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The Vazante and Canastra groups revisited: Sm-Nd and Sr isotopes — evidence for contribution from Tonian intraplate magmatism during passive margin development along the SW São Francisco margin, Brazil

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Abstract

Combined Sm-Nd isotope studies and U-Pb ages of detrital zircons have shown significant differences between the provenance patterns of Neoproterozoic metasedimentary successions in the Southern Brasília belt. The Vazante and Canastra groups are passive margin deposits with source areas in the Archean/Paleoproterozoic São Francisco Craton basement and Mesoproterozoic cover units. In literature, the younging trend of Nd model ages observed in the Vazante Group is interpreted as resulting from the contribution of the Neoproterozoic Goiás Magmatic Arc. Also, detrital zircons younger than 0.90 Ga were not recorded in the Vazante or Canastra groups, which zircon populations are older than 0.93 Ga. This work presents new Sm-Nd and Sr isotope data of metasedimentary rocks from the Vazante and Canastra groups, collected in a 400 km2 area in northwest Minas Gerais, Brazil. The improved database of previously published and new data corroborates with the younging pattern of TDM along the Vazante Group. Isochronic diagrams show that samples from Vazante and Canastra groups scatter along mixing lines between the fields defined by the older cratonic rocks and the more juvenile ones. Here we present the Tonian Intraplate Magmatism within the São Francisco Craton as the juvenile source.

KEYWORDS: Sedimentary provenance; Brasília Belt; Brasiliano Orogeny; radiogenic isotopes.

INTRODUCTION

Isotope compositions of Nd and Sr have proved valuable tools for the study of the provenance of ancient sedimentary successions (McCulloch & Wasserburg 1978, Miller & O'Nions 1984, Patchett 2003). The Nd and Sr isotopic composition of modern fluvial systems also have allowed the identification of mixing of sediments with isotopically contrasting source areas (Basu *et al*. 1990, Allègre *et al*. 1996, Gingele & Deckker 2004). Shifts in the isotope composition and crustal residence ages along the stratigraphic record of sedimentary basins have been used to detect major changes in sedimentary provenance, reflecting continent-scale tectonic changes (Gleason *et al*. 1994, Boghossian *et al*. 2000, Stevenson *et al*. 2000, Savoy *et al*. 2000).

The Southern Brasília belt (Dardenne 2000, Valeriano *et al*. 2008a, Valeriano 2017) hosts expressive exposures of Neoproterozoic metasedimentary successions deposited along the western margin of the São Francisco paleocontinent (Alkmim & Martins Neto 2012). All of these successions presently crop out as metamorphic nappes and foreland fold-thrust systems (Fig. 1), as result of the ~0.63 to ~0.60 Ga Brasiliano orogenic events associated with terrane accretion and continental collisions during the amalgamation of the Gondwana supercontinent (Almeida *et al*. 2000, Brito Neves & Fuck 2013).

In the last decades, the stratigraphy and sedimentary provenance patterns of the Neoproterozoic metasedimentary units along the former western margin of the São Francisco paleocontinent have been investigated with the intensive use of whole-rock Nd isotopes (Pimentel *et al*. 2001, Seer *et al*. 2001, Silva *et al*. 2006, Rodrigues 2008, Santana 2011) and of U-Pb ages of detrital zircons (Piuzana *et al*. 2003, Valeriano *et al*. 2004a, 2004b, Pimentel *et al*. 2011, Dias *et al*. 2011, Rodrigues *et al*. 2012, Falci *et al*. 2018). These studies have established that some units, such as the Paranoá, Vazante, and Canastra groups, as well as the lower part of the Araxá Group, developed along the passive margin of the São Francisco Craton,

Supplementary material
Supplementary data associated with this article can be found in the online version: Supplementary Table A.

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with youngest detrital zircons ages around 0.90 Ga. In contrast, the Ibiá Group and the upper part of the Araxá Group show younger T_{DM} model ages and expressive contents of young (~0.60 Ga) detrital zircons, therefore interpreted as fore-arc units with contribution from the Goiás Magmatic Arc (Pimentel & Fuck 1992, Pimentel 1992, 2016, Pimentel *et al.* 1997, 2000, 2011, Rodrigues *et al.* 1999, 2012, Laux *et al.* 2005, Dias *et al.* 2011, Falci *et al.* 2018).

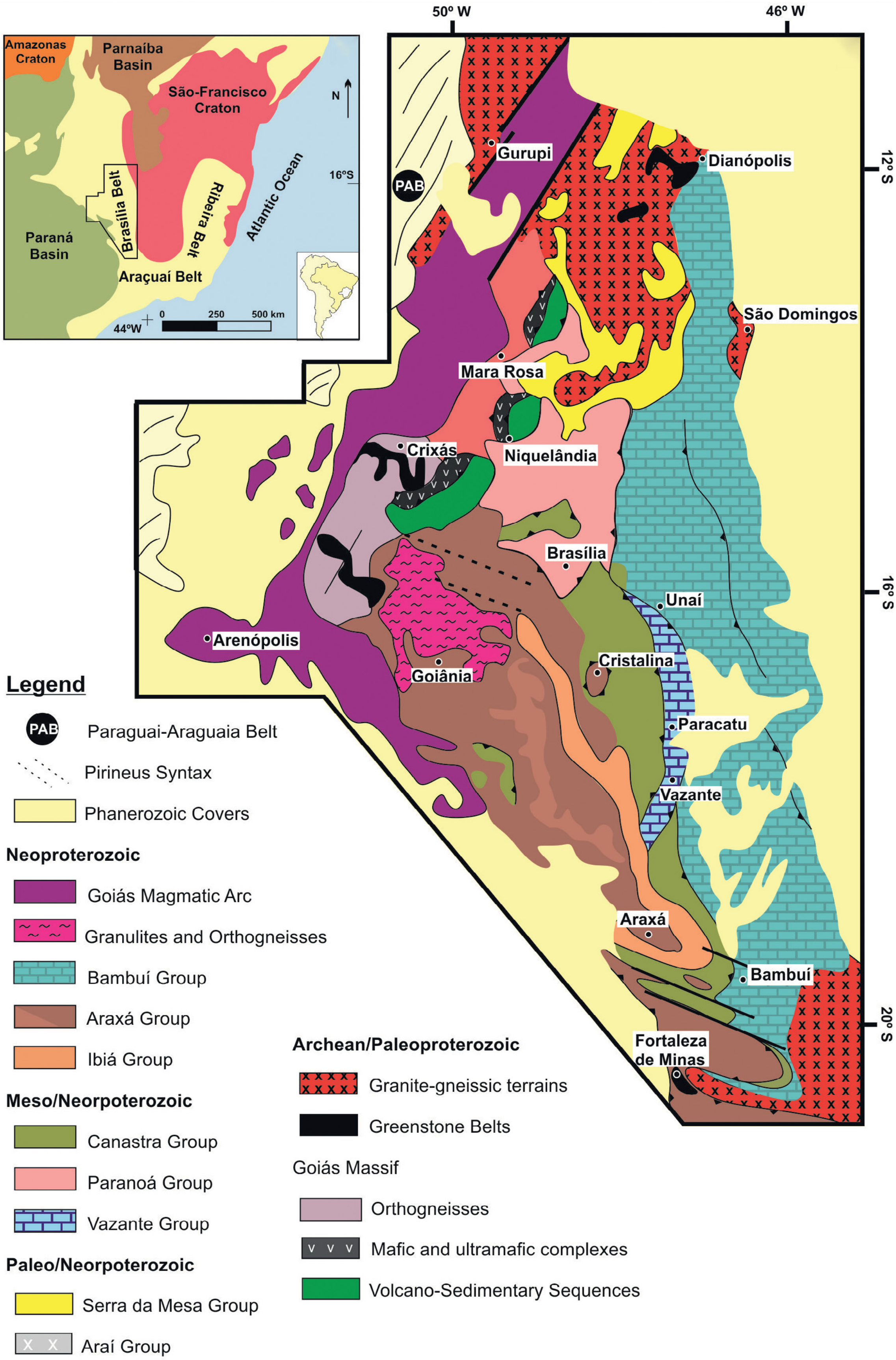

Figure 1. Geotectonic setting. (A) Neoproterozoic Brasília belt limit (black polygon); (B) Brasília belt and its units in the west edge of the São Francisco Craton (after Dardenne 2000).

More recently, works from Rodrigues (2008), Santana (2011) and Rodrigues *et al.* (2012) have shown a shift of T_{DM} ages with a younging trend along the stratigraphy of the Vazante Group, also suggesting contribution of juvenile detritus from the Goiás Magmatic Arc in these units. The detrital zircon record for the Vazante and Canastra groups, however, shows youngest concordant ages around 0.90 Ga, therefore precluding provenance from the Goiás Magmatic Arc. Additionally, Re-Os geochronology also indicates an onset of sedimentation older than 1.30 Ga for the Vazante Group, and older than 1.00 Ga for the Canastra Group (Bertoni *et al.* 2014).

To further investigate the provenance of the Vazante and Canastra groups, this work presents new Sm-Nd and Sr isotope whole-rock data for 38 samples from outcrops and borehole cores in the Vazante-Paracatu region, NW Minas Gerais state. This work also presents a new alternative hypothesis for explaining the younging uptrend of T_{DM} ages, based on the widespread occurrence of juvenile Tonian (ca. 0.90 Ga) intraplate magmatism (Teixeira 1985, Machado *et al.* 1989, Teixeira & Figueiredo 1991, Correa-Gomes & Oliveira 2002, Chaves & Neves 2005, Silva *et al.* 2008, Danderfer *et al.* 2009), coeval to rifting and passive margin development in the southern São Francisco Craton.

GEOLOGICAL SETTING

Since the end of the Rhyacian and Orosirian orogenic events that amalgamated the basement of the São Francisco-Congo Paleocontinent (Noce *et al.* 2000, Barbosa & Sabaté 2004, Barbosa *et al.* 2015, Caxito *et al.* 2015, Degler *et al.* 2018), this ancient paleo-continental block remained essentially stable from ~1.80 Ga until the onset of Neoproterozoic Brasiliano orogenic events (~0.64 Ga). During this protracted interval of platform conditions, the São Francisco paleocontinent (Heilbron *et al.* 2017) suffered at least four major rifting events that were recorded by rift-sag intracratonic sedimentary basins of the Espinhaço and São Francisco Supergroups (Pedrosa-Soares & Alkmim 2011, Alkmim & Martins-Neto 2012, Guadagnin *et al.* 2013, 2015) and associated intraplate magmatism.

The first rifting event took place at ~1.75 Ga with the installation of the Espinhaço continental rift system, where the Lower Espinhaço Supergroup (Brito Neves *et al.* 1995, Guadagnin *et al.* 2013, 2015, Santos *et al.* 2015) contains intercalations of felsic volcanic and epiclastic deposits. Coeval to the volcanic manifestations, alkaline plutonic magmatism is widespread within the basement complexes, such as the Lagoa Real suite, in Bahia State, Brazil (Cordani *et al.* 1992), and the Borrachudos, and associated suites in the reworked São Francisco basement of the Southern Araçuaí belt (Chemale Jr. *et al.* 1998, Silva *et al.* 2002).

The second rifting event occurred at ~1.50 Ga, with the deposition of the Middle Espinhaço Supergroup in the Paramirim aulacogen (Danderfer *et al.* 2009) and in the Chapada Diamantina plateau (Danderfer *et al.* 2009, Guadagnin *et al.* 2013, 2015).

The third rifting event took place at ~1.20 Ga, with the deposition of the diamond-bearing Sopa-Brumadinho Formation (Upper Espinhaço Supergroup) and overlying marine strata, interpreted as evolved in a sag-style sedimentary phase of the basin at about 1.20 Ga (Martins-Neto 2000, Chemale Jr. *et al.* 2012, Guadagnin *et al.* 2013, 2015, Santos *et al.* 2013).

The Lower and Middle Espinhaço Supergroup units are crosscut by basic and mafic (doleritic dikes and gabbros) intrusive rocks related to several magmatic events dated at: 1.70 Ga (Silva *et al.* 1995); 1.50 Ga (Babinski *et al.* 1999); 1.20 to 1.00 Ga (Renne *et al.* 1990); and 0.90 Ga (Machado *et al.* 1989, Silva *et al.* 2008).

Successful rifting eventually took place at ~0.90 Ga, leading to individualization of the São Francisco Congo (SFC) paleocontinent with the development of peripheral passive margin sedimentary basins (Alkmim & Martins-Neto 2012). In the western margin of the SFC paleocontinent (presently in the Southern Brasília belt), the passive margin sedimentary successions are represented by the Vazante Group, the Canastra Group and lower parts of the Araxá Group (Pimentel *et al.* 2001, Falci *et al.* 2018). This extensional episode is also accompanied by the last tholeiitic mafic dike emplacement episode cited above, at 0.90 Ga, recorded in the cratonic basement (*i.e.*, Salvador-Ilhéus, Perdões-Formiga, Quadrilátero Ferrífero region, Maravilha-Esmeraldas, Pará de Minas — Teixeira 1985, Teixeira & Figueiredo 1991, Correa-Gomes & Oliveira 2002, Chaves & Neves 2005) and expressive dike-sill complexes, such as the Pedro Lessa Suite (Machado *et al.* 1989), emplaced within the Espinhaço Supergroup strata (Danderfer *et al.* 2009).

The passive margin sedimentary basins around the SFC paleocontinent evolved until tectonic inversion during Brasiliano orogenic events related to the amalgamation of the Gondwana supercontinent. Coeval with passive margin development around the SFC paleocontinent also occurred subduction of oceanic lithosphere and development of magmatic arcs, which eventually accreted against the SFC paleocontinent. In the Brasília belt, the ~0.90 Ga Arenópolis, Sanclerlândia, and Mara Rosa orthogneisses display juvenile isotopic characteristics, interpreted as intra-oceanic magmatic arcs (Pimentel *et al.* 1991, Pimentel & Fuck 1992, Pimentel 2016). Arc magmatism persisted with more continental characteristics until accretion at ~0.63 Ga.

The Brasiliano orogeny, in the Southern Brasilia belt, started at ~0.64 Ga, with subduction of the distal continental margin and fore-arc successions, represented by the Ibiá Group and the upper part of the Araxá Group (Seer & Dardenne 2000, Piuzana *et al.* 2003, Valeriano *et al.* 2004a, 2004b, Silva *et al.* 2006, Falci *et al.* 2018). The collisional phase involved the accretion of microcontinents such as the Paranapanema block (Mantovani *et al.* 2005) and the Goías Massif (Jost *et al.* 2005), and of the Mara Rosa, Arenópolis and Goiás magmatic arcs. Exhumation of metamorphic nappes in the internal zones of the orogen (Fig. 1), such as the Araxá, Passos, and Varginha-Guaxupé nappes, took place at 0.61–0.60 Ga (Valeriano *et al.* 2004a, 2004b), with thrusting onto the external thrust-fold belt composed of the low-grade metasedimentary rocks of the Vazante and Canastra groups, and the Bambuí group foreland basin deposits (Dardenne 2000, Valeriano *et al.* 2004a, 2004b, Alkmim & Martins-Neto 2012, Reis *et al.* 2017, Valeriano 2017, Uhlein *et al.* 2017).

Vazante Group

The Vazante Group (Fig. 1B) crops out along with a ~250 km in N-S oriented belt among the lowermost sheets that thrust the Bambuí Group rocks in the foreland zone. Quartzitic and phyllitic thrust sheets of Canastra Group rocks (Campos Neto 1984) cover the Bambuí sequence tectonically. The Vazante Group comprises a pelitic-dolomitic shallow marine platform sequence of passive margin environment, originally considered as a formation within the Bambuí Group (Branco & Costa 1961).

The age of sedimentation of the Vazante group is controversial. *Conophyton Sp.* stromatolites are the only paleontological indication for the sedimentation age interpreted by Dardenne (2000) as a loose indication for Late Mesoproterozoic, also loosely indicated by a Re-Os age of 1304 ± 210 Ma (Bertoni *et al.* 2014). A Neoproterozoic upper age limit for the sedimentation of the Vazante Group is better constrained by U-Pb ages of the youngest concordant detrital zircons of the Rocinha Formation, around 935 ± 14 Ma (Rodrigues *et al.* 2012).

The sedimentation character of the Vazante Group varies from siliciclastic to carbonatic along the stratigraphic column. The lithostratigraphic column of the Vazante Group evolved along many publications, until Dardenne (2000) presented it in the most complete form, subdivided in seven formations. From base to top, the formations are Retiro/Santo Antônio do Bonito, Rocinha, Lagamar, Serra do Garrote, Serra do Poço Verde, Morro do Calcário and Serra da Lapa.

The Santo Antônio do Bonito Formation is the basal unit formed by white quartzite, locally conglomeratic, interlayered with slaty levels and restrict diamictite horizons. Related to these rocks are phosphorite occurrences in Coromandel (MG). The Rocinha Formation is composed by rhythmic sandy and pelitic rocks, with dark-grey carbonatic slates with pyrite and thin phosphatic laminations. The Lagamar Formation consists of a basal psammo-pelitic-carbonated alternation of conglomerates, quartzite, and slates of the Arrependido Member and the upper stromatolitic bioherm dolomites with breccias and dark-grey limestones of the Sumidouro Member. The Serra do Garrote Formation is composed by dark-grey to greenish-grey slates, sometimes rhythmic and carbonaceous, with thin pyrite-rich interbedded quartzite. The Serra do Poço Verde Formation is a dominantly dolomitic sequence intercalated with thin pelitic layers, subdivided into four members: Lower Morro do Pinheiro; Upper Morro do Pinheiro; Lower Pamplona; and Medium Pamplona. The dolomites vary in color, from dark/light-grey to pink, with cyanobacteria mats, columnar stromatolites sometimes with Birdseye's features, with the presence of breccias and interbedded pelitic rocks and greenish marls. The Morro do Calcário Formation corresponds to the Upper Pamplona Member of Rigobello *et al.* (1988) and is a stromatolitic bioherm dolomite association with dolerite, breccias, and oolitic and oncolytic dolorudite facies. The Serra da Lapa Formation is the upper unit of the Vazante Group, firstly described by Madalosso and Valle (1978) and Madalosso (1980), consisting of grey carbonaceous phyllites and grey carbonatic-rich slates with lenses of dolomite, meta-siltstones, and quartzite.

Dolomites of the Vazante Group host the most important Zn and Pb deposits in Brazil, the Vazante and Morro Agudo mines. The Vazante Mine ore bodies are tectonic controlled by a main SE-dipping normal fault and occur within dolomitic strata, between the lower Serra do Pamplona and upper Morro do Pinheiro members, of the Serra do Poço Verde Formation, that is controlled by a main SE-dipping normal fault (Dardenne 2000, Monteiro *et al.* 2006, 2007). The Morro Agudo deposits occur in fore-reef facies of dolomitic rocks from the Morro do Calcário Formation (Dardenne 1978).

Canastra Group

The Canastra Group (Fig. 1B) is thrusted upon the Vazante, Paranoá and Bambuí groups (Campos Neto 1984), and is subdivided, from base to top, into three formations by Dardenne (2000): Serra do Landim, Paracatu and Chapada dos Pilões.

The basal Serra do Landim Formation was initially attributed to the Vazante Group (Madalosso & Valle 1978, Madalosso 1980) until the work of Freitas-Silva and Dardenne (1994), that suggested a tectonic sequence in which this unit was in the base of the Canastra Group. This unit composes greenish laminated calc-phyllites with intercalations of light-grey calc-schists.

The intermediate Paracatu Formation was firstly defined by Almeida (1969) as thick beds of pyrite-bearing black carbonaceous phyllites with intercalations of quartzite lenses. Subdivided into two members by Freitas-Silva and Dardenne (1994), the lower Morro do Ouro member presents relatively continuous quartzite levels, and the Serra da Anta member corresponds to carbonaceous phyllites with thin quartzite levels. The Paracatu formation hosts the largest gold mine presently in operation in Brazil, where Au occurs in syn-metamorphic quartz veins within the carbonaceous phyllites (Freitas-Silva 1991).

The topmost Chapada dos Pilões Formation is composed by turbiditic intercalations of quartzite and phyllite of the lower Serra da Urucânia Member, and by shallow platform quartzites of the overlying Serra da Batalha Member.

The sedimentation age of the Canastra Group is loosely constrained by the youngest U-Pb ages of concordant detrital zircons of 1.03 Ga (Rodrigues *et al.* 2010) and by a Re-Os age of 1002 ± 45 Ma, from the basal Paracatu Formation (Bertoni *et al.* 2014).

SAMPLING AND ANALYTICAL PROCEDURES

Sampling

The studied samples are fine-grained metasedimentary rocks, either meta-pelitic slates or sericite phyllites (Tab. 1). Fine-grained metasedimentary clastic rocks were chosen because they normally reflect mixtures of source areas from a wider geographic scope in sedimentary basins, as compared to sandstones or coarser sediments (McCulloch & Wasserburg 1978, Basu *et al.* 1990).

Table 1. UTM coordinates and a brief description of the 38 analyzed samples from the Vazante and Canastra groups rocks.

SAMPLE	NORTHING	EASTING	DESCRIPTION
CANASTRA GROUP			
Paracatu Formation			
MOC - 010A			
MOC - 010B	302807	8021069	Fine-grained grey-blueish carbonaceous phyllite with meta-arenite lenses, pyrite and quartz veins extremely deformed
MOC - 010C			
MOC - 200	297933	8022512	Fine-grained grey-greenish laminated slate interlayered with thin carbonaceous strata with sericite
MOC - 203	297803	8022914	Fine-grained grey-blueish laminated slate with sericite
MOC - 442	292971	8015284	Carbonaceous phyllite
MOC - 644B	305582	8017924	Medium to coarse-grained white quartzite with slate pebbles and pyrite
Serra do Landim Formation			
VZ-MA-F42-4A			Grey carbonaceous phyllite interlayered with meta-arenite
VZ-MA-F42-4B	306273	8063126	
VZ-MA-F42-5A			Grey carbonaceous phyllite interlayered with meta-arenite
VZ-MA-F42-5B			
VAZANTE GROUP			
Serra da Lapa Formation			
MOC - 446	296702	8012710	Fine-grained grey slate
MOC - 447	296670	8012594	Fine-grained greenish laminated slate
MOC - 558B	294536	8012513	Silicified grey carbonaceous slate with lenses of meta-arenite and meta-pelite
MOC - 615	294624	8006440	Silicificated grey marble
MOC - 640	297803	8011576	Fine-grained beige laminated phyllite interlayered with carbonaceous slates and meta-arenites lenses
MOCT-01			Intercalations of carbonaceous phyllites and marbles
MOCT-02			
MOCT-03			Greenish dolarenite
MOCT-04	304263	8018145	Laminated carbonaceous phyllite
MOCT-05			Laminated carbonaceous phyllite interlayered with dololutite and slate lenses
MOCT-06			Dolarenite with algal mats and dissolutions interlayered with black carbonaceous slates with pyrite
MOCT-11			Laminated carbonaceous phyllite interlayered with marls
VZ-MA-F42-1			Grey carbonaceous phyllite interlayered with meta-arenite
VZ-MA-F42-2	306273	8063126	Grey carbonaceous phyllite interlayered with meta-arenite
VZ-MA-F42-3			Grey carbonaceous phyllite with lenses of meta-arenite
Morro do Calcário Formation			
MOC - 023A	297529	8019983	Fine-grained grey-bluish slate with thin lenses of meta-arenite, quartz veins and fractures
MOC - 044A	297140	8019443	Fine-grained grey-bluish slate with thin lenses of meta-arenite
MOC - 044B			Fine-grained grey-bluish slate with thin lenses of meta-arenite
Serra do Poço Verde Formation			
AMF - 217 - 1	312248	8102188	Grey carbonaceous phyllite with lenses of meta-arenite
AMF - 217 - 2			Grey carbonaceous phyllite with lenses of meta-arenite and intraformational breccias
Serra do Garrote Formation			
AMF - 217 - 3			Grey carbonaceous phyllite with lenses of meta-arenite
AMF - 217 - 4	312248	8102188	Black carbonaceous phyllite
AMF - 217 - 5			Black carbonaceous phyllite with lenses of meta-arenite
AMF - 217 - 6			Grey carbonaceous phyllite with lenses of meta-arenite
MOC - 527	308765	8020980	Fine-grained black carbonaceous phyllite with water intemperate crust
MOC - 561	296257	8012611	Fine-grained pink silicificated slate with algal mats

Thirty-eight samples (Tab. 1) from the Vazante Group upper units and the Canastra Group were selected from fresh outcrops and drill cores for Sm-Nd and Sr isotope analysis. The samples are distributed in an area of 400 km² around the Vazante town (Fig. 2), where detailed geologic maps and structural data were recently presented by Carvalho *et al.* (2016).

Twenty-six samples of slates and phyllites from the Vazante Group and 12 samples from the Canastra Group (Tab. 1) were analyzed. The Vazante Group samples comprise, from bottom to top: six carbonaceous slate samples from the basal Serra do Garrote Formation; two slate samples from the Serra do Poço Verde Formation; three slate samples from the middle Morro do Calcário Formation; and fifteen fine-grained carbonaceous phyllite samples from the upper Serra da Lapa Formation. The Canastra Group samples comprise eight phyllite samples from the Paracatu Formation and four from the Serra do Landim Formation.

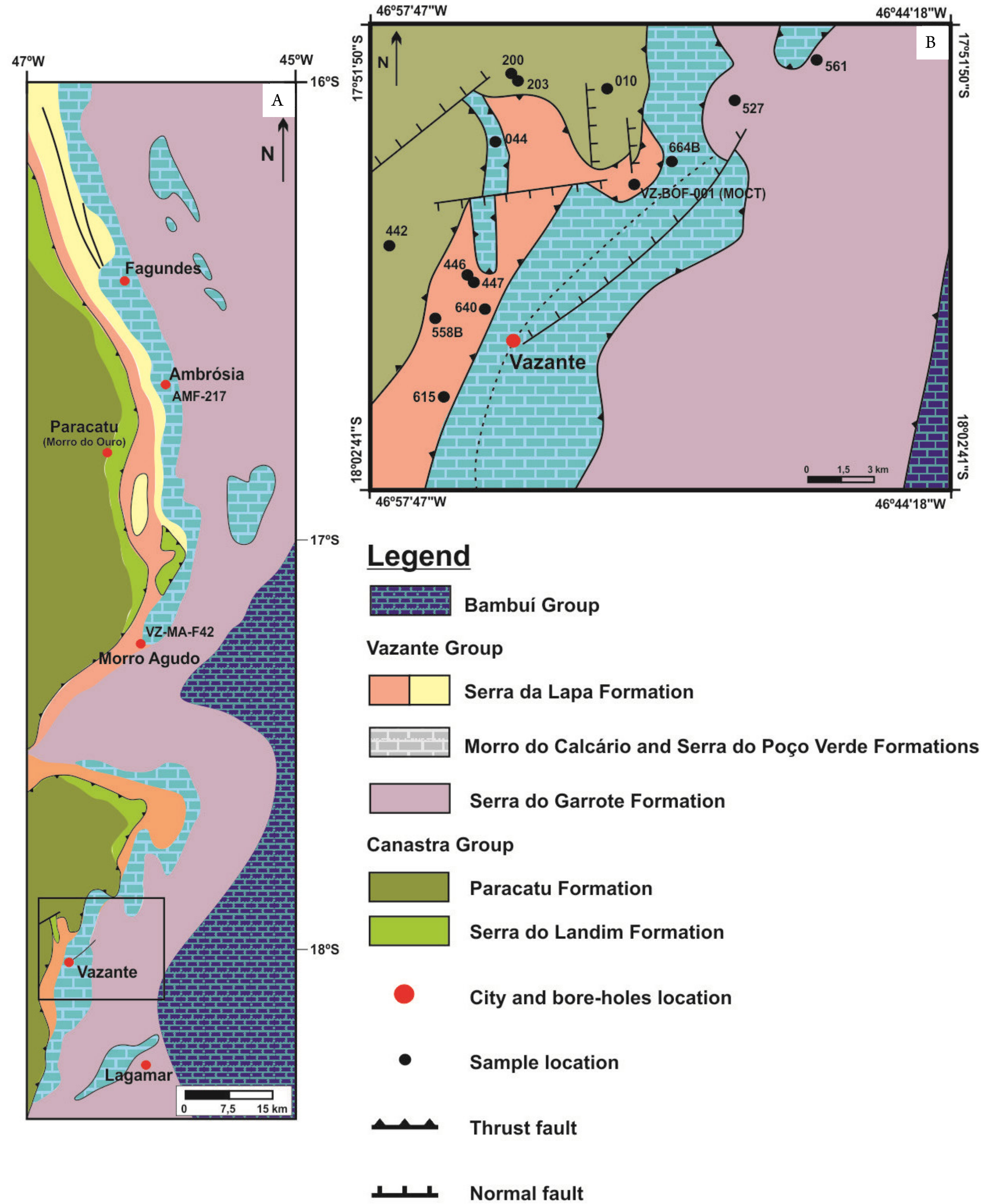

Figure 2. Sample location maps. (A) Sampled drill cores in the geological map of Vazante-Paracatu region of Dardenne (2000 *apud* Monteiro *et al.* 2006, 2007). Rectangle refers to a map area of (B) sampled outcrops in the geological map of the Vazante area, after Carvalho *et al.* (2016).

Analytical procedures

Samples were cut and milled at the Geological Laboratory of Samples Processing (Laboratório Geológico de Processamento de Amostras — LGPA), from the Universidade do Estado do Rio de Janeiro (UERJ), using a Spex mixer/mill.

The chemical and spectrometric procedures were carried out in the Laboratory of Geochronology and Radiogenic Isotope (Laboratório de Geocronologia e Isótopos Radiogênicos — LAGIR), at the UERJ (Valeriano *et al*. 2003, 2008b, 2009, Neto *et al*. 2009), where positive air pressure clean rooms were equipped with high efficiency particulate arrestance (HEPA) air filters. The chemical preparation started with the digestion of approximately 50 mg of sample powder, mixed with a ^{150}Nd/^{149}Sm spike double tracer solution dissolved in Savillex® polytetrafluoroethylene (PTFE) beakers vials. Samples dissolution occurred in cycles of two periods during 5 days with hydrofluoric acid (HF) (3 mL at 49%) and HNO_3 (0.5 mL at 7 M). Chemical separation of Sr, Sm, and Nd occurred according to the techniques described by Gioia (1997), using Teflon columns filled with chromatographic ion exchange resins. In the primary column, the AG 50 W-X8BIORAD ion exchange resin was used to separate the Sr (with HCl 2.5 M) and rare-earth elements (REE) (with HCl 6 M). In the secondary column, the LN-spec Eichrom resin was used for the extraction of Nd (with HCl 0.18 M) and Sm (with HCl 0.5 M). The Sr, Sm, and Nd are then separately deposited onto previously degassed double Re filaments, together with H_3PO_4 (1N) as ionization activator.

The spectrometric analyses were performed with the TRITON — ThermoFinnigan Multi-collector — , a thermal ionization mass spectrometer (TIMS), in which isotope ratios measured with up to 8 Faraday cups in multi-collector (static) mode. The isotopic ratios were averages of 160 cycles for Nd, 80 cycles for Sm and 100 cycles for Sr. Isotopic normalizations were made using the natural ratios of ^{87}Sr/^{86}Sr = 8.375209, ^{146}Nd/^{144}Nd = 0.7219, ^{152}Sm/^{149}Sm = 0.56083. Total blanks were measured below 200 pg for Nd and below 70 pg for Sm. Repeated analyses of NBS-987 (n = 140) and JNd1 (n = 214) standard reference materials (Tanaka *et al*. 2000) yielded the average ratios ^{87}Sr/^{86}Sr = 0.710239 ± 0.000007 and ^{143}Nd/^{144}Nd = 0.512100 ± 0.000006 (2σ absolute standard errors).

The Rb and Sr contents of respectively 125 and 142 ppm, used for the calculation of Nd and Sr initial isotope ratios at 0.90 Ga, were taken from the North American Shale Composite (NASC) reference values for fine-grained rocks given by Gromet *et al*. (1984).

RESULTS

The Sm-Nd and Sr isotope analytical results (Tab. 2) for Vazante and Canastra groups show a wide range of very evolved $\varepsilon Nd_{(0)}$ for both group samples, ranging from -14 to -27 and from -6 to -29, respectively. Strontium isotope ratios show very radiogenic values, from 0.742539 to 0.976970 in the Vazante Group samples, and from 0.739460 to 0.917562 in the Canastra Group samples.

To evaluate differences of isotopic composition at the approximate time of sedimentation of the Vazante and Canastra groups, the measured isotope ratios were calculated for initial ratios at 0.90 Ga, which coincides roughly with the U-Pb age of the youngest concordant detrital zircon populations in these units (Valeriano *et al*. 2004a, 2004b, Rodrigues 2008, Pimentel *et al*. 2011).

Calculated isotope ratios for 0.90 Ga result in much narrower ranges of $\varepsilon Nd_{(900)}$ for the Vazante and Canastra groups, from -4.8 to -14.3 and from -4.8 to -16.0, respectively (Fig. 3). These values indicate roughly the same spectra of source areas for both units. A shift can be observed from the bottom units from the Vazante Group (Serra do Garrote, Morro do Calcário and Serra do Poço Verde formations), with high negative $\varepsilon Nd_{(900)}$ of about -10.0, increasing to -5.0 in the Serra da Lapa Formation. Calculated $\varepsilon Nd_{(900)}$ for the Canastra Group is concordant to the upper units of the Vazante Group (Serra da Lapa Formation). The range of calculated initial ^{87}Sr/^{86}Sr ratios (900 Ma) is also similar for both Canastra and Vazante groups, *i.e.*, from 0.740703 to 0.975134 and from 0.737624 to 0.915732, respectively (Fig. 3).

Ratios of ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd are very fractionated and vary respectively from 0.0700 to 0.1842 and from 0.511359 to 0.512307 for the Vazante Group, and from 0.0935 to 0.1254 and from 0.511299 to 0.511948 for the Canastra Group.

Both Vazante and Canastra groups display T_{DM} model ages respectively, from 1.70 Ga to 2.35 Ga and from 1.67 Ga to 2.16 Ga (Fig. 3). For the Vazante Group, although youngest T_{DM} ages of 1.70 Ga are related to both the upper Serra da Lapa Formation and the basal Serra do Garrote Formation, an indication of the evolutionary trend in model ages along the stratigraphy are interpreted by data analysis.

DISCUSSION

For evaluation of the significance of isotope ratio patterns in the Vazante and Canastra groups in terms of their sedimentary provenance, a database of Sm-Nd and Sr isotope ratios was compiled from the literature (Suppl. Tab.), including the most representative lithologies of the basement of São Francisco Craton, including Archean-Paleoproterozoic granite-greenstone associations and mafic-ultramafic complexes and Tonian anorogenic magmatic associations.

The 38 new isotope data for Vazante and Canastra groups' samples were integrated with previously available data for the same units in Figure 4 (Pimentel *et al*. 2001, Seer *et al*. 2001, Silva *et al*. 2006, Rodrigues 2008, Santana 2011, Rodrigues *et al*. 2012). Vazante and Canastra groups show a range of model ages very similar with highly negative εNd. The T_{DM} model ages vary from 1.41 to 3.03 Ga and from 1.47 and 2.34 Ga, respectively, for Vazante and Canastra groups. As also observed by Rodrigues (2008), Santana (2011) and Rodrigues *et al*. (2012), the T_{DM} model ages describe a younging trend, considering the major mode of T_{DM} age distribution. The Serra do Garrote Formation presents a dominant peak at ca. 2.10 Ga, followed by the

Table 2. Sm-Nd and Sr isotope results for Vazante and Canastra groups.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Abs. Error (2s 10^{-6})	T^{DM} (Ga)	$^{87}Sr/^{86}Sr$	Abs. Error (2s 10^{-6})
CANASTRA GROUP								
Paracatu Formation								
MOC - 010A	4.5	21.9	0.1254	0.511886	9	1.88	0.864346	8
MOC - 010B	5.2	29.9	0.1061	0.511807	6	1.67	0.868184	9
MOC - 010C	6.8	36.6	0.1120	0.511821	8	1.74	0.917568	6
MOC - 200	4.6	22.4	0.1254	0.511894	5	1.86	0.800633	7
MOC - 203	7.3	37.2	0.1190	0.511681	6	2.06	0.784052	10
MOC - 442	1.2	7.9	0.0961	0.511673	3	1.70	0.739460	7
MOC - 644B	3.3	21.3	0.0935	0.511299	3	2.10	0.860456	9
Landim Formation								
VZ-MA-F42-4A	5.1	26.4	0.1179	0.511906	5	1.71	0.756804	4
VZ-MA-F42-4B	5.1	26.4	0.1170	0.511921	5	1.68	0.790565	7
VZ-MA-F42-5A	18	87.4	0.1243	0.511948	6	1.76	0.751947	12
VZ-MA-F42-5B	5.1	24.9	0.1237	0.511921	4	1.79	0.753417	3
VAZANTE GROUP								
Serra da Lapa Formation								
MOC - 446	12	59.9	0.1209	0.511668	7	2.12	X	X
MOC - 447	4.7	29.1	0.0980	0.511548	6	1.88	X	X
MOC - 558B	3.2	15	0.1275	0.511778	9	2.09	0.753052	10
MOC - 615	5.4	27.3	0.1196	0.511938	7	1.70	0.797272	6
MOC - 640	14.4	69.8	0.1252	0.511932	7	1.80	0.890711	5
MOCT-01	4.9	27.5	0.1073	0.511655	7	1.89	0.888410	6
MOCT-02	5	27	0.1129	0.511818	8	1.76	0.827213	8
MOCT-03	2.3	16	0.0851	0.511241	9	2.04	X	X
MOCT-04	19.1	62.6	0.1842	0.512307	8	3.03	0.779764	9
MOCT-05	3.9	23.7	0.0983	0.511396	6	2.06	0.976970	4
MOCT-06	1.9	16.1	0.0700	0.511187	9	1.89	0.866732	9
VZ-BOF-001-11	11.9	45.3	0.1588	0.512145	4	2.23	0.800081	8
VZ-MA-F42-1	1.3	9	0.0869	0.511534	7	1.74	0.912539	8
VZ-MA-F42-2	3.1	15.5	0.1218	0.511931	6	1.74	0.759687	8
VZ-MA-F42-3	5.5	27.6	0.1214	0.511914	3	1.76	0.891380	7
Morro do Calcário and Serra do Poço Verde Formation								
MOC - 023A	5.9	35.5	0.1012	0.511558	8	1.91	X	X
MOC - 044A	3.1	19.9	0.0947	0.511512	9	1.87	0.882314	8
MOC - 044B	3.9	23	0.1022	0.511510	9	1.99	0.906522	8
AMF - 217 - 1	5.8	32.6	0.1080	0.511560	6	2.02	0.911520	8
AMF - 217 - 2	1.1	5.7	0.1190	0.511359	6	2.52	0.742539	8
Serra do Garrote Formation								
AMF - 217 - 3	0.5	3.1	0.0997	0.511420	9	2.06	0.820065	9
AMF - 217 - 4	3.7	2.8	0.1090	0.511539	5	2.07	0.753906	6
AMF - 217 - 5	6	33.5	0.1079	0.511435	8	2.18	X	X
AMF - 217 - 6	5.8	33	0.1056	0.511450	9	2.12	0.886721	5
MOC - 527	3.4	15.9	0.1288	0.511632	9	2.35	0.863246	7
MOC - 561	1.8	9.5	0.1172	0.511662	2	2.05	0.846521	7

Abs.: absolute

Morro do Calcário and Serra do Poço Verde formations, with major modes around ca. 2.00 Ga. These units are followed by the Serra da Lapa Formation, which shows dominant mode at 1.80 Ga (Figs. 3 and 4).

Ranges of $\varepsilon Nd_{(900)}$ values and ratios of $^{147}Sm/^{144}Nd$ also express this upward shift. Units of the inferior portion of the Vazante group column show more negative $\varepsilon Nd_{(900)}$ ranges than the upper Serra da Lapa Formation and rocks from the Canastra Group. Results for the Serra do Garrote vary from -8 to -13, and between -10 to -12 for the Morro do Calcário and Serra do Poço Verde formations. The uppermost unit, the Serra da Lapa formation, and the overlying rocks from the Canastra group, with ranges respectively of -1 to -15 and from -3 to -17, indicates an input of juvenile material.

Values of $f_{(Sm/Nd)}$ are between -0.06 and -0.54 for the Vazante Group, and between -0.14 and -0.54 for the Canastra Group.

The metasedimentary units of the Southern Brasília belt exhibit a pattern of Proterozoic T_{DM} model ages, usually interpreted as derived from erosion of two contrasting source areas (Pimentel *et al.* 2001, 2011, Rodrigues 2008, Santana 2011, Rodrigues *et al.* 2012, Falci *et al.* 2018), a Paleoproterozoic/Archean rock association in the São Francisco Craton and Neoproterozoic juvenile sources from the Goiás Magmatic Arc. The São Francisco Craton is pointed as the main source area to Vazante and Canastra groups, while the Goiás Magmatic Arc is pointed out as a more restricted, less expressive younger source (Pimentel *et al.* 2001, 2011, Seer *et al.* 2001, Rodrigues 2008, Dias *et al.* 2011).

The new and compiled Sm-Nd data for the Vazante and Canastra groups are presented in the T_{DM} age histograms of Figure 5, in comparison with another major isotopic rock reservoir as potential source areas. Differences in T_{DM} Nd model ages (DePaolo & Wasserburg 1976) for sedimentary rocks, or their metamorphosed products, should reflect differences in the contributions of source areas with different ranges of T_{DM} ages. The basement associations of the SFC show T_{DM} model ages older than 1.80 Ga (Teixeira 1985, Sato 1998), in contrast with Tonian anorogenic magmatic rocks emplaced in the cratonic area, and with rocks from the accreted Goiás Magmatic Arc. In the cratonic area, Tonian anorogenic tholeiitic mafic swarms and dike-sill complexes display T_{DM} values between 0.93 Ga and 1.63 Ga (Correa-Gomes & Oliveira 2002, Chaves & Neves 2005, Rosa *et al.* 2005, Girardi *et al.* 2013). The Goiás Magmatic Arc rocks display T_{DM} ages varying between 0.77 and 1.41 Ga (Rodrigues *et al.* 1999, Pimentel *et al.* 2000, Laux *et al.* 2005).

The older (> 1.90 Ga) T_{DM} values found in the Vazante and Canastra group rocks, along with the main Paleoproterozoic/Archean modes of U-Pb ages of detrital zircons, clearly indicate the São Francisco cratonic basement as the main source area for the sedimentation of the basal passive margin units (Pimentel *et al.* 2001, 2011). However, the younger T_{DM} ages, as well as

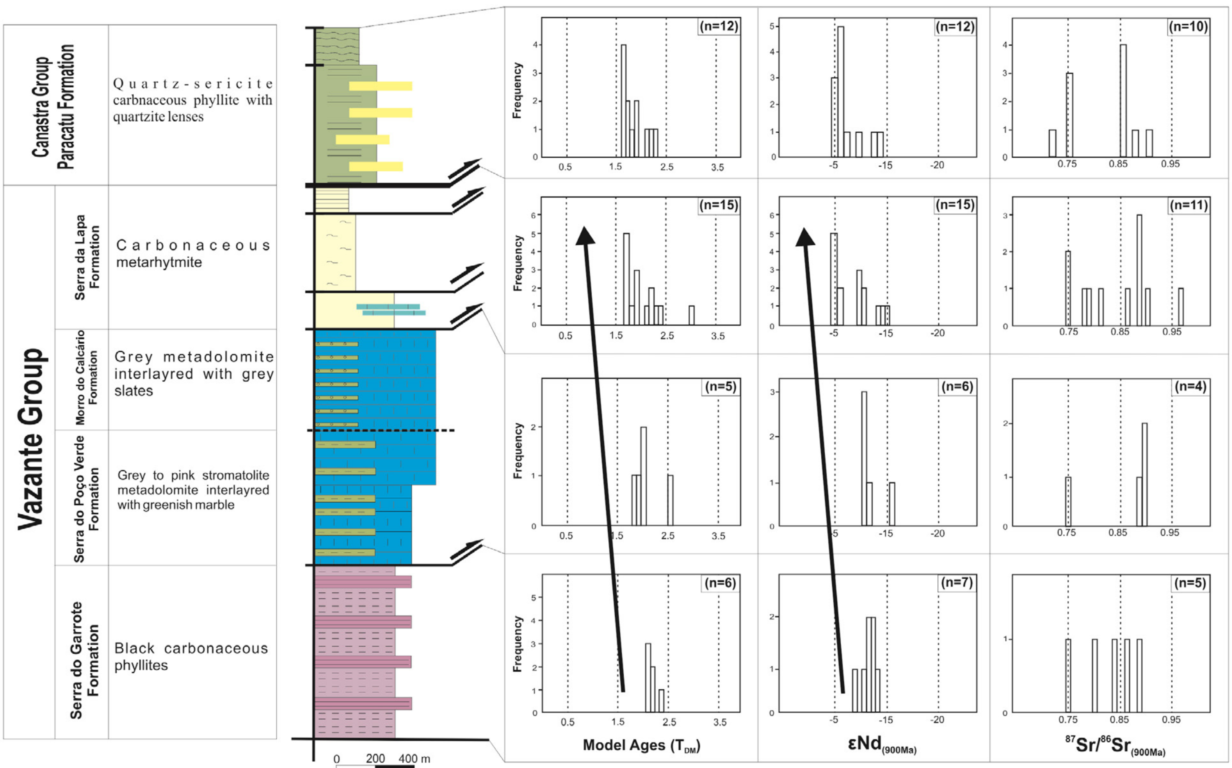

Figure 3. Stratigraphic column for the Vazante and Canastra groups units (Carvalho *et al.* 2016), with the distribution of new T_{DM} ages, and εNd and $^{87}Sr/^{86}Sr$ ratios calculated for 900 Ma. The Nd data show younging trend provenance patterns for the Vazante and Canastra groups.

the significant presence of zircon populations younger than 1.20 Ga found in these units, must be explained by a mixture of these old cratonic sources with some younger, more juvenile source.

Based on detrital zircons ages between 1.35 and 1.16 Ga found by Valeriano *et al.* (2004a), Westin and Campos Neto (2013) and Frugis *et al.* (2018) in the Southern Brasília belt metasedimentary rocks, Klein (2008) suggested that the 1.20 Ga Nova Aurora orthogneisses are a potential source area of sediments. The absence of Ediacaran (~0.60 Ga) detrital zircons from the Goiás Magmatic Arc and the presence of Neoproterozoic (~1.00 Ga) detrital zircons in the record of the Vazante and Canastra groups (Valeriano *et al.* 2004a, 2004b, Pimentel *et al.* 2011, Rodrigues *et al.* 2012, Pimentel 2016) are used to interpret these younger

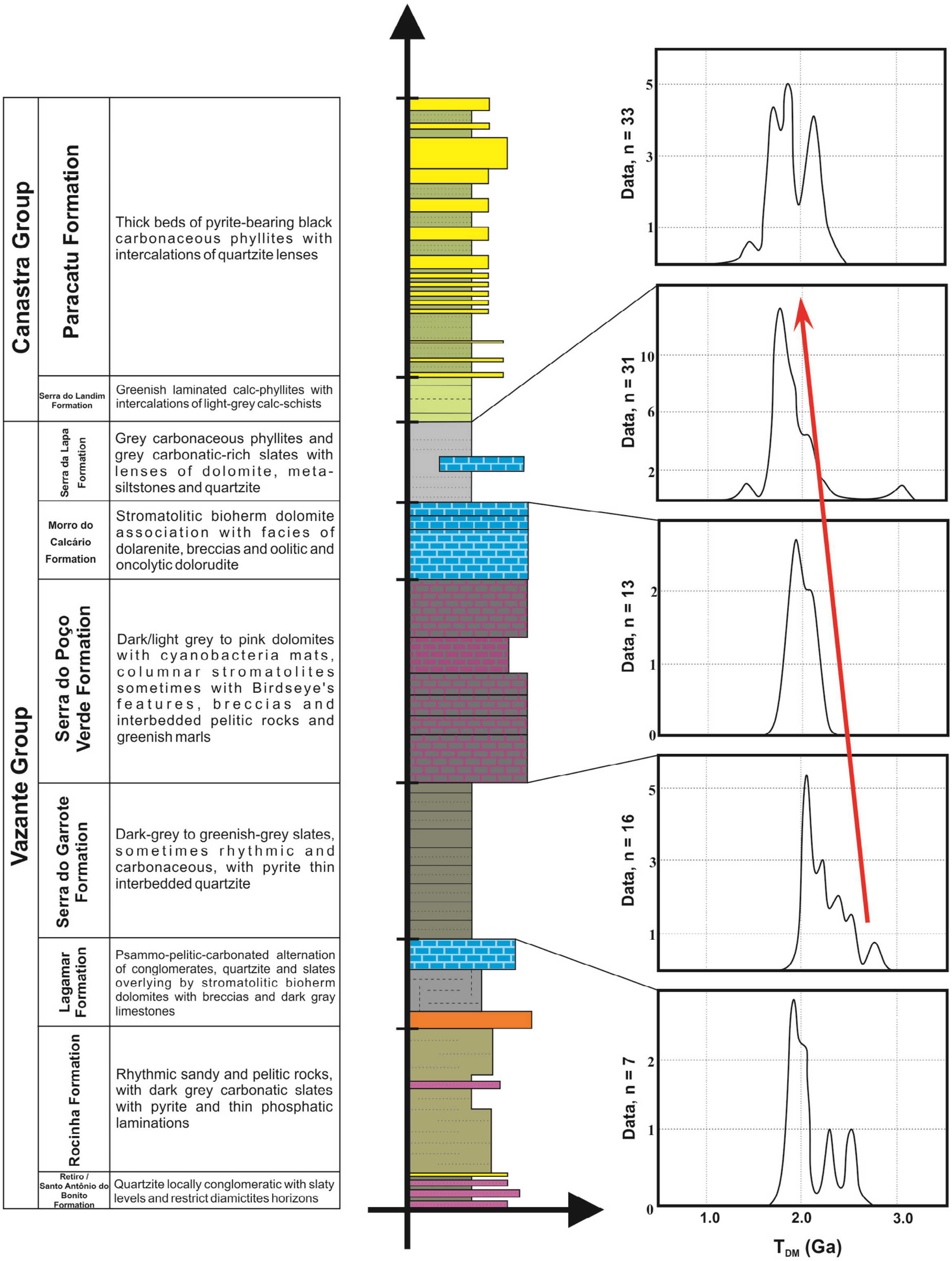

Figure 4. T_{DM} data in Vazante and Canastra groups stratigraphic column (based on Dardenne 2000) with new and previous Sm-Nd T_{DM} ages for their metasedimentary rocks (Pimentel *et al.* 2001, Seer *et al.* 2001, Silva *et al.* 2006, Rodrigues 2008, Santana 2011, Rodrigues *et al.* 2012, Carvalho 2015).

Mesoproterozoic T_{DM} ages. Here it is postulated that those ages should more likely be from juvenile Tonian intraplate magmatic rocks within the SFC. Reported examples are the tholeiitic dolerites and gabbros of the Pedro Lessa Suite and mafic-ultramafic complexes that border the SFC craton, such as the Brejo Seco Complex, in the northern SFC margin (Salgado *et al*. 2016).

There are others possibilities of Tonian source areas of zircon grains besides intraplate magmatism of Pedro Lessa Suite and Brejo Seco Complex. The expressive rift-related bimodal volcanic rocks of the West Congo Belt and their correlatives in Brazil are one of them (Tack *et al*. 2001). Also, the Cariris Velhos Belt (magmatic arc), of the Borborema Province (Santos *et al*. 2010), which actually occurs in the fold belts that border the northern SFC margin, such as in the Riacho do Pontal Belt (Caxito *et al*. 2014b) and in the Sergipano Belt (Oliveira *et al*. 2010), would be another one.

The youngest ages of sedimentation for Vazante and Canastra groups are respectively of 1.30 Ga and 1.00 Ga (Bertoni *et al*. 2014). U-Pb zircon ages data explains the 1.00 Ga age of deposition, but do not allow to interpret the isochron of 1.30 Ga as the depositional age of Vazante Group. An alternative explanation for the observed T_{DM} pattern would be a progressive exposure of some older isotopically juvenile rock reservoir, of which there is no obvious candidate. Furthermore, even in this case, the 0.90 Ga zircon content must to be accounted for.

The $f_{(Sm/Nd)}$ *vs*. εNd isochronic diagram of Figure 6 (McDaniel *et al*. 1994a, 1994b) corroborates to the hypothesis of mixing of old, cratonic sources, with younger, juvenile Tonian anorogenic magmatic associations. The Vazante and Canastra group samples scatter around a 2.00 Ga reference line, interpreted here as a mixing line of old cratonic sources, which scatter along the 2.70 Ga reference isochron and Tonian

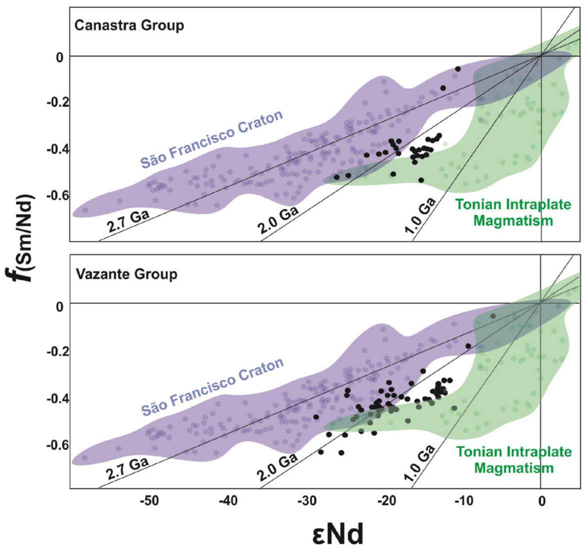

Figure 6. Sm-Nd provenance patterns in εNd versus $f_{(Sm/Nd)}$ diagram for the metasedimentary rocks from Vazante (n = 67) and Canastra (n = 33) groups, along with data from the cratonic basement (n = 191, Teixeira 1985, Sato 1998) and Tonian anorogenic magmatic rocks (n = 39, Tack *et al.* 2001, Correa-Gomes & Oliveira 2002, Chaves & Neves 2005, Rosa *et al.* 2005, Girardi et al. 2013, Salgado *et al.* 2016).

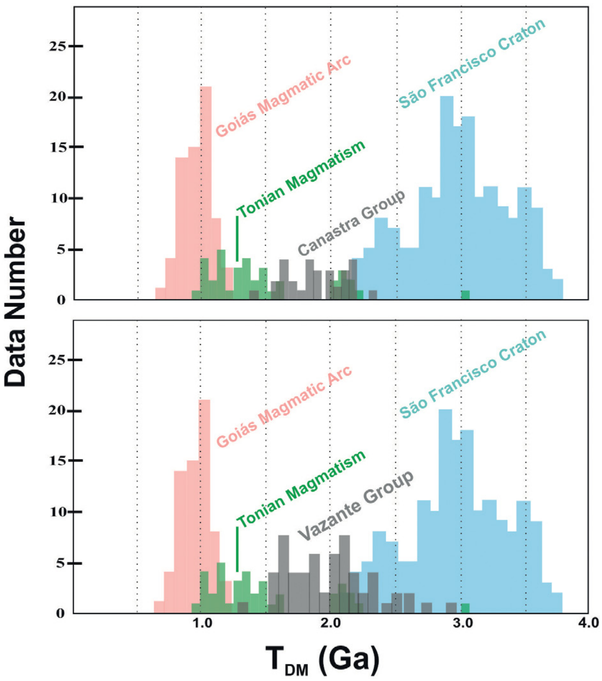

Figure 5. T_{DM} histograms for the metasedimentary rocks from Vazante and Canastra groups (n = 100, Pimentel et al. 2001, Seer *et al.* 2001, Silva *et al.* 2006, Rodrigues 2008, Santana 2011, Rodrigues *et al.* 2012, Carvalho 2015), along with data from the basement (n = 191, Teixeira 1985, Sato 1998) and Tonian anorogenic magmatic rocks (n = 39, Tack *et al.* 2001, Correa-Gomes & Oliveira 2002, Chaves & Neves 2005, Rosa *et al.* 2005, Girardi *et al.* 2013, Salgado et al. 2016) among the cratonic area, and the Goiás Magmatic Arc (n = 82, Pimentel & Fuck 1992, Pimentel *et al.* 1997, Rodrigues et al. 1999, Pimentel *et al.* 2000, Laux *et al.* 2005).

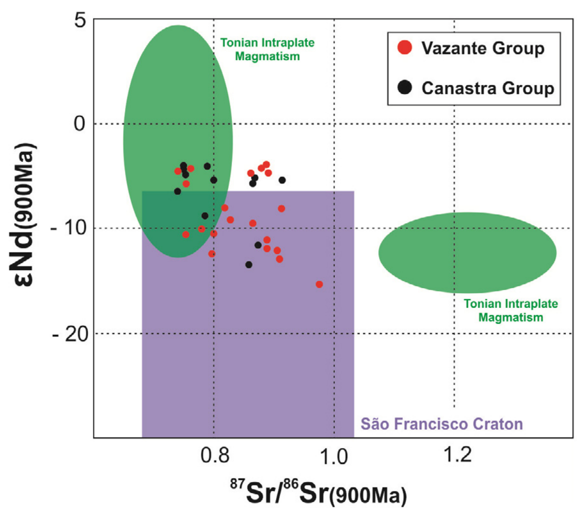

Figure 7. Nd and Sr provenance patterns for the metasedimentary rocks from groups Vazante (n = 26) and Canastra (n = 12) in diagrams of $^{87}Sr/^{86}Sr$ versus εNd calculated for 0.90 Ga, compared to the cratonic basement (n = 191, Teixeira 1985, Sato 1998) and Tonian anorogenic magmatic rocks (n = 39, Tack *et al.* 2001, Correa-Gomes & Oliveira 2002, Chaves & Neves 2005, Rosa *et al.* 2005, Girardi *et al.* 2013, Salgado *et al.* 2016).

anorogenic metabasic rocks along the 1.00 Ga reference isochron. Reference isochron would indicate ages between 2.00 and 1.00 Ga for both Vazante and Canastra groups.

In this context, the younging trend of T_{DM} ages observed along the stratigraphy of the Vazante Group (Fig. 4), as firstly pointed out by Rodrigues (2008) and corroborated by Santana (2011) and Rodrigues *et al*. (2012), can be interpreted as resulting from increasing influence of coeval Tonian anorogenic magmatic rocks in provenance of this unit. The young trend is compatible to the deposition in passive margin environments and could explain the lithologic and geochemical characteristics noticed by Santana (2011) in the Serra da Lapa Formation, of the Vazante Group.

The isochronic diagram of $^{87}Sr/^{86}Sr$ *vs*. εNd (Fig. 7) from analyzed samples also indicates that Vazante and Canastra groups' rocks are a mixture of at least two components. Data calculated for 0.90 Ga, the minimal age of sedimentation, indicate that some younger component was involved in their isotopic signature. Measured data for today exhibit fractionation for Vazante and Canastra groups' samples very similar to cratonic isotope signatures.

The combined use of detrital zircon U-Pb ages and whole-rock Sm-Nd data for provenance studies in other passive margin basins that border the SFC, such as the Araçuaí Orogen and the Rio Preto Fold Belt, has shown mixture between older sources located in the cratonic basement and Tonian rift-related sources (Fig. 8). Compared to the Vazante and Canastra groups, Gonçalves-Dias *et al.* (2016) interpreted the provenance patterns of the Jequitinhonha Complex, located on the SE border of the SFC, in the Araçuaí Orogen, as resulted from the mixture between cratonic and Tonian rift-related volcanic rocks of the West Congo belt (Tack *et al.* 2001). Caxito *et al.* (2014a) reached the same conclusion for the Canabravinha Formation, in the Rio Preto Fold Belt, northwestern margin of the SFC. Such kind of mixture seems, then, a recurrent situation along the SFC craton margins.

CONCLUSIONS

The analysis of the new data, in the context of the isotope database from the literature, shows that the Vazante and Canastra groups' rocks have Sm-Nd and Sr compositions that result from mixing of Archean-Paleoproterozoic cratonic sources with an important juvenile, younger Tonian component.

The Canastra and Vazante groups samples show very similar spectra of radiogenic εNd and $^{87}Sr/^{86}Sr$ values and T_{DM} model ages between 1.70 and 2.20 Ga, which contrast with those of sin-orogenic units of the Southern Brasília belt, *i.e.*, the Ibiá and Araxá groups, with a wider range of T_{DM} ages between 1.00 and 2.20 Ga.

The absence of younger than ~0.90 Ga detrital zircons in the Vazante and Canastra groups, observed by several previous works, indicates that at least in the initial stages of passive margin development the Goiás Magmatic Arc was still too distant from the São Francisco paleocontinent to provide clastic input.

This work raises the Tonian anorogenic magmatism as the main responsible source of the young and juvenile isotopic component recorded in the Vazante and Canastra groups' rocks, corroborating a passive margin environment with sediments coming exclusively from continental areas at east.

The mixture between old and juvenile source areas are also presented in other fold belts surrounding the São Francisco Craton, suggesting this is a typical situation in the cratonic margins.

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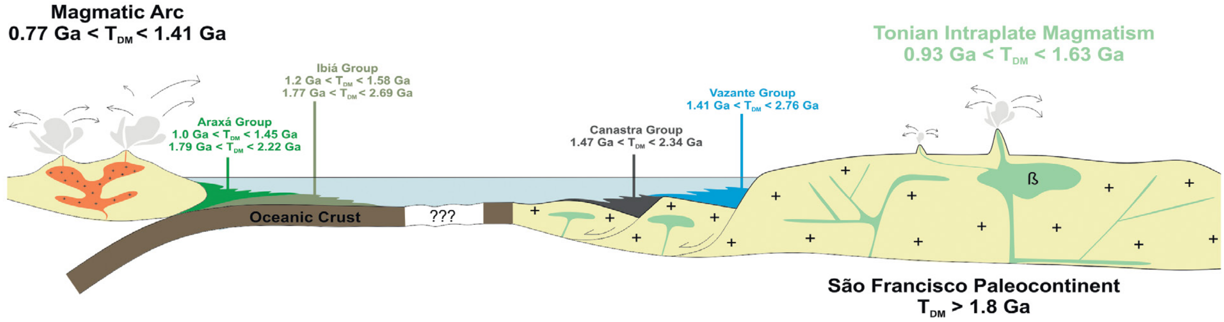

Figure 8. Tectonic setting for the development of the Canastra and Vazante passive margins with Tonian source areas within the São Francisco Craton.

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C. M. V. took part in field campaigns during the main author's master thesis development and provided expertise concerning Brasília Belt tectonic development. He also revised and improved the manuscript.
G. D. O. provided advice in field campaigns on the geology of the Vazante and Canastra groups during the main author's master thesis development and revised and improved the manuscript.
C. C. A. N. ran all isotope analyses and helped with the interpretation of the data.
M. H. helped with interpretation of the data, provided expertise on São Francisco Craton geology, and also revised and improved the manuscript.
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