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https://doi.org/10.1590/2317-4889202220210053

BJGEO
Brazilian Journal of Geology

The statherian taphrogenesis of the South American Platform

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Abstract

Records of Statherian intracontinental ruptural tectonics, magmatism and sedimentation events are recognized all over the South American Platform as an immediate tectonic response to the formation of a large continental domain during Rhyacian-Orosirian orogenic collage. In this paper, we present a preliminary synthesis of the variety of tectonic-sedimentary and magmatic occurrences of these taphrogenic processes along the Statherian Period, which are recorded in all cratons, as well as in the basement of most Brasiliano orogenic belts. The Statherian rock units are better preserved over the cratons, and within the Brasiliano structural provinces they are reduced by erosional processes and discretely overprinted by Tonian and Cryogenian structures, and strongly by the Ediacaran-Brasiliano Orogeny. Clastic sediments are dominantly mature, primary structures clearly pointing to the environmental setting. Anorogenic bimodal magmatism, represented by volcanic and plutonic rocks is common, where felsic rocks are largely dominant. Their geochemical signature indicates within-plate settings and dike swarms are common within the cratons. The magmatism was very intense locally, suggesting LIP occurrences, although in need of additional geophysical and petrological support. The taphrogenic and magmatic events took place within Orosirian and Rhyacian basement, in which main tectonic-magmatic events ceased just before the Late Statherian, occasionally extending into the Calymmian.

KEYWORDS: Taphrogenesis; Statherian; mafic dikes; acid volcanism; granitic plutonism; intracontinental basins and belts.

INTRODUCTION

The aim of this paper is to review and synthesize dispersed information on tectonic events and their respective lithostructural records that took place within the South American Platform during the Statherian, locally extending into the Calymmian. We understand that the review and synthesis of lithostructural and chronological data are critical actions to better characterize geological events operating within the platform after the major Rhyacian-Orosirian orogenic collage, which contributed to the formation of the Columbia supercontinent by the end of the Orosirian. The Statherian is represented by two distinct and well-characterized sets of tectonic events, each preserving well-documented features of their geological setting through rocks and structural records.

First, a remarkable 2,100 km long and ca. 200 km wide, generallly NNW-ESE trending Statherian accretionary system, known as the Rio Negro–Juruena belt (1.8-1.55 Ga), is exposed in the central part of the Amazonian Craton. The ca. 250 km long Caracol Arc, in the eastern part of the Rio Apa cratonic domain to the south of the Pantanal region, is its probable continuity. It was possibly also the continuity of the southern segment (in pre-Gondwana times) of the Transcontinental Belt (Labrador, Gothian-Kongsbergian belts) of the Northern hemisphere. This Amazonian feature is rather well-studied, with a recent synthesis by Fraga *et al.* (2020), among many others available. As discussed in the next section, an alternative interpretation for this outstanding structure was postulated by Rizzotto *et al.* (2019) as the West Amazonia Igneous Belt (WAIB).

Second — the focus of this review — there are the more or less coeval volcanic, plutonic, sedimentary, and volcanic–sedimentary records dispersed over the South American Platform, many of which still uncharted. This set of rock units records different tectonic settings, many of which were reworked and superimposed by younger tectonic events when not previously removed by erosional processes. It should be stressed that such rock associations are exposed in similar contexts — general composition and tectonic history — in other continents that became part of Gondwana later on, and even in Laurentia and Baltica. These facts and circumstances — that escape the classic orogenesis models, mobilists as well as fixists — had already been framed as Statherian Taphrogenesis by Brito Neves *et al.* (1995), following the previous propositions of Krenkel (1922) and Sengör (1990), as well as several authors reporting similar records worldwide. The label is not wrong, but it is incomplete when all lithostructural features of the recorded Statherian phenomena are taken into consideration, since this designation leaves aside the diverse tectonic-stratigraphic history that took place in subsequent age periods, sometimes leaving behind undeniable continuity and links with Meso- and Neoproterozoic events. Such is the case,

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for instance, of the Espinhaço Supergroup, the deposition of which, although starting in the lower Statherian, records a tectonic history reaching the end of the Neoproterozoic.

Presently, these rock assemblages are recognized in different types of structural provinces, including cratons and Brasiliano fold belt systems, be it as basement of mobile belts or as basement inliers branching out fold belts. They may even be co-participants of some Neoproterozoic foreland fold-and-thrust belts, in which they may form the main volcanic-sedimentary constituents of post-Statherian intracontinental fold belts, such as Brasiliano fold belts. In most cases, their occurrences are relatively dispersed in small areas when compared to their original extent, due to long-lived erosion during the Proterozoic and later times. This is a consequence of their features and non-orogenic origin, formed after very important global Rhyacian-Orosirian orogenic collage took place, resulting in vast continental masses, in subaerial settings and submitted to subsequent erosional events along various time periods.

Despite of frequent superimposed tectonic-metamorphic processes due to Mesoproterozoic (Sunsas/Aguapeí; Cariris Velhos, etc.) and Neoproterozoic (different Brasiliano stages) orogenies, and even Phanerozoic covers and tectonic processes, the Statherian lithostructural assemblages were relatively well preserved, although they may not be fully recognized throughout the continent. There may be instances in which superimposed orogenic processes and structures prevent their identification. In addition, it should be stressed that the main Phanerozoic basins of the South American Platform cover large parts of the cratonic domains, where in general, the Statherian assemblages are best preserved. Therefore, it is to be expected that progress of future geological and geochronological investigations, including larger scale mapping, may uncover currently unknown occurrences.

The Statherian lithostructural units are relatively similar, though not necessarily chronocorrelated in all continents. This likely has to do with the "supercontinent dance" after the late Paleoproterozoic large amalgamation. In the last century, it was initially thought that the Statherian events constituted a kind of landmark of the absence of orogenic processes, which did not take place until the Brasiliano Orogeny. On this account, the Mesoproterozic was labelled as cratogenic *par excellence* (the "Geocracy domain", "the boring billion years"). Today, this way of thinking was discarded, following the important discovery of orogenic events in the middle (Calymmian-Stenian) and at the end of the Mesoproterozoic (Stenian) to the Eotonian, and even the early Brasiliano (800-750 Ma, Tonian-Cryogenian). The discovery of late to post-Mesoproterozoic orogenic phenomena in the South American continent, aside of being a remarkable scientific advance of the current century thanks to larger mapping scales, tells us a story of strong Mesoproterozoic tectonic activity.

Taking into account the notorious Statherian lithostructural and magmatic landmarks, sub lithospheric causes should be considered, given the evolution of the inner Earth. Several authors (e.g. Klein *et al*. 2012, Chaves and Rezende 2019, among others) have forwarded possible comparisons of the phenomena in South America with contemporary intraplate events in other continents, in some cases equivalent to LIPs. Some of the occurrences addressed below have been considered the result of late Paleoproterozoic LIPs, although in need of additional geophysical and petrological data. It should be noted that these are unique phenomena and litho-structural processes, regardless of the chronic dissent between mobilists and fixists and respective nomenclature. Larger and improved geological and geophysical data sets are crucial to support correct classifications. It is also necessary to add that several orogenic collages were underway at the start of the Statherian worldwide (e.g. Transcontinental, Gothian-Kongsbergian in the northern hemisphere) as well as the Rio Negro-Juruena Belt in Amazonia, Singhbum-Chottanagpur in India, Halls Creek, Mount Isa, and Barramundi in Australia. Therefore, even in Brazil (Amazonian Craton, Rio Apa block), there are records of Statherian orogenesis generating undeniable accretionary assemblages at the same time as rock units related to the Statherian taphrogenesis were forming. That is, in dealing with Statherian records, it is necessary to discriminate intracontinental domains, the focus of this work, from juvenile accretionary systems.

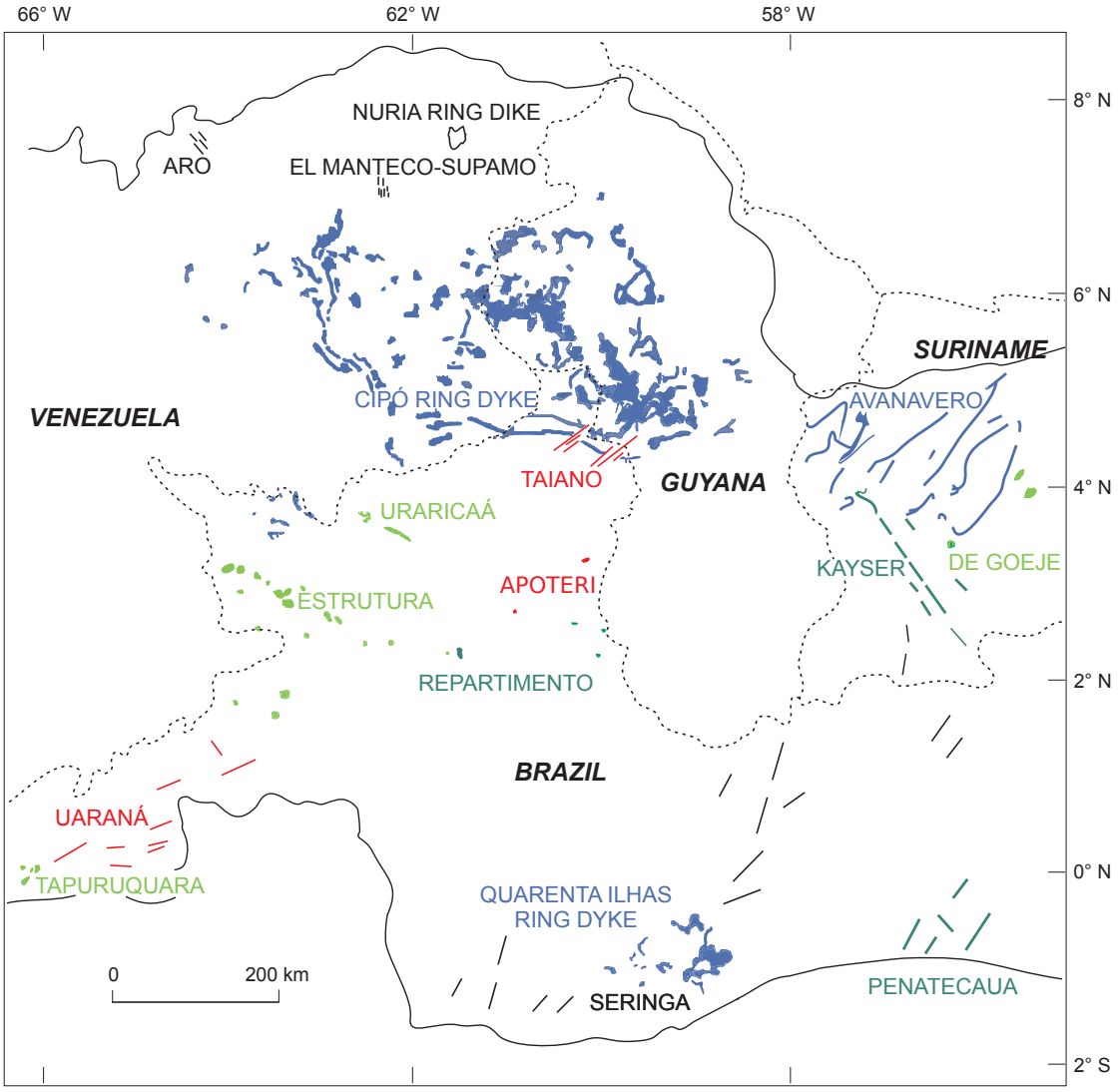
AMAZONIAN CRATON AND RIO APA BLOCK

The structural province comprising the Amazonian Craton and the Rio Apa block, in both the Guyana and Central Brazil shield areas, records prominent Statherian magmatism in terms of diverse rock types, reflecting distinct tectonic settings. Some occurrences are rather well studied from a geochemical-petrological-geochronological standpoint, whereas others are less investigated due to lack of adequate mapping, dense tropical forest cover and rather difficult access.

Avanavero-Crepori-Quarenta Ilhas mafic magmatism (Avanavero "LIP", according to some authors)

The Avanavero suite, one of the more important dike swarms of the South American continent, comprises mafic dikes and sills exposed in the Guyana shield, mainly north of 2°N, in Suriname and eastern Venezuela, as well as some other areas (e.g. Quarenta Ilhas, NE of Manaus, Brazil; Crepori) (Fig. 1). The occurrence area comprises around 300,000 km^2, including the substratum of the Paleoproterozoic "Maroni-Itacaiúnas" Belt and particularly intruding the gently folded Orosirian Roraima Group (1.95-1.87 Ga). Aside from geochemical and petrological data, relevant geochronological studies were performed (Reis *et al*. 2013). Due to accurate U-Pb analyses on baddeleyite, the Avanavero magmatism can be placed at the beginning of the Statherian, with age determinations between 1780 and 1795 Ma, the maximum variation spanning around 15 m.y.

The Avanavero rocks are melanocratic, medium- to coarse-grained, comprising mainly diabase and gabbro, and subordinate diorite and quartz diorite (Reis *et al*. 2013). The main minerals are plagioclase (andesine-labradorite), pyroxene (augite>>pigeonite), amphibole, biotite, and magnetite, ilmenite, apatite, baddeleyite as accessories and sericite and epidote as



Source: Reis *et al.* (2013).

Figure 1. Statherian Avanavero-Quarenta Ilhas dike swarm ("LIP"), center–north of the Amazonian Craton. Blue, Avanavero sills and dikes; dark green, Mesoproterozoic anorthosite/gabbro and dikes; light green, Mesoproterozoic (1.8–1.17Ga) mafic-ultramafic bodies; red, Mesoproterozoic dikes; black, unknown age.

secondary minerals. TiO_2 contents allow to divide the rock types into basalts and andesite basalts, respectively, with low and high contents. In AFM diagrams, these rocks plot in the tholeiite series field, and in the composition discriminant diagram, andesite-basalt is dominant. In general, they display E-MORB signature and are usually interpreted as the result of mantle-derived intraplate magmatism.

The geotectonic implication and causes of the outstanding regional geographic-geologic extent of the Avanavero suite, as well as the lack of preferential direction are still under consideration, but several suggestions and possibilities have been put forward, such as LIP-type underplating due to crustal extension resulting from Rhyacian-Orosirian collisional interaction and orogenic collapse of the previously named Maroni-Itacaiúnas and Ventuari-Tapajós belts. It is worth mentioning that this magmatism intercepts the late Orosirian Uatumã SLIP (Klein *et al.* 2012), affecting both the Iriri-Iricoumé-Iwokrama volcanic rocks and the gently folded Roraima cover. The lack of geophysical data prevents further interpretation.

Igneous system of the Southwestern part of the Amazonian Craton (West Amazonia Igneous Belt or Rio Negro-Juruena belt)

The so-called West Amazonia Igneous Belt (WAIB, Rizzotto *et al.* 2019), comprising a plutonic-volcanic-sedimentary association, is exposed in the Central Brazil shield, southwestern Amazonian Craton, extending from western Mato Grosso (around 54°W) to the border of Rondônia and Amazonas (around 62°W), between the Alto Tapajós Basin and the Caiabis-Dardanelos cover (Fig. 2). The WAIB exposures underlie around 130,000 km^2, extending for about 940 km in the E-W direction, along latitude 10°S. Their basement comprises dominant Orosirian "Ventuari-Tapajós" belt rocks and part of the Statherian "Rio Negro-Juruena" belt. Most workers understand this Statherian magmatic system as linked to an accretionary orogenic feature, named Rio Negro-Juruena Orogenic Belt (see Bartorelli *et al.* 2020).

The WAIB comprises extensive igneous activity, including plutonic (stocks, A-type batholiths) and subvolcanic intrusions, coeval to volcanic rocks (rhyolite, trachite, dacite,

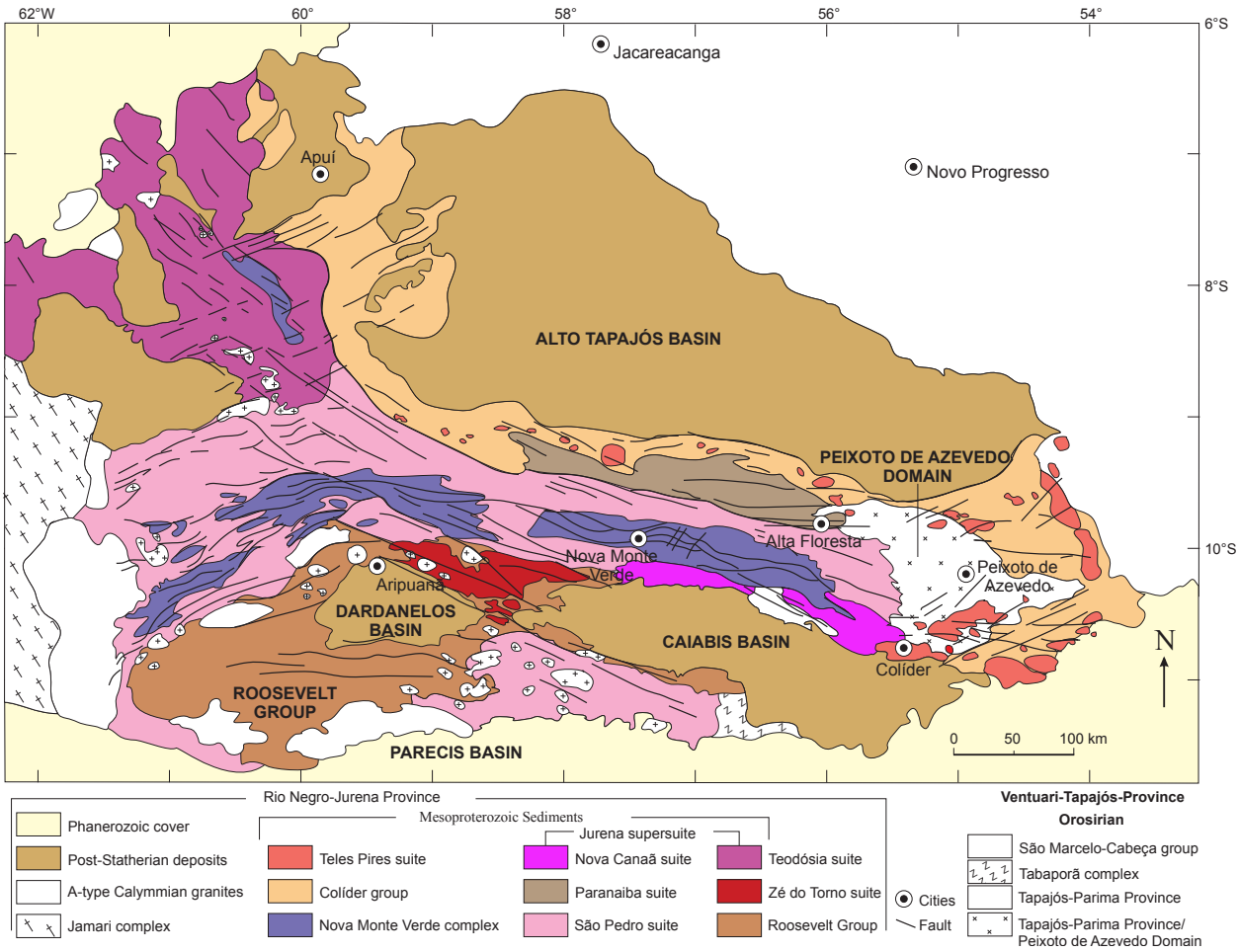


Figure 2. West Amazonian Igneous Belt (WAIB, ca. 130,000 km^2), WSW of the Amazonian Craton, according to the original proposition of Rizzotto *et al.* (2019). For some other authors, this area is just the southern branch of a large accretionary belt (Rio Negro-Juruena belt).

ignimbrite), volcanoclastic deposits, as well as mafic dikes and other intrusions. U-Pb ages on zircon and baddeleyite define a very small upper Statherian range. Rocks of this igneous system are deformed and metamorphosed in variable degrees. Several suites and supersuites have been distinguished, displaying very close ages and development (Rizzotto *et al.* 2019):

- Juruena supersuite: granite, monzogranite, granodiorite, ranging from isotropic to strongly deformed and sheared varieties. Igneous flow structures were preserved locally. Ages range between 1810 Ma and 1770 Ma;
- Colíder Group: acid volcanic deposits dominate, including pyroclastic and epiclastic rocks, exposed almost continuously along the WAIB belt, from the Alto Tapajós Basin to near Aripuanã. Isotopic ages indicate consistent values between 1810 Ma and 1766 Ma;
- Teles Pires suite: felsic plutonic and subvolcanic intrusions, associated in space and time to the Colíder Group deposits. Intrusive as well as transitional relations have been observed. Recent age determinations range between 1794 Ma and 1757 Ma. The rocks display an alkali-calcic trend represented by peraluminous to slightly metaluminous high-K granites, geochemically similar to the Colíder volcanics;
- Teodósia and Zé do Torno suites: granitoids and subvolcanic rocks, sparsely distributed along the northern Serra do Cachimbo border, and along the southern Roosevelt Basin border;
- Roosevelt Group: terrigenous metavolcanosedimentary sequence exposed along the Juruena and Roosevelt rivers interfluvium, characterized by subaquatic deposition structures. The upper unit comprises rhytmite, mudstone, chert, tuff, Mn-rich siltite and iron formation. The middle unit is composed of ignimbrite and volcanic-clastic conglomerate. The lower unit includes dacite and rhyolite. The sequence was deformed under low-grade conditions, displaying E-W to SW-NE trending synformal folds. Ages range from 1763 Ma to 1740 Ma;
- Vespor mafic suite: gabbro and diorite plutons and dikes, sometimes metamorphosed under amphibolite facies conditions. Magma mixing with Colíder Group rocks is rather common. Age determination of a gabbro yielded 1779 ± 6 Ma, whereas the Sm-Nd T_{DM} model ages range between 2.2 and 1.93 Ga, with positive ε_{Nd}, suggesting a slightly contaminated mantle source.

There are many characteristics in this singular accumulation of igneous rocks, suggesting intraplate magmatism. These are mainly felsic rocks with dominant alkali-calcic trend, peraluminous to slightly metaluminous, ferrous, pointing to A-type magmatism, especially the Juruena and Teles Pires supersuites and the Colíder Group. Intermediary rock types are almost absent. In addition, presence of Orosirian (2.05-1.87 Ga) and

some Archean inherited zircon grains suggest partial melting of the pre-existing "Ventuari-Tapajós" basement. Taking these features into account, as well as the near absence of deformation, Rizzotto *et al.* (2019) suggest that the association may record a Silicic Large Igneous Province (SLIP), that is, an important tectono-magmatic event related to a mantle plume, partially contemporary to the Uatumã SLIP installed further northeast, within the Central Brazil and Guyana shields. In both instances, geological and geochemical data as well as tectonic conditions favor this interpretation, although some other questions were raised (required conditions, see Ernst 2014), including deep geophysical data.

Post-Orosirian anorogenic magmatism of the Pará-Amapá border

Anorogenic-type granites, alkaline and ultramafic rocks intrude the Amapá Block Archean and Orosirian basement units north of the Equator, between 52° and 56° W, in an area of rather difficult access and lacking ideal geological knowledge. These rocks are taken as recording the post-orogenic extension in the region (Ricci *et al.* 2001, Rosa Costa *et al.* 2014), and are considered of relevant metalogenic potential. Currently, the main rock units known in the area are the following:

- The Parintins intrusive suite, exposed east of 54° W, between the Cupixi and Ibitinga rivers, intrudes the Rhyacian belt that straddles along the northeastern and northern margins of the continent. The suite comprises isotropic monzogranite, granodiorite and tonalite, including minor microgranite and microsyenogranite, assumed to be of Statherian age as suggested by regional correlations;
- The Uaiãpi Granite comprises half a dozen, 5 to 700 km^2, elliptic to circular granite stocks and batholiths. They intrude NW-SE-trending Archean and Paleoproterozoic volcano-sedimentary rocks, between 52^0 and 54° W, close to the Equator. The intrusions are formed mainly of medium- to coarse-grained hastingsite syeonogranite. Pb-Pb zircon evaporation data yielded an age of 1753 ± 3 Ma (Vasquez and Lafon 2001);
- Along the Camaipi River, mafic intrusions of alkaline affinity are recognized (Ricci *et al.* 2001). They exhibit a semicircular shape, composed of medium- to coarse-grained, locally porphyritic nepheline monzogabbro (malignite), nepheline monzosyenite (essexite) and nepheline-bearing aegirine monzodiorite. No age determinations are available up to now, and the supposed Statherian age relies on regional correlations. In addition, Rosa Costa *et al.* (2014) refer to several small mafic bodies of presumed Statherian age intruding the Archean Amapá Block;
- Some indications of mafic to intermediary rocks known as "Boa Macaca" and "Portela" are also presumed to be of Statherian age;
- The Araguari-Mururé ultramafic rock is a hornblende- and opaque minerals-rich mafic-ultramafic semicircular stock exposed between the Araguari and Mururé rivers (1°30' N, 52°20' W), thought to be related to the Camaipi River Group (Rosa Costa *et al.* 2014). Its strong magnetic zoning is easily recognized in aeromagnetic images.

Anorogenic Magmatism in the northern Amazonas State (near Colombia and Venezuela boundaries)

A number of A-type anorogenic granites are exposed in the northern part of Amazonas (from the Colombia border up to the Venezuela border) along the upper Rio Negro River, following the Equator between 70° and 66° W. Regional correlations indicate that they intruded the ENE-WNW Caiaburu Complex in the southeastern part of the Orosirian Rio Urubu belt granitoids, gneiss and migmatite, after the development of the 1880-1870 Ma old Uatumã SLIP. They are mainly monzogranites of ferroan signature, and available zircon U-Pb geochronological data point to Statherian ages (Almeida *et al.* 2013, Reis *et al.* 2021). From West to East, the exposed intrusions are: "Tiquié" hornblende granite and syenite (1747 ± 8 Ma), Marié-Mirim monzogranite and syenite (1756 ± 12 Ma), and Marauiá amphibole-biotite monzogranite (1746 ± 7 Ma). All exposed intrusions display inherited zircon grains from the basement (Cauaburi and Tapajós-Parima). Their crystallization ages can be defined as Early Statherian (1746-1756 Ma), that is, they are younger than the late Orosirian silicic Uatumã LIP.

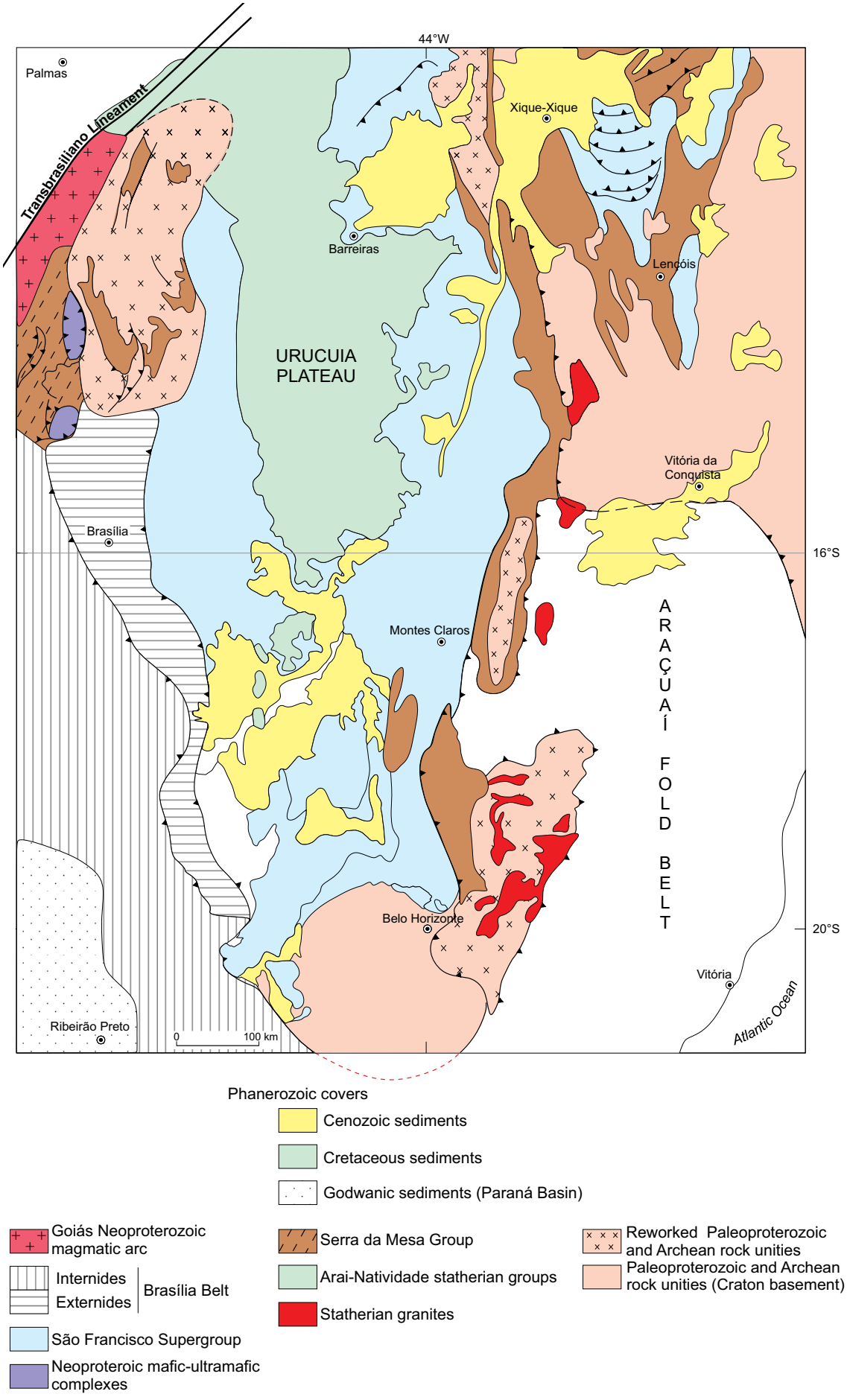
Rio Apa

Two issues concern the Rio Apa block: its geographic-geologic-geotectonic relationship with the Amazonian Craton — their connection being admitted by most scholars — and the nature of its Statherian record.

The Rio Apa massif (in the physiographic-geological sense) is exposed 300 km to the south of the classic areas of the Amazonian Craton, separated by the sedimentary deposits of the Pantanal Matogrossense. Its integration as a probable protrusion of the craton is admitted by many geologists. A Rhyacian-Orosirian terrane stands out as an Eopaleoproterozoic basement inlier in the west of this cratonic segment, intruded by various granite generations. To the east, the Caracol Arc is exposed. The Statherian Alto Tererê volcanic-sedimentary basin rests over this juvenile terrain, comprising Al-rich schists, quartzite and metabasalt, initially taken as a continental, post-arc basin. Recent studies based on geochemical, petrological and geochronological data concluded that the basin was formed in a back-arc setting (Lacerda Filho *et al.* 2016, Ribeiro *et al.* 2020).

THE SÃO FRANCISCO CRATON, ITS MARGINAL FOLD BELTS AND BASEMENT INLIERS (SÃO FRANCISCO PALEOCONTINENT OR PARAMIRIM PALEOCRATON, ALMEIDA, 1981)

A number of Statherian sedimentary deposits and varied associated igneous rocks are exposed within the São Francisco Craton and in the basement of the surrounding mobile belts (Fig. 3). Compared to those of the Amazonian Craton, they are more accessible given the physiographic conditions. Even so, better insight into their geology may reveal additional types, especially concerning mafic dike swarms, some of which lack detailed petrological and geochronological studies.



Source: based upon Cordani *et al.* (2016).

Figure 3. The São Francisco Craton and its marginal belts and associated basement inliers, exihibiting the Statherian belts and anorogenic granites. Note occurrences of the Espinhaço Range and of the "Borrachudos" and "Lagoa Real" granitic complexes in the central and eastern parts.

It should be noted that the units discriminated below are reasonably well studied, but they are not the only ones. As it will be shown, many of the units recognized within the São Francisco Craton extend to the basement of the marginal folded systems. In some cases, the Statherian units were strongly reworked, deformed and metamorphosed during the Brasiliano Orogeny, which poses some difficulties in matching them to the ones exposed within the craton.

Several Statherian QPC-type sedimentary deposits and associated volcanic and plutonic rocks occur in the central-eastern portion of the South American Platform, between 40º and 48º W and 10º and 20º S. They underlie a discontinuous area of ca. 750,000 km^2, mainly concentrated in Bahia and Minas Gerais to the east, and in Goiás and Tocantins to the west, as well as some probable occurrences in Piauí, the latter demanding additional studies.

Espinhaço Taphrogenesis: West-central Bahia, central-southeast Minas Gerais, South Tocantins, North Goiás

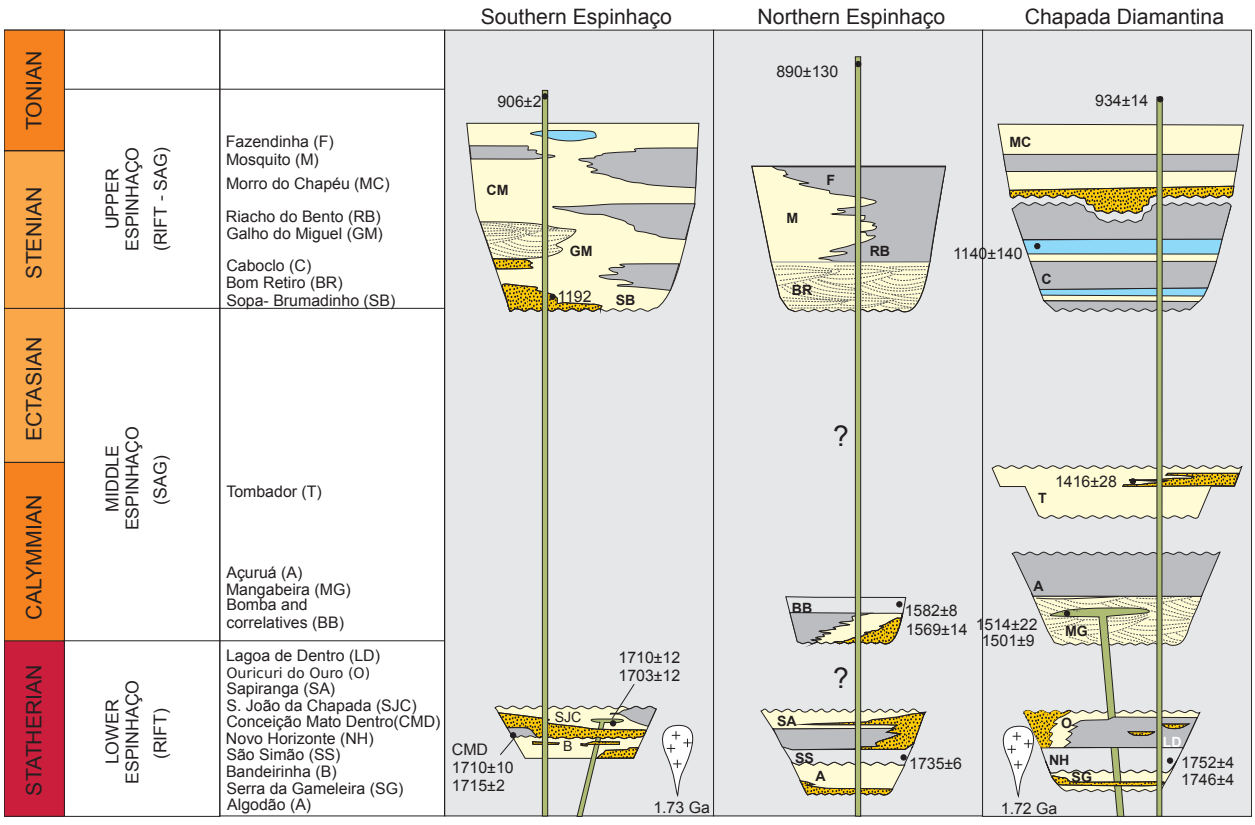
The ca. 1,100 km long and roughly N-S- trending Espinhaço Range extends between 10º and 20º S, from northern Bahia to southeastern Minas Gerais. Its width varies from several hundred km to the north to a few tens of km to the south. It represents an intracontinental basin, including rifts and sags, that was turned into a deformation corridor along Mesoproterozoic times, consummated in the late Brasiliano Orogeny, associating intracontinental holomorphic fold belts (Espinhaço Supergroup *sensu lato*) and platform-type moderately deformed covers (Chapada Diamantina). The paleogeographic and tectonic history is long and multiphased, its development stretching from the early Statherian (ca. 1780 Ma) to the Tonian (ca. 900 Ma). Later on, these units were partially re-structured in the Ediacaran up to the start of the Cambrian (Guadagnin and Chemale Jr. 2015, Guadagnin *et al.* 2015). Imprinting of the Brasiliano deformation, preceded by earlier phases, which are as of yet not properly identified or understood, diverse in form and intensity, resulting in local features that hinder clarifying the unit's long history. Difficulties notwithstanding, there is a wealth of geological maps, academic studies and surveys of mineral resources (e.g. diamond, gold, carbonate, quartz crystal, dumortierite, amethyst, cassiterite) covering the multiphase history of the Espinhaço Range. The thickness of the succession is variable, reaching up to 5,000 m.

The many scientific contributions to the Espinhaço Supergroup in the last 55 years were recently synthesized by Guimarães *et al.* (2012), Guadagnin and Chemale Jr. (2015) and Guadagnin *et al.* (2015). The supergroup displays distinct paleogeographic representations:

- Southern Espinhaço in Minas Gerais;
- Northern Espinhaço and Chapada Diamantina in central Bahia, the latter only moderately folded.

Despite some local dissention, given the large number of researchers working on different aspects, including stratigraphy and geochronology, there is a well-accepted lithostratigraphic column available (Fig. 4).

It should also be noted that to the west, beyond the São Francisco Craton, Statherian lithostratigraphic units are recorded in the substrate of the Brasília Belt, with minor (Natividade



Source: Guadagnin and Chemale (2015) and Guadagnin *et al.* (2015).

Figure 4. Scheme of the stratigraphic, tectonic, magmatic and geochronological evolution of the Espinhaço Supergroup, from the south of Minas Gerais to the north of Bahia.

and Araí groups, externides) or major (Serra da Mesa Group, internides) tectonic-sedimentary differentiation degrees. Similarly, to the east of the craton, in the basement of the Araçuaí Belt, supracrustal sequences as well as granite intrusions related to the Espinhaço development are exposed, which have to be clearly distinguished from the Brasiliano events.

Lower units of the Espinhaço Supergroup

The lower units of the Espinhaço Supergroup comprise both immature and mature clastic deposits, various stages of volcanism and associated plutonic intrusions, which record a lower Statherian (1730 ± 20 Ma) rifting episode. The middle supergroupunits, deposited in Calymmian time (ca. 1560-1400 Ma), developed in sag conditions, comprising varied clastic sedimentation. After phases of uplift and erosion during a large time interval, comprising the entire Ectasian, the upper Chapada Diamantina Group of sedimentary rocks was deposited (rift-sag phase?) from the start of the Stenian to the early Tonian.

The lower portion of the supergroup, historic mark, and precursor of the Statherian Taphrogenesis concept in the continent (Brito Neves *et al.* 1995), is formed of diverse clastic sedimentary deposits (alluvial, lacustrine, aeolian) and felsic volcanic rocks that bear different labels (Rio dos Remédios, Conceição do Mato Dentro, Bandeirinha, São Simão). They comprise dacite, rhyolite, andesite, tuff and volcanic ash, of peraluminous and alkaline trend, typical of intracontinental setting and crustal contribution, generally metamorphosed under low-grade conditions and strongly modified due to magmatic or metamorphic fluids. In recent revisions, this unit has been labelled as the Lower Espinhaço sequence (e.g. Guadagnin *et al.* 2015).

These rocks are exposed along a ca. 960,000 km^2 area, locally preserving features of a precursor intracontinental rift. The initial stage took place at the lower Statherian through intracratonic rifts, comprising the roughly parallel rift system developed on the western São Francisco paleocontinent (Natividade, Araí, Serra da Mesa), nearly 500 km westwards from the Espinhaço trend. As noted below, in Goiás and Tocantins, only the Statherian rifts are recorded. In the particular case of the Serra da Mesa Group, the Brasiliano deformation and metamorphism were rather strong.

Some mafic sills and dike swarms intruded the sedimentary deposits and their basement exposed along the Paramirim valley. This set of mafic rocks has been labelled as Chapada Diamantina-Paramirim "province" (Leal *et al.* 2012).

A wealth of geochronological data (zircon U-Pb and others) regarding the volcanic rocks is available, with ages ranging between 1750 and 1710 Ma (Guadagnin *et al.* 2015). K-Ar and Ar-Ar isotopic determinations record overprinted deformation and isotopic re-homogenization due to the Brasiliano Orogeny. In fact, in the Bahian sector, the Espinhaço opened and preceded the Brasiliano deformation corridor path that led to its isotopic rejuvenation.

Middle and Upper Group

The second evolution phase of the large stratigraphic record is discordant and reflects a tectonic setting of "sag-type" moderate subsidence. It developed with several interruptions and unconformity surfaces along the Calymmian, displaying several stratigraphic units. The last stage shows variable tectonic settings (rift-sag) and likely closed in the Tonian. 1.4 Ga old detrital zircon grains were found within the Tombador Formation, the basal unit of the upper Chapada Diamantina Group, and Tonian zircon grains have been recorded in younger units, exposed in the ranges north of the Espinhaço (Santo Onofre Group, Alcântara *et al.* 2017).

Statherian Dike Swarms

The presence of Statherian dike swarms is a marked and constant feature indicating Statherian extension after the important Rhyacian and Orosirian orogenies in the paleocontinent (Fig. 5). Some of these swarms are relatively well-known, with ages ranging from the start of the Statherian (ca. 1.8 Ga) up to the beginning of the Calymmian. However, there are several dike swarms cutting through the cratonic basement domains to the Proterozoic belts, which need to be better studied and dated.

Pará de Minas Dike Swarm

The Pará de Minas dike swarm extends from the south of Belo Horizonte to the SW limit of the São Francisco Craton, partially covered by Neoproterozoic and Phanerozoic sedimentary deposits. The mafic dikes may reach 400 km in length and tens of meters in thickness, averaging 50 m (Chaves 2013). The area of exposure of the swarm is about 450 km long and 200 km wide, trending NW-SE. They are rather well exposed and well recorded in aeromagnetometric images (Chaves 2013, Chaves and Rezende 2019). The dikes are of gabbro-diorite and diabase composition, with ophitic to sub-ophitic texture,

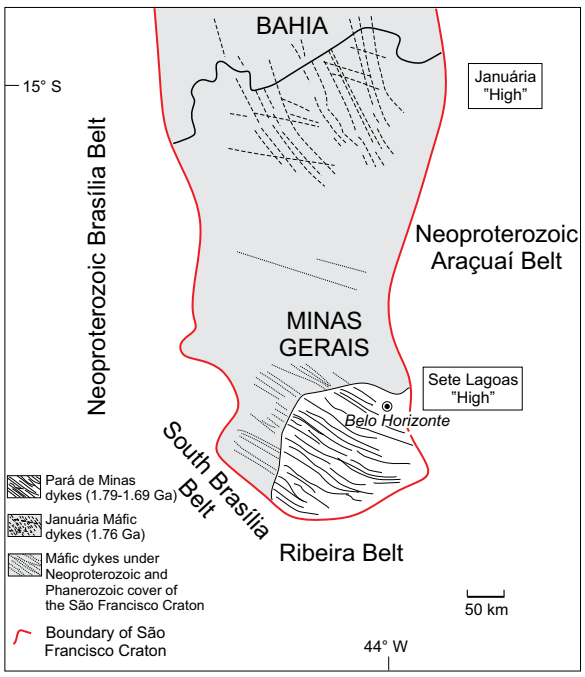


Figure 5. Staherian dike swarms of the southern part of the São Francisco Craton (Chaves 2013, Chaves and Rezende 2019). They are associated to tectonic basement "highs", positioned to the north and south of the so-called "Pirapora aulacogen".

transitioning to basalt at the borders. Some of the dikes are porphyritic, with up to 15 cm-long plagioclase phenocrysts, some displaying NW-SE igneous flow structures. Chemically they vary from tholeiitic andesite-basalt to trachibasalt. At the border of the craton they were recrystallized by the Brasiliano event.

U-Pb age determinations on baddeleyite range from 1978 ± 4 Ma to 1702 ± 3 Ma (Chaves and Rezende 2019). These ages are equivalent to other mafic rocks, felsic volcanics and intrusions of the Espinhaço within the craton, similar rocks exposed in forebulge marginal terrains of the craton as well as in other structural provinces of South America and other continents.

Januária Dike Swarm

The Januária dike swarm occurs in the central portion of the São Francisco Craton, near Januária, between Manga and São Romão, in northern Minas Gerais. It is poorly exposed due to the extensive Neoproterozoic cover. The dikes are found in a NE-SW trending ca. 450 km long and 250 km wide area. Despite the cover, aeromagnetic images illustrate the dikes rather well; their widths averaging around 40 m. Eastwards, the dikes cut across the Archean basement inliers within the Araçuaí Belt, such as the Porteirinha block.

The dikes are dominantly composed of metadiabase, displaying low-grade greenschist facies parageneses, comprising tremolite-actinolite, epidote, clinozoizite, zoizite and biotite partially or totally altered to chlorite. The low-grade metamorphism happens due to superimposition of the Brasiliano Orogeny at the eastern margin of the craton.

Isotopic U-Pb determinations on baddeleyite yielded age values between 1750 and 1760 Ma. These ages compare to those of the Pará de Minas dike swarm (Chaves and Rezende 2019).

Chapada Diamantina-Paramirim "province"

Mafic intrusions cut across the Archean Paramirim basement block and the quartzite ridges that it separates, trending NNW-SSE for around 400 km between Gentio do Ouro (11º20' S) and Condeúba (15º S), in Bahia. There are quite a few mafic intrusions (gabbro-norite) of general tholeiite affinity. Part of the intrusions cut across the basement and the Espinhaço Supergroup, and they occur partially as sills within this folded unit. This domain, comprising an area of more than 4,000 km^2, has been labelled the Chapada Diamantina-Paramirim province (Leal *et al.* 2012). It should be mentioned that not all of these intrusions are well known from the geological and geochronological standpoint, and some have not even been mapped, despite their geographic, geologic and tectonic significance. Therefore, it is quite possible that there are intrusions of different ages and tectonic significance.

The mafic rocks are isotropic and display little variation in composition, grain size and texture, with occasional differentiation. In general, they are made of plagioclase (andesine-labradorite) and augite, as well as lower proportions of hornblende, biotite, opaque minerals and zircon. The average width of the dikes is 2-5 m and they may extend up to 10 km long.

There are only few age determinations regarding these rocks. Zircon U-Pb ages range between 1730 and 1760 Ga (Babinski *et al.* 1999, Danderfer *et al.* 2009), similar to felsic intrusions known as part of the start of the taphrogenesis. On the other hand, there is a group of ages between 1500 and 1800 Ma, which appear to be dominant. According to Leal *et al.* (2012), it seems that there are distinct generations of extension events along time, adding Stenian-Tonian events to the ones mentioned above, during which an important phase of igneous intrusions linked to the Rodinia break-up took place in Bahia.

In our understanding, the Statherian intrusion event is related to the onset of the rifting process leading to the Espinhaço basin formation and deposition of the basal Espinhaço Supergroup units. In turn, the Calymmian intrusions would be related to the ending of this first structuring phase of the large taphrogenic basin (Piauí-Bahia-Minas Gerais/Goiás-Tocantins).

Statherian Plutonism

Lagoa Real Complex: central São Francisco Craton

The Lagoa Real unit presents a complex igneous and metamorphic history encompassing an association of porphyritic to cumulate alkali-feldspar granites and syenites, divided into the São Timóteo and Jurema facies. Varied degrees of deformation and metamorphic recrystallization resulted in the formation of N-S-trending bands of protomylonite (Piripiri, Cercado), ultramylonite (Caitité) and augen gneiss (Lagoa Grande), along *ca.* 110 km of the Paramirim valley (13º30'-14º30'S), composing the association of the so-called Lagoa Real complex (Cruz *et al.* 2007). About half a dozen litho-structural units were recognized and mapped in the area, displaying a polycyclic metamorphic-metasomatic and deformation history leading to local formation of microclinite, epidosite and albitite hosting uranium mineralization.

The igneous intrusions, dated at 1706 ± 107 Ma (Turpin *et al.* 1988, Cordani *et al.* 1992, Lobato *et al.* 2015), are considered to be related to the lower group of the Espinhaço Supergroup. However, they underwent a complex evolution at the end of the Mesoproterozoic and along the Neoproterozoic in association with the Araçuaí orogenic belt evolution. The albitite uranium mineralization was dated at 960 Ma (Turpin *et al.* 1988), this age being assigned to a still unknown early stage of the Neoproterozic orogeny that likely took place before the main Ediacaran events of the Brasiliano Orogeny. The economic relevance of the Uranium deposits, with estimated reserves of 100,000 tons, should be stressed.

Borrachudos intrusion, SE of the São Francisco Craton (Guanhães and Porteirinha inliers)

The Borrachudos Suite, considered contemporary to the Statherian rift phase of the Espinhaço Supergroup, is exposed NE of Belo Horizonte, intruding the Guanhães and Porteirinhas basement inliers of the Araçuaí Belt. They are mainly composed of stocks of very homogeneous composition, including dominant amphibole granite, biotite granite and amphibole-biotite granite, bearing the tectonic and geochemical features of intra-plate A-type granites. They occur mainly along ca. 170 km, between Peçanha (18º30' S) and João Monlevade (20º S). U-Pb zircon ages range between 1729 ± 14 Ma and 1595 ± 10 Ma (Dussin *et al.* 1977,

Magalhães *et al.* 2018). Most intrusions are small stocks of coarse-grained granite, mostly isotropic, but displaying some orientation towards their borders. They are roughly coeval to the deformed Lagoa Real intrusions and also to the Pará de Minas dike swarm, some of which are exposed nearby, highlighting the bimodal magmatic character and the relevance of the cratogenic rupture processes affecting the ancient paleocontinent (Columbia).

The Rio de Contas Ibitiara "Tin Province" of Bahia

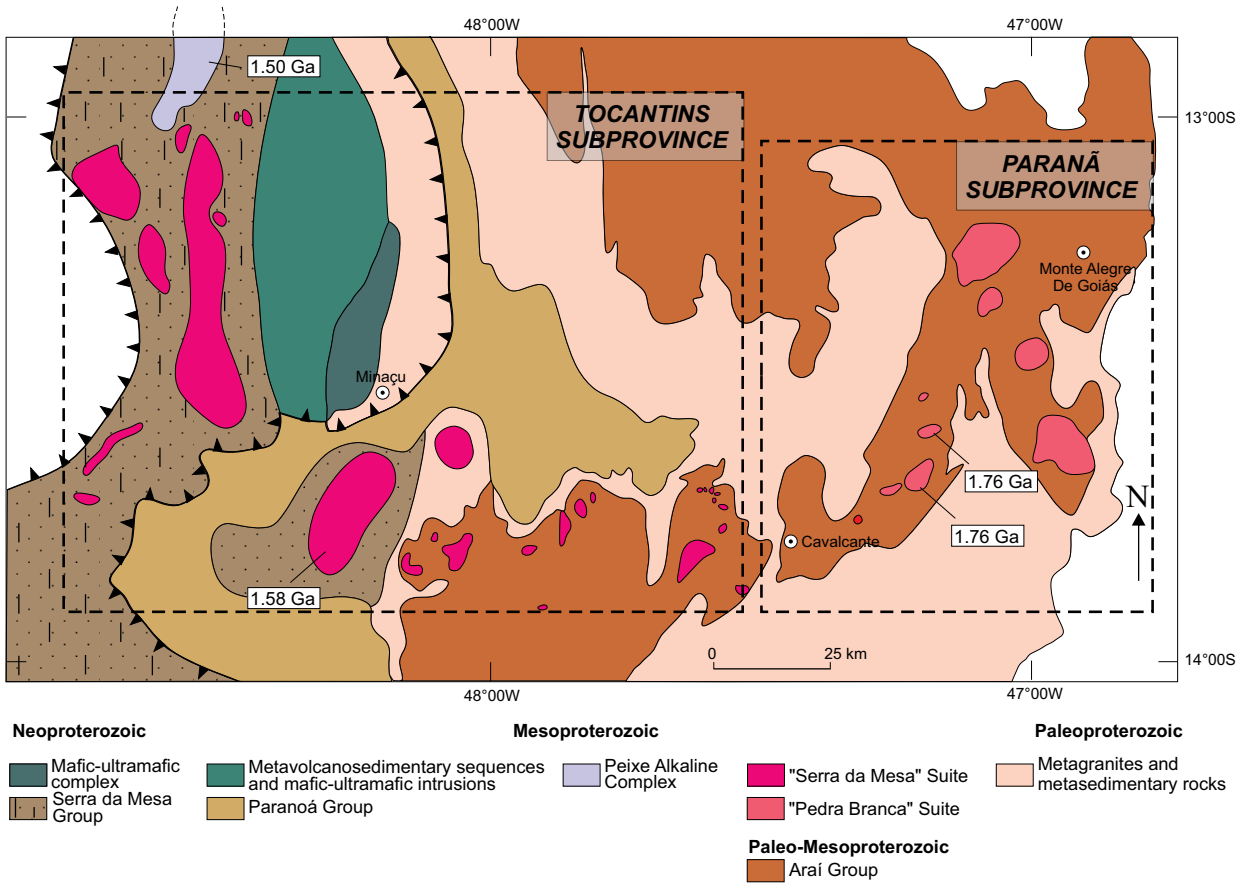
The Rio de Contas-Ibitiara mineral province is located along the Paramirim River, central Bahia, between 12º and 14º S, occupying ca. 120 km long and 30-50 km wide area and around 4,000 km^2, which exposes the Archean basement and Paleoproterozoic granite intrusions of the São Francisco Craton (Martins *et al.* 2008).

Several supergenic vein-type mineral deposits as well as alluvial deposits bear gold, barite, quartz crystals, cassiterite, diamond, copper, etc. The presence of cassiterite linked to the Espinhaço volcanism has spawned a large number of mines and diggings, largely handmade, quite irregular in terms of method and time. Actually, the presence of barite is the most important in volume (ca. 16 million tons) and exploitation.

The Goiás Tin Granite province, West of the São Francisco Craton (Brasília Belt)

Along the Tocantins-Goiás border (13º-18ºS), in the Tocantins Province, around 30 granite bodies have been mapped, some of which are tin-bearing.. They are sparsely distributed in an area of around 200,000 km^2, intruded into the internal and external zones of the Brasília Belt (Fig. 6). Four distinct sub-provinces in terms of geological characteristics and location are recognized: Rio Paranã, Tocantins (N Goiás), Pirinópolis (W of Brasília) and Ipameri (18º S). The granites intruded Archean and Paleoproterozoic basement and are at least partially coeval to the Araí Group felsic volcanism. Westwards, they display deformation and metamorphic recrystallization in the internides domains, whereas eastward, toward the border of the São Francisco Craton, they show less deformation and metamorphism. The intrusions generally comprise peraluminous, intracratonic A-type granites, several presenting mineral deposits of cassiterite-fluorite-sulphide to the east, and cassiterite-tantalite-columbite to the west. Since the pioneering work of Marini and Botelho (1986), a large geologic, petrologic, geochemical and metallogenic data set has been established on these granites.

Several age determinations through various methods are available. Alkaline granites and rhyolite lavas of the eastern Rio Paranã sub-province yielded U-Pb zircon ages of 1770 ± 2 Ma (Pimentel *et al.* 1991), which are around 150 my older than the western Tocantins sub-province intrusions. Most K-Ar and Rb-Sr age determinations refer to the superimposed Brasiliano orogenic events.



Source: from Cordeiro and Oliveira (2017).

Figure 6. Northern Brasília belt showing the Statherian to Calymmian Tin-bearing granite sub provinces in the externides (Paranã) and internides (Tocantins). The Rio do Peixe alkaline complex, of likely post-Statherian age, is exposed in the northwest part of the figure.

Fold belts and covers at the eastern and western margins of the craton

The São João del Rey Group (Tiradentes and Carandaí formations)

A metasedimentary succession bearing affinities whith the Espinhaço Group, traditionally referred as the São João del Rey Group, is exposed between Prados and São João del Rey, underlying the Neoproterozoic Andrelândia Group in the southeasternmost portion of the São Francisco Craton, 120 km to the south of Belo Horizonte. Its base, the Tiradentes Formation, unconformably overlies the Paleoproterozoic craton basement. It comprises a nearly 1,000 m thick succession of psammite and pelite beds, mainly pebbly quartzite, pure quartzite and some phyllite. Four mappable units/facies separated by unconformities have been discriminated (Tiradentes, São José, Tejuco, Lenheiro). Detrital zircon U-Pb data define age peaks at 1763 ± 14, 2123 ± 5, 2745 ± 15 and 2971 ± 15 Ma, the first taken as the maximum depositional age (Ribeiro *et al.* 2013), similarly to the Espinhaço Supergroup lower units. The overlying Carandaí Formation's detrital zircon grains display six age peaks between 1379 ± 5 and 3058 ± 50 Ma, the youngest being considered the maximum depositional age (Ribeiro *et al.* 2013), and possibly related to faults similarly to what was already described for the middle Espinhaço.

Araçuaí fold belt (northernmost part of the Mantiqueira Structural Province)

Statherian lithostratigraphic units of the Espinhaço Supergroup are exposed all along the southeastern São Francisco Craton, between 15°S and 20°S, covering the Porteirinha, Guanhães and Gouveia basement inliers of the Araçuaí Fold Belt. These Statherian covers, folded during the Brasiliano Orogeny, compose and characterize the foreland fold-and-thrust-belt of the Araçuaí system. The westward vergence towards the craton is well preserved in these Espinhaço rocks, even working out as a basement to the superposed orogenic system. Showing several erosional windows of inliers, these rocks are privileged markers of the centripetal folding dynamics in relation to the craton. The variously segmented range formed during the Brasiliano Orogeny is still rather well preserved (Noce *et al.* 2007, Pedrosa Soares *et al.* 2007). The rocks circumscribe the Archean and Paleoproterozoic basement inliers and are in line with the Paramirim tectonic setting.

Araí, Natividade and Serra da Mesa Groups, Tocantins Province (West of the São Francisco Craton)

Correlative units of the lower Espinhaço Supergroup overlie the basement of the Brasília Belt, south of 11°S. Part of these units are moderately folded along the external zone of the belt (Araí, Natividade), but in the internal zone of the belt (Serra da Mesa) they are strongly deformed.

- The Natividade Group corresponds to the northernmost (north of 12°S) erosive remnant of these units. It is an intracontinental basin QPC-type sequence, which unconformably overlies the Paleoproterozoic basement. It underlies NNE-trending and 850 m-high mesas and comprises four lithostratigraphic units, with ages still unknown (Gorayeb *et al.* 1988). The presumed Statherian age is based on regional observations (Toscani *et al.* 2021). From the base to the top, the succession comprises: The Santa Clara unit, pure and micaceous quartzite with conglomerate, limestone and dolomite intercalations; The Mato Virgem unit, dolomite marble, phyllite and slate, with local sandstone intercalations; The Córrego Fundo unit, micaceous quartzite, phyllite and slate; The Jacuba unit, pure and micaceous quartzite, with some arkose layers (Tanizaki *et al.* 2015, Toscani *et al.* 2021). The group is affected by east-verging fold, presumably developed during the Brasiliano Orogeny;
- The sedimentary-volcanic-plutonic system of the Araí Group is exposed in SE Tocantins and NE Goiás, mainly within the external zone of the Brasília Belt. It occupies a large part of the Conceição-Natividade forebulge, a large salient of the reworked basement of the São Francisco paleocontinent, exposed northwestward of the craton (Brito Neves *et al.* 2021). The Araí system comprises around 22,000 km² of scattered, discontinuous and irregular exposures and includes two diverse tecto-no-lithostratigraphic sequences (Tanizaki *et al.* 2015) portraying the constraining Statherian taphrogenic processes, similarly to the Espinhaço Supergroup: Arraias Formation: pre-rift sequence of aeolian quartzite, conglomerate, imature quartzite, discordantly overlying the Paleoproterozoic basement; rift sequence of quartzite and conglomerate, intercalated with rhyiolite, rhyodacite and tuff, which underlie microgabbro intercalated in metapelite; Traíras Formation: post-rift transitional to marine sequence of carbonate-bearing metasiltite, fine-grained quartzite and metasiltite of shallow marine environment. The volcanic rocks of the Arraias Formation were dated at 1771 ± 21 Ma by the zircon U-Pb method (Pimentel *et al.* 1991);
- Serra da Mesa Group: As a potential correlative of the Araí Group, the Serra da Mesa Group is exposed in the internal zone of the Brasília Belt, bordered by the Neoproterozoic Mara Rosa Arc of the Goiás Magmatic Arc along the Rio dos Bois fault. It is strongly deformed and, metamorphosed, and intruded by granites and pegmatites. Folds are complex, tight and refolded, trending NNE. Metamorphism reached high-T amphibolite facies conditions. The base of the group is dominated by fine- to medium-grained quartzite, quartz schist, sillimanite-biotite-muscovite schist, frequently in tectonic contact with the underlying gneisses. Towards the top, muscovite-biotite schist is dominant, displaying quartzite, calc-silicate rocks and marble intercalations (Marques 2009).

MANTIQUEIRA PROVINCE

In the previous section during the discussion on the eastern margin of the São Francisco Craton, we have already considered the evolution of the northenmost part of the Mantiqueira

Province (Araçuaí belt). Here we review the central (Ribeira Belt) and southern part (Don Feliciano Belt) of the Mantiqueira Province, south of 23º S, on which a very diversified of publications is available.

Ribeira Belt

The Ribeira Belt, extending from north Rio de Janeiro to east Paraná, displays a very complex and distinct framework compared with the Araçuaí Belt. In its southern portion, two tectonic domains are recognized, separated by the Lancinha–Cubatão lineament. In the northern domain, the exposed Statherian lithostratigraphic records are very significant, preceding a long subsequent Mesoproterozoic volcano-sedimentary history (Fig. 7).

Apiaí Superterrane

The NE-trending Apiaí superterrane, exposed in the south-southwestern portion of the Ribeira belt, is limited by the Lancinha-Cubatão lineament to the southwest, by the Early Neoproterozoic Embu terrane to the southeast, covered by the Paraná Basin to the north-northwest, and by the Jundiuvira fault to north-northeast (Fig. 7). The Statherian rock record comprises metasedimentary and metavolcanic rocks of the São Roque Group basal formations. In the south, this age interval is recorded in orthogneiss cores tectonically underlying dominantly Mesoproterozoic metasedimentary and metavolcanic units.

São Roque domain

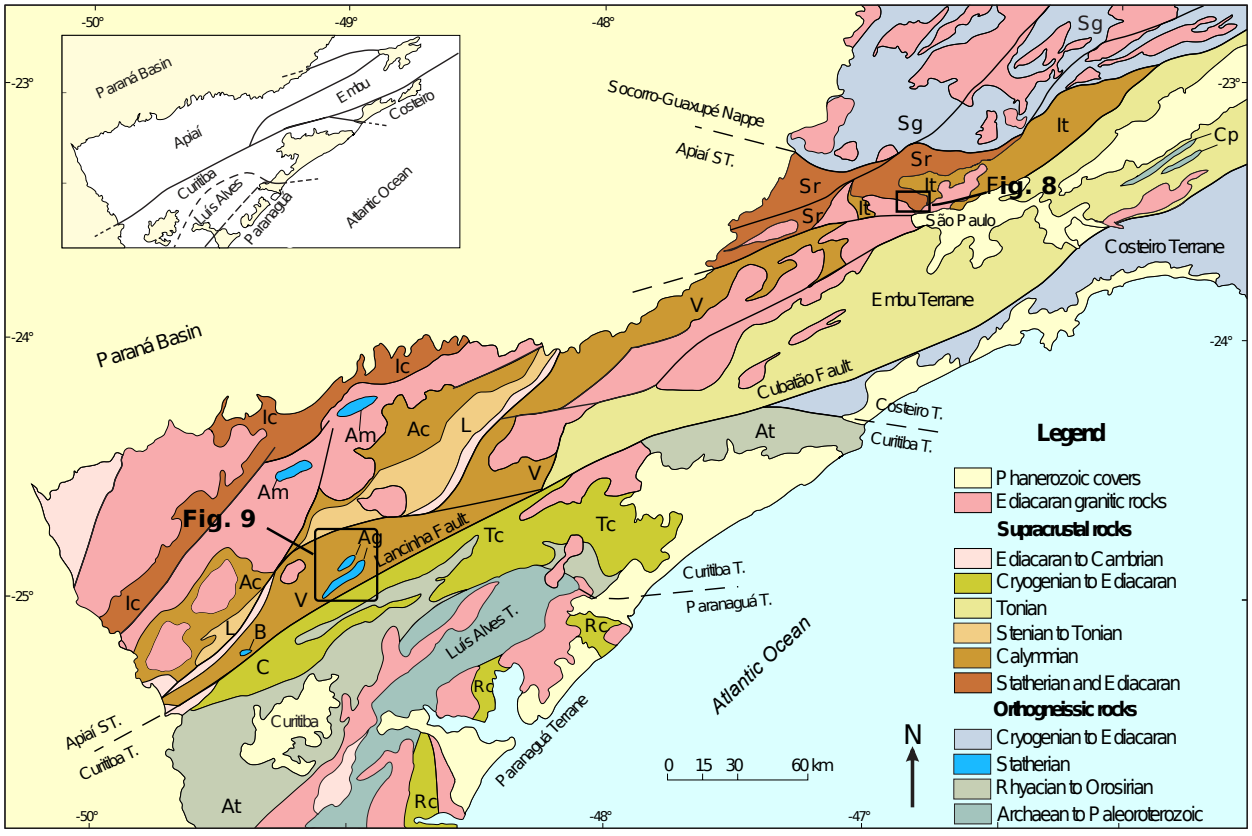
In the northern portion of the Apiaí superterrane, two volcanic-sedimentary units stand out: the Statherian São Roque Group and the Calymmian Serra de Itaberaba Group (Juliani *et al.* 2000).

The São Roque Group is limited by the Jundiuvira and Taxaquara faults to the north and south, respectively. It comprises varied, complexly deformed low-grade volcanic-sedimentary units, intruded by Neoproterozoic granites, and subdivided into three formations (Henrique-Pinto *et al.* 2015) (Figs. 7 and 8).

The basal Boturuna Formation includes metarkose with polymictic conglomerate, metaquartz-arenite and small metatrachidacite layers. Maximum depositional age was estimated at 1.7-1.8 Ga, the age of detrital zircon grains ranging between 3.4 and 1.7 Ga, with a main peak at 2.2 Ga (Henrique-Pinto *et al.* 2015). The Polvilho metatrachidacite was dated at 1760±17 Ma, deriving from parent melts of an unexposed Archaean to Paleoproterozoic crust in a within–plate setting, with lithogeochemical similarities to A-type granites (Van Schmus *et al.* 1986, Henrique-Pinto *et al.* 2018).

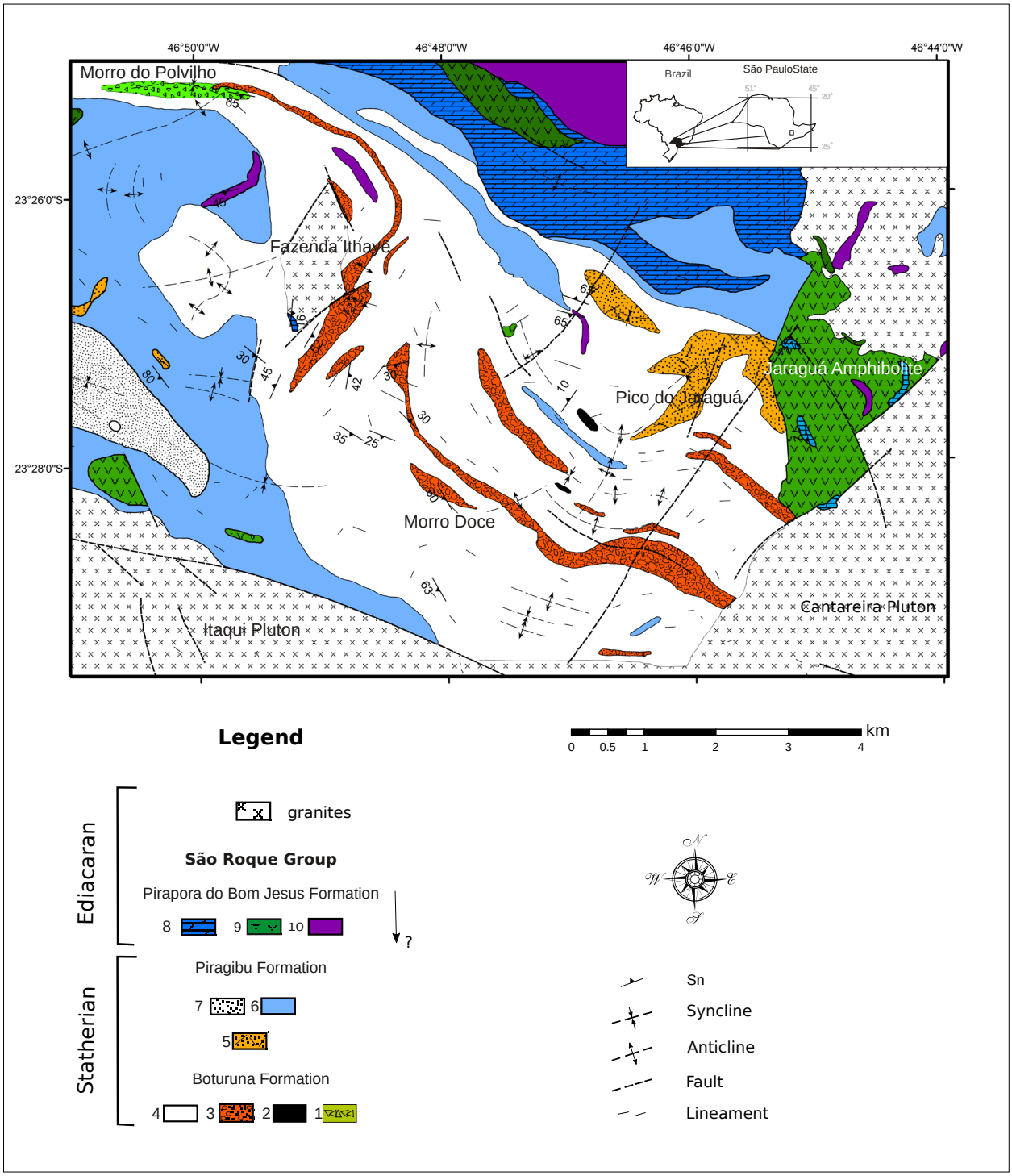
The middle Piragibu Formation is mainly comprised of rhythmic metaclaystone and intercalated metagraywacke interpreted as turbidite deposits; limited detrital zircon data suggest a pattern similar to the Boturuna Formation (Campanha *et al.* 2019).

On the other hand, the upper Pirapora do Bom Jesus Formation (Bergmann 1988) is composed of MORB-like



Source: modified from Campanha *et al.* (2015) and Faleiros *et al.* (2011). Sg: Socorro-Guaxupé nappe; *Apiaí superterrane: Sr:* São Roque Group; It: Serra de Itaberaba Group; Ic: Itaiacoca Group; V: Votuverava Group; Ac: Água Clara Formation; L: Lageado Group; Am: Apiaí Mirim complex; Ag: Anta Gorda (Tigre) core; B: Betara core; *Embu Terrane*: Cp: Rio Capivari Complex; *Curitiba Terrane*: C: Capiru Formation; Tc: Turvo-Cajati Formation; At: Atuba Complex; *Paranaguá Terrane:* Rc: Rio das Cobras Formation.

Figure 7. Main tectonostratigraphic terranes of the southern Ribeira Belt (central Mantiqueira Province).



Source: modified from Henrique-Pinto *et al.* (2018).

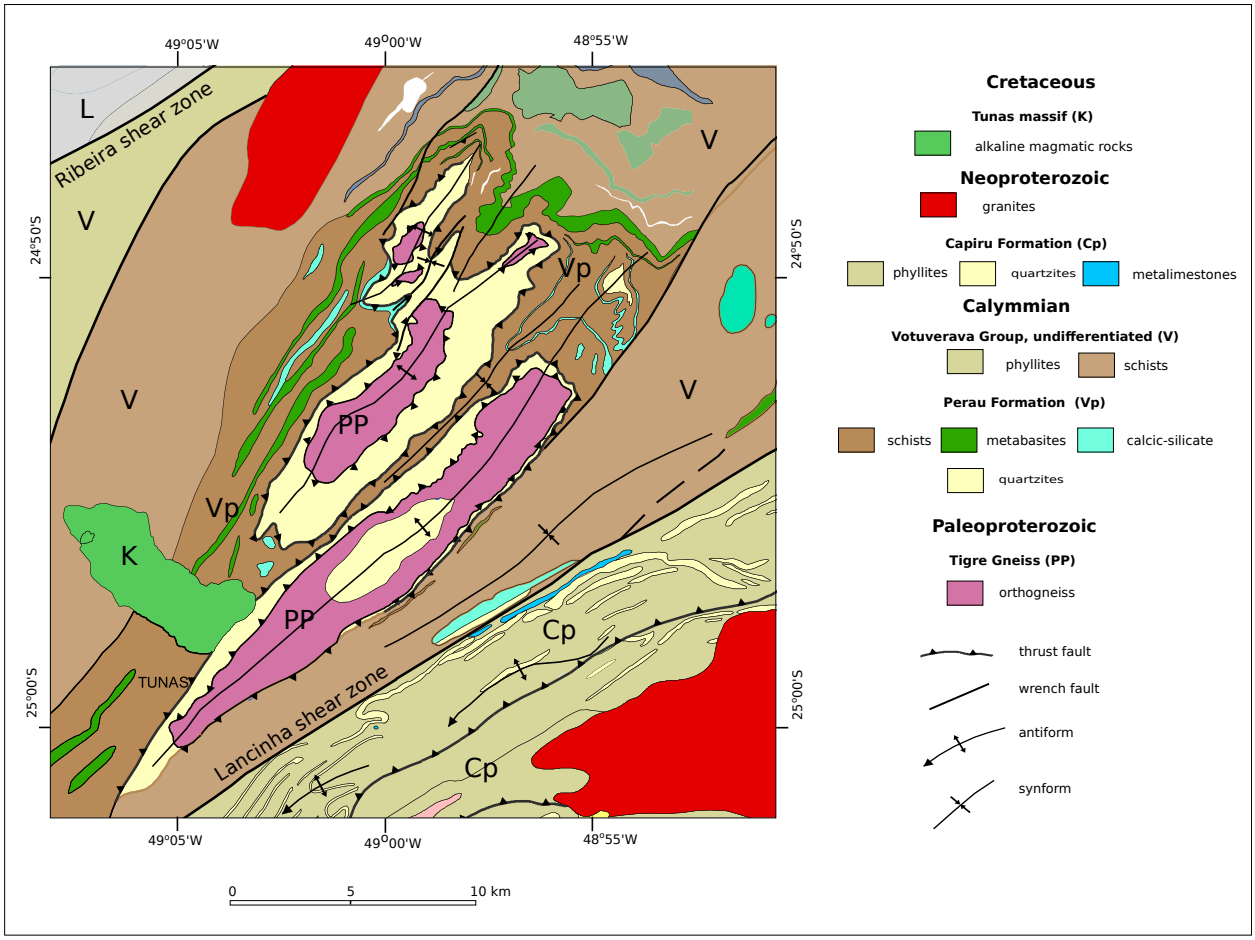
Figure 8. Geologic map of part of the São Roque Group: 1) acid metavolcanic rocks; 2) basic metavolcanic rocks; 3) metaconglomerate; 4) metarkose; 5) quartzite; 6) phyllite; 7) metasandstone; 8) metalimestone and calcic-silicate; 9) amphibolite; 10) schist.

tholeiitic pillow metabasalts associated with pyroclastic rocks, metaultrabasic rocks and metalimestones showing well-preserved stromatolite structures. It seems to represent a nappe brought up upon the lower units. Its age is not well defined, inconclusive data pointing either to Ediacaran or Statherian magmatism (Hackspacher *et al.* 2000, Oliveira *et al.* 2011).

Ortogneissic cores (subjacent to the Mesoproterozoic volcanic-sedimentary piles)

Several restricted Archean/Paleoproterozoic orthogneiss cores tectonically underlie piles of essentially Mesoproterozoic volcanic-sedimentary sequences formed in a marine environment, including backarc setting (Siga Jr. *et al.* 2011a, 2011b, Campanha *et al.* 2015). The "Betara", "Perau", "Tigre" and "Anta Gorda" cores occur within the Votuverava Group and cores of the Apiaí-Mirim Complex within the Água Clara Formation (Figs. 7 and 9).

The orthogneisses comprise mainly Archean and Paleoproterozoic granodiorite, coupled with subordinate Statherian (1800-1750 Ma) anorogenic A-type mylonitic metasyenogranite. The latter has been interpreted as related to extensional rift-like processes (Kaulfuss 2001, Cury



Source: modified from Caltabellotta *et al.* (2016).

Figure 9. Geologic map showing the Paleoproterozoic (Rhyacian to Statherian) orthogneiss cores from the Anta Gorda anticlinorium and surrounding units.

et al. 2002, Siga Jr. *et al.* 2011a, 2011b). The contacts with the overlying Mesoproterozoic supracrustals are marked by low-angle shear zones in a core complex-like geometry (Fig. 9).

Together, all these occurrences suggest an initial cratonic setting (eastern border of the Paranapanema craton?), affected by early Statherian taphrogenesis and associated igneous intrusions. This initial Statherian stage of intracontinental basins would be followed by Mesoproterozoic deposition of complex volcanic-sedimentary sequences (Calymmian to Ectasian), many of which showcharacteristics of oceanic affiliation.

This geological-geotectonic framework may be compared to the one exposed in southeast Minas Gerais, east of the São Francisco Craton, characterized by marginal inliers (Porteirinha, Guanhães and Gouveia, see above) of the Araçuaí system externides marked by anorogenic Statherian plutonism and volcanism (1.75 Ga). In general, the lithostructural, magmatic and geochronologic context observed in the basal formations of the São Roque Group is similar to those of the lower Espinhaço Supergroup, displaying metapsammite and minor felsic volcanic intercalations dated at 1.76 Ga. The Espinhaço Supergroup records initial felsic volcanism at ~1.75 Ga, an intermediary to upper post-Stenian portion (< 1.2 Ga), and a mafic dike swarm at 1.1-0.9 Ga (Chemale Jr. *et al.* 2012, Guadagnin and Chemale Jr. 2015, Henrique-Pinto *et al.* 2015).

Dom Feliciano Belt- General geological features

The southernmost portion of the Mantiqueira Province is represented by the Dom Feliciano Belt, exposed along 1,400 km of the South American coast, from the southeast of the Luís Alves Craton (ca. 26°30´S) to center-eastern Argentina (Hueck *et al.* 2018). The belt comprises a central zone of Neoproterozoic supracrustal rocks, the Brasiliano Pelotas-Aiguá magmatic arc granites as well as the Nico Perez and Punta Del Leste tectonostratigraphic terranes exposed to the west and southeast, respectively. Statherian events are recorded in the Paleoproterozoic basement inliers of the Dom Feliciano Belt as megaxenoliths within granites and especially in the western Nico Perez superterrane.

Statherian occurrences along the central Dom Feliciano belt

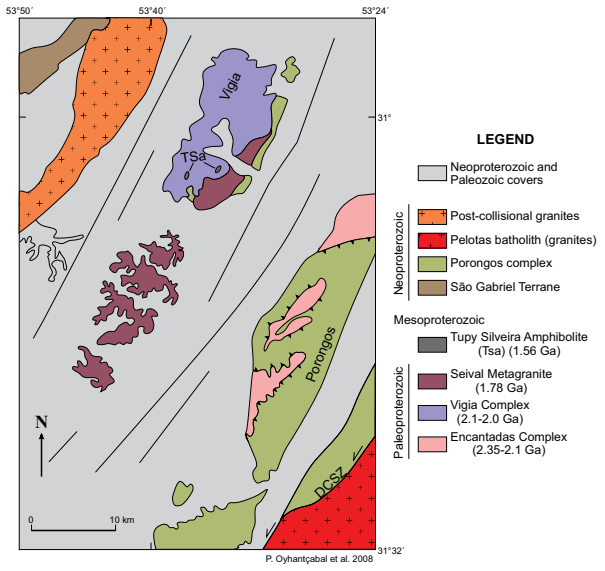
Along the central belt itself, there are two remarkable occurrences to be mentioned, the Capivarita metagabbro-anorthosite and the Seival orthogneiss.

- The Capivarita metagabbro-anorthosite is exposed in two large megaxenoliths/roof pendants within the Pelotas-Aiguá batholith (one trending N-S, the other E-W), ca. 118 km WSW of Porto Alegre (along the BR-290 highway, approximately 52°30´W; Oyhantçabal *et al.* 2018a). Westward, they are limited by the Passo do Marinheiro

shear zone. Anorthosite is the main rock, with some gabbro and Fe-Ti oxide layers. It is a light grey, medium- to coarse-grained homogeneous rock, with rather well-preserved igneous layering (Oyhantçabal *et al*. 2018a). Zircon U-Pb and Lu-Hf isotopic data (Chemale Jr. *et al*. 2011) yielded inherited Orosirian detrital grains, igneous grains dated at 1573 ± 21Ma and metamorphic titanite ages around 500 Ma. The age data record a history of Statherian to Calymmian igneous intrusion affected by Brasiliano granite magmatism and regional metamorphism. It should be noted that the age of the gabbro-anorthosite is near contemporary to the Tandilia dike swarm, underlining the Statherian events within the Rio de la Plata Craton and in the basement of the neighbouring Dom Feliciano Belt;

- Seival Orthogneiss: The 35 km long, irregular, sub-elliptic Seival Orthogneiss intruded the Vigia Complex gneiss dome of trondhjemite, tonalite and granodiorite of probable Rhyacian age (Fig. 10), overprinted by Brasiliano metamorphism. The dome is exposed as a *basement inlier* within the Tijucas Belt metasedimentary rocks in south center Rio Grande do Sul (Oyhantçabal *et al*. 2018a).

The Seival rocks comprise mainly pink leucogranites and subordinate granodiorite, frequently isotropic. Discriminant geochemistry diagrams point to a post-collisional setting. U-Pb zircon determinations yielded ages between 1785 and 1763 Ma, generally with small uncertainties. The Seival intrusion into the basement indicates that the Statherian extension event is an important feature both in the Rio de La Plata Craton and in the pre-Rhyacian inliers of the Dom Feliciano Belt. This is also recorded in the central (Ribeira) and north central (Araçuaí basement) portions of the Mantiqueira Province, regardless of the geotectonic framework imposed by later Mesoproterozoic (Rodinia) and Neoproterozoic (Gondwana) configurations.



Source: Oyhantçabal *et al.* (2018b).

Figure 10. Dom Feliciano belt showing pre-Brasiliano basement (basement inlier of the "Vigia" dome) intruded by the Statherian Seival granite (Brasiliano orthogneiss).

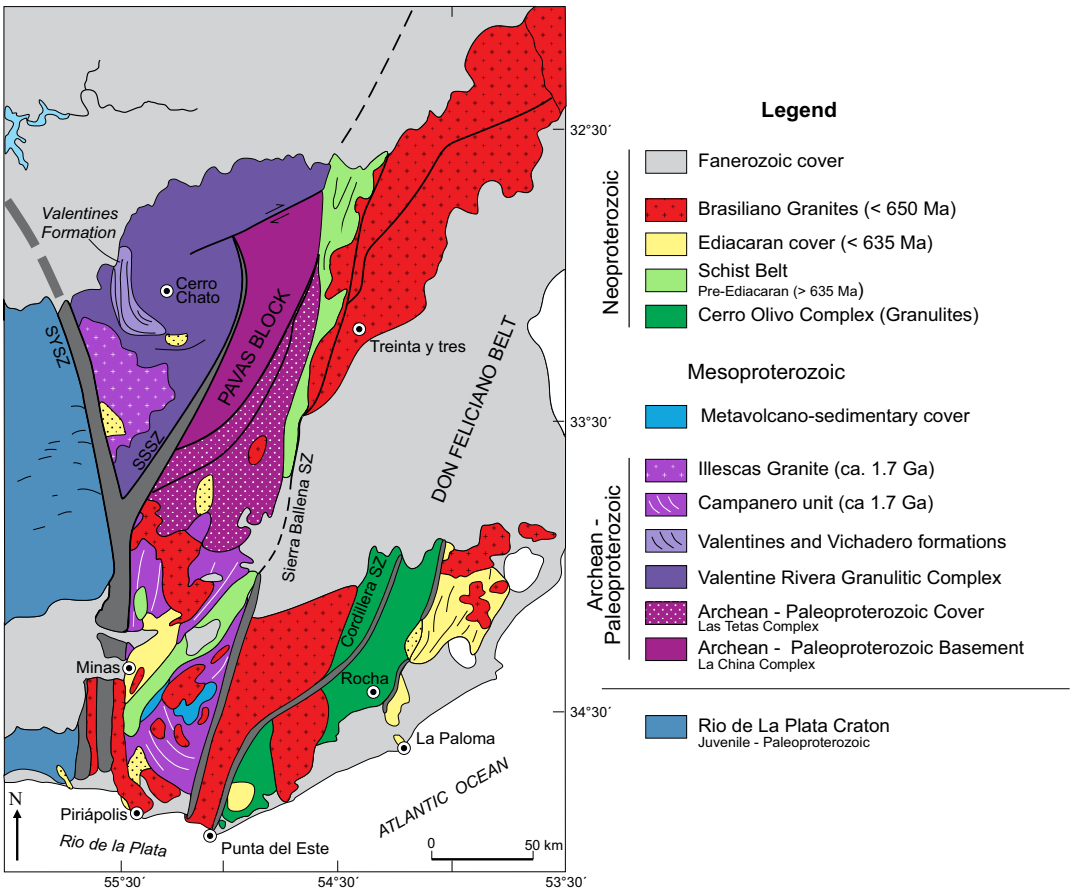
Nico Pérez Superterrane

The Nico Pérez superterrane is an important basement inlier of the Dom Feliciano belt, positioned in the southwestern portion of the belt by the Caçapava shear zone (NNE strike, ca. 600 km long), and separated from the Rio de La Plata Craton by the Sarandi del Yi shear zone (NNW strike) (Fig. 11). Aside from the main Nico Pérez block, east of the Sarandi del Yi shear zone (Oyhantçabal *et al.* 2018b), other terranes part of this basement inlier have been recognized, such as the Rivera island (surrounded by Gondwanic sediments) at the Brazil-Uruguay border, and the Taquarembó block, in southern Brazil, working out as the foreland for the Tonian São Gabriel magmatic arc. The main occurrences of Statherian rock units are exposed in the main part of the superterrane, between the Sarandi del Yi and Sierra Balena shear zones, in the Cerro Chato (Illesca rapakivi granite) and Pavas blocks (Campanero unit).

- Illesca Rapakivi granite: The Statherian Illesca pluton is located in the southwestern Cerro Chato terrane (Fig. 11), truncated westward by the Sarandi del Yi lineament, which makes up the western limit of the Nico Perez superterrane. The batholith displays an irregular triangular form underlying an area of 750 km^2 and intruding the pre-Rhyacian rocks of the Valentines Complex. The intrusion is partially covered by the Neoproterozoic Arroyo del Soldado Group.The pluton comprises granite, quartz syenite and granophyre, with typical rapakivi texture, such as wiborgite and piterlite (Gaucher and Blanco 2014). Southwards, the rocks present fine-grained subvolcanic textures. Isotopic Rb-Sr (1780 ± 30 Ma) and U-Pb zircon (1784 ± 5 Ma) determinations ratify the lower Statherian age. Such as the case in Florida, the intrusion records an extension event preserved from the rather strong Brasiliano deformation in the domains adjacent to the craton;
- Campanero Orthogneiss: The Campanero Orthogneiss is located south of the Pavas block, between Minas and Punta del Este, underlying an approximately rectangular area of about 4,600 km^2, bounded by the the Sarandi del Yi and Sierra Balena lineaments (Oyhantçabal *et al.* 2018b). It is a pre-Brasilliano granite batholith, which in contrast to the Illesca rapakivi granite, underwent strong Brasilliano deformation, confirmed by radiometric ages around 620 Ma. It intruded the basement Valentines and Vichadero complexes of Paleoproterozoic or older age of the Nico Perez superterrane, and was later intruded by the Carapé Granite. The Campanero Orthogneiss comprises slightly peraluminous, high-K calc-alkaline felsic rocks, including some supracrustal remnants (amphibolite, micaschist, BIF). The texture varies from medium-grained to mylonitic. U-Pb discordia zircon ages range from 1735 to 1754 Ma (Sanchez-Bettucci *et al.* 2004), suggesting temporal correlation with the Illesca intrusion and association to intraplate extension.

RIO DE LA PLATA CRATON

The Statherian taphrogenesis is very well represented in the two main shield areas of the Rio de La Plata craton:



Source: Oyhantçabal *et al.* (2018b).

Figure 11. Nico Pérez superterrane to the east of the Sarandi del Yi shear zone, which separates it from the Rio de la Plata Craton. Two terranes are identified in this important inlier, both of them recording Statherian plutonism: The Illesca rapakivi granite (in the Cerro Chato terrane) and the Campanero orthogneiss (in the Pavas Terrane).

"Piedras Altas" (Uruguay) and "Tandilia" (south of Buenos Aires, Argentina) (Fig. 12).

Florida Dike Swarm

The Florida dike swarm cuts through the main exposed area (ca. 8,000 km^2) of the Rhyacian "Piedras Altas terrane", the main shield area of the Rio de La Plata Craton, central-southwest Uruguay. The ENE-WSW-trending dikes are limited to the east by the dextral Sarandi del Yi lineament, and extend WSW for more than 200 km, to Colonia. Individual dikes may reach up to 50 km long and 50 m thick (Fig. 12).

The dikes are mainly made up of tholeiitic basalt and andesite of high and low TiO_2, respectively. The dykes are enriched in LILE and LREE and display negative E_{Nd} and positive E_{Sr} values, suggesting a metasomatised mantle source. Baddeleyte U-Pb data yielded an age of 1790 ± 5 Ma (Teixeira *et al.* 2013).

Tandilia Dike Swarm

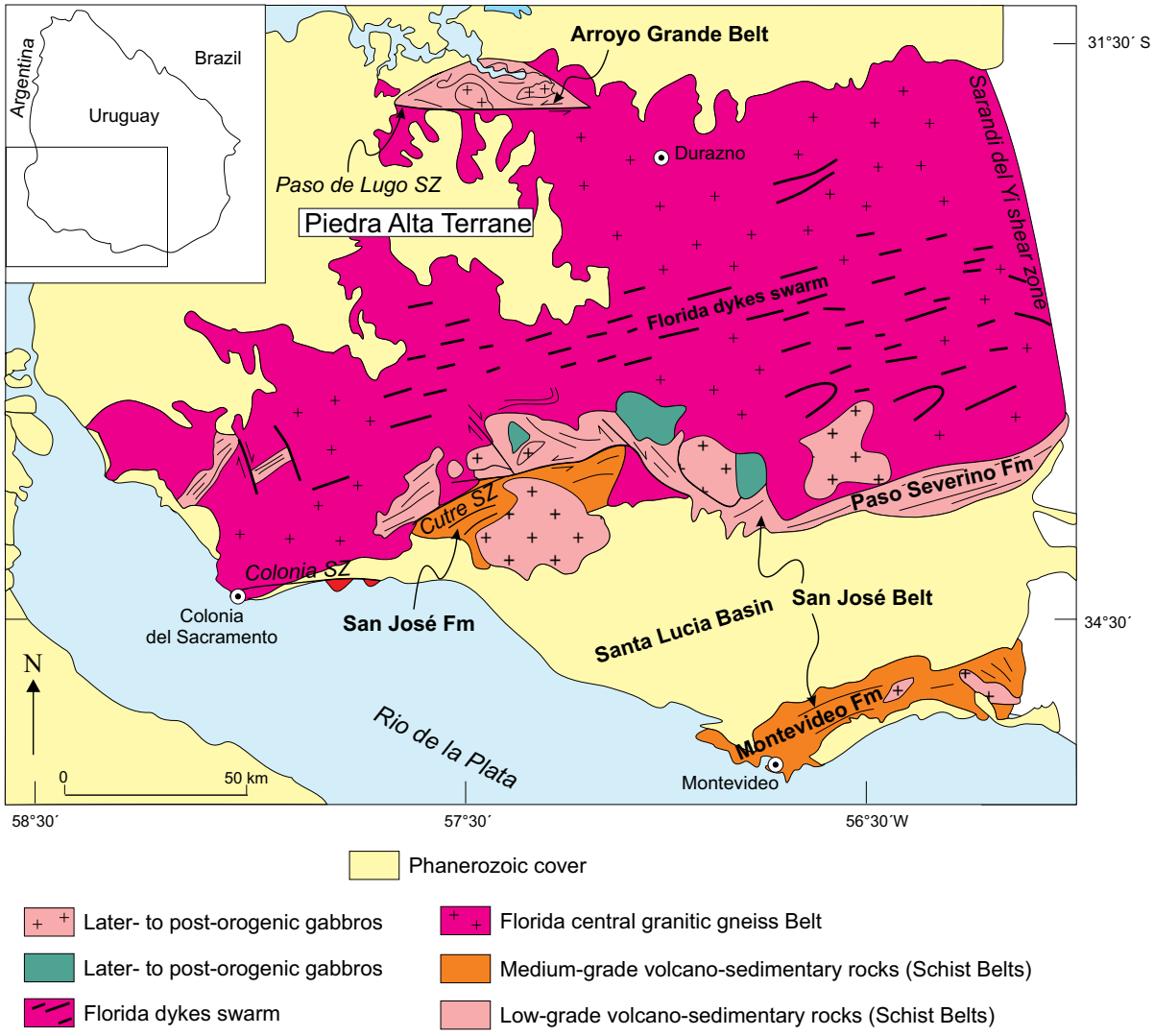
A small fraction of the Rio de La Plata Craton is located about 200 km south of Buenos Aires in a semi-circular area of about 9,000 km^2, between the sedimentary basins of Salado and Claramecó, where the pre-Orosirian Buenos Aires Complex basement rocks are partially exposed.

Two dike generations occur in Tandilia. E-W-trending calk-alkaline dikes were dated at ca. 2,000 Ma by the Ar-Ar method. The NW-trending swarm, known as Tandilia, comprises up to 50 m thick and tens of kilometers long dikes, occasionally covered by Phanerozoic deposits. According to Iacumin *et al.* (2001), they are high- and low-TiO_2 tholeiitic basalts and andesite-basalts, bearing ophitic texture with augite overgrown by hornblende, and some olivine. Magnetite and ilmenite are accessory minerals, coupled with apatite and epidote. Crystalization temperatures were estimated between 1,130 and 1,205°C.

U-Pb isotopic determinations on badelleyte point to age of 1583 ± 11 Ma, close to the Statherian-Calymmian boundary and ca. 400 My younger than the E-W-trending dikes, thus suggesting a new extensional period for the craton. This Calymmian phase/age is also pointed out in the Capivarita gabbro-anorthosite exposed as mega-xenolith in the adjacent eastern Dom Feliciano Belt.

BORBOREMA PROVINCE

The Borborema Province ocupies the northeastern portion of the South American continent. Developed at the end of the Neoproterozoic, the province underlies an area of ca. 450,000 km^2, which is marked by the alternating fold belts and basement inliers, rendering a mosaic-like folded region (Brito Neves 2020 and references therein). Transcontinental



Source: Oyhantçabal *et al.* (2018a).

Figure 12. Rio de La Plata Craton, Uruguay, to the west of the Sarandi del Yi shear zone, showing the Statherian Florida dike Swarm crosscutting the Piedras Altas terrane, shield domain of the craton.

lineaments like the Transbrasiliano (LTB), Patos (Pt) and Pernambuco (Pe) and several others in between, in part even linked to them, allow for dividing the province into four subprovinces: Médio Coreaú (NW of LTB), northern (between LTB ant Pt), Transversal Zone (between Pt and Pe) and southern (between Pe and and the northern border of the São Francisco Craton). There are exposures of typical Statherian lithostratigraphic units in all subprovinces, all reworked during the Brasiliano tectonic events, occasionally hindering their proper discrimination.

Médio Coreaú subprovince

In the smallest of the subprovinces, largely covered by the Phanerozoic Parnaíba Basin and recent coastal deposits, there is a ca. 30 km^2 occurrence of volcanic rocks exposed at the contact of the basal Caiçaras Formation and the Trapiá-Frecheirinha Formation of the QPC-type Ubajara Group. Labeled as "Saquinho" (Sq, Fig. 13), the sequence comprises trachyandesite, rhyodacite, rhyolite, tuff and volcanic breccia. Zircon U-Pb age of the rhyolite is 1785 ± 2 Ma (Santos *et al.* 2011).

Northern subprovince

The northern subprovince underlies large parts of Central-East Ceará and Central-West Rio Grande do Norte, comprising a large variety of Statherian sedimentary, volcanic and plutonic units, strongly deformed in the late Neoproterozoic. There is evidence that large parts of the supracrustal units were removed by erosion along the Mesoproterozoic and in the Cenozoic. The main preserved exposures are found between the Jaguaribe and Portalegre shear zones, in Central-East Ceará. They are divided into the Jaguaribe, Orós and Peixe Gordo belts in Ceará (Jaguaribe River basin) and the São José or Encanto belt in western Rio Grande do Norte.

Médio Jaguaribe Domain (Estern Ceará State)

The lithostratigraphic sequence displays lithological and tectonic similarities in the westernmost Orós (about 310 km long, trending E-W to N-S), Jaguaribe (ca. 40 km, trending N-S) and Peixe Gordo (15x10 km, trending NW-SE) belts in Ceará, the latter partially covered by Cretaceous deposits, and the Encanto Belt (43x20 km, trending N-NE) in Rio Grande do Norte (Cavalcanti 1999, Sá 1991), comprising:

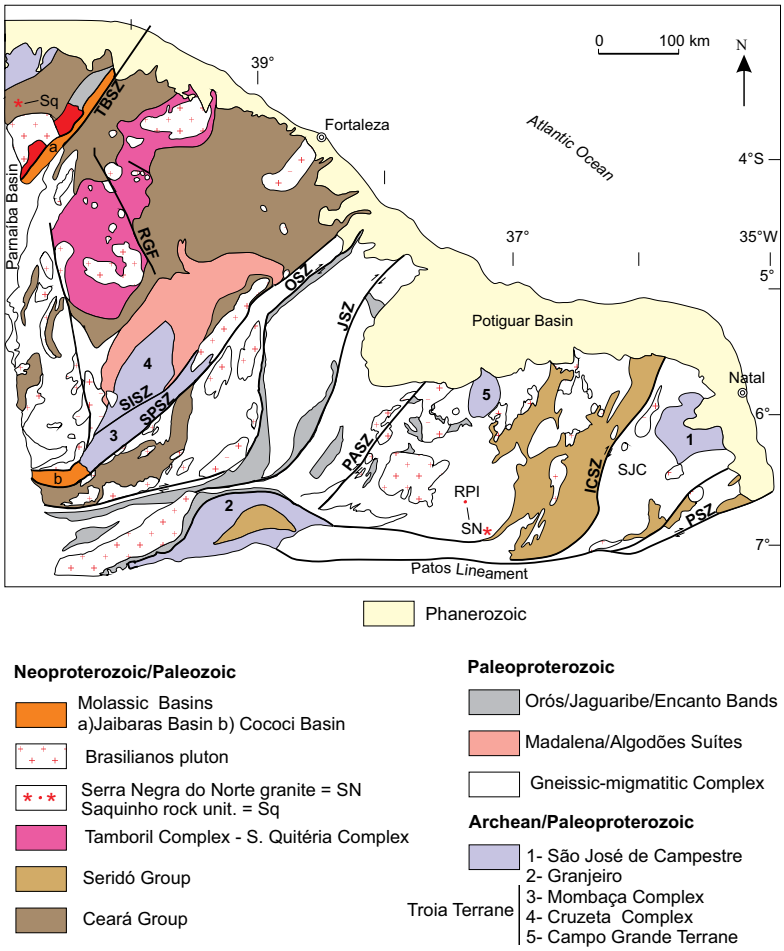


Figure 13. Northern part of the Brasiliano Borborema Province, northeast of Brazil, showing the northwestern Médio Coreaú and the northern subprovince, and exhibiting the classical style of alternating Proterozoic fold belts and basement inliers. The Statherian granites and some local volcanics are present in some of the fold belts. See legend.

- Basal metavolcanic and metaclastic rocks (Campo Alegre Formation);
- Carbonate layers (limestone, magnesite), with eventual metavolcanic flows and tuff intercalations (Santarém Formation).

In the small Encanto area, metapelites dominate, including quartzite and amphibolite layers.

Geochronological determinations carried out on volcanic rock samples indicate lower Statherian ages (1.8-1.7 Ga, Cavalcanti 1999), whereas general deformation and the varied granitoid intrusions, many transformed into augen gneiss, are related to the Neoproterozoic Brasiliano Orogeny.

Taking the Meso-Cenozoic deposits covering the Peixe Gordo and Encanto units into account, it is clearly evidenced that the original Statherian "basins" were much larger in the past. It should also be noted that other strongly deformed and metamorphosed supracrustal belts in the subprovince could represent former Statherian units.

Serra do Deserto granitic suite

Several narrow strips of augen gneiss are exposed along the N-NE Orós, Icó, Jaguaribe, Encanto/São José, Portalegre and other strike-slip faults, between 6º and 7º S, close to the Ceará-Rio Grande do Norte border. They are composed of granite, granodiorite and rarely syenite, displaying typical cm-sized feldspar porphyroclasts. Referred to as Serra do Deserto suite (Cavalcanti 1999), they were dated around 1763-1764 Ma, indicating an important taphrogenic and magmatic event, coupled with sedimentary basins formation.

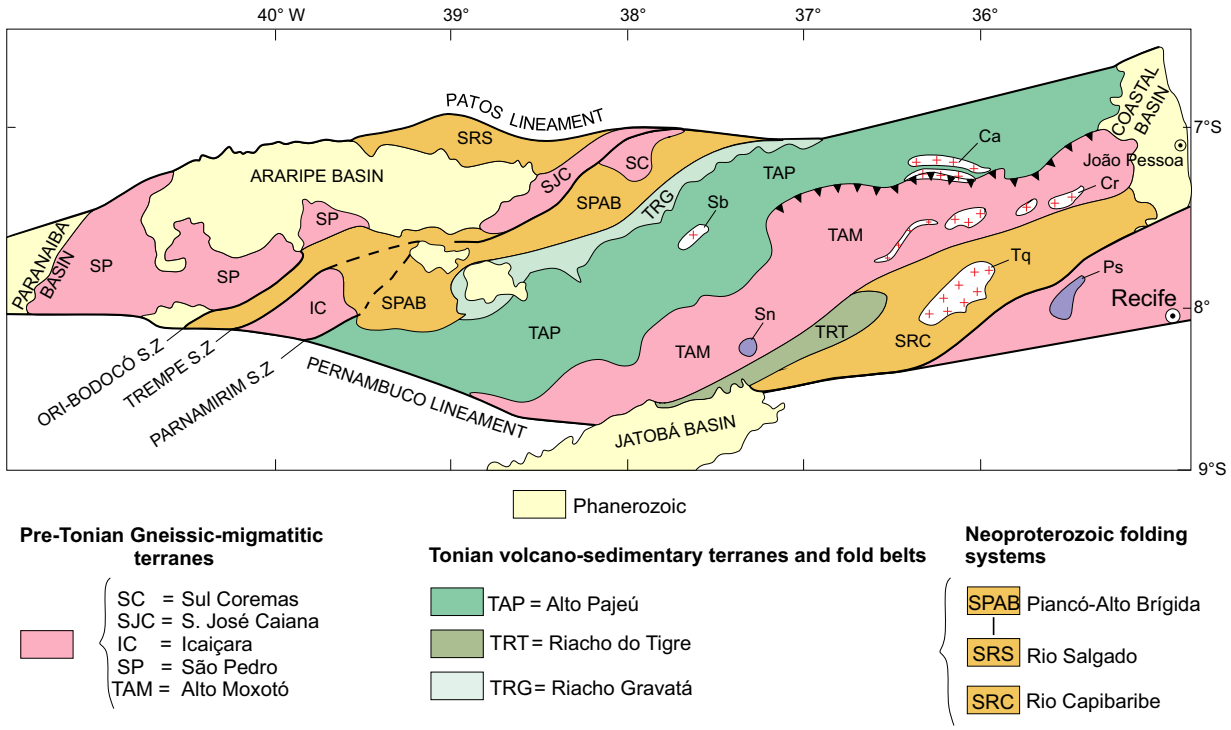
Serra Negra do Norte granite

In western Rio Grande do Norte, between the Jaguaribe and Portalegre shear zones, the "Rio Piranhas massif" is one of the richest regions of the Borborema Province in granite intrusions. The region's basement is mostly represented by the Rhyacian Caicó Complex, with Archean T_{DM} ages and some local Archean nuclei.

A single alkaline granite stock, the Serra Negra do Norte Granite, is exposed in the southeast portion of this "massif", and was dated at 1.76 Ga (Hollanda *et al.* 2011). This small intrusion (ca. 50 km^2), trending N-NE, comprises mostly I-type metaluminous syenogranite, with monzogranite and syenogranite enclaves, septs and dikes (Campos *et al.* 2000), and displays some brittle-ductile structures related to the Patos Lineament exposed a few kilometers to the south.

Central or Transversal Zone subprovince

The Transversal Zone of the Borborema Province (Fig. 14) has been the focus of many studies (e.g. Santos *et al.* 2010,



Source: (Lages *et al.* (2019) and Brito Neves (2020).

Figure 14. Transversal Zone subprovince, between the Patos (to the north) and Pernambuco (to the south) lineaments. The Statherian is recorded in small anorogenic granite and gabbro-anorthosite intrusions. All of them are somewhat reworked by the Brasiliano tectonics.

Van Schmus *et al.* 2011). In this subprovince, Neoproterozoic Tonian and Cryogenian-Ediacaran fold belts are branched by pre-Statherian basement inliers, mainly of Rhyacian and Orosirian ages, and some of Archean ages. There are several Statherian granites and gabbro-anorthosite intrusions inside these inliers, as well as into the fold belts basement, suggesting Statherian taphrogenesis within the subprovince.

Gabbro-anorthosite stocks

The Passira meta-anorthosite complex, intruded into the Paleoproterozoic basement of the Rio Capibaribe terrane, is exposed about 80 km NW of Recife (Ps, Fig. 14). It displays a nearly 170 km^2 irregular triangle form, comprising meta-anorthosite alternating with SE-dipping tabular metagabbro, noritic metagabbro and Fe-Ti-rich ultramafic lenses (Accioly 2000). A series of P-rich Fe-diorite dikes is also present. Isotopic age determinations yielded a Statherian U-Pb age of 1770 ± 2 Ma and a T_{DM} age of 2.4 Ga. The rocks underwent high-grade metamorphism up to the granulite facies, superimposed by low-grade partial recrystallization at 612 ± 100 Ma. Geochemical and petrogenetic data suggest an anorogenic setting, possibly related to underplating (Accioly 2000).

The Sítio Piranhas meta-anorthosite (Accioly *et al.* 2011) forms ill-exposed bands intruded into the basement of the Alto Moxotó terrane, in central-southeast Pernambuco, west of Sertânia. Aside from the anorthosite, it is also composed of hornblende norite, hornblende gabbro, olivine magnetitite, leucogabbro and monzodiorite enriched in zircon and apatite. These rocks underwent granulite facies metamorphism and were retrograded along the late Brasiliano Congo-Cruzeiro do Nordeste shear zone. Although there are no original ages available, similarities to the Passira intrusion suggest a Statherian age, which is still an open question.

Anorogenic granites

There is a large concentration of granites in the Transversal Zone, associated to Brasiliano magmatic arcs and/or shear zones. However, due to typology characteristics and geochronological data, a few of these intrusions are related to Statherian events, even though they were affected by Brasiliano thermo-tectonic overprinting. There is a clear possibility that the small number may be increased by studies in progress.

- The Taquaritinga do Norte intrusion (Tq, Fig. 14) underlies the homonymous range, about 100 km WNW of Recife and 15 km SW of the Passira anorthosite complex. It is an NE-trending, 70 km long and 20 km wide, irregular body intruding the Paleoproterozoic basement of the Rio Capibaribe terrane (Sá *et al.* 2002), and cut across by the Brasiliano Fazenda Nova and Toritama granites. It comprises syenogranite and monzogranite turned into facoidal gneiss during the Brasiliano Orogeny, bearing characteristic large microcline porphyroblasts and south-dipping sub horizontal foliation. Biotite and hastingsite are the mafic minerals present, apatite, garnet and zircon are accessory minerals. U-Pb zircon data yielded an age of 1521 ± 7 Ma (Sá *et al.* 2002). Some additional structural and geochronological data suggest discrete superposition of the Cariris Velhos event and strong reworking during the Brasiliano Orogeny. The Calymmian age is considered preliminarly to be related to the final events of the Statherian taphrogenesis. Smaller

intrusions are recognized between 36º and 36º30'S, SSW of Campina Grande, Paraíba (Lages *et al*. 2019);

- The "Carnoió"-type stocks (Cr, Fig. 14) intruded Rhyacian gneisses and migmatites of the Alto Moxotó terrane eastern portion. They are now NE-trending orthogneiss of monzogranite, syenogranite, alkali granite and quartz syenite compositions. They are mostly granoblastic, locally porphyroblastic, strongly foliated rocks, with hastingsite and occasionally biotite. U-Pb zircon age determinations point to 1638 ± 13 Ma, with the lower intercept indicating Brasiliano reworking and metamorphic recrystallization (Lages *et al*. 2019). T_{DM} ages are Neoarchean. Geochemical data underline intraplate A-type intrusion features;
- The "Caloete"-type intrusions (Ca, Fig. 14) are exposed close to Boa Vista, at the northern border of the Alto Moxotó terrane with the Tonian Alto Pajeú terrane. They are strongly foliated along the E-W direction due to the Patos Lineament, comprising mylonitic leucogranite and mesocratic banded biotite-muscovite gneiss of peraluminous granite-granodiorite composition (Lages *et al*. 2019). U-P zircon data yielded a concordant age of 1652 ± 19 Ma;
- The Serra da Barra intrusion is exposed in the Sucuru River valley, close to Sumé (Santos 2012; Sb, Fig. 14). It comprises alkali-feldspar granite and syenogranite, with geochemical signature of metaluminous intraplate A-type intrusion (Santos 2012) within the Alto Moxotó terrane Paleoproterozoic basement. The U-P zircon age is 1645 ± 20 Ma, with 2.6-30 Ga T_{DM} ages and E_{Nd} between -7 and -10, suggesting a crustal source.

Southern subprovince

So far there is no confirmed Statherian record in the southern subprovince, either in the basement of the Sergipano, Riacho do Pontal and Rio Preto fold belts, or in the large (> 40,000 km²) reworked northern basement of the São Francisco Craton.

However, there are some candidate rocks with similar features to the Statherian record within the craton and in other Brasiliano provinces:

- The psamitic cover (Itabaiana quartzite) of the Itabaiana dome in the Sergipano Belt, which has been compared by some authors to the Tombador Formation, Chapada Diamantina Group;
- Quartzite, psammo-pelitic and volcanic rocks of the Serra do Garapa, SW of São Raimundo Nonato, Piauí, which are the likely northern continuation of the Espinhaço exposures along the Serra do Boqueirão, Bahia.

These records require additional geological and geochronological investigations in order to confirm their geological setting and age.

CONCLUDING REMARKS

- Important disruptive tectonic and associated magmatic phenomena characterize the South American platform during the Statherian. These taphrogenic and magmatic processes are recorded in all cratons and in their previous original areas, as well as in all Brasiliano mobile belts, some of which took place as basin forming tectonics for the sedimentary deposits later on converted into folded belts;
- The associated magmatism is almost always of bimodal character, its geochemical signature indicating within-plate setting;
- Equivalent phenomena are recorded in Africa and India as well as in Laurentia and Baltica, although not showing the extent, frequency and distribution recorded in South America;
- Characteristically, the taphrogenic and magmatic events took place within Orosirian or Rhyacian basement, in which tectonic-magmatic main events ceased just before the Late Statherian, in some cases extending to the Calymmian;
- Evidence and tectonic inheritance of the Statherian events may be different in other structural provinces. However, in general, tectonic rupture and anorogenic granitic and/or mafic magmatism are characteristic features. Dike swarms are common within cratons;
- In South America as a whole, in several instances, these events and processes were succeeded by plate interaction in the Calymmian, such as the case of the Mantiqueira Province. Therefore, there are dissensions among structural provinces in terms of nature, time span, extent and history of the Statherian tectonic and magmatic activity;
- There are excellent examples of Statherian anorogenic basins in the Borborema Province, such as the ones in Ceará and Rio Grande do Norte, which were later on (after ca. 1000 Ma), turned into Brasiliano fold belts. Despite the Neoproterozoic metamorphism, the original Statherian ages of intra-continental volcanism are largely preserved;
- After the tectono-magmatic activity, there were periods of local stable cratonic conditions until the beginning of the Neoproterozoic. In Ceará, within the Borborema Province, there was stability for around 1 Gy, favoring the "boring billion years" nickname occasionally applied to the Mesoproterozoic;
- In the Ribeira Belt, Central Mantiqueira Province, Statherian units may be considered to be related to the reworked border of a cratonic nucleus (Paranapanema?) that evolved to a continental margin adjacent to an oceanic realm in the Mesoproterozoic. The exposed sequences suggest an initial cratonic setting, affected by early Statherian taphrogenesis, associated to igneous intrusions and deposition of sedimentary sequences. The taphrogenic events were then followed by Calymmian to Stenian passive margin deposits and complex marine volcanic-sedimentary sequences, which were later strongly deformed during the Brasiliano Orogeny due to tectonic interaction of the Paranapanema Craton and Embu terrane;
- The São Francisco craton, as well as marginal basement inliers within surrounding fold-and-thrust belts are evidenced by Statherian anorogenic plutonism and volcanism and by the Statherian to Calymmian-Stenian basin evolution of the Espinhaço Supergroup and correlated units;
- There are geological-geotectonic framework and age similarities between the basal units of the Apiaí superterrane and

the lower Espinhaço Supergroup. However, Mesoproterozoic evolution of the Apiaí superterrane also includes plate margin settings, in contrast to the continental character of the Espinhaço Supergroup stratigraphic column, usually interpreted as deposited in a rift-sag basin;

- Several Statherian dike swarms in the Amazonian (Avanavero) and São Francisco (Pará de Minas, Januária) cratons have been suggested as representing LIPs, a classification that is yet to be ratified by additional geological and geophysical investigation;
- The Statherian tectonic-magmatic events provided valuable mineral resources in Bahia (Pb, Pb-Zn, Sn, semiprecious stones, diamond) and Goiás (Sn, In). There is still much to explore, since there is interesting record of diamonds in some detrital units;
- It should be noted that not all Statherian records have been duly investigated and explored, lacking larger scale geological investigation and age determinations;
- The general features of the South American Statherian record, as well as of its counterparts in Africa, India, Laurentia and Baltica, indicate global processes, possibly associated to mantle evolution. Therefore, highlighting Brazilian or South American events alone is extremely restrictive and much less than daring.

ACKNOWLEDGEMENTS

The authors would like to thank CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for research fellowships, FAPESP (Fundação de Amparo à Pesquisa do Estado de S. Paulo) and CNPq-CAPES-FAPDF grant to INCT Estudos Tectônicos for continuous support of this research, including field and laboratory work. Especially we would like to thank CNPq grants 301065/2016-0 (RAF) and 305701/2019-3 (GACC). Authors are also most grateful to anonymous reviewers and BJG Editors for very helpful comments and suggestions that greatly improved the manuscript.

ARTICLE INFORMATION
Manuscript ID: 20210053. Received on: 07/06/2021. Approved on: 10/30/2021.
B.B.B.N. wrote the first draft of the paper and he was responsible for the Borborema, São Francisco and Amazonian structural provinces. R.A.F. was responsible for the Central Brazil structural provinces and he gave strong contribution to the final manuscript. G.A.C.C. was responsible for the structural provinces of the southeast region and gave important contribution to the figures and tables.
Competing interests: The authors declare no competing interests.

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