) Dn-folds in the Raposos Group (Quartzite), looking to NE (UTM 23K 721531 7562861); (B) Isoclinal D1+2 folds in the Raposos Group, near Paraty looking SW (23K 536084 7450925).

Figure 16. Examples of structures from the Oriental and Cabo Frio terranes: (A) Main foliation (S1+2) cut by sinistral NW transtensive shear zone (ZC) with leucogranite intrusion; (B) Schistosity S1+2 with dextral porphyroclasts kinematic indicators nearby the CTB; (C) Recumbent D2 folding alternating layers of garnet-biotite gneiss, biotite gneiss and calc-silicate rocks parallel to S1 foliation containing leucosome veins; (D) D2 hinge zone with sub-horizontal axis and low angle axial surface, paragneisses of the Búzios group (24K 204408 7479407).
The Oriental Terrane also presents numerous examples of D4 folds and NW-trending shear zones, orthogonal to the belt. They display normal vertical component and both dextral and sinistral lateral components. They are usually associated with Late Cambrian to Ordovician granitic veins and pegmatites and were ascribed to the transtensional collapse of the orogenic belt (Heilbron et al. 2000).

**Deformation within the Cabo Frio Terrane**

The Cabo Frio terrane docked during Cambrian times. Differently from the other terranes, it displays three phases of recumbent folding (Heilbron et al. 1982), equivalent in time to the D3 folding and shear zones of the previously docked terrane (see Tab. 1).

The S1 foliation is parallel to leucosomatic veins and intensely refolded by D2 and D3 recumbent folds. Good examples can be seen at the excellent coastal outcrops of Búzios Cape and Cabo Frio region (Fig. 16). The stereoplots of Figure 14 show the subhorizontal S1 foliation, which is transposed by D2 and D3 folds. The stretching lineation is subhorizontal and has NNW-SSE direction. The stretching lineation and the kinematic indicators confirm top to NW tectonic transport within the Oriental Terrane. The basal contact of the Cabo Frio Terrane is complexly folded as the result of the superposition of folding and shearing and the E-verging subhorizontal collapse. The same D4 transtensional structures observed at the Oriental Terrane are frequently observed in the Cabo Frio Terrane, but filled by pegmatites.

**Sin-collisional granite generation**

The diachronic amalgamation of the Ribeira belt terranes resulted in three collision episodes (Heilbron et al. 2017, Machado et al. 1996, Schmitt et al. 2004, Heilbron & Machado 2003, Neto et al. 2014). The oldest one of ca. (630) 620 – 595 Ma resulted from the docking of the Central terrane (Paraíba do Sul-Embú Terrane and Cambuci Domain, the inner Arc). The second one of ca. 600 – 565 Ma represents the docking of the Oriental Terrane (the Outer Arc); and finally, the third one resulted from docking of the Cabo Frio Terrane (Angola Craton) at ca. 535 – 510 Ma.

Due to these multiple collisions, a diversity of magmatic rock bodies was generated. They are widespread occupying 16.5% of the area of Rio de Janeiro State, but especially more abundant within the Oriental Terrane, where the bodies have batholith dimensions (Fig. 17). According to the time relationship with the collision episodes and deformational phases, they were subdivided in three major periods: \( \gamma_2 \) early (ca. 620 – 600 Ma), \( \gamma_2 \) syn (ca. 605 – 575), and \( \gamma_3 \) late (575 – 565 Ma) collisions 1 and 2; and \( \gamma_4 \) (ca. 535 – 520 Ma) coeval with the Cambrian docking (Machado et al. 1996, Heilbron & Machado 2003, Mendes et al. 1999, Tupinambá et al. 2012, Silva et al. 2002).

The sin-collision granitoids vary from typical S-type peraluminous leucogranites to megacrystic I-type metaluminous granites, including hybrid types with both igneous and metasedimentary sources (Fig. 18). Variations to the green charnockite series rocks are common, with the presence of ortho-pyroxene instead of biotite, or clinopyroxene instead of hornblende.

**Figure 17.** Map of the syn-collisional granitoids rocks in the Rio de Janeiro State.
Figure 18. Selected examples of syn-collision granitoid rocks: (A) (musc-garnet) foliated granitoid with lenses of refractory rocks from the metasedimentary country rocks (ca. 580 Ma); (B) opx bearing mylonitic leucogranite (ca. 620 Ma); (C) hand sample of the garnet leucocharnockite (ca. 605 – 580 Ma); (D) biotite leucogranite (ca. 610 – 585 Ma); (E) hornblende bearing magacrystic and equigranular facies granitoids (ca. 858 to 575 Ma); (F) foliated megacrystic granite (facoidal granite type, ca. 575 – 565 Ma); (G) biotite granitoid (Serra dos Órgãos Batolith, ca. 570 – 560 Ma); (H) leucogranite with basement rock xenolith at Paraíba do Sul Shear Zone (ca. 535 – 525 Ma).
Deformation is very heterogeneous but in general is concentrated along the borders of the large plutonic bodies, though some examples of mylonitic granitoids occur nearby the major sutures or the syn-D3 shear zones.

Among the Y2 early collision granitoids, three types are most common:

- foliated leucogranites (Cordeiro Suite and minor bodies);
- hybrid foliated to mylonitic leucocarnockites (Pedra Madeira, Salvaterra, São João do Paraíso);

Figure 19. Map of the post-collisional granites in the Rio de Janeiro State.

Figure 20. Examples of the post-collisional granitoid rocks: (A) Frade granitoid at Três Picos Massif (peak elevation of 2,318 m) with leucogranite veins (photo by Ivan Dias); (B) equigranular leucogranite veins of the Pedra Branca Massif cutting the orthogneisses of the Rio Negro Arc; (C) detailed of the equigranular hipidiomorphic texture of the leucogranite; (D) geological section of the Serra dos Órgãos Range with a large sill of the Teresópolis biotite granite (Fernandes et al. 2009); (E) equigranular texture of the Mambucaba granite; (F) magmatic flow in the porphyritic Frades.
hybrid garnet biotite porphyroid granitoids (Serra do Turvo, Serra da Concórdia, Serra das Araras, Angelim, Campo Alegre, Bananal plutons).

Obtained U-Pb ages are between ca. 620 and 580 Ma (Machado et al. 1996, Mendes et al. 2006, 2007, Tupinambá et al. 2012, Heilbron & Machado 2003).

The sin Y2 granitoids are widespread and form large stocks and batholiths. The most common varieties include the following types:

- megacrystic granites locally with green varieties with Opx (Pão de Açúcar or Augen Gneiss, Itacoatiara, Desengano, Pedra Selada, Serra do Lagarto, Funil, Campello, Côrrego Fundo, Pedra Bonita, Cassorotita);
- foliated charnockites (Bela Joana Suite);
- garnet tourmaline-bearing granites (Resgate Suite) and minor leucogranitic bodies. Ages are between ca. 580 and 570 Ma.

The late collision Y3 granitoids are less foliated and were dated at ca. 570 – 565 Ma. The most important bodies are the Serra do Órgãos Batholith, with (hornblende)-biotite granodiorites to granites, and the Angelim pluton represented by a garnet-hornblende biotite granodiorite.

Finally, the ca. 535 to 520 Ma T4 granitoids are coeval with the collision of the Cabo Frio terrane. In previously docked terranes, they are represented by stocks of mainly highly evolved type I granitoids that occur preferentially along the D3 shear zones and they are represented by stocks of mainly highly evolved type I granitoids. The most important examples are the Fortaleza, Getulândia, Serra do Ipiranga and other minor bodies (Caju, Fecheiras and Rosilha). Foliated and deformed leucosomes of Cambrian age were described in the orthogneisses of the Região dos Lagos unit in the Cabo Frio Terrane and within the high-grade metasedimentary rocks of the Búzios groups (Heilbron et al. 1982, Schmitt et al. 2004).

POST-COLLISIONAL MAGMATISM, DEFORMATION AND THE RECORD OF OROGENIC COLLAPSE

The youngest tectonic episode recorded within the crystalline basement rocks of the Rio de Janeiro is related to the transtensional collapse of the orogen, probably caused by slab detachment (Valeriano et al. 2016). This tectonic phase is represented by ca. 510 to 480 Ma post-collision magmatic rocks, predominantly granitic in composition with small gabbroic bodies.

Two groups of post-collision granites crop out at Rio de Janeiro State (Valeriano et al. 2011, 2016). The post-collision granitoids occur as batholiths, stocks, plugs, and a variety of dikes, sills, and laccolith geometries. They intrude with sharp contacts the country rocks and are especially abundant in the Oriental Terrane (Figs. 19 and 20).

These granites have Cambrian to Ordovician ages (ca. 510 – 480 Ma) and are represented by a diverse group of acidic plutonic rocks (leucocratic monzogranites, aplites, and pegmatites) and subordinately intermediate to basic stocks (diorites, gabbros) belonging to the Suruí and Nova Friburgo Suites. Valeriano et al. (2011) proposed a subdivision of post-collisional magmatism in the states of Rio de Janeiro and Espírito Santo into two main magmatic pulses: a Cambrian one (~510 Ma), with late-collisional character, and an Ordovician one (~485 Ma), with frankly post-collisional features. The older granitoids (Suriu Suite) are leucocratic to hololeucocratic, frequently exhibiting phryritic and equigranular facies. Magmatic flow structures are also common. The largest bodies are the Parati, Pedra Branca, Suruí and Vila Dois Rios. The last one is a charnockitic variety with Opx and green color. The younger (Nova Friburgo suite) are represented by leucocratic granitoids, mostly with equigranular facies, with biotite, and traces of hornblende and magnetite.

TOWARDS AN INTEGRATED NEOPROTEROZOIC TECTONIC MODEL

Based on the detailed geological map integrated with new geochemical and geochronology data, a comprehensive tectonic evolution of the Proterozoic to Cambrian rocks that integrate the crystalline basement of Rio de Janeiro is revisited (Fig. 21). The geological units were interpreted as their tectonic setting to build up the distinct terranes amalgamated during three pulses of the Brasiliano orogeny.

The siliciclastic metasedimentary rocks of the Andrelândia-Raposos Group represent the passive margin successions that crop out only in the Occidental terrane. The available U-Pb data for detrital zircons indicate, in all samples studied in the state, that the basement complexes from SFC were the main source rocks to form the distal part of the basin. Few Mesoproterozoic zircons and a second mode of Tonian zircons complete the available data (Valladares et al. 2004). The younger detrital zircons are in the ca. 760 to 695 Ma interval. Metamorphic ages fall in the ca. 630 to 580 Ma interval. Interlayered amphibolites with extensional signatures, TDM model ages around 1.0 Ga and one reported crystallization age of ca. 766 Ma, together with detrital zircon signatures bracket the sedimentation to Tonian-Cryogenian period (Paciullo et al. 2000, Marins 2000, Gonçalves & Figueiredo 1992, Heilbron et al. 1989, 2019).

The Central Terrane (Paraíba do Sul, Embú, and Cambuci Domain) presents the continental record of the inner arc. The plutonites of the Serra da Bolivia and Marceleza complexes are the testimony of the subduction period, between ca. 650 and 595 Ma. The arc-related rocks intrude both the Paleoproterozoic basement and the high-grade metasedimentary units probably coeval (The Paraíba do Sul-Embú and Bom Jesus do Itabapoana groups). Few provenance studies indicate both Paleoproterozoic and Inner arc derivation, suggestive for active margin basins (Heilbron & Machado 2003). These metasedimentary units have in common predominantly psamo-pelitic compositions and dolomitic marble intercalations.

A long history of subduction outboard of these continental blocks very well documented at the Oriental terrane. The Outer Arc system is more complex, with expanded suites of the alkaline,
tholeiitic, and shoshonitic series, and a long-lived period of arc rock generation, extending from the Tonian to the early Ediacaran time interval. They are represented by the magmatic orthogneisses of the older Serra da Prata and the younger Rio Negro Complexes (Tupinambá et al. 2012, Peixoto et al. 2017). Coeval metasedimentary units accompanied the arc evolution from a more primitive Tonian stage (Italva Group, Peixoto et al. 2017) to the evolved and younger Cryogenian to Early Ediacaran stage (São Fidelis group, Lobato et al. 2015, Fernandes et al. 2015).

The close of all oceanic spaces resulting in the diachronic collisions of the different terranes of the belt against the São Francisco Congo paleocontinent. The first one resulted in the subduction of the passive margin of the SFC below the Central Terrane. The ca. (630) 620 – 595 Ma episode is the older Neoproterozoic collision detected at RB in Rio de Janeiro State (Heilbron et al. 2017). Medium to high-pressure metamorphism (only reported at Minas Gerais State) is coeval. The Main Deformation resulted on a transpressive thrust system verging to NW, with a dextral lateral component. In Rio de Janeiro, due to its erosion level, the record of foreland and succession basins are missing, but it appears close to suture at the Mantiqueira Range in Minas Gerais State. Several syn-collisional granitoids (I- to S type and hybrids) testify the crustal shortening and melting.

The docking of the Outer Arc system (Oriental terrane) at ca. 605 – 595 Ma that resulted in the high-temperature metamorphism and progressive deformation subsequently follows this episode. Again, the generation of multiple and varied granitoid plutons accompanied this hot collision episode.

Finally, in the Cambrian, between ca. 535 to 510 Ma, the back-arc space between the outer Arc and the outboard Angola paleocontinent was closed, resulting in the late orogeny and docking the Cabo Frio terrane. The episode of subduction-collision and exhumation was faster and high-pressure K-bearing granulites are preserved at the Búzios Capes. Deformation overrides the previously docked terranes, resulting in regional normal folding and discrete dextral shear zones.

Closing the very dynamic tectonic evolution that resulted on the amalgamation of this sector of Western Gondwana, bimodal magmatism and transtensive structures mark the transition to the stable intracontinental setting of the supercontinent.

**CONCLUSIONS**

The synthesis presented here stresses the importance of how combining robust geochronology and geochemical data with detailed and accurate geological mapping allows a better understanding of complex and polycyclic regions

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**Figure 21.** Envisaged tectonic model for the Neoproterozoic Evolution.
such as the case of the basement geology of Rio de Janeiro State. The interpretation proposed here is the result of many review publications of 35 years of research work, including the published geological map of the Rio de Janeiro State in 1:400,000 scale.

Open questions such as the improving correlations between the Paleoproterozoic paleocontinents, the precise duration of the Neoproterozoic passive margin stage, the shutdowns and maximums in the subduction-related magmatic record, the reconstruction of the active margin basins and the better constraints on the collapse episode of the Ribeira belt are key points for future investigations.

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