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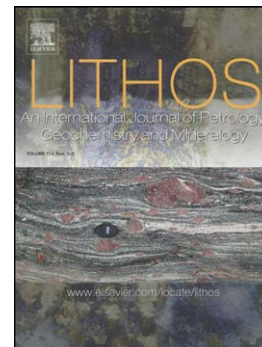
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Geochemistry of komatiites and basalts from the Rio das Velhas and Pitangui greenstone belts, São Francisco Craton, Brazil: Implications for the origin, evolution, and tectonic setting

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ABSTRACT

The Neoproterozoic Rio das Velhas and Pitangui greenstone belts are situated in the southern São Francisco Craton, Minas Gerais, Brazil. These greenstone belts were formed between ca. 2.79-2.73 Ga, and consist mostly of mafic to ultramafic volcanics and clastic sediments, with minor chemical sediments and felsic volcanics that were metamorphosed under greenschist facies. Komatiites are found only in the Rio das Velhas greenstone belt, which is composed of high-MgO volcanic rocks that have been identified as komatiites and high-Mg basalts, based on their distinctive geochemical characteristics. The Rio das Velhas komatiites are composed of tremolite+actinolite+serpentine+albite with a relict spinifex-texture. The Rio das Velhas komatiites have a high magnesium content ($(\text{MgO})_{\text{adj}} \geq 28$ wt.%), an Al-undepleted Munro-type $[(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ and $(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}}$] ratio ranging from 27 to 47 and 0.48 to 0.89, relatively low abundances of incompatible elements, a depletion of light rare earth elements (LREE), a pattern of non-fractionated heavy rare-earth elements (HREE), and a low $(\text{Gd}/\text{Yb})_{\text{PM}}$ ratio (≤ 1.0). Negative Ce anomalies suggest that alteration occurred during greenschist facies metamorphism for the komatiites and high-Mg basalts. The low $[(\text{Gd}/\text{Yb})_{\text{PM}} < 1.0]$ and $[(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}} < 0.9]$, high $[(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}} > 18]$ and high HREE, Y, and Zr content suggest that the Rio das Velhas komatiites were derived from the shallow upper mantle without garnet involvement in the residue. The chemical compositions $[(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$, $(\text{FeO})_{\text{adj}}$, $(\text{MgO})_{\text{adj}}$, $(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}}$, Na, Th, Ta, Ni, Cr, Zr, Y, Hf, and REE] indicate that the formation of the komatiites, high-Mg basalts and basalts occurred at different depths and temperatures in a heterogeneous mantle. The komatiites and high-Mg basalts melted at liquidus temperatures of ~1450–1550°C, whereas the Pitangui basalts below 1000°C. The Pitangui basalts are enriched in the highly incompatible LILE (large-ion lithophile elements) relative to the moderately incompatible HFS (high field strength)

elements. The Zr/Th ratio ranging from 76-213 and the relationship between the Nb/Th and Th/Yb ratios indicate that there is no crustal contamination in the Pitangui greenstone basalts. New multi-dimensional discrimination diagrams and conventional normalized multi-element diagrams indicate an island arc (IA) setting for the komatiites and high-Mg basalts from the Rio das Velhas and a mid ocean-ridge (MOR) to IA setting for the basalts from the Pitangui greenstone belts.

Keywords: Komatiites, High-Mg basalts, Basalts, Geochemistry, Greenstone belt, tectonic setting

1. Introduction

One of the largest shield in the world is the Brazilian Shield, which is also known as the South American Platform. The important parts of this platform are Neoproterozoic orogenic belts and cratons (Almeida et al., 1981; Almeida et al., 2000; Hartmann and Delgado, 2001; Hartmann et al., 2008) that are mainly divided into three cratonic bodies: the Amazon Craton (Santos et al., 2000; Tassinari et al., 2000; Tohver et al., 2004; Cordani and Teixeira 2007; Teixeira et al., 2010; Geraldés et al., 2015), the São Francisco Craton (Almeida 1977; Mascarenhas 1981; Delgado et al., 1994; Teixeira et al., 1996, 2015), and the Rio de la Plata Craton (Basei et al., 2000; Rapela et al., 2007; Sánchez Bettucci et al., 2010; Oyhantçabal et al., 2011). Besides these cratonic domains, smaller cratonic fragments occur, such as the São Luís Craton (Sadowski 2000; Klein et al., 2005; Klein and Moura, 2008) and the Luís Alves Craton (Basei et al., 2000; Cordani et al., 2000; Fuck et al., 2008). The Amazonian craton is the largest, and comprises Archean and Proterozoic terrains and has remained tectonically stable since the Neoproterozoic. It has been subdivided into several provinces based on their

ages (Teixeira et al., 1989; Tassinari and Macambira, 1999; Santos et al., 2000; Cordani and Teixeira 2007; Teixeira et al., 2010). The São Francisco Craton is surrounded by Neoproterozoic orogenic belts, is one of the largest cratonic domains in eastern Brazil, and represents a crustal tangibility during the Brasiliano Orogeny, which occurred 630–500 Ma ago, during the amalgamation of West Gondwana (Almeida, 1977; Almeida et al., 1981; Trompette, 1994; Cordani et al., 2000; Alkmim et al., 2001; Tohver et al., 2006; Campos and Carneiro, 2008; Teixeira et al., 2014). This craton is subdivided into several Archean to Palaeoproterozoic blocks: Gavião, Guanambi-Correntina, Jequié, Mairi, Serrinha, and Itabuna-Salvador-Curaça (Teixeira and Figueiredo, 1991; Teixeira et al., 1996; Ledru et al., 1997; Barbosa and Sabaté, 2004; Teixeira et al., 2010; Oliveira et al., 2010; Teixeira et al., 2017). The Rio de la Plata Craton is mainly located in Uruguay, and extends into southern Brazil in the form of many cratonic fragments in the Neoproterozoic belts (Rapela et al., 2007; Oyhantçabal et al., 2011).

Archean greenstone belts consist of metamorphosed mafic to ultramafic volcanic sequences with associated sedimentary rocks and minor quantities of intermediate to felsic igneous rocks. High-Mg volcanic rocks, particularly komatiites and basalts are more abundant in Archean greenstone belts as compare than felsic rocks. Komatiites and basalts provide a means of constraining both mantle composition and magma generation temperature in time (Hofmann, 1988, 1997; Condie, 2015; Condie et al., 2016). The komatiites and basalts allow us to track these properties of the mantle back to at least 3.8 Ga (Abbott et al., 1994; Herzberg and O'Hara, 1998; Arndt et al., 2008). In this context, numerous studies have been done on komatiites from southern Africa, Australia, Brazil, Canada, Finland and India (Jahn et al., 1982; Rajamani et al. 1985; Barnes et al. 1988; Arndt et al., 1989; Polat et al., 1999; Polat and Kerrich 2000; Chavagnac 2004; Arndt et al., 2008; Stiegler et al., 2010; Dostal and Mueller, 2012;

Konnunaho et al., 2013; Manikyamba et al., 2013; Mole et al., 2014; Saha et al., 2015; Jayananda et al., 2016; Waterton et al., 2017). Furthermore, the geodynamic evolution of Archean komatiite magma has been the subject of much discussion—that is whether komatiite magmas are generated by the anhydrous melting of deep mantle or the wet melting of shallow mantle (Parman et al., 1997; Polat et al. 1999; Arndt 2003). Similarly, the tectonic context of magma generation of komatiites is still a matter of debate (Parman et al., 2004; Arndt et al., 2008), although many researchers have suggested that komatiite magmas are derived from anomalously hot mantle plumes (Herzberg 1995; Herzberg et al., 2010; Arndt et al., 2008).

The study areas, the Rio das Velhas and Pitangui greenstone belts, are located in the southern part of the São Francisco Craton. Earlier studies of the Rio das Velhas greenstone belt were conducted mainly on field relationships and the petrographic, geochemical, and geochronological characteristics of basaltic and sedimentary rocks (Zucchetti et al., 2000a, 2000b; Oliveira et al., 2011; Romano et al., 2013; Teixeira et al., 2014, 2015; Hartmann et al., 2006). However, no detailed geochemical studies have been performed on komatiites and high-Mg basalts. Similarly, there are no available studies on the geochemistry and petrogenesis of the basalts of the Pitangui greenstone belt. Therefore, in this work, we present the field-relationships and geochemistry of ultramafic to mafic volcanic rocks of both the Rio das Velhas and Pitangui greenstone belts to discuss their petrogenesis, Archean mantle evolution and tectonic setting.

2. Geological Setting

The São Francisco Craton is mainly divided into two parts: the northern craton and the southern craton. The northern part has been divided into four crustal blocks: Jequié, Gavião, Serrinha, and Itabuna-Salvador-Curaça (Barbosa and Sabaté, 2004). The southern part consists of several gneiss complexes (Bonfim, Passa Tempo, Divinópolis,

Campo Belo, Guanhães, Baçã, Belo Horizonte, Santa Bárbara, Caeté), greenstone belts (Rio das Velhas, Pitangui, Piumhi, Rio Paraúna, Fortaleza de Minas, Barbacena), and the Mineiro orogen (Alkmim and Teixeira 2017; Teixeira et al., 2017; Moreno et al., 2017 and references therein).

The Archean greenstone belts of the São Francisco Craton (Fig. 1a) are situated in the southern part of the craton (in the state of Minas Gerais) and in the Gavião block in the north (Cunha and Fróes, 1994; Lobato et al., 2001a; Menezes Leal et al., 2015; Teixeira et al., 2017). The Rio das Velhas (Fig. 1a) and Pitangui (Fig. 1b) greenstone belts are located in the southern part of the São Francisco Craton, (Dorr, 1969; Zucchetti et al., 2000a, 2000b; Baltazar and Zucchetti, 2007; Vial et al., 2007; Teixeira et al., 2017).

The Rio das Velhas greenstone belt consists of the Nova Lima and Maquiné Groups. From bottom to top, the Nova Lima Group is divided into five main lithofacies units (Baltazar and Zuchetti, 2007): Unit 1, mafic to ultramafic volcanic rocks with minor felsic volcanics; Unit 2, sedimentary and volcano-chemical sedimentary rocks; Unit 3, upper clastic-chemical sedimentary rocks; Unit 4, volcanoclastic rocks; and Unit 5, resedimented sedimentary rocks. The Nova Lima Group clastic sediments are in gradational contact with the overlying Maquiné Group—a 2000-m-thick sequence of phyllite and quartz–phyllite of the Palmital Formation (O'Rourke, 1957) and quartz schist, conglomerate, phyllite and greywacke of the Casa Forte Formation (Gair, 1962). Massive komatiites to pillowed komatiitic basalts occur in Unit 1 above the Nova Lima Group (Zucchetti et al., 2000a, b; Baltazar and Zucchetti 2007). The massive komatiites are characterized by a spinifex texture, layers with cumulus olivine/intercumulus orthopyroxene, and a layer of lahar-type breccia (Zucchetti et al., 2000a, b). The pillowed komatiitic basalts are locally interleaved with marine carbonaceous sediments (Schrank et al., 1990). The pillowed basalt volcanism and carbonate precipitation were

followed by the submarine deposition of banded iron formations (BIFs) and pelites (which are covered with sandstone-greywacke), a sequence of conglomerate-greywacke, and pelite-greywacke. Whole-rock Sm–Nd analyses indicate an age of 2927 ± 180 Ma for the basaltic rocks (Lobato et al., 2001b), whereas U–Pb and Pb–Pb zircon analyses yielded ages of 3035 Ma, 2930 Ma, and 2800 Ma for the felsic volcanism (Lobato et al., 2001b; Noce et al., 2002, 2005). Furthermore, Machado et al. (1992) explained that the felsic volcanism took place between 2776 and 2772 Ma. Later, Carneiro (1992) described this age interval as being related to the Rio das Velhas Orogenic Event, in which Archean crust was formed and other volcanism occurred. The clastic sedimentary rocks of the upper unit of the greenstone belt are dominated by greywacke–argillite sequences. The Maquiné Group consists of sandstones and conglomerates that overlie the Nova Lima Group. Moreira et al. (2016) constrained a maximum depositional age of 2730 Ma for the sediments of the Maquiné Group.

The Pitangui greenstone belt was divided into two units by Frizzo et al. (1991). The basal unit consists of mafic and ultramafic meta-igneous rocks approximately 200 meters thick. The upper unit consists of metavolcanic rocks (i.e., rhyolite to andesite) with a strong contribution of pyroclastic volcanics and metasedimentary rocks consisting of carbonaceous phyllites, BIFs and ironstones. The thickness of this unit is about 2000 m. Silva (2016) and Silva et al. (submitted) presented new U–Pb zircon ages for the rocks of the Pitangui greenstone belt and nearby basement. The basement gneiss was dated at 2876 ± 7 Ma, whereas a metabasalt and metagabbro from the greenstone belt yielded ages of 2798 ± 3 Ma and 2729 ± 10 Ma, respectively. The youngest detrital zircon population in two metasedimentary rocks (slate and phyllite) indicated an average age of 2720 Ma ($n=8$ grains) and three other grains showed an average age of approximately 2670 Ma. Recently, Soares et al. (2017) divided the belt into three units:

a lower unit of predominantly metavolcanic ultramafic and mafic rocks interbedded with thinner metasedimentary intervals of BIFs, turbiditic metasediments and metapelites; a middle unit of turbiditic metasediments interbedded with metavolcanic intermediate rocks, minor BIFs, and quartzites; and an upper unit composed of quartzites and polymictic metaconglomerates. According to Soares et al. (2017), the rocks from all three units were metamorphosed under upper-greenschist to lower-amphibolite facies and are bounded by domes composed of Tonalite-Trondhjemite-Granodiorite (TTG) and late- to post-tectonic alkaline granitoids. U-Pb ages of detrital zircon grains from the lower-unit metasediment indicate a maximum depositional age of 2859 ± 11 Ma (Soares et al., 2017).

3. Sampling and Petrography

For this study, we collected representative samples of komatiites and high-Mg basalts from the Rio das Velhas greenstone belt and basalts from the Pitangui greenstone belt (Table 1).

3.1 Komatiites: Rio das Velhas greenstone belt

Komatiites in the Rio das Velhas greenstone belt are restricted to the greenschist facies. Selected fresh komatiites were sampled from a single flow and a scattered unit near the Morro do Onça and Rio das Velhas (Table 1). The 0.5–1.5-m-thick komatiitic flow is composed of a spinifex layer. Random and oriented spinifex komatiites occur in the upper and lower parts of the spinifex layer, respectively. The principal minerals associated with komatiites are tremolite-actinolite, chlorite, albite, and serpentine (Fig. 2a–b).

3.2 High-Mg basalt: Rio das Velhas greenstone belt

Fresh high-Mg basalts were collected from the Nova Lima–Caeté and Santa Bárbara regions, which consist of fine-grained actinolite schists, occurring in pillowed and massive flows. The basalts contain plagioclase quartz, opaque minerals, albite, epidote, and chlorite.

3.3 Basalt: Pitangui greenstone belt

The Pitangui greenstone belt is predominantly formed by basalts and restricted gabbros. The basalts are dark and very fine- to fine-grained and form expansive flows. The foliation trend is predominantly NW-SE, dipping 20° to 80° NE–E. The S_n schistosity is the main structure. On outcrops, the pillowed basalts follow the S_n foliation, and, are mainly composed of plagioclase, actinolite, chlorite, talc, and quartz. Epidote, hornblende, clinozoisite, carbonate, opaque minerals, apatite, zircon, and titanite are accessory minerals (Fig. 2c).

The metagabbro occurs as an elongated pluton. It is gray to green, inequigranular, and coarse- to medium-grained. It has foliation of N15W to N10E, plunging between 50° and 85° NE–SE. The metagabbro is composed of hornblende, albite, augite, quartz, chlorite and talc. Accessory minerals are epidote, actinolite, clinozoisite, zircon, apatite, titanite, and opaque minerals (Fig. 2d).

4. Geochemical analytical procedures

Major and trace element analysis

For the analyses of the major elements and selected trace elements (Table 1), 1.2 g of the powdered sample were weighed and mixed with 6 g of lithium borate flux (comprising 35.3% tetraborate and 64.7% metaborate). The mixture was melted on a model M4-30 Claisse fusion system using a Pt–Au crucible at 1000°C for \approx approximately 8 min before being poured into a circular Pt mould and quenched in air to

produce a flat disc. For trace element determinations, 9 g of sample powder was pressed into a pellet using 1.2 g of wax binding agent. The analyses of both the fused discs and pressed pellets were performed at the Institute of Geosciences, University of Campinas (UNICAMP) using a Philips PW 2100 X-ray fluorescence spectrometer. The analytical procedures were performed as described by Vendemiatto and Enzweiler (2001). Fe-oxidation adjustment followed the procedure of Middlemost (1989) on an anhydrous basis to 100%. This was easily achieved using the computer program, IgRoCS_M1 (Verma and Rivera-Gómez 2013). Data quality was controlled routinely through analyses of the international reference rocks W-2 and BHVO for the major elements, and RGM-1 and WSE for the trace elements. The relative errors were 0.4–1.5% for the major and minor elements, and 1.5–10% for the trace elements.

The remaining rare earth and other trace elements were analyzed on a quadrupole Thermo (Xseries2) ICP-MS at the Institute of Geosciences, University of Campinas. The analytical procedures were based on those of Eggins et al. (1997) and Liang et al. (2000). Cotta and Enzweiler (2009) described details of the instrument and sample preparation. The standards used for this work, were BRP-1, RGM-1 and GSP-2, with a 10% standard deviation.

5. Geochemical Results

On the total alkalis vs. silica diagram (TAS; Le Bas et al., 1986; Fig. 3), the komatiites and high-Mg basalts plotted out mainly in the micro-basalt and basalt field, whereas the remaining nine samples plotted out in the basaltic andesite to andesite fields. These nine samples belonged to the Pitangui greenstone belt. According to the TAS diagram, the komatiites and high-Mg basalts were classified as komatiites because TAS can be used only for fresh rocks; therefore we used new multi-dimensional classification diagrams (Verma et al., 2016, 2017), that are based on altered-rock classifications. First, the

samples were divided into common-Mg and high-Mg content groups (Fig. 4), then further plotted onto new multi-dimensional classification diagrams; the komatiites and high-Mg basalts were classified as komatiite and boninite respectively (Fig. 5a–d).

5.1. Whole-rock major and trace elements

5.1.1. Rio das Velhas komatiites

The analyzed samples were komatiitic in composition with $(\text{MgO})_{\text{adj}}$ content ranging from 28.61 wt.% to 38.54 wt.%. Similarly, the Ni (871–1989 ppm), and Cr (2799–4093 ppm) contents in the spinifex textured samples were high, but the $(\text{TiO}_2)_{\text{adj}}$ (0.15–0.235 wt.%) was low relative to other komatiites (Table 1; Dostal and Mueller, 2004). The Rio das Velhas komatiites have a narrow range of $(\text{SiO}_2)_{\text{adj}}$ content (41.39–46.4 wt.%). In Jensen's (1976) triangular diagram of $(\text{Al}_2\text{O}_3)_{\text{adj}}\text{-MgO}_{\text{adj}}\text{-(Fe}_2\text{O}_3\text{+TiO}_2)_{\text{adj}}$, the komatiite samples plotted out in the komatiite field (Fig. 6). All eight komatiite samples were of the Al-undepleted Munro-type with $(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}}$ ratios between 0.49 and 0.89 and $(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ ratios between 27.6 and 47.4.

5.1.2. Rio das Velhas High-Mg basalts

The high-Mg basalts were characterized by 43.7–45.7 wt.% $(\text{SiO}_2)_{\text{adj}}$, 39.5–41.5 wt.% $(\text{MgO})_{\text{adj}}$, 0.83–2.6 wt.% $(\text{Al}_2\text{O}_3)_{\text{adj}}$, 0.83–2.6 wt.% $(\text{TiO}_2)_{\text{adj}}$, and 2552–2943 ppm Ni (Table 1). The $(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ ratios (10.8–18.2) were similar to those of associated komatiites (Table 1). In Jensen's (1976) triangular diagram for $(\text{Al}_2\text{O}_3)_{\text{adj}}\text{-MgO}_{\text{adj}}\text{-(Fe}_2\text{O}_3\text{+TiO}_2)_{\text{adj}}$, the high-Mg basalts plotted out in the komatiite field (Fig. 6).

5.1.3. Pitangui basalts

The basalts were characterized by 49.4–59.8 wt.% $(\text{SiO}_2)_{\text{adj}}$, 3.3–9.6 wt.% $(\text{MgO})_{\text{adj}}$, 15.0–17.3 wt.% $(\text{Al}_2\text{O}_3)_{\text{adj}}$, 0.62–2.31 wt.% $(\text{TiO}_2)_{\text{adj}}$, and 81–402 ppm Ni (Table 1). The

$(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ ratios ranged from 7.5–23.8. In the triangular diagram of $(\text{Al}_2\text{O}_{3\text{adj}}-\text{MgO}_{\text{adj}}-(\text{Fe}_2\text{O}_3+\text{TiO}_2)_{\text{adj}})$, these samples plotted out in the high-Fe tholeiite, high-Mg tholeiite, basalt, and andesitic fields (Fig. 6).

On the Fenner's binary diagrams of the major elements vs. $(\text{MgO})_{\text{adj}}$, the majority of the major element oxides formed two clusters (komatiite and basalt) but together defined moderate trends for some of the major element oxides (Fig. 7). $(\text{SiO}_2)_{\text{adj}}$, $(\text{TiO}_2)_{\text{adj}}$, $(\text{Al}_2\text{O}_3)_{\text{adj}}$, $(\text{Fe}_2\text{O}_3)_{\text{adj}}$, $(\text{CaO})_{\text{adj}}$, and $(\text{P}_2\text{O}_5)_{\text{adj}}$ exhibited moderate negative correlation with $(\text{MgO})_{\text{adj}}$ whilst $(\text{K}_2\text{O})_{\text{adj}}$ and $(\text{Na}_2\text{O})_{\text{adj}}$ did not define any trend (see Fig. 7). For trace elements on the Fenner's diagrams, only Ni and Cr showed positive correlation with $(\text{MgO})_{\text{adj}}$, whereas Ba, Yb, Y, Nd, and Zr showed moderate negative correlation (Fig. 8). Other trace element such as Rb showed scattering. The positive trends observed for Ni and Cr could be related to olivine fractionation, whereas the scattering of Rb could be due to post-magmatic alteration processes.

5.2. Trace and rare earth element (REE) compositions

The trace element (including rare-earth element) compositions of the Rio das Velhas and Pitangui greenstone belts are presented in Table 1. A primitive mantle normalized (McDonough and Sun, 1995) multi-element diagram (Fig. 9a–c) showed a wide range in the concentration of the trace elements. In general, the Rio das Velhas komatiites and high-Mg basalts and the Pitangui basalts are enriched in highly incompatible LILE (e.g., Rb, Ba, U, Sr and LREE) relative to the moderately incompatible HFS elements (e.g., Nb, Ta, Th, and HREE). The normalized trace-element patterns are enriched in incompatible elements with negative Nb, Ta and Eu anomalies and a positive Zr anomaly (Fig. 9a–c) suggesting a subduction-related source.

Chondrite-normalized (McDonough and Sun, 1995) rare-earth element (REE) plots are shown in Figure 10. The komatiites and high-Mg basalts showed little variation in their REE contents and exhibited a total REE content ranging from 1.40 to 6.75 ppm and 4.0 to 19.0 ppm, respectively. The Pitangui basalts displayed significant variation for REE but generally showed a higher total REE (18.9–64.1 ppm) compared to the komatiites and high-Mg basalts. The komatiite and high-Mg basalt samples displayed LREE-depleted ($\text{La}/\text{Sm}_{\text{cn}}=0.66\text{--}6.3$) to enriched ($\text{La}/\text{Sm}_{\text{cn}}=0.70\text{--}13.9$) patterns, whereas the basalts showed flat LREE patterns ($\text{La}/\text{Sm}_{\text{cn}}=1.13\text{--}2.00$; Fig. 10). Both the komatiites and high-Mg basalts had moderately depleted ($\text{Gd}/\text{Yb}_{\text{cn}}=0.32\text{--}0.82$) to flat ($\text{Gd}/\text{Yb}_{\text{cn}}=1.1\text{--}4.2$) HREE patterns whereas basalts showed flat HREE patterns ($\text{Gd}/\text{Yb}_{\text{cn}}=1.0\text{--}1.4$; Fig. 10). The komatiites and high-Mg basalts showed primitive geochemical characteristics. Zucchetti et al. (2000b) suggested that the rare-earth element patterns of the basalts and komatiites of the Rio das Velhas greenstone belts are similar to those of lavas derived from the partial melting of a mantle plume.

6. Discussion

6.1 Geochronology of the Rio das Velhas greenstone belt

The published ages of the Rio das Velhas greenstone belts are presented in Table 2. In this study, we discuss qualitatively the possible time frame of komatiite volcanism in the Rio das Velhas greenstone belt with respect to the timing of the surrounding TTG gneisses.

On the basis of U-Pb zircon dates Lana et al. (2013) suggested three magmatic events for the Quadrilátero Ferrífero area. The oldest TTG emplacement occurred during the Santa Barbara event ca. 3212–3210 Ma. The second event, named Rio das Velhas I, occurred from 2930–2900 Ma and was marked by the main magmatic additions of

juvenile TTG rocks and the tectonic accretion of mafic–ultramafic greenstone belt terrains. The third event, Rio das Velhas II, from 2800–2770 Ma, is characterized by convergence-related felsic volcanic and plutonic rocks and the deposition of turbiditic wackes in the main greenstone belt sequence. Farina et al. (2015) suggested a fourth magmatic event, named the Mamona event (2760–2680 Ma), during which numerous potassic granitoids were emplaced, leading to the cratonization of the region.

According to Lobato et al. (2001ab), a Sm–Nd isochron age of 2927 ± 180 Ma was reported for basaltic rocks from the Rio das Velhas greenstone belt. For volcanoclastic greywackes, Machado et al. (1992) and Noce et al. (2005) reported a U–Pb zircon age of 2792–2751 Ma. Similarly, a dacite flow intercalated within the sequence of mafic-to-ultramafic volcanic rocks showed a zircon age of 2772 ± 6 Ma as reported by Machado et al. (1992). From the above evidences, we speculate that the komatiites and high-Mg basalts probably originated at 2790–2750 Ma or earlier, given that the Sm–Nd isochron technique is not as robust as the U–Pb zircon technique and the above Sm–Nd age overlaps the error of the 2790–2750 Ma age interval. This suggestion implies an origin of the ultramafic to felsic volcanics during the Rio das Velhas II magmatic event, following the model proposed by Lana et al. (2013) for this event, which was marked by the emplacement of a felsic pluton and associated volcanic rocks in volcanic-arc systems developed around the margins of the 3220–2900 Ma continental block.

6.2 Geochronology of the Pitangui greenstone belt

Only few ages are available for this greenstone belt and the adjacent gneiss complex. As presented in Section 2, the ages for the greenstone belt (Silva 2016; Silva et al. submitted) are 2798 Ma for the metabasalt, 2729 Ma for the metagabbro, and 2876 Ma for the gneiss from the Divinópolis complex. Detrital zircon grains from the clastic sedimentary rocks show a maximum depositional age of 2720 Ma, or possibly 2670 Ma

(Silva 2016; Silva et al. submitted) or 2859 Ma (Soares et al., 2017). If we correlate these data with the main magmatic events in the Quadrilatero Ferrífero area (Lana et al., 2013), the Pitangui basalts are coeval with the Rio das Velhas II magmatic event and the metagabbro was emplaced later during the Mamona event.

6.3 Degree of post-magmatic alteration

Geochemical and isotopic studies of Archean komatiites across the world have revealed that the mobility of LILE and REE in most cases is controlled by secondary processes, such as metamorphism or hydrothermal alteration (Arndt et al., 1989; Gruau et al., 1992; Lesher and Stone, 1996; Chavagnac, 2004). The mobility of LILE persists without affecting the abundances of HFSE, HREE, Zr, and Hf (Lesher and Stone, 1996; Arndt, 1986). Silica mobility shows a negative correlation between $(\text{SiO}_2)_{\text{adj}}$ and $(\text{MgO})_{\text{adj}}$ (Fig. 7), although it is possible that the komatiite samples may have lost silica due to serpentinization, and therefore fall below the olivine fractionation line (Fig. 11). Thus, the preserved mineralogy (e.g., serpentine) indicates recrystallization under low-grade conditions. In this study, we used immobile elements (HFSE and REE) for the interpretation of petrogenetic processes. The chondrite-normalized diagram showed a flat REE pattern, whereas the primitive mantle-normalized diagram indicated zigzag patterns of LILE due to alteration and mobility. Furthermore, the major elements, such as $[(\text{Al}_2\text{O}_3)_{\text{adj}}, (\text{CaO})_{\text{adj}}, (\text{TiO}_2)_{\text{adj}}$ and $(\text{P}_2\text{O}_5)_{\text{adj}}]$ showed smooth fractionated trends with MgO (Fig. 7), which suggests that there was no major alteration of the komatiites. Interpretation of the immobile elements (HFSE and REE) showed that there were no significant secondary alteration processes. The komatiites and high-Mg basalts showed negative Ce anomalies (see Figs. 9–10), whereas the basalts showed positive Ce anomaly. According to Braun et al. (1993), the Ce anomalies are produced by different oxidation states such as Ce^{3+} and Ce^{4+} . Once Ce^{4+} reacts with water, it precipitates in the

form of CeO_2 . The depletion of Ce and the resulting negative Ce anomalies could be attributed to the removal of Ce by circulating fluids during metamorphism. This process indicates that the Rio das Velhas greenstone belt komatiites may have experienced alteration during greenschist facies metamorphism. In some greenstone belts, Eu anomalies have been used to discover hydrothermal secondary alteration processes (Ludden et al., 1982; Arndt, 1994; Lécuyer et al., 1994). In summary, the studied komatiites and high-Mg basalts were not affected by large-scale alteration processes. Thus, the geochemical data of these rocks can be used to constrain the Archean mantle.

6.4 Crustal contamination

Mantle-derived magma can be contaminated by crustal material either by the assimilation of wall rock or the thermal erosion of continental lithosphere. Incompatible element ratios (i.e., between LREE and HFSE) are suitable indicators for evaluating crustal contamination, because these ratios are enriched in continental crust compared to the mantle. Field relationships and stratigraphy reveal that the Rio das Velhas komatiites are associated with pillowed basalts and a submarine environment (Zucchetti et al., 2000a, 2000b). Furthermore, the negative Nb anomalies could reflect mantle either source characteristics or crustal contamination during magma emplacement, whereas the studied komatiites did not indicate LREE enrichment, thus showing mantle inheritance. Except for two samples that had low Zr/Th ratios of 8.5 and 23.3, the Zr/Th ratio in our samples had a range of 111–504, which is similar to or higher than the primitive mantle value of 116 (Fan and Kerrich 1997). The Zr/Th ratio of the continental crust is ~ 20 , which precludes crustal contamination for the Rio das Velhas komatiites, high-Mg basalts and the Pitangui basalts. These results are also supported by the Th/U, La/Sm, Nb/Y, and Zr/Nb ratios, because the ratio value for most of the samples was close to the recommended values for Archean primitive mantle (Campbell

2002; Condie 2003). Finally, the bi-variate diagram of Pearce (2008), which is based on petrogenetic modelling of immobile trace elements (Nb-Yb vs Th-Yb), did not show any crustal contamination (Fig. 12a–b).

6.5 Mantle source composition

Geochemical ratios such as $[(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}}]$, $(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ and $(\text{Gd}/\text{Yb})_{\text{PM}}$ are most useful for evaluating mantle source characteristics in terms of the fractionation or retention of garnet in the mantle residue (Jahn et al., 1982, Chavagnac, 2004). Archean komatiites are divided into two types: Al-depleted and Al-undepleted (e.g., Arndt and Nesbitt, 1982; Fan and Kerrich, 1997; Sproule et al., 2002). Furthermore, Arndt (2003) classified komatiites as Al-depleted Barberton-type and Al-undepleted Munro-type. Al-depleted or Barberton type komatiites are characterized by sub-chondritic ratios $[(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}} \leq 16]$ and $[(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}} > 1.0]$, flat REE patterns with enriched incompatible elements, and a high $[(\text{Gd}/\text{Yb})_{\text{PM}} > 1.0]$ value. Conversely, Al-undepleted or Munro type komatiites are characterized by near chondritic ratios $[(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}} > 20]$ and $[(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}} \leq 1.0]$, relatively low abundances of incompatible elements, the depletion of light rare earth elements (LREE) and non-fractionated heavy rare earth elements (HREE) patterns and a low $[(\text{Gd}/\text{Yb})_{\text{PM}} \leq 1.0]$. In this study, the Rio das Velhas komatiites were classified as Al-undepleted komatiites due to an $(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ ratio ranging from 27–47 and a $(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}}$ ratio ranging from 0.48–0.89, which suggest that garnet entered into the melt phase during partial melting of the mantle. The low $(\text{La}/\text{Yb})_{\text{PM}}$, $(\text{Th}/\text{Nb})_{\text{PM}}$, and $(\text{Sm}/\text{Yb})_{\text{PM}}$ ratios (0.16–1.41, 0.51–2.37, and 0.22–0.84, respectively) support a high degree of mantle melting. The low $(\text{TiO}_2)_{\text{adj}}$ contents also corroborate this hypothesis. Figure (13a–b) shows binary plots of $[(\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ vs

$(\text{Gd}/\text{Yb})_{\text{PM}}$ and $[(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}} \text{ vs } (\text{Gd}/\text{Yb})_{\text{PM}}]$ for garnet partial melts using data from this study.

6.6 Temperature and melting processes of komatiite magmas

Komatiitic rocks have a very high melting point of more than 1600 °C. Hanson and Langmuir (1978) modelled the partial melting of mantle pyrolite at 1 atmosphere of pressure. They used the model equation of Roeder and Emslie (1970) for the partitioning of magnesium and iron between olivine and melt and calculated the abundances of $(\text{MgO})_{\text{adj}}$ and $(\text{FeO})_{\text{adj}}$ in the resultant melts and residual solids. The $(\text{MgO}-\text{FeO})_{\text{adj}}$ diagram shows fields of melts and of residual solids, both contoured for the percentage of partial melting and associated temperatures (Fig. 14). Olivine fractional crystallization trends in melts of differing composition are superimposed on the melt field. Furthermore, we plotted komatiites, high-Mg basalts, and basalts on bivariate diagrams of $(\text{MgO})_{\text{adj}}$ vs $(\text{FeO})_{\text{adj}}$. The komatiites and high-Mg basalts plotted out in the field of liquidus that probably co-existed with mantle peridotite, whereas the basalts were plotted out outside the liquidus field, due to differences between the equilibrium and fractional crystallization of olivine (Fig. 13). The komatiites corroborate a high degree (>30%) of mantle melting with a liquidus temperature of 1500°C. Therefore, the komatiites and basalts were derived from the mantle at different temperatures and depths.

6.7 Tectonic setting discrimination

In this study, we used new multi-dimensional discrimination diagrams to infer the plate tectonic setting, because conventional bivariate and ternary diagrams for tectonic discrimination were shown to work unsatisfactory (Verma 2010). The most important

reasons for this failure are related to the use of limited databases, the problem of closed or constant sum compositional variables, and eye-fitted tectonic field boundaries and distribution of compositional data (Armstrong-Altrin 2015; Verma 2015, Verma et al., 2012, 2013; 2015a, 2015b; Verma and Armstrong, 2016). Therefore, the new multi-dimensional discrimination diagrams proposed by Verma et al. (2006), Verma and Agrawal (2011) and Verma and Verma (2013), which are based on log-ratio transformation and linear discriminant analysis, have been used to understand tectonic regime dominant for magma genesis. The set of two diagrams by Verma et al. (2006) requires the availability of a complete data set of all major elements (Fig. 15a–b). These diagrams have four tectonic settings and can discriminate between basic and ultrabasic magmas. The other set by Verma and Agrawal (2011) is based on the availability of concentration data for the so-called relatively immobile elements (Nb, V, Y, Zr, and $(\text{TiO}_2)_{\text{adj}}$; Fig. 16 a–b). Similarly, for intermediate rock diagrams, the first five diagrams are based on immobile major and trace elements $(\text{MgO})_{\text{adj}}$, $(\text{TiO}_2)_{\text{adj}}$, $(\text{P}_2\text{O}_5)_{\text{adj}}$, Nb, Ni, V, Y, and Zr, whereas the other set, by Verma and Verma, (2013), is based on immobile trace elements (La, Yb, Ce, Sm, Nb, Th, Y, and Zr; Table 3).

In the new multi-dimensional discrimination diagrams by Verma et al. (2006) the komatiite and high-Mg basalt samples from the Rio das Velhas greenstone belt were discriminated as an IAB setting, whereas the Pitangui greenstone belt basalts were discriminated as a MORB setting (Fig. 15a–b). Simultaneously, we used immobile major-trace element based discrimination diagrams (Verma and Agrawal, 2011) and most of the samples were also plotted in an IAB setting for the Rio das Velhas komatiites and high-Mg basalts, and a MORB setting for the Pitangui (Fig. 16a–b). Finally, nine samples of Pitangui basalts of intermediate composition indicated an IA setting (Table 3). We clarify that the intermediate rocks were discriminated as island arc

(IA), continental arc (CA), within-plate (CR+OI), and collision tectonic settings, because one tectonic setting is missing from these sets (e.g., MORB from the intermediate diagrams and Col from the basic diagrams). Therefore, the Rio das Velhas komatiites and high-Mg basalts were probably generated in an IA setting or a subduction-related setting, whereas the Pitangui basalts indicate a MORB to IA setting (Verma and Agrawal, 2011). The negative Nb and Ta anomalies in the primitive mantle-normalized multi-element diagrams for the Rio das Velhas and Pitangui greenstone belts also support these findings. In some island arc settings, komatiites and high-Mg basalts were probably extruded in the fore-arc region (Parman and Grove, 2004).

Conclusions

The main outcomes of the study can be summarized as follows:

1. The Rio das Velhas greenstone belt is composed mainly of komatiites and high-Mg basalts, whereas the Pitangui greenstone belt is composed of normal basalts.
2. Major- and trace-element ratios such as $[(\text{CaO}/\text{Al}_2\text{O}_3)_{\text{adj}}, (\text{Al}_2\text{O}_3/\text{TiO}_2)_{\text{adj}}$ and $(\text{Gd}/\text{Yb})_{\text{PM}}$ indicate that the Rio das Velhas komatiites are similar to Al-undepleted Munro-type komatiites.
3. The Rio das Velhas komatiites and high-Mg basalts were derived from partial melting of the mantle at different depths with the influence of garnet in the melt phase. The spinifex structure reveals very high eruption temperatures ($\sim 1450\text{--}1550^\circ\text{C}$) for these komatiites and high-Mg basalts.
4. Trace-element data, particularly incompatible element contents suggest that the komatiites, high-Mg basalts, and basalts were derived from depleted mantle.

5. The studied komatiites and high-Mg basalts were not affected by large-scale alteration processes. Thus, the geochemical data of these rocks can be used to constrain Archean mantle composition and processes.

6. New multi-dimensional discrimination diagrams and conventional multi-element normalized diagrams suggest a subduction-related—especially island-arc—tectonic setting for the Rio das Velhas komatiites and high-Mg basalts. A MORB to IA setting is suggested for the Pitangui greenstone belt because the MORB setting is absent from the intermediate rock diagrams.

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Figure legends

Figure 1a. Simplified geologic map of the Rio das Velhas Supergroup, São Francisco Craton, Brazil (modified after Zucchetti et al., 2000a, 2000b).

Figure 1b. Simplified geologic map of the Pitangui greenstone belt, São Francisco Craton, Brazil (adapted from Romano, 2007).

Figure 2. (a-b) Occurrences and field and micro-photography of the Rio das Velhas komatiites (15MGEO-1A&5A) (spinifex texture) and mineral composition of tremolite-actinolite+chlorite+albite +serpentine; (c) field rock and micro-photograph of basalts (PM 14-01) from the Pitangui greenstone belt; (d) field rock and microphotograph of gabbros (PM 14-10A) from the Pitangui greenstone belt.

Figure 3. Sample classification in the TAS diagram of Le Bas et al. (1986) obtained from the IgRoCS computer program (Verma and Rivera-Goméz, 2013) of the Rio das Velhas komatiites, high-Mg basalts and Pitangui basalts.

Figure 4. Samples plotted in diagram based on discriminant function $DF_{(HMg-com)M}$ and Common (Com) rock subdivision based on major elements compositions (M); the classification field boundary $(HMg - Com)_{boundary}$ is shown for reference.

Figure 5a-d. Diagrams based on ilr-transformed major-elements (M) for achieving the subdivision of High-Mg rocks (1–komatiite; 2–meimechite; 3–picrate; 4–boninite, Verma et al., 2016).

Figure 6. Major elements $(Al_2O_3_{adj}-MgO_{adj}-(Fe_2O_3+TiO_2)_{adj})$ triangular plot (modified after Jenson, 1976).

Figure 7. Fenner's binary diagram showing moderate to strong fractionation trends for selected major elements oxide versus $(MgO)_{adj}$.

Figure 8. Fenner's binary diagram showing correlation for selected trace elements versus $(MgO)_{adj}$.

Figure 9a-c. Primitive mantle-normalized multi-element plots for the Rio das Velhas and Pitangui greenstone belts (McDonough and Sun, 1995).

Figure 10. Chondrite-normalized rare-earth element plots for the Rio das Velhas and Pitangui greenstone belts (McDonough and Sun, 1995).

Figure 11. Bivariate $(SiO_2/Al_2O_3)_{adj}$ versus $(FeO+MgO)_{adj}/Al_2O_3)_{adj}$ diagram of Pearce (1968) for Rio das Velhas komatiites. Arrows indicate lines for olivine, orthopyroxene and clinopyroxene.

Figure 12a-b. Petrogenetic modelling of the Th/Yb–Nb/Yb projection after Pearce (2008). A) subduction zone enrichment of depleted and enriched mantle wedges by fluids, with percentages of subduction component in wedge; note that enrichment is higher in depleted mantle wedges; B) crustal contamination of depleted and enriched magmas with the continental crust; F denotes percentage of magma left.

Figure 13a-b. Bivariate plot of $[(Al_2O_3/TiO_2)_{adj}]$ versus $(Gd/Yb)_{PM}$ ratios and $[(CaO/Al_2O_3)_{adj}]$ versus $(Gd/Yb)_{PM}$ ratio for Rio das Velhas komatiites.

Figure 14. Field of partial melts and residue, calibrated in liquidus temperature plotted on a $(FeO)_{adj}$ – $(MgO)_{adj}$ (wt.%) diagram for the Rio das Velhas komatiite, high-Mg basalts and Pitangui basalts (after Hanson and Langmuir, 1978).

Figure 15a-b. Application of the set of two log–ratio transformed major element–based discriminant function DF1–DF2 discrimination diagrams (see the subscript m2 in all these diagrams; Verma et al., 2006) for basic rock samples from Rio das Velhas and Pitangui greenstone belts, Brazil. The four fields that can be discriminated are: IAB–island (and continental) arc basic rocks; CRB–continental rift basic rocks; OIB–ocean island basic rocks; MORB–mid-ocean ridge basic rocks.

Figure 16a-b. Application of the set of two log–ratio transformed immobile trace element–based discriminant function DF1–DF2 discrimination diagrams (see the subscript t1 in all these diagrams; Verma and Agrawal, 2011) for basic rock samples from Rio das Velhas and Pitangui greenstone belts, Brazil.

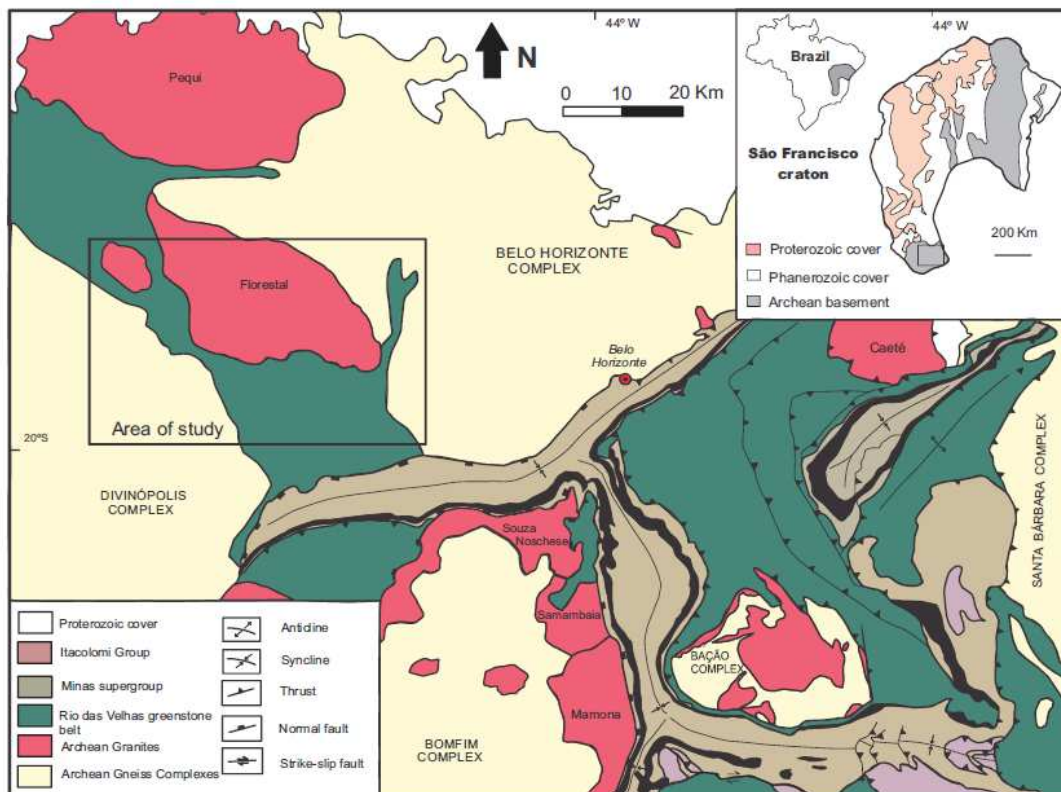


Fig. 1a

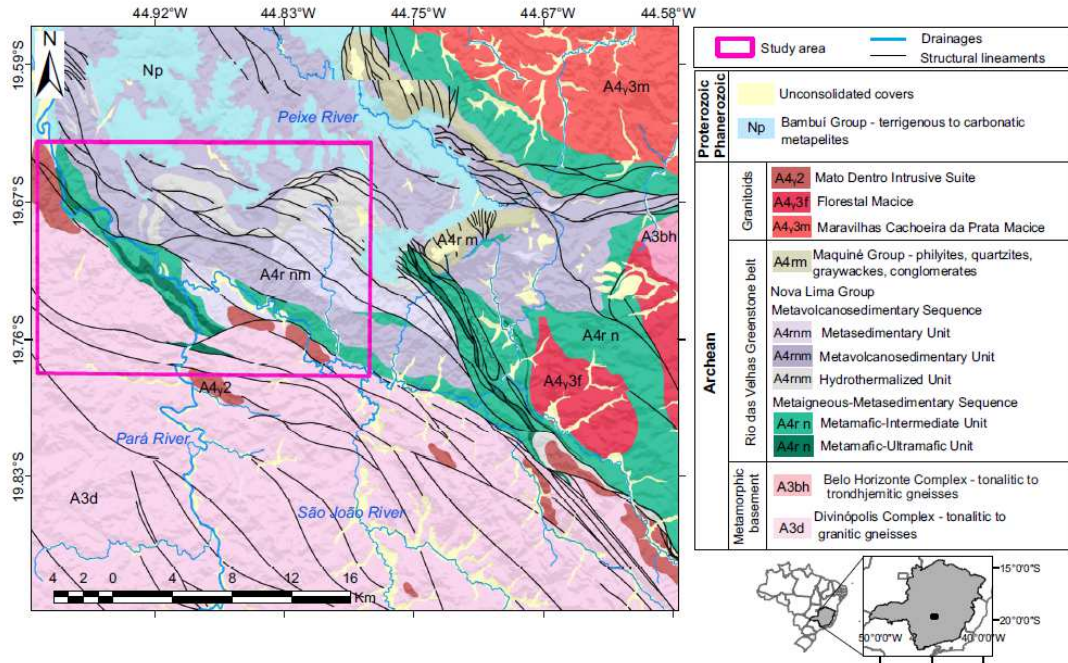


Fig. 1b

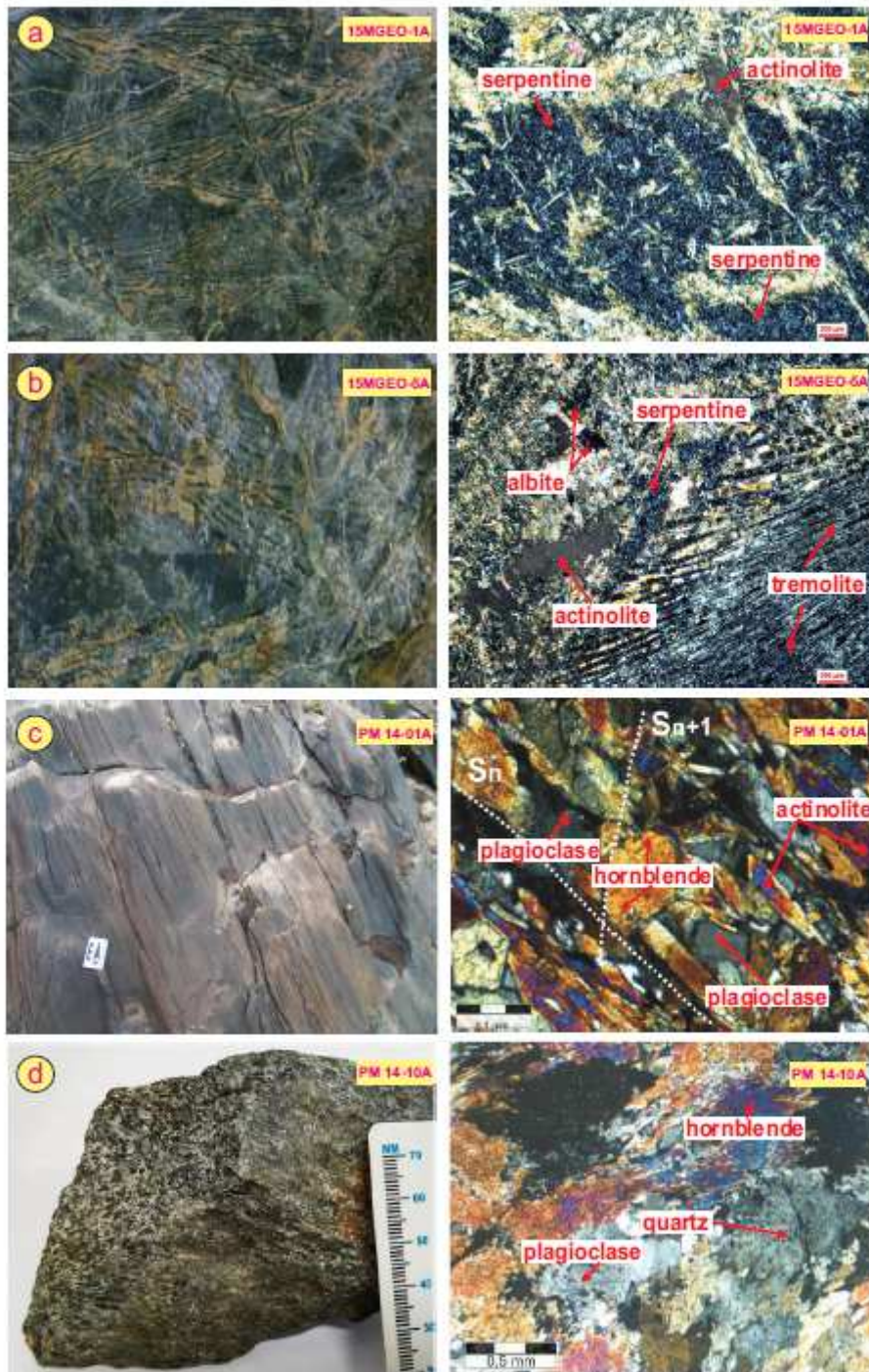


Fig 2ad

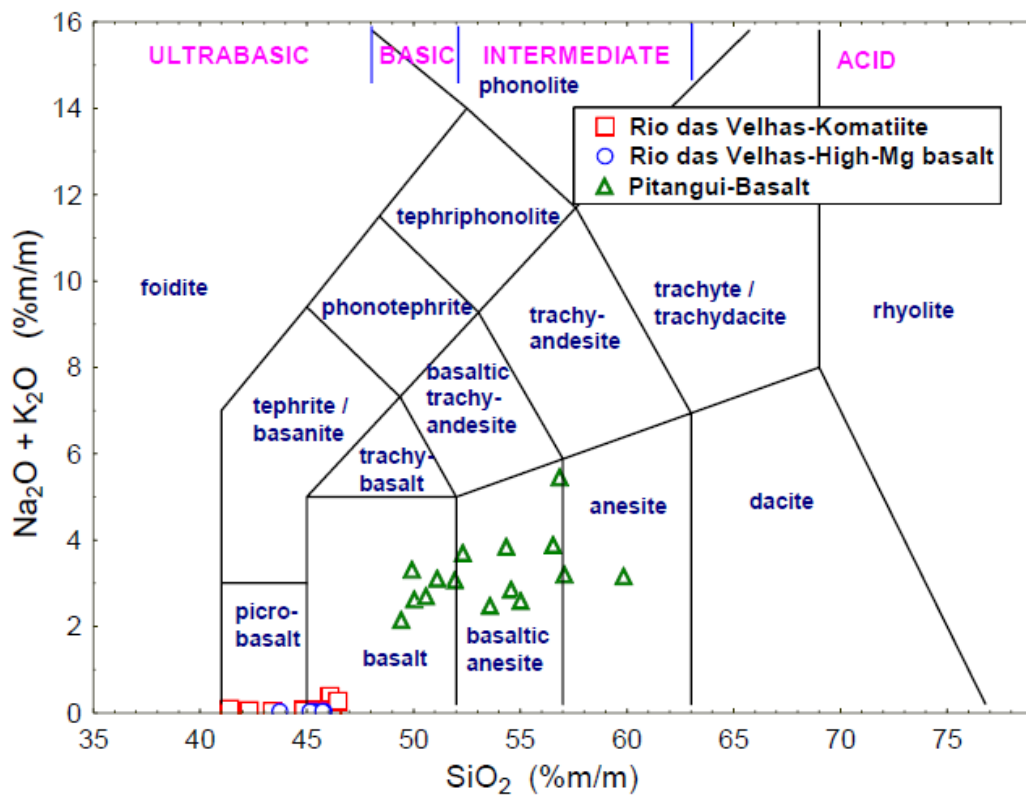


Fig. 3

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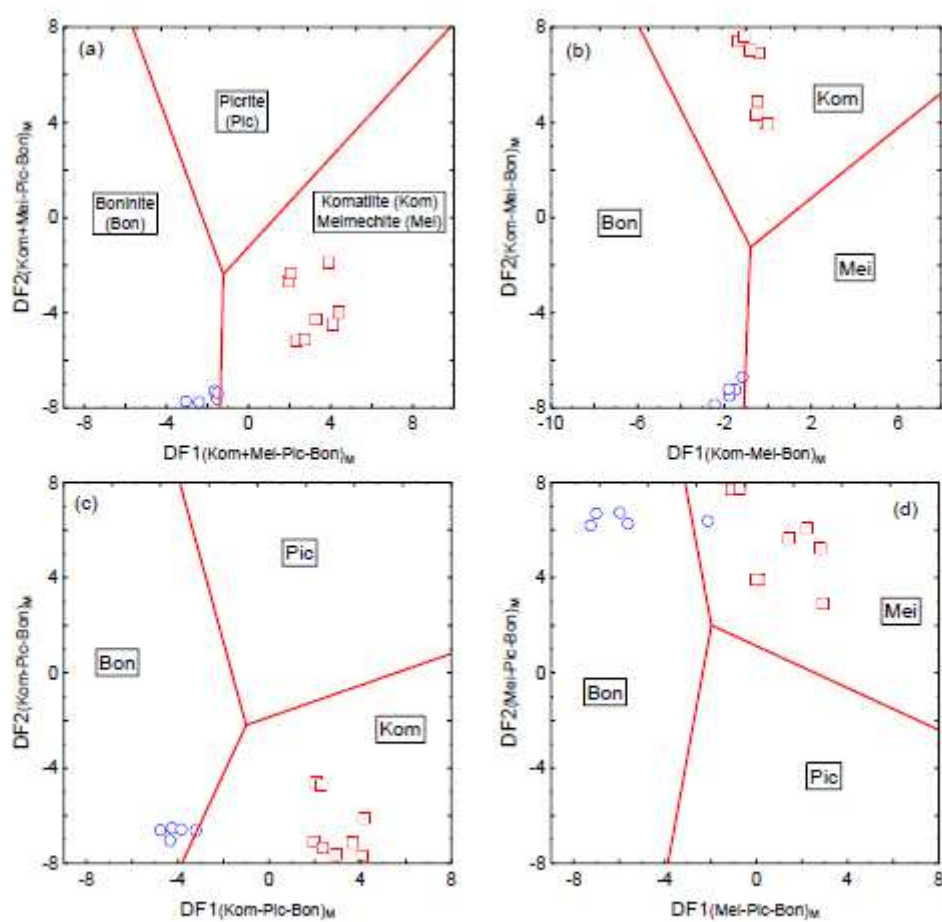


Fig. 5a-d

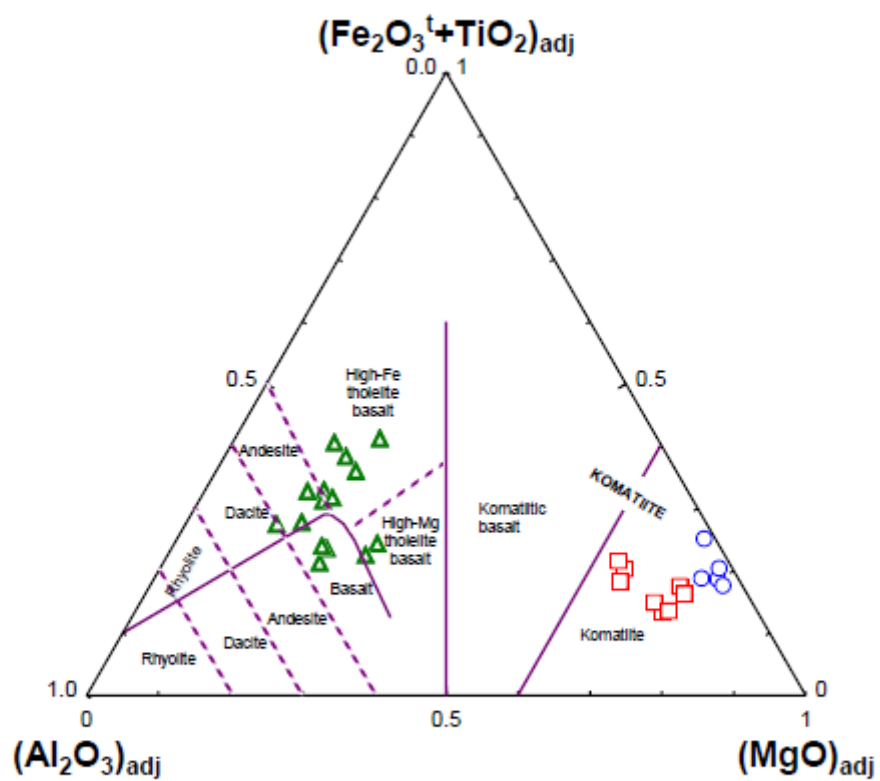


Fig. 6

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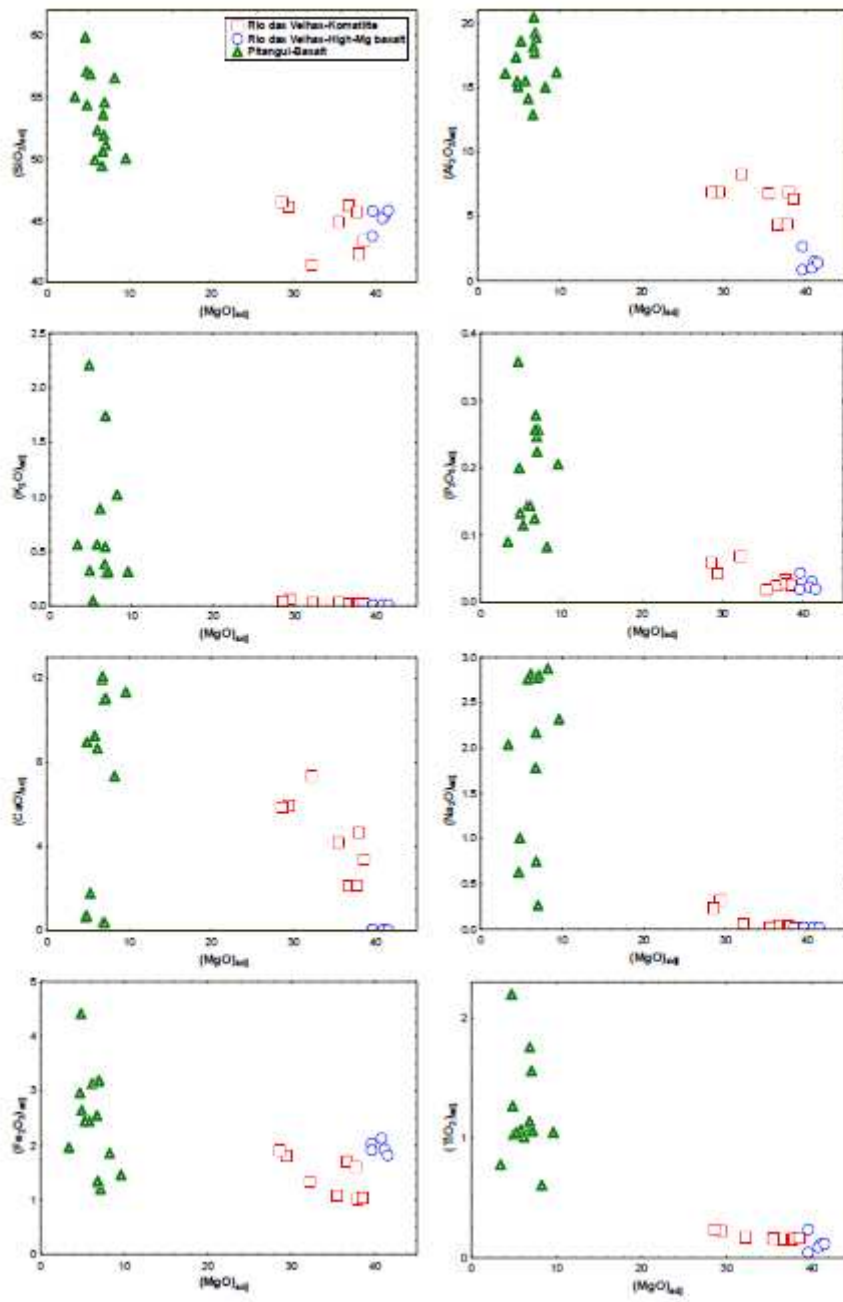


Fig. 7

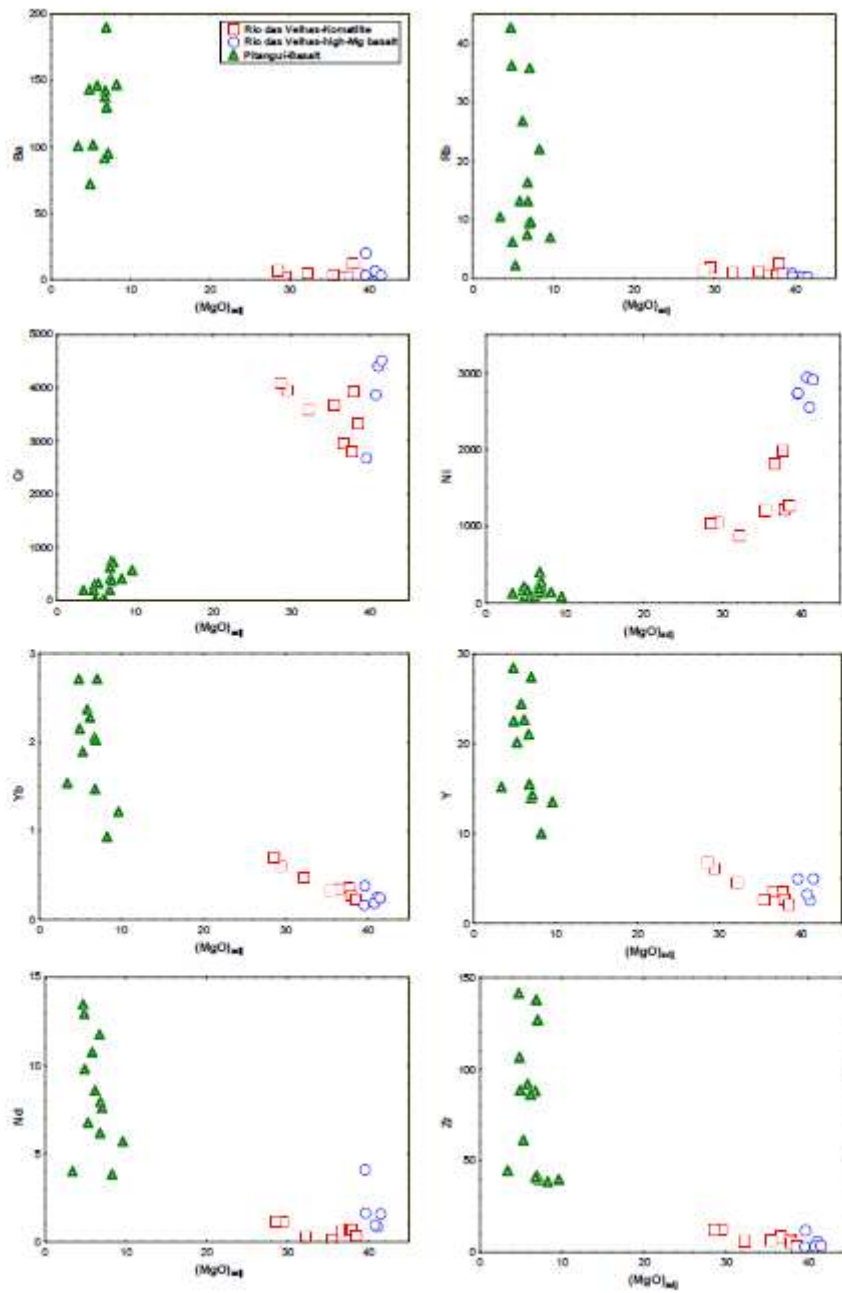


Fig. 8

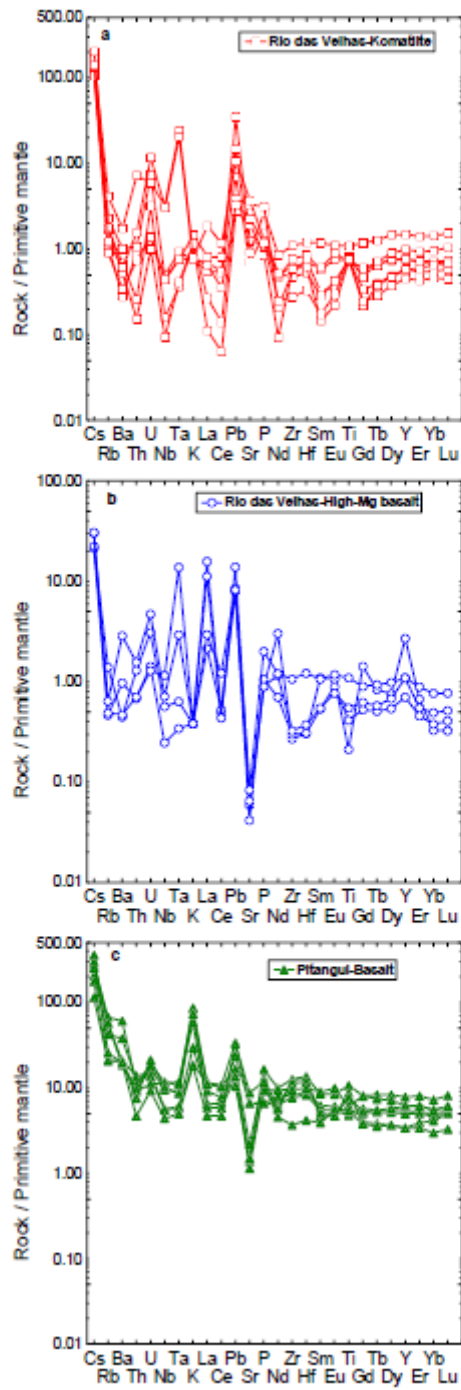


Fig. 9a-c

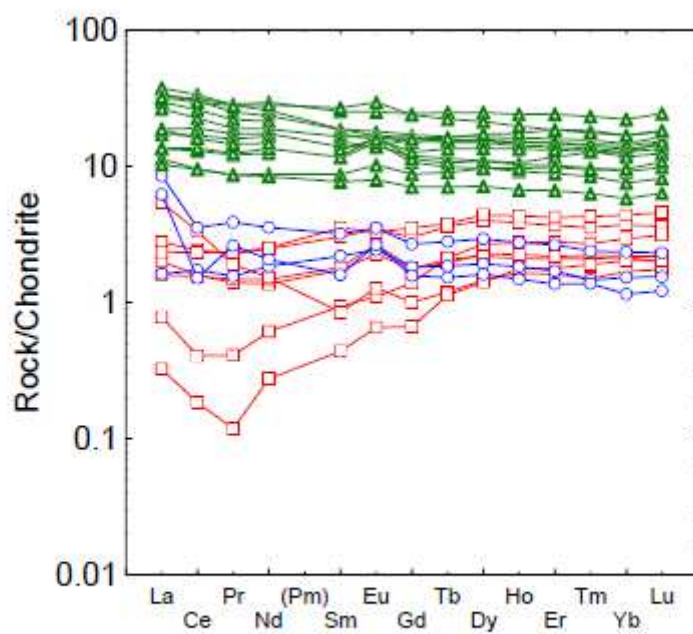


Fig. 10

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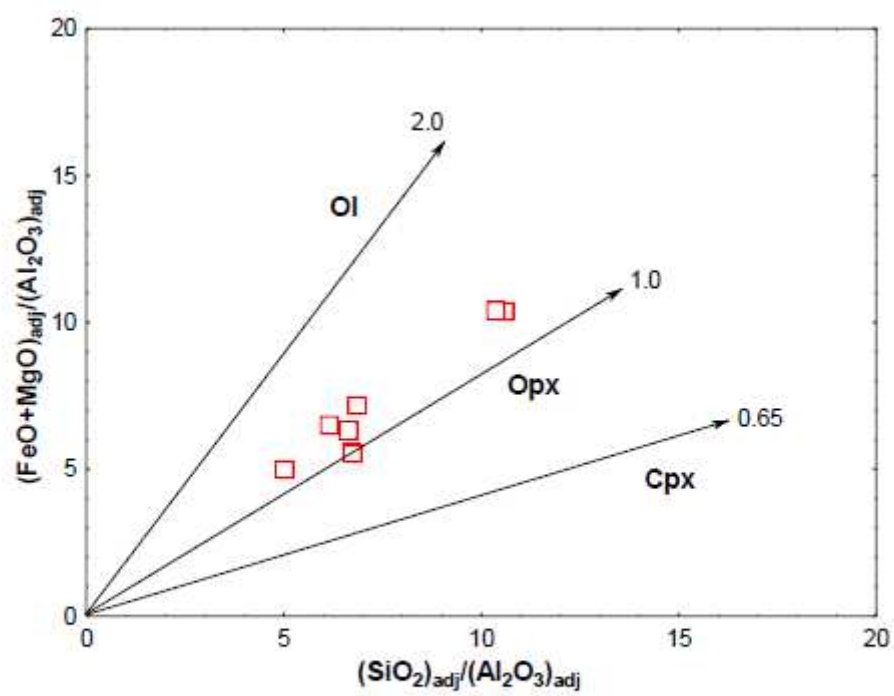


Fig. 11

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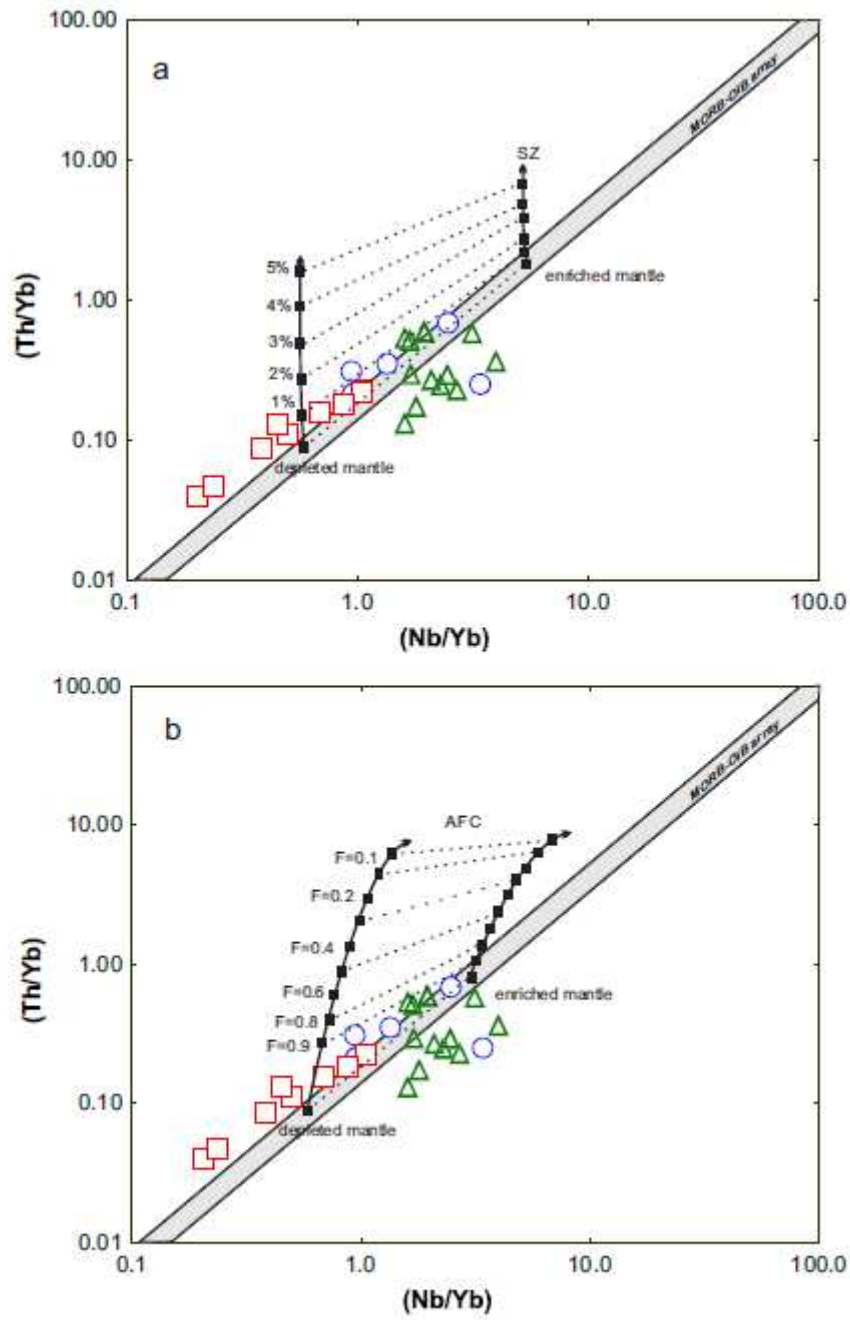


Fig. 12a-b

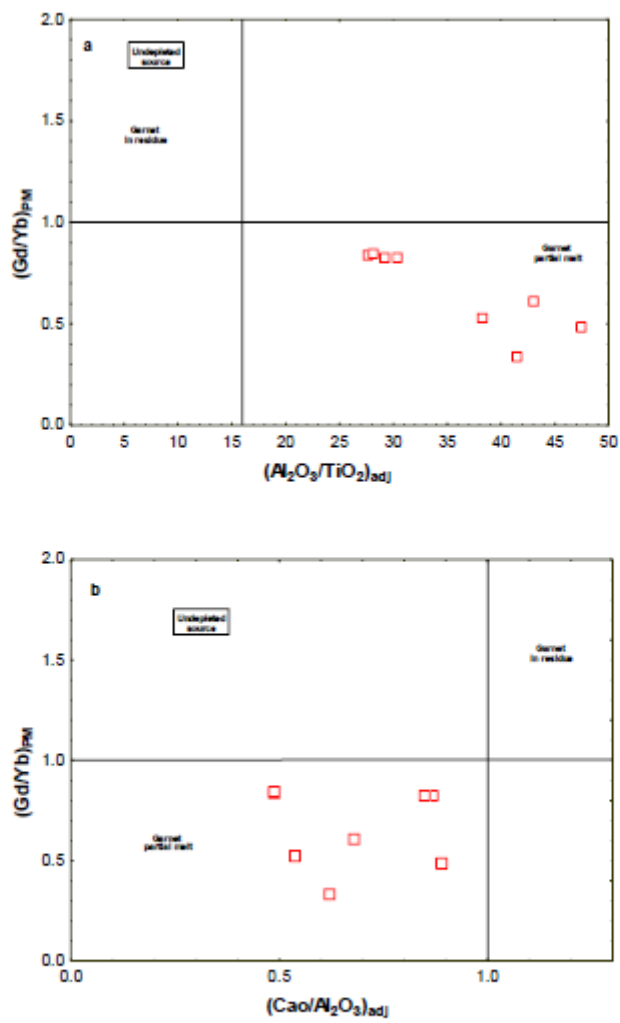


Fig. 13a-b

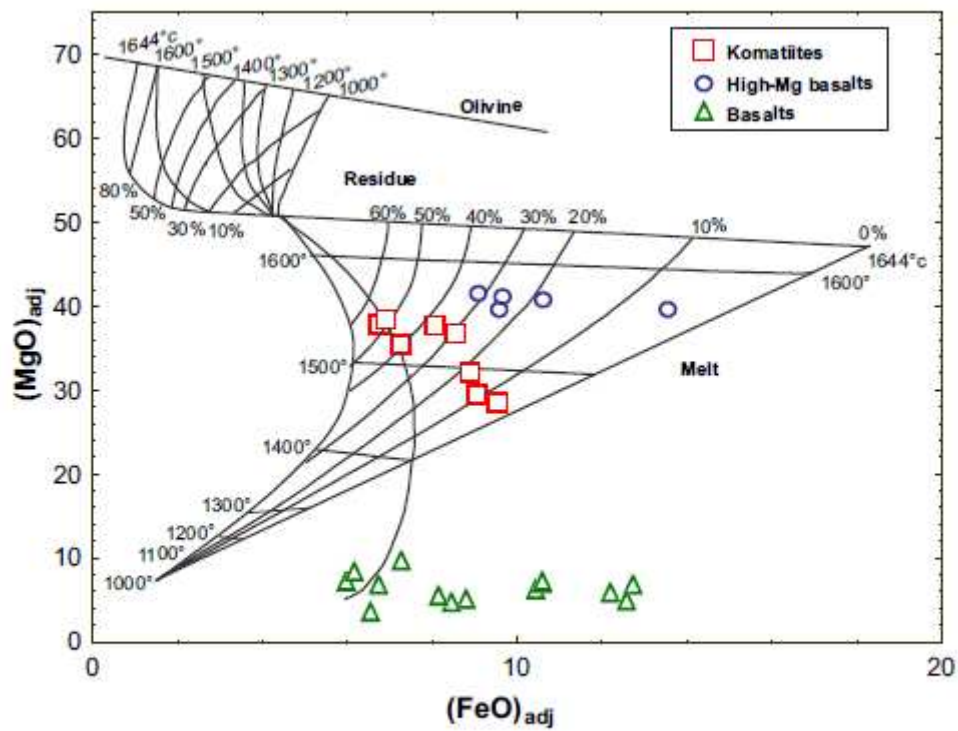


Fig. 14

ACCEPTED

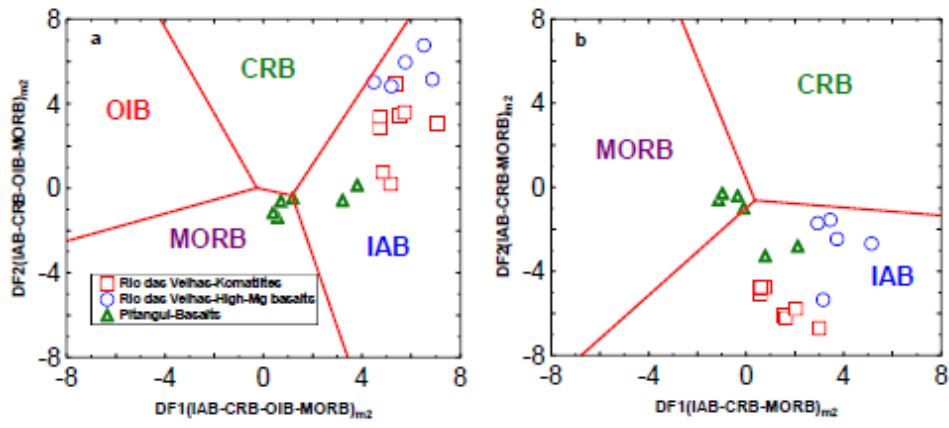


Fig. 15a-b

ACCEPTED MANUSCRIPT

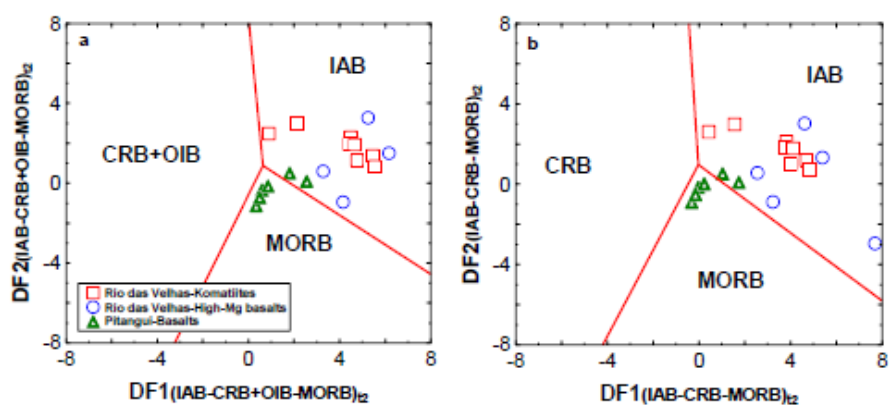


Fig. 16a-b

Table 1. Representative whole rock compositions of komatiites and basalts from the greenstone belt, São Francisco craton, Brazil. Major elements in weight percent and trace elements in ppm.

Sample	15MGE0-1A	15MGE0-1B	15MGE0-1C	15MGE0-1D	15MGE0-5A	15MGE0-5B	15MGE0-5C	15MGE0-5D	15MGE0-2A	15MGE0-2B	15MGE0-2C	15MGE0-2E	15MGE0-3
	Rio das Velhas greenstone belt												
Rock unit	Komatiite	Komatiite	Komatiite	Komatiite	Komatiite	Komatiite	Komatiite	Komatiite	High-Mg basalt	High-Mg basalt	High-Mg basalt	High-Mg basalt	High-Mg basalt
Locality	Morro do Onça	Morro do Onça	Morro do Onça	Morro do Onça	Rio das Velhas	Rio das Velhas	Rio das Velhas	Rio das Velhas	Caeté-Sabara	Caeté-Sabara	Caeté-Sabara	Caeté-Sabara	Caeté-Sabara
Long. (°W):	44.36	44.36	44.36	44.36	43.44	43.44	43.44	43.44	43.69	43.69	43.69	43.69	43.68
Lat. (°S):	20.32	20.32	20.32	20.32	20.04	20.04	20.04	20.04	19.89	19.89	19.89	19.89	19.92
SiO ₂	42.09	40.98	40.33	42.39	35.71	35.54	38.84	36.77	39.3	38.17	39.31	39.79	39.87
TiO ₂	0.206	0.14	0.138	0.215	0.15	0.134	0.141	0.14	0.097	0.04	0.078	0.103	0.206
Al ₂ O ₃	6.27	3.87	3.89	6.29	7.12	5.78	5.85	5.37	1.32	0.73	0.85	1.21	2.3
Fe ₂ O ₃	10.84	9.95	9.33	11.41	9.69	7.18	7.91	7.39	10.98	14.91	12.13	10.36	10.93
MnO	0.152	0.12	0.121	0.149	0.169	0.142	0.122	0.134	0.14	0.115	0.129	0.134	0.113
MgO	26.88	32.56	33.36	26.1	27.81	31.89	30.73	32.66	35.6	34.55	35.52	36.07	34.55
CaO	5.44	1.89	1.9	5.35	6.34	3.92	3.63	2.88	0.04	0.03	0.02	0.02	0.05
Na ₂ O	0.29	0.04	0.03	0.21	0.05	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02
K ₂ O	0.06	0.02	0.02	0.04	0.03	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01
P ₂ O ₅	0.039	0.022	0.029	0.054	0.059	0.023	0.016	0.022	0.027	0.017	0.02	0.017	0.038
LOI	7.02	9.41	9.86	6.81	12.59	14.41	12.3	13.68	11.14	10.53	10.87	11.2	10.81
Total	99.3	99	99	99	99.7	99	99.6	99.1	98.7	99.1	98.9	98.9	98.9
Adj Value													
(SiO ₂) _{adj}	46.08	46.18	45.65	46.46	41.39	42.30	44.85	43.39	45.38	43.73	45.15	45.81	45.74
(TiO ₂) _{adj}	0.23	0.16	0.16	0.24	0.17	0.16	0.16	0.17	0.11	0.05	0.09	0.12	0.24
(Al ₂ O ₃) _{adj}	6.86	4.36	4.40	6.89	8.25	6.88	6.76	6.34	1.52	0.84	0.98	1.39	2.64
(Fe ₂ O ₃) _{adj}	1.81	1.71	1.61	1.91	1.34	1.02	1.09	1.04	1.93	2.03	2.13	1.82	1.91
(FeO) _{adj}	9.05	8.55	8.05	9.54	8.90	6.78	7.24	6.91	9.67	13.54	10.63	9.10	9.56
(MnO) _{adj}	0.17	0.14	0.14	0.16	0.20	0.17	0.14	0.16	0.16	0.13	0.15	0.15	0.13
(MgO) _{adj}	29.43	36.69	37.76	28.61	32.24	37.96	35.49	38.54	41.11	39.59	40.80	41.53	39.64
(CaO) _{adj}	5.96	2.13	2.15	5.86	7.35	4.67	4.19	3.40	0.05	0.03	0.02	0.02	0.06
(Na ₂ O) _{adj}	0.32	0.05	0.03	0.23	0.06	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02
(K ₂ O) _{adj}	0.07	0.02	0.02	0.04	0.03	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01
(P ₂ O ₅) _{adj}	0.04	0.02	0.03	0.06	0.07	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.04
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Ba	2.31	1.96	2.38	7.04	4.74	12.12	3.72	4.29	3.08	3.11	6.79	3.28	20.03
Be	0.09	0.11	0.04	0.08		0.02			0.08	0.08	0.08		0.33
Co	89.62	100.61	103.48	96.43	80.39	76.50	70.63	73.68	121.31	130.89	172.15	128.11	145.65
Cr	3955.58	2958.40	2799.20	4093.88	3584.55	3931.79	3678.53	3333.82	4407.94	2681.29	3871.38	4514.95	5360.64
Cs	1.54	1.21	0.85	1.39	0.83	1.28	1.59	1.10	0.80	0.17	0.18	0.24	0.24
Cu	15.26	6.23	23.17	34.95	0.64	0.70	0.83	0.80	10.13	1.31	7.80	4.85	10.62
Ga	5.86	3.76	3.68	5.26	4.73	3.80	3.97	3.51	2.24	1.37	1.59	1.66	3.20
Hf	0.40	0.26	0.21	0.37	0.23	0.16	0.19	0.10	0.20	0.09	0.10	0.12	0.38
Li	5.65	3.87	3.24	5.30	15.89	25.81	28.47	23.26	0.28	0.24	0.25	0.23	0.31
Nb	0.41	0.36	0.31	0.32	0.04	0.05	0.07	0.04	0.23	0.40	0.18	0.82	0.51
Ni	1050.94	1815.22	1989.41	1033.67	871.07	1212.75	1205.34	1266.44	2552.64	2730.57	2943.34	2911.53	2738.07
Pb	7.52	2.47	0.50	1.05	0.27	0.76	0.20	0.24	1.10	0.61	0.56	0.99	0.59
Rb	1.83	0.68	0.57	1.44	1.08	2.61	1.13	0.77	0.28	0.89	0.30	0.31	0.41
Sb	0.18	0.04	0.03	0.07	5.22	7.57	5.85	6.11	13.60	9.15	7.91	7.72	8.07
Sc	23.35	13.79	13.99	23.63	24.88	18.05	17.80	16.18	13.79	9.62	12.94	15.66	12.01
Sr	27.01	26.25	14.90	19.36	69.79	78.05	41.61	47.25	0.90	1.24	0.88	1.37	1.75
Ta	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.03	0.01	0.57	0.12
Th	0.10	0.08	0.06	0.09	0.02	0.62	0.01	0.13	0.05	0.11	0.06	0.06	0.13
U	0.11	0.02	0.03	0.15	0.07	0.12	0.02	0.25	0.15	0.07	0.03	0.03	0.10
V	121.62	92.74	95.39	154.78	124.32	89.80	92.87	85.72	89.57	71.06	89.54	69.75	87.78
Y	6.09	3.52	3.45	6.76	4.51	2.66	2.63	2.07	2.54	12.31	3.19	4.94	4.96
Zn	97.50	52.67	49.85	68.56	61.22	38.01	36.02	37.12	110.87	54.11	92.12	90.40	164.21
Zr	12.52	8.66	7.00	12.32	6.12	5.27	6.56	3.10	5.97	3.02	3.33	3.62	11.92
La	0.66	0.48	0.38	0.56	0.19	1.29	0.08	0.45	0.38	10.88	1.48	7.73	2.02
Ce	1.50	0.98	0.96	1.43	0.25	2.06	0.11	0.63	1.06	0.87	0.93	0.77	2.17
Pr	0.21	0.13	0.14	0.22	0.04	0.18	0.01	0.07	0.15	0.98	0.24	0.39	0.36
Nd	1.14	0.63	0.68	1.15	0.28	0.70	0.13	0.34	0.85	4.09	0.95	1.57	1.63
Sm	0.45	0.26	0.27	0.53	0.14	0.13	0.07	0.08	0.33	0.49	0.24	0.24	0.47
Eu	0.20	0.13	0.15	0.19	0.06	0.07	0.04	0.05	0.14	0.18	0.15	0.13	0.20
Gd	0.60	0.35	0.36	0.70	0.28	0.20	0.13	0.14	0.36	0.85	0.31	0.37	0.54
Tb	0.13	0.08	0.07	0.14	0.08	0.04	0.04	0.03	0.07	0.09	0.06	0.06	0.10
Dy	0.99	0.54	0.56	1.09	0.66	0.36	0.35	0.28	0.47	0.56	0.40	0.50	0.72
Ho	0.21	0.12	0.12	0.24	0.15	0.09	0.10	0.06	0.10	0.14	0.08	0.10	0.15
Er	0.59	0.33	0.35	0.68	0.45	0.26	0.29	0.21	0.27	0.32	0.22	0.26	0.43
Tm	0.09	0.05	0.06	0.11	0.07	0.04	0.05	0.04	0.04	0.03	0.03	0.04	0.06
Yb	0.60	0.35	0.35	0.71	0.47	0.27	0.33	0.23	0.25	0.16	0.19	0.24	0.38
Lu	0.09	0.05	0.05	0.11	0.08	0.04	0.05	0.03	0.04	0.02	0.03	0.04	0.06

Bi	0.20	0.19	0.14	0.25	0.016	0.016	0.015	0.017	0.033	0.021	0.031	0.03	0.051
Cd	0.06	0.07	0.07	0.07	0.036	0.029	0.071	0.034	0.034	0.065	0.055	0.043	0.047
Mo	0.07	0.06	0.06	0.09	0.031	0.056	0.156	0.063	0.116	0.064	0.389		
Sn	1.81	0.06	0.08	0.55		0.043		0.04	0.12	0.03	0.07	0.05	0.56
W	0.65	0.64	0.45	0.49	0.231	25.95	0.21	74.86	0.37	0.22	0.25	13.88	0.82
(Al ₂ O ₃ /TiO ₂) _{adj}	30.44	27.64	28.19	29.26	47.47	43.13	41.49	38.36	13.61	18.25	10.90	11.75	11.17
(CaO/Al ₂ O ₃) _{adj}	0.87	0.49	0.49	0.85	0.89	0.68	0.62	0.54	0.03	0.04	0.02	0.02	0.02
ΣREE	6.46	3.91	3.93	6.75	2.52	5.36	1.41	2.35	4.02	19.09	4.90	11.95	8.56
(La/Sm) _{CN}	0.91	1.16	0.88	0.66	0.83	6.37	0.74	3.64	0.74	13.98	3.89	19.94	2.67
(Gd/Yb) _{CN}	0.81	0.82	0.83	0.81	0.47	0.59	0.33	0.51	1.19	4.24	1.37	1.24	1.15
(Gd/Yb) _{PM}	0.83	0.84	0.84	0.82	0.48	0.61	0.33	0.52	1.22	4.34	1.40	1.27	1.17
(Th/Nb) _{PM}	1.92	1.82	1.70	2.38	1.63	2.27	1.63	0.51	1.86	2.28	2.78	0.61	2.20
(Sm/Yb) _{PM}	0.83	0.82	0.85	0.83	0.33	0.51	0.22	0.38	1.46	3.33	1.41	1.11	1.39
(La/Yb) _{PM}	0.79	0.99	0.77	0.57	0.28	1.28	0.17	1.42	1.12	48.20	5.69	22.91	3.84
(Nb/Nb*)	0.90	1.04	0.98	0.49	0.33	1.78	0.29	4.81	0.66	0.07	0.16	0.20	0.25
(Ta/Ta*)	1.33	1.91	1.75	0.83	0.77	13.31	1.29	32.43	1.07	0.08	0.22	2.36	1.01
(Ti/Ti*)	0.83	0.95	0.88	0.84	1.18	1.45	1.88	2.03	0.75	0.11	0.52	0.59	0.96
(Eu/Eu*)	1.15	1.31	1.47	0.93	0.95	1.38	1.20	1.43	1.23	0.85	1.68	1.33	1.20
(Ce/Ce*)	0.98	0.95	1.03	1.01	0.69	0.92	0.84	0.79	1.10	0.05	0.35	0.07	0.58
(Zr/Th)	131.79	111.08	111.06	135.37	278.18	8.55	504.38	23.34	114.77	27.42	57.41	60.38	89.64
(Nb/Yb)	0.69	1.04	0.88	0.45	0.24	8.37	0.20	9.57	0.95	2.49	0.94	3.40	1.34
(Th/Yb)	0.16	0.23	0.18	0.13	0.05	2.26	0.04	0.59	0.21	0.68	0.31	0.25	0.35

Table 1 continue.

Sample	PM14 -01A	PM14 -01B	PM14 -01C	PM14 -01D	PM14 -08A	PM14 -08B	PM14 -08C	PM14 -08D	PM14 -10A	PM14 -10B	PM14 -10C	PM14 -10D	PM14 -11B	PM14 -11C	PM14 -12C
Pitangui greenstone belt															
Rock unit	Basalt	Basalt	Basalt ic anesite	Basalt	Basalt ic anesite	Basalt	Basalt	Basalt ic anesite	Gabbr os	Gabbr os	Gabbr os	Gabbr os	Basalt ic anesite	Basalt	Basalt ic anesite
Locality	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui	Pitan gui
Long. (°W):	44.93	44.93	44.93	44.93	44.92 93	44.92 93	44.92 93	44.92 93	44.89 22	44.89 22	44.89 22	44.89 22	44.93 40	44.93 40	44.96 63
Lat. (°S):	19.41	19.41	19.41	19.41	19.69 42	19.69 42	19.69 42	19.69 42	19.73 66	19.73 66	19.73 66	19.73 66	19.69 11	19.69 11	19.67 43
SiO ₂	47.68	48.58	53.24	51	56.87	50.06	51.14	54.24	50.51	49.78	48.74	49.16	54.34	48.82	54.78
TiO ₂	1.06	1.07	1.03	1.01	2.2	1.76	1.56	1.27	1.06	1.06	1.05	1.14	1.05	0.78	0.61
Al ₂ O ₃	12.46	15.09	14.77	13.79	16.5	19.14	18.05	14.72	17.23	18.37	15.76	17.65	17.79	14.29	14.56
Fe ₂ O ₃	16.13	15.61	12.19	14.38	11.77	14	14.05	17.52	8.38	7.68	9.34	8.59	11	8.21	8.48
MnO	0.28	0.23	0.2	0.23	0.14	0.24	0.18	0.12	0.12	0.11	0.12	0.13	0.19	0.22	0.14
MgO	6.5	5.66	4.81	6.01	4.46	6.39	6.59	4.59	6.77	6.99	9.37	6.61	5.06	3.01	8
CaO	11.55	9.04	8.8	8.47	0.63	0.38	0.37	0.68	10.69	10.78	11.06	11.76	1.71	11.67	7.13
Na ₂ O	1.72	2.69	3.46	2.75	0.6	0.7	0.25	0.96	2.7	2.73	2.26	2.11	5.18	1.81	2.79
K ₂ O	0.37	0.55	0.32	0.87	2.42	1.63	2.44	2.1	0.3	0.31	0.31	0.53	0.05	0.5	0.99
P ₂ O ₅	0.12	0.14	0.13	0.14	0.34	0.26	0.21	0.19	0.24	0.25	0.2	0.25	0.11	0.08	0.08
LOI	1.93	1.17	0.91	1.19	3.84	5.18	4.97	3.41	1.71	1.71	1.54	1.83	3.32	10.4	2.23
Total	99.8	99.83	99.86	99.84	99.77	99.74	99.81	99.8	99.71	99.77	99.75	99.76	99.8	99.79	99.79
Adj Value															
(SiO ₂) _{adj}	49.41	49.91	54.33	52.30	59.84	53.57	54.56	57.06	51.92	51.10	50.03	50.58	56.83	55.01	56.54
(TiO ₂) _{adj}	1.10	1.10	1.05	1.04	2.31	1.88	1.66	1.34	1.09	1.09	1.08	1.17	1.10	0.88	0.63
(Al ₂ O ₃) _a	12.91	15.50	15.07	14.14	17.36	20.48	19.26	15.49	17.71	18.86	16.18	18.16	18.61	16.10	15.03
(Fe ₂ O ₃) _{adj}	2.55	2.45	2.64	3.13	2.97	3.18	3.19	4.41	1.31	1.20	1.46	1.35	2.45	1.97	1.86
(FeO) _{adj}	12.75	12.23	8.81	10.45	8.48	10.61	10.62	12.61	6.57	6.01	7.31	6.74	8.15	6.56	6.20
(MnO) _{adj}	0.29	0.24	0.20	0.24	0.15	0.26	0.19	0.13	0.12	0.11	0.12	0.13	0.20	0.25	0.14
(MgO) _{adj}	6.74	5.81	4.91	6.16	4.69	6.84	7.03	4.83	6.96	7.18	9.62	6.80	5.29	3.39	8.26
(CaO) _{adj}	11.97	9.29	8.98	8.69	0.66	0.41	0.39	0.72	10.99	11.07	11.35	12.10	1.79	13.15	7.36
(Na ₂ O) _a	1.78	2.76	3.53	2.82	0.63	0.75	0.27	1.01	2.78	2.80	2.32	2.17	5.42	2.04	2.88
(K ₂ O) _{adj}	0.38	0.57	0.33	0.89	2.55	1.74	2.60	2.21	0.31	0.32	0.32	0.55	0.05	0.56	1.02
(P ₂ O ₅) _{adj}	0.12	0.14	0.13	0.14	0.36	0.28	0.22	0.20	0.25	0.26	0.21	0.26	0.12	0.09	0.08
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Ba	91.68	146.1 9	72.20	265.0 7	424.1 0	142.4 5	129.9 3	143.3 8	189.9 42	95.33 1	527	138	101.6 98	100.7 04	146.9 2
Be	0.46	0.51	0.58	0.48	0.45	0.51	0.62	0.45			0.27	0.24	0.36	0.24	0.26
Co	77.54	62.59	54.65	56.87	55.05	144.7 2	72.88	42.31			28.35	41.70	42.37	43.51	44.37
Cr	210.9 4	18.54	27.79	16.33	205.1 7	426.2 6	378.6 3	314.7 0	750	733	578.0 7	633.1 2	334.8 7	204.5 8	416.0 2
Cs	0.48	0.91	0.25	1.64	2.15	1.40	2.01	2.39			0.97	2.84	0.32	1.23	0.58
Cu															

Ga	15.23	15.70	15.19	13.98	19.40	20.49	17.26	14.48	14.7	14.2	13.39	15.14	13.82	11.66	9.51
Hf	2.55	2.73	2.63	2.56	4.21	4.11	3.60	3.06			1.23	1.29	1.88	1.40	1.19
Li	11.86	20.11	6.82	20.39	49.23	101.3 3	79.43	48.78			7.28	8.90	57.05	39.67	14.85
Nb	6.31	4.07	4.02	3.97	8.34	8.14	6.81	7.20	2.9	2.8	2.11	3.14	3.03	2.27	1.81
Ni	242.7 9	85.38	86.84	82.69	160.2 2	402.0 5	278.8 4	208.2 6	131	173	81.19	185.4 3	167.0 7	127.0 3	138.7 5
Pb	2.13	2.42	2.25	1.67	1.12	1.18	0.96	0.75	3.5	3.9	1.99	2.33	0.82	0.93	0.84
Rb	7.49	13.28	6.29	26.87	42.78	13.23	35.85	36.30	9.5	9.7	7.06	16.41	2.29	10.54	22.08
Sb	0.07	0.16	0.10	0.10	12.35	13.56	6.23	6.50			1.66	1.67	4.64	0.86	0.66
Sc	36.27	39.58	40.82	38.01	38.69	40.34	41.68	32.06	37	36	21.10	27.11	36.82	26.77	32.59
Sr	106.8 6	138.6 8	134.4 5	139.0 3	29.25	46.38	24.06	31.57	208	181	163.7 8	184.6 9	91.08	126.5 9	78.88
Ta	0.44	0.24	0.25	0.25	0.45	0.48	0.37	0.35			0.13	0.20	0.16	0.12	0.11
Th	1.16	1.17	1.10	1.08	0.92	0.78	0.82	0.65	2.3		0.36	0.40	0.33	0.21	0.50
U	0.31	0.32	0.28	0.28	0.40	0.23	0.36	0.45			0.16	0.19	0.14	0.49	0.15
V	243.1 2	262.6 8	290.0 6	250.0 1	310.7 0	302.2 1	300.6 9	246.6 3	218	242	181.9 2	229.8 0	219.9 0	169.5 8	207.7 2
Y	21.07	24.44	22.54	22.67	35.65	15.51	27.41	28.45	14	14.3	13.54	15.47	20.17	15.19	10.05
Zn	129.2 5	120.8 7	99.34	102.0 0	78.43	138.1 8	92.23	58.62	56	63	37.92	59.06	74.61	64.55	56.34
Zr	88.27	91.94	88.61	86.33	141.6 1	137.9 9	126.9 8	106.6 0	42	40	39.94	41.19	61.46	44.88	38.86
La	8.93	7.98	7.07	6.29	7.83	4.46	4.07	7.58			3.19	3.23	4.43	2.70	2.45
Ce	20.63	18.61	15.99	13.83	19.29	11.73	10.36	18.21	13	8	7.98	8.37	9.83	5.86	5.85
Pr	2.62	2.33	2.05	1.76	2.66	1.61	1.48	2.58			1.13	1.16	1.35	0.80	0.81
Nd	11.79	10.77	9.82	8.60	13.49	7.97	7.61	12.96	16	16	5.72	6.18	6.77	4.03	3.86
Sm	2.78	2.76	2.55	2.45	3.76	2.07	2.24	3.99			1.70	1.74	1.97	1.29	1.14
Eu	0.94	1.02	0.91	0.92	1.42	0.79	0.79	1.66			0.85	0.94	0.89	0.58	0.45
Gd	3.27	3.40	3.18	3.02	4.86	2.39	3.17	4.78			2.14	2.26	2.54	1.76	1.41
Tb	0.54	0.60	0.56	0.56	0.90	0.41	0.59	0.81			0.36	0.38	0.49	0.33	0.26
Dy	3.68	4.07	3.87	3.80	6.13	2.70	4.26	5.26			2.40	2.71	3.35	2.39	1.76
Ho	0.77	0.88	0.82	0.81	1.32	0.58	0.96	1.08			0.50	0.56	0.73	0.53	0.37
Er	2.23	2.56	2.38	2.39	3.87	1.88	2.98	2.96			1.42	1.62	2.12	1.58	1.06
Tm	0.33	0.38	0.35	0.36	0.58	0.31	0.45	0.44			0.21	0.24	0.32	0.23	0.16
Yb	2.06	2.38	2.16	2.28	3.57	2.03	2.72	2.72			1.22	1.48	1.90	1.54	0.94
Lu	0.33	0.41	0.35	0.38	0.60	0.37	0.44	0.45			0.20	0.24	0.31	0.27	0.16
Bi															
Cd															
Mo															
Sn	0.77	0.58	0.68	0.53	1.07	0.92	0.86	0.80				0.31	0.38	0.15	0.12
W	0.22	0.22	0.25	0.78	0.40	0.18	0.24	0.11			0.48	0.43	0.06	0.15	0.27
(Al ₂ O ₃ /TiO ₂) _{adj}	11.75	14.10	14.34	13.65	7.50	10.88	11.57	11.59	16.25	17.33	15.01	15.48	16.94	18.32	23.87
(CaO/Al ₂ O ₃) _{adj}	0.93	0.60	0.60	0.61	0.04	0.02	0.02	0.05	0.62	0.59	0.70	0.67	0.10	0.82	0.49
ΣREE	57.22	54.08	48.19	43.65	64.15	36.59	37.85	60.21			26.62	28.41	33.64	21.48	18.89
(La/Sm) _{CN}	2.00	1.80	1.73	1.60	1.30	1.35	1.13	1.19			1.17	1.16	1.41	1.30	1.34
(Gd/Yb) _{CN}	1.29	1.16	1.19	1.07	1.10	0.95	0.94	1.42			1.42	1.24	1.08	0.92	1.21
(Gd/Yb) _{PM}	1.32	1.18	1.22	1.09	1.13	0.97	0.96	1.45			1.45	1.27	1.11	0.94	1.24
(Th/Nb) _{PM}	1.54	2.42	2.29	2.29	0.93	0.80	1.01	0.75	6.65		1.42	1.06	0.90	0.78	2.31
(Sm/Yb) _{PM}	1.50	1.29	1.31	1.19	1.17	1.13	0.91	1.63			1.55	1.31	1.15	0.93	1.35
(La/Yb) _{PM}	3.11	2.41	2.35	1.98	1.57	1.58	1.07	2.00			1.88	1.57	1.68	1.26	1.87
(Nb/Nb*)	0.68	0.35	0.55	0.24	0.32	0.85	0.78	0.64			0.07	0.36	0.40	0.35	0.21
(Ta/Ta*)	0.81	0.36	0.58	0.26	0.30	0.87	0.73	0.54			0.08	0.41	0.36	0.31	0.21
(Ti/Ti*)	0.99	0.89	0.94	0.91	1.31	2.14	1.44	0.76			1.24	1.20	1.04	1.20	1.19
(Eu/Eu*)	0.95	1.02	0.97	1.03	1.01	1.08	0.90	1.17			1.36	1.45	1.22	1.17	1.08
(Ce/Ce*)	1.03	1.05	1.02	1.00	1.03	1.07	1.04	1.01			1.03	1.06	0.98	0.97	1.02
(Zr/Th)	76.10	78.31	80.70	79.71	153.4 2	176.9 1	154.1 0	165.2 8	18.26		111.5 7	103.7 5	188.5 2	213.7 0	78.18
(Nb/Yb)	3.07	1.71	1.86	1.74	2.33	4.01	2.51	2.65			1.73	2.13	1.60	1.47	1.92
(Th/Yb)	0.56	0.49	0.51	0.47	0.26	0.38	0.30	0.24			0.29	0.27	0.17	0.14	0.53

$$\text{Nb/Nb}^* = 2^* \text{Nb}_{\text{PM}} / (\text{Ba} + \text{La})_{\text{PM}}$$

$$\text{Ta/Ta}^* = 2^* \text{Ta}_{\text{PM}} / (\text{Ba} + \text{La})_{\text{PM}}$$

$$\text{Ti/Ti}^* = \text{Ti}_{\text{PM}} / ((\text{Eu} + \text{Y})/2)_{\text{PM}}$$

$$\text{Eu/Eu}^* = 2^* \text{Eu}_{\text{PM}} / (\text{Sm} + \text{Gd})_{\text{PM}}$$

$$\text{Ce/Ce}^* = 2^* \text{Ce}_{\text{PM}} / (\text{La} + \text{Pr})_{\text{PM}}$$

adj = Adjusted value

PM= Primitive mantle normalized value (taken from McDonough and Sun, 1995)
CN= Chondrite-normalized (taken from McDonough and Sun, 1995)

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Table 2. Published geochronology of the greenstone belt of Rio das Velhas.

SL. No.	Greenstone belt	Rock	Method	Age	References
1	Rio das Velhas	Volcanic	TIMS	2776 ± 26 Ma	Machado et al. (1992)
2	Rio das Velhas	Volcanic	SHRIMP	2792 ± 11 Ma	Noce et al. (2005)
3	Rio das Velhas	Volcanic	TIMS	2751 ± 11 Ma	Noce et al. (2005)
4	Rio das Velhas	Volcanic	TIMS	2777 ± 7 Ma	Noce et al. (2005)

Table 3. Application of multidimensional diagrams to Neoproterozoic (2700 Ma) intermediate rocks of the Pitangui greenstone belt.

Magma type, Figure name	Figure type	Total number of samples	Number of discriminated samples				
			Arc			CR+OI [x ± s] [p_CR+OI] Θ	Col [x ± s] [p_Col] Θ
			IA+CA [x ± s] [p_IA+CA] Θ	IA [x ± s] [p_IA] Θ	CA [x ± s] [p_CA] Θ		
Intermediate; Verma and Verma (2013); log- ratios of immobile trace elements	(IA+CA- CR+OI-Col)	9	6 [0.861±0.103] (0.6929- 0.9313)	---	---	3 [0.589±0.059] (0.5289-0.6474)	0 (0)
	(IA-CA- CR+OI)	9	---	9 [0.780±0.136] (0.4381-0.8812)	0 (0)	0 (0)	---
	(IA-CA-Col)	9	---	8 [0.814±0.083] (0.6734-0.9587)	1(0.5263)	---	0 (0)
	(IA-CR+OI- Col)	9	---	8 [0.881±0.068] (0.7822-0.9544)	---	1(0.5297)	0 (0)
	(CA-CR+OI- Col)	9	---	---	7 [0.800±0.168] (0.5396- 0.9496)	2 [0.724±0.081] (0.6665, 0.7816)	0 (0)
Diagrams based on log- ratios of immobile trace elements	{Σn} {Σprob} [%prob]	45	{6} {5.1685} [---]	{25} {20.5840} [69%]	{8} {6.1232} [21%]	{6} {3.7458} [10%]	{0} {0} [0%]

IA–island arc; CA–continental arc; IA+CA–combined island and continental arcs, i.e., arc setting; CR–continental rift; OI–ocean island; CR+OI –combined continental rift and ocean island, i.e., within-plate (WP) setting; Col–collision; Θ the probability values for samples from a given locality are represented by (pIA+CA) – probability for the combined island and continental arc setting in the first diagram; [pIA] – probability for the island arc setting in the diagrams; [pCA] – probability for the continental arc setting in the diagrams; [pCR+OI] – probability for the combined continental rift and ocean island setting in all diagrams; [pCol] – probability for the collision setting in the diagrams; – mean ± 1SD (standard deviation) of the probability estimates for all samples discriminated in a given tectonic setting; these are reported in [], the values are rounded mostly following the indications put forth by Verma (2005); the final rows give a synthesis of results as {Σn} {Σprob} [%prob], where {Σn} is the total number of samples or data points plotting in all five diagrams is reported in the column of total number of samples, whereas the sum of samples plotting in a given tectonic field is reported in the respective tectonic field column; {Σprob} is the sum of probability values for all samples plotting in a given tectonic field is reported in the respective tectonic field column; and [%prob] is the total probability of a given tectonic setting expressed in percent after assigning the probability of IA + CA to IA and CA (using weighing factors explained in Verma and Verma, 2013).