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Evolution of reworked Paleoproterozoic basement rocks within the Ribeira belt (Neoproterozoic), SE-Brazil, based on U–Pb geochronology: Implications for paleogeographic reconstructions of the São Francisco-Congo paleocontinent

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ABSTRACT

Geological, geochemical and geochronological data suggest that the basement exposed in the Occidental terrane of the Neoproterozoic-Ordovician Ribeira belt represents the continuation of the São Francisco paleocontinent, which was amalgamated at the end of the Rhyacian (Transamazonian Orogeny). The Mantiqueira complex represents a cordilleran-type active margin of the Archean paleocontinent, while the Juiz de Fora complex represents juvenile Paleoproterozoic material, probably developed within an oceanic setting (primitive arc or plateau?). The latter unit was probably accreted to the active margin of the paleocontinent during the latest stages of the Transamazonian Orogeny, around ca. 2.05 Ma, causing the deformation and metamorphism of the Mantiqueira complex. At this time, to the west and on the cratonic foreland, concurrent deformation of the Minas passive margin and sedimentation of the Sabará basin took place. Subsequent to the Transamazonian Orogeny, the basement associations were intruded by intraplate alkaline and basic rocks related to rifting events between ca. 1.7 and 1.3 Ga that resulted in the development of intracratonic basins. The Paleoproterozoic suture located between the Mantiqueira and Juiz de Fora Paleoproterozoic terranes probably controlled the Neoproterozoic passive margin tectonics and also the development of a major thrust surface during the Neoproterozoic/Cambrian Brasiliano convergence.

1. Tectonic setting and objectives

The Ribeira belt (Brito-Neves et al., 1999; Almeida et al., 2000; Cordani et al., 2003), SE-Brazil, occupies a central position in Western Gondwana (Fig. 1a) and is one of the key components for reconstructing the history of this supercontinent. Recent geological data for the central segment of the Ribeira belt reveal a complex history with the accretion of a cordilleran arc and the collision of at least two terranes onto the eastern margin of the São Francisco plate (Heilbron et al., 2000, 2004a,b, 2008; Trouw et al., 2000; Fig. 1b). The first-order organization of the belt comprises four tectono-stratigraphic terranes, progressively reworked or accreted onto the margin of São Francisco (SFC). From NW to SE, these terranes are (Fig. 2a): (a) the reworked margin of the SFC, defined as the Occidental terrane; (b) The Paraíba do Sul-Embú terrane that is thrust over the Occidental terrane; (c) the Oriental (Serra do Mar) terrane that includes the Neoproterozoic magmatic arc of the belt (Tupinambá et al., 2000), and (d) The Cabo Frio terrane, which was accreted later, at ca. 520 Ma (Schmitt et al., 2004). The suture between the Occidental and Oriental terranes is a conspicuous NW-dipping shear zone (Central Tectonic Boundary) that can be traced continuously for at least 200 km, from the coast of São Paulo state to the Serra dos Orgãos mountains, Rio de Janeiro state.

In spite of the tectonic complexity, a striking feature of the Ribeira belt is a high proportion of reworked Paleoproterozoic basement rocks throughout most of the terranes (Fig. 1b). The innermost Occidental terrane is regarded as the reworked border of the São Francisco-Congo paleocontinent (Heilbron et al., 2004a, 2008), and for this reason basement associations of this terrane should be accounted for in paleogeographic reconstructions during the Paleoproterozoic.

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[1] In memoriam.

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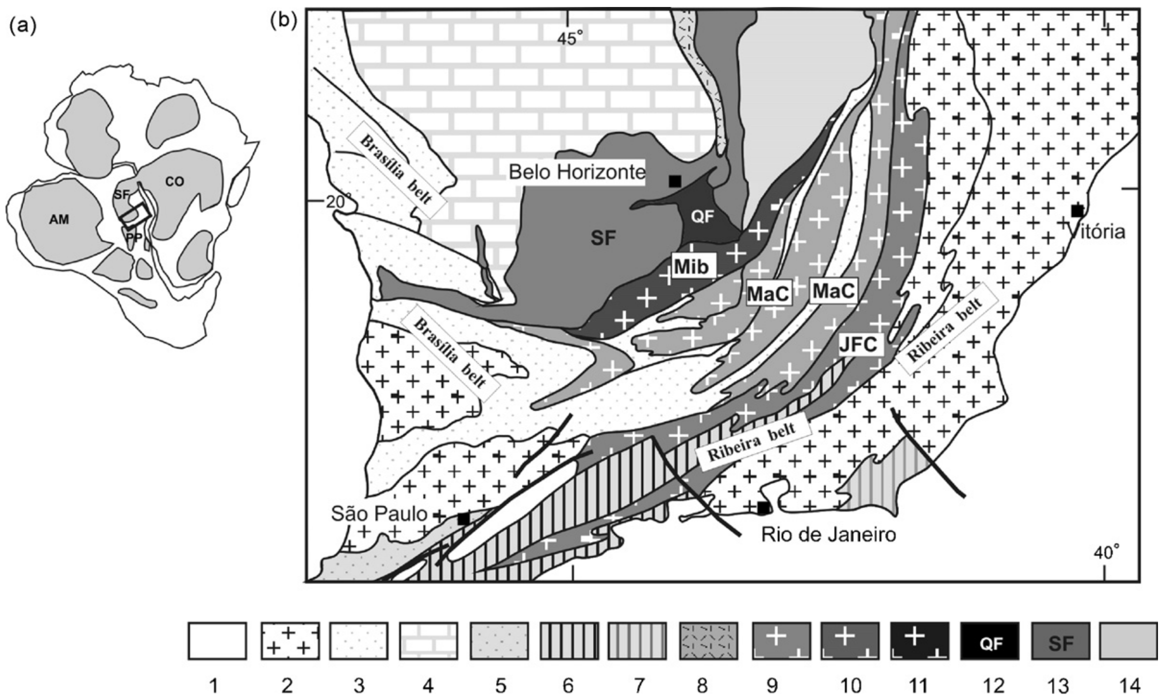

Fig. 1. (a) Location of the investigated area in Western Gondwana Scenario. (b) Tectonic map pf southeastern Brazil with the location of the Paleoproterozoic units described (compiled from Heilbron et al., 2008; Valeriano et al., 2004; Noce et al., 2007). Legend: (1) Phanerozoic sediments; (2) Neoproterozoic magmatic arcs of Brasília, Ribeira and Araçuaí belts; (3) Neoproterozoic passive margin sequences; (4) Bambuí Group; (5) Apiaí terrane; (6) Embú and Paraíba do Sul terranes; (7) Cabo Frio terrane; (8) Mesoproterozoic Espinhaço sequences; (9) Mineiro belt; (10) Mantiqueira complex and related rocks; (11) Juiz de Fora complex mixed with Neoproterozoic sequences; (12) Minas Supergroup at Iron Quadrangle; (13) Archean sucessions at southern São Francisco Craton; (14) Guanhães terrane.

In order to contribute to the knowledge and distribution of the Paleoproterozoic belts of SE-Brazil, in the context of West Gondwana, we report new LA-MC-ICPMS and ID-TIMS U–Pb data from 15 samples of pre-1.8 Ga basement associations from the Occidental terrane. The geochronologic data are interpreted in terms of the main metamorphic and magmatic episodes within the inner portions of the belt, along with available geochemical and geological data. Important issues related to this reworked Paleoproterozoic orogen are discussed, such as the accretionary geodynamic evolution of the Paleoproterozoic orogen and the implications of the original extent of the São Francisco-Congo paleocontinent to paleogeographic reconstructions.

2. Previous data for the São Francisco Craton

The Paleoproterozoic orogenic episodes are relatively well described, both at the southern and eastern portions of the present São Francisco Craton. At its southern tip, the orogen is referred to as the Mineiro belt (Teixeira et al., 1998, 2000; Fig. 1b). The broad age intervals and tectonic evolution is relatively well constrained by the studies of several authors, such as Machado et al. (1996a), Alkmin and Marshak (1998), Teixeira et al. (1998, 2000), Noce et al. (1998), Barbosa and Sabaté (2002, 2004) and Ávila et al. (2006a,b). The orogen is characterized by a rift-passive margin sequence (Minas Supergroup) that evolved since ca. 2.5 Ga along the margin of a former Archean continental block. Deformation of the cover and basement sequences between 2.25 and 2.00 Ga developed a thrust and fold belt verging to the northwest. Pre-collisional rocks are as old as ca. 2.2 Ga and late-stage granitoid rocks may be as young as ca. 1.9 Ga. Late-stage dome-and-keel structures in the Iron Quadrangle region have been interpreted as the result of late-stage orogenic collapse at 2095 Ma (Alkmin and Marshak, 1998). Flysch-type sedimentation represented by the Sabará formation (Brueckner et al., 2000), found on top of the passive margin sequence has been interpreted as representing deposition within a foreland tectonic setting (Machado et al., 1996a). The internal domains of the orogen are exposed to the south and east of the Iron Quadrangle, within the Ribeira and Araçuaí belts, respectively. Previous data include TIMS, LA-ICPMS and SHRIMP U–Pb ages (Heilbron and Machado, 2003; Silva et al., 2002; Noce et al., 2007).

3. Basement associations of the Occidental terrane: the reworked internal zone of the Paleoproterozoic orogen

Basement associations are frequently exposed within all of the structural domains of the Occidental terrane (Fig. 2a), referred to from west to east as the Autochthonous, the Andrelândia and the Juiz de Fora Domains (Heilbron et al., 2000, 2008). These were deformed and metamorphosed during the Neoproterozoic-Cambrian orogenic episodes of the Brasiliano collage. Detailed geological mapping carried out at the central segment of the Ribeira belt (Fig. 2b) allows the discrimination between basement and cover successions.

3.1. The Autochthonous domain

The Autochthonous domain borders the southeastern São Francisco Craton and is composed of Archean-Paleoproterozoic cratonic basement discordantly overlain by distinct greenschist to amphibolite facies Meso- to Neoproterozoic metasedimentary successions (Trouw et al., 2000). The basement rocks include Archean granite-greenstone belt associations, i.e. the Barbacena complex and the Rio das Velhas Supergroup (Pires, 1978), and other heterogeneous units of orthogneisses, migmatites, and granulites of unknown age. However, these are presumed to be Archean and Paleoproterozoic granitoids (e.g., Piedade complex) generated during the orogenic cycle developed between 2.20 and 1.86 Ga (Machado et al., 1992; Machado and Carneiro, 1992; Noce et al., 1998; Teixeira et al., 2000).

In the northern sector of this domain, proximal to São João del Rei in the context of the Mineiro belt, ca. 2.2–1.9 Ga gabbros, diorites, and TTG orthogneisses are common (Ávila et al., 2006a,b; Teixeira et al., 1998, 2000). In contrast, granitic to granodioritic compositions predominate to the south (Ribeiro et al., 2003), including the conspicuous alkaline Serra do Matola complex (Fig. 2b).

A very important regional unconformity juxtaposes various low grade metasedimentary sequences over the basement associations.

3.2. The Andrelândia Domain

The Andrelândia Domain comprises the basal allochthonous thrust sheet of the Occidental terrane in the Ribeira belt (Fig. 2a and b). Rock associations include the Mantiqueira basement complex and the Andrelândia Megasequence, one of the Neoproterozoic passive margin successions of the southern São Francisco Paleocontinent (Paciullo et al., 2000). These units were deformed

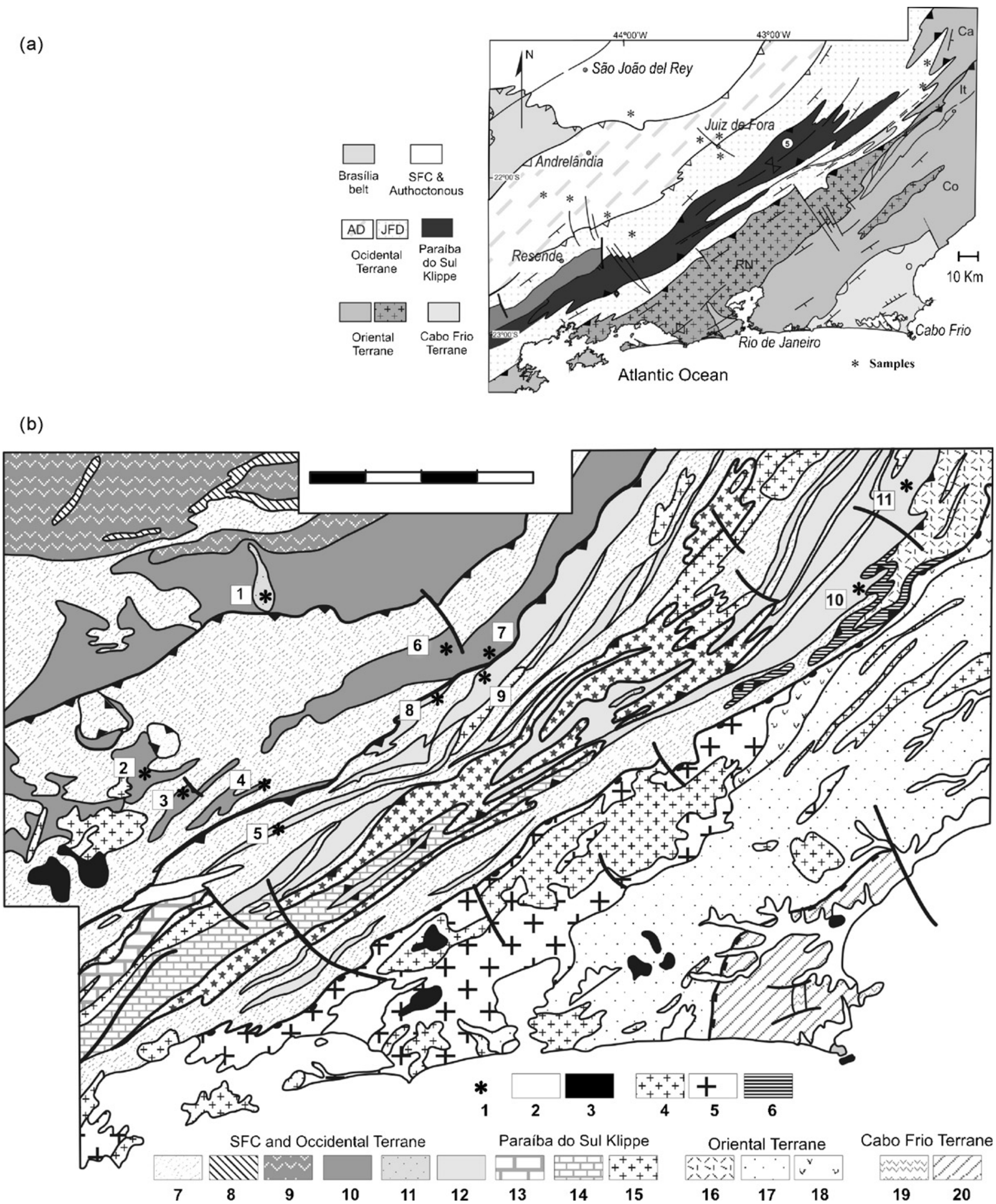

Fig. 2. (a) Tectonic map of Ribeira belt (compiled from Heilbron et al. (2004a,b) and Tupinambá et al. (2007)). Asterisks are sampled units. (b) Geological map of the studied area (Compiled from Heilbron et al. (2004a,b) and Tupinambá et al. (2007)). Legend: (1) sampled outcrops; (2) Phanerozoic cover; (3) K-T alkaline rocks; (4–6) Neoproterozoic magmatic rocks: (4) post-to syn-collisional granitoids; (5) Rio Negro Magmatic Arc; (6) Serra da Bolivia Magmatic Arc; (7–12) units of São Francisco Craton and Occidental terrane: (7) Neoproterozoic metasediments, (8) Meso to Paleoproterozoic metasediments, basement associations, (9) Barbacena complex, (10) Matola alkaline complex and (11) Mantiqueira complex, (12) Juiz de Fora complex; (13–15) units of the Paraíba do Sul Klippe: (13) Embú complex, (14) Paraíba do Sul complex and (15) Quirino complex; (16–18) units of the Oriental terrane: metasediments of the Cambuci, Costeiro and Italva groups; (19 and 20) units of the Cabo Frio terrane: (19) metasediments of the Búzios group, (20) Região dos Lagos basement complex.

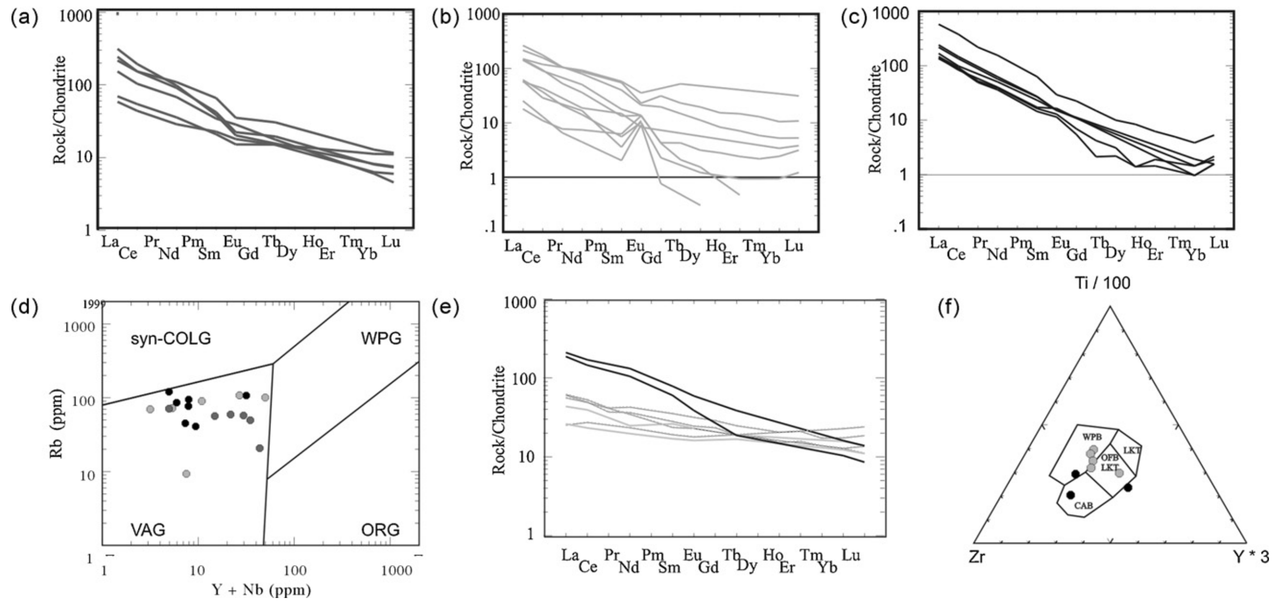

Fig. 3. Geochemical data of the Mantiqueira Complex (compiled from Duarte et al., 2004, 2005). (a–c) Chondrite-normalized plot of rare earth elements of the calc-alkaline suites (Boynton, 1984); (d) Rb × Y+Nb tectonic discriminant diagram (Pearce et al., 1984), fields are: syn-colg – syn-colllisional granitoids, WPG – within plate granitoids, VAG – volcanic arc granitoids, ORG-ocean ridge granitoids; (e) chondrite-normalized plot of the basic suites; (f) Ti/100 × Zr × Y tectonic discriminant diagram (Meschede et al., 1986) for the basic suites; fields are: WPB – within plate basalts, LKT – Low-K tholeeites, OFB – ocean floor basalts,. CAB – calc-alkaline basalts.

and metamorphosed during the Brasiliano orogeny at amphibolite facies and locally at granulite facies conditions. The main structural features of this domain are map-scale folds of the basement-cover unconformity (Fig. 2b) that show two phases of isoclinal to tight folding related to the development of the main schistosity.

The Mantiqueira Complex (Teixeira, 1996; Teixeira et al., 1998, 2000) is a very heterogeneous unit that comprises several calc-alkaline gneiss-migmatitic suites with amphibolite layers, and is intruded by granite plutons and by younger felsic and mafic dykes. Alkaline felsic plutons also intrude these gneisses. Available Rb–Sr and U–Pb isotopic data indicate both Archean and Paleoproterozoic ages. Bruekner et al. (2000) suggest the presence of reworked Archean rocks in this unit, as also presented by Fischel et al. (1998) Ragatky et al. (1999).

Based on detailed geological and geochemical investigations carried out in the Juiz de Fora region (Fig. 3), Nogueira and Choudhuri (2000) and Duarte et al. (2004) proposed the subdivison of the Mantiqueira complex into several calc-alkaline composi-

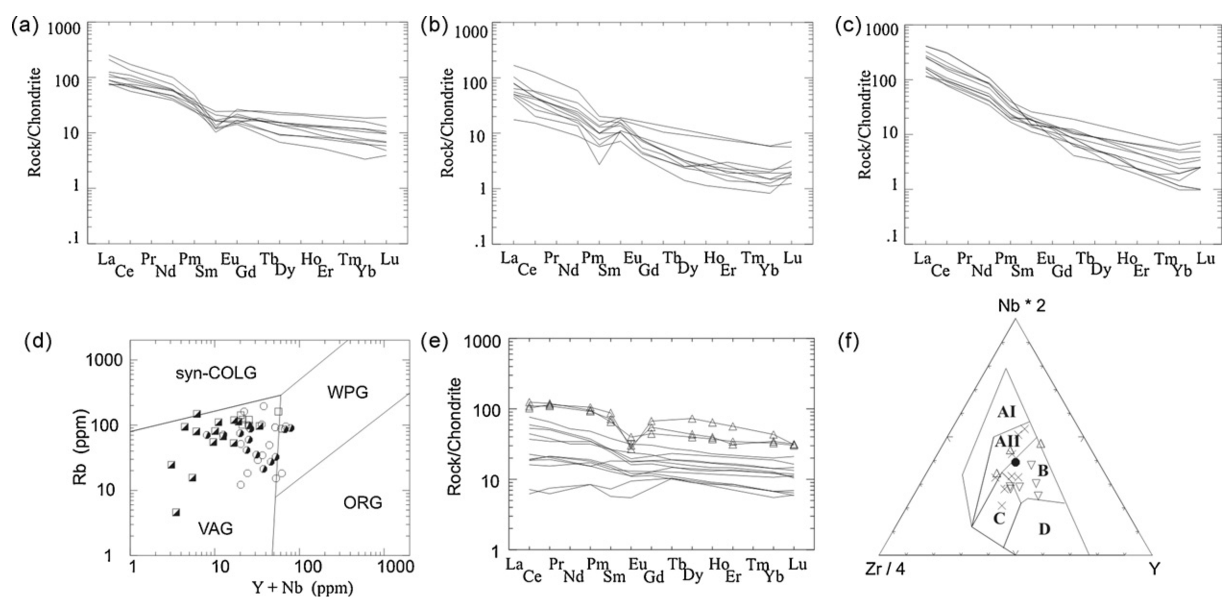

Fig. 4. Selected geochemical data plots of the Juiz de Fora complex, compiled from Heilbron et al. (1997) and Heilbron et al. (1998) and Duarte et al. (1997). Symbols: open and half-filled squares for High-K calc-alkaline suites, circles for medium-K calc-alkaline suites, inverted triangles and X for tholeiitic suites, and inverted triangles for alkaline basic rocks. (a) Chondrite-normalized (Boynton, 1984) REE signature of the medium-K calc-alkaline geochemical group of Juiz de Fora complex; (b) chondrite-normalized REE signature of the high-K calc-alkaline geochemical group of JFC; (c) chondrite-normalized REE signature of anomalous rocks of the high-K calc-alkaline group of JFC; (d) Rb × Y + Nb tectonic discriminant diagram (Pearce et al., 1984) for the calc-alkaline series, fields are the same of (d) and (e) chondrite-normalized REE signature of the basic rocks of the Juiz de Fora complex. Symbols: alkaline basic granulites (open triangles); tholeiitic basic granulites (curves without symbols); (f) 2Nb × Zr/4 × Y tectonic discriminant diagram of Meschede (1986) for the basic granulites of the Juiz de Fora complex. Fields of diagram are: AI, AII – intraplate alkali basalts; AII, C – intraplate tholeiites; B – field of P-type MORB; D – field of N-type MORB; C, D – fields of volcanic arc basalts.

tional groups and one additional very heterogeneous tholeiitic group. In stratigraphic order, the calc-alkaline groups are: tonalitic to granodioritic banded orthogneisses with $[La/Yb]_N$ ratios of 6–9 and tonalitic to granodioritic weakly foliated orthogneisses with higher $[La/Yb]_N$ ratios (20–38), represented in Fig. 3a; leucogneisses with widely varying $[La/Yb]_N$ ratios (Fig. 3b); and augen gneisses of granitic composition, intrusive in all of the above units, with $[La/Yb]_N$ ratios >100 (Fig. 3c).

The compositions of all groups of calc-alkaline orthogenesis are comparable to those of continental-arc and collisional magmatism of active tectonic margins (Fig. 3d).

Basic rocks display signatures from within plate to oceanic settings (Fig. 3e and 3f).

3.3. *The Juiz de Fora Domain*

The Juiz de Fora Domain represents a strongly imbricated thrust system that overlies the Andrelândia Domain (Fig. 2b) and can be considered as a crustal scale ductile shear zone (Heilbron et al., 1998). Basement associations comprise the Juiz de Fora complex while the deformed Neoproterozoic cover succession is correlated to the Andrelândia megasequence (Trouw et al., 2000). Thrust shuffling of the basement and cover associations occurs down to the outcrop scale. Both units are metamorphosed to upper amphibolite–granulite facies.

The Juiz de Fora complex comprises orthogranulites of a wide compositional range, with enderbites and charno-enderbites predominating over charnockites and basic rocks. The felsic granulites (Fig. 4) were subdivided into three distinct calc-alkaline geochemical groups (Heilbron et al., 1997, 1998; Duarte et al., 1997, 2000). One (Fig. 4a) is a medium-K group with moderately fractionated REE chondrite-normalized patterns, and with negative Eu anomalies. The remaining two groups (Fig. 4b and c) are high-K (K_2O up to 4.1%) represented by granites and subordinated granodiorites. Compared to the medium-K group, the latter are enriched in LILE, and display more fractionated REE chondrite-normalized patterns due to substantial depletion in HREE and positive Eu anomalies. Chemical compositions of both groups are consistent with typical magmatism occurring in modern magmatic arcs at convergent tectonic settings (Fig. 4d). There are also compositional indications for a progressive maturity of the arc towards the east, with enrichment in LILE.

The most abundant basic rocks of the Juiz de Fora complex are low-TiO_2-P_2O_5 tholeiitic rocks that show some compositional variation within a small number of samples. Chondrite-normalized REE patterns (Fig. 4e) display flat to more fractionated patterns and define a negative Eu anomaly.

The second basic group comprises alkaline to transitional basic rocks enriched in TiO_2 and in all incompatible trace elements. Based on the chondrite-normalized REE abundances, this group displays enrichment in REE with less fractionated patterns (more flat HREE distribution), and negative Eu anomalies ($Eu/Eu^* = 0.31–0.74$). This geochemical signature is consistent with those of intra-continental tectonic settings.

4. U–Pb geochronology of the reworked Paleoproterozoic rocks

4.1. *Sampling and analytical procedures*

The location of analyzed samples is shown in map of Fig. 2. Analytical results were obtained at the geochronology laboratories of the GEOTOP at Université du Quebec at Montreal and at the Radiogenic Isotope Facility at the Department of Earth and Atmospheric Sciences, University of Alberta (Edmonton, Canada). Sample preparation was carried out at Rio de Janeiro State University and Ouro Preto Federal University, Brazil. Detailed descriptions of the methodologies employed at Montreal and Edmonton are found in Heilbron and Machado (2003), Valeriano et al. (2004) and Simonetti et al. (2005, 2006, 2008).

Table 1
List of analysed samples.

Sample	Rock type	Lat.	Long.
Mantiqueira complex			
MA-01	Syenitic gneiss	593,454	7,624,765
1061	Layered hornblende tonalite-granodiorite gneiss	663,269	7,597,884
1060	Coarse-grained hornblende leucogneiss	663,269	7,597,884
1059	Amphibolite	663,269	7,597,884
G20	Hornblende-biotite gneiss	593,188	7,554,980
LI-JRL-12	Layered hornblende tonalite-granodiorite gneiss	553,037	7,557,456
LI-JRL-04	Augen granitic gneiss	561,569	7,552,683
1056	Augen granitic gneiss	677,317	7,594,271
1058	Leucogneiss	677,317	7,594,271
Juiz de Fora complex			
1070	Mafic granulite	202,898	7,637,149
1076	Enderbitic granulite	208,357	7,665,456
1065	Charnockite granulite	673,320	7,594,282
CJE-44	Alkaline mafic granulite	600,120	7,538,241
1062	Charno-enderbitic granulite	663,968	7,590,047

4.2. *Results*

A list of the samples, including coordinates is presented in Table 1. The analytical results are displayed in Table 2 (ID-TIMS) and Tables 3 and 4 (LA-MC-ICPMS), at supplementary files. Due to the low precision of measured $^{207}Pb/^{235}U$ obtained at GEOTOP's LA-MC-ICPMS laboratory, the ages of the youngest zircons (<1 Ga) are presented on measured $^{238}U/^{206}Pb$ versus measured $^{207}Pb/^{206}Pb$ concordia diagrams (Tera and Wasserburg, 1972).

The isotopic characteristics of the mineral standard used at Edmonton are reported by Stern and Amelin (2003). Age calculations and concordia plots were performed using the Isoplot software (Ludwig, 2003). The data-point error ellipses in the U–Pb plots are 2 sigma.

4.2.1. *Autochthonous domain*

A single sample of the Autochthonous domain was analyzed from the syenitic Matola gneiss (sample MA-01), outcropping near to the basal tectonic contact of the overlying Andrelândia Domain (Fig. 2b). The LA-MC-ICPMS analyses (University of Alberta) were obtained from pale brown to colorless, short-prismatic (2:1–3:1) zircons, which exhibit typical magmatic zoning, with many containing aegirine inclusions. Some of the zircon grains display an irregular outlines, suggesting magmatic corrosion processes. Metamorphic overgrowth was not observed. The results yield a discordia (Fig. 5) with an upper intercept of 2127 ± 29 Ma, regarded as the crystallization age of the protolith. A lower intercept of 550 ± 99 Ma points to the age of the Brasiliano overprint.

4.2.2. *Mantiqueira Complex: the basement association of the Andrelândia Domain*

A layered tonalite-granodiorite gneiss (sample 1061), locally migmatitic, representing one of the oldest, common units of the complex, and a ca. 3m wide dyke of leucogranite were collected in a quarry near the city of Juiz de Fora (Fig. 2b). Lenses of an older migmatitic hornblende banded gneiss with amphibolite layers occur at this quarry. The gneiss is composed of hornblende,

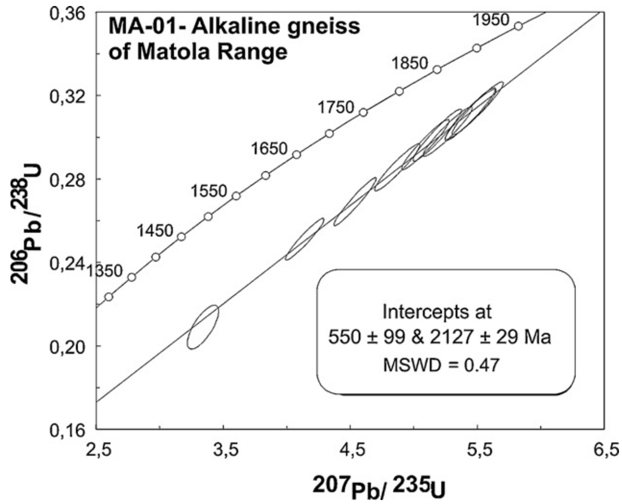

Fig. 5. Concordia diagram for the syenitic orthogneiss of the Matola complex (LA-ICPMS data, sample MA-01).

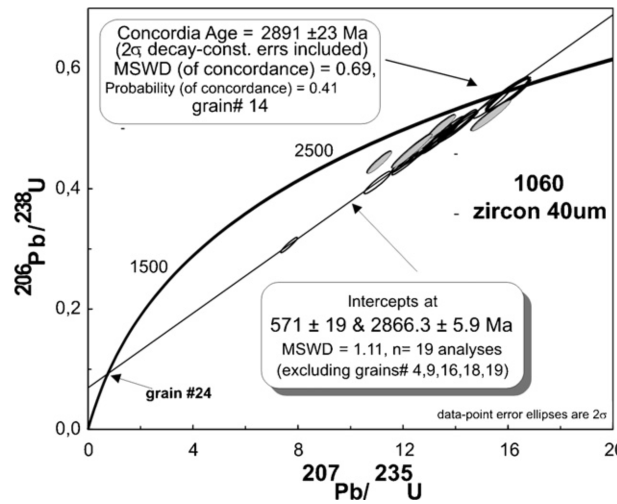

Fig. 7. Concordia diagram for the tonalitic orthogneiss of the Mantiqueira complex (LA-ICPMS data, sample 1060).

biotite, plagioclase, K-feldspar, quartz, titanite, opaque minerals, and zircon. Zircon grains extracted from the grey granodioritic gneiss are colorless to pale yellow, prismatic to subequant and subrounded or irregular in outline. In spite of the obvious metamorphic character of the sampled unit, no core-overgrowth relationships were observed. A group of zircon defines a discordia (Fig. 6) with 2220 ± 52 and 787 ± 260 Ma intercepts, whilst another group defines a concordia age of 2041 ± 8 Ma. Two analyses on a single grain yield $^{207}Pb/^{206}Pb$ ages of 2781 Ma (Table 3, see supplementary files). Given the lack of distinct morphological and chromatic characteristics, these ages can be interpreted in several ways. Our preferred interpretation is that the gneiss precursor crystallized at 2200 Ma and underwent deformation and metamorphism at 2041 Ma. The 2781 Ma old grain is regarded as inherited.

Sample 1060 is a coarse-grained leucogneiss composed of traces of hornblende, biotite, K-feldspar, plagioclase, quartz, zircon, and monazite; the leucogranite comprises amphibolite enclaves. Sample 1060 yielded euhedral and pale yellow zircon crystals, some of which display thin overgrowths. Most of the grains plot on a discordia line (Fig. 7) with upper and lower intercept ages of 2866 ± 6 Ma and 571 ± 19 Ma, respectively; the latter is compatible with the Brasiliano overprint (Table 3, see supplementary files). The zircon grain #14 of sample 1060 is concordant at 2891 ± 23 Maa. Since the leucogneiss and amphibolite patches occur together as lenses within all orthogneisses of the Mantiqueira complex, the preferred interpretation is that these represent relict Archean crust. This interpretation is supported by the presence of inherited Archean zircons in many rocks belonging to the complex; e.g. the aforementioned sample 1061.

Another common rock of the Mantiqueira Complex is a banded hornblende-biotite gneiss with lenses and boudins of amphibolite. A sample of the gneiss (G20; Fig. 2b) yielded pale brown and anhedral zircon with irregular outline, otherwise similar to that of sample 1061. Most of the U–Pb analyses are distributed along a discordia (Fig. 8) yielding an age of 2121 ± 43 Ma (Table 4, see supplementary files). A core of one grain yielded a minimum age of ca. 2.3 Ga. Titanite from this sample and from a hornblende-biotite clot was analyzed previously and yielded minimum ages of 569 Ma (8% discordant), 565 Ma (3% discordant) and 604 ± 4 Ma (analyses 8A-1, 8B1 and 8B-2 of Machado et al., 1996b).

Two other samples of the migmatitic biotite gneiss were collected south of Andrelândia, in the outskirts of Carvalhos town (Fig. 2b). Zircon grains are pale yellow to colorless with magmatic zoning, and lack older cores. These yielded discordia lines

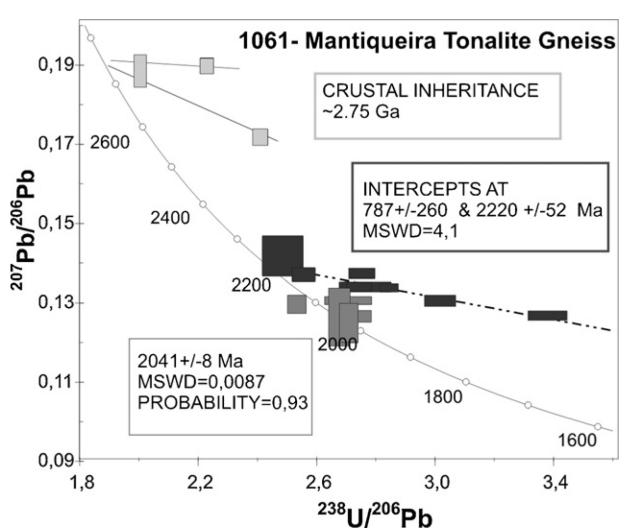

Fig. 6. Tera–Wasserburg (1972) diagram for the tonalitic orthogneiss of the Mantiqueira complex (LA-ICPMS data, sample 1061).

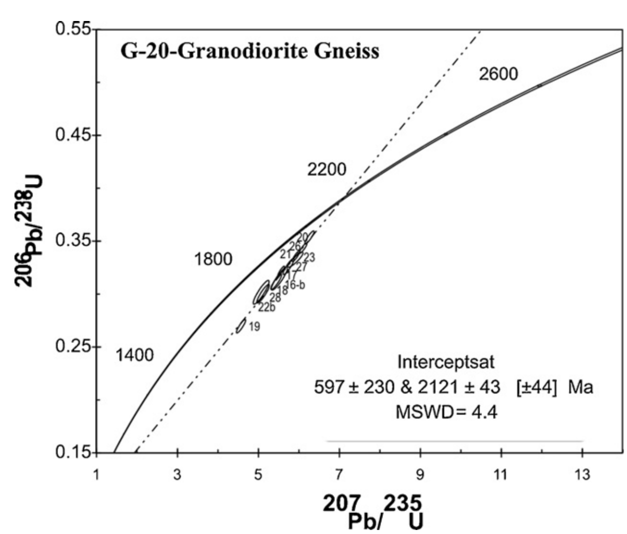

Fig. 8. Tera–Wasserburg (1972) diagram for the granodioritic orthogneiss of the Mantiqueira complex (LA-ICPMS data, sample G-20).

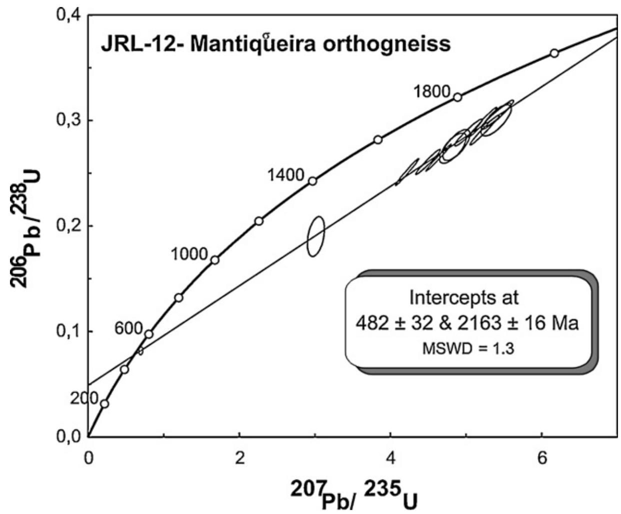

Fig. 9. Concordia diagram for the migmatitic orthogneiss of the Mantiqueira complex (LA-ICPMS data, sample JRL-12).

(Figs. 9 and 10) with upper intercepts of 2163 ± 16 Ma (LI-JRL-12) and 2209 ± 79 Ma (LI-JRL-04).

An augen granitic gneiss interpreted as one of the youngest rock units of the Mantiqueira Complex was collected (sample 1056) from a quarry near to Juiz de Fora city (Fig. 2b). It is composed of hornblende, biotite, megacrystals of K-feldspar, plagioclase, quartz, apatite, titanite, opaque minerals, and zircon. This sample yielded a single zircon population of subequant yellow to pale brown crystals with an age of 2170 ± 15 Ma (Table 4, see supplementary files; Fig. 11).

Two other samples from the Mantiqueira complex were collected at the same quarry (Fig. 2b). One is represented by a lenticular body of a leucogneiss (1058) banded with amphibolite (sample 1059). Sample 1058 yielded very complex results (Fig. 12) with most of the zircons defining a discordia line with upper and lower intercepts of 2107 ± 10 and 579 ± 130 Ma, and these are interpreted as the crystallization age and metamorphic overprint, respectively. Some concordant zircons yield an age of 2096 ± 27 Ma and overlaps with the upper intercept discordia age given the associated uncertainties. Very discordant grains forced through the lower intercept age of 579 Ma rendered upper intercept ages of 2850 and 2441 Ma and. These grains are regarded as inherited components.

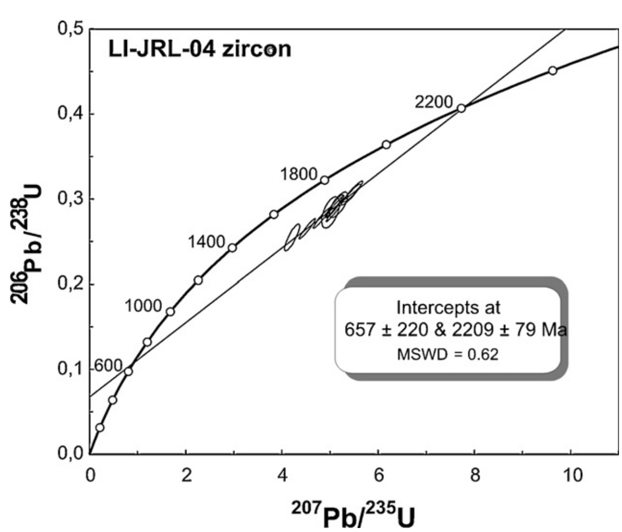

Fig. 10. Concordia diagram for the migmatitic orthogneiss of the Mantiqueira complex (LA-ICPMS data, sample LI-JRL-04).

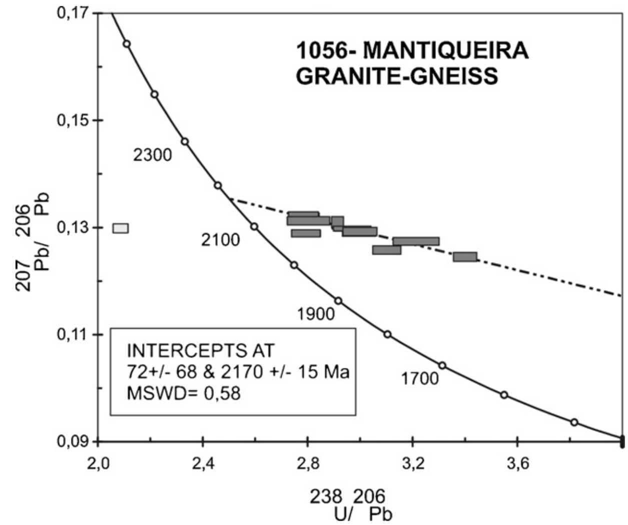

Fig. 11. Tera–Wasserburg (1972) diagram for the granitic orthogneiss of the Mantiqueira complex (LA-ICPMS data, sample 1056).

Sample 1059 represents an amphibolite enclave collected within the leucogneiss. The sample yielded very few equidimensional zircon grains that define a concordia age of 606 ± 7 Ma (Fig. 13). This age is interpreted as caused by episodic lead loss due to the initial metamorphic overprint of the Brasiliano orogeny.

4.2.3. Juiz de Fora complex: the basement association of the Juiz de Fora Domain

A variety of mafic granulite with tholeiitic chemical signature is considered among the oldest rock assemblages of the Juiz de For a Complex. In general, the mafic granulites occur as lenses and/or boudins within the felsic granulites. Sample 1070 (Table 2, see supplementary files; Fig. 2b) was collected south of Itaperuna town and is composed of clinopyroxene, hornblende, biotite, plagioclase, quartz, zircon, and opaque minerals. Zircon grains from this sample are colorless to pale yellow, and mostly have subequant to short-prismatic habit. Thin pyramidal overgrowths are occasionally observed. Three of four U–Pb determinations by ID-TIMS (Table 2, see supplementary files) define a discordia line with intercepts at 2427 ± 9 Ma and 654 ± 12 Ma (Fig. 14). Another analysis plots below the discordia, most probably due to insufficient abrasion.

Sample 1076 was collected in the northwest sector of Rio de Janeiro state (Fig. 2b). It is a typical enderbitic granulite from the medium-K calc-alkaline series of the complex. The zircon grains are typically rounded and clear. LA-MC-ICPMS analytical data define a discordia line with intercepts of 1966 ± 38 Ma and 587 ± 15 Ma (Fig. 15), interpreted respectively as the crystallization and the Brasiliano metamorphic overprint ages. Few strongly discordant zircon grains suggest some older inheritance, a rare feature in the complex (Table 3, see supplementary files).

A charnockite sample from the high-K calc-alkaline series (sample 1065; Fig. 2b) was collected at a quarry located south of Juiz de Fora. The charnockite is composed of orthopyroxene, biotite, K-feldspar, quartz, plagioclase, zircon, and allanite. This sample yielded mostly concordant ages at 2199 ± 17 Ma, interpreted as dating crystallization. Discordant grains point to the Brasiliano metamorphic overprint at 633 ± 140 Ma (Table 3, see supplementary files; Fig. 16a). Two concordant grains rendered a concordant age of 2154 ± 11 (Fig. 16b).

An additional sample of charnockite from the high-K calc-alkaline series of the complex was previously dated by Machado et al. (1996b). The U–Pb data on zircon and monazite yielded a dis-

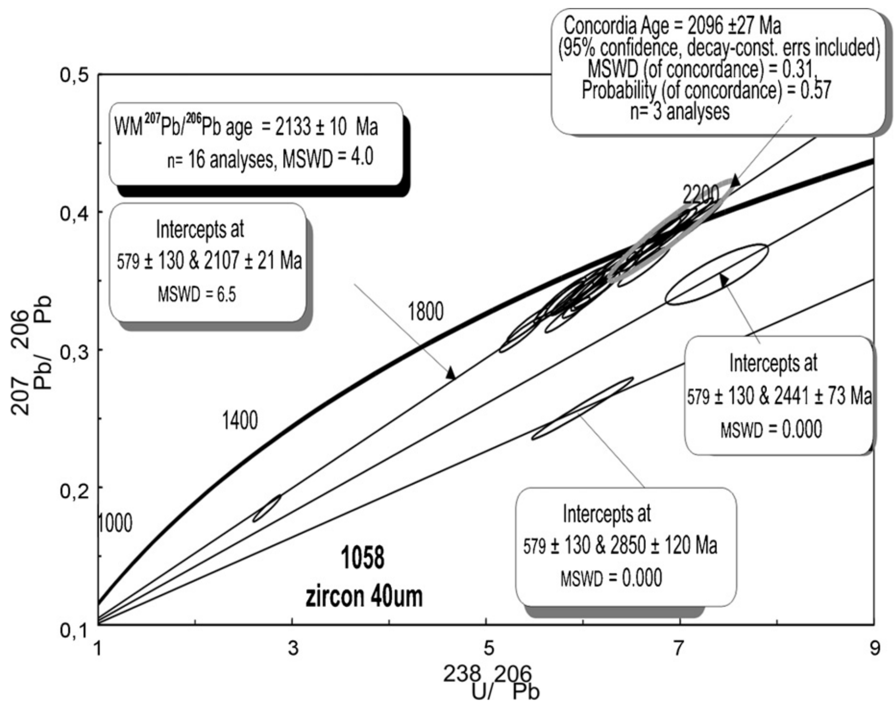

Fig. 12. Concordia diagram for the leucogneiss of the Mantiqueira complex (LA-ICPMS data, sample 1061).

cordia with intercepts at 2134 Ma and 579 Ma. A monazite grain is concordant at 563 ± 3 Ma.

The last two granulite samples investigated rendered younger ages. The first one (sample CJE-44) was collected from near to Conservatória town (Fig. 2b) and is a mylonitic alkaline mafic granulite composed of ortho- and clinopyroxene, plagioclase, K-feldspar, quartz, and opaque phases. This sample yielded a crystallization age of 1765 ± 34 Ma and an age of metamorphism of 586 ± 14 Ma (Table 3, see supplementary files; Fig. 17). Two zircons record concordant lower intercept ages of 586 ± 14 and 599 ± 2 Ma. Another granulite lens from the same outcrop rendered similar results, a discordia with intercepts at 1687 ± 48 Ma and 619 ± 21 Ma, and a concordant age of 584 ± 2 Ma in the Tera-Wasserburg diagram. The other granulite sample (1062) is a felsic and mylonitic calc-alkaline enderbite (Fig. 2b), very different from the common felsic granulites

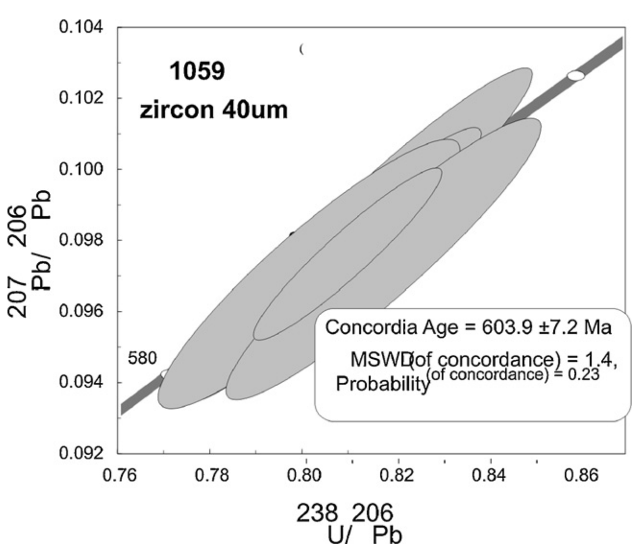

Fig. 13. Concordia diagram for the diorite of the Mantiqueira complex (LA-ICPMS data, sample 1059).

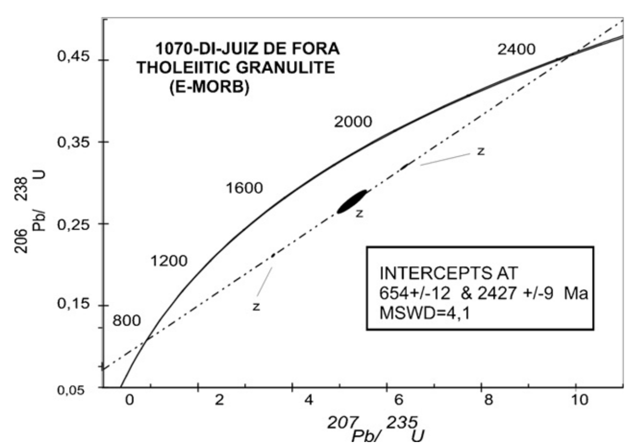

Fig. 14. Concordia diagram for the tholeiitic basic granulite of the Juiz de Fora complex (LA-ICPMS data, sample 1070).

of the Juiz de Fora complex. Sample (1062) yielded pale yellow to colorless zircon grains defining a discordia with intercepts at 1656 ± 69 Ma and 591 ± 5 Ma, and a concordant grain at the lower intercept (Fig. 18). The two granulite samples studied here record atypical late Palaeoproterozoic ages that are probably related to the Espinhaço rifting event (Brito Neves, 1995; Martins-Neto, 2000), well documented in the São Francisco Craton.

5. Discussion: a geodynamic model for the Paleoproterozoic active margin of the southern São Francisco paleocontinent

The new data confirm the interpretation, previously presented by Heilbron et al. (2000) and Duarte et al. (2004), that the basement rocks presently exposed along the Ribeira belt in the Rio de Janeiro State represents the southwards continuation of the São Francisco paleocontinent. This southernmost zone of the paleocontinent was amalgamated by the end of the Rhyacian

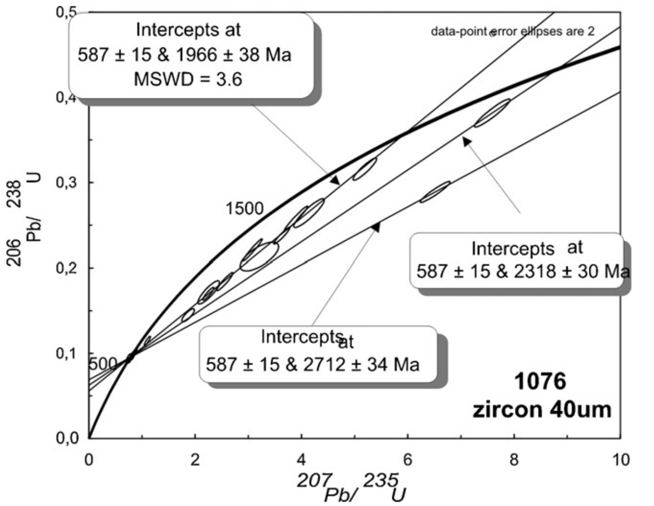

Fig. 15. Concordia diagram for the enderbitic granulite of the Juiz de Fora complex (TIMS data, sample 1070).

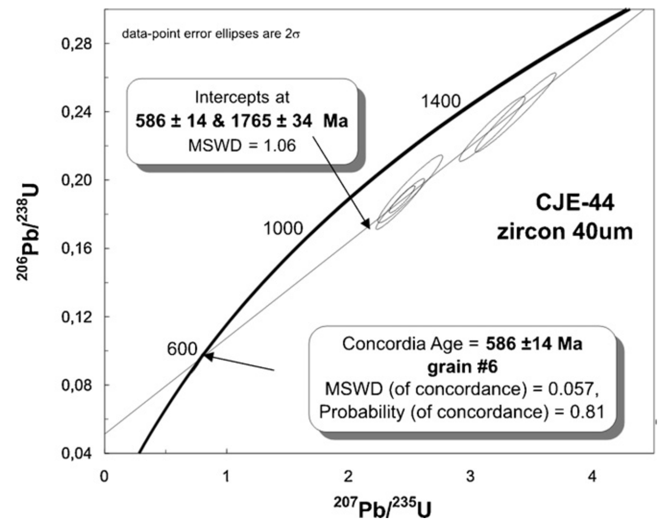

Fig. 17. Concordia diagram for the alkaline granulite of the Juiz de Fora complex (LA-ICPMS data, sample CJE-44).

orogenic events. An integrated geodynamic model is discussed below.

5.1. *2.2–2.1 Ga: pre-accretion stage*

The Mantiqueira complex represents the reworked margin of an Archean paleocontinent hosting calc-alkaline arc-related banded gneisses (ca. 2.2 Ga) and collisonal granitoids (ca. 2.15 Ga). The complex also includes lenses of Archean rocks within the Paleoproterozoic orthogneisses. The latter display Archean T_{DM} Sm-Nd model ages and inherited zircons. These features indicative of an older crustal component suggest that the development of the Mantiqueira magmatic arc took place in a cordilleran-type tectonic setting.

A westward-directed subduction beneath the São Francisco paleocontinent between 2.22 and 2.07 Ga is proposed here in order to explain the geographic distribution of the compositional series of the complex and the cordilleran geochemical signature, that intruded the margin of the former Archean paleocontinent (Fig. 19a). This model is supported by the distribution of the more evolved magmas to the WNW, including syenites and alkali gran-

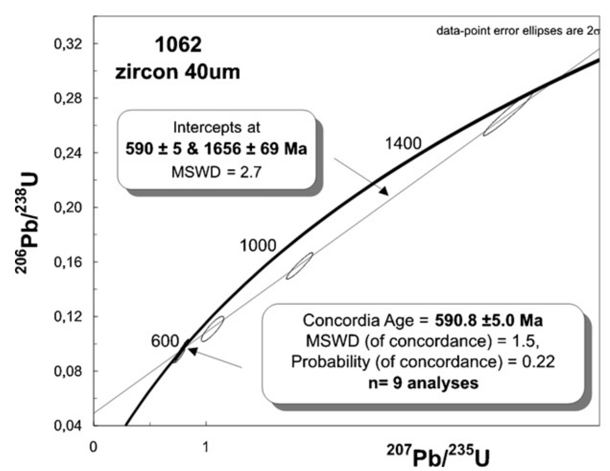

Fig. 18. Concordia diagram for the enderbitic granulite of the Juiz de Fora complex (LA-ICPMS data, sample 1062).

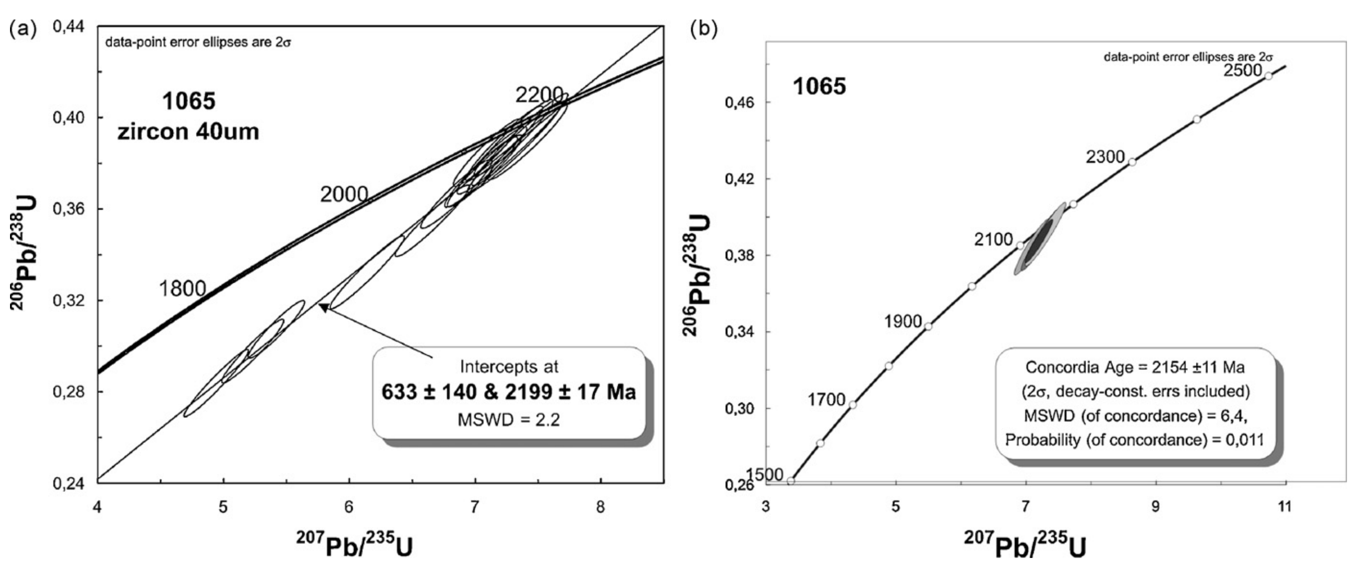

Fig. 16. Concordia diagram for the charnockitic granulite of the Juiz de Fora complex (LA-ICPMS data, sample 1065).

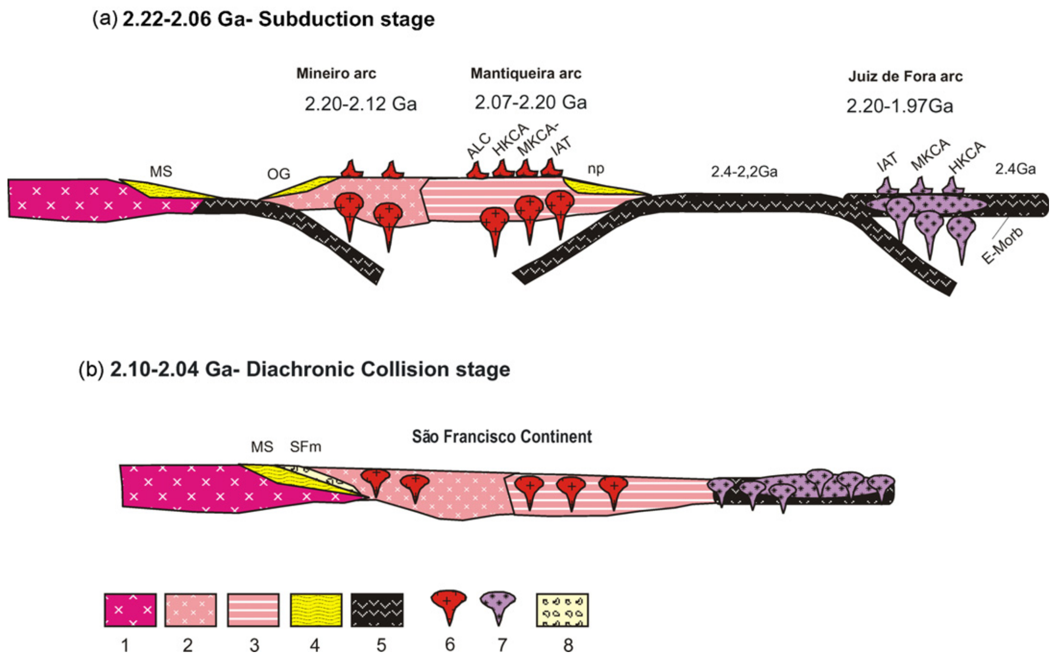

Fig. 19. Tectonic evolution of the Rhyacian Orogen in southeastern Brazil, as envisaged for the period between ca. 2.4 and 1.1 Ga. 1–3: Archean microcontinents, 4-passive margin sucessions (MS-Minas supergroup, OG- Ouro Grosso succession, np- not present), 5- ocean floor successions, 6- cordilleran magmatic arc, 7- intra-oceanic magmatic arc, 8-flysch successions (Sfm-Sabará formation).

ites from the Matola complex, located near the overlying basal thrust surface of the Andrelândia Domain (Fig. 2b), and of the more primitive calc-alkaline and tholeiitic magmas to ESE.

In the overlying Juiz de Fora thrust sheet, the basement association is represented by orthogranulites with a wide compositional range. The major lithological units are two calc-alkaline suites (ca. 2.1 Ga) with juvenile isotopic signature, and minor tholeiitic basic rocks (ca. 2.4 Ga) with both mid-ocean ridge basaltic and island arc geochemical signatures.

The data suggest that the Juiz de Fora complex originated in an intra-oceanic setting, relatively more distant from the Archean continental margin of the São Francisco paleocontinent, and later

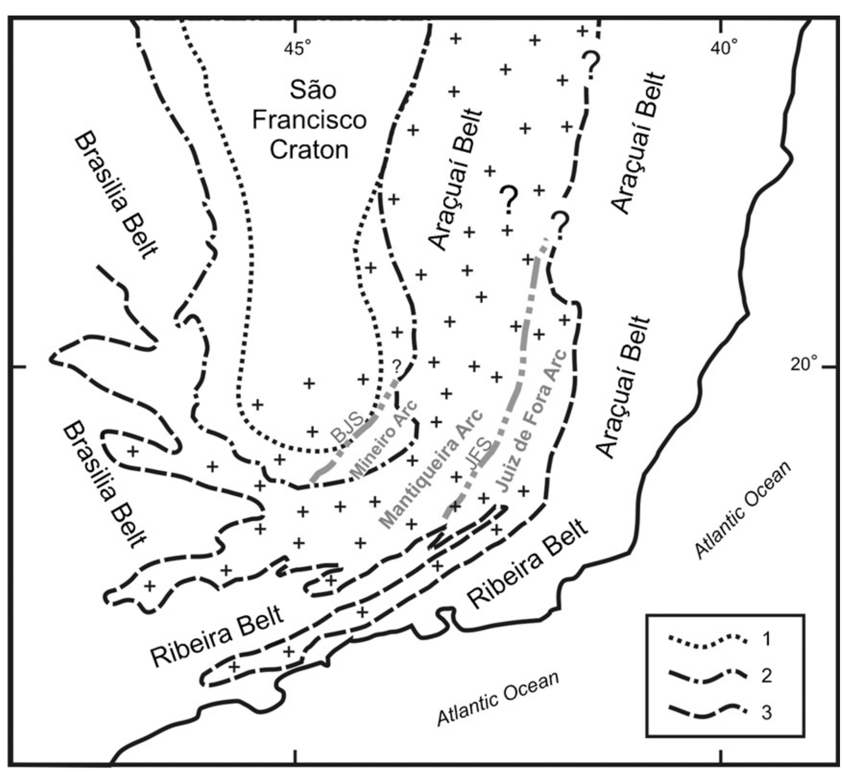

Fig. 20. Tectonic sketch of southeast Brazil depicting the southern limits of the São Francisco Craton according to (1) Almeida (1977) and (2) Alkmin et al. (1993). The minimum areal extent of the São Francisco Paleocontinent (3) is shown. Crosses represent the outcrop area of basement complexes. JBS and JFS represent the Jeceaba-Bom Sucesso and Juiz de Fora sutures.

accreted onto the active (cordilleran) margin of the São Francisco paleocontinent. Geochemical data and geochronological age distributions of the magmatic bodies (Fig. 19a) indicate that the most primitive island arc tholeiites (IAT) and medium-K calc-alkaline series predominate within the lower thrust sheets (located to the west); while the majority of the high-K series and the occurrence of MORB-like basic rocks are related to the upper sheets (located to the east). This geochemical distribution, together with the progressive younging of the ages to the east, suggests an east-vergent subduction between 2.22 and 2.05 Ga. Alternatively a period of subduction erosion could also result in eastwards movement of the subduction zone. The MORB-like basic rocks of 2.4 Ga could represent relicts of the former ocean crust or plateau basalts located further to the east.

A third Paleoproterozoic magmatic arc, the Mineiro belt, is located in the southern part of the São Francisco Craton, between the Iron Quadrangle, to the NW, and the Mantiqueira complex to the SE. The distribution of the Archean rocks within the middle of this sector of the SFC, and the occurrence of coeval magmatic arc-related rocks at the Mineiro and Mantiqueira arcs both suggest double subduction under an Archean micro-continent, which acted as host rocks to the Mantiqueira and Mineiro arcs (Fig. 19a).

The present northwestern border of this micro-continent is the Bonsucesso-Jeceaba suture, which marks the limit with the Archean cratonic block to the northwest, spared from Paleoproterozoic orogenic activity, represented by the Campos Gerais, Campo Belo, Bonfim, Belo Horizonte, Bação and other orthogneiss-migmatite complexes (Noce et al., 1998; Carneiro et al., 1998; Oliveira and Carneiro, 2001; Campos et al., 2003) and associated greenstone-belts, such as the Rio das Velhas Supergroup (Fig. 20b).

5.2. 2.10–2.04 Ga collision stage

The diachronic amalgamation of these three magmatic arcs (Mineiro, Mantiqueira and Juiz de Fora) after 2.1 Ga resulted in the building of the southern segment of the São Francisco paleoplate. This age interval is coeval with the development of the Sabará syn-compressional basin overlying the Minas Supergroup in the Iron Quadrangle, located more to the north, in the foreland zone of the Paleoproterozoic orogen. Furthermore, the Sabará sediments that contain 2125 Ga detrital zircons (Machado et al., 1996b) are affected by the Rhyacian NW-verging thursting and also by a 2.06 Ga metamorphic aureole (Bruekner et al., 2000) related to a dome-and-keel tectonics (Alkmin and Marshak, 1998).

To the east, in the internal portion of the orogen, an important tectono-metamorphic episode at ca. 2.04–2.05 Ga is recorded within the Mantiqueira orthogneisses and is interpreted as genetically related to the accretion of the intra-oceanic Juiz de Fora arc onto the active continental margin located at the southern end of the São Francisco Craton (Fig. 19b). Finally, after ca. 2.0 Ga, the deposition of the Itacolomi Quartzites unconformably overlaying the Sabará wakes at the Iron Quadrangle, was in course (Machado et al., 1996b).

5.3. 1.7–1.6 Ga and younger rifting events

The Mantiqueira and Juiz de Fora associations host mafic (ca. 1.7 Ga) and felsic (ca. 1.66 Ga) intrusive rocks that are related to the Espinhaço rifting event of the São Francisco paleocontinent. In the southern São Francisco paleocontinent, this event resulted in the opening of the intracratonic São João del Rei-Tiradentes, Itacolomi, Serra do Ouro Grosso and other quartzite-rich continental rift basins.

Younger rifting took place during the 1.0–0.9 Ga interval, related to the development of the Neoproterozoic Andrelândia passive margin sedimentary basin.

5.4. The Neoproterozoic orogenic overprint

Brasiliano reworking of the basement complexes resulted on amphibolite facies metamorphism and several phases of folding in the Mantiqueira complex and, granulite facies metamorphism coeval with the development of a pervasive mylonitic foliation in the Juiz de Fora complex. Metamorphic ages defined by lower intercept ages of discordia lines and also by concordant zircons yelded values between ca. 604 and 570 Ma.

6. Conclusions

At least three magmatic arcs were developed and accreted to the former São Francisco Archean continent during the Paleoproterozoic, and are exposed as basement inliers along the Neoproterozoic Ribeira belt in SE-Brazil. (Fig. 20).

The Mantiqueira arc yielded U–Pb ages between 2.22 and 2.10 Ga, broadly coincident with those reported for the Mineiro arc. In a possible scenario, these arcs were built respectively along the eastern and western margins of an Archean microcontinent that later collided against the southeastern margin of the main Archean São Francisco protocontinent at between 2.10 and. 2.05 Ga. In the studied area, this microcontinent runs roughly along the Mantiqueira range in southern Minas Gerais state. Its continuation to the northeast could be represented by the Guanhães terrane, but until now, except for the voluminous Staterian rift related Borrachudos Suite, no other Paleoproteroic ages have been obtained from the Guanhães basement block.

The resulting suture zone separates the Mineiro arc rocks from the Archean granite-greenstone block, running from the Iron Quadrangle area to the southeast, along the Jeceaba-Bom Sucesso lineament, as suggested by Campos et al. (2003) and Campos (2004).

The rocks of the Juiz de Fora arc represent a probable intra-oceanic environment with U–Pb ages between 2.20Ga and 1.97 Ga, containing relics of older (ca. 2.4 Ga) ocean floor and/or plateaus assemblages.

The collision of the three blocks resulted in the building of the southern part of the São Francisco paleocontinent.

Following the amalgamation and continental growth of the São Francisco paleocontinent at ca. 2.05–2.04 Ga, within plate magmatic rocks yielded U–Pb ages between 1.77 Ga and 1.66 Ga, related to extensional processes that resulted in the development the Espinhaço, Itacolomi and other minor rift basins.

The reworked southernmost continuation of the São Francisco paleocontinent, represented by strongly reworked Paleoproterozoic basement rocks in the central segment of the Ribeira belt, implies a much broader southernmost São Francisco Archean-Paleoproterozoic block, rather than the usually depicted narrow promontory protruding south, bringing important implications to paleogeographic reconstructions of the São Francisco Craton in the context of western Gondwana.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2010.02.002.

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