Precambrian Research 183 (2010) 617–634

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Layered intrusions and volcanic sequences in Central Brazil: Geological and geochronological constraints for Mesoproterozoic (1.25 Ga) and Neoproterozoic (0.79 Ga) igneous associations

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ARTICLE INFO

Article history:
Received 3 March 2009
Received in revised form 6 June 2010
Accepted 16 June 2010

Keywords:
Layered intrusion
Mafic–ultramafic
Geochronology
Neoproterozoic
Mesoproterozoic

ABSTRACT

A 350-km long belt of layered complexes and associated volcano-sedimentary sequences forms a continental-scale feature exposed along the internal portion of the Neoproterozoic Brasília Belt in central Brazil. This study provides new geochronological results and a critical review of the available data of these igneous associations of central Brazil. Precise age dating combined with geological and petrological studies indicate that this belt consists of two distinct igneous rock associations. The 1.25 and 0.79 Ga igneous episodes are constrained by reliable U–Pb zircon ages (SHRIMP and ID-TIMS) obtained in different regions and lithotypes of this belt. Both igneous associations were affected by high-grade metamorphism and tectonism at ca. 0.76 Ga, which partially disrupted the original igneous stratigraphy of the layered complexes and volcano-sedimentary sequences. The present configuration of this belt results from later events, probably caused by final ocean closure and continental collision between the São Francisco and Amazonian continents at ca. 0.63 Ga.

The 1.25 Ga magmatic event represents an igneous rock association comprising extensive bimodal volcanic rocks (Palmeirópolis, Juscelândia and Indaianópolis sequences) and associated large mafic layered intrusions (Serra dos Borges and Serra da Malacacheta complexes). Geochemical data of mafic volcanic rocks indicate compositions similar to MORB, suggesting a tectonic setting where continental rifting led to the opening of an ocean basin. Large layered intrusions coeval to the volcano-sedimentary sequence consist mainly of olivine plus plagioclase cumulates, with abundant troctolite and leucotroctolite, associated with olivine gabbro, gabbro, anorthosite and pyroxenite. These layered intrusions are characterized by moderately primitive olivine compositions (Fo 63–76), positive $\varepsilon_{Nd(1250Ma)}$ values, low contents of incompatible trace elements and LREE-depleted mantle-normalized-REE patterns. These features suggest an origin from the same depleted mantle source that produced the extensive MORB-type volcanism. Intrusion of layered complexes possibly occurred since the early stages of rifting, being emplaced both at the base of and within the volcanic pile. Different magmatic ages and fractionation trends of layered bodies suggest that they represent a cluster of intrusions that originated during the time span of the continental to oceanic ridge rifting event.

The 0.79 Ga igneous association consists of three large layered intrusions (Niquelândia, Barro Alto, and Canabrava complexes). Despite intense tectonism, several striking geological similarities between the three separate bodies have been used to suggest that they originally constituted a single continuous magmatic structure. These layered intrusion are characterized by thick ultramafic zones, highly primitive compositions of olivine (up to Fo 93) and extensive Fe-enrichment trends of pyroxenes. Layered mafic–ultramafic rocks have abundant evidence of crustal contamination, including highly negative $\varepsilon_{Nd(800Ma)}$ values, as well as older crustal xenoliths and zircon xenocrysts. Cyclic units consisting of successive layers of dunite, harzburgite, orthopyroxenite, websterite and gabbronorite occur throughout the stratigraphy of these layered intrusions. The Niquelandia Complex ranks among the thickest layered intrusions in the world, and together with the Barro Alto and Canabrava layered intrusions represent an enormous volume of mantle-derived magma emplaced into the crust during a continental rifting event.

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0301-9268/$ – see front matter
doi:10.1016/j.precamres.2010.06.008

The 1.25 and 0.79 Ga rifting events are not exposed in the Brasília Belt or in the São Francisco Craton. This supports previous interpretations suggesting that these igneous rock associations are part of an exotic block in the Brasília Belt.
Equivalent Mesoproterozoic (ca. 1.25 Ga) and Neoproterozoic (ca. 0.79 Ga) extensional events have been reported in other continents (e.g., North America). These igneous associations described within an allochtonous block in the Brasília Belt provide additional constraints, therefore, for continental reconstruction models before the break-up of Rodinia.

1. Introduction

The 350-km long array of layered complexes and associated volcano-sedimentary sequences in central Brazil is a continental-scale feature exposed along the internal portion of the Neoproterozoic Brasília Belt in central Brazil. The geology, petrology and age of these layered complexes have been the subject of major controversy over the last three decades (see Ferreira Filho et al., 1992, 1994; Pimentel et al., 2004 for reviews of the geology, geochronological database and tectonic interpretations). Our current understanding of these layered complexes is based upon four major arguments: (i) the existence of two petrologically distinct magmatic systems (e.g., Ferreira Filho, 1994; Ferreira Filho et al., 1998); (ii) these magmatic systems have different ages, the older crystallized at ca. 1.25 Ga while the younger at ca. 0.79 Ga (e.g., Pimentel et al., 2004, 2006, submitted for publication); (iii) both magmatic systems were overprinted by tectonism and associated metamorphism at ca. 0.76 Ga (e.g., Ferreira Filho et al., 1994; Pimentel et al., 2004); and (iv) they are exposed within exotic tectonic fragments of originally larger systems (e.g., Ferreira Filho, 1998; Pimentel et al., 2004). Even though these arguments are now supported by robust geological, petrological and isotopic data, descriptions of these layered complexes have maintained former nomenclatures, disseminating several misleading and inappropriate terms. This problem is illustrated by current descriptions of the Niquelândia Complex, an example known worldwide of a major layered intrusion, which includes rocks from both the 1.25 Ga (designated Upper Layered Series of the complex) and the 0.79 Ga magmatic systems (designated Lower Layered Series of the complex). Inconsistencies in the nomenclature of these magmatic systems can complicate efforts to establish global correlations. In this review, we attempt to clarify this issue and evaluate the existing data in the context of additional U–Pb data that support previous interpretations (e.g., Pimentel et al., 2004).

2. Regional geology

The Tocantins Province (Fuck et al., 1994) consists of orogenic belts formed during the Neoproterozoic Brasiliano/Pan-African cycle, including the Brasilia belt (Dardenne, 2000) in central Brazil (Fig. 1). These orogenic belts formed during the collision of three major cratonic blocks, the Amazon and São Francisco cratons and the covered Paraná block (Pimentel et al., 2000).

The Barro Alto, Niquelândia and Canabrava complexes are exposed along the internal portion of the Neoproterozoic Brasília Belt (Fig. 1; for a review see Dardenne, 2000; Pimentel et al., 2000). This is a well preserved and exposed accretionary orogenic belt, made of: (i) thick and extensive sedimentary sequences along the western margin of the São Francisco Craton, most of them considered to be passive margin sequences; (ii) a juvenile magmatic arc (the Goiás Magmatic Arc) in the western part of the orogen; (iii) exposure of older terrains made of Archean greenstone-belts and TTG associations, known as the Goiás Archean Block; (iv) a large NNW-oriented metamorphic complex comprising Neoproterozoic granulites and granites (the Anápolis-Itauçu granulites). Final ocean closure and continental collision happened at ca. 630 Ma ago.

3. The layered complexes and associated volcano-sedimentary sequences

The three large layered mafic–ultramafic complexes, forming a 350-km long discontinuous belt, represent one of the most prominent features of the geology of the Neoproterozoic Brasília Belt, in central Brazil (Fig. 1). The intrusions are, from south to north, the Barro Alto, Niquelândia and Canabrava complexes (Fig. 2). To the west, these complexes are in contact with bimodal volcano-sedimentary sequences known, respectively, as the Juscelândia, Indaianópolis and Palmeirópolis sequences (Fig. 2). Both layered complexes and volcano-sedimentary sequences were affected by high-grade metamorphism, progressive from amphibolite facies in the west to granulite facies in the east, and associated tectonism. It has long been accepted that the original igneous stratigraphy of layered complexes and volcanic sequences was partially disrupted by tectonism and high-grade metamorphism (Danni et al., 1982; Ferreira Filho et al., 1992). On the other hand, the remarkable geological similarities between these three complexes and volcano-sedimentary sequences have also been recognized. Even though the petrologic-tectonic interpretations have changed over the years, these similarities were used to suggest originally continuous structures (Wernick and Almeida, 1979; Danni et al., 1982; Ferreira Filho, 1998; Pimentel et al., 2000).

In recent years several studies have reached general agreement regarding major metamorphic, petrological and geochronological aspects of these layered complexes and volcano-sedimentary sequences. These features, which provide a broad geological framework to discuss their magmatic evolution, include:

(a) The layered complexes and volcano-sedimentary sequences were affected by a Neoproterozoic (ca. 760–770 Ma) high-grade (amphibolite to granulite facies) metamorphic event. This fact was first recognized by Ferreira Filho et al. (1994) and has been confirmed by several studies undertaken afterwards (see Pimentel et al., 2004 for a review of ages associated with metamorphism).
(b) The layered complexes comprise two petrologically distinct magmatic systems (Danni et al., 1982; Girardi et al., 1986; Ferreira Filho, 1994; Ferreira Filho et al., 1998; Ferreira Filho and Pimentel, 2000; Pimentel et al., 2004, 2006; Rivalenti et al., 2008). Current interpretation of these different systems include both the existence of two magmatic events with distinct ages and tectonic setting (Pimentel et al., 2004, 2006, submitted for publication) or differences resulting simply from physical–chemical processes operating in a single igneous body (Correia et al., 2007; Rivalenti et al., 2008). This controversy results mainly from different interpretations of geochronological data and will be addressed in the following sections.
(c) Volcano-sedimentary sequences (Palmeirópolis, Indaianópolis and Juscelândia) comprise metamorphosed (mainly greenschist and amphibolite facies) bimodal volcanic rocks. Litho-

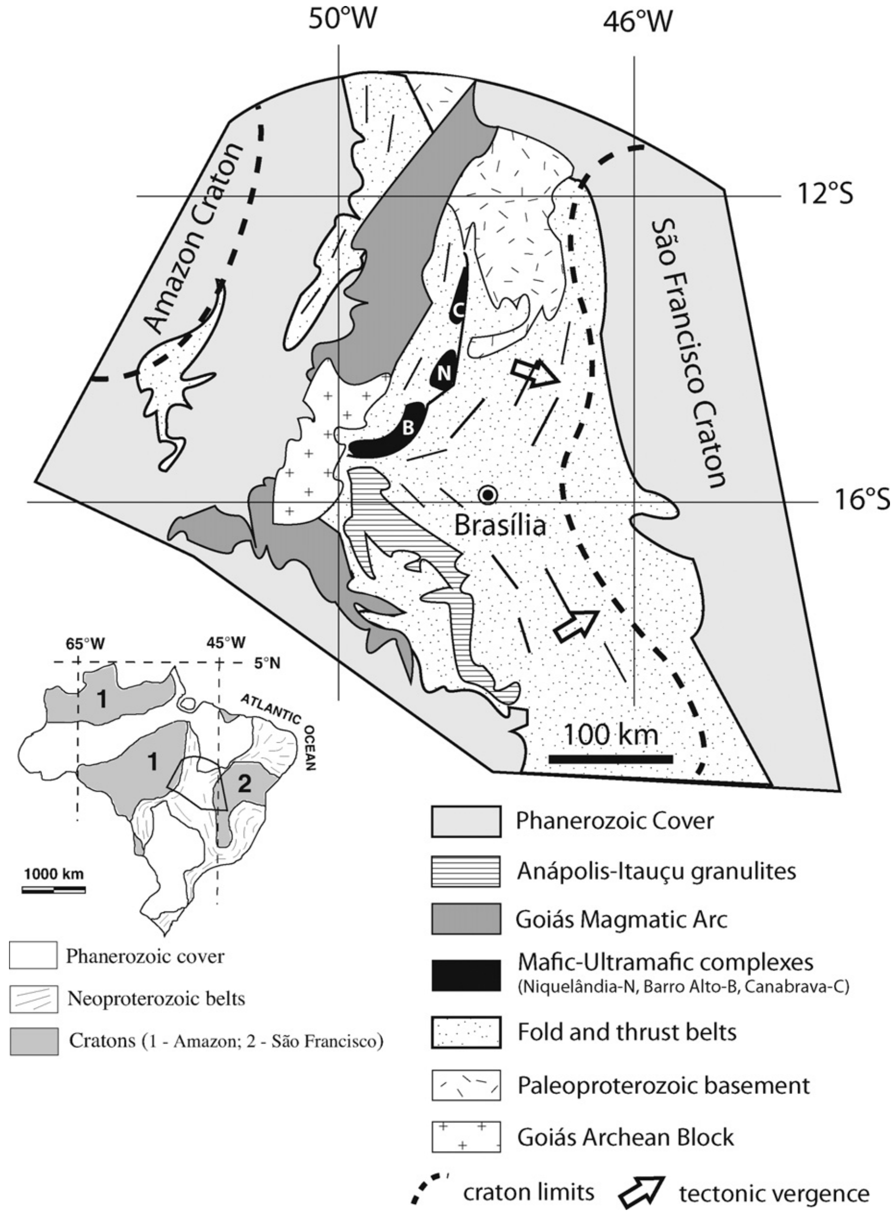

Fig. 1. Regional sketch map of the Tocantins Province in central Brazil.

geochemical characteristics of mafic volcanic rocks are typical of basalts from a mid-ocean ridge (Araujo and Nilson, 1987; Kuyumjian and Danni, 1991); possibly representing early stages of an ocean basin development (Moraes et al., 2003). SHRIMP U–Pb zircon ages are available just for volcanic rocks of the Juscelândia sequence (ca. 1.26–1.27 Ga; e.g., Moraes et al., 2006), but several additional dates with different methods and/or different rock types point to similar ages for the Palmeirópolis and Indaianópolis sequences (Pimentel et al., 2000; Moraes et al., 2006).

(d) The present configuration of the volcano-sedimentary sequences and layered complexes results from later events, probably caused by final ocean closure and continental collision between the São Francisco and Amazonian continents (ca. 0.63 Ga). The final tectonic exhumation of the mafic–ultramafic complexes along the Rio Maranhão Thrust Zone may be attributed to this stage.

Interpretation of the major geologic and stratigraphic features of the layered complexes and associated volcanic sequences has not changed significantly since the review by Pimentel et al. (2000). However, the geochronological database has substantially improved since then, demanding a complete reassessment of magmatic ages and their stratigraphic implications. In the following sections a critical review of the geochronological data will be presented, in order to introduce a revised geological–stratigraphic scheme for these magmatic events.

4. Age dating of layered complexes and volcanic rocks

4.1. Previous geochronological data

Several isotopic studies aimed to determine the timing of igneous crystallization and metamorphism of the layered complexes and associated volcanic sequences in central Brazil produced a large database. These data were revised by Pimentel et al. (2004, 2006, submitted for publication) and Moraes et al. (2006). Even though distinct interpretations regarding the tectonic evolution were adopted by different authors (e.g., Correia et al., 1997, 1999, 2007), when critically reviewed, the data indicate clusters of age

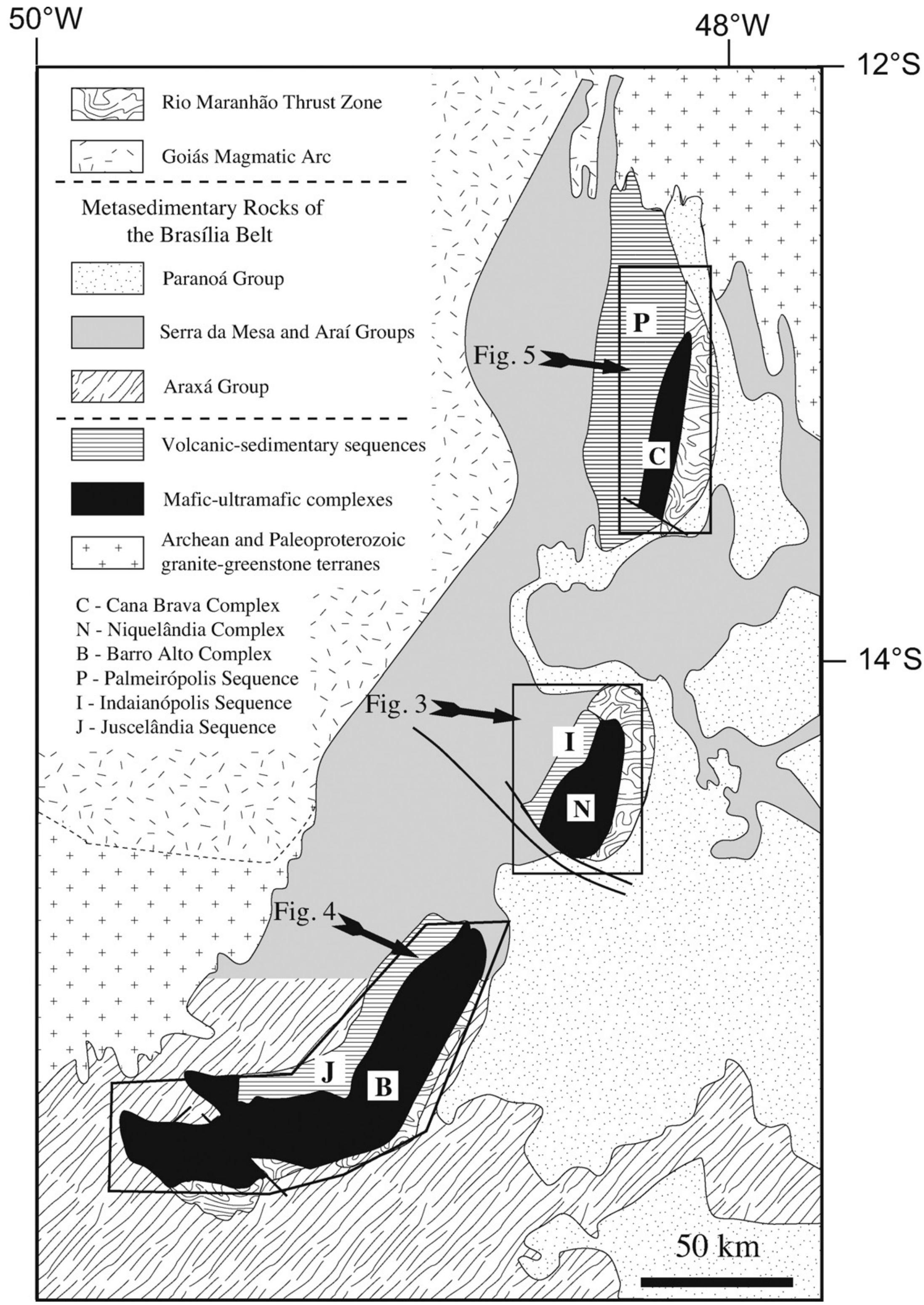

Fig. 2. Distribution of layered intrusions and volcano-sedimentary sequences in central Brazil. The location of Figs. 3–5 is indicated in the map.

values revealing two major magmatic events (ca. 1.25 and 0.79 Ga) and one major metamorphic episode (ca. 760 Ma). The existence of an overprinted metamorphic event at ca 760 Ma is now widely accepted (Ferreira Filho et al., 1994; Pimentel et al., 2004, 2006; Moraes et al., 2006; Correia et al., 2007) and will not be addressed in the present study. Table 1 shows a critically revised dataset of age dating for layered intrusions and associated volcanic sequences in central Brazil. Table 1 contains data collected in outcrops either precisely indicated in maps or known by the authors, providing a consistent geological–petrological framework for interpretations.

The ca. 1.25 Ga age for layered intrusions is well constrained by U–Pb zircon ages in the Serra dos Borges (formerly known as the Upper Series of the Niquelândia Complex) and Serra da Malacacheta complexes (see Table 1 and Figs. 3 and 4 for references and

Table 1
Summary of geochronological data for layered complexes and volcano-sedimentary sequences.

	U–Pb age (Ma)	Sm–Nd isochron (Ma) and $\varepsilon_{Nd}(T)$	Other methods (Ma)
Mesoproterozoic Magmatic association (ca 1.25 Ga)			
Layered Complex			
Serra dos Borges	1245 ± 4.2[f]	1347 ± 69 (+4.1)[a]	
	1248 ± 23[b]	1352 ± 99 (+4.9)[a]	
Serra da Malacacheta	1267 ± 9[e]		1266 ± 17 (Rb–Sr isochron)[i]
	1280 ± 14[e]		
	1286 ± 1[g]		
	1302 ± 3[g]		
Volcano-sedimentary sequence			
Indaianópolis	1299 ± 3[g]		
Juscelândia	1277 ± 15[d]		
	1263 ± 15[d]		
	1266 ± 17[e]		
Palmeirópolis		1242 ± 92 (+4.9)[k]	1170–1270 (Pb–Pb galena)[j]
Neoproterozoic Magmatic Association (ca 0.79 Ga)			
Layered Complex			
Niquelândia	799 ± 6[b]	767 ± 38 (−5.8)[c]	
	797 ± 10[c]		
	794 ± 6[h]		
Barro Alto	796 ± 2[g]		
Canabrava	799 ± 1[k]		
Canabrava	782 ± 3[k]		

References
[a] Ferreira Filho and Pimentel (2000).
[b] Pimentel et al. (2004).
[c] Pimentel et al. (2006).
[d] Moraes et al. (2006).
[e] Suita et al. (1994).
[f] Pimentel et al. (submitted for publication).
[g] Correia et al. (1999).
[h] Ferreira Filho et al. (1994).
[i] Fuck et al. (1989).
[j] Araujo et al. (1996).
[k] This study.

location of dated samples). U–Pb ages of samples from the Serra dos Borges complex are slightly younger than those from the Serra da Malacheta complex (Table 1), indicating the existence of intrusions with different ages in the Mesoproterozoic. U–Pb zircon data of rocks from the Indaianópolis and Juscelândia volcano-sedimentary sequences indicate crystallization ages close to those obtained for Mesoproterozoic layered complexes (Table 1). These suggest that the ca. 1.25 Ga magmatic event is represented by layered intrusions and coeval volcanic sequences.

Neoproterozoic ages for the Serra dos Borges and Serra da Malacacheta complexes were suggested by Correia et al. (2007) based on U–Pb (SHRIMP) zircon data of anorthosites. Petrographic descriptions provided by the authors indicate that samples selected for age dating are highly recrystallized amphibolite facies meta-anorthosites (this information was confirmed by field check of the sampled outcrops by C.F. Ferreira Filho). Dated zircon crystals are pale-gray with rounded edges and just a few grains show thin overgrowths and oscillatory growth zonation. U–Pb results for these samples indicate scattered ages for zircons from the Serra da Malacacheta (between 733 ± 27 and 799 ± 36 Ma) and Serra dos Borges (between 761 ± 22 and 977 ± 25 Ma) meta-anorthosites. These results suggest that the authors dated mainly metamorphic (ca. 760–770 Ma) or highly reset inherited zircons.

The ca. 0.79 Ga age for layered intrusions is well constrained by U–Pb zircon ages in the Niquelândia and Barro Alto complexes (see Table 1 and Figs. 3 and 4 for references and location of dated samples). Several published conventional (Ferreira Filho et al., 1994; Suita et al., 1994) and SHRIMP (Correia et al., 1996) U–Pb zircon data indicating scattered and older (1.6–2.0 Ga) magmatic ages for the Niquelândia and Barro Alto complexes are now interpreted as resulting from inherited zircon grains. Inheritance of older zircons was demonstrated by SHRIMP U–Pb zircon studies supported by cathodo-luminescence imagery in samples previously dated by conventional methods in the Niquelândia Complex (Pimentel et al., 2004). Robust lithogeochemical data indicate the contamination of mafic–ultramafic rocks with crustal rocks (Ferreira Filho et al., 1998; Rivalenti et al., 2008). This contamination with old crustal material resulted in poorly defined Sm–Nd and Re–Os whole-rock isochrons, as well as negative $\varepsilon_{Nd}(T)$ values (see Pimentel et al., 2004 for discussion). A Sm–Nd isochron of 767 ± 38 Ma was obtained from a whole rock and igneous mineral concentrates of a gabbronorite from the Niquelândia Complex (Pimentel et al., 2004). The $\varepsilon_{Nd}(T)$ value of −5.8 for this Sm–Nd isochron is compatible with contamination of the original magma by older crustal material, as previously discussed.

4.2. New geochronological data

Of the three-layered complexes in central Brazil, the Canabrava intrusion (Fig. 5) is the most poorly known in terms of its geochronology. In the present study we discuss new U–Pb TIMS zircon ages for mafic rocks of the Canabrava Complex, as well as preliminary Sm–Nd whole-rock isochron for metabasalts of the Palmeirópolis sequence (see Fig. 5 for location of dated samples).

Eight samples of fine-grained amphibolites of the Palmeirópolis volcano-sedimentary sequence were selected for Sm–Nd isotopic analysis and the analytical results are in Table 2. Sm–Nd isotopic analyses followed the method described by Gioia and Pimentel (2000) and was carried out at the Geochronology Laboratory of the University of Brasília. The analyses resulted in an isochron indi-

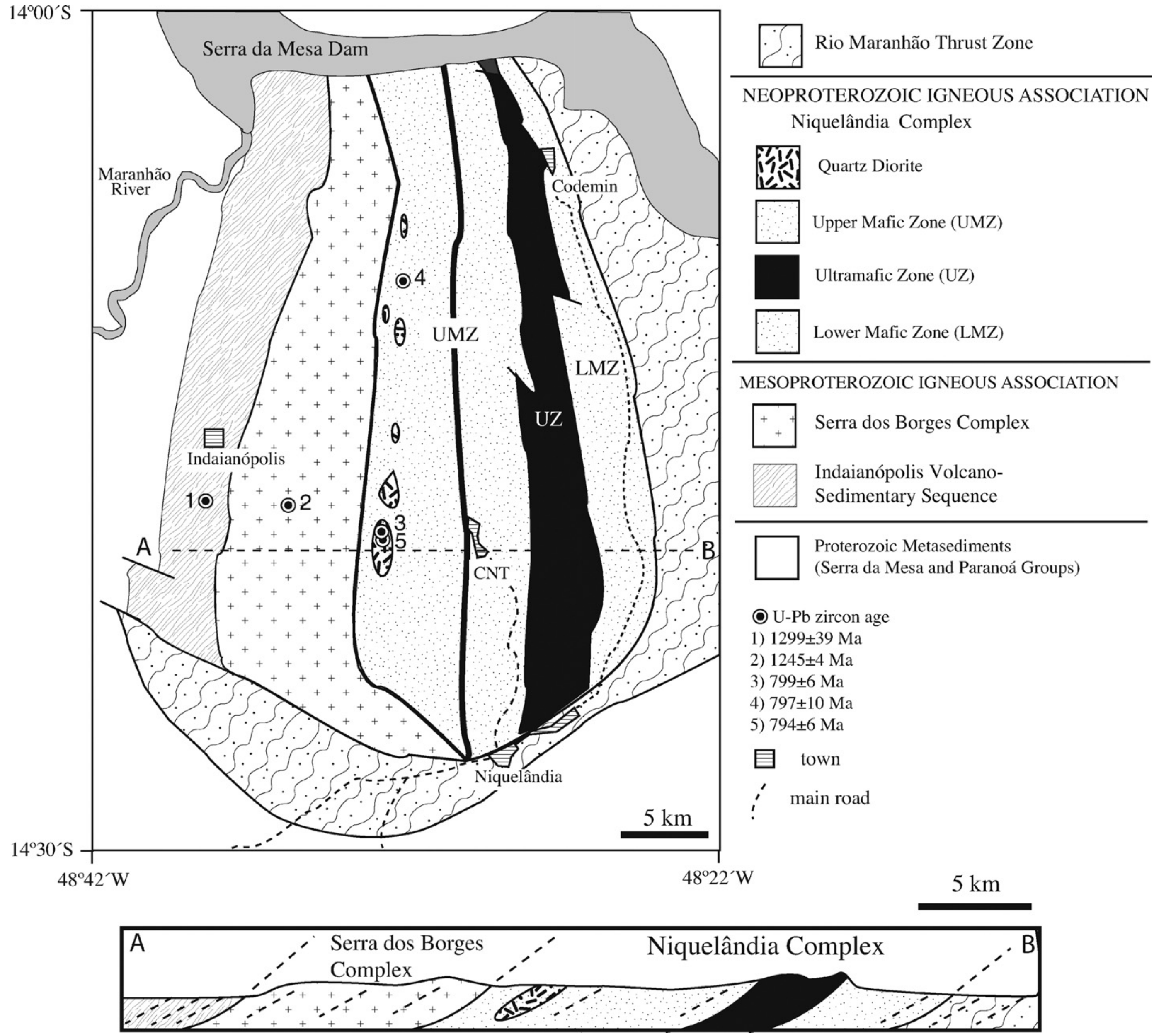

Fig. 3. Geological sketch map and geological section (A and B) of the Niquelândia region. See Table 1 for references of U–Pb zircon ages located in the map.

cating an age of ca. 1.24 Ga and an $\varepsilon_{Nd}(T)$ value of +4.9 (Fig. 6A). The data are very similar to those reported for metavolcanic rocks of the Juscelândia volcano-sedimentary sequence and also indicate derivation of the original magma from a depleted mantle source.

For ID-TIMS U–Pb analyses, zircon fractions were dissolved in concentrated HF and HNO_3 ($HF{:}HNO_3 = 4{:}1$) using microcapsules in Parr-type bombs. Analytical procedures, data reduction and age calculations of these analyses followed the method described by Pimentel et al. (2006). Two samples of the Canabrava mafic–ultramafic complex were selected for the U–Pb zircon analyses. Sample locations are indicated in the map of Fig. 5 and analytical data are in Table 3.

Sample CANA2 is a quartz diorite located at the westernmost portion of the complex (coordinates 791796S and 8508999W, DATUM Corrego Alegre). This medium-grained rock consists of orthopyroxene, clinopyroxene, plagioclase and minor interstitial quartz and brownish amphibole. Accessory minerals include apatite and prismatic zircon crystals. Three fine-grained (ranging from ca. 150 to 250 μm) prismatic zircon crystals were selected from a homogeneous population of mainly fine-grained prismatic crystals. Investigated zircon grains are colorless euhedral crystals with no cracks and inclusions.

Sample CANA7 is a typical gabbronorite from the eastern part of the intrusion (coordinates 801621S and 8510927W, DATUM Cor-

Table 2
Sm–Nd isotopic data for whole-rock samples of amphibolites from the Palmeirópolis volcano-sedimentary sequence.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm (2SE)$
SY PP 146	4.211	12.88	0.1978	0.512921 (12)
SY PP 131B	3.532	11.69	0.1828	0.512753 (08)
SY PP 142	3.196	10.90	0.1772	0.512753 (09)
SY PP 143	3.472	10.51	0.1998	0.512911 (12)
SY PP 22A	3.177	11.44	0.1678	0.512645 (10)
SY PP 147	8.025	27.23	0.1781	0.512764 (06)
SY PP 137	3.373	11.65	0.1753	0.512711 (05)
SY PP 109b	3.401	13.69	0.1501	0.512510 (08)

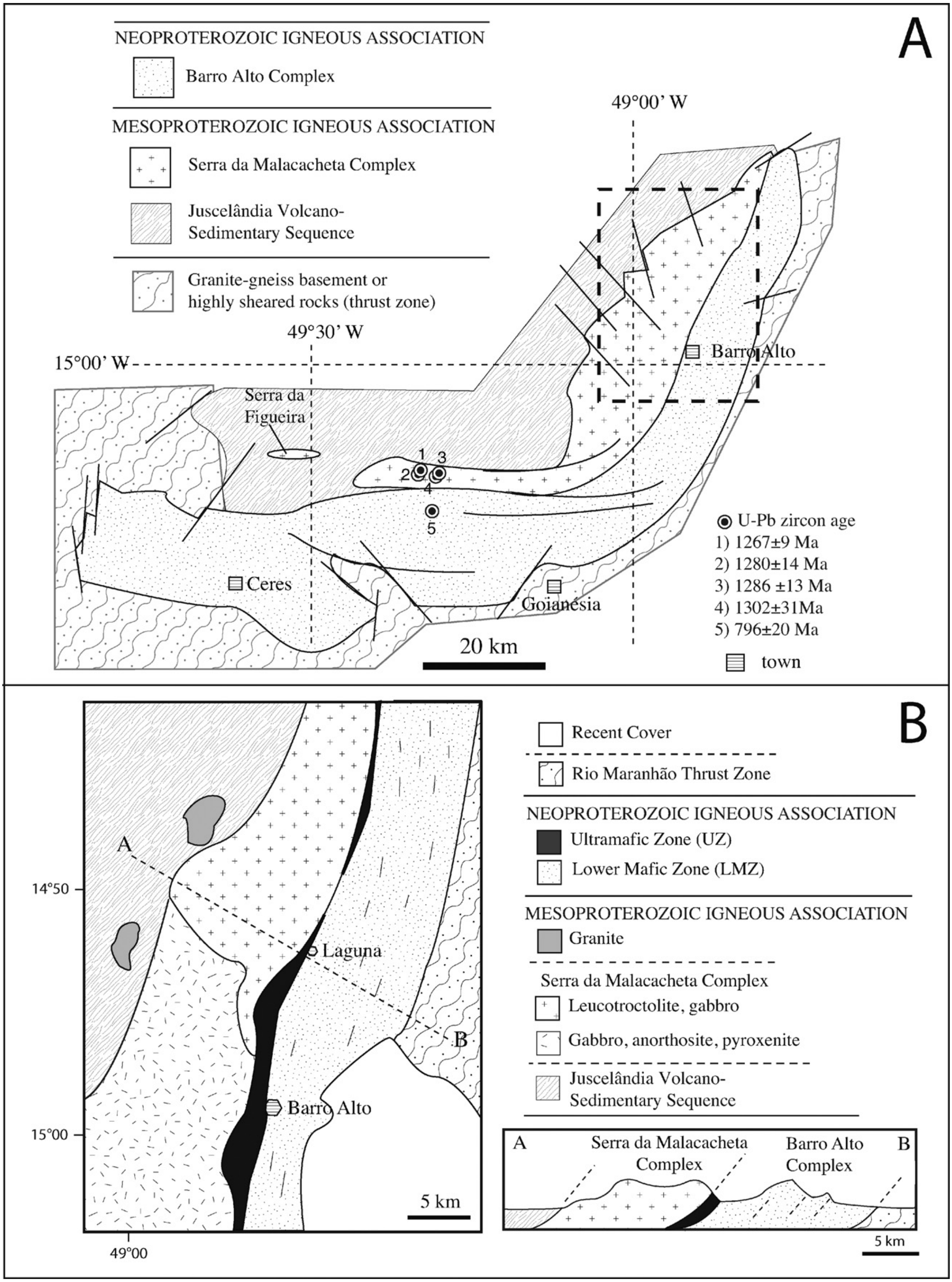

Fig. 4. (A) Geological sketch map of the Ceres-Goianésia-Barro Alto region. See Table 1 for references of U–Pb zircon ages located in the map. (B) Geological sketch map and geological section (A and B) of the Barro Alto region (dashed rectangle in the upper figure).

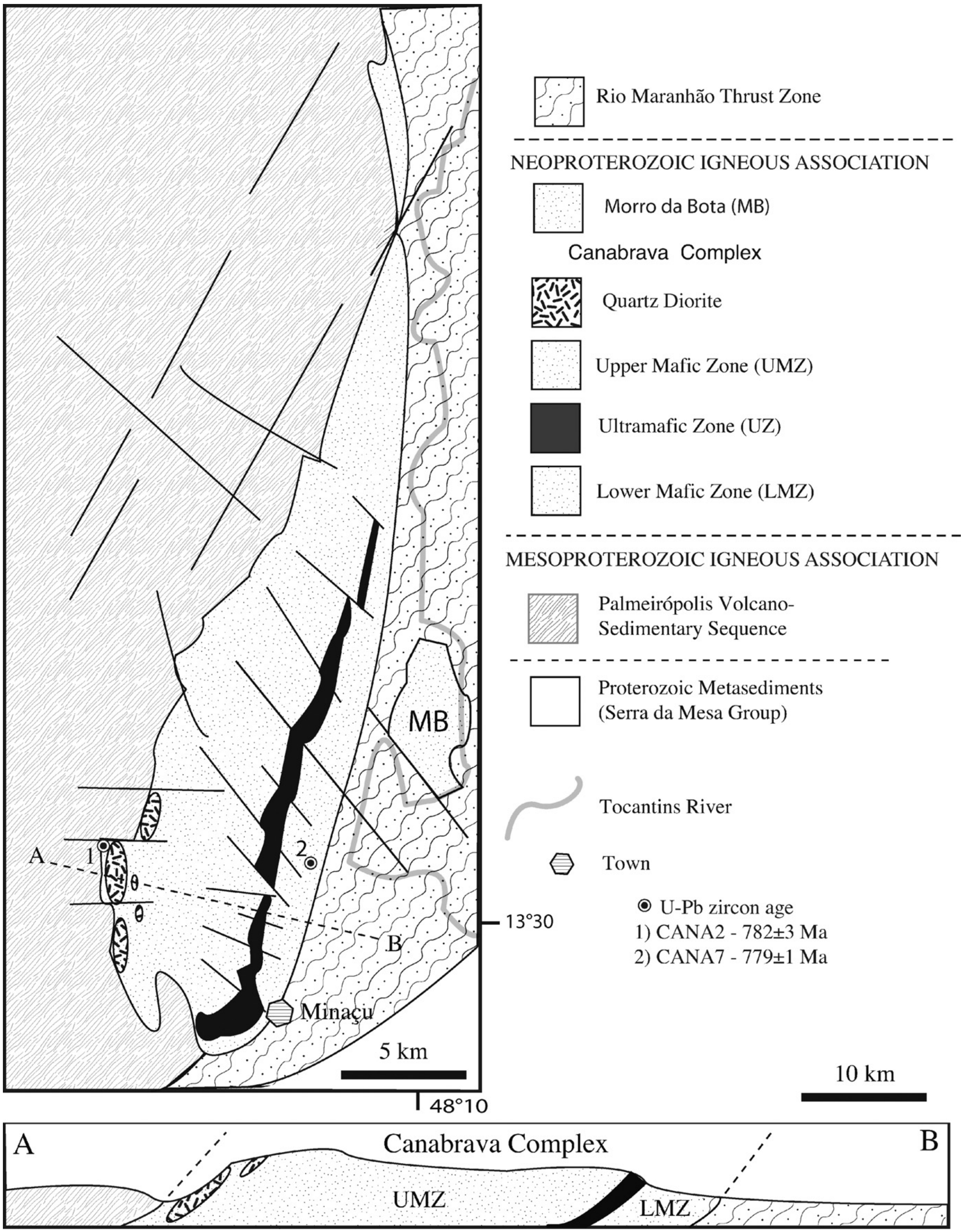

Fig. 5. Geological sketch map and geological section (A and B) of the Minaçu region. See Table 1 for references of U–Pb zircon ages located in the map.

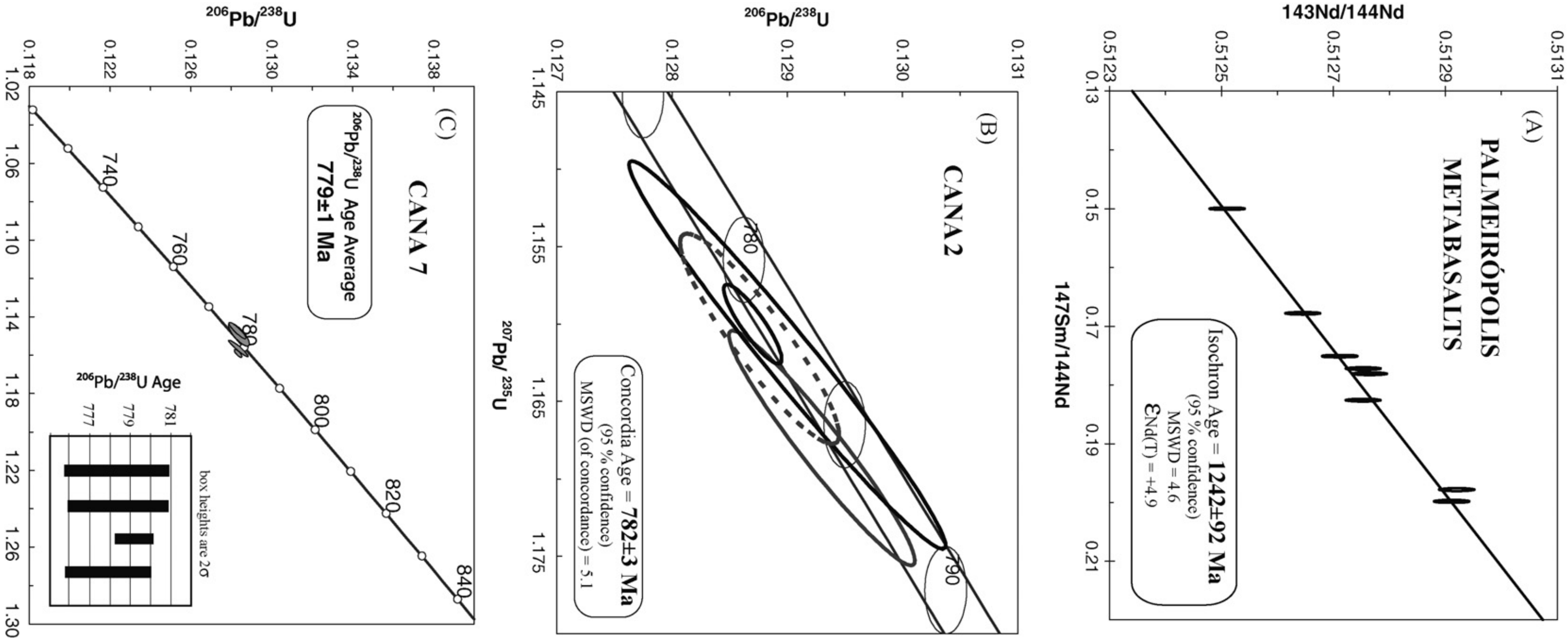

Fig. 6. (A) Sm–Nd whole-rock isochron for fine-grained amphibolites of the Palmeirópolis volcano-sedimentary sequence. (B) U–Pb zircon age of a diorite sample of the Canabrava Complex. (C) U–Pb zircon age of a gabbronorite sample of the Canabrava Complex. Data-point error ellipses are 2σ.

Table 3
U–Pb isotopic data for mafic rocks of the Canabrava layered complex.

Sample fraction	Size (mg)	U (ppm)	Pb (ppm)	Th (ppm)	U/Th	$^{206}Pb/^{204}Pb$	$^{*207}Pb/^{235}U$	2SE (%)	$^{*206}Pb/^{238}U$	2SE (%)	Correl. coeff. (rho)	$^{207}Pb/^{*206}Pb$	2SE (%)	6/8 Age (Ma)	7/5 Age (Ma)	7/6 Age (Ma)
CANA2																
V	0.071	72.98	9.66	15.33	0.21	7471	1.168	0.53	0.1293	0.51	0.96	0.0655	0.14	784 ± 4.0	786 ± 4.2	789 ± 1.1
X	0.041	85.51	11.24	26.54	0.31	5115	1.160	0.18	0.1287	0.16	0.88	0.0653	0.08	781 ± 1.2	782 ± 1.4	785 ± 0.6
R	0.038	88.55	11.82	28.64	0.32	878	1.162	0.88	0.1290	0.87	0.98	0.0653	0.16	782 ± 6.8	783 ± 6.9	785 ± 1.3
CANA7																
K	0.059	78.58	13.45	18.44	0.23	2676	1.148	0.43	0.1281	0.33	0.79	0.0648	0.26	779 ± 2.6	776 ± 3.3	770 ± 2.0
L	0.050	51.61	8.64	21.76	0.42	2002	1.157	0.32	0.1282	0.31	0.96	0.0654	0.09	778 ± 2.4	781 ± 2.5	787 ± 0.7
M	0.083	103.50	16.81	13.11	0.12	6687	1.162	0.15	0.1281	0.12	0.80	0.0655	0.09	780 ± 0.9	783 ± 1.2	792 ± 0.7
N	0.103	56.40	8.40	10.56	0.19	3359	1.146	0.29	0.1283	0.27	0.91	0.0648	0.12	778 ± 2.1	775 ± 2.2	767 ± 0.9

rego Alegre). This medium-grained adcumulate rock consists of orthopyroxene, clinopyroxene and plagioclase. Four relatively large (ranging from ca. 250 to 300 μm) prismatic zircon crystals were selected from a population of mainly fine-grained (<200 μm) crystals or fragmented grains. Investigated zircon grains are all colorless and euhedral crystals with no cracks and inclusions.

Zircons from samples CANA2 and CANA7 show morphological features that are typical of igneous zircons in layered mafic rocks. They resemble zircon crystals from similar rocks dated in the Niquelândia Complex (Pimentel et al., 2004, 2006). Three zircon analyses of sample CANA2 are concordant and indicated a concordia age of 782 ± 3 Ma (Fig. 6B). Four zircon crystals from sample CANA7 yielded a discordia with a weighted average $^{206}Pb/^{238}U$ age of 779 ± 1 Ma (Fig. 6C).

The new geochronological data presented here reinforce previous studies which have suggested that the eastern part of the large mafic intrusions in Goiás are Neoproterozoic, having crystallized at ca. 0.79 Ga, and that the volcano-sedimentary sequences to the west are part of a different association formed during the Mesoproterozoic at ca. 1.25 Ga. The concordia age of sample CANA2 is however slightly younger (ca. 10 Ma) than those obtained from the Niquelândia and Barro Alto complexes.

5. The Mesoproterozoic (ca. 1.25 Ga) igneous association

The Mesoproterozoic igneous association consists of large layered intrusions and associated bimodal volcanic sequences outcropping in central Brazil. Layered intrusions with olivine plus plagioclase cumulates predominate, with abundant troctolite and leucotroctolite, as well as olivine gabbro, gabbro, anorthosite and pyroxenite. Because these intrusions were formerly considered by some authors (Girardi et al., 1986; Ferreira Filho et al., 1992) to represent the upper and more fractionated part of the 0.79 Ga intrusion, a misleading nomenclature (Upper Series) was developed. In this review we restored old terms (Serra dos Borges Complex, see Danni et al., 1982 for original references) to rename these intrusions.

5.1. Serra dos Borges Complex

The Serra dos Borges Complex (Fig. 3) corresponds to what was previously described as the Gabbro-Amphibolite Zone (Girardi et al., 1986) or Upper Layered Series (Ferreira Filho, 1994; Ferreira Filho et al., 1998), interpreted as the upper part of the Niquelândia Complex. The geology and petrology of the Serra dos Borges Complex is described in several papers (Girardi et al., 1986; Ferreira Filho et al., 1992, 1998; Ferreira Filho and Pimentel, 2000), and only a brief summary is presented here.

This large (40 km long and up to 10 km wide) mafic-layered intrusion has tectonic contacts with the Niquelândia Complex to the east and the Indaianópolis sequence to the west. Ductile deformation and metamorphic recrystallization are heterogeneous through the complex, being pervasive along major fault zones where amphibolites (including diopside- and/or garnet-bearing amphibolite) and banded meta-anorthosite were formed. Primary rocks consist mainly of interlayered "gabbroic" rocks (gabbro, olivine gabbro, olivine gabbronorite) and "anorthositic" rocks (anorthosite, leucotroctolite, leuco-olivine-gabbro), with rare clinopyroxenite and massive ilmenite magnetite. Even though layering occurs on a scale ranging from that of an outcrop up to a few hundreds of meters-wide, no stratigraphic markers or zones were mapped along strike throughout the complex. Description of large continuous outcrops and drill holes indicate the progressive transition with fractionation from olivine + plagioclase cumulate, to olivine + plagioclase + clinopyroxene cumulate, to plagioclase + clinopyroxene + ilmenite/magnetite cumulate. Orthopyroxene does not occur as a cumulus mineral, and occurs as interstitial (intercumulus) mineral or forming reaction coronas between cumulus olivine and plagioclase (Fornoni Candia et al., 1989). Petrographic data suggest the following crystallization order for the parental magma:

olivine + plagioclase
olivine + plagioclase + clinopyroxene
plagioclase + clinopyroxene
plagioclase + clinopyroxene + ilmenite/magnetite

The crystallization sequence of the Serra dos Borges complex is characterized by abundant olivine + plagioclase cumulates. This feature, together with the absence of *liquidus* orthopyroxene, is consistent with crystallization from silica undersaturated magmas (possibly an olivine tholeiite). This crystallization trend resembles those observed in some of the layered intrusions of the Duluth Complex (Miller and Ripley, 1996). The compositional variation of olivine (Fo 63–76) and the absence of significant amounts of ultramafic cumulates suggest a moderately primitive parental magma. Olivine and pyroxene mineral compositions do not display a distinct Fe-enrichment trend suggesting crystallization under high oxygen-fugacity conditions (Ferreira Filho et al., 1998). This interpretation is supported by accessory Fe-Ti oxides as well as interlayered massive ilmenite–magnetite bodies. Positive $\varepsilon_{Nd(1250Ma)}$ values coupled with low contents of incompatible trace elements and LREE-depleted mantle-normalized-REE patterns for mafic cumulates of the Serra dos Borges complex suggest an origin from a depleted mantle source (Ferreira Filho et al., 1998; Ferreira Filho and Pimentel, 2000; Rivalenti et al., 2008).

5.2. Serra da Malacacheta Complex

The Serra da Malacheta complex (Fuck et al., 1981; Danni et al., 1984), located mainly between the Barro Alto layered intrusion and the Juscelândia volcanic-sedimentary sequence (Fig. 4), includes heterogeneous plutonic rocks, as well as their deformed and metamorphosed products. In the southern EW-trending section of the complex the stratigraphy and crystallization sequence of plutonic rocks are poorly understood due to pervasive deformation and metamorphic recrystallization. Several studies developed in the southern region produced detailed maps and a robust tectonic-metamorphic framework for the Serra da Malacacheta complex (Fuck et al., 1981; Danni et al., 1984; Moraes and Fuck, 1994, 1999, 2000). In this region, heterogeneously transformed mafic plutonic rocks were named as Cafelândia amphibolite (Moraes and Fuck, 1994). A ca. 10 km long and 2 km wide mafic intrusion in the Juscelândia volcano-sedimentary sequence, known as Serra da Figueira body (Danni et al., 1984; see Fig. 4A for location), has partially preserved plutonic igneous rocks within fine-grained amphibolite (metabasalt). The Serra da Figueira body consists of olivine gabbro and gabbro, suggesting the fractionation from olivine + plagioclase cumulates at the base, to olivine + plagioclase + clinopyroxene cumulate, and plagioclase + clinopyroxene cumulate in the top. This body is considered to represent a discrete mafic pluton of the Serra da Malacheta complex, intrusive into the Juscelândia sequence (Danni et al., 1984).

Primary magmatic structures are better preserved in the NS-trending northern part of the Serra da Malacacheta complex (Fig. 4), where cumulate rocks outcrop over large areas. In this region two distinct sequences of heterogeneously transformed mafic and ultramafic plutonic rocks were mapped. Interlayered leucotroctolite, olivine leucogabbro and leucogabbro predominate to the north and west of the town of Laguna. Leucotroctolite is the most abundant rock type, and are frequently characterized by reaction coronas between olivine and plagioclase crystals. Gabbroic rocks may result from a larger amount of interstitial clinopyroxene, usually consisting of irregular pods with clinopyroxene oikocrysts, or from the onset of cumulus clinopyroxene. Gabbroic rocks with cumulus clinopyroxene have ilmenite and magnetite as frequent accessory minerals. The crystallization sequence, characterized by progressive transition from olivine + plagioclase cumulate, to olivine + plagioclase + clinopyroxene cumulate, to plagioclase + clinopyroxene + ilmenite/magnetite cumulates, is identical to the one described for the Serra dos Borges Complex. Interlayered clinopyroxenite, gabbro, leucogabbro and anorthosite predominate to the west of the town of Barro Alto. This crystallization sequence, characterized by repeated cycles of clinopyroxene cumulate (clinopyroxenite) and clinopyroxene + plagioclase cumulate (gabbro), is different from the one described west of Laguna and for the Serra dos Borges Complex, suggesting that the 1.25 Ga igneous association includes different discrete mafic layered intrusions.

Systematic studies of cryptic variation are not available for the Serra da Malacacheta Complex. Olivine and clinopyroxene compositions (Suita, 1996) are similar to those obtained for the Serra dos Borges Complex, indicating moderately primitive compositions. Available geochemical data indicate low contents of incompatible trace elements and LREE-depleted REE patterns for mafic cumulates (Suita, 1996), suggesting an origin from depleted mantle sources. This interpretation is supported by the $\varepsilon_{Nd(1270Ma)}$ value +4.2 for the Cafelândia amphibolite (Moraes et al., 2003).

5.3. Volcano-sedimentary sequences

The Palmeirópolis, Indaianópolis and Juscelândia volcano-sedimentary sequences (Fig. 2) form three tectonically separated units sharing several remarkable similarities in their stratigraphic sequence, metamorphism and geochemistry of volcanic rocks. These bimodal volcanic sequences were revised by Pimentel et al. (2000), and just a brief updated summary is presented here (an extensive list of references is provided by Pimentel et al., 2000).

The Juscelândia volcano-sedimentary sequence is ca. 90 km long and up to 20 km wide (Figs. 2 and 4). This sequence comprises metamorphosed bimodal volcanic rocks, pelitic and chemical sedimentary rocks and intrusive or sub-volcanic granites. Mafic volcanic rocks (metabasalts) associated with metachert predominate at the base of the volcanic pile. They are mainly transformed into fine-grained amphibolites, but pillowed basalts were locally preserved. The intermediate zone of the volcano-sedimentary sequence has felsic volcanic rocks (fine-grained quartz-feldspathic gneiss) whereas metapelitic sedimentary rocks (mica schists) predominate in the upper zone. Metamorphic conditions are mainly amphibolite and greenschist facies (Moraes and Fuck, 1994, 1999, 2000), with granulite facies conditions described locally (Ferreira Filho et al., 1999). Geochemical characteristics of mafic and felsic rocks suggest a transitional setting between a continental rift and an ocean basin as the most likely tectonic setting of volcanism and sedimentation of the Juscelândia sequence (Moraes et al., 2003).

The Indaianópolis volcano-sedimentary sequence (Fig. 3) is ca. 40 km long and up to 12 km wide. The lower unit of the volcanic pile comprises fine-grained amphibolite (metabasalt) intercalated with minor metachert and metapelites (garnet mica schist). The intermediate unit has felsic to intermediate metatuff (fine-grained gneiss and schist) intercalated with amphibolite and amphibole schist. The upper unit consists of pelitic and chemical metasedimentary rocks. Metamorphic conditions are mainly amphibolite and greenschist facies. Intrusive and sub-volcanic granites occur throughout the volcano-sedimentary pile. Metabasalts of the lower unit have tholeiitic composition similar to mid-ocean ridge basalts.

The Palmeirópolis volcano-sedimentary sequence (Figs. 2 and 5) underlies an area of about 2500 km^2 (ca. 80 km long and up to 35 km wide). This is the most extensive volcano-sedimentary sequence and hosts volcanogenic Zn–Cu massive sulfide deposits associated with hydrothermally altered metabasalts (Araujo et al., 1996). The lower unit, in the eastern part of the sequence, is mainly composed of fine-grained amphibolite (metabasalt) interlayered with minor metamorphosed banded iron formation and chert. Primary igneous structures such as pillows and relict phenocrysts are rarely preserved. The intermediate unit has felsic to intermediate metavolcanic rocks (mainly quartz–feldspathic schist), whereas the upper unit consists of pelitic and chemical metasedimentary rocks. Metamorphic conditions are mainly of amphibolite and greenschist facies. Intrusive and sub-volcanic granites predominate in the lower and intermediate unit. Metabasalts of the lower unit have tholeiitic composition similar to mid-ocean ridge basalts. Both E-MORB and N-MORB-type basalts exist, and the geochemical characteristics of mafic rocks suggest, similarly to the Juscelândia Sequence, a transitional setting from continental rift to ocean basin (Araujo, 1996).

6. The Neoproterozoic (ca. 0.79 Ga) igneous association

The Neoproterozoic igneous association consists of three separated large layered intrusions (Niquelândia, Barro Alto and Canabrava). The original igneous stratigraphy of these complexes has been partially disrupted by intense deformation associated with high-grade metamorphism, although original igneous textures and structures are frequently preserved (Danni et al., 1982; Ferreira Filho et al., 1992). Despite intense tectonism, several striking geological similarities between the three separate bodies have been used to suggest that they originally constituted a single continuous magmatic structure (Ferreira Filho, 1998). The better studied and exposed Niquelândia Complex will be considered in more detail, while key features of the Barro Alto and Canabrava complexes will be correlated to those described for Niquelândia. A schematic stratigraphic correlation between these layered complexes is provided for reference in Fig. 7.

6.1. Niquelândia Complex

The Niquelândia Complex (Fig. 3) corresponds to what was previously described as the Lower Sequence (Girardi et al., 1986) or Lower Layered Series (Ferreira Filho, 1994, 1998) of a larger layered intrusion. The geology and petrology of the Niquelândia Complex is described in several papers (Girardi et al., 1986; Ferreira Filho et al., 1992, 1998; Ferreira Filho and Pimentel, 2000; Rivalenti et al., 2008), and a summary of main aspects will be considered in this review. The southern and eastern limits of the Niquelândia Complex are marked by an important west-dipping shear zone (the Rio Maranhão Thrust Zone in Fig. 3) and, to the west, the complex is in tectonic contact with the Serra dos Borges Complex. The stratigraphy of the Niquelândia Complex is displayed by NS-trending layers with westward dip (Fig. 3).

The stratigraphy (Fig. 8) consists of three major zones mapped throughout the intrusion. The Lower Mafic Zone (LMZ) consists mainly of gabbronorite with minor websterite, orthopyroxenite and harzburgite. The LMZ lies along the eastern portion of the intrusion and is considered to be an unusually thick basal border group of the Niquelândia layered complex. This interpretation is supported by the stratigraphic position of the LMZ as well as by the relatively primitive nature of its gabbroic rocks, when compared with the Upper Mafic Zone (UMZ). The upper contact of

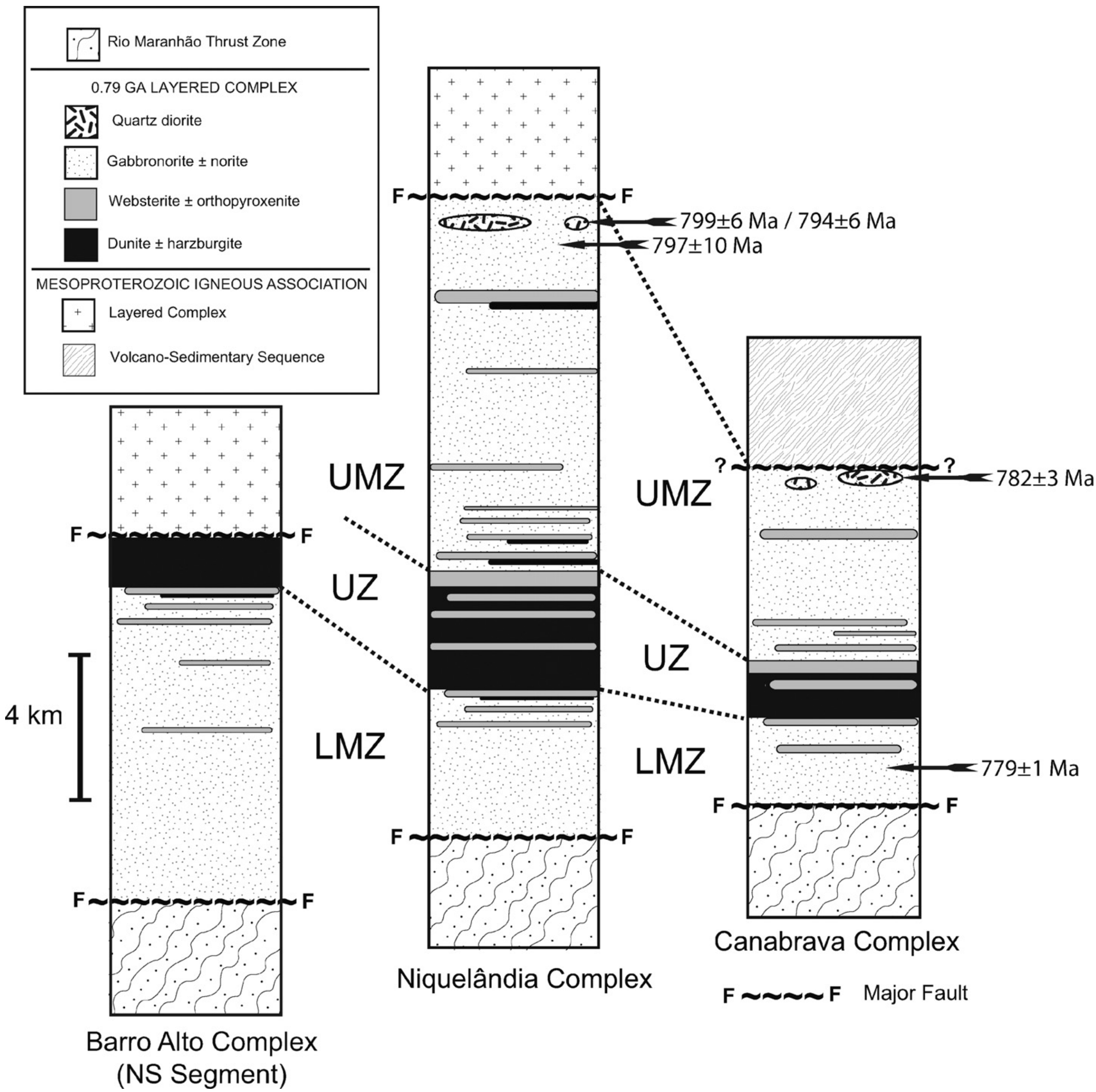

Fig. 7. Stratigraphic correlation between Niquelândia, Barro Alto and Canabrava layered complexes. See Table 1 for references of indicated U–Pb zircon ages.

the LMZ with the Ultramafic Zone (UZ) is gradational and characterized by a progressive increase of interlayered ultramafic rocks. The UZ consists mainly of interlayered dunite and harzburgite at the base, followed by interlayered dunite, harzburgite, orthopyroxenite, websterite and minor gabbronorite to the top. The UMZ consists mainly of gabbronorite with interlayered websterite and minor dunite and harzburgite. Interlayered ultramafic rocks are abundant in the lower part of the UMZ, becoming progressively less frequent toward the top. Quartz dioritic bodies and associated granitic pods occur at the uppermost part of the UMZ. Quartz diorites have accessory apatite and zircon, and frequently have enclaves of mafic rocks (mainly gabbronorite but also websterite) or xenoliths of crustal sialic rocks (possibly metasediments). Quartz dioritic and associated granitic bodies are interpreted to be highly contaminated melt pods resulting from partial melting of the roof in the upper part of the magma chamber. This interpretation, supported by the stratigraphic distribution of these quartz dioritic bodies, was also indicated by isotope studies. U–Pb zircon ages indicate magmatic crystallization at 0.79 Ga for the quartz diorites and older ages (including ca. 1.25 Ga) for xenoliths and inherited zircons (Pimentel et al., 2004, 2006).

Cyclic layering and cryptic variations provide constraint on the processes that operated during the formation of the Niquelândia Complex. Cyclic units consisting of successive layers of dunite, harzburgite, orthopyroxenite, websterite and gabbronorite occur throughout the stratigraphy. This same sequence is displayed in drill holes intercepting different stratigraphic horizons of all three major zones. Besides providing frequent facing criteria for layered

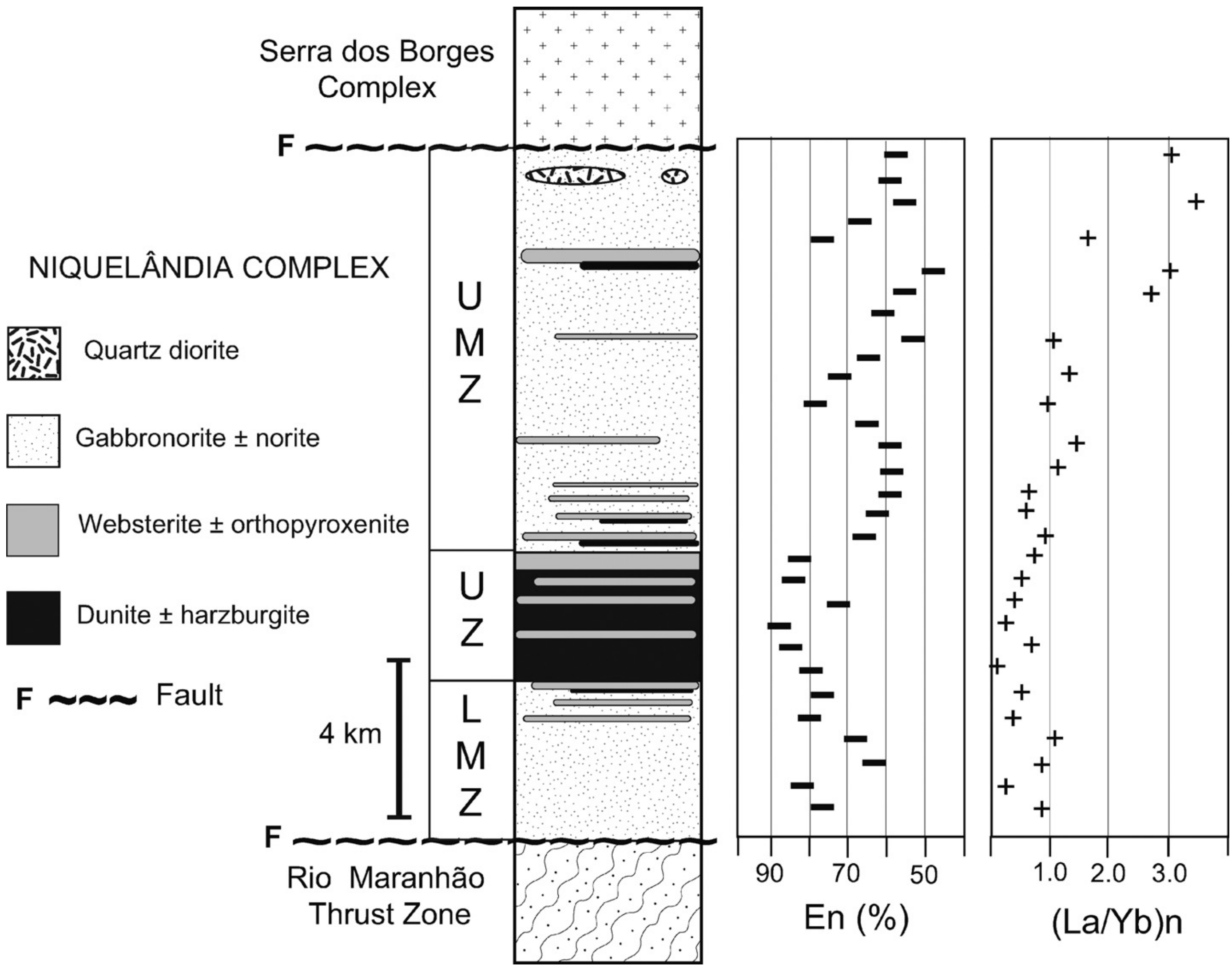

Fig. 8. Stratigraphy of the Niquelândia Complex. The diagram includes variation of orthopyroxene compositions and mantle-normalized La/Yb ratios for gabbronorite throughout the stratigraphy (modified from Ferreira Filho, 1994).

rocks, these repeated cyclic units indicate the evolution of the Niquelândia Complex by fractional crystallization in a frequently replenished magma chamber. Cyclic units of the Niquelândia Complex show the transition from olivine + chromite cumulate (dunite), to orthopyroxene + chromite cumulate (orthopyroxenite), to orthopyroxene + clinopyroxene cumulate (websterite), and orthopyroxene + clinopyroxene + plagioclase (gabbronorite). In the most fractionated gabbronorite, the orthopyroxene is replaced by Ca-poor clinopyroxene (pigeonite), indicated by orthopyroxene crystals with two non-orthogonal sets of exsolution lamellae (inverted pigeonite). These data suggest the following crystallization order for the parental magma:

olivine + chromite
orthopyroxene + chromite
orthopyroxene + clinopyroxene
orthopyroxene + clinopyroxene + plagioclase
pigeonite + clinopyroxene + plagioclase

This trend of crystallization is similar to what is described for several cratonic layered intrusions, including the Great Dyke (Wilson, 1982). Cryptic variations of orthopyroxene, clinopyroxene and olivine in the Niquelândia Complex provide a clear picture of the upward fractionation trend in the UZ and LMZ (Ferreira Filho et al., 1996, 1998; Medeiros and Ferreira Filho, 2001). The composition of the most magnesian olivine (Fo 92–93) indicates a distinctively primitive parental magma of the Niquelândia Complex. Pyroxene compositions of gabbronorite from the UMZ show a progressive Fe-enrichment trend toward the top and marked compositional reversals (Fig. 8).

Geochemical and isotopic data for cumulate rocks of the Niquelândia Complex indicate significant crustal contamination by older sialic crust. These are indicated by highly variable contents of incompatible elements, with sharp increase in absolute contents and La/Yb ratios (Fig. 8) toward the upper zone, as well as highly negative $\varepsilon_{Nd(800Ma)}$ values (Ferreira Filho et al., 1998; Pimentel et al., 2004, 2006; Rivalenti et al., 2008). Geochemical and isotope data are best modeled by using AFC (assimilation and fractional crystallization) formulation (Ferreira Filho et al., 1998; Rivalenti et al., 2008).

6.2. *Barro Alto Complex*

The Barro Alto Complex (Fig. 4) is the largest layered intrusion in central Brazil, extending for 150 km and up to 30 km wide. The geology, structure and metamorphic petrology of the Barro Alto

Complex were considered in several papers (see Pimentel et al., 2000 for a review and references). However, no systematic studies were carried out on the igneous fractionation of the layered sequence.

The complex was divided into an EW-trending segment and a NS-trending segment (Ferreira Filho, 1998). These are informally described as the EW and NS segments of the Barro Alto complex, being separated by a poorly defined fault structure where major zones and layering of both segments are truncated. The EW segment consists mainly of abundant gabbronorite and minor pyroxenites. In this segment no major stratigraphic marker or large-scale fractionation pattern is observed. The EW segment possibly represents the result of the juxtaposition of several parallel tectonic slices (Ferreira Filho, 1998), which explains the absence of a coherent trend of fractionation. This interpretation is supported by the existence of large (up to few km long and up to 1 km wide) slices of gneissic rocks (possibly basement rocks) and supracrustal sequences, including metamorphosed volcano-sedimentary rocks, within mafic–ultramafic layered rocks. Studies undertaken in specific sections of the EW segment indicate the existence of repeated cycles of websterite and gabbronorite, suggesting fractionation from orthopyroxene + clinopyroxene cumulates to orthopyroxene + clinopyroxene + plagioclase cumulates. Quartz dioritic rocks, usually with abundant enclaves of gabbronorite and xenoliths of supracrustal rocks, similar to those described in the uppermost part of the UMZ of the Niquelândia Complex, are scattered throughout the EW segment. Distinct from these occurrences in the Niquelândia and Canabrava complexes, where they are restricted to a specific stratigraphic horizon, they are randomly distributed in the EW segment of the Barro Alto Complex. Mineral compositions of primary pyroxenes and incompatible element contents of gabbronorite, websterite and quartz diorite of the EW segment (Suita, 1996; Oliveira, 1993) are similar to those obtained for similar rocks in the UMZ of the Niquelândia Complex. These results suggest that the EW segment consists of highly tectonized slices of a stratigraphic sequence equivalent to the UMZ of the Niquelândia Complex (Fig. 7).

In contrast to the EW segment, the NS segment consists of two major zones mapped throughout the intrusion (Fig. 4). The stratigraphy of the NS segment is displayed by ca. 015°-trending layers with steep westward dip. The Lower Mafic Zone (LMZ) is about 60 km long and up to 15 km wide, consisting mainly of gabbronorite with minor websterite and orthopyroxenite. Layered rocks are highly tectonized in the eastern contact with the Rio Maranhão Thrust Zone. The western upper contact with the Ultramafic Zone (UZ) is however gradational and characterized by a progressive westward increase of interlayered ultramafic rocks. Drill holes intercepting the stratigraphic sequence of the LMZ below the UZ consist of several cyclic units of dunite, harzburgite, orthopyroxenite, websterite and gabbronorite. Cyclic units in the upper portions of the LMZ are similar to those described in the Niquelândia Complex, showing the upward transition from olivine + chromite cumulate (dunite), to orthopyroxene + chromite cumulate (orthopyroxenite), to orthopyroxene + clinopyroxene cumulate (websterite), and orthopyroxene + clinopyroxene + plagioclase (gabbronorite). The Ultramafic Zone (UZ) is 60 km long and less than 4 km wide. This zone is almost continuous, being just interrupted for few km north of Laguna (Fig. 4). The western contact of the UZ with the Serra da Malacacheta complex is tectonic, characterized by highly sheared serpentinites. The UZ is well exposed just to the south of the Barro Alto town. In this area the UZ consists of a monotonous sequence of interlayered dunite and harzburgite (olivine + chromite cumulate with intercumulus orthopyroxene) with rare interlayered pyroxenite. The composition of the most magnesian olivine from dunite of the UZ (Fo 91–92) indicates a remarkably primitive composition for the parental magma.

6.3. Canabrava Complex

The geology and petrology of the Canabrava Complex (Fig. 5) are described in detail by Correia (1994) and Lima (1997). The southern and eastern limits of the Canabrava Complex are marked by an important west-dipping shear zone (the Rio Maranhão Thrust Zone in Fig. 5). To the west the complex is in contact with the Palmeirópolis volcano-sedimentary sequence. The stratigraphy of the Canabrava Complex (Fig. 7) is displayed by ca. 005°-trending layers with steep westward dip, except for the fault truncated southern portion.

The stratigraphy consists of three major zones mapped throughout the intrusion. The basal Lower Mafic Zone (LMZ) consists mainly of gabbronorite with interlayered pyroxenite (websterite and minor orthopyroxenite). Cumulate rocks of the LMZ are highly tectonized by the Rio Maranhão Thrust Zone, especially in the eastern part. The LMZ is considered to be a stratigraphic equivalent of Niquelândia's LMZ (Fig. 7). The Ultramafic Zone (UZ) consists mainly of interlayered dunite, harzburgite and pyroxenite. Except for the faulted southern portion, the UZ is less than 500 m thick, becoming progressively thinner and discontinuous due to transverse faults, until it disappears to the north. The Upper Mafic Zone (UMZ) consists mainly of gabbronorite with interlayered pyroxenite. These pyroxenites (mainly websterite with minor orthopyroxenite) are abundant in the lower part of the UMZ, becoming progressively less frequent and thinner toward the top. Quartz–dioritic bodies and associated granitic pods occur at the uppermost part of the UMZ. Quartz- and phlogopite-bearing diorites have accessory apatite and zircon, and frequently have enclaves of gabbronorite or xenoliths of crustal sialic rocks. These bodies were interpreted to be later quartz-bearing noritic intrusions (Lima, 1997). However, they are remarkably similar to quartz–dioritic bodies described in the Niquelândia Complex, outcropping also along a specific stratigraphic horizon in the uppermost part of the UMZ. These features suggest that they probably also represent highly contaminated melt pods resulting from partial melting of the roof in the upper part of the magma chamber.

Cyclic layering of the Canabrava Complex is very similar to what is described in the Niquelândia Complex. Cyclic units in the LMZ and UMZ consist of successive layers of websterite and gabbronorite, whereas sequences of dunite, harzburgite, orthopyroxenite, websterite and gabbronorite occur in the UZ. These repeated cyclic units suggest that the evolution of the Canabrava Complex occurred by fractional crystallization in a frequently replenished magma chamber. Systematic studies of cryptic variation in the Canabrava Complex are not available, but the compositional features of orthopyroxene, clinopyroxene and olivine are similar to those described for equivalent stratigraphic zones in the Niquelândia Complex (Lima, 1997). Even though just a few analyses of olivine from the UZ are available, the composition of the most magnesian olivine (Fo 89) indicates a primitive parental magma for the Canabrava Complex.

7. Tectonic setting

Geological investigations supported by reliable age dating indicate the existence of two major igneous rock units related to Meso- and Neoproterozoic rifting events in central Brazil (Pimentel et al., 2004). Schematic cartoon sections illustrate major tectonic features associated with these igneous associations (Fig. 9). The following discussion addresses key features related to the evolution of these igneous associations, consider-

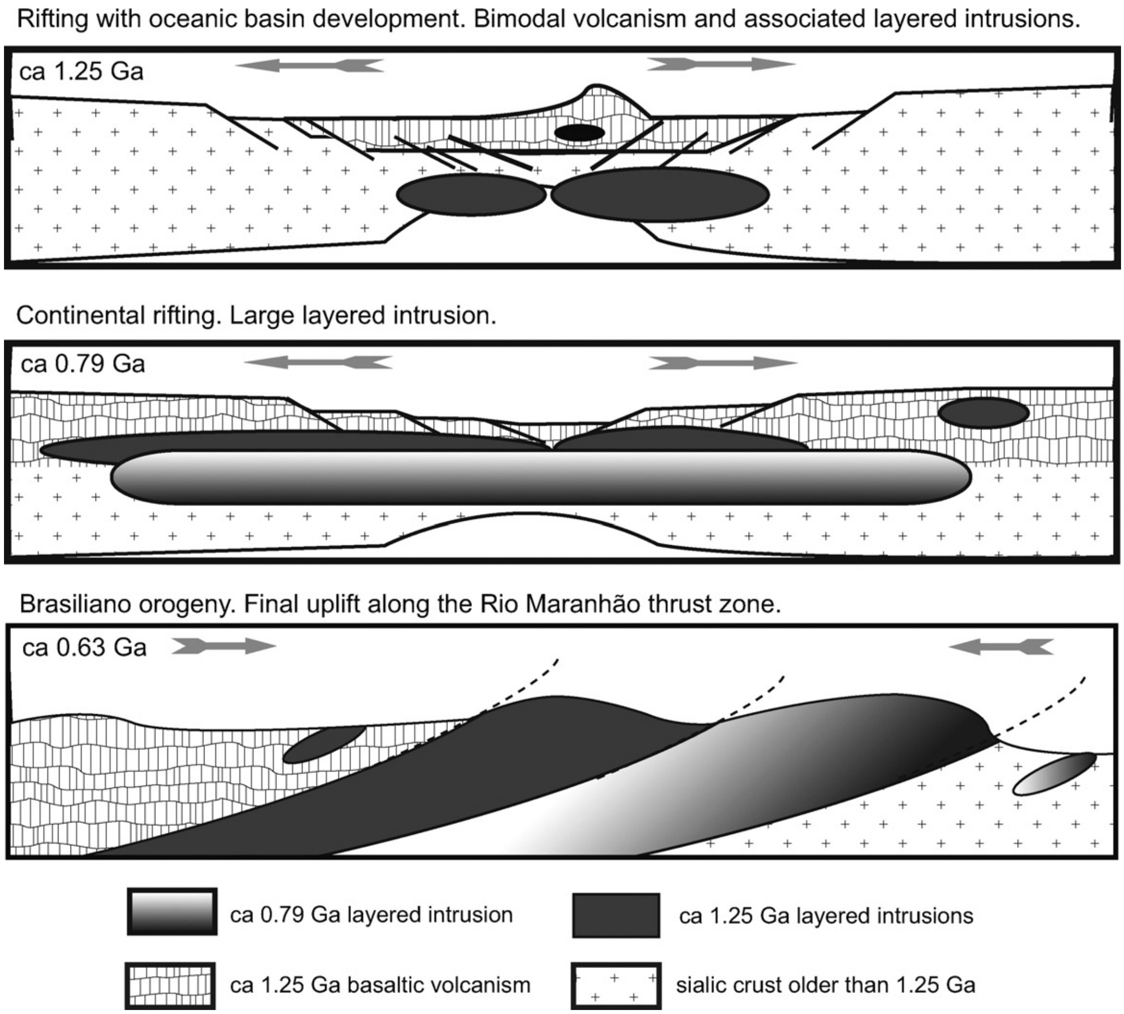

Fig. 9. Cartoon sections showing major tectonic events associated with the 1.25 and 0.79 Ga igneous associations.

ing also their relationship with Precambrian terrains in Brazil and worldwide.

7.1. The 1.25 Ga igneous association

The 1.25 Ga magmatic event represents an igneous association composed of extensive basaltic bimodal volcanism (Palmeirópolis, Juscelândia and Indaianópolis sequences) and associated large mafic layered intrusions (Serra dos Borges and Serra da Malacacheta complexes). Geochemical data of mafic volcanic rocks indicate composition similar to MORBs, suggesting a tectonic setting where continental rifting led to an ocean basin and oceanic lithosphere. A mid-ocean ridge (Danni and Kuyumjian, 1984; Araujo, 1986, 1996; Araujo et al., 1996) or a back-arc basin (Kuyumjian and Danni, 1991; Pimentel et al., 2004) was suggested as the tectonic environment for these sequences. Moraes et al. (2003, 2006) have argued that a continental rift provides a better tectonic environment for the origin of the Juscelândia sequence. These authors considered that bimodal volcanism and associated granites are not common in mid-ocean ridges, proposing that the Juscelândia sequence originated mainly in a continental rift that evolved to opening of an ocean basin. Despite differences in the timing and relative importance of the amount of oceanic lithosphere developed, there is general agreement regarding the interpretation that these sequences represent a major event of continental rifting that evolved to an ocean basin. The coeval mafic layered intrusions were also considered to have originated in this rift environment (Ferreira Filho and Pimentel, 2000; Pimentel et al., 2000, 2004). These layered intrusions are characterized by positive $\varepsilon_{Nd(1250Ma)}$ values, low incompatible trace element abundances and LREE-depleted mantle-normalized-REE patterns (Ferreira Filho et al., 1998; Ferreira Filho and Pimentel, 2000; Rivalenti et al., 2008). These features suggest an origin from the same depleted mantle source that produced the extensive MORB-type volcanism. Intrusion of layered complexes possibly occurred since the early stages of rifting, being placed both below and within the volcanic pile (as suggested by the Serra da Figueira body). Different magmatic ages and fractionation trends of layered bodies suggest that they represent a cluster of intrusions emplaced during the transition from continental rifting to oceanic ridge setting.

The ca 1.25 Ga rift event (Fig. 9) has not been described before in other parts of the Brasília Belt or even within the São Francisco Craton (Pimentel et al., 2004). Although equivalent Mesoproterozoic extensional events have been reported in other continents (e.g., Laurentia and Baltica, Gower et al., 1990; Hoffman, 1991; Osmani, 1991; Bingen et al., 2002), they are not at all common in the Precambrian terrains of South America. The ca. 1.25 Ga oceanic crust is considered too old to represent the rifting event which led to the deposition of the passive margin sequences in the Brasília Belt (Dardenne, 2000; Pimentel et al., 2000) or its counterpart in Africa (Renne et al., 1990; Tack et al., 2001). Pimentel et al. (2004) considered that the mismatch between this ca. 1.25 Ga event and those recorded in the Brasília Belt suggests that they are part of an exotic block, accreted to the western margin of the São Francisco Craton during the Neoproterozoic. An allochtonous origin is supported by the coincidence with a regional gravimetric discontinuity typical of suture zones (Marangoni et al., 1995).

7.2. The 0.79 Ga igneous association

The 0.79 Ga magmatic event is represented by igneous associations forming large layered intrusions. The pile of cumulate rocks of the Niquelândia complex is estimated to be about 10 km thick (Girardi et al., 1986; Ferreira Filho et al., 1992). The persistent lateral continuity of three thick distinct zones with characteristic fractionation patterns and geochemical signature, indicate that the Niquelândia complex ranks among the thickest large layered intrusion in the world. Together with the Barro Alto and Canabrava layered intrusions, they indicate a very large volume of mantle-derived magma reaching the crust at ca. 0.79 Ga (Fig. 9). These layered intrusions are characterized by thick ultramafic zones (mainly dunite, harzburgite and websterite), highly primitive compositions of olivine (up to Fo 91–93) and extensive Fe-enrichment trend of pyroxenes. Cyclic units consisting of successive layers of dunite, harzburgite, orthopyroxenite, websterite and gabbronorite occur throughout the stratigraphy of these layered intrusions. These cyclic units show the transition from olivine + chromite cumulate (dunite), to orthopyroxene + chromite cumulate (orthopyroxenite), to orthopyroxene + clinopyroxene cumulate (websterite) and orthopyroxene + clinopyroxene + plagioclase (gabbronorite), typical of deep-seated tholeiitic magma chambers. Repeated cyclic units indicate the evolution by fractional crystallization in a frequently replenished magma chamber. Contamination of the parental magma with old sialic crust is indicated by abundant geochemical and isotopic data, including highly negative $\varepsilon_{Nd(800Ma)}$ values, as well as by the presence of older crustal xenoliths and zircon xenocrysts. The original structure of these layered intrusions is poorly constrained. Their present disrupted and linear form (Fig. 2) is a tectonic feature, associated with final uplift (Fig. 9) towards the end of the Neoproterozoic (ca. 630 Ma, see Pimentel et al., 2004). The original geometry of these layered complexes would probably correspond to thick sill-like intrusions, similar to the Bushveld Complex (e.g., Eales and Cawthorn, 1996), or funnel-shaped intrusions such as the Muskox intrusion (e.g., McBirney, 2006). They may well represent tectonically disrupted parts of an originally single layered intrusion, as proposed by Ferreira Filho (1998), or possibly different intrusions of the same magmatic suite. The same U–Pb ages for Niquelândia and Barro Alto complexes, together with striking similarities in their stratigraphy, suggests an originally continuous layered intrusion. However, U–Pb ages reported in this study for the Canabrava Complex are slightly younger than those indicated for the Niquelândia and Barro Alto complexes (Table 1). This age difference favors the interpretation that this large magmatic suite evolved through distinct pulses of magma.

These large layered intrusions were interpreted to be associated with continental rifting (Fig. 9), but just recently obtained reliable Neoproterozoic ages (Pimentel et al., 2004, 2006) provided time constraint to fit this event within the evolution of the Brasília Belt. Pimentel et al. (2004) pointed out that the ca. 0.79 Ga event is roughly coeval with the worldwide extensional event at ca. 0.75 Ma which has been assigned to the fragmentation of the Rodinia supercontinent (e.g., Dalziel, 1991, 1997; Pisarevsky et al., 2003). However, as discussed by Kröner and Cordani (2003) and Cordani et al. (2003), it seems difficult to fit the 0.79 Ga rifting event (e.g., the break-up of Rodinia) within the evolution of the Brasília Belt. This mismatch provides additional evidence for the existence of an exotic block in central Brazil, accreted to the western margin of the São Francisco Craton during the Neoproterozoic.

Accepting the allochtonous origin of ca 0.79 Ga layered intrusions in central Brazil leads to the question of its possible connection with major magmatic events in the world. Many large igneous provinces (LIPs) are closely associated with large mafic and/or ultramafic intrusions, and are usually inferred to result from partial melting of the head of a mantle plume (e.g., Eldholm and Coffin, 2000). Many plume-related LIPs are precursors of rifting and continental break-up (e.g., Courtillot et al., 1999). The 0.79 Ga igneous association in central Brazil is roughly coeval with the 0.78 Ga Gunbarrel event in western North America (Ernst and Buchan, 2001; Harlan et al., 2003). This event includes a continental-scale fanning swarm of dikes related to the separation of Laurentia and Australia during the break-up of Rodinia (Park et al., 1995). The break-up of Rodinia was a diachronous process which started in the western margin of Laurentia at ca. 0.78 Ga (Dalziel, 1997). The exact continental arrangement of Rodinia is still debated with at least three proposed configurations (e.g., Dalziel, 1992; Pisarevsky et al., 2003), and the 0.79 Ga igneous association in central Brazil provides additional data to be considered in such models.

8. Conclusions

Accurate ages combined with geological descriptions lead to the characterization of two distinct igneous associations in central Brazil. The 1.25 and 0.79 Ga igneous mafic and ultramafic rocks are now constrained by U–Pb dating in different regions and rock types. Geological description and nomenclature of layered intrusions in central Brazil were re-examined and a new assessment is presented. The Niquelândia, Barro Alto and Canabrava complexes are now restricted to 0.79 Ga layered intrusions, whereas the Serra dos Borges complex and Serra da Malacacheta complex are used to designate the 1.25 Ga layered intrusions located, respectively, in the Niquelândia and Goianésia-Barro Alto regions. Layered intrusions of the 0.79 and 1.25 Ga igneous units have remarkably different rock types, crystallization sequences and lithogeochemical and isotopic compositions. Together with U–Pb dating these features should be used to correlate layered intrusions in central Brazil with each specific igneous associations, providing a useful starting point for future studies.

The 1.25 and 0.79 Ga igneous suites are interpreted to result from two different rifting events. However, evidences of such events are not described in the Brasília Belt or in other parts of the São Francisco Craton. The mismatch between the 1.25 and 0.79 Ga rifting events with those described for the Brasília Belt, supports previous interpretations suggesting that these rocks are part of an exotic block in the Brasília Belt. It is worth mentioning that high-grade metamorphism of this exotic terrain (ca. 0.76 Ga) is considerably older than ages obtained for the regional peak of metamorphism in the Brasília belt (ca. 0.65 Ga). This allochtonous block may have accreted to the western margin of the São Francisco Craton during the Neoproterozoic, probably during the 0.76 Ga metamorphic event (Pimentel et al., 2004). Equivalent and roughly coeval Meso- and Neoproterozoic extensional events have been reported in other continents (e.g., North America). The igneous rock associations described within an allochtonous block in the Brasília Belt may, thus, provide additional constraints for continental reconstructions before the break-up of Rodinia.

Acknowledgements

The authors are grateful to the Brazilian Research Council (CNPq) for continuous support to field and laboratory work and for research grants. Cesar F. Ferreira Filho and Márcio M. Pimentel are CNPq Research Fellows. The authors are thankful for helpful critical reading and suggestions for further improvement provided by Precambrian Research reviewers (Sandra Kamo and one anonymous) and editors.

References

Araujo, S.M., 1986. Petrologia e mineralizações sulfetadas da Sequência vulcano-sedimentar de Palmeirópolis, Goiás. Unpublished M.Sc. Dissertation, Institute of Geoscience, Universidade de Brasília, Brasília, Brazil, 196 pp.

Araujo, S.M., 1996. Geochemical and isotopic characteristics of alteration zones in highly metamorphosed volcanogenic massive sulfide deposits and their potential application to mineral exploration. Unpublished Ph.D. Thesis, Department of Geology, University of Toronto, Toronto, Canada, 210 pp.

Araujo, S.M., Nilson, A.A., 1987. Caracterização petroquímica e petrotectônica dos anfibolitos da sequência vulcano-sedimentar de Palmeirópolis, Goiás. In: 1st Cong. Bras. Geoquímica, Anais, vol. 1, Porto Alegre, SBGq, pp. 335–348.

Araujo, S.M., Scott, S.D., Longstaffe, F.J., 1996. Oxygen isotope composition of alteration zones of highly metamorphosed volcanogenic massive sulfide deposits: Geco, Canada and Palmeirópolis, Brazil. Econ. Geol. 91, 697–712.

Bingen, B., Mansfeld, J., Sigmond, E.M.O., Stein, H., 2002. Baltica-Laurentia link during the Mesoproterozoic 1.27 Ga development of continental basins in the Sveconorwegian Orogen, Southern Norway. Can. J. Earth Sci. 39, 1425–1440.

Cordani, U.G., D'Agrella-Filho, M.S., Brito-Neves, B.B., Trindade, R.I., 2003. Tearing up Rodinia: the Neoproterozoic paleogeography of South American cratonic fragments. Terra Nova 15, 350–359.

Correia, C.T., 1994. Petrologia do Complexo Máfico-Ultramáfico de Cana Brava. Goiás. Unpublished Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brazil, 151 pp.

Correia, C.T., Girardi, V.A.V., Lambert, D.D., Kinny, P.D., Reeves, S.J., 1996. 2 Ga U–Pb (SHRIMP II) and Re–Os ages for the Niquelândia basic–ultrabasic layered intrusion, central Goiás, Brazil. In: 39th Cong. Bras. Geologia, Anais, vol. 6, Salvador, SBG, pp. 187–189.

Correia, C.T., Girardi, V.A.V., Tassinari, C.C.G., Jost, H., 1997. Rb–Sr and Sm–Nd geochronology of the Cana Brava layered mafic–ultramafic intrusion, Brazil, and considerations regarding its tectonic evolution. Rev. Bras. Geociências 27, 163–168.

Correia, C.T., Jost, H., Tassinari, C.C.G., Girardi, V.A.V., Kinny, P., 1999. Ectasian Mesoproterozoic U–Pb ages (SHRIMP-II) for the metavolcano-sedimentary sequences of Juscelândia and Indaianópolis and for high-grade metamorphosed rocks of Barro Alto stratiform igneous complex, Goiás State, central Brazil. In: SAAGI-South American Symposium on Isotopic Geology, vol. 2, Actas SEGEMAR, Córdoba, pp. 31–33.

Correia, C.T., Girardi, V.A.V., Basei, M.A.S., Nutman, A., 2007. Cryogenian U–Pb (SHRIMP I) zircon ages of anorthosites from the upper sequences of Niquelândia and Barro Alto complexes, central Brazil. Rev. Bras. Geociências 37, 70–75.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., Besse, J., 1999. On casual links between flood basalts and continental breakup. Earth Planet. Sci. Lett. 166, 177–195.

Dalziel, I.W.D., 1991. Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. Geology 19, 598–601.

Dalziel, I.W.D., 1992. On the organisation of American plates in the Neoproterozoic and the breakout of Laurentia. GSA Today 2, 237–241.

Dalziel, I.W.D., 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis and environmental speculation. Bull. Geol. Soc. Am. 109, 16–42.

Danni, J.C.M., Fuck, R.A., Leonardos Jr., O.H., 1982. Archean and lower Proterozoic Units in Central Brazil. Geol. Rundsch. 71, 291–317.

Danni, J.C.M., Kuyumjian, R.M., 1984. A origem dos anfibolitos basais da sequência vulcano sedimentar de Juscelândia, Goiás. In: 33rd Cong. Bras. Geologia, Anais, vol. 9, Rio de Janeiro, RBG, pp. 4126–4136.

Danni, J.C.M., Fuck, R.A., Kuyumjian, R.M., Leonardos, O.H., Winge, M., 1984. O Complexo de Barro Alto na região de Ceres-Rubiataba, Goiás. Rev. Bras. Geociências 14, 128–136.

Dardenne, M.A., 2000. The Brasília Belt. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), The Tectonic Evolution of South America, Rio de Janeiro. Proceedings of the 31st International Geological Congress, pp. 231–263.

Eales, H.V., Cawthorn, R.G., 1996. The Bushveld Complex. In: Cawthorn, R.G. (Ed.), Layered Intrusions. Elsevier, Amsterdam, pp. 181–229.

Eldholm, O., Coffin, M.F., 2000. Large igneous provinces and plate tectonics. In: Richards, M., et al. (Eds.), The History and Dynamics of Global Plate Motions, vol. 121. American Geophysical Union, Monograph, pp. 309–326.

Ernst, R.E., Buchan, K.L., 2001. Large mafic magmatic events through time and links to mantle–plume heads. Geol. Soc. Am. Special Paper 352, 483–575.

Ferreira Filho, C.F., 1994. The Niquelândia Mafic–Ultramafic Layered Intrusion, North Goiás, Brazil: Petrology, Age and Potential for PGE Ore Deposits. Unpublished Ph.D. Thesis, University of Toronto, Toronto, Canada, 270 pp.

Ferreira Filho, C.F., 1998. Geology and petrology of the large layered intrusions of central Brazil: implications for PGE mineralization. In: Platinum Symposium, Rustemburg, South Africa, Extended Abstracts, pp. 107–110.

Ferreira Filho, C.F., Nilson, A.A., Naldrett, A.J., 1992. The Niquelândia mafic–ultramafic complex, Goiás, Brazil: a contribution to the ophiolite vs. stratiform controversy based on new geological and structural data. Precambrian Res. 59, 125–143.

Ferreira Filho, C.F., Kamo, S., Fuck, R.A., Krogh, T.E., Naldret, A.J., 1994. Zircon and rutile geochronology of the Niquelândia layered mafic and ultramafic intrusion, Brazil: constraints for the timing of magmatism and high grade metamorphism. Precambrian Res. 68, 241–255.

Ferreira Filho, C.F., Silva, C.B., Lopes, R.O., 1996. Variação críptica de olivina em dunitos da Unidade Ultramáfica do Complexo de Niquelândia, GO. In: Proceedings of the 39th Cong. Bras. Geologia, Anais, vol. 6, Salvador, SBG, pp. 179–182.

Ferreira Filho, C.F., Naldrett, A.J., Gorton, M.P., 1998. REE and pyroxene compositional variation across the Niquelândia layered intrusion, Brazil: petrological and metallogenetic implications. Trans. Inst. Mining Metallurg. 107, B1–B21.

Ferreira Filho, C.F., Araujo, S.M., Cruz, H.P., 1999. Estruturas vulcânicas em granulitos da sequência vulcano-sedimentar Juscelândia, GO. Rev. Bras. Geociências 29, 461–468.

Ferreira Filho, C.F., Pimentel, M.M., 2000. Sm–Nd isotope systematics and REE–Hf–Ta–Th data of troctolites and their amphibolitized equivalents of the Niquelândia Complex upper layered series, central Brazil: further constraints for the timing of magmatism and high-grade metamorphism. J. South Am. Earth Sci. 13, 647–659.

Fornoni Candia, M.A., Mazzucchelli, M., Siena, F., 1989. Sub-solidus reactions and corona structures in the Niquelândia Layered Complex (Central Goiás, Brazil). Mineral. Petrol. 40, 17–37.

Fuck, R.A., Danni, J.C.M., Winge, M., Andrade, G.F., Barreira, C.F., Leonardos, O.H., Kuyumjian, R.M., 1981. Geologia da Região de Goianésia. In: 18th Simp. Geologia do Centro-Oeste, Goiânia, pp. 447–467.

Fuck, R.A., Brito-Neves, B.B., Cordani, U.G., Kawashita, K., 1989. Geocronologia Rb–Sr no Complexo Barro Alto, Goiás: Evidência de metamorfismo de alto grau e colisão continental há 1300 Ma no Brasil Central. Geochim. Brasil. 3, 125–140.

Fuck, R.A., Pimentel, M.M., Silva, L.J.H.D., 1994. Compartimentação tectônica da porção oriental da Província Tocantins. In: 38th Cong. Bras. Geologia, Anais, vol. 1, Camboriú, SBG, pp. 215–216.

Gioia, S.M.C., Pimentel, M.M., 2000. The Sm–Nd isotopic method in the Geochronology Laboratory of the University of Brasília. Anais da Academia Brasileira de Ciências 72, 219–245.

Girardi, V.A.V., Rivalenti, G., Sinigoi, S., 1986. The petrogenesis of the Niquelândia layered basic–ultrabasic complex, Central Goiás, Brazil. J. Petrol. 27, 715–744.

Gower, C.F., Ryan, A.B., Rivers, T., 1990. Mid-Proterozoic Laurentia–Baltica: an overview of its geological evolution. In: Gower, C.F., Rivers, T., Ryan, A.B. (Eds.), Mid-Proterozoic Laurentia–Baltica. Geological Association of Canada Special Paper 38, pp. 1–20.

Harlan, S.S., Heaman, L., LeCheminant, A.N., Premo, W.R., 2003. Gunbarrel mafic magmatic event: a key 780 Ma time marker for Rodinia plate reconstructions. Geology 31, 1053–1056.

Hoffman, P., 1991. Did the break-out of Laurentia turn Gondwanaland inside-out? Science 252, 1409–1412.

Kröner, A., Cordani, U.G., 2003. African, southern Indian and South American cratons were not part of the Rodinia supercontinent: evidence from field relationships and geochronology. Tectonophysics 375, 325–352.

Kuyumjian, R.M., Danni, J.C.M., 1991. Geoquímica de anfibolitos da sequência de Juscelândia, Goiás: implicações geotectônicas. Rev. Bras. Geociências 21, 218–223.

Lima, T.M., 1997. Geologia, estratigrafia e petrologia da porção sul do Complexo máfico-ultramáfico de Cana Brava. Goiás. Unpublished M.Sc. Dissertation, Universidade de Brasília, Brasília, Brazil, 312 pp.

Marangoni, Y., Assumpção, M., Fernandes, E.P., 1995. Gravimetria em Goiás, Brasil. Rev. Bras. Geofísica 13, 205–219.

McBirney, A.R., 2006. Igneous Petrology. Jones & Bartlett Publishers, pp. 550.

Medeiros, E.S., Ferreira Filho, C.F., 2001. Caracterização geológica e estratigráfica das mineralizações de platina e paládio associadas à Zona máfica Superior do Complexo de Niquelândia, GO. Rev. Bras. Geociências 31, 29–36.

Miller, J.D., Ripley, E.M., 1996. Layered intrusions of the Duluth Complex, Minnesota, USA. In: Cawthorn, R.G. (Ed.), Layered Intrusions, Developments in Petrology, vol. 15. Elsevier, pp. 257–301.

Moraes, R., Fuck, R.A., 1994. Deformação e metamorfismo das sequências Juscelândia e Serra da Malacacheta, Complexo Barro Alto, Goiás. Rev. Bras. Geociências 24, 189–197.

Moraes, R., Fuck, R.A., 1999. Trajetória *P*–*T* Horária para o Metamorfismo da Sequência Juscelândia, Goiás: Condições do Metamorfismo e Implicações Tectônicas. Rev. Bras. Geociências 29, 603–612.

Moraes, R., Fuck, R.A., 2000. Ultrahigh temperature metamorphism in central Brazil: the Barro Alto Complex. J. Metamorph. Geol. 18, 345–358.

Moraes, R., Fuck, R.A., Pimentel, M.M., Gioia, S.M.C.L., Figueiredo, A.M.G., 2003. Geochemistry and Sm–Nd isotope characteristics of bimodal volcanic rocks of Juscelândia, Goiás, Brazil: Mesoproterozoic transition from continental rift to ocean basin. Precambrian Res. 125, 317–336.

Moraes, R., Fuck, A.R., Pimentel, M.M., Gioia, S.M.C.L., Hollanda, M.H.B.M., Armstrong, R., 2006. The bimodal rift-related volcanosedimentary sequence in Central Brazil: Mesoproterozoic extension and Neoproterozoic metamorphism. J. South Am. Earth Sci. 20, 287–301.

Oliveira, A.M., 1993. Petrografia, estratigrafia, petroquímica e potencialidade para Elementos do Grupo da Platina (EGP) do Complexo de Barro Alto, na região de Goianésia, Goiás. Unpublished M.Sc. Dissertation, Universidade de Brasília, Brasília, Brazil, 86 pp.

Osmani, I.A., 1991. Proterozoic mafic dyke swarms in the Superior Province of Ontario. In: Thurston, P.C., Williams, H.R., Sutcliffe, R.H., Stott, G.M. (Eds.), Geology of Ontario, Ontario Geological Survey Special, vol. 4. Ontario Geol. Surv. Prec. Geol. Sect., pp. 661–681.

Park, J.K., Buchan, K.L., Harlan, S.S., 1995. A proposed giant radiating dyke swarm fragmented by the separation of Laurentia and Australia—based on paleomag-

netism of circa 780 Ma mafic intrusions in western North America. Earth Planet. Sci. Lett. 132, 129–139.
Pimentel, M.M., Fuck, R.A., Jost, H., Ferreira Filho, C.F., Araujo, S.M., 2000. The basement of the Brasília Fold Belt and the Goiás Magmatic Arc. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), The Tectonic Evolution of South America, Rio de Janeiro. Proceedings of the 31st International Geological Congress. Rio de Janeiro, pp. 195–229.
Pimentel, M.M., Ferreira Filho, C.F., Amstrong, R.A., 2004. Shrimp U–Pb and Sm–Nd ages of the Niquelândia Layered Complex: Meso (1.25 Ga) and Neoproterozoic (0.79 Ga) extensional events in Central Brazil. Precambrian Res. 132, 132–135.
Pimentel, M.M., Ferreira Filho, C.F., Armele, A., 2006. Neoproterozoic age of the Niquelândia complex, Central Brazil: further ID-TIMS and Sm–Nd isotopic evidence. J. South Am. Earth Sci. 21, 228–238.
Pimentel, M.M., Ferreira Filho, C.F., Baxe, O.S.S., submitted for publication. Mesoproterozoic Magmatic and Neoproterozoic Metamorphic ages of the Niquelândia Complex's Upper Series in central Brazil: further ID-TIMS U–Pb and Sm–Nd isotopic evidence. J. South Am. Earth Sci.
Pisarevsky, S.A., Wingate, M.T.D., Powell, C.McA., Johnson, S.P., Evans, D.A.D., 2003. Models of Rodinia assembly and fragmentation. In: Yoshida, M., Windley, B.F., Dasgupta, S. (Eds.), Proterozoic East Gondwana Assembly and Break-up. Geol. Soc. Lond. Spec. Publ., vol. 206, pp. 35–55.
Renne, P.R., Onstott, T.C., D'Agrella-Filho, M.S., Pacca, I.G., Teixeira, W., 1990. $^{40}Ar/^{39}Ar$ dating of 1.0–1.1 Ga magnetizations from the São Francisco and Kalahari cratons: tectonic implications for Pan-African and Brasiliano mobile belts. Earth Planet. Sci. Lett. 101, 349–366.
Rivalenti, G., Correia, C.T., Girardi, V.A.V., Mazzicchelli, M., Tassinari, C.C.G., Bertotto, G.W., 2008. Sr–Nd isotopic evidence for crustal contamination in the Niquelândia complex, Goiás, Central Brazil. J. South Am. Earth Sci. 25, 298–312.
Suita, M.T.F., 1996. Geoquímica e Metalogenia de Elementos do Grupo da Platina (EGP + Au) em Complexos Máfico-Ultramáficos do Brasil: Critérios e Guias com Ênfase no complexo Máfico-Ultramáfico Acamadado de Alto Grau de Barro Alto (CBA, Goiás). Unpublished Ph.D. Thesis. Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, 600 pp.
Suita, M.T.F., Kamo, S., Kroght, T.E., Fyfe, W.S., Hartmann, L.A., 1994. U–Pb ages from the high-grade Barro Alto mafic–ultramafic complex (Goiás, central Brazil): middle Proterozoic continental mafic magmatism and upper Proterozoic continental collision. In: International Conference on Geochron. Cosmochr. Isot. Geol., ICOG, Abstracts, vol. 8, Berkeley, USGS, p. 309.
Tack, L., Wingate, M.T.D., Liégeois, J.P., Fernandez-Alonso, M., Deblond, A., 2001. Early Neoproterozoic magmatism (1000–910 Ma) of the Zadinian and Mayumbian Groups (Bas-Congo): onset of Rodinia rifting at the western edge of the Congo craton. Precambrian Res. 110, 277–306.
Wernick, E., Almeida, F.F.M., 1979. The geotectonic environments of Early Precambrian granulites in Brazil. Precambrian Res. 8, 1–17.
Wilson, A.H., 1982. The geology of the Great Dyke, Zimbabwe: the ultramafic rocks. J. Petrol. 23, 240–292.