Geochemistry, Nd isotopes and U–Pb geochronology of a 2350 Ma TTG suite, Minas Gerais, Brazil: Implications for the crustal evolution of the southern São Francisco craton

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ABSTRACT

The Paleoproterozoic is considered the main period of crustal growth in the South American continent, with voluminous production of granitoid suites emplaced during the onset of the ca. 2.2–2.1 Ga Trans-Amazonian orogeny. This work documents and interprets mineral chemistry, whole rock geochemistry, Nd isotopes and U–Pb geochronology data for the high-aluminium Lagoa Dourada TTG suite. This suite constitutes a hitherto unknown episode of Paleoproterozoic (ca. 2350 Ma) juvenile felsic plutonism in the southern São Francisco craton, Minas Gerais, Brazil. It is also a rare example of juvenile continental crust production in the global crustal age-gap between 2.45 and 2.2 Ga. The suite is composed of metaluminous to slightly peraluminous, low-Mg#, low-K and high-Ca, biotite-hornblende to hornblende-biotite ($\pm$ garnet-magnetite) tonalites and biotite trondhjemites, varying from ~62 to 73 wt.% SiO₂. The trace element geochemistry of the suite is characterized by mildly depleted Nd isotope compositions [$\epsilon_{\text{Nd}}(t) = +1.0$ to $+2.1$], low large-ion-lithophile element (LILE, i.e., Rb, Ba, and including the highly incompatible Th) and heavy Rare Earth element (REE, Yb < 1.00 ppm) contents. The suite is also characterized by high Sr/Y ratios (≥ 41 up to 81), high (La/Yb)_N ratios (≥ 12 up to 46), and positive Eu/Eu* anomalies. These data are consistent with the derivation of the suite from a tholeiitic metabasaltic source, which had a short crustal residence time prior to melting. The chemical diversity of the suite is attributed mainly to the fractional crystallization of hornblende and accessory minerals, coupled with plagioclase accumulation in the tonalitic parental melt. Emplacement of new batches of magma could explain samples which diverge from the proposed liquid line of descent of the suite. The composition and age of the Lagoa Dourada suite suggest a link with the accretion of greenstone belt packages in an intra-oceanic tectonic setting.

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1. Introduction

High-aluminium tonalite–trondhjemite–granodioritic suites (TTG suites, Barker, 1979; Condie, 2005; Martin et al., 2005) are characterized by $\text{Mg\#} \leq 50$ ($\text{Mg\#} = 100 \times \text{mol MgO}/[\text{MgO} + \text{FeO}_t]$), low Cr and Ni (average 29 and 14 ppm, respectively), high Al₂O₃ (>15% at 70% SiO₂), high Sr (>300 ppm) and strongly fractionated light/heavy REE patterns, with low heavy REE (Yb < 1.8 ppm) and Y (<20 ppm). A number of geochemical, petrologic and experimental studies have shown that these suites can be derived from partial melting of tholeiitic metabasaltic rocks, leaving garnet amphibolite to eclogite residues (Martin, 1986; Drummond and Defant, 1990; Rapp and Watson, 1995; Rapp, 1997; Willie et al., 1997; Clemens

et al., 2006). Tectonic settings suggested for these suites commonly include amphibolitic lower continental crust, mafic rocks at the base of thickened arc crust or at the roots of an oceanic plateau, or young descending slabs (Martin, 1986; Drummond et al., 1996; Petford and Atherton, 1996; Barnes et al., 1996; White et al., 1999; Whalen et al., 2002; Smithies et al., 2003). TTG suites with Nd isotope compositions in the range of depleted mantle values at the time of crystallization are attributed to be a consequence of the two step model for the generation of these rocks: extraction of basaltic precursors from the mantle, followed soon after by high pressure melting at garnet amphibolitic to eclogitic conditions, in order to preserve the isotopic composition of the mafic protolith (Martin, 1987; Barnes et al., 1996; Clemens et al., 2006; Stevenson et al., 2009).

The Paleoproterozoic is a particularly important period of crustal growth for the South American continent, with the production of numerous juvenile, subduction-zone related granitoid

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Fig. 1. The southern São Francisco craton (SFC) in relation to the major tectonic units of the South America continent (A). Boxes B and C show the location of the Lagoa Dourada suite (star) inside the Mineiro belt.

Adapted with modifications from Hartmann and Delgado (2001, A), Teixeira et al. (2000, B) and Heineck et al. (2003, B and C). The age of crystallization of selected granitoid suites (million years) are highlighted in the little boxes in B and C. Source of data: (a) this article; (b) unpublished, first author's data; (c) Noce (1995); (d) Noce et al. (2000); (e) Noce et al. (2007a); (f) Noce et al. (2007b); (g) Campos and Carneiro (2008); (h) Ávila et al. (2010, and references therein, range of ages from different plutons). Legend of cities in B: BH: Belo Horizonte, LD: Lagoa Dourada, SJ: São João Del Rei.

suites associated with the ca. 2.2–2.1 Ga Trans-Amazonian orogeny (Cordani and Sato, 1999; Almeida et al., 2000). This paper provides new mineralogical, whole rock geochemical, U–Pb and Nd-isotope data for the Lagoa Dourada TTG suite. This ca. 2350 Ma suite

represents a hitherto unknown earlier period of crustal growth in the Paleoproterozoic of southeastern Brazil and a rare example of juvenile crustal growth in an era with a paucity of global crust formation (Condie et al., 2009a,b; Condie and Aster, 2010).

Fig. 2. Geological context of the Lagoa Dourada suite in relation to the surrounding granitoid terrains, southern Quadrilátero Ferrífero area. Classification of the granitoid suites according to first author's unpublished data (see summary in Table 1).

Source: Geology adapted from Heineck et al. (2003) with modifications.

2. Geological setting

The Lagoa Dourada suite outcrops within a Paleoproterozoic belt bordering the Archean nuclei of the southern São Francisco craton, on the southern edge of the Quadrilátero Ferrífero region, Minas Gerais, southeastern Brazil (Fig. 1). This region is known for its abundance of Late-Archean and Paleoproterozoic rock-packages and comprises one of the most important gold and iron provinces of the South American continent (Almeida et al., 2000; Hartmann and Delgado, 2001). The Archean rocks of the Quadrilátero Ferrífero area consist of the well-preserved ca. 2.77 Ga Rio das Velhas greenstone belt, with greenschist to low-amphibolite facies volcano-sedimentary successions dominated by tholeiitic and komatiitic volcanic rocks and acid volcanoclastics, followed by volcano-exhalative banded iron formations and upper turbiditic, graywacke-sandstone and conglomerate-sandstone formations (Noce et al., 2005; Baltazar and Zuchetti, 2007). The greenstone belt is surrounded by >2.9 Ga high grade banded TTG gneisses and intrusive Neoproterozoic tonalitic to granitic plutonic suites (Machado et al., 1992; Machado and Carneiro, 1992; Teixeira et al., 1996; Noce et al., 2007b). The Archean rocks are covered by a thick platformal metasedimentary sequence—the Minas Supergroup, deposited between ~2.5 and 2.12 Ga (Dorr, 1969; Machado et al., 1996; Alkmim and Marshak, 1998; Hartmann et al., 2006). Extensive areas of

intermediate to felsic plutonic rocks are exposed on the southern and eastern edge of the Quadrilátero Ferrífero and are collectively grouped into a single lithotectonic unit referred to as Mineiro belt (Fig. 1, Noce et al., 2000; Teixeira et al., 2000). The plutonic rocks of the Mineiro belt intrude elongated greenstone belts trending NE–SW from Congonhas lineament in the north, to São João Del Rei in the southwest (Fig. 1). These supracrustal sequences are composed mainly of tholeiitic and komatiitic metavolcanic rocks interleaved with metamorphosed volcano-exhalative manganese sedimentary rocks (Toledo, 2002; Ávila et al., 2010).

The Mineiro belt is broadly divided into a western and an eastern domain. The western domain (Fig. 1) consists of wide areas of massive to variably deformed tonalitic, trondjemitic and granodioritic to granitic plutons (including the Lagoa Dourada suite), and minor scattered gabbroic and dioritic bodies, all of which are partially overlain by the low greenschist facies metasedimentary rocks of the Mesoproterozoic to Neoproterozoic São João Del Rei and Andrelândia Groups. The eastern domain of the Mineiro belt is characterized by a predominance of homogeneous to banded medium- to high-grade plutonic orthogneisses-labeled as Mantiqueira Complex in Fig. 1. The major period of the intermediate to felsic plutonism of the Mineiro belt is ascribed to be ca. 2.2–2.1 Ga in accordance with the Trans-Amazonian tectonic cycle of the South American Platform (Noce et al., 2000; Silva et al., 2002; Noce et al., 2007a;

Table 1

Summary of field and petrographic features for granitoids and associated country rocks from southern Quadrilátero Ferrífero region, Minas Gerais.

Group	Field aspects. Known areal exposition (KAE)	QAP classif. Ab-An-Or classif.	% of mafic minerals	Accessory minerals
Lagoa Dourada suite	Foliated to gneissic, with variable grain size and mafic mineral contents. Intruded by multiple crosscutting aplitic diking. KAE > 50 km ² .	To to Tdj To	<10% to 25% Hbl absent to >Bt	Ap, Zrn, Ttn, Aln and $\pm$ Grt, with Mgt. Magnetic in hand specimen
Alto Maranhão tonalite	Abundant magma mingling structures with dioritic magmatic enclaves. Generally well foliated and with multiple syn- to post-magmatic diking. KAE > 100 to 250 km ² .	Qz-Di to To To/Gd ($\pm$ Tdj)	15–45% Hbl:Bt ratio 0.8–1.3	Ap, Zrn, Aln, Ilm, Ttn. Growth of Ep over Aln
Mato Dentro pluton	Abundant magma mingling structures with dioritic magmatic enclaves in the most mafic portions of the pluton. KAE > 15 to 30 km ² .	To to Gd To	<10% to 25% Hbl may be absent	Same as Alto Maranhão tonalite
Congonhas pluton	Massive to foliated or sheared, with heterogeneous biotite distribution, from randomly scattered to clustered in biotite rich centimeter scale micaceous enclaves. KAE < 20 km ² .	Gd to Tdj Tdj and boundary Tdj/Gt	<10%, with Bt and Ms	Mainly Zrn and Ap. Biotite rich enclaves with Ms, Ilm, Ttn, Zrn, Ap, and rare Aln.
Miscellaneous tonalites	Scarce dioritic magmatic enclaves. Well foliated, sometimes gneissic in shear zones. Locally with xenoliths and/or roof pendants of amphibolite country rocks. KAE > 50 km ² .	To/Tdj or Gd To/Tdj	<10% to 20% Hbl absent or subordinate to Bt	Same as Alto Maranhão tonalite
Serra do Camapuã tonalites	Scarce dioritic magmatic enclaves, with amphibolite wall rock xenoliths. Slightly to well foliated. KAE > 50 km ² .	To to Gd To/Tdj/Gd boundary	<10% to 15% Hbl absent or very subordinate to Bt	Same as Alto Maranhão tonalite
Fazenda Bandeirinhas granodiorite	Kf-porphyratic Hbl-Bt granodiorite, well foliated to gneissic, with folded felsic leucocratic aplitic and pegmatitic dikes. KAE not determined.	Gd Gd	<10% to 20% Hbl absent or subordinate to Bt	Same as previous, with Mgt instead of Ilm. Magnetic in hand specimen
Conselheiro Lafaiete trondhjemitic and grano-diorites	Foliated to gneissic, locally with complex fold patterns and multiple felsic trondhjemitic and granitic dyking. KAE > 50 km ² .	Gd and Tdj Gd/Tdj/Gt boundary	$\leq$ 10%, only Bt, partially replaced by muscovite	Ap, Zrn, Ttn, Aln. Growth of Ep over Aln
Resende Costa granodiorite – rites	Homogeneous well foliated, with deformed aplite and pegmatite dikes. KAE not determined.	Gd to Tdj Gd and Tdj	$\leq$ 10%, only Bt	Ap, Zrn, Ttn, Aln. Growth of Ep over Aln
TH – country rock amphibolite	Foliated, fine to medium grained mafic amphibolite. Occurs as roof pendants or xenoliths on various granitoids. Contains Hbl, Pl, Qtz, Ttn, Ep and opaque minerals. Bt is locally observed.			
Gn1 – trondhjemitic gneiss	Foliated to banded, medium grained biotite tonalitic to trondhjemitic orthogneiss.			
Gn2 – qz dioritic gneiss	Banded medium grained biotite-hornblende-quartz-plagioclase gneiss. With accessory Ttn, Ep, Aln, Zrn, Ap and opaque minerals.			
Gn3 – qz dioritic gneiss	Banded and complexly folded medium grained biotite-hornblende-quartz-plagioclase gneiss. With Ttn, Ep and opaque minerals.			

Apatite (Ap), allanite (Aln), biotite (Bt), epidote (Ep), hornblende (Hbl), ilmenite (Ilm), magnetite (Mgt), plagioclase (Pl), quartz (Qtz), titanite (Ttn), zircon (Zrn), garnet (Grt), muscovite (Ms), diorite (Di), quartz diorite (Qz-Di), granodiorite (Gd), tonalite (To), trondhjemitic (Tdj).

Campos and Carneiro, 2008; Ávila et al., 2010). Fig. 2 shows the location of the samples discussed in this work, along with a classification of some of the granitoid suites of the Mineiro Belt occurring at the southern edge of the Quadrilátero Ferrífero region, which is based in a repertory of unpublished field, whole rock geochemical, U–Pb and Nd-isotopic data obtained over the last decade by the first author of the present study. A synopsis of these data is presented in Table 1.

3. Analytical methods

Microprobe analyses of biotite, plagioclase and garnet were obtained at Universidade Federal de Minas Gerais, Belo Horizonte, Brazil using a Jeol JXA 8900 RL. The general operating procedures used a 15 kV accelerating voltage and a 20 nA beam current in conjunction with natural and synthetic minerals as standards. ICP-OES and ICP-MS measurements of major and trace elements

Fig. 3. Macroscopic view of the tonalites and trondhjemites of the Lagoa Dourada suite. In (a) and (b) are represented the outcrops of the biotite-hornblende tonalites (samples LD1A, LD2A and B, LD3A and B, and LD4A, B and C). The biotite-hornblende tonalite in (b) is intruded by highly foliated and slightly discordant thin dikes (dk), which are constituted by biotite-hornblende tonalitic aplites (sample LD1D). In (c) are represented the biotite trondhjemites (outcrop LD5), which vary from a medium grained main facies (left, samples LD5A and B) to a fine grained facies (right, sample LD5C). The transitional contact between these two facies suggests they are syn-magmatic. In (d) is the classification of the analyzed rocks of the suite according to the normative Ab-An-Or diagram of O'Connor (1965), with the subdivisions **** adopted by Barker (1979). To: tonalite, Gd: granodiorite, Tdj: trondhjemite, Gt: granite, qMz: quartz monzonite. Chemical data from Table 5.

Fig. 4. (a) Textural feature of a garnet crystal from the hornblende-biotite tonalite LD4B (transmitted light). (b) Range of compositions of the different garnet crystals analyzed by electron microprobe (data from Table 2). The garnet compositions vary between Ca-Mg- and Mn-rich almandine. Also plotted for comparison are the compositions of the Mn-rich almandine from the Peñón Rosado S-type tonalite (PRT, Dahlquist et al., 2007) and phenocrysts of Ca-Mg almandine from the calc-alkaline andesites and dacites of the Northern Pannonian Basin (CAV, types 1A and 1B, Harangi et al., 2001).

were obtained on whole rock powders at ACTLABS and ACME laboratories (Canada) using a lithium metaborate/tetraborate fusion to digest the samples. Zircon U–Pb (ID-TIMS) and whole rock Sm–Nd isotopic analyses were made at the GEOTOP–UQAM, Montreal, Canada. The rocks for U–Pb geochronology were crushed, and heavy minerals were separated on a Wilfley table. The heavy minerals were further separated by the use of heavy liquids.

Fig. 5. Range of composition of the almandine garnets from the hornblende-biotite tonalite LD4B in terms of wt.% CaO and MnO. Symbols as in Fig. 4. Grey field indicates range of composition of igneous garnets crystallized at high pressures derived from mantle and/or igneous crustal sources (Harangi et al., 2001).

Table 2

Chemistry of minerals from the tonalite LD4B, Lagoa Dourada suite. Amphibole was not analyzed.

Biotite		Plagioclase			Garnet									
Ox.		Ox.	core	bord	Ox.	Ca–Mg almandine variety			Mn almandine variety					
SiO ₂	35.52	SiO ₂	60.68	63.78	SiO ₂	38.19	37.51	38.19	38.25	38.23	36.38	36.82	36.45	37.12
TiO ₂	1.57	TiO ₂	0.00	0.01	TiO ₂	0.08	0.08	0.06	0.02	0.08	0.02	0.02	0.02	0.07
Al ₂ O ₃	16.79	Al ₂ O ₃	23.93	22.24	Al ₂ O ₃	21.69	21.67	21.60	21.75	21.34	20.71	20.88	20.71	21.03
Cr2O3	0.01	FeO _t	0.08	0.07	FeO	31.37	30.72	30.30	29.74	30.82	25.61	25.42	29.41	29.41
FeO _t	21.08	MnO	0.03	0.08	Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00
MnO	0.20	MgO	0.00	0.01	MnO	1.88	1.82	1.62	1.37	1.32	16.73	15.43	11.24	11.25
MgO	10.35	CaO	5.34	3.19	MgO	4.13	3.84	4.15	4.66	4.10	1.61	1.47	2.07	1.96
CaO	0.01	Na ₂ O	8.76	10.06	CaO	4.60	4.30	4.81	4.97	5.39	0.34	0.37	0.68	0.77
Na ₂ O	0.07	K ₂ O	0.08	0.06	Na ₂ O	0.01	0.04	0.01	0.03	0.03	0.04	0.05	0.03	0.05
K ₂ O	9.32	Total	98.92	99.50	K ₂ O	0.02	0.01	0.01	0.01	0.02	0.00	0.00	0.00	0.00
F	0.26	Si	2.727	2.833	Total	101.96	99.99	100.75	100.82	101.33	101.43	100.46	100.60	101.66
Cl	0.04	Al	1.268	1.164	Si	5.946	5.957	6.004	5.982	5.979	5.867	5.984	5.899	5.944
Total	95.22	Fe _t	0.003	0.003	Al ^{IV}	0.054	0.043	0.000	0.018	0.021	0.133	0.016	0.101	0.056
Si	5.489	Ca	0.257	0.152	Al ^{VI}	3.927	4.012	4.002	3.992	3.912	3.802	3.983	3.850	3.914
Al	3.059	Na	0.764	0.866	Fe ³⁺	0.115	0.024	0.000	0.030	0.102	0.341	0.044	0.255	0.139
Ti	0.183	K	0.005	0.004	Ti	0.009	0.010	0.007	0.003	0.009	0.002	0.002	0.002	0.009
Cr	0.001	Total	5.023	5.020	Cr	0.000	0.000	0.000	0.002	0.001	0.000	0.000	0.000	0.000
Fe _t	2.724	%An	25.1	14.9	Mg	0.958	0.908	0.972	1.087	0.956	0.387	0.356	0.500	0.467
Mn	0.026	%Ab	74.5	84.8	Fe ²⁺	3.969	4.055	3.984	3.860	3.929	3.112	3.411	3.725	3.800
Mg	2.385	%Or	0.46	0.35	Mn	0.248	0.245	0.216	0.181	0.174	2.284	2.124	1.541	1.526
Ca	0.002				Ca	0.767	0.732	0.810	0.833	0.904	0.059	0.065	0.119	0.132
Na	0.020				Na	0.004	0.011	0.003	0.010	0.009	0.014	0.015	0.008	0.014
K	1.837				K	0.003	0.002	0.001	0.002	0.004	0.000	0.000	0.000	0.001
Total	15.726				Total	16.000	16.000	16.000	16.000	16.000	16.000	16.000	16.000	16.000
F	0.125				Alm	66.8	68.3	66.6	64.8	65.9	53.3	57.3	63.3	64.1
Mg/Mg + Fe _t	0.47				Esp	4.2	4.1	3.6	3.0	2.9	39.1	35.7	26.2	25.8
FeO/MgO	2.04				Pyr	16.1	15.3	16.3	18.2	16.0	6.6	6.0	8.5	7.9
					Gross	12.9	12.3	13.5	14.0	15.2	1.0	1.1	2.0	2.2

Analyses by microprobe. Garnet calculated on the basis of 24 oxygen atoms and 16 cations, Fe³⁺ calculated as suggested by Droop (1987). Alm = 100 × Fe²⁺/(Fe²⁺ + Mg + Mn + Ca); Spes = 100 × Mn/(Fe²⁺ + Mg + Mn + Ca); Pyr = 100 × Mg/(Fe²⁺ + Mg + Mn + Ca); Gross = 100 × Ca/(Fe²⁺ + Mg + Mn + Ca). Biotite calculated on the basis of 22 oxygen atoms, plagioclase on the basis of 8 oxygen atoms.

Zircons were separated into magnetic and nonmagnetic fractions using a Franz magnetic separator. Selected individual grains were abraded to minimize the effects of Pb loss or to remove metamorphic overgrowths. The selected grains were weighed, mixed with a ²⁰⁵Pb–²³³U–²³⁵U spike and subsequently dissolved in an HF–HNO₃ solution. Uranium and lead were separated using an anion exchange resin and the resulting uranium and lead fraction was loaded on single Re filaments and analyzed using a solid source VG

Sector mass spectrometer with a Daly detector. The isotopic ratios were corrected for fractionation, spike, blank, and initial common lead, and regressions were calculated using IsoplotEX. Samples for Sm–Nd isotopic analyses were dissolved in a HF–HNO₃ mixture in high-pressure Teflon vessels. A ¹⁵⁰Nd–¹⁴⁹Sm tracer was added to determine Nd and Sm concentrations. The REE were then purified by cation exchange chromatography, and Sm and Nd were subsequently separated following the procedure of Richard et al. (1976).

Table 3

U–Pb isotopic data for rocks of the Lagoa Dourada suite.

Fraction ^a	Weight (mg)	U (ppm)	Pbrad (ppm)	Pbcom ^b (pg)	Th/U	²⁰⁶ Pb/ ²⁰⁴ Pb ^c	Isotopic ratios						Ages							
							²⁰⁶ Pb/ ²³⁸ U ^d	±1 σ %	²⁰⁷ Pb/ ²³⁵ U ^d	±1σ%	²⁰⁷ Pb/ ²⁰⁶ Pb ^d	±1σ%	²⁰⁶ Pb/ ²³⁸ U	±2σ	²⁰⁷ Pb/ ²³⁵ U	±2σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±2σ	Disc.	σ
Sample LD5A																				
A (1),t,ic	0.0010	363	169	3.0	0.353	3348	0.4382	0.16	9.104	0.17	0.15069	0.05	2342.6	6.2	2348.6	3.1	2353.7	0.9	0.6	0.95
B (1),sp,ic	0.0018	248	112	2.8	0.291	4614	0.4239	0.18	8.754	0.20	0.14979	0.05	2278.0	7.0	2312.7	3.6	2343.5	0.8	3.3	0.97
C (1),f,lp,ic	0.0010	303	139	2.9	0.273	2871	0.4325	0.15	8.972	0.17	0.15047	0.10	2316.8	6.0	2335.2	3.1	2351.3	1.7	1.7	0.81
Sample LD4A																				
A (1),t,br	0.0010	518	235	4.1	0.246	3352	0.4326	0.17	8.922	0.19	0.14957	0.06	2317.6	6.8	2330.1	3.4	2341.0	1.0	1.2	0.95
B (1),t,br	0.0010	314	145	3.2	0.313	2622	0.4331	0.16	8.934	0.18	0.14961	0.05	2319.7	6.2	2331.3	3.2	2341.5	0.8	1.1	0.96
C (1),lp,br	0.0010	349	159	4.3	0.256	2183	0.4318	0.23	8.922	0.23	0.14987	0.10	2313.6	9.1	2330.1	4.2	2344.5	1.7	1.6	0.91
D (1),f,l,br	0.0010	306	142	4.2	0.309	2219	0.4368	0.16	9.055	0.18	0.15036	0.06	2336.2	6.3	2343.6	3.2	2350.0	1.0	0.7	0.95
E (1),t,ic	0.0020	248	116	5.4	0.312	2552	0.4382	0.15	9.083	0.17	0.15035	0.05	2342.4	5.8	2346.4	3.0	2349.9	0.9	0.4	0.95

^a All fractions are zircon. Number in parentheses is the number of grains in the analysis. Morphology: ic – colorless, pk – pink, br – brown, t – tip, f – fragment, sp – short prisme, lp – long prism.

^b Total common lead (spike, blank and mineral).

^c Measured ratio corrected for Pb fractionation.

^d Corrected for Pb fractionation, blank (Pb = 4 pg, U = 0.5 pg), spike and initial common lead.

Fig. 6. Concordia diagram with the U–Pb isotopic data of the tonalitic and trondhjemitic rocks of the Lagoa Dourada suite. See Fig. 2 localities. Error ellipses are at 2σ . Data from Table 3.

The total procedural blanks are less than 150 pg. The Sm and Nd analyses were done using a triple filament assembly in a VG-Sector-54 mass spectrometer. The Nd and Sm isotopes were measured in dynamic and static modes, respectively. Repeated measurements of the JNdi-1 Nd standard (Tanaka et al., 2000) yielded a value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512106 \pm 7$ ($n = 37$). The Sm and Nd concentrations and the $^{147}\text{Sm}/^{144}\text{Nd}$ ratios have an accuracy of 0.5% that corresponds to an average error on the initial ε_{Nd} value of ± 0.5 epsilon units.

Fig. 7. ε_{Nd} versus age diagram showing the Nd-isotopic evolution of the rocks of the Lagoa Dourada suite. The line TH represents the Nd-isotopic evolution of the country rock amphibolite, and the bar indicates the field of the three gneisses (Gn1, Gn2 and Gn3). These latter samples represent the Nd-isotopic evolution of older mafic and intermediate-to-felsic crustal materials from the surrounding terrains. See Fig. 2 for the sample localities. Data from Table 4. Typical error is $0.5 \varepsilon_{\text{Nd}}$. DM and CHUR denote depleted mantle (after DePaolo, 1981) and chondritic uniform reservoir, respectively.

4. Sampling and petrography

The collected granitoids came from five work stations of fresh, well exposed outcrops of moderate to highly deformed tonalitic and/or trondhjemitic rocks. The outcrops are all in the neighborhood of the town of Lagoa Dourada (Figs. 1 and 2, work stations labeled LD1 to LD5), contain similar petrological assemblages and are defined in this work as the Lagoa Dourada suite. The granitoids and the surrounding country rocks were metamorphosed to low-amphibolite facies metamorphism, but the prefix meta- is suppressed in the subsequent discussions for simplicity. The granitoids (Fig. 3a–c) are medium grained, foliated to gneissic, encompassing biotite-hornblende tonalites with $\sim 10\%$ up to $\sim 25\%$ mafic mineral content (work stations LD1 to LD4) to biotite trondhjemites (LD5 station). All the rock-types occupy the tonalitic field in the normative Ab–An–Or classification diagram, with the more felsic lying closer to the tonalite/trondhjemite boundary line (Fig. 3d). The biotite trondhjemites from work station LD5 include the main medium grained phase of the outcrop (samples LD5A and LD5B) and a finer grained trondhjemitic phase (sample LD5C). The observed transitional contact between these two facies (Fig. 3c), suggests that the finer grained phase was emplaced as a syn-magmatic batch of magma during the evolution of the suite. In contrast, at the other work stations, the medium grained biotite-hornblende tonalites are intruded by thin dikes of highly foliated fine-grained tonalitic aplites. Sample LD1D represents one of these dikes (Fig. 3b), which is petrographically similar to its host. In this case however, the dikes are interpreted as being emplaced as post-magmatic and pre- to syn-deformational phases.

Fig. 8. Diagrams with the classification of the rocks of the Lagoa Dourada suite based on major elements. (a) Cationic Ca–Na–K classification diagram, tonalitic–trondhjemitic (Tdj) and calk–alkaline (CA) trends as proposed by Barker and Arth (1976). Grey field represents the composition of the Archean high-aluminium TTG suites (Martin et al., 2005). (b) Classification diagram based on the wt% K_2O versus SiO_2 . The fields of the medium- and low-K series are from Le Maitre (1989). (c) The K_2O/Na_2O ratio versus SiO_2 . (d) The A/CNK index versus SiO_2 . Symbols of the rock types are indicated in the figure, wt.% silica in brackets.

All the granitoids contain zircon, apatite and allanite as accessory minerals, the latter with epidote coronas. Traces of K-feldspar are found in the biotite trondhjemitic. In addition, magnetite is also a distinctive accessory mineral. Garnet and pyrrhotite are found in some specimens, the former in the tonalites of the work stations LD1 and LD4, and in the tonalitic aplite dike LD1D. Results of microprobe analyses of plagioclase, biotite and garnet from the tonalite LD4B are presented in Table 2. The plagioclase is oligoclase (An_{29} to An_{15}) and the biotite is a ferri-ferous variety, with $Mg/(Mg + Fe_t)$ from 0.45 to 0.48. Garnet shows two distinct compositions (Fig. 4a and b): (i) a Ca–Mg almandine (average $Alm_{66.5}$ $Spess_{33.6}$ $Pyr_{16.4}$ $Gross_{13.6}$); and (ii) a manganese rich type (average $Alm_{59.5}$ $Spess_{31.7}$ $Pyr_{7.2}$ $Gross_{1.6}$). The Ca–Mg almandine plot in the compositional field of igneous garnets crystallized in magmas derived from mantle and/or igneous crustal sources (Fig. 5; Harangi et al., 2001), whereas the Mn-rich almandine are likely associated with post-magmatic recrystallization of the suite at low pressure (Dahlquist et al., 2007).

5. U–Pb geochronology

Two facies of the Lagoa Dourada suite were chosen for U–Pb ID-TIMS zircon geochronology: a garnet hornblende–biotite tonalite (LD4A), and a biotite trondhjemitic (LD5A). The results are presented in Table 3. Zircons from both samples are very similar, ranging from colorless to brown, short to long prismatic, bipyramidal crystals (Fig. 6). A regression of three zircon fractions from the biotite trondhjemitic LD5A yielded a best fit line with an upper intercept age of $2356.1 \pm 3.1/-2.4$ Ma (MSWD = 0.40). Similarly, a regression of five zircon fractions from the hornblende–biotite tonalite LD4A yielded an upper intercept age of 2349.9 ± 4 Ma (MSWD = 0.275; Fig. 6). These ages are nearly identical within error and indicate that both samples crystallized at ca. 2350 Ma. The ages are older than the generally accepted ca. 2.2–2.1 Ga age range for Trans-Amazonian pre- to syn-orogenic felsic plutonic suites of the southern Quadrilátero Ferrífero region (Noce et al., 2000; Silva et al., 2002; Noce et al., 2007a; Campos and Carneiro, 2008; Ávila et al.,

2010). Thus the Lagoa Dourada suite constitutes an earlier event of felsic plutonic magmatic activity in the scope of the Mineiro belt.

6. Nd isotope composition

The Nd isotope compositions of selected samples of the Lagoa Dourada suite are presented in Table 4. This includes a biotite–hornblende tonalite (LD3A), a hornblende–biotite tonalite (LD4B) and a biotite trondhjemitic (LD5B). Table 4 also includes four representative samples of the enclosing country rocks sampled next to the Congonhas lineament (Fig. 2). These rocks are a metabasaltic tholeiitic amphibolite (sample TH), a trondhjemitic gneiss (sample Gn1) and two samples of quartz dioritic gneisses (samples Gn2 and Gn3, see Fig. 2 for locations of the samples). The results for all the analyzed rocks are presented in the ϵ_{Nd} versus time diagram in Fig. 7. The Nd isotope data of the rocks of the Lagoa Dourada suite yielded T_{DM} ages ranging from 2.4 to 2.5 Ga and $\epsilon_{Nd}(t = 2350\text{Ma})$ values of +1.0 to +2.1 (Fig. 7). The amphibolite and the trondhjemitic and quartz-dioritic gneisses yielded $\epsilon_{Nd}(t = 2350\text{Ma})$ values of −1.5, −7.4, −10.6 and −7.8 respectively (Fig. 7). Calculated T_{DM} ages of the felsic gneisses yielded values from 2.9 to 3.3 Ga (Table 4). These data suggest that the parental magmas of the Lagoa Dourada suite were somewhat juvenile, with a slightly depleted Nd-isotopic signature of its source rock. This rules out any significant contribution from the older country rocks such as the tholeiitic amphibolite or the quartz-dioritic and/or trondhjemitic gneisses, all of which have distinctively negative ϵ_{Nd} values at the time of crystallization of the Lagoa Dourada suite ca. 2350 Ma.

7. Whole rock geochemistry

7.1. Major and trace elements

Chemical analyses of the Lagoa Dourada suite are given in Table 5. The biotite–hornblende to hornblende–biotite tonalites, and the biotite trondhjemitic can be grouped as a progression from: (i) low silica tonalites (LD1A, LD2A, LD2B and the aplitic tonalite dike LD1D, all within the range of 62.2–64 wt.% SiO_2);

Fig. 9. Harker diagrams for the major elements to the rocks of the Lagoa Dourada suite. Legend as in Fig. 8. Oxides in wt.%.

(ii) to medium silica tonalites (LD3A, LD3B, LD4A, B and C with 66.7–70.0 wt.% SiO₂); and (iii) to high silica trondhjemites (LD5A, LD5B and the syn-magmatic finer grained biotite trondhjemite facies LD5C, all three samples with 71.3–72.7 wt.% SiO₂). General classifications based on the major elements are presented in Fig. 8. The Lagoa Dourada suite is defined as a metaluminous to slightly peraluminous, intermediate to felsic (62–73% SiO₂), low-K, TTG suite (Fig. 8a–d). More felsic members of the suite show slightly higher potassium contents (up to 1.2 wt.% K₂O) and A/CNK ratios (A/CNK = mol Al₂O₃/CaO + Na₂O + K₂O, up to 1.03).

Overall, the three groups of rocks of the Lagoa Dourada suite show coherent trends of negative correlation of silica with the major oxides CaO, Al₂O₃, MgO, Fe₂O₃, P₂O₅ and TiO₂, and with the trace elements such as Sr, Y, V, Sc and Zr (Figs. 9 and 10). The wt.% Na₂O and the Nb content show somewhat scattered distributions, but trend to lower values in the most siliceous rocks. The general positive correlation of silica with K₂O (Fig. 8b) is accompanied by similar behavior of the trace elements Rb, Ba, Th

and U (Fig. 10). In comparison with average compositions of TTG suites (Barker, 1979; Drummond and Defant, 1990; Martin, 1999; Smithies, 2000; Condie, 2005; Martin et al., 2005), the rocks of the Lagoa Dourada suite can be classified as a high-aluminium TTG suite; with Al₂O₃ ≥ 15 at 70% SiO₂, low Rb (generally ≤ 30 ppm), Ba (≤ 244 ppm), Th (≤ 2.6 ppm), U (≤ 1.1 ppm), Y (5–11 ppm) and Nb (5–8 ppm), and moderately high Sr (323–466 ppm). With respect to the trondhjemite definition proposed by Barker (1979), the rocks of the Lagoa Dourada suite with >68 wt.% SiO₂ are Ca-rich trondhjemites (with 3.3–4.2 wt.% CaO compared to typical values of 1.5–3.0%). The FeO*/MgO ratio of these rocks (2.9–3.4) are comparable to average ratios for trondhjemites (2–3; Barker, 1979; FeO* [FeO* = 0.9*Fe₂O_{3(t)}]). The high silica biotite trondhjemites LD5A, B and C tend to form a coherent group in both major and trace element diagrams (Figs. 3 and 8–10). The biotite-hornblende tonalitic aplite dike LD1D (Fig. 3) has a major element chemical composition similar to that of the low silica tonalites, but the aplite is consistently more concentrated in Sr, Rb, Ba, Th, U and V and less

Fig. 10. Harker diagrams of selected trace elements for the rocks of the Lagoa Dourada suite. Legend as in Fig. 8. Trace elements in ppm. Note logarithmic scale for Th and U.

concentrated in Nb (Figs. 8–10; Y, Zr and Sc concentrations are similar).

7.2. Rare earth elements

Chondrite-normalized REE diagrams of the Lagoa Dourada suite are presented in Fig. 11. The Lagoa Dourada suite, like

most TTG suites, have low heavy REE contents ($\text{Yb} \leq 1.0 \text{ ppm}$), high light/heavy REE ratios ($\text{La}_N/\text{Yb}_N \geq 10$), and positive europium anomalies, although for the latter attribute this is not true for all TTG suites (Condie, 2005; Martin et al., 2005). Correlations of SiO_2 with La and Yb, and with light/heavy REE and with Eu/Eu^* ratios are presented in Fig. 12. La and Yb show a steady-state behavior for the light REE and a somewhat negative correlation

Fig. 11. Chondrite-normalized REE patterns of the rocks of the Lagoa Dourada suite. Symbols indicated in the figure, wt.% SiO₂ in brackets. Chondrite values after Taylor and McLennan (1985).

between the heavy REE and silica (Fig. 12a and b), leading to the more siliceous samples having slightly higher light/heavy REE ratios (Figs. 11c and 12). The Eu/Eu* ratios increase with increasing silica content (Fig. 12d). Tonalites LD4 B and C have higher light REE and lower heavy REE contents compared to the other tonalites with equivalent wt.% SiO₂ (Fig. 12a and b). This results in a higher degree of light/heavy REE fractionation (Fig. 12c) and the crossing chondrite-normalized REE profiles seen in Fig. 11b. The biotite-hornblende aplitic tonalite dike LD1D has higher light and middle REE contents when compared to the other low silica tonalites, resulting in a higher (La/Yb)_N ratio and no Eu/Eu* anomaly (Figs. 11a and 12a–d).

7.3. Primitive mantle-normalized diagrams

Primitive mantle-normalized multi-element diagrams of the Lagoa Dourada suite are presented in Fig. 13. Also plotted for comparison is the average composition of the Proterozoic TTG suites compiled by Condie (2005). These diagrams show the following common characteristics between the Lagoa Dourada suite and the Proterozoic TTG's: (i) negative slopes between the LIL and the high-field-strength (HFS) elements; (ii) negative spikes for Nb–Ta, P and Ti relative to their neighboring elements; and (iii) lower than tholeiitic values of Y and Yb (not shown in Fig. 13). In contrast, the Lagoa Dourada suite is consistently depleted in LIL elements (K, Rb, Ba,

Fig. 12. Harker diagrams for La (a) and Yb (b); and for the (La/Yb)_N (c) and Eu/Eu* (d) ratios to the rocks of the Lagoa Dourada suite. Legend as in Fig. 8.

Fig. 13. Primitive mantle-normalized multielement patterns of the rocks of the Lagoa Dourada suite. Symbols indicated in the figure, wt.% SiO₂ in brackets. The average composition of Proterozoic TTG suites is shown for comparison (Ave. TTG Prot., data from [Condie, 2005](#)). Primitive mantle values after [Sun and McDonough \(1989\)](#).

as well as thorium) and light REE, and consequently shows strong positive spikes of strontium relative to the light REE (Fig. 13).

8. Discussion

In this section, the field, mineralogical, geochemical and isotopic data of the Lagoa Dourada suite are interpreted in the light of processes related to the origin and the magmatic evolution of the TTG suites. A summary of the petrological characteristics of the Lagoa Dourada suite and a comparison with the average composition of Proterozoic TTG suites are given in [Table 6](#).

8.1. Source rock

The tonalitic and trondhjemitic rocks of the Lagoa Dourada suite have high Ca contents and low LILE (e.g. K, Rb, and Ba), light REE, Th and U contents ([Table 6](#)). In addition, the suite has depleted Nd isotope compositions ($\varepsilon_{\text{Nd}}(t) = +1.0$ to $+2.1$, [Table 3](#)); lower than tholeiitic values of Y and Yb ([Fig. 13](#)); positive Eu/Eu* and Sr/Sr* anomalies on chondrite-normalized and primitive mantle-normalized diagrams ([Figs. 11 and 13](#)); and low Mg#, Cr and Ni contents (<20 ppm). The low Mg# of the Lagoa Dourada suite rocks, when compared at a similar silica content with the Mg# of the other TTG suites ([Smithies, 2000; Smithies et al., 2003; Condie, 2005](#);

Fig. 14. Diagrams of Nb/Ta versus Zr/Sm ratios (a), Sr/Y ratio versus Y (ppm) (b) and chondrite-normalized (La/Yb)_N ratio versus Yb_N (c) for the rocks of the Lagoa Dourada suite. In (b) and (c) are the calculated modeled compositions of melts derived from partial melting of different tholeiitic source rocks (S1 and S2) with eclogitic to garnet amphibolite residues (R1 and R2). Labeled tick marks in (b) and (c) indicate % of partial melting. Tholeiitic source compositions and residues are indicated in (c). The curves in (b) and (c) were calculated according to the batch melting equation (Rollinson, 1993) and using the partition coefficients adopted by Martin (1987). Fields in (a) are after Foley et al. (2002), with the lines representing the primitive mantle values of Sun and McDonough (1989). The fields of compositions of the high aluminium TTG suites (TTG field) and of the ADR suites in (b) and (c) are respectively after Petford and Atherton (1996) and Martin (1986). The plot representing the average composition of the Late Archean and the Proterozoic TTG suites are after Condie (2005), and the plot representing the average composition of the Archean TTG suites with <3.0 Ga is from Martin et al. (2005). The representative composition of N- and E-MORB in (a) is after Klein (2004). Legend of the rocks to all figures in (b), and wt.% SiO₂ in brackets.

Fig. 15. Chondrite-normalized REE patterns of the melts derived from the partial melting of a tholeiitic source rock with flat REE pattern and left behind hornblende eclogitic residues. In (a) the modeled melts are compared with the REE pattern of the representative parental magma of the Lagoa Dourada suite; and in (b) the modeled melts are compared with the average composition of the two tonalitic rocks of the suite which contain steeper REE pattern and much higher $(La/Yb)_N$ ratio. The REE of the modeled melts were calculated according to the batch melting equation (Rollinson, 1993) and adopting the same partition coefficients as Martin (1987). F indicates % of melt.

Martin et al., 2005; Clemens et al., 2006; Stevenson et al., 2009; Moyen et al., 2010), indicates that the above mentioned depletion in incompatible trace elements is not an artifact of the degree of fractionation, but a genetic attribute that might be related to the

geochemistry of the source rock and the depth of melting (Moyen et al., 2010). The absence of associated gabbro/diorite with the Lagoa Dourada suite rules out derivation from differentiation of a mafic melt (Arth et al., 1978). Therefore the most probable source

Fig. 16. Logarithmic diagram of compatible (V) versus incompatible (Rb, Th, K) elements, indicating the vectors of fractional crystallization (FC) and partial melting (PM). Based on Martin (1987). wt.% SiO_2 in brackets.

Fig. 17. Covariance diagrams between the wt.% CaO (a) and $100 \times \text{Mg\#}$ (b) against the wt.% K_2O , Sr, Zr, Ce and Yb (ppm) for the rocks of the Lagoa Dourada suite. Arrow indicates vectors to the residual liquids of the suite. Legend as in Fig. 16. Position of the average composition of the Proterozoic TTG suites is indicated (data from [Condie, 2005](#), 67.3 wt.% SiO_2).

rock for the suite is the melting of a mafic source ([Martin, 1986; Martin, 1987; Rapp and Watson, 1995; Willie et al., 1997; Martin et al., 2005; Martin et al., 2005 and references therein, Clemens et al., 2006](#)).

The depleted Nd isotope compositions of the Lagoa Dourada TTG suite suggest that the suite was derived from the melting of a mafic crust that had not long been separated from the mantle. Correlations of HFS element ratios, such as Nb/Ta versus Zr/Sm (Fig. 14a), in

the suite are consistent with the melting of a tholeiitic source that left behind residual garnet amphibolite and/or hornblende eclogite (Foley et al., 2002). The absence of plagioclase in the residue is indicated by the relatively high Sr and low Y contents of the suite and by the Sr/Y versus Y graph of Fig. 14b. In this diagram, samples of the Lagoa Dourada suite follow the modeled compositions of liquids derived from tholeiitic sources with eclogitic to garnet–clinopyroxene amphibolite residues containing no plagioclase. It is important to note that only the high-Sr tholeiitic source (S1 source, with Sr = 170 ppm) can account for the samples with lower Sr/Y ratios and higher Y contents (Fig. 14b). Finally, on the (La/Yb)_N versus Yb_N graph (Fig. 14c), it is noteworthy that none of the samples of the Lagoa Dourada suite plots on the line of pure eclogite residue (R1) from a tholeiitic source with flat REE pattern (S1), nor on the line of garnet–clinopyroxene amphibolite residue (R2) to tholeiitic source with enriched light REE pattern (S2). The diagram suggests that the suite was derived from a light REE enriched tholeiitic source with eclogite residue, or a flat REE tholeiitic source with a mixed garnet–clinopyroxene amphibolite residue. The latter option is judged more realistic because of the high degree of partial melting required for the eclogite residue (>20% to 30% for two samples of the LD4 station, and >40% for all other samples). Thus, the most probable source rock for the Lagoa Dourada suite was a tholeiitic source with a flat REE pattern, ~27 ppm Y and Sr/Y ~ 7 (e.g. Sr ~ 170 ppm). Melting took place relatively soon after the extraction of this mafic rock from the mantle and in the stability field of garnet–clinopyroxene amphibolite to hornblende eclogitic residues.

8.2. Parental magma

The most primitive rocks of the Lagoa Dourada suite are tonalites LD1A and LD2A and B, with 62–64% SiO₂. These tonalites have the highest compatible element contents (i.e., Ca, Mg, Fe, Ti, P, V, Sr, Sc, Zr and middle to heavy REE) and the lowest incompatible element contents (i.e. K, Rb, Th and U, Figs. 9–12). For these reasons, the average composition of these three tonalites is assumed to be representative of the parental magma of the suite. This parental magma composition is much less siliceous than the average Archean and Proterozoic high-aluminium TTG suite (e.g. ~68% SiO₂; Condie, 2005). However, tonalitic/dacitic compositions with ~64% SiO₂ are also associated with the definition of the TTG suites (i.e., the high-aluminium tonalite–trondhjemite–dacite–TTD-series of Drummond and Defant, 1990; or the Phanerozoic Na-rich granitoids exemplified by Smithies, 2000). The REE pattern of the assumed parental magma of the Lagoa Dourada suite can be reproduced using a tholeiitic source with a flat REE pattern, moderate degrees of partial melting (~10% to 20%) and hornblende eclogitic residues with 57% Cpx + 30% Hbl + 13% Grt (Fig. 15a, modeled using batch melting equations of Rollinson, 1993). Modeling the tonalitic samples LD4 B and C, the only samples with higher La/Yb_N ratios (Figs. 11 and 12), and starting with the same tholeiitic composition, requires lower degrees of melting and residues richer in garnet instead of clinopyroxene (42% Cpx + 30% Hbl + 28% Grt, Fig. 15b).

8.3. Magmatic differentiation

The Lagoa Dourada tonalitic and trondhjemitic rocks range from ~62 to ~73% SiO₂, showing tight inter-element correlation on the Harker diagrams between the low and the high silica members of the suite (Figs. 9 and 10). This suggests crystal fractionation as a possible mechanism to explain the magmatic differentiation of the suite (Kalsbeek, 2001; Huang et al., 2010). Fractional crystallization of hornblende, plagioclase, and accessory Fe–Ti oxides, zircon and apatite are indicated by the negative correlation of silica with Al, Ca, Fe, Mg, Ti and P as well as by trace elements such as V,

Sr, Zr and Y. Crystal fractionation is also indicated by plots of the different granitoid samples on logarithmic graphs of compatible (e.g. V) versus incompatible (e.g. Rb, Th or K) elements in the suite (Fig. 16).

Fig. 17 explores the possible role of fractional crystallization between different members of the suite through the construction of covariation diagrams of K₂O, Sr, Ce, Y and Zr as function of the CaO content and the Mg#. Because both the CaO content and the Mg# are affected by hornblende and plagioclase, geochemical variations against these proxies can be used to examine the influence of plagioclase and amphibole fractionation on the tonalitic to trondhjemitic suites (Arth et al., 1978; Kalsbeek, 2001). The overall coherent behavior of the different suite members in these diagrams suggests that their compositions reproduce the hypothetical liquid line of descent of the suite starting from the proposed parental magma. The fractionating phases are the mineral assemblages observed in the investigated samples (Pl + Hbl + Zrn + Ap + Fe – Ti minerals ± Aln and Grt). Rocks (LD4B and C) with higher light REE and lower heavy REE contents (Yb) cannot be modeled from the same parental magma as the other samples (Evans and Hanson, 1997), and are interpreted as representing different batches of magma produced from the same source under different melting conditions (Fig. 15). The presence of more than one melting event and intrusion of new batches of magma is supported by field observations in the form of the tonalitic aplite dikes (LD1D; Fig. 3b). Indeed, the geochemistry of the post-magmatic, pre- to syn-deformational tonalitic aplite dike (sample LD1D) has largely the same major element content as the intruded tonalitic samples at the same silica level (Fig. 9), but consistently higher trace element contents (Sr, Ba, Th, U, and light REE; Figs. 10 and 11). This suggests that these magmatic dike phases are not derived from the same batches of magma as the tonalites. Nor do they represent the residual liquids of the main magma of the suite. Rather, they are most likely derived from different melt batches produced under different melting conditions.

8.4. Geotectonic implications

This study of the Lagoa Dourada suite demonstrates that construction of the Paleoproterozoic southern margin of the São Francisco craton included juvenile TTG plutonic crust that formed at ca. 2350 Ma. Geochemical and petrological parameters of the suite are consistent with its derivation from partial melting of MORB-like tholeiitic metabasaltic rocks with flat REE patterns. Moreover, the mantle-like $\epsilon_{\text{Nd}}(t)$ values of +1.0 to +2.1 indicate a short crustal residence time for the source protolith prior to melting. Thus, the emplacement of the suite is envisaged to represent the growth of new continental crust by partial melting of the depleted mantle to generate a MORB-type tholeiites, followed by the partial melting of these tholeiites to yield the parental magma of the suite. This model reproduces the two-stage petrogenesis of Archean TTG first proposed by Martin (1986). The depleted mantle model ages (T_{DM}) of the suite vary from ~2.4 to 2.5 Ga and are only slightly older than the intrusion age (Table 4). These observations exclude lithologies such as the tholeiitic amphibolites or the quartz-dioritic and trondhjemitic gneisses from the northern edge of the Mineiro belt as possible source rocks and/or as possible crustal contaminants (Figs. 1, 2 and 7 and Table 4).

Major and trace element geochemistry and modeling, based on batch melting equations, suggest the melting region was situated in the hornblende eclogitic stability field, indicating a minimum of ~30 to 40 km depth and 700–800 °C (Peacock et al., 1994; Rapp and Watson, 1995; Rapp, 1997; Foley et al., 2002; Clemens et al., 2006). A high pressure setting is also suggested by the accessory almandine garnet found in some members of the suite. The high CaO (>4%) and low MnO (<3%) contents of the Ca–Mg-rich variety of the

Table 4Nd isotope composition of rocks of the Lagoa Dourada suite, and country rock metabasaltic amphibolite, quartz dioritic and trondhjemitic gneisses.^a

Sample no.	Age (Ga)	Sm (ppm) ^b	Nd (ppm) ^b	¹⁴⁷ Sm/ ¹⁴⁴ Nd ^b	¹⁴³ Nd/ ¹⁴⁴ Nd ^c	2σ	ε _{Nd} (0)	ε _{Nd} (t) ^d	T _{DM} (Ga) ^e
Lagoa Dourada suite									
LD3A	2.350	2.24	11.0	0.1233	0.511554	15	−21.2	+1.0	2.5
LD4B	2.350	2.40	17.6	0.0821	0.510941	5	−33.1	+1.5	2.4
LD5B	2.350	1.85	10.1	0.1111	0.511422	6	−23.7	+2.1	2.4
TH – metabasaltic country rock amphibolite									
TH	2.350 ^f	3.08	10.7	0.1750	0.512226	22	−8.0	−1.5	
Gneisses									
Gn1 – trondhjemitic	2.350 ^f	2.75	28.9	0.0574	0.510104	9	−49.4	−7.4	2.9
Gn2 – qz dioritic	2.350 ^f	8.38	55.2	0.0917	0.510473	10	−42.2	−10.6	3.2
Gn3 – qz dioritic	2.350 ^f	4.38	21.9	0.1210	0.511068	9	−30.6	−7.8	3.3

^a Sm and Nd concentrations and ¹⁴⁷Sm/¹⁴⁴Nd ratios accurate to within 0.5%.^b ¹⁴³Nd/¹⁴⁴Nd normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219.^c ε_{Nd}(t) values from crystallization ages and chondritic ratios of ¹⁴³Nd/¹⁴⁴Nd = 0.512638 and ¹⁴⁷Sm/¹⁴⁴Nd = 0.1966. Maximum error is 0.5 ε_{Nd} units.^d Nd model ages calculated using depleted mantle model of DePaolo (1981).^e Crystallization age unknown, the attributed ages are used to calculate ε_{Nd}(t) and to test possible crustal contaminant rocks for the granitoids of the Lagoa Dourada suite.^f For sample localities see Fig. 2. UTM coordinates for gneisses are 7730700N and 639650E (Gn1); 7718957N and 647974E (Gn2); 7704900N and 645903E (Gn3); for the TH amphibolite is 7710491N and 637066 E; to the other samples see Table 5.

almandine garnets (Figs. 4 and 5; Table 2) are consistent with the compositions of igneous garnets (Harangi et al., 2001; Yuan et al., 2009). In addition, experimental and petrological studies indicate that these igneous garnets form in hydrous metaluminous andesitic to dacitic magmas at relatively high P (>7 kbar) and T (800–950 °C, Day et al., 1992; Alonso-Perez et al., 2009). These findings corroborate the high pressure setting of generation/crystallization of the Lagoa Dourada suite, as was deduced by the geochemistry and the trace element modeling.

Tectonic scenarios envisaged to account for the above mentioned isotopic, geochemical and mineralogical data of the Lagoa Dourada suite could include partial melting of subducted hot oceanic slab, melting of hydrous mafic rocks in arc systems or melting in the root zones of oceanic plateaus (see for example Martin et al., 2005; Condie, 2005 for discussion about tectonic settings to TTG suites). Slab melting produces magmas analogous to adakitic magmas (Drummond et al., 1996; Martin, 1999), however the Lagoa Dourada suite lacks any evidence of having equilibrated,

Table 5

Major and trace element data of rocks from the Lagoa Dourada suite. Oxides in wt.%, trace elements in ppm.

Sample	Locality																					
	Northing		Easting																			
	UTM	UTM	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O _{3t}	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Total	Ba	Rb	Sr	Y	Zr	Nb	Th	
Lagoa Dourada suite ^a																						
LD1A	7689900	602500	62.19	0.87	16.56	6.22	0.08	2.25	5.72	4.85	0.34	0.23	0.50	99.81	98	4	466	11	182	8.2	0.2	
LD2A	7691279	604036	63.40	0.75	16.54	5.52	0.07	1.92	5.32	4.82	0.61	0.21	0.70	99.86	145	10	461	9	221	6.9	1.0	
LD2B	7691279	604036	63.59	0.78	16.67	5.55	0.06	1.92	5.41	4.67	0.51	0.25	0.67	100.08	148	11	452	11	261	7.0	0.7	
LD3A	7692325	598880	66.70	0.47	16.62	3.67	0.05	1.20	4.18	5.24	1.06	0.14	0.60	99.93	244	23	366	8	129	5.6	1.9	
LD3B	7692325	598880	67.77	0.47	16.46	3.58	0.05	1.15	4.24	5.07	1.08	0.16	0.50	100.53	243	22	361	8	170	5.0	1.8	
LD4A	7689582	598535	66.86	0.52	16.25	4.46	0.07	1.32	4.27	4.95	0.63	0.17	0.40	99.90	131	9	400	5	154	8.3	1.3	
LD4B	7689582	598535	68.65	0.46	15.87	3.75	0.05	1.16	4.22	4.76	0.48	0.15	0.40	99.95	113	30	390	5	173	6.8	2.6	
LD4C	7689582	598535	69.99	0.47	15.00	4.07	0.06	1.18	3.95	4.43	0.56	0.16	0.10	99.97	120	56	375	6	160	7.3	2.4	
LD5A	7688562	591318	71.29	0.33	14.91	3.07	0.06	0.84	3.31	4.43	1.16	0.11	0.40	99.91	198	23	343	8	155	6.8	2.5	
LD5B	7688562	591318	72.66	0.33	14.60	3.01	0.04	0.80	3.29	4.23	1.20	0.12	0.52	100.80	188	22	323	6	140	6.0	2.0	
LD5C	7688562	591318	71.05	0.27	15.57	2.67	0.05	0.62	3.27	4.90	1.00	0.10	0.40	99.90	217	23	369	6	154	5.2	2.6	
LD1D	7689900	602500	64.00	0.83	16.95	5.08	0.05	1.66	4.70	4.78	0.78	0.25	0.70	99.78	422	29	650	11	190	4.5	9.9	
Sample																						
	Ni	Cr	V	Sc	Hf	Ta	U	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
LD1A	28	<20	91	9	4.3	0.4	0.3	14.80	29.60	3.97	17.10	3.44	1.19	2.96	0.440	2.190	0.410	1.090	0.150	1.000	0.140	
LD2A	<20	<20	53	8	5.1	0.5	0.3	11.90	25.60	3.21	13.80	2.77	1.02	2.35	0.360	1.760	0.340	0.910	0.130	0.790	0.110	
LD2B	<20	<20	60	8	5.3	0.5	0.3	14.00	27.40	3.87	13.40	2.80	1.20	2.60	0.350	1.900	0.350	1.000	0.130	0.800	0.125	
LD3A	<20	<20	55	5	3.3	0.5	0.6	11.60	25.00	2.80	10.90	2.14	0.80	1.93	0.290	1.500	0.270	0.700	0.100	0.670	0.100	
LD3B	<20	<20	52	5	3.8	0.5	0.5	12.60	24.40	3.07	10.40	2.20	0.94	1.90	0.300	1.500	0.300	0.800	0.110	0.650	0.105	
LD4A	<20	<20	51	4	3.9	0.6	0.7	14.50	28.30	2.99	10.70	1.82	0.88	1.51	0.210	1.000	0.190	0.490	0.070	0.450	0.070	
LD4B	<20	<20	40	4	4.2	0.6	0.4	28.80	52.20	5.25	18.60	2.60	1.02	1.41	0.190	0.870	0.160	0.380	0.060	0.420	0.050	
LD4C	<20	<20	42	4	4.6	0.7	0.5	25.70	45.20	4.62	16.70	2.40	0.93	1.50	0.200	1.030	0.170	0.440	0.060	0.480	0.080	
LD5A	<20	<20	30	3	4.3	0.9	1.1	13.70	27.60	2.97	10.90	1.82	0.76	1.47	0.240	1.170	0.240	0.670	0.100	0.670	0.110	
LD5B	<20	<20	29	3	3.3	0.9	0.8	13.00	24.00	2.98	9.40	1.70	0.84	1.40	0.200	1.200	0.230	0.600	0.090	0.600	0.090	
LD5C	<20	<20	17	2	3.7	0.5	0.7	16.30	31.10	3.23	11.30	1.86	0.67	1.44	0.220	1.060	0.200	0.560	0.080	0.570	0.080	
LD1D	<20	<20	113	7	4.6	0.2	0.8	26.70	64.80	6.33	25.40	4.25	1.28	3.34	0.430	2.050	0.350	0.890	0.130	0.830	0.120	

^a Samples LD1A, LD2A, LD2B, LD3A, LD3B and LD4A are biotite-hornblende tonalites with ~10% up to ~20% mafic mineral contents. Samples LD4B and LD4C are hornblende-biotite tonalites with ~10% mafic mineral contents. Samples LD5A, LD5B and LD5C are biotite trondhjemitic, the latter a syn-magmatic finer grained phase. Sample LD1D is a highly foliated biotite-hornblende aplitic tonalite dike from the LD1 station.

Table 6
Petrogenetic parameters for the Lagoa Dourada suite.^a

Age U–Pb	2350–Ma
Nd isotopes	Juvenile, depleted source, $\epsilon_{Nd}(t) > 0$
Rock types	Hbl–Bt To to Bt–Tdj
Ab–An–Or classif. ^b	To–Tdj normative
Acc. Minerals	Zrn, Ap, Mgt, Ttn, Grt $\pm$ Aln
Major elements	
Silica content	Intermediate to acid (62–73 wt.%)
A/CNK index	Metaluminous to slightly peraluminous; $0.88 \leq A/CNK \leq 1.03$
Al ₂ O ₃ classif. ^b	High Al, ≥ 14.6 wt.% Al ₂ O ₃ ,
K ₂ O vs. SiO ₂ ^c	Low-K series
K ₂ O/Na ₂ O	Very low, ≤ 0.3
Na ₂ O (wt.%)	High, $\geq 4.2\%$; trondhjemitic members
CaO-classif. ^b	High-Ca, ≥ 3.3 wt.%, with oligoclase and Ca–Mg almandine garnet
Mg–classif. ^d	Low-Mg, ≤ 1.9 wt.% MgO, $0.34 \leq Mg\# \leq 0.42$
Trace elements	
Cr (ppm)	Low, < 20
LILE (ppm)	Low Rb (≤ 56), low Ba (≤ 244) and moderate to slightly high Sr (466–323)
Rb/Sr	Low, ≤ 0.15 ; most of values between 0.02 and 0.08
K/Rb	Moderate to high, 83–670; most of values ≥ 360
Sr/Ba	High, ≥ 1.5 up to 4.8
REE total (ppm)	Low, 56–112; most of values < 80
HREE – Yb (ppm)	Low, ≤ 1.00
(La/Yb) _N	Moderate to high, ≥ 10 to 46; most of values between 10 and 22
(La/Sm) _N	Moderate to high, 2.7–7.0; most of values between 2.7 and 5.5
(Gd/Yb) _N	Moderate to high, 1.8–3.0;
Eu/Eu* anomalies	Positive anomalies, ≥ 1.1 to 1.6
HFSE (ppm)	Very low Th (0.7–2.6), moderate Nb (5–8), moderate to high Zr (≥ 128 to 261), low Y (5–11)
LILE/HFSE	
Ba/La	Low (3.9–21)
Th/La	Low (0.01–0.18)
Sr/Nd	Moderate (21–37)
La/Sm	Moderate (4.3–11.1)
Sr/Y	Moderate to high (41–81), most of values between 41 and 54

^a Only the granitoid rocks of the suite were used for this classification. The post-magmatic low silica tonalitic aplite dike (sample LD1D) was not used. Unless indicated, the classification is based on comparison with the average composition (and standard deviation) of Proterozoic high-Al TTG suite (67.3 wt.% SiO₂, *Condie, 2005*). Moderate, low or high refers, respectively to lower or higher contents than this reference frame.

^b Classification according *Barker (1979)*, Al₂O₃ ≥ 15 wt.% to 70% wt.% SiO₂. To: tonalite; Grd: granodiorite; Tdj: trondhjemitic.

^c Classification according *Le Maitre (1989)*.

^d Classification as “low” Mg types is based on the arbitrary limit Mg# = 0.5.

or reacted with the mantle wedge, (e.g., Mg# > 47 and high-Cr and -Ni; *Smithies, 2000*). The flat REE tholeiitic source of the Lagoa Dourada suite, as inferred from geochemical modeling, is more consistent with melting within a non-enriched environment such as a juvenile subduction environment, flat subduction, or an oceanic plateau (*Smithies et al., 2003*). The Lagoa Dourada suite is broadly associated with major tracts of the ca. 2.2–2.1 Ga Paleoproterozoic Trans-Amazonian plutonic suites of the Mineiro belt (*Figs. 1 and 2*), all of which intrude a series of NE–SW greenstone belts within the southwestern Quadrilátero Ferrífero region (*Teixeira et al., 2000; Campos and Carneiro, 2008; Ávila et al., 2010*). There are no precise geochronological data for these greenstone belts. They may be Neoproterozoic like the ~2.77 Ga Rio das Velhas Supergroup greenstone belt north of the Engenho fault (*Fig. 1*), but could also be Paleoproterozoic oceanic counterparts to the platformal Minas Supergroup (*Toledo, 2002; Campos and Carneiro, 2008; Ávila et al., 2010*). Further studies of the granitoids and greenstone belts are

required to determine if melting of these greenstone belt sequences led to the generation of the Lagoa Dourada suite. The Lagoa Dourada suite represents a small (50–80 km²), but unequivocal example of juvenile crust produced within a period known for a lack of crust formation (*Condie et al., 2009a,b; Condie and Aster, 2010*). This finding reinforces a growing body of evidence (*Vasquez et al., 2008; Santos et al., 2009*) indicating that, although rare on a global scale, ca. 2.35–2.30 Ga juvenile granitoids are an important component of the Proterozoic evolution of the São Francisco craton in Brazil.

9. Conclusions

This study establishes a new episode of crustal growth (ca. 2350 Ma) for the southern margin of the São Francisco craton, southeastern Brazil. This episode is represented by the Lagoa Dourada high-aluminium TTG suite. The mineralogical, geochemical, Nd isotopes and U–Pb geochronological data indicate the granitoids were likely derived from tholeiitic source rocks melted at the hornblende eclogitic stability field soon after they were extracted from the mantle. Fractional crystallization is suggested as the main mechanism controlling the magmatic differentiation of the suite, along with concomitant episodic emplacement of different batches of magma that represent different parameters of melting of the source. Accessory Ca–Mg almandine garnet of probable igneous origin indicates the magmas crystallized at relatively high pressure and temperature. The petrogenesis of this suite seems to be related to the partial melting of the roots of tholeiitic greenstone belt packages in an intra-oceanic tectonic setting. The Lagoa Dourada suite is a rare example of ca. 2350 Ma juvenile crust formation linking two major periods of prolonged orogenic granitoid magmatism during the Precambrian in Brazil; the Neoproterozoic, characterized by the large terrains dominated by TTG batholiths and derivative gneissic complexes, and the Paleoproterozoic 2.2–2.1 Ga production of TTG and granitic calc-alkaline suites.

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