An Acad Bras Cienc (2021) 93(1): e20190791 DOI 10.1590/0001-3765202120190791
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

GEOSCIENCES

Aeromagnetometry and aerogammaspectrometry integrated with U-Pb zircon geochronology of northern Bossoroca ophiolite, Brasiliano Orogen

LÉO A. HARTMANN, AMANDA J. MASSUDA, TIARA CERVA-ALVES, CRISTIANO LANA, CAROLINA G. LEANDRO & JAIRO F. SAVIAN

Abstract: Age delimitation integrated with aeromagnetometric and aerogammaspectrometric survey advances the understanding of ophiolite evolution in the Brasiliano Orogen. We focused on the Bossoroca ophiolite, because oceanic crustal and mantle rocks contain zircon in metasomatic chloritite. A metadiorite and a metavolcanoclastic rock were also studied to delimit relationship between ophiolite and island-arc infrastructure and superstructure. Zircon crystals were dated by laser ablation inductively coupled plasma emission spectroscopy. Ages of zircon from Campestre metavolcanoclastic rock are 920-840 (peak 842) Ma, Bossoroca chloritite 900-800 (peak 868 Ma) and Capivaras metadiorite 698 Ma. Ages 920-800 Ma correspond to processes in the oceanic crust, whereas 698 Ma was a late magmatic intrusion (Capivaras metadiorite) into the island-arc infrastructure. Aeromagnetometric and aerogammaspectrometric data delimit the occurrence and structure of the ophiolite. These are major multiproxy markers of geotectonic processes early in the Brasiliano Orogen.

Key words: Bossoroca ophiolite, Brasiliano Orogen, U-Pb zircon geochronology, aerogeophysics.

INTRODUCTION

Integrated retrieval of U-Pb ages of zircon and aeromagnetometric and aerogammaspectrometric description of ophiolites establish fundamental parameters in the evolution of oceanic crust and mantle within host infrastructure of island arcs (Blakely 1995, Dickson & Scott 1997). Uncoding the time capsule is commonly made from associated rocks that contain zircon, such as plagiogranite and gabbro (e.g. Samson et al. 2004, Queiroga et al. 2007, Dilek & Thy 2006, Karaoglan et al. 2013). Host granitic rocks are regularly dated with use of zircon. But direct dating of zircon formation and alteration in the oceanic crust and mantle is a large step toward elucidation of processes in the oceanic realm and later accretion to the island arc (e.g. Arena et al. 2016, 2017, 2018). This dating can be done on zircon formed during serpentinization of harzburgite either in the mid-ocean ridge or above subduction zone. Geophysical survey (aeromagnetometry and aerogammaspectrometry) are proxies for description and delimitation of ophiolite structure and localization of subsurface geological targets. Use is made of data density and physical contrast between target and host rocks (Blakely 1995, Dickson & Scott 1997, Rosa & Fuck 2014).

Mesozoic ophiolites are abundant in large collisional orogens such as Himalayas-Alps (Liu et al. 2016). Less ubiquitous in the Tonian, e.g. Brasiliano Orogen, ophiolites are nevertheless abundant both in juvenile crust and fold and thrust belts, including the Araguaia, Brasília, Araçuaí belt and Dom Feliciano belts (e.g., Szubert 1980, Hartmann et al. 2019, Strieder & Nilson 1992, Queiroga et al. 2007, Suita et al. 2004, Hodel et al. 2019). Pioneering age delimitation of oceanic alteration processes by Arena et al. (2016, 2017, 2018) and Hartmann et al. (2019) allows deeper understanding of ophiolites and sutures in the largest orogen of South America.

We selected the Bossoroca ophiolite because of presence of key rock associations and structures, including metasomatic rocks, and because the ophiolite is positioned at the base of the suprastructure and delimited by the infrastructure. Chloritite related to serpentinite, in addition to amphibolite, allows the study of oceanic processes; age of a diorite constrains the formation of the host island arc infrastructure. Oceanic processes occurred in the Tonian (920-800 Ma), ophiolite obducted into a 698 Ma granitic-volcanic island arc. The arcuate shape of the ophiolite seen in aerogeophysical images was caused by obduction onto an island arc.

MATERIALS AND METHODS

We integrated field geology with aeromagnetometric and aerogammaspectrometric data and zircon U-Pb geocronology. Geological data were obtained over several decades on the shield and on the ophiolite (Jost & Hartmann 1984, Szubert 1980, Laux 2017, Gubert et al. 2016, Hartmann et al. 2019); detailed work led to discovery of metasomatic rocks, including chloritite and tourmalinite.

Techniques here reported for the airborne geophysical survey of the shield by the Geological Survey of Brazil (CPRM 2010a), including aerogammaspectrometry and aeromagnetometry, follow Hartmann et al. (2016). Data acquisition was made by LASA PROSPECÇÕES S.A. (CPRM 2010a). The flight was at an elevation of 100 m above the terrain, line spacing at 500 m and control lines spaced 10,000 m oriented NS and EW. The survey covered 159,789.21 km of flights. Border regions of the shield were also covered, including strips of the Paleozoic-Mesozoic Paraná Basin to the north, west and south and the Quaternary coastal plain in the east. A Scintrex CS-2 equipment was used for the acquisition of magnetic data. Two equipment were used in two different airplanes for the acquisition of gammaspectrometric data, the Exploranium GR-820 and the Radiation Solutions Inc./RS500 spectrometers. Radar altimeters King 405 and Collins ALT-50 and barometers Fugro/Enviro were used in different airplanes to obtain the digital terrain model of the shield.

The geophysical magnetic (total magnetic field) and gamma spectrometry (potassium, thorium and uranium channels) data processing was done at LASA PROSPECÇÕES S.A., Rio de Janeiro, involving the application of Oasis Montaj GEOSOFT routines, version 7.1.1. Maps were generated in several scales, and also a data bank. This data bank was deposited at UFRGS by the Geological Survey of Brazil office in Porto Alegre; maps were produced by the authors of the digital elevation model, anomalous magnetic field (AMF), analytical signal, and K%. Selected maps are here presented in two scales and interpreted. This remote sensing of rock types allowed the contouring of the geology and interpretation of structures.

Three selected rock samples (Supplementary Material - Table SI) were studied with optical petrography, whereas backscattered electron images of zircon crystals were done at Universidade Federal do Rio Grande do Sul.

Table I. Geographic coordinates of studied samples.

Sample	Latitude	Longitude
BO17	30°20'18.43"	53°45'3.11"
C3P4	30°19'28.46"	53°45'3.97"
C3P17	30°21'29.74"	53°47'42.83"

Zircon is present in metasomatic chloritite, also in amphibolite and metadiorite. Zircon was separated mechanically from rock samples at UFRGS by standard crushing and milling followed by heavy liquids. The crystals were mounted in epoxy and polished to half their thickness. Detailed methodology of U-Pb isotopic measurements is in Supplementary Material.

Geological setting

The Bossoroca ophiolite is part of the early, juvenile segment of the Brasiliano Orogen. This major structure of South America spans the eastern half of the continent (Hartmann & Delgado 2001) and is mostly collisional, but juvenile segments occur in the Goiás arc (500 km long; Pimentel & Fuck 1992), Araxá fold-and-thrust belt (1000 km long; Strieder & Nilson 1992, Brown et al. 2020), Araguaia fold-and-thrust belt (800 km long; Hodel et al. 2019), Araçuaí belt (1000 km long; Queiroga et al. 2007), Porongos fold-and-thrust belt (150 km long; Arena et al. 2018), and in the presently-studied São Gabriel terrane (100 km long; Hartmann & Remus 2000, Hartmann et al. 2019). Selected ophiolites from the terrane were studied by Goñi (1962), Szubert (1980), Arena et al. (2016, 2017, 2018, 2020), Laux (2017), Hartmann & Chemale (2003), and Hartmann et al. (2019), and their position in the foreland of the Brasiliano Orogen by Pertille et al. (2015). African counterpart of the terrane occurs in the Arabian-Nubian Shield (Stern 2018).

The São Gabriel terrane is in the western portion of the Sul-Riograndense Shield (Figure 1), southern Brasiliano Orogen (Hartmann et al. 2000), and is composed of two main rock associations (Table II). The TTG (tonalite-trondhjemite-granodiorite) infrastructure corresponds to Cambaí Complex, whereas the andesitic volcanoclastic, sedimentary and volcanic superstructure is included in the Vacacaí Group (Campestre, Pontas do Salso and Bela Vista Formations, part of Passo Feio Formation). The Cambaí Complex and Vacacaí Group occur in rolling hills, 200-300 m elevation in the pampas (Figure 2a). Ophiolites are extraneous units in the island arc and thus are designated stratigraphically as Cerro Mantiqueiras, Ibaré, Palma, Cambaizinho and Bossoroca ophiolites (Figure 2b), and portions of Passo Feio Formation. We adopt a lithostratigraphic classification equivalent to Kozdrój et al. (2018) in the Arabian Shield, because the overall geological controls are similar and clarify the organization of the terrane. Previous subdivisions of the terrane included several formations and complexes (e.g., Robertson 1966, Ribeiro & Fantinel 1978, Naumann et al. 1984, Koppe et al. 1985, Koppe & Hartmann 1990, Babinski et al. 1996, Hartmann et al. 1999, 2007, 2011, Garavaglia et al. 2002, Lena et al. 2014, Gubert et al. 2016, Basei et al. 2018, Vedana et al. 2018), including metavolcano-sedimentary sequences and juvenile calk-alkaline gneisses (e.g., Saalmann et al. 2005, Hoerlle et al. 2019). The stratigraphic nomenclature here simplified includes the historical names 'Vacacaí, Cambaí' and extracts ophiolites into a new stratigraphic class, thus solving the long-lived, apparently contradictory stratigraphic organization of the terrane. The ophiolites are named for each occurrence; integration can be made with Cerro do Ouro ophiolite, following Goñi (1962).

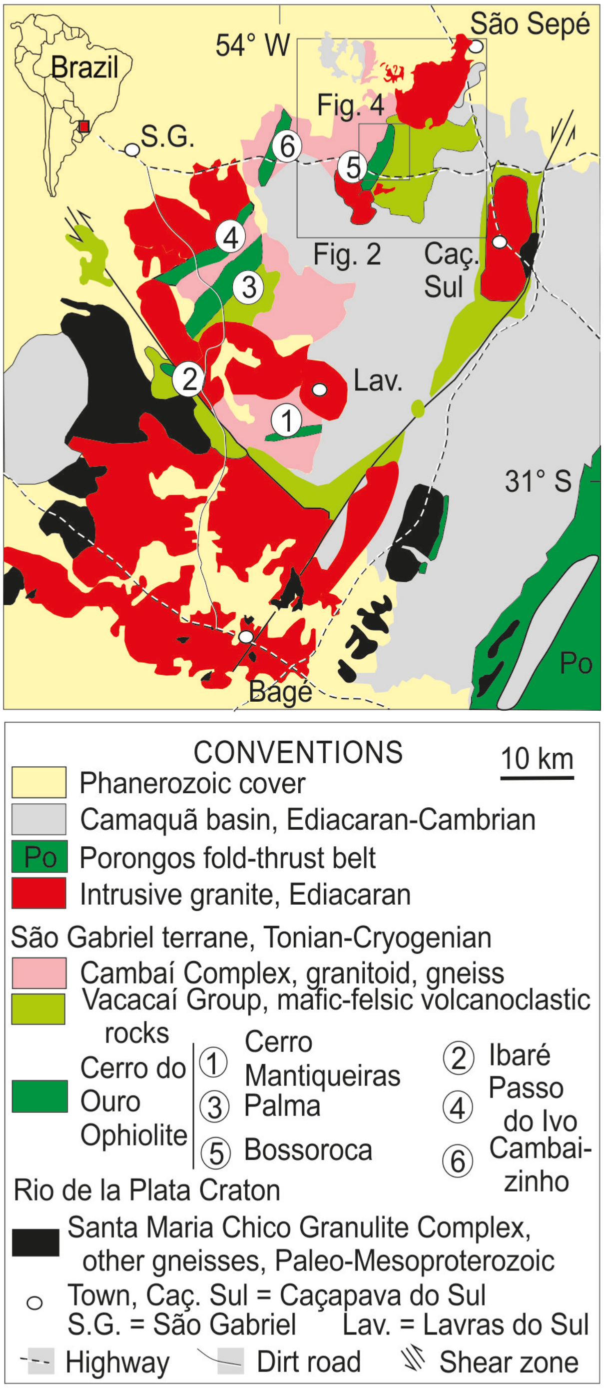

Figure 1. Geological map of São Gabriel terrane. Cerro do Ouro ophiolite includes several disrupted, numbered ophiolites. Updated from Hartmann et al. (2019), using CPRM (2010b) and Hoerlle et al. (2019). Location of Figures 2 and 4 shown.

The advance in understanding of geotectonic evolution of Sul-Riograndense Shield with use of aerogeophysics (Hartmann et al. 2016) positions the São Gabriel terrane in gammaspectrometric domain TGP3 and magnetometric domain SMP3. Domain TGP3 displays strong contrast with TGP5, because juvenile rocks of the Tonian terrane have lower gammaspectrometric emission rates than the Ediacaran-Cambrian granitic, sedimentary and volcanic rocks of TGP5. To the south of the terrane, granulitic rocks also have low emission rates; intrusive granites have high rates. Surrounding Paraná Basin sedimentary rocks have intermediate to low rates, whereas Camaquã Basin displays intermediate to high values. SMP3 contains high-magnetic rocks interspersed with low-magnetic granitic, volcanic and sedimentary rocks of the Seival Association (Chemale 2000, Chemale et al. 1995). Low-magnetic domains SMP2 (to east) and SMP5 (to west) extend in NE direction; both are similar to the basement of the Porongos fold-and-thrust belt (e.g., eastern portion of SMP2). SMP5 is covered by Paraná Basin sedimentary rocks, whereas western portion of SMP2 is covered by sedimentary (some volcanic) rocks of Camaquã Basin.

Main rocks in the ophiolites are metaserpentinite, amphibolite, quartz-plagioclase granofels, banded iron formation, albitite, and chert. Metasomatic rocks are minor in volume but significant and include rodingite, chloritite and tourmalinite. Grade of metamorphism reached greenschist facies, e.g., Ibaré ophiolite, middle amphibolite facies (Cerro Mantiqueiras ophiolite) and dominantly low-amphibolite facies (Cambaizinho and Bossoroca ophiolites; e.g., Massuda et al. 2020). Contact metamorphism by TTG on the ophiolites is not described, but postectonic granites (e.g., Cerro da Cria, São Sepé Granites) caused intense

Table II. Stratigraphy of São Gabriel terrane (São Gabriel island arc + obducted ophiolites) and associated units, with selected examples and approximate ages.

Geotectonics	Stratigraphic unit	Description	Age, Ma
Intraplate	Paraná Basin	Voluminous siltite, some lamite, conglomerate, limestone	450-60
Post-orogenic	São Sepé, Ramada, São Manoel, Lavras Granites	Shallow level, strong contact aureole	600-550
Foreland	Camaquã Basin	Volcanics, trachyandesite, sedimentary rocks	575
São Gabriel island-arc	Superstructure, Vacacaí Group – Campestre, Pontas do Salso, Bela Vista, Passo Feio (in part) Formations	Island-arc volcanics and sediments, turbidite, graywacke, tuff, andesite	755
	Infrastructure, Cambaí Complex – Lagoa da Meia-Lua Suite, Sanga do Jobim granite, Cerca de Pedra granodiorite, Imbicuí gneiss	Granitic rocks, syntectonic, no contact metamorphism on ophiolites or Vacacaí Group.	(770), 730-700, 690
Oceanic crust + mantle	Ophiolites: Cerro Mantiqueiras, Cambaizinho, Palma, Ibaré, portions of Passo Feio	Ultramafic, mafic, andesitic, volcanosedimentary rocks.	920-720
	Bossoroca ophiolite (Arroio Lajeadinho Formation)	Steeply dipping foliation, NNE direction, WNW dip. Talc-olivine metaserpentinite, amphibolite, BIF, gabbro-harzburgite. Metasomatites – Chromite-talc-magnesite fels, tourmalinite, rodingite, chloritite. Obducted at base of suprastructure. Gold specks in alluvium.	920-720

thermal aureoles on the ophiolites and host island-arc rocks (Mattos et al. 2004).

The 2-km wide Bossoroca ophiolite extends for 20 km NE and dips 60-80º to NNW. The ophiolite was obducted during the Neoproterozoic into the base of the Campestre Formation volcanoclastic rocks which occur to the east. Dominant foliation contains low-amphibolite facies mineral assemblage and corresponds to D2 of Saalmann et al. (2006, 2007). The foliation marks the obduction of the ophiolite into an oceanic volcanic-sedimentary arc. Transcurrent faulting marked D3, whereas D4 corresponds to local thrusting. Rio de La Plata

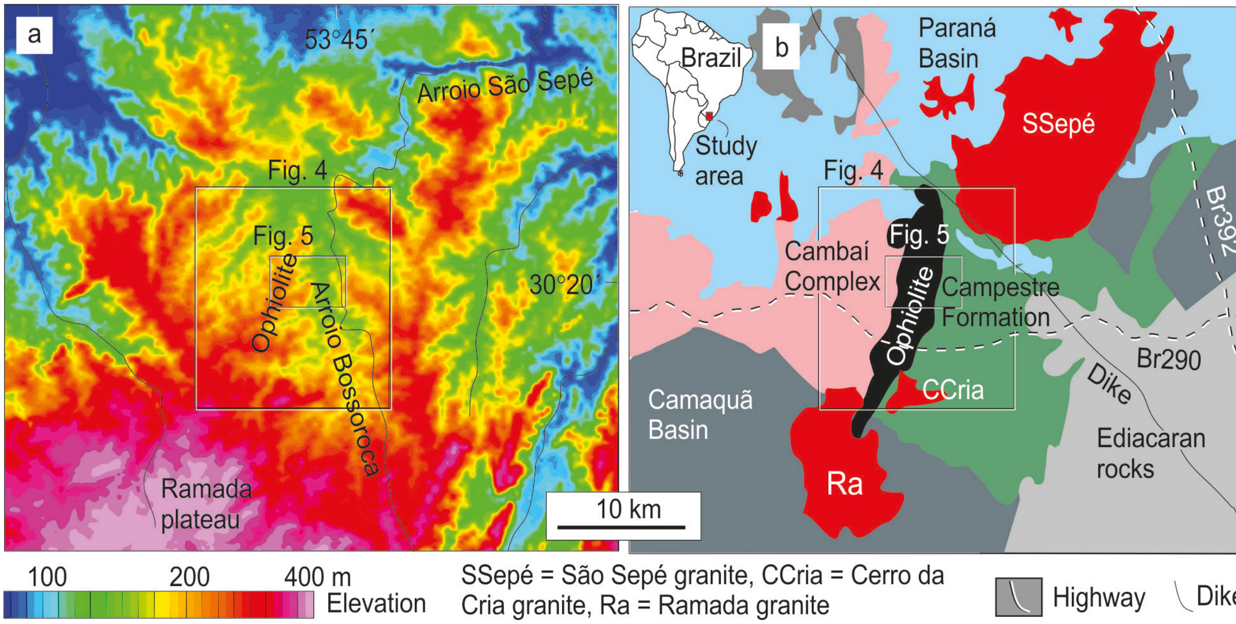

Figure 2. a Digital terrain model from aerial survey (CPRM 2010a); creeks signaled by black lines; b Geological map of Bossoroca ophiolite (CPRM 2010b) at base of suprastructure (Campestre Formation) and top of infrastructure (Cambaí Complex); highways indicated (e.g., Br290); one selected NW dike from the Cretaceous Rio Grande dike swarm indicated by black line and 'dike'. Inset shows location in South America; position of ophiolite shown; location of Figures 4, 5 indicated.

Craton rocks occur below the juvenile terrane, as described from isotopic composition of young granites and base metal ore, corresponding to a metacraton in the region (Santos et al. 2018). Electrical structure of lithosphere indicates the presence of craton underneath the juvenile terrane (Bologna et al. 2019).

Primeval age of Bossoroca ophiolite was determined by U-Pb isotopes from metasomatic zircon included in ocean-floor tourmaline (Hartmann et al. 2019). Zircon is 920 Ma-old, $\varepsilon Hf_{(920\ Ma)}$ = +12. This is presumably the age of formation of the ophiolite at a ridge within the Proto-Adamastor Ocean. Age of obduction onto the island-arc remains undetermined. Cambaí Complex infrastructure magmatism and deformation was determined by zircon U-Pb geochronology (Hartmann et al. 2011) at 753-680 Ma. Volcanism in the superstructure Campestre Formation was estimated at 753-757 Ma by Machado et al. (1990), Remus et al. (1999) and Gubert et al. (2016). Ediacaran volcanism, sedimentation (Camaquã Basin rocks) and granitic magmatism (e.g., São Sepé Granite) occurred at 600-550 Ma. Undated shear zones and faults cross the terrane in NW and NE directions. Cretaceous Rio Grande dike swarm forms NW-directed lineaments.

RESULTS

Structure of the ophiolite is arcuate (Figures 2b, 3, 4) and is mapped more accurately with support from aerogeophysical images. Anomalous magnetic field (Figure 3a) shows magnetic dipoles corresponding to contrasting magnetic rock bodies. Analytic signal applied to AMF (Figure 3b) allowed delineation of the anomalies with greater magnetic susceptibility, peaks of the sources centered on the edges of the anomalous body. The ophiolite is mostly intensely magnetic, but non-magnetic portions, e.g. chromite-talc-magnesite granofels, increase the width of the body as seen on the analytical signal image. The signal is strong (0.1-0.2 nT/m) in magmatic Cambaí Complex, weak (0.02-0.04 nT/m) in metasedimentary Campestre Formation (Figure 4). Gamma-ray emission is low over most of the ophiolite (Figure 4), which shows low K concentration (0.1 – 0.3%), but K concentration is high in Cambaí Complex and Campestre Formation (0.5-1.0%). Emission rates from eTh and eU follow distribution of K (not shown).

The ophiolite has many serpentinite bodies with sizes ranging from 10-1000 m. Intense serpentinization partly obliterates the metamorphic 'jackstraw' texture of olivine + talc observed in the serpentinite bodies. Metasomatic rocks include chromite-talc-magnesite granofels, chloritite and massive tourmalinite, all in direct contact with serpentinite. These rocks and studied amphibolite and metadiorite are in amphibolite facies of regional metamorphism (Massuda et al. 2020). Studied sample distribution inside, east and west of ophiolite body is shown in Figure 5.

Studied zircon crystals have varied internal structures. In sample BO17 (chloritite), observation of 140 crystals in BSE images (20 shown in Figure 6) displays mostly anhedral (some euhedral) external faces. Internal structure shows large homogeneous cores and complex narrow rims. No euhedral zoning is observed. Size of crystals is ~120 mm with aspect ratio 2:1. Crystals have few inclusions and are little fractured but a fracture may be present around the core. Baddeleyite overgrowth on zircon is seen in Figure 4g.

Zircon from sample C3P4 (Campestre volcanoclastic rock) was observed in 30 BSE images (16 shown in Figure 7). Crystals are homogeneous and similar, with marked internal euhedral zoning, anhedral to euhedral. Size of crystals is 100-120 mm, aspect ratio 1.2:1. Very few mineral inclusions and fractures are observed. Sector zoning is present in Figures 5a, o.

In sample C3P17 (Capivaras metadiorite), observation of 41 BSE images (24 shown in Figure 8) reveals anhedral to subhedral (rounded) zircon crystals. Internal structure is similar in the crystals and complex. Diffuse geometry corresponds to medium gray tones (BSE) in cores, surrounded or crossed by lighter grey tones in zircon portions. Opposite light and dark tones are seen in CL images. Size of crystals is 200-300 mm and reaching 400 mm, aspect ratio 2:1. Very few mineral inclusions are present; a few fractures cross the crystal, concentrated in the darker in BSE portions.

Zircon U-Pb isotopic data (Table SI) are displayed in concordia diagrams (Figure 9). Sample BO17 (chloritite) had 70 analyses made on zircon; 62 were used for age calculation and 8 were discarded. Concordia diagram shows a spread of concordant ages from 960-700 Ma but mostly from 920-820 Ma. Bell-shaped distribution shows maximum at 869 Ma.

Out of a total of 42 analyses on zircon from sample C3P17 (Capivaras metadiorite), 31 were used for calculations and 11 discarded. Concordia age is 698 ±4 Ma, interpreted as the magmatic age of the diorite. Analyses on a few light grey (BSE) portions of zircon indicate similar age to the magmatic portions.

In sample C3P4 (Campestre metavolcanoclastic rock), 42 spots were analyzed on zircon, 32 were used in calculations and 10 discarded. Concordia age is 842 ±5 Ma, corresponding to the magmatic age of detrital inheritance.

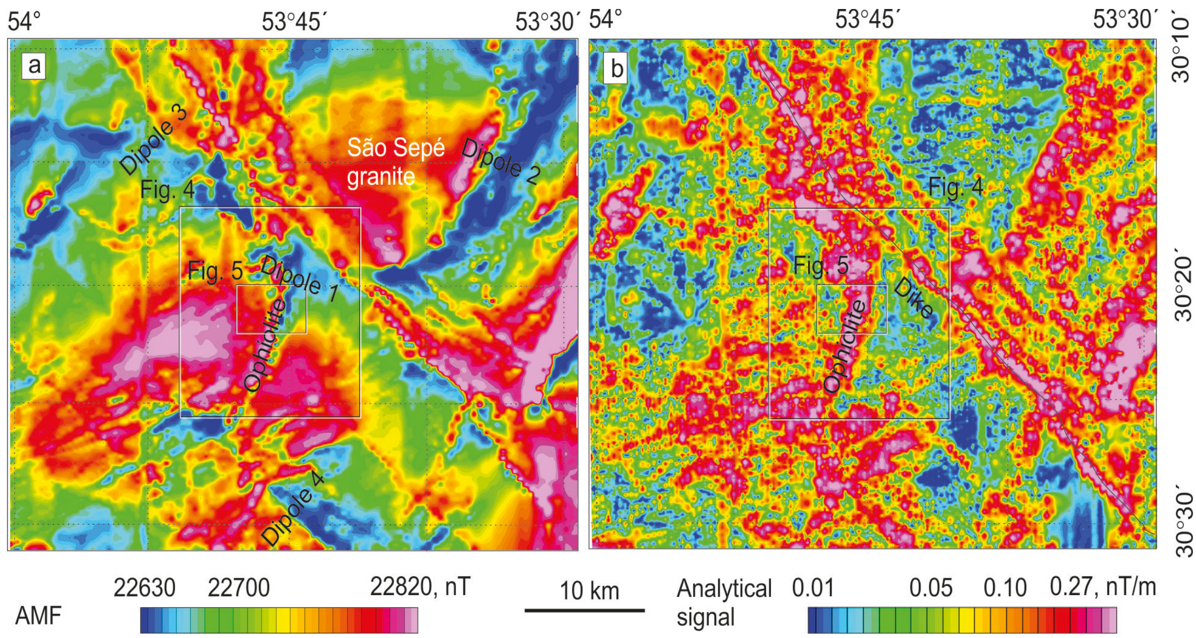

Figure 3. a Regional anomalous magnetic field; position of four main dipoles shown; **b** Regional analytical signal amplitude; Bossoroca ophiolite is the NS body in core of rectangle; one selected NW dike from the Cretaceous Rio Grande Dike Swarm indicated by black line and 'dike'. Position of ophiolite shown; location of Figure 5 indicated.

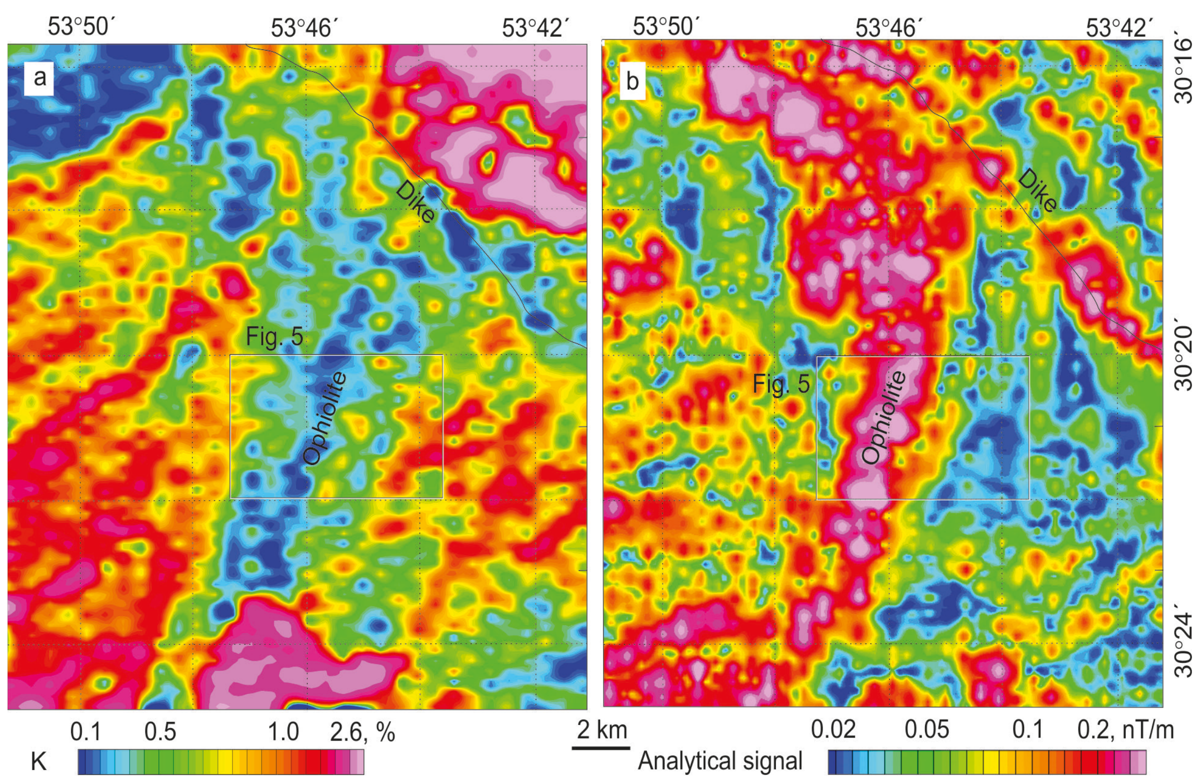

Figure 4. a K (%) aerogammaspectrometric map; ophiolite is the elongated, N-S low-K body; **b** Aeromagnetometric (analytical signal amplitude) map; Bossoroca ophiolite is the elongated N-S, high-magnetic (ASA) arch. One selected NW dike from the Cretaceous Rio Grande Dike Swarm indicated by black line and 'dike' in both images. Position of ophiolite shown; location of Figure 5 indicated.

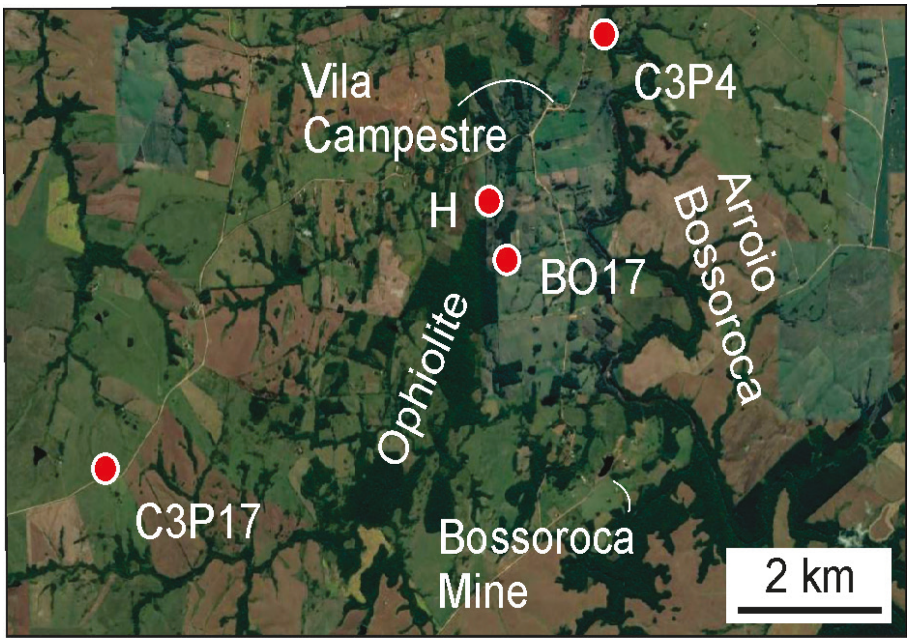

Figure 5. GoogleEarth image of studied area, indicating position of ophiolite and studied samples. Sample H was studied by Hartmann et al. (2019).

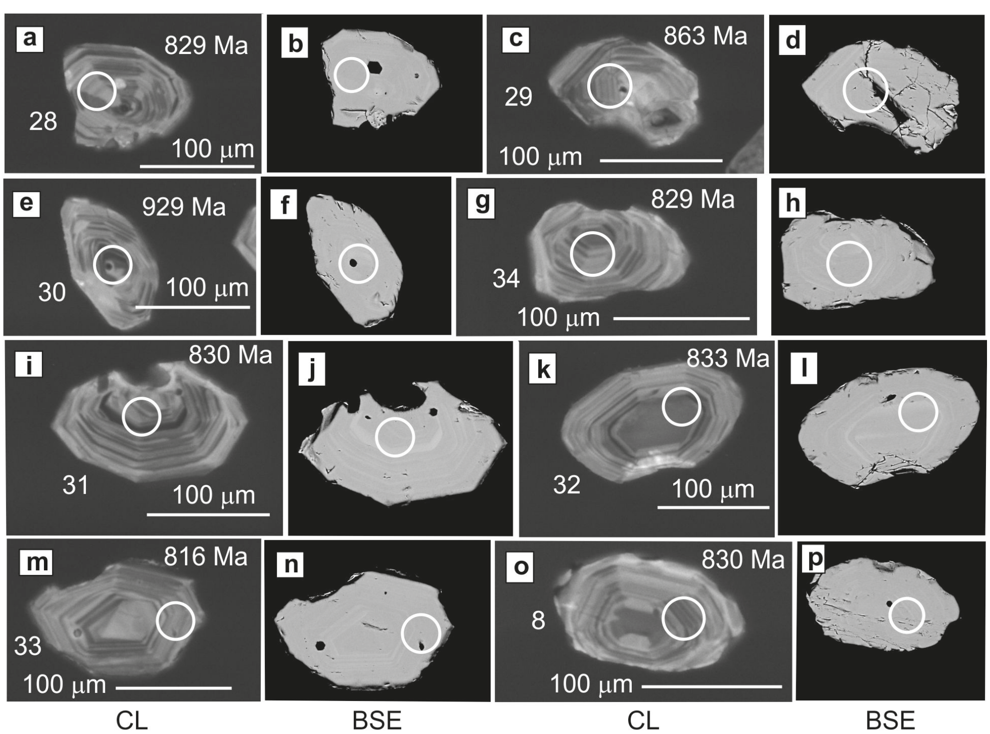

Figure 6. Selected digital images of dated zircon grains, sample BO17, chloritite from the Bossoroca ophiolite. Analysis number and age shown. Columns containing either BSE or CL images indicated at bottom.

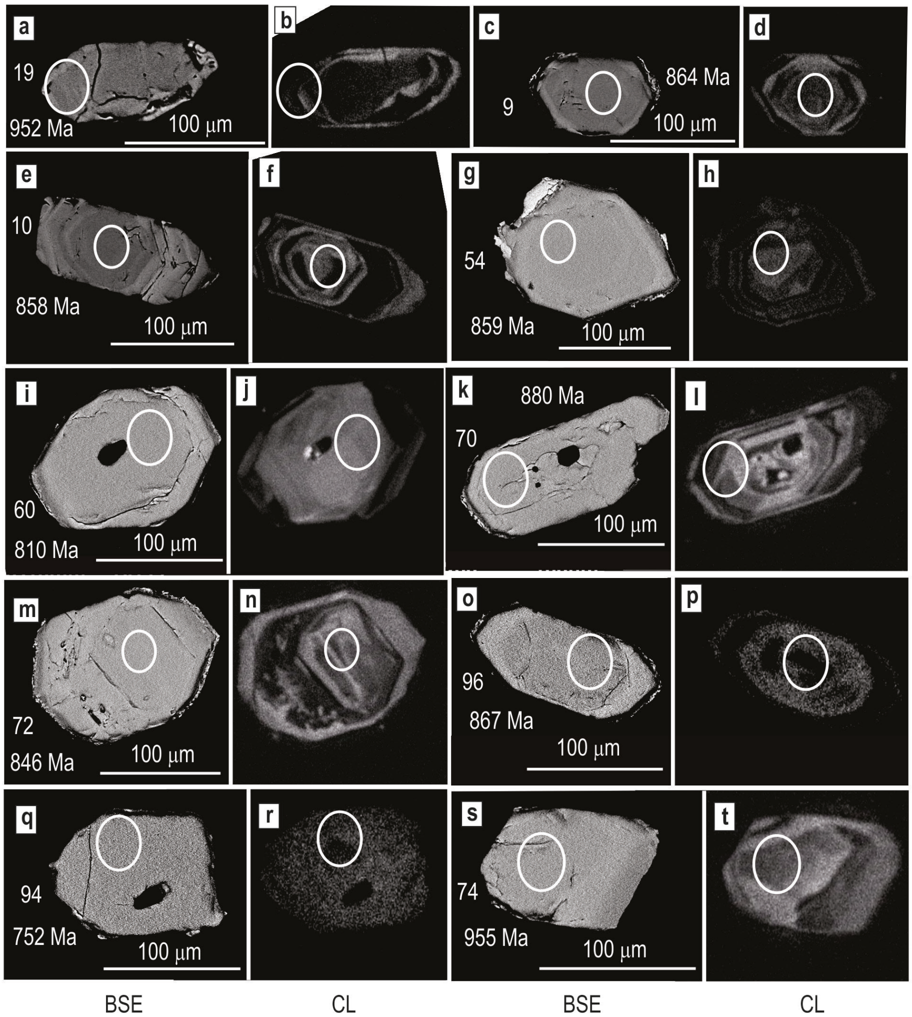

Figure 7. Selected digital images of dated zircon grains, sample C3P4, Campestre volcanoclastic rock. Columns containing either BSE or CL images indicated at bottom. Analysis number and age shown.

DISCUSSION

Bossoroca ophiolite is a key oceanic crustal and mantle fragment in the Brasiliano Orogen. Study by Hartmann et al. (2019) ascertained the depleted mantle affinity of zircon from a tourmalinite and oceanic origin of the tourmaline. We presently establish the structure of the ophiolite from field and aerogeophysics. Ages of geological processes with U-Pb isotopes are constrained on zircon from a metasomatic chloritite (960-700 Ma but mostly from 920-820 Ma, peak 869 Ma) within the ophiolite, metadiorite (698 ±4 Ma) from the infrastructure of the juvenile island arc, and detrital zircon (842 ±5 Ma) from a Campestre metavolcanoclastic rock from the superstructure. Volcanism in the superstructure is considered 757 ± 17 Ma old from a dacitic metatuff – Zrn U/Pb SHRIMP II (e.g., Remus et al. 1999).

Capivaras metadiorite is part of the Cambaí Complex, and is the youngest intrusion identified in the infrastructure along the western border of the studied ophiolite. Most of the granitic and gneissis rocks in the complex have ages 750-700 Ma (Hartmann et al. 2011). Age of zircon from the metavolcanoclastic rock is older than previous studies, which placed the interpreted magmatic age near 750 Ma. We interpret the age 842 ±5 Ma as corresponding to the source area of the detrital zircon. This is supported by the sedimentary characteristics of the rock and

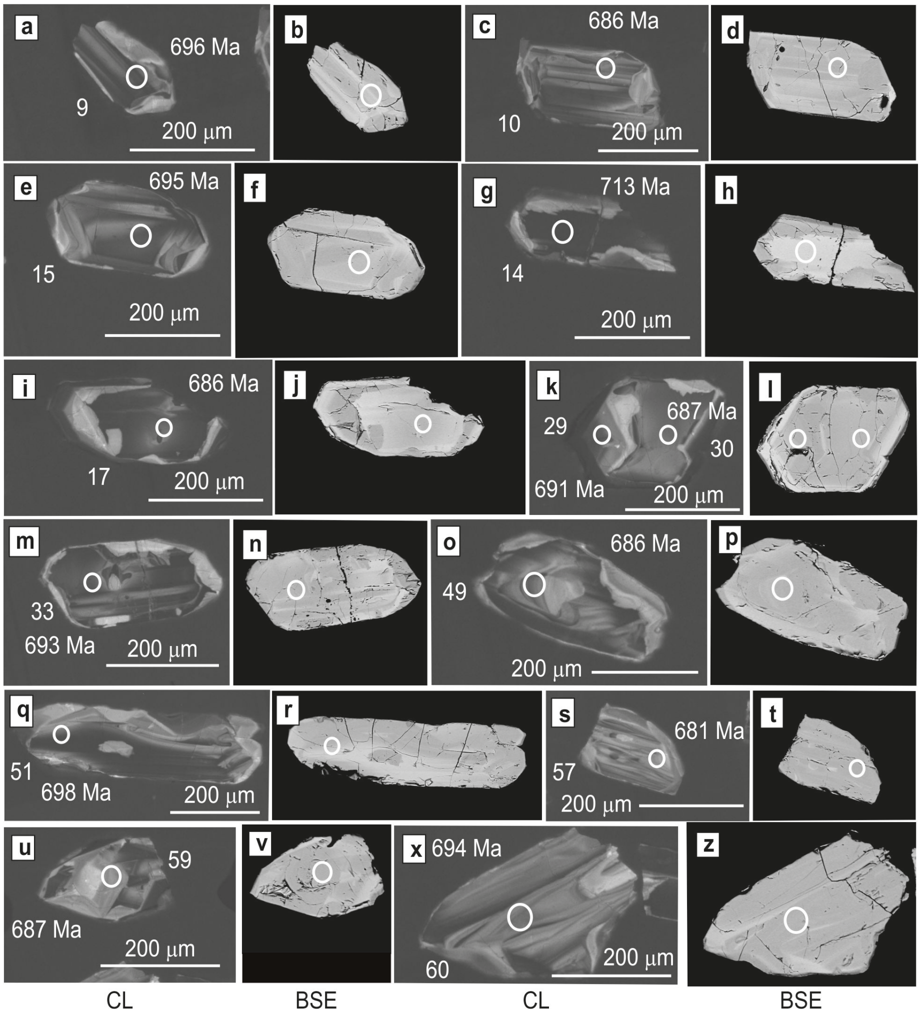

Figure 8. **Selected digital images of dated zircon grains, sample C3P17, Capivaras metadiorite. Columns containing either BSE or CL images indicated at bottom. Analysis number and age shown.**

the structure of zircon crystals, which is similar in size and geometry to the core of the zircon crystals from the chloritite within the ophiolite. Ages from the chloritite place the ophiolite within the time span of formation of the Cerro do Ouro Ophiolite in the terrane (Arena et al. 2016, 2017, 2018, Hartmann et al. 2019). The dominant age of 869 Ma is characteristic of the Passinho Arc, the oldest evolved crust identified in the terrane; these older ages characterize the Bossoroca ophiolite (Hartmann et al. 2019).

Lithostratigraphy of the juvenile São Gabriel terrane, including the studied ophiolite, is organized into the infrastructure (granitic rocks and gneisses) Cambaí Complex, superstructure (volcanic, sedimentary, volcaniclastic rocks) Porongos Group, and Cerro do Ouro Ophiolite. Porongos Group includes the studied Campestre Formation, and Pontas do Salso, Bela Vista Formations. The Cerro do Ouro Ophiolite includes all ophiolites in the São Gabriel terrane, and these are the studied Bossoroca ophiolite, and Cambaizinho, Palma, Ibaré, Cerro Mantiqueiras ophiolites.

Two types of ophiolites are present in the terrane, one contained in the infrastructure – Cambaizinho and Cerro Mantiqueiras ophiolite, and the other at the base of the superstructure – studied Bossoroca, and Palma, Ibaré ophiolites. In the Arab-Nubian Shield, this classification is significant, because gold deposits are concentrated in ophiolites at the

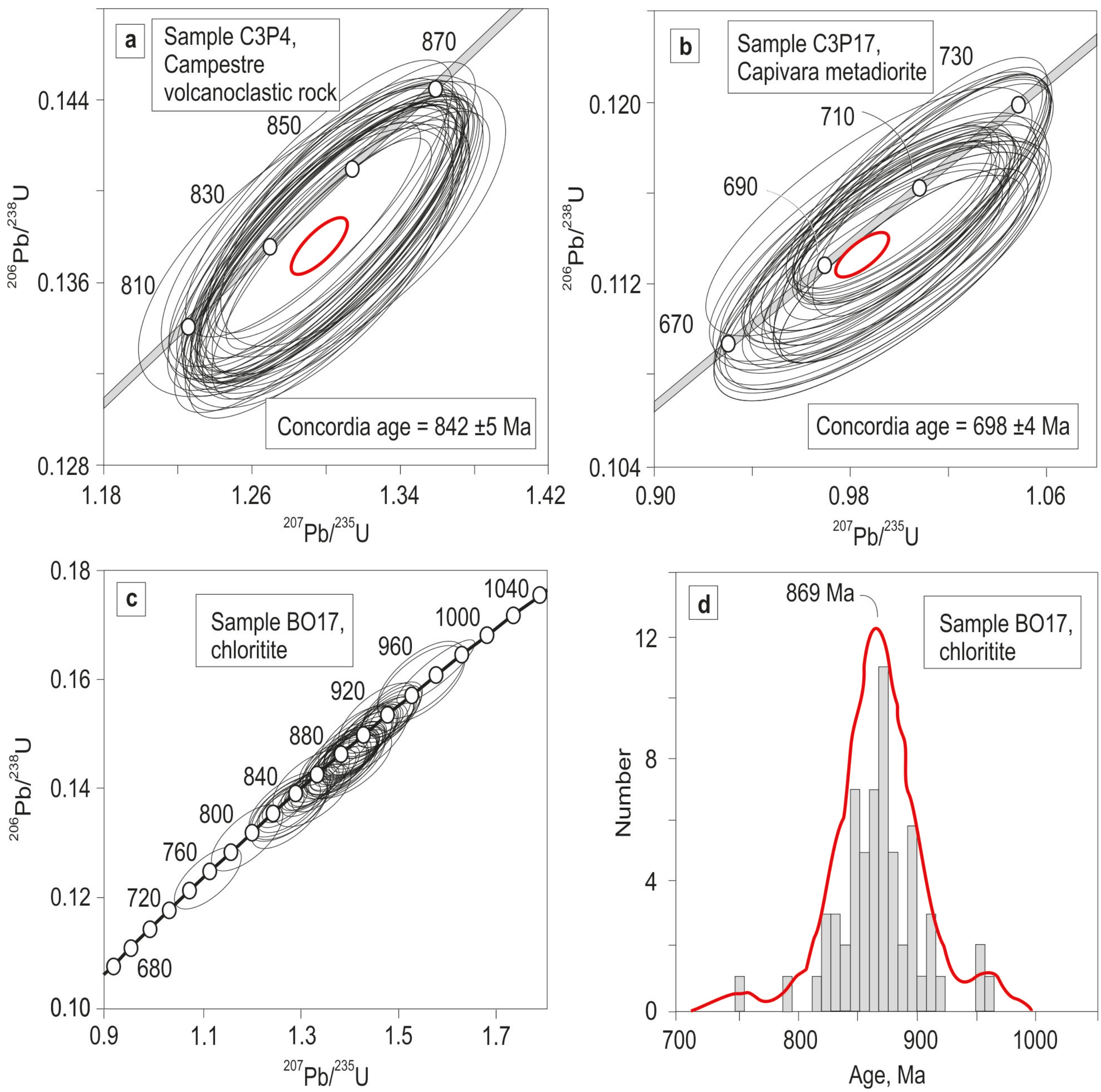

Figure 9. U-Pb concordia diagrams of dated zircon from three rock samples. a Sample C3P4, Campestre metavolcanoclastic rock; b Sample C3P17, Capivaras metadiorite; c Sample BO17, chloritite; d Frequency histogram of ages from sample BO17, chloritite.

base of the superstructure. All ophiolites in the terrane are mélanges, because serpentinite is interspersed with rocks formed in the oceanic crust, e.g. amphibolite (extensive in Cerro Mantiqueiras ophiolite), banded iron formation and metachert (all ophiolites), metapelite and para-amphibolite (Cambaizinho ophiolite), metavolcanoclastic rocks (Bossoroca, Palma, Ibaré ophiolites). These are tectonic mélanges in the sense of Raymond (2019), commonly interpreted as formed in the accretionary prism above a subduction zone. Because main trusting of the São Gabriel terrane occurred towards ESE, the presence of a west-dipping subduction zone is suggested to the east of the region in the Tonian (Saalmann et al. 2006).

Integrated investigation of an ophiolite, infrastructure and superstructure, with use of field survey, aeromagnetometry and aerogammaspectrometry and zircon U-Pb geochronology allows the perception of several key points in evolution. Improved cartography of the Bossoroca ophiolite leads to dating of the three main units, namely a chloritite within the ophiolite formed by metasomatism in oceanic floor, a metadiorite formed late in the Cambaí Complex and a metavolcanoclastic rock from the Porongos Group (Campestre Formation).

CONCLUSIONS

The Bossoroca ophiolite is an independent stratigraphic unit obducted in the Tonian at the base of island-arc superstructure (Porongos Group, Campestre Formation) and on top of the infrastructure (Cambaí Complex). Zircon formation in the chloritite from the ophiolite started at 920 Ma, peaked at 869 Ma and continued mostly until 800 Ma and even 700 Ma, therefore mostly during the Tonian. Host island-arc concluded formation at 698 Ma as observed in syntectonic metadiorite from Cambaí Complex. Metavolcanoclastic rock from superstructure has detrital zircon with age of 841 Ma; Campestre Formation is considered 757 Ma old from previous studies. Ophiolite obduction is estimated as syntectonic with metadiorite intrusion and deformation at 698 Ma.

Acknowledgments

We acknowledge field support by Cassiana R. L. Michelin, Mariana Werle, Vitor C. Dias, and Bossoroca Mine geologist José Alírio Lenzi. Aerogeophysical data bank was made available to Universidade Federal do Rio Grande do Sul (deposited in authors computer) by CPRM – Geological Survey of Brazil. Continued support from Conselho Nacional do Desenvolvimento Científico e Tecnológico (CNPq) is gratefully registered.

REFERENCES

ARENA KR, HARTMANN LA & LANA C. 2016. Evolution of Neoproterozoic ophiolites from the southern Brasiliano Orogen revealed by zircon U-Pb-Hf isotopes and geochemistry. Prec Res 285: 299-314.

ARENA KR, HARTMANN LA & LANA C. 2017. Tonian emplacement of ophiolites in the southern Brasiliano Orogen delimited by U-Pb-Hf isotopes of zircon from metasomatites. Gond Res 49: 296-332.

ARENA KR, HARTMANN LA & LANA C. 2018. U-Pb-Hf isotopes and trace elements of metasomatic zircon delimit the evolution of the neoproterozoic Capané ophiolite in the southern Brasiliano Orogen. Int Geol Rev 60: 911-928.

ARENA KR, HARTMANN LA, LANA CC, QUEIROGA GN & CASTRO MP. 2020. Geochemistry and $\delta^{11}B$ evolution of tourmaline from tourmalinite as a record of oceanic crust in the Tonian Ibaré ophiolite, southern Brasiliano Orogen.. An Acad Bras Cienc 92: e20180193.

BABINSKI M, CHEMALE JR F, HARTMANN LA, VAN SCHMUS WR & SILVA LC. 1996. Juvenile accretion at 750-700 Ma in southern Brazil. Geology 24: 439-442.

BASEI MAS, FRIMMEL HE, CAMPOS NETO MC, GANADE DE ARAUJO CE, CASTRO NA & PASSARELLI CR. 2018. The Tectonic History of the Southern Adamastor Ocean Based on a Correlation of the Kaoko and Dom Feliciano Belts. In: Siegesmund et al. (Eds), Geology of Southwest Gondwana, Regional Geology Reviews. Springer International Publishing AG, part of Springer Nature, p. 63-85.

BLAKELY RJ. 1995. Potential theory in gravity and magnetic applications: Australia, Cambridge University Press, 464 p.

BOLOGNA MS, DRAGONE GN, MUZIO R, PEEL E, NUÑEZ-DEMARCO P & USSAMI N. 2019. Electrical structure of the lithosphere from Rio de la Plata Craton to Paraná Basin: Amalgamation of cratonic and refertilized lithospheres in SW Gondwanaland. Tectonics 38: 77-94.

BROWN MT, FUCK RA & DANTAS EL. 2020. Isotopic age constraints and geochemical results of disseminated ophiolitic assemblage from Neoproterozoic melange, Central Brazil. Prec Res 339: 105581.

CERVA-ALVES T, HARTMANN LA, REMUS MVD & LANA C. 2020. Integrated ophiolite and arc evolution, southern Brasiliano Orogen. Prec Res 341: 105648.

CHEMALE JR F. 2000. Evolução geológica do Escudo Sul-riograndense. In: Holz M & De Ros LF (Eds), Geologia do Rio Grande do Sul. Centro de Investigação do Gondwana. Instituto de Geociências-UFRGS, Porto Alegre, p. 13-52.

CHEMALE JR F, HARTMANN LA & SILVA LC DA. 1995. Stratigraphy and tectonism of the Brasiliano cycle in southern Brazil. Comm Geol Survey Namibia 10: 151-166.

CPRM – SERVIÇO GEOLÓGICO DO BRASIL. 2010a. Projeto Aerogeofísico Escudo do Rio Grande do Sul. LASA PROSPECÇÕES S.A., Technical report, 260 p.

CPRM – SERVIÇO GEOLÓGICO DO BRASIL. 2010b. Mapa Geológico do Estado do Rio Grande do Sul; Nota Explicativa.

DICKSON BL & SCOTT KM. 1997. Interpretation of aerial gamma-ray surveys – adding the geochemical factors: AGSO Jour Austr Geol Geoph 17: 187-200.

DILEK Y & THY P. 2006. Age and petrogenesis of plagiogranite intrusions in the Ankara mélange, central Turkey. Island Arc 15: 44-57.

GARAVAGLIA L, BITENCOURT MF & NARDI LVS. 2002. Cumulate diorites related to post-collisional, Brasiliano/Pan-African mafic magmatism in the Vila Nova Belt, southern Brazil. Gond Res 5: 519-534.

GERDES A & ZEH A. 2009. Zircon formation versus zircon alteration – new insights from combined U-Pb and Lu–Hf in-situ LA-ICP-MS analyses, and consequence for the interpretation of Archean zircon from the Central Zone of the Limpopo Belt. Chem Geol 261: 230-243.

GOÑI JC. 1962. Origine des roches ultrabasiques et serpentineuses du précambrian de Rio Grande do Sul (Brèsil): mode de gisement et mineralizacions. Boletim da Escola de Geologia da URGS, Porto Alegre 12: 1-89.

GUBERT ML, PHILIPP RP & BASEI MAS. 2016. The Bossoroca Complex, São Gabriel Terrane, Dom Feliciano Belt, southernmost Brazil: U-Pb geochronology and tectonic implications for the neoproterozoic São Gabriel Arc. J South Am Earth Sci 70: 1-17.

HARTMANN LA & CHEMALE JR F. 2003. Mid amphibolite facies metamorphism of harzburgites in the Neoproterozoic Cerro Mantiqueiras Ophiolite, southernmost Brazil. An Acad Bras Cienc 75: 109-128.

HARTMANN LA, CHEMALE JR F & PHILIPP RP. 2007. Evolução geotectônica do Rio Grande do Sul no Pré-Cambriano. In: Frantz JC & Ianuzzi R (Eds), 50 anos de Geologia no Rio Grande do Sul. UFRGS-PETROBRAS, Porto Alegre, p. 97-123.

HARTMANN LA & DELGADO IM. 2001. Cratons and orogenic belts of the Brazilian Shield and their contained gold deposits. Min Dep 36: 207-217.

HARTMANN LA, LEITE JAD, SILVA LC, REMUS MVD, MCNAUGTON NJ, GROVES DI, FLETCHER IR, SANTOS JOS & VASCONCELLOS MAZ. 2000. Advances in SHRIMP geochronology and their impact on understanding the tectonic and metalogenic evolution of southern Brazil. Austr Jour Earth Sci 47: 829-844.

HARTMANN LA, LOPES WR & SAVIAN JF. 2016. Integrated evaluation of the geology, aerogammaspectrometry and aeromagnetometry of the Sul-Riograndense Shield, southernmost Brazil. Int Geol Rev 88: 75-92.

HARTMANN LA, NARDI LVS, FORMOSO MLL, REMUS MVD, LIMA EF & MEXIAS AS. 1999. Magmatism and metallogeny in the crustal evolution of Rio Grande do Sul shield, Brazil. Pesquisas em Geociências (UFRGS) 26: 45-63.

HARTMANN LA, PHILIPP RP, SANTOS JOS & MCNAUGHTON NJ. 2011. Time frame of 753-680 Ma juvenile accretion during the São Gabriel orogeny, southern Brazil. Gond Res 19: 84-99.

HARTMANN LA & REMUS MVD. 2000. Origem e evolução das rochas ultramáficas do Rio Grande do Sul desde o Arqueano até o Cambriano. In: Holz M & De Ros LF (Eds), Geologia do Rio Grande do Sul, Porto Alegre: Ed. CECO/UFRGS, p. 55-78.

HARTMANN LA, WERLE M, MICHELIN CRL, LANA C, QUEIROGA GN, CASTRO MP & ARENA KR. 2019. Proto-Adamastor ocean crust (920 Ma) described in Brasiliano Orogen from coetaneous zircon and tourmaline. Geosc Front 10: 1623-1633.

HODEL F, TRINDADE RIF, MACOUIN M, MEIRA VT & LANA CC. 2019. A Neoproterozoic hyper-extended margin associated with Rodinia's demise and Gondwana's build-up: The Araguaia Belt, central Brazil. Gond Res 66: 43-62.

HOERLLE GS, REMUS MVD, DANI N, GOMES MEB & RONCHI LH. 2019. Evolution of fluorite-mica-feldspar veins: Evidences of a fossil geothermal system in the São Gabriel terrane and consequences for Pb-Zn-Cu metallogeny. J South Am Earth Sci 92: 209-221.

JACKSON SE, PEARSON NJ, GRIFFIN WL & BELOUSOVA EA. 2004. The application of laser ablation inductively coupled plasma mass spectrometry to in situ U-Pb zircon geochronology. Chem Geol 211: 47-69.

JOST H & HARTMANN LA. 1984. Província Mantiqueira - Setor Meridional. In: Almeida FFM & Hasui Y (Eds), O Pré-Cambriano do Brasil, p. 345-368.

KARAOGLAN FG, PARLAK O, KLOTZLI U, THONI M & KOLLER F. 2013. U-Pb and Sm–Nd geochronology of the Kizildag (Hatay, Turkey) ophiolite: implications for the timing and duration of suprasubduction zone type oceanic crust formation in the southern Neotethys. Geol Mag 150: 283-299.

KOPPE JC & HARTMANN LA. 1990. Geochemistry of the Bossoroca greenstone belt. Southernmost Brazil. Geoch Brasil 2: 167-174.

KOPPE JC, HARTMANN LA, LISBOA PFC & MONTEIRO RN. 1985. Aspectos geológicos e estratigráficos do Complexo Bossoroca, São Sepé, RS. In: Simpósio Sul-Brasileiro de Geologia, 2, Florianópolis. Anais... SBG, p. 32-36.

KOZDRÓJ W, KENNEDY AK, JOHNSON PR, ZIÓŁKOWSKA-KOZDRÓJ M & KADI K. 2018. Geochronology in the southern Midyan terrane: a review of constraints on the timing of magmatic pulses and tectonic evolution in a northwestern part of the Arabian Shield. Int Geol Rev 60: 1290-1319.

LAUX JH. 2017. Geologia e recursos minerais da Folha Lagoa da Meia Lua - SH. 21–Z–B-VI, Escala 1:100.000, estado do Rio Grande do Sul. Porto Alegre: CPRM, 255 p.: il. color.

LENA LOF, PIMENTEL MM, PHILIPP RP, ARMSTRONG R & SATO K. 2014. The evolution of the Neoproterozoic São Gabriel juvenile terrane, southern Brazil based on high spatial resolution U-Pb ages and ^{18}O data from detrital zircons. Prec Res 247: 126-138.

LIU CZ, CHUNG SL, WU FY, ZHANG C, XU Y, WANG JG, CHEN Y & GUO S. 2016. Tethyan suturing in Southeast Asia: Zircon U-Pb and Hf-O isotopic constraints from Myanmar ophiolites. Geology 44: 311-314.

LUDWIG KR. 2003. Isoplot/Ex Version 3.00: A Geochronological Toolkit for MicrosoftExcel. Berkeley Geochronology Center, Berkeley, CA. Special Publication 4, 71 http://bgc.org/isoplot_etc/isoplot.html.

MACHADO N, KOPPE JC & HARTMANN LA. 1990. A Late Proterozoic U-Pb age for the Bossoroca Belt, Rio Grande do Sul, Brazil. J South Am Earth Sci 3: 87-90.

MASSUDA AJ, HARTMANN LA, QUEIROGA GN, CASTRO MP, LEANDRO CG & SAVIAN JF. 2020. Mineralogical evolution of the northern Bossoroca ophiolite, São Gabriel terrane. Brazilian Jour Geol 50(4): e20190120.

MATTOS IC, PHILIPP RP, MEXIAS AS & GOMES MEB. 2004. Metamorfismo de contato no Complexo Bossoroca, porção SW do Complexo Granítico São Sepé, RS, Brasil. Rev Bras Geoc 34: 1-10.

NAUMANN MP, HARTMANN LA, KOPPE JC & CHEMALE JR F. 1984. Sequências supracrustais, gnaisses graníticos, granulitos e granitos intrusivos da região de Ibaré-Palma, RS: geologia, aspectos estratigráficos e considerações geotectônicas. In: Congresso Brasileiro de Geologia, 33. Rio de Janeiro. Anais... SBG, p. 2417-2424.

PERTILLE J, HARTMANN LA, PHILIPP RP, PETRY TS & LANA CC. 2015. Origin of the Ediacaran Porongos Group, Dom Feliciano Belt, southern Brazilian Shield, with emphasis on whole rock and detrital zircon geochemistry and U-Pb, Lu-Hf isotopes. J South Am Earth Sci 64: 69-93.

PHILIPP RP, PIMENTEL MM & BASEI MAS. 2018. The Tectonic Evolution of the São Gabriel Terrane, Dom Feliciano Belt, Southern Brazil: The Closure of the Charrua Ocean. In: Siegesmund S et al. (Eds), Geology of Southwest Gondwana, Regional Geology Reviews. Springer International Publishing AG, part of Springer Nature, p. 243-265.

PIMENTEL MM & FUCK RA. 1992. Neoproterozoic crustal accretion in central Brazil. Geology 20: 375-379.

QUEIROGA GN, PEDROSA-SOARES AC, NOCE CM, ALKMIM FF, PIMENTEL MM, DANTAS E, MARTINS M, CASTAÑEDA C, SUITA MTF & PRICHARD F. 2007. Age of the Ribeirão da Folha ophiolite, Araçuaí Orogen: The U-Pb zircon dating of a plagiogranite. Geonomos 15: 61-65.

RAYMOND LA. 2019. Perspectives on the roles of melanges in subduction accretionary complexes: A review. Gond Res 74: 68-89.

REMUS MVD, MCNAUGHTON NJ, HARTMANN LA, KOPPE JC, FLETCHER IR, GROVES DI & PINTO VM. 1999. Gold in the Neoproterozoic juvenile Bossoroca volcanic arc of southernmost Brazil: Isotopic constraints on timing and sources. J South Am Earth Sci 12: 349-366.

RIBEIRO M & FANTINEL LMA. 1978. Associações petrotectônicas do escudo Sul-Riograndense: I. Tabulação e distribuição das associações petrotectônicas do Escudo do Rio Grande do Sul. Iheringia, Série Geologia, Porto Alegre 5: 19-54.

ROBERTSON JF. 1966. Revision of the stratigraphy and nomenclatura of rock units in the Caçapava-Lavras region, state of Rio Grande do Sul, Brazil. Notas e Estudos, IG-UFRGS 1: 41-54.

ROSA JWC & FUCK RA. 2014. Geophysical structures and tectonic evolution of the southern Guyana shield, Brazil. J South Am Earth Sci 52: 57-71.

SAALMANN K, REMUS MVD & HARTMANN LA. 2005. Geochemistry and crustal evolution of volcano-sedimentary successions and orthogneisses in the São Gabriel Block, Southernmost Brazil - Relics of Neoproterozoic magmatic arcs. Gond Res 8: 143-161.

SAALMANN K, REMUS MVD & HARTMANN LA. 2006. Tectonic evolution of the Neoproterozoic São Gabriel block, southern Brazil: constraints on Brasiliano orogenic evolution of the Rio de La Plata cratonic margin. J South Am Earth Sci 21: 204-227.

SAALMANN K, REMUS MVD & HARTMANN LA. 2007. Neoproterozoic magmatic arc assembly in the southern Brazilian Shield – constraints for a plate tectonic model for the Brasiliano orogeny. Geot Res 95: 41-59.

SAMSON SD, INGLIS JD, D'LEMOS RS, ADMOU H, BLICHERT-TOFT J & HEFFERAN K. 2004. Geochronological, geochemical, and Nd–Hf isotopic constraints on the origin of Neoproterozoic plagiogranites in the Tasriwine ophiolite, Anti-Atlas orogen, Morocco. Prec Res 135: 133-147.

SANTOS JOS, CHERNICOFF CJ, ZAPPETTINI EO, MCNAUGHTON NJ & HARTMANN LA. 2018. Large geographic and temporal extensions of the Río de La Plata Craton, South America, and its metacratonic eastern margin. Int Geol Rev 61: 56-85.

STERN RJ. 2018. Neoproterozoic formation and evolution of Eastern Desert continental crust – The importance of the infrastructure-superstructure transition. Jour Afr Earth Sci 146: 15-27.

STRIEDER AJ & NILSON AA. 1992. Estudo petrológico de alguns fragmentos tectônicos da mélange ofiolítica em Abadiânia (GO): 1 – O protólito dos corpos de serpentinito. Rev Bras Geoc 22: 338-352.

SUITA MTF, PEDROSA-SOARES AC, LEITE CAS, NILSON AA & PRICHARD HM. 2004. Complexos ofiolíticos do Brasil e a metalogenia comparada das faixas Araçuaí e Brasília. In: Pereira ES, Castroviejo R & Ootiz F (Eds). Complejos ofiolíticos em Ibero América: Edita Proyecto XIII.1, Madrid-España 379: 101-132.

SZUBERT EC. 1980. Depósitos de ouro e rochas u1trabásicas na faixa ofiolitica de Palma, São Gabriel, RS. Mineralogia e Metalurgia (RJ) 43: 14-19.

VAN ACHTERBERGH E, RYAN CG, JACKSON SE & GRIFFIN WL. 2001. Data reduction software for LA–ICP–MS. In: Sylvester PJ (Ed), Laser ablation-ICP mass spectrometry in the earth sciences: Principles and applications: Ottawa, Ontario, Mineral Assoc Canada, Short Course 29: 239-243.

VEDANA LA, PHILIPP RP & BASEI MAS. 2018. Tonian to early Cryogenian synorogenic basin of the São Gabriel Terrane, Dom Feliciano Belt, southernmost Brazil. Int Geol Rev 60: 109-133.

SUPPLEMENTARY MATERIAL

Table SI. **LA-ICP-MS zircon U-Pb geochronological data.**

How to cite

HARTMANN LA, MASSUDA AJ, CERVA-ALVES T, LANA C, LEANDRO CG & SAVIAN JF. 2021. Aeromagnetometry and aerogammaspectrometry integrated with U-Pb zircon geochronology of northern Bossoroca ophiolite, Brasiliano Orogen. An Acad Bras Cienc 93: e20190791. DOI 10.1590/0001-3765202120190791.

Manuscript received on July 11, 2019;
accepted for publication on July 31, 2019

LÉO A. HARTMANN[1]
https://orcid.org/0000-0001-7863-5071

AMANDA J. MASSUDA[1]
https://orcid.org/0000-0001-8567-161X

TIARA CERVA-ALVES[1]
https://orcid.org/0000-0001-6381-4077

CRISTIANO LANA[2]
https://orcid.org/0000-0001-6302-9706

CAROLINA G. LEANDRO[1]
https://orcid.org/0000-0003-0371-4511

JAIRO F. SAVIAN[1]
https://orcid.org/0000-0002-5032-3217

[1]Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Avenida Bento Gonçalves, 9500, 91501-970 Porto Alegre, RS, Brazil

[2]Departamento de Geologia, Escola de Minas, Universidade Federal de Ouro Preto, Morro do Cruzeiro, 35400-000 Ouro Preto, MG, Brazil

Correspondence to: **Léo Afraneo Hartmann**
E-mail: leo.hartmann@ufrgs.br

Author contributions

All authors contributed to the formulation and planning of the study, revised and improved the manuscript. Léo A. Hartmann, Amanda J. Massuda and Tiara Cerva-Alves participated in geological field work. Cristiano Lana supervised and efetivated the isotopic analyses. Carolina G. Leandro and Jairo F. Savian formulated the geophysical parts of the manuscript, organized and interpreted the geophysical maps.