CAPÍTULO II

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Mafic Magmatism Associated with the Goiás Magmatic Arc in the Anicuns Region, Goiás, Central Brasil: Sm-Nd Isotopes and New ID-TIMS and SHRIMP U-Pb Data

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Abstract

Rocks exposed in the Anicuns region, in the eastern part of the Goiás Magmatic Arc are represented dominantly by amphibolites (metavolcanic and metaplutonic) and metapelitic rocks. New U-Pb results demonstrate that this association is Neoproterozoic and that mafic rocks crystallized during two main periods: (i) between ca. 890 and 815 Ma, and (ii) between ca. 630 and 600 Ma. Metagabbro and metadiorite samples JHL-14, JHL-15, JHL-23, AMB-01 and JHL-26B have U-Pb zircon ages of 886 ± 5 Ma, 862 ± 5 Ma, 815 ± 10 Ma, 856 ± 15 Ma, and 839 ± 9 Ma, respectively, and comprise the older group. The Late Neoproterozoic intrusive Anicuns-Santa Bárbara gabbro-diorite and Americano do Brasil suites are coeval. Four samples of the first (SB-01, JHL-04, JHL-22C and JHL-19) yielded U-Pb ages of 598 ± 8 Ma, 612 ± 6 Ma, 623 ± 13 Ma and 622 ± 6 Ma, respectively, whereas zircon grains from one norite sample of the Americano do Brasil Complex yielded a concordia age of 626 ± 8 Ma. All mafic rocks investigated present T_{DM} model ages of ca. 1.0 Ga, comparable to model ages of metaigneous rocks of the Goiás Magmatic Arc. $\varepsilon_{Nd}(T)$ values are strongly positive, indicative of the depleted nature of the mantle source (MORB-like), similarly to volcanic and plutonic rocks of the arc-type volcano-sedimentary sequences exposed to the west. The lithological associations comprising the supracrustal sequences in the Anicuns area, however, are compatible with origin in an oceanic or fore-arc setting, rather then in an intraoceanic arc setting (rocks of andesitic/dacitic/rhyolitic composition are absent). $^{147}Sm/^{144}Nd$ ratios for most of the mafic rocks investigated, however, are smaller than 0.19 and indicate a relative enrichment in LREE, which is not characteristic of N-MORB mafic magmas.

2.1 INTRODUCTION

The Goiás Magmatic Arc in central Brazil, consists of several arc-type metavolcano-sedimentary sequences associated with tonalitic to granitic orthogneisses, forming an extensive Neoproterozoic juvenile terrain along the western part of the Brasília Belt (Pimentel and Fuck, 1992; Pimentel et al., 2000a). Mafic volcanic and plutonic rocks are associated with voluminous calc-alkaline andesites, dacites, and rhyolites in some of these sequences (e.g. Bom Jardim de Goiás and Arenópolis; Seer, 1985; Pimentel and Fuck, 1986), but they also form bimodal associations with rhyolites in others (e.g. Iporá and Jaupaci sequences). The metavolcanic rocks typically present very primitive geochemical and isotopic characteristics, with low initial $^{87}Sr/^{86}Sr$ ratios and positive $\varepsilon_{Nd}(T)$ values. Felsic metavolcanic rocks have U-Pb zircon ages between ca. 0.9 and 0.64 Ga (Pimentel et al., 1991; Rodrigues et al., 1999). Most of the previous isotopic, geochronological and petrological studies concentrated on intermediate to felsic members of this magmatism, and little is known about the associated mafic rocks. Fine-grained amphibolites of the Arenópolis volcano-sedimentary sequence are probably the best known representatives of these Neoproterozoic mafic metavolcanic rocks. They comprise low-K tholeiites to calc-alkaline metabasalts, with primitive isotopic compositions (initial $^{87}Sr/^{86}Sr$ of ca. 0.7026 and $\varepsilon_{Nd}(T)$ of ca. +6.9; Pimentel, 1991), representing the early stages of development of an intraoceanic island arc system. Small metamorphosed gabbro-diorite intrusions are also recognized within the Arenópolis Sequence, and one has been recently dated at 890 $\pm$ 9 Ma (SHRIMP U-Pb zircon age; Pimentel et al., 2003), corresponding to plutonic/subvolcanic equivalent of the volcanic sequence.

The Anicuns-Itaberaí Sequence, exposed along the contact between the eastern part of the Goiás Magmatic Arc and the Anápolis-Itauçu high-grade terrain, is represented dominantly by amphibolites (metavolcanic and metaplutonic) and metapelitic rocks, with subordinate iron formations, cherts, marbles, and ultramafic rocks of uncertain age. It has been correlated, in the past, with the Archean Serra de Santa Rita greenstone belt, exposed to the north (Barbosa, 1987), or with Paleoproterozoic sequences such as the Silvânia Sequence within the Anápolis-Itauçu Complex (Lacerda Filho et al., 1991) and the Mossâmedes volcanics (Nunes, 1990). Recent studies based mainly on Sm-Nd isotopic characteristics of the Anicuns-Itaberaí rocks, however, suggest that they are considerably younger and might be part of the Neoproterozoic Goiás Magmatic Arc (Pimentel et al., 2000a, b; Laux et al., 2001, 2002a, b) (Tables 2.1a, b, c).

In this paper we discuss new U-Pb and Sm-Nd isotopic data from coarse-grained mafic rocks exposed within the Anicuns-Itaberaí Sequence, which demonstrate that this rock assemblage belongs to the Goiás Magmatic Arc and was formed during at least two main episodes in the Neoproterozoic.

Table 2.1a Summary of previous Sm-Nd results of the area.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (± 1σ)	T_{DM},(Ga)	Referen.
AMB-1	3.02	14.34	0.127	0.512396 (13)	1.13	1,2
AMB-2	3.32	15.41	0.133	0.512526 (12)	0.97	1,2
FSP-2635	1.88	07.66	0.148	0.512596 (24)	1.03	1,2
PONT-1	7.34	45.09	0.098	0.512317 (23)	0.96	2
PONT-2	8.40	41.54	0.122	0.512438 (07)	0.91	2
PONT-3	3.81	21.96	0.105	0.512296 (45)	1.06	2
PONT-4A	3.63	24.08	0.091	0.512249 (21)	0.99	2
PONT-4B	7.01	39.92	0.106	0.512164 (12)	1.23	2
PONT-4C	5.01	19.50	0.155	0.512570 (05)	1.10	2
MP-593E	11.72	72.7	0.097	0.511353(24)	2.21	3
MP-593I	10.78	66.3	0.098	0.511350(20)	2.42	3

1-Gioia (1997); 2- Pimentel et al., (2000b); 3- Pimentel et al., (1997).

Table 2.1b Summary of previous Sm-Nd whole-rock isochron age of the area.

Americano do Brasil Layered Complex	614 ± 82	0.9	+2.4	1
Pontalina	762 ± 77	3.3	+2.9	2

1-Gioia (1997); 2- Pimentel et al., (2000b).

Table 2.1c Summary of previous Rb-Sr whole-rock isochron age of the area.

Mossâmedes Sequence	1582 ± 101	0.70527	1
Mossâmedes Sequence	1978 ± 55	0.70232	1
Gongomé Intrusion	637 ± 19	0.70153	2

1- Pimentel et al., (1997); 2- Winge (1995).

2.2 REGIONAL GEOLOGICAL SETTING

The Tocantins Province represents a large Brasiliano/Pan-African orogen that developed between three major continental blocks: the Amazon, São Francisco, and Paranapanema cratons. The province comprises three main fold belts, known as the Paraguay Belt in the southwest, the Araguaia Belt in the northwest and the Brasília Belt underlying large areas of the eastern part of the Tocantins Province, along the western margin of the São Francisco Craton (for a review see Pimentel et al., 2000a).

The Brasília Belt represents one of the best preserved and the most complete Neoproterozoic orogens in Brazil, comprising: (i) a thick Meso-Neoproterozoic sedimentary pile that includes the Paranoá, Canastra, Araxá, Ibiá, Vazante, and Bambuí groups, overlying mostly Paleoproterozoic and minor Archean basement (Almeida et al., 1981; Fuck et al., 1993, 1994, 2001; Pimentel et al., 2000a, b); (ii) the Goiás Massif, a micro-continent (or allochthonous sialic terrain) composed of Archean rock units (the Crixás-Goiás granite-greenstones) and associated Proterozoic formations, and (iii) a large Neoproterozoic juvenile arc in the west (Goiás Magmatic Arc) (Fig. 2.1).

The several sedimentary/metasedimentary rock units, which occur in the eastern part of the Brasília Belt, display tectonic vergence to the east, towards the São Francisco Craton. They are more intensely deformed and metamorphosed towards the west, reaching amphibolite facies conditions in the central part of the belt (Fuck et al., 1993, 1994; Dardenne, 2000).

Metasedimentary rocks belonging to the Araxá and Canastra groups underlie large areas in the central-southern part of the Brasília Belt (Figs. 2.1 and 2.2). Nappes and thrust sheets of these units overlie Paleoproterozoic basement represented by 2.1 Ga volcano-sedimentary sequences and associated granites (e.g. Silvânia and Rio do Peixe sequences and Jurubatuba granite; Fischel et al., 2001a, b; Piuzana et al., 2003a).

High-grade rocks of the Anápolis-Itauçu Complex are exposed in the central-southern part of the belt (Figs. 2.1 and 2.2). They include para- and orthogranulites, as well as strongly deformed intrusive granites. Recent data have indicated that the

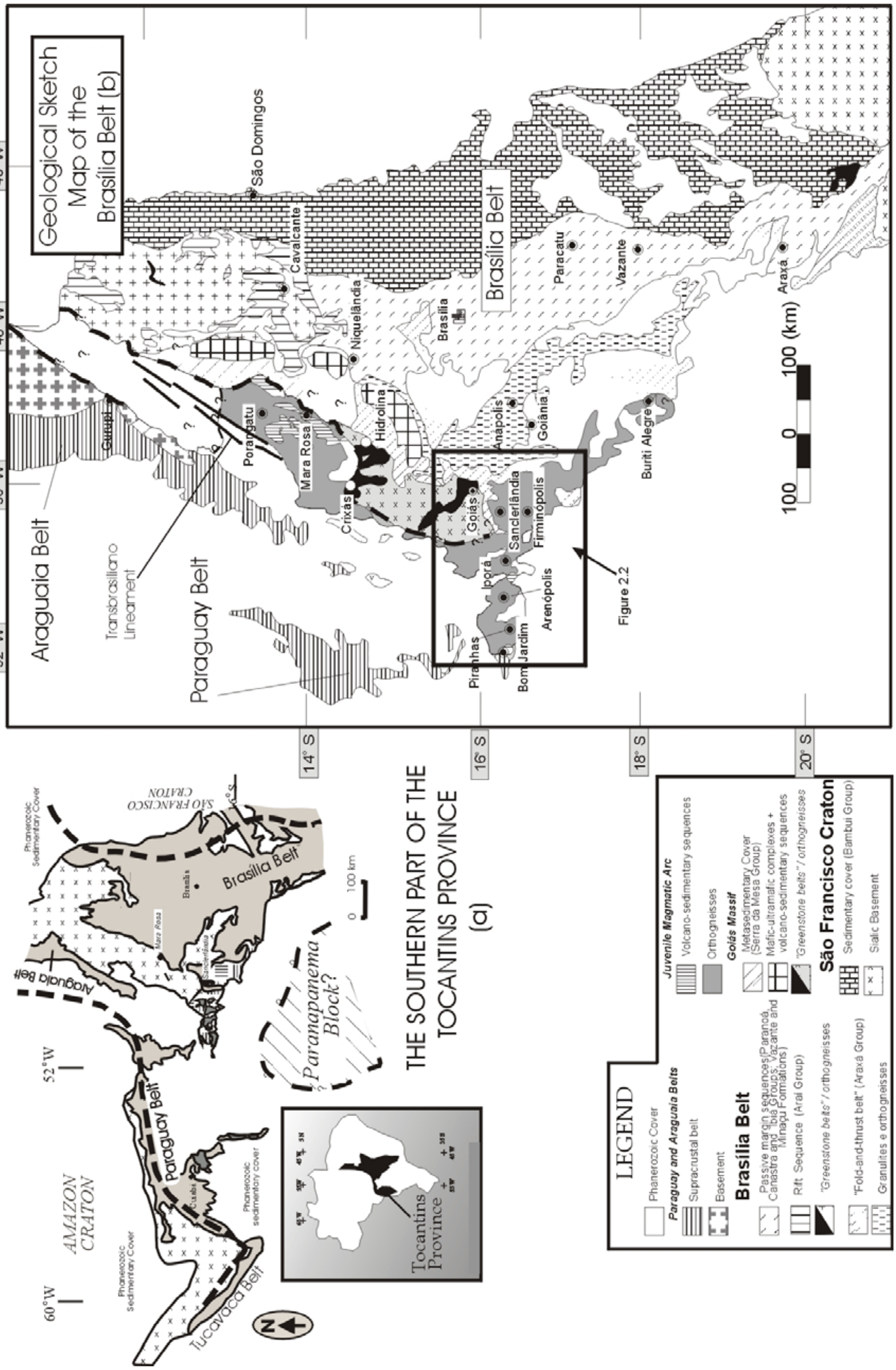

Figure 2.1 - Geological sketch map of the Brasília Belt in the eastern part of Tocantins Province, central Brazil (after Fuck et al., 1994).

Nd Isotopic signatures and metamorphic ages of the Araxá metasediments, Anápolis-Itauçu felsic granulites, and intrusive granites are all very similar (Fischel et al., 1998, 1999; Pimentel et al., 1999, 2001; Seer, 1999), demonstrating that at least part of the aluminous granulites of the Anápolis-Itauçu Complex may represent high-grade equivalents of the Araxá metasedimentary rocks. Therefore, source areas of the original Araxá sediments may have included Neoproterozoic juvenile areas such as the Goiás Magmatic Arc (Fischel et al., 1998, 1999; Pimentel et al., 1999, 2001; Piuzana et al., 2003a).

In the central part of the Brasília Belt is the Goiás Massif (Fig. 2.2), represented by: (i) Archean greenstone belts and TTG orthogneisses; (ii) Paleoproterozoic orthogneisses largely covered by younger supracrustal rocks; (iii) and mafic-ultramafic layered complexes of Barro Alto, Niquelândia, and Canabrava and associated volcano-sedimentary sequences. The eastern margin of the Goiás Massif is marked by a regional gravimetric discontinuity typical of suture zones (Haralyi and Hasui 1981, Marangoni et al., 1995). Therefore, the massif is interpreted as an allochtonous block amalgamated to the Brasília Belt during the Neoproterozoic (Brito Neves and Cordani, 1991; Pimentel et al., 2000b).

The Neoproterozoic juvenile arc (Goiás Magmatic Arc) is composed of volcano-sedimentary sequences associated with calcic to calc-alkaline tonalite/granodiorite gneisses (Fig. 2.2). The main arc terranes are known as the Arenópolis and Mara Rosa arcs, located in western and northern Goiás, respectively (Pimentel and Fuck, 1992; Pimentel et al., 1991, 1997). In both areas, geological evolution started at ca. 890-860 Ma in intraoceanic island arcs with the crystallization of very primitive tholeiitic to calc-alkaline volcanics and associated tonalites/granodiorites. These rocks have $\varepsilon_{Nd}(T)$ values between ca. +3.0 and +6.0 and T_{DM} values mostly between ca. 0.8 and 1.1 Ga (Pimentel et al., 1991, 1997, 2000b; Pimentel and Fuck, 1992). Geochemical and isotopic data (Pimentel, 1991; Pimentel et al., 1997) suggest that the original tonalitic/andesitic magmas were similar to modern adakites, commonly positioned above subduction zones where young and hot oceanic lithosphere was subducted under oceanic lithosphere. Calc-alkaline igneous activity was recurrent during the Neoproterozoic and lasted until ca. 640 Ma, with younger magmas becoming progressively more evolved. The main metamorphic episode occurred at ca. 630 Ma, as indicated by U-Pb titanite and Sm-Nd garnet ages (for a review, see Pimentel et al., 2000a), when final ocean closure probably took place.

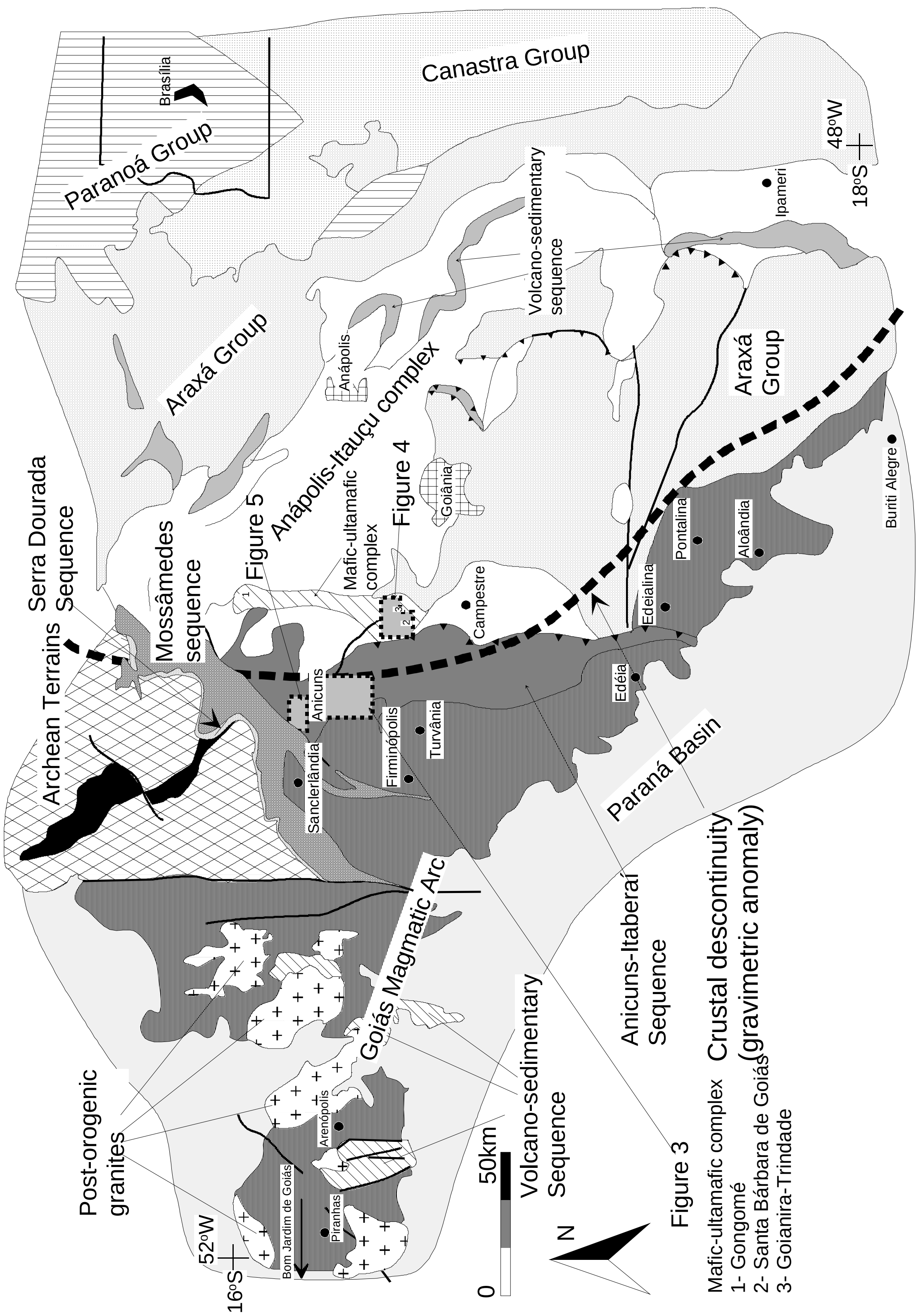

Figure 2.2 - Geological sketch map of the southern part of the Goiás Magmatic Arc, with the location of the studied areas (Pimentel et al., 2000a).

There has been considerable debate on the real areal distribution of these juvenile terrains, since geochronological and isotopic data are still sparse and insufficient. Recent U-Pb and Sm-Nd data have shown that the juvenile arc extends to the southeast and northeast, disappearing under the Paraná and Parnaíba Phanerozoic basins, respectively (Figs. 2.1 and 2.2). They underlie a very large area, which constitutes a significant portion of the Brasília Belt (Pimentel et al., 2000a; Fuck et al., 2001). In this context, the Anicuns-Itaberaí sequence represents a key geological unit for the understanding of the evolution of the Goiás Magmatic Arc and adjacent terrains because: (i) it represents one of the largest supracrustal sequences within this tectonic unit, (ii) it has been traditionally considered to be an Archean or Paleoproterozoic greenstone sequence, and (iii) it coincides with a regionally important gravimetric discontinuity, separating a gravimetric high to the west and a gravimetric low to the east (Baêta Junior, 1994). Zircon crystals from amphibolites intercalated with metasedimentary rocks of the Anicuns-Itaberaí Sequence (AIS) and from intrusive mafic-ultramafic bodies were dated mainly with conventional ID-TIMS U-Pb methods and their Nd isotopic compositions were investigated in order to provide means of comparison with mafic rock units from other sequences within the Goiás Magmatic Arc.

2.3 GEOLOGY OF THE ANICUNS REGION

In the Mossâmedes-Anicuns region (Figs. 2.2 and 2.3), Barbosa (1987) recognized three distinct supracrustal sequences and assigned different ages to them based on field relationships and structural data: (i) the Anicuns-Itaberaí Sequence (AIS) was interpreted as the southern extension of the Serra de Santa Rita (Goiás Velho) greenstone belt, (ii) the Mossâmedes Sequence (Simões, 1984), west/northwest of Anicuns, has been interpreted to be of Mesoproterozoic age, equivalent to the Araxá Group, and (iii) a younger detrital sequence (conglomerates, quartzites and schists) forming the roughly E-W Serra Dourada ridge to the north. The north/south supracrustal sequence, referred to as the Anicuns-Itaberaí Sequence

(AIS) by Barbosa (1987), has been divided into two distinct geological units by Nunes (1990): (i) the Córrego da Boa Esperança Sequence (CBES) in the west has been correlated with the Araxá Group and consists of metapelites, andesitic/dacitic meta-tuffs, and iron formation (Nunes, 1990) (Fig. 2.3); (ii) the AIS in the east, separated from the CBES by a NNW reverse fault, is composed of mafic/ultramafic metavolcanic rocks, metacherts, metarhytmites, and marble lenses. It was correlated with the Serra de Santa Rita greenstone belt (Fig. 2.2).

Both Nunes (1990) and Barbosa (1987) have suggested that the metavolcanic rocks in this region have calc-alkaline or calc-alkaline/tholeiitic nature, indicating a magmatic arc setting for their origin.

Three generations of granitic rocks, as well as small mafic and mafic-ultramafic bodies are intrusive into the supracrustal sequences. The granitoid intrusions are tonalites, granodiorites, and granites with subordinate quartz syenite, monzonites, and monzodiorites (Barbosa, 1987; Nunes, 1990).

The mafic/intermediate intrusions are collectively referred to as the Anicuns-Santa Bárbara Gabbro-Diorite Suite (Lacerda Filho and Oliveira, 1995). Two examples of this suite, the Córrego Seco (Nunes, 1990) and Santa Bárbara (Silva and Nilson, 1990) intrusions, were investigated in this study (Figs. 2.3 and 2.4). The Córrego Seco Complex (Fig. 2.3) comprises gabbro, diorite and amphibolite and, in some places, crosscutting relationships with the AIS are observed. This complex has been correlated with the Americano do Brasil intrusion, exposed to the north of the AIS (Pfrimer et al., 1981; Nunes, 1990) (Fig. 2.5). The Santa Bárbara Gabbro-Anorthosite Complex (Fig. 2.4) is made up dominantly of metagabbro and meta-anorthosite, with minor ultramafic rocks; it has been interpreted as a metamorphosed layered mafic-ultramafic intrusion (Silva and Nilson, 1990).

The Americano do Brasil Mafic-Ultramafic Suite comprises small layered bodies known as the Americano do Brasil, Mangabal I, Mangabal II, Adelândia, Fronteira do Norte, Palmeiras, and Serra do Gongomé, exposed to the north of the investigated area (Pfrimer et al., 1981; Nilson 1981, 1984; Candia and Girardi, 1985; Winge, 1995). The Americano do Brasil intrusion (Fig. 2.5) includes metagabbro, metagabbronorite, olivine gabbro, amphibolite, metadunite, metaperidotite, metapyroxenite, and hornblendite (Nilson, 1984). The Serra do Gongomé and Americano do Brasil complexes have been dated at 637 ± 19 Ma and 610 ± 50 Ma, by Rb-Sr and Sm-Nd whole-rock isochrons, respectively (Winge, 1995; Gioia, 1997) (Table 2.1b). The high initial Sr isotopic ratio of the Gongomé intrusion (0.7153) indicates interaction with older continental crust, whereas the positive $\varepsilon_{Nd}(T)$ value (approximately +2.4) of the Americano do Brasil original magma indicates little or no contamination with ancient sialic crust.

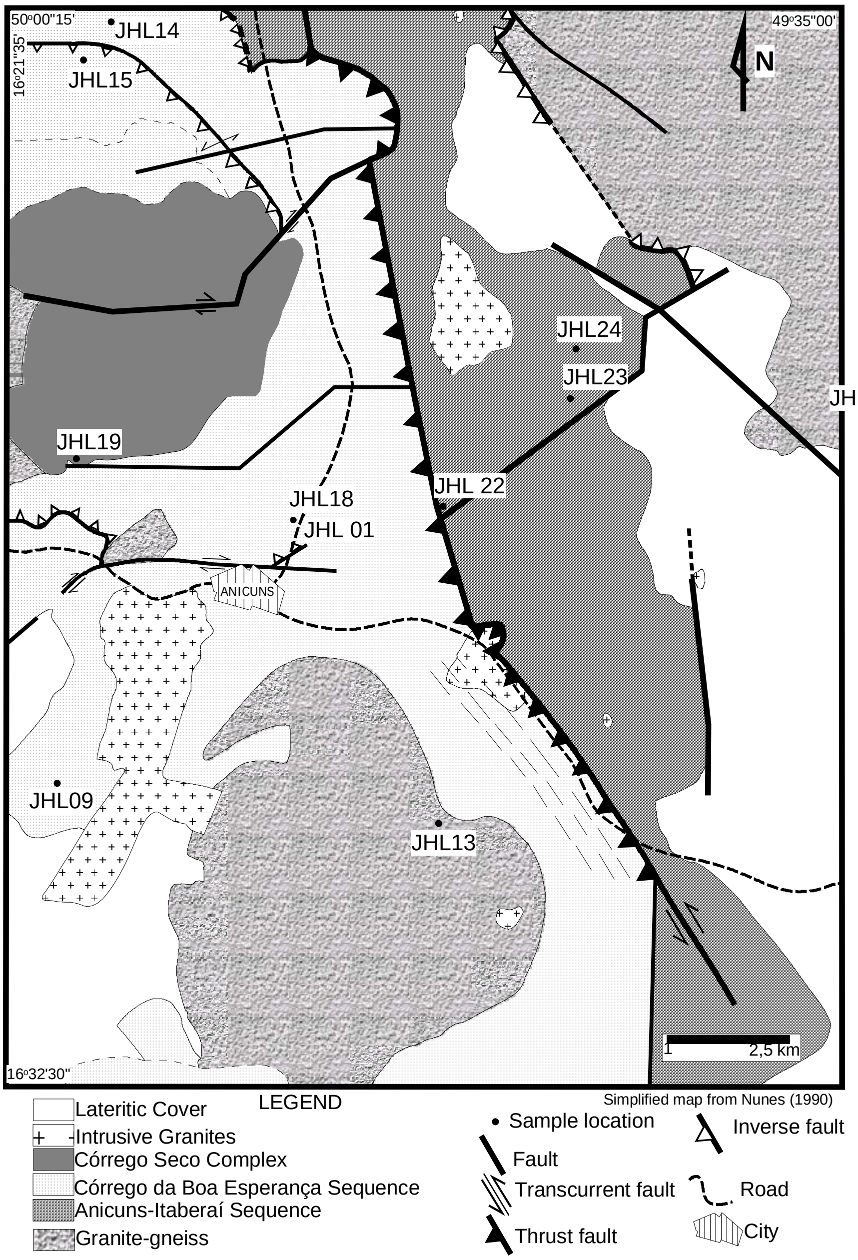

Figure 2.3 - Geological map of the Anicuns region, with location of the studied samples (simplified from Nunes, 1990).

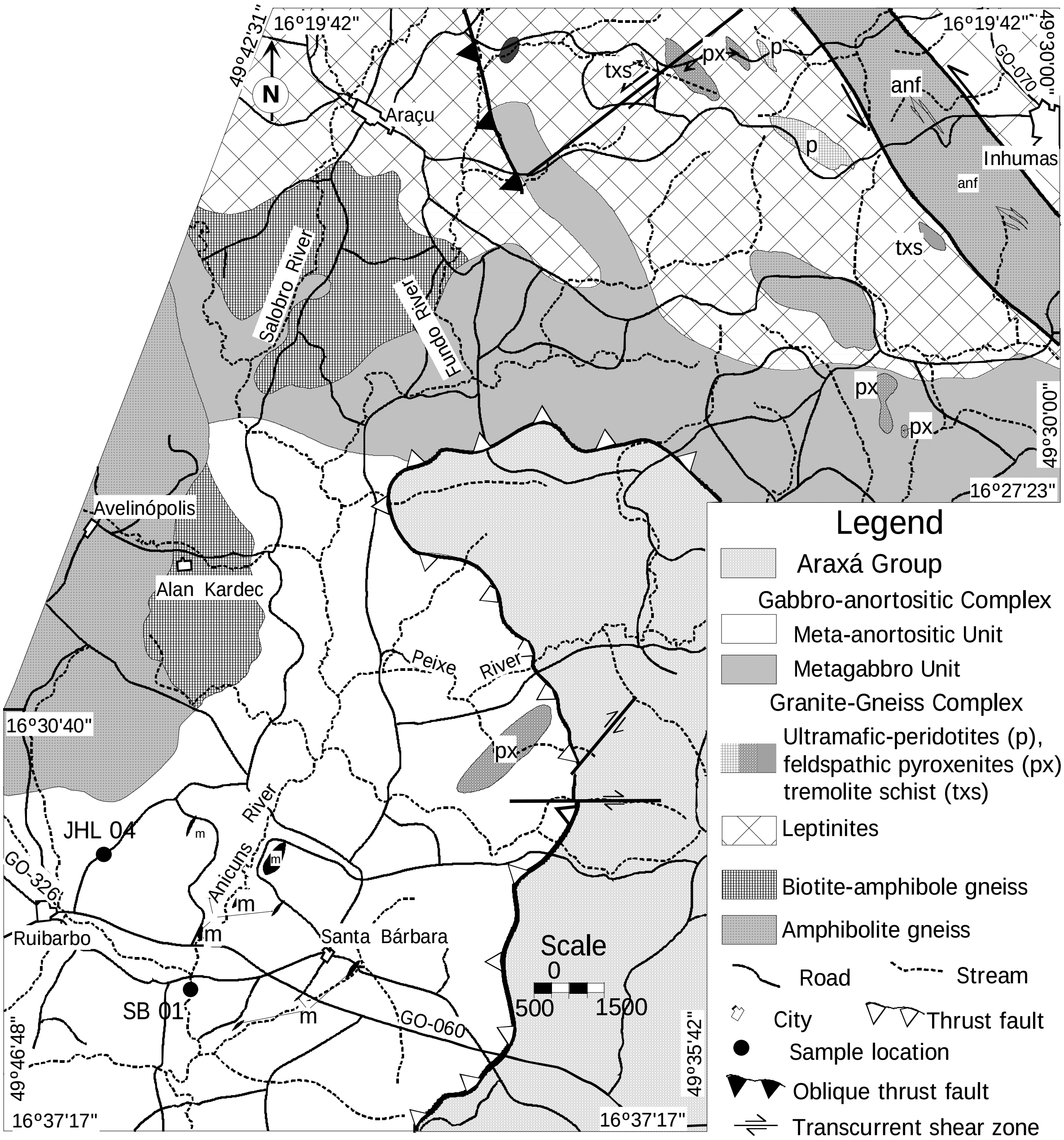

Figure 2.4 - Geological map of the Santa Bárbara de Goiás-Inhumas region, Goiás Brazil (after Silva and Nilson, 1990).

2.4 ANALYTICAL PROCEDURES

Zircon concentrates were extracted from ca. 10 kg rock samples, using conventional gravimetric (DENSITEST®) and magnetic (Frantz isodynamic separator) techniques at the Geochronology Laboratory of the University of Brasília. Final purification was achieved by hand picking using a binocular microscope.

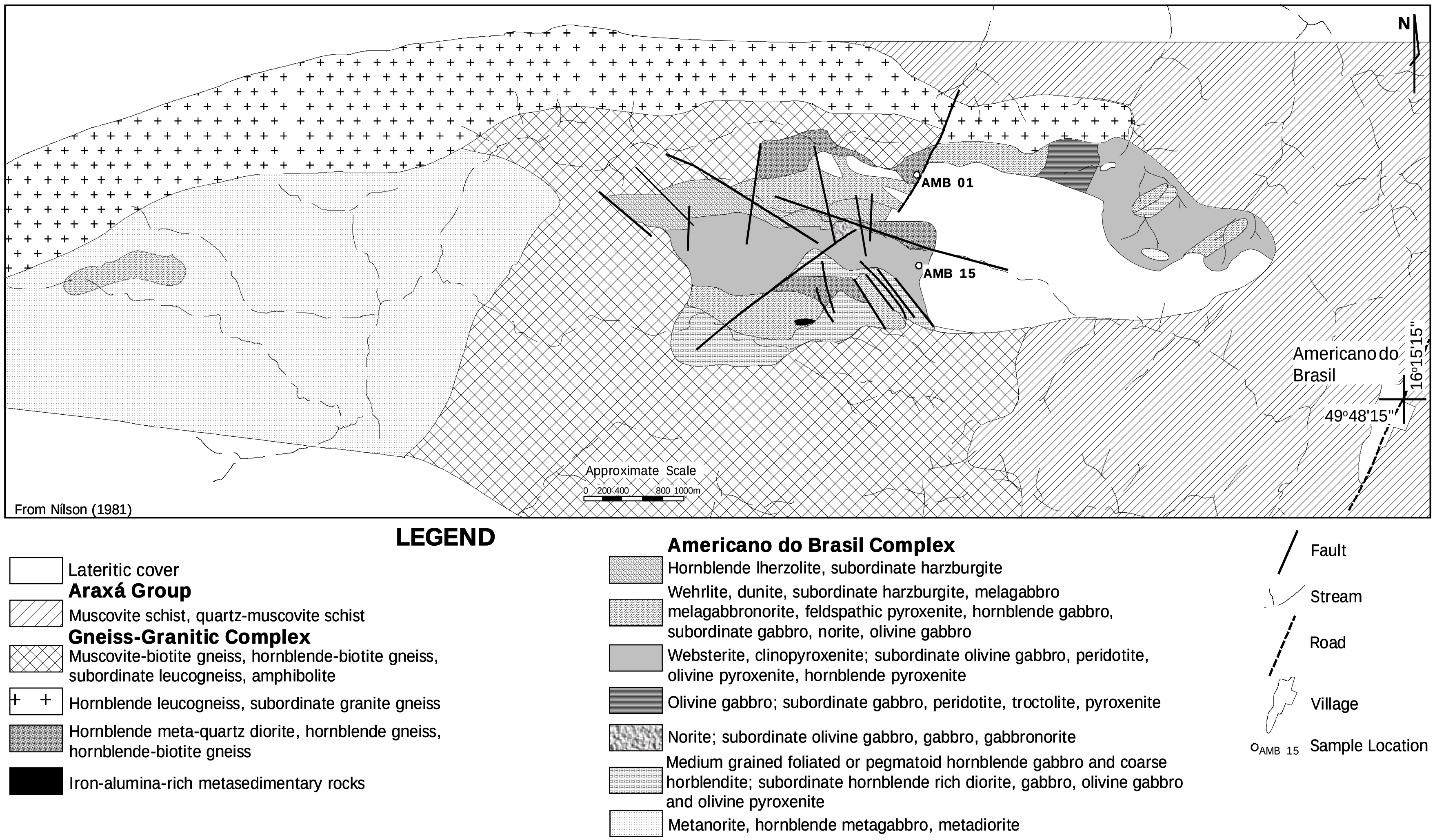

Figure 2.5 - Geological map of the Americano do Brasil Layered Complex (from Nilson, 1981).

For conventional U-Pb analyses, fractions were dissolved in concentrated HF and HNO_3 ($HF:HNO_3$ = 4:1) using microcapsules in Parr-type bombs. A mixed ^{205}Pb-^{235}U spike was used. Chemical extraction followed standard anion exchange technique, using Teflon microcolumns, following procedures modified from Krogh (1973). Pb and U were loaded together onto single Re filaments with H_3PO_4 and silica gel, and isotopic analyses were carried out at the Geochronology Laboratory of the University of Brasília on a Finnigan MAT-262 multi-collector mass spectrometer equipped with secondary electron multiplier - ion counting. Procedure blanks for Pb, at the time of analyses, were better than 20 pg. PBDAT (Ludwig, 1993) and ISOPLOT-Ex (Ludwig, 2001a) were used for data reduction and age calculation. Errors for isotopic ratios are 2σ. Ion microprobe analyses were carried out using SHRIMP I at the Research School of Earth Sciences, Australian National University, Canberra, Australia. Zircon grains were mounted in epoxy resin and polished. Transmitted and reflected light microscopy, as well as scanning electron microscope cathodoluminescence imagery was used to investigate the internal structures of the zircon crystals prior to analysis. Data were collected and reduced as described by Williams and Claesson (1987) and Compston et al., (1992). Uncertainties are given at 1σ level, and final age quoted at 95% confidence levels. Reduction of raw data was carried out using Squid 1.02 (Ludwig, 2001b). U/Pb ratios were referenced to the RSES standard zircon AS3 (1099 Ma, $^{*206}Pb/^{238}U$ = 0.1859, Paces and Miller, 1993). U and Th concentrations were determined relative to those measured in the RSES standard SL13.

Sm-Nd isotopic analyses followed the method described by Gioia and Pimentel (2000) and were carried out at the Geochronology Laboratory of the University of Brasília. Whole rock powders (ca. 50 mg) were mixed with ^{149}Sm-^{150}Nd spike solution and dissolved in Savillex capsules. Sm and Nd extraction of whole-rock samples followed conventional cation exchange techniques, using Teflon columns containing LN-Spec resin (HDEHP – diethylhexil phosphoric acid supported on PTFE powder). Sm and Nd samples were loaded on Re evaporation filaments of double filament assemblies and the isotopic measurements were carried out on a multi-collector Finnigan MAT 262 mass spectrometer in static mode. Uncertainties of Sm/Nd and

$^{143}Nd/^{144}Nd$ ratios are better than ±0.4% (1σ) and ±0.005% (1σ) respectively, based on repeated analyses of international rock standards BHVO-1 and BCR-1. $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd$ of 0.7219 and the decay constant used was 6.54×10^{-12} a^{-1}. T_{DM} values were calculated using the DePaolo (1981) model.

2.5 RESULTS AND DISCUSSION

Nine new ID-TIMS ages and one SHRIMP U-Pb age, as well as sixteen new Sm-Nd isotopic results of mafic rocks of the Anicuns region are discussed in this work (Fig. 2.6). Mafic rocks from the four main distinct geological units recognized in the area have been investigated: Córrego da Boa Esperança and Anicuns-Itaberaí sequences, the Anicuns-Santa Bárbara Gabbro-Diorite Intrusive Suite, and the Americano do Brasil intrusion. One additional diorite sample (AMB-01) representing the country-rocks of the Americano do Brasil intrusion was also studied.

2.5.1 Córrego da Boa Esperança Sequence

Zircon crystals from two amphibolite samples within the Córrego da Boa Esperança Sequence [samples JHL-14, JHL-15 (Fig 2.3) (Tables 2.2 and 2.3)] were dated by the U-Pb method. JHL-14 is an amphibole-garnet schist, most likely derived from a gabbro. Zircon grains separated from this sample were analysed using SHRIMP-RG. Cathodoluminescence images reveal that the zircon grains present well developed sector zoning typical of crystals formed from mafic magmas (Fig. 2.7b). Analyses of 13 spots on 12 zircon grains yield a concordia age of 886 ± 5 Ma (Fig. 2.7a), interpreted as the crystallization age of the original magma. The date is identical, within error, to the SHRIMP U-Pb age observed for the Morro do Baú intrusion within the Arenópolis Volcano-Sedimentary Sequence, in the western part of the Goiás Magmatic Arc (Pimentel et al., 2003). Sm-Nd isotopic analysis of the JHL-14 sample yielded a strongly positive $\varepsilon_{Nd}(T)$ of +4.4, indicative of the depleted nature of the mantle source (Table 2.4).

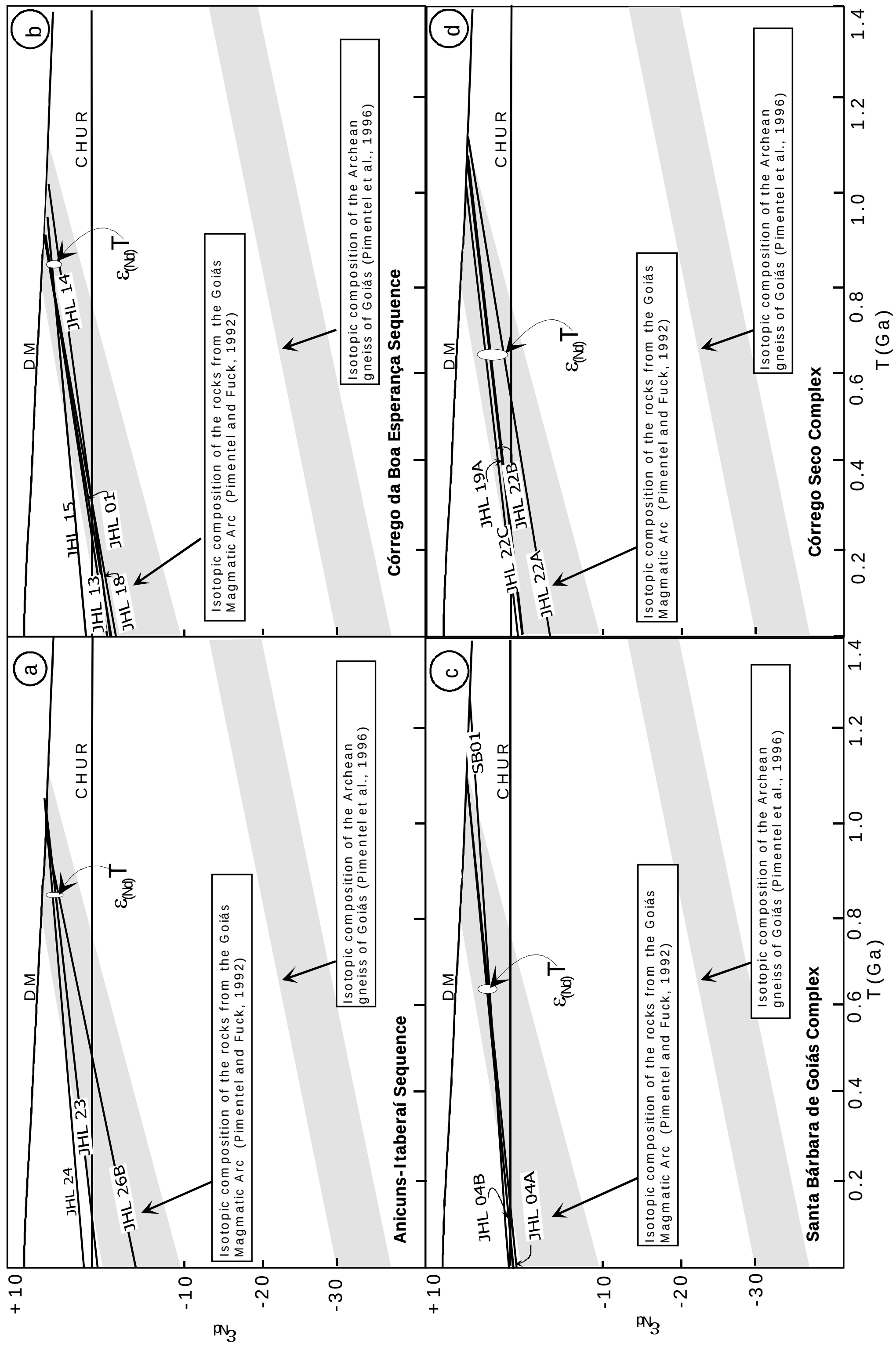

Figure 2.6 - Evolution diagram of ε_{Nd} x Time, showing patterns similar to Goiás Magmatic Arc of Pimentel and Fuck (1992); (a) Córrego da boa Esperaça Sequence, (b) Anicuns-Itaberaí Sequence, (c) Santa Bárbara de Goiás Complex, (d) Córrego Seco Complex.

Sample JHL-15 is an amphibole schist, which is most likely also derived from the metamorphism and deformation of a small plutonic or sub-volcanic intrusion. Zircon grains in this sample form yellow, long prismatic crystals. Four zircon fractions define a discordia indicating the upper intercept age of 862 ± 5 Ma (Fig. 2.8a). Sm-Nd isotopic composition of this sample also indicate derivation of the original mafic magma from a depleted mantle source, with ε_{Nd}(T) of +5.5 (Table 2.4). Other amphibolite samples associated with the Córrego da Boa Esperança Sequence, samples JHL-1, JHL-9, JHL-13, and JHL-18, also present positive ε_{Nd}(T) values between +4 and +5 at T = 830 Ma (reference Sm-Nd isochron age – Fig. 2.9), with T_{DM} values of ca. 1.0 Ga (Table 2.2). Samples JHL-1 and JHL-18 are fine-grained amphibolites/metabasalts, whereas JHL-9 and JHL-13 are metagabbros.

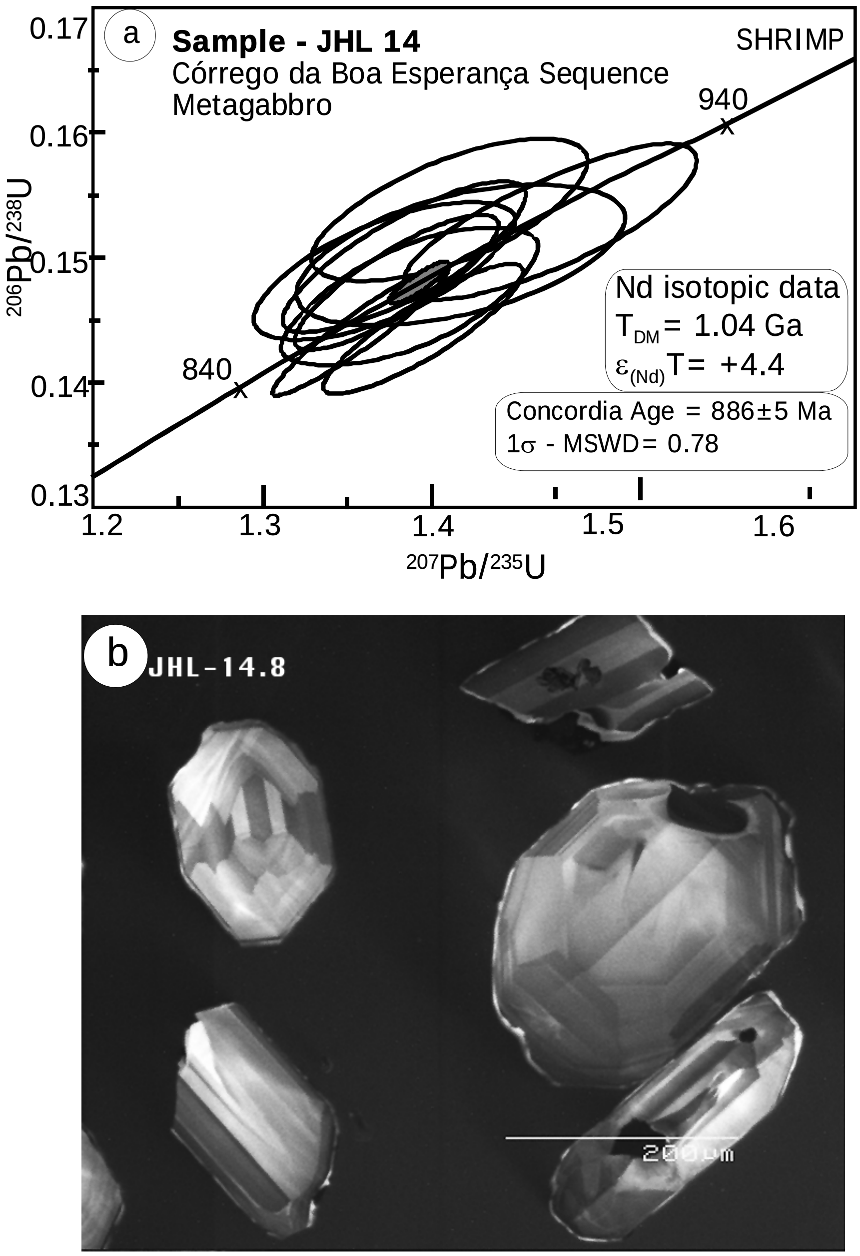

Figure 2.7 - SHRIMP U-Pb concordia diagram for sample JHL-14 (a), and zircon cathodoluminescence images (b).

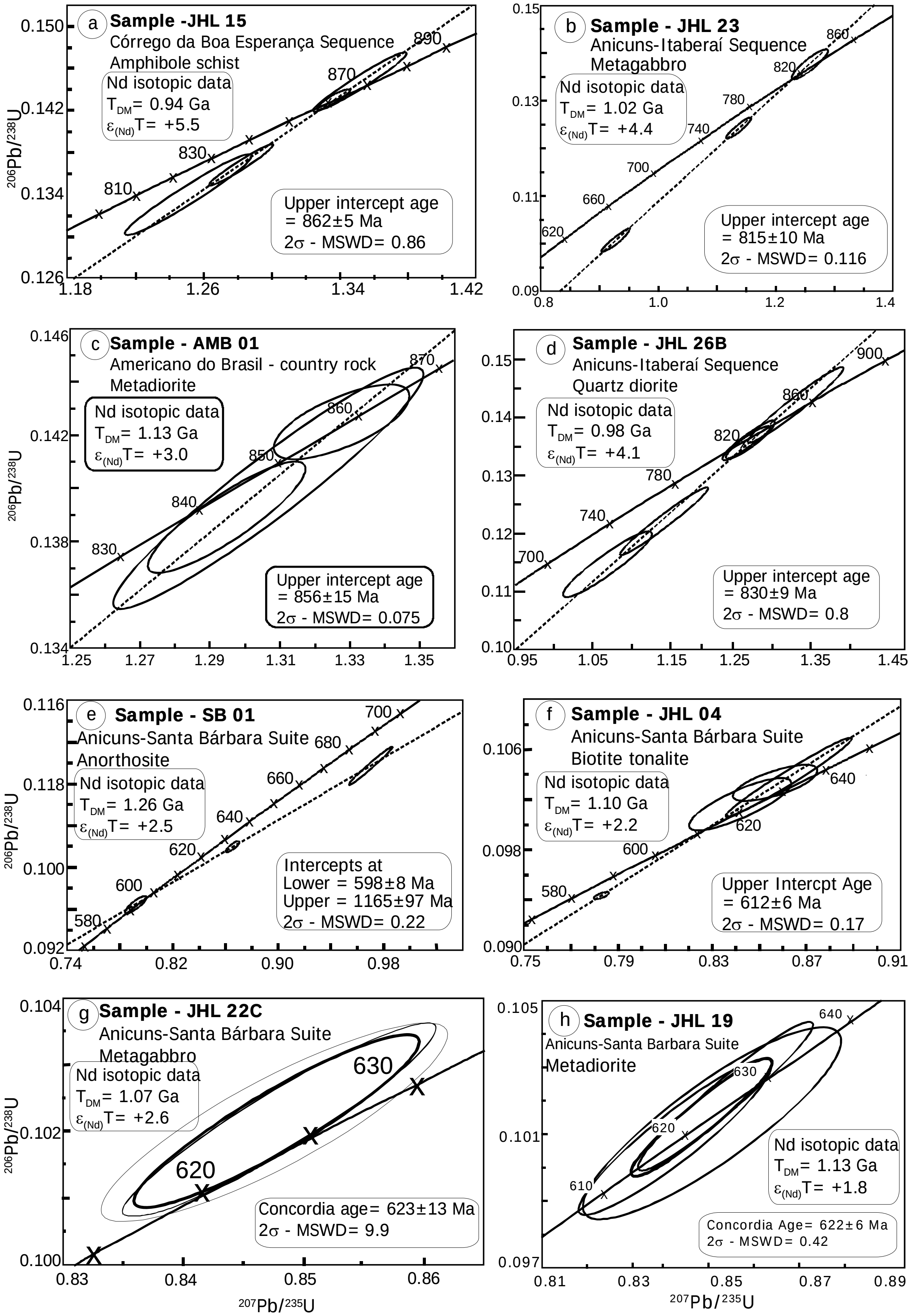

Figure 2.8 - ID-TIMS U-Pb concordia diagram for Anicuns-Itaberaí Sequence (b, d); Córrego da Boa Esperança Sequence (a); Córrego Seco Complex (g, h); Santa Bárbara de Goiás Complex (e, f); and Americano do Brasil Layered Complex dioritic country rock (c).

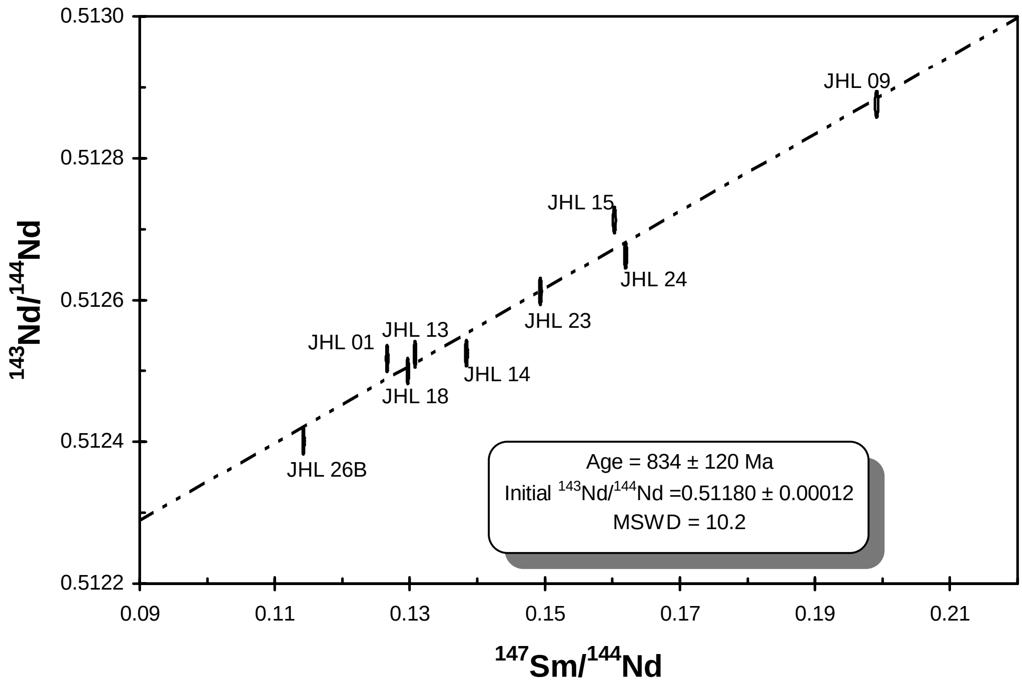

Figure 2.9 – Reference Sm-Nd whole-rock isochron for the mafic rocks.

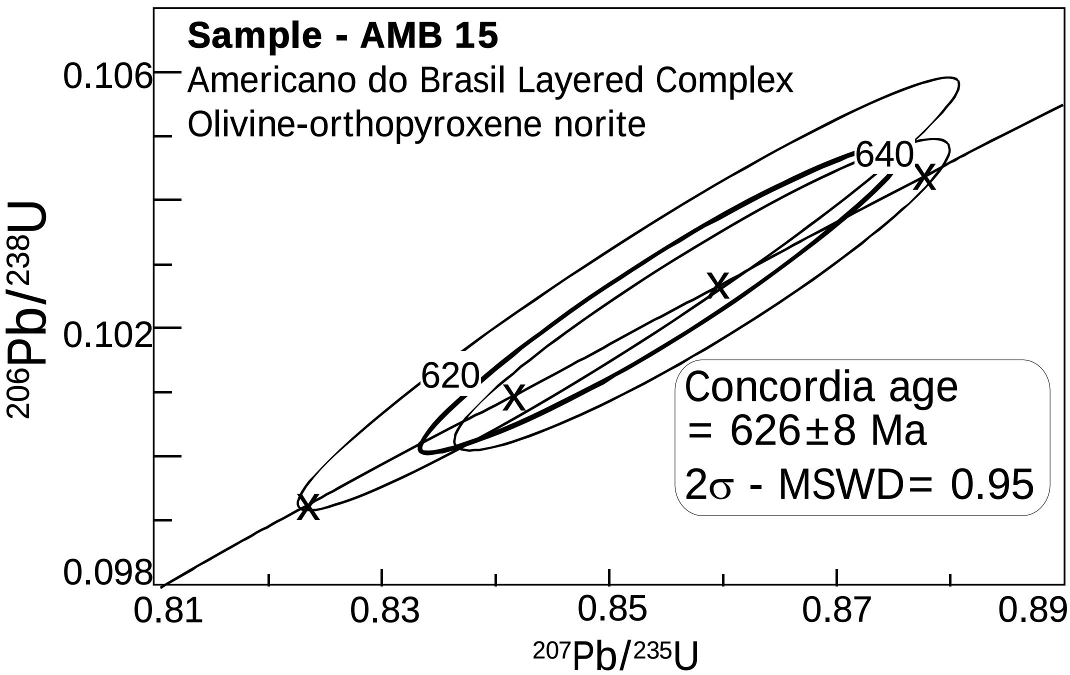

Figure 2.10 – ID-TIMS U-Pb concordia diagram for Americano do Brasil Layered Complex.

2.5.2 Anicuns-Itaberaí Sequence

Two samples from the Anicuns-Itaberaí Sequence were studied (Table 2.3). Sample JHL-26B is a quartz diorite with preserved igneous texture, whereas JHL-23 is a coarse-grained amphibolite (metagabbro). Zircon grains from JHL-26B are prismatic and yellowish, and the analyses of five zircon fractions align along a discordia indicating the upper intercept age of 830 ± 9 Ma (Fig. 2.8d). The Nd isotopic composition of this sample reveals the depleted nature of the mantle source with an ε_{Nd}(T) of +4.1 (Table 2.4).

Zircon grains separated from JHL-23 are prismatic and brownish yellow, and they yielded an upper intercept age of 815 ± 10 Ma (Fig. 2.8b), interpreted as the igneous crystallization age, and identical, within uncertainty, to the age of sample JHL-26B. The Nd isotopic composition also demonstrates origin from a depleted mantle, with an ε_{Nd}(T) of +4.4 (Table 2.4).

An additional amphibolite sample of this sequence has ε_{Nd}(850 Ma) of +4.3 and T_{DM} model age of 0.98 Ga (Table 2.4) (reference Sm-Nd isochron age – Fig. 2.9).

2.5.3 Anicuns-Santa Bárbara Gabbro-Diorite Suite

Four selected samples from the Anicuns-Santa Bárbara Gabbro-Diorite Suite were investigated (JHL-22C, JHL-19, JHL-04, SB-01; Figs. 2.3 and 2.4; Table 2.3). Sample JHL-19 corresponds to a diorite belonging to the Córrego Seco Complex, intrusive into the Córrego da Boa Esperança Sequence. Zircon crystals are colorless and needle-shaped, and yield the concordia age of 622 ± 6 Ma (Fig. 2.8h). Nd isotopic composition indicates derivation of the original magma from a depleted mantle source, with an ε_{Nd}(T) of +1.8 (Table 2.4). Sample JHL-22C is an amphibolite/metagabbro intrusive into the Anicuns-Itaberaí Sequence. Analyses of two zircon fractions are semi-concordant indicating the crystallization age of 623 ± 13 Ma (Fig. 2.8g), identical, within error, to sample JHL-19. Initial Nd isotopic characteristics also indicate a depleted mantle source (ε_{Nd}(T) = +2.6) (Table 2.4). Samples JHL-04 and SB-01 are from the Santa Bárbara de Goiás Complex (Silva and Nilson, 1990). Anorthosite SB-01 has anhedral, colorless zircon crystals. One concordant analysis indicates the $^{206}Pb/^{238}U$ age of 594 ± 10 Ma. The other two analytical points seem to have incorporated some inherited Pb. A discordia line through the three points indicates a lower intercept age of 598 ± 8 Ma, interpreted as the crystallization age, and the upper intercept age of 1165 ± 97 Ma, suggesting Mesoproterozoic inheritance (Fig. 2.8e). Sample JHL-04 is a biotite tonalite with an upper intercept zircon age of 612 ± 6 Ma (Fig. 2.8f), interpreted as the age of igneous crystallization of the original magma. Nd isotopic characteristics of Santa Bárbara samples also indicate derivation of the original magma from a depleted mantle with ε_{Nd}(T) values between +2.2 and +2.5 (Table 2.4). Sample SB-01 (Santa Bárbara de Goiás Anorthosite) displays a slightly older T_{DM} value of 1.25 Ga (Table 2.4), suggesting a small contribution from an older source, which is also indicated by the inheritance pattern observed for that sample.

Two additional samples of the Anicuns-Santa Bárbara Gabbro-Diorite Suíte (JHL-22a and b) present ε_{Nd}(T= 630 Ma) of + 0.8 and +2.6, respectively, and a T_{DM} of ca. 1.0 Ga.

2.5.4 Americano do Brasil Layered Complex

Zircon grains separated from one sample of the Americano do Brasil intrusion and one from a country-rock diorite have been investigated (Table 2.3). Sample AMB-15 is an olivine-othopyroxene norite and zircon grains separated from it are anhedral, light brown, and produced two concordant analyses with the age of 626 ± 8 Ma (Fig. 2.10). Initial Nd isotopic composition indicated by the whole-rock Sm-Nd isochron of this rock unit (Gioia, 1997) also indicates origin of the parental basic magma from a depleted mantle source (ε_{Nd}(T) of +2.4).

Sample AMB-01 is a metadiorite with preserved igneous texture, representing the country rocks of the Americano do Brasil intrusion. The prismatic zircon grains analyzed result in concordant to semi-concordant analytical points indicating the crystallization age of 856 ± 15 Ma (Fig. 2.8c). The ε_{Nd}(T) value of this sample is positive (+3.0), indicating the primitive nature of the original magma.

2.6 CONCLUSIONS

The new U-Pb results demonstrate that mafic rocks associated with the Anicuns-Itaberaí and Córrego da Boa Esperança sequences are Neoproterozoic and crystallized during two main time intervals: (i) between ca. 890 and 815 Ma, and (ii) between ca. 630 and 600 Ma. The geochronological results, coupled with field data and Nd isotopic characteristics of metasedimentary rocks of the supracrustal associations (Laux et al., 2001), suggest that the Anicuns-Itaberaí and Córrego da Boa Esperança sequences are roughly of the same age. This is also demonstrated by a reference Sm-Nd isochron age for amphibolite samples of the Anicuns-Itaberaí and Córrego da Boa Esperança sequences (Fig. 2.9), showing also that the original magmas of amphibolites from both sequences have similar ε_{Nd}(T), suggesting similar petrogenetic processes and perhaps same tectonic setting of origin.

Although the Anicuns-Santa Bárbara gabbro-diorite and Americano do Brasil suites have the same age, they might not be genetically equivalent, as suggested by some authors (Nilson, 1984; Silva and Nilson, 1990).

All mafic rocks analysed present T_{DM} model ages of ca. 1.0 Ga, equivalent to model ages found for rocks of the Goiás Magmatic Arc (Fig. 2.7; Pimentel and Fuck, 1992). ε_{Nd}(T) values are strongly positive, indicative of the depleted nature of the mantle source (MORB-like). However, the lithological associations found in these supracrustal sequences are different from other island arc-like sequences of the Goiás Magmatic Arc, in which felsic and intermediate volcanic products are abundant (e.g. the Arenópolis Sequence; Pimentel and Fuck, 1986). The conspicuous presence of metachert, marble, metapelite and the dominance of mafic metaigneous rocks suggest that these supracrustal sequences in the Anicuns region are equivalent to the Córrego Santo Antônio Unit, underlying the western part of the Arenópolis Sequence, which has been interpreted as an oceanic or fore-arc sequence. $^{147}Sm/^{144}Nd$ ratios of most of the mafic rocks investigated are less than 0.19 and indicate a relative enrichment in LREE, which is not characteristic of N-MORB mafic magmas.

The area of exposure of the Anicuns-Itaberaí Sequence coincides with a regionally important gravimetric discontinuity (Fig. 2.2) indicating that it marks an important crustal boundary, possibly separating juvenile rocks of the Goiás Magmatic Arc to the west from rocks of the Anápolis-Itauçu Complex to the east, where older crustal components are registered in the Nd isotopic compositions of the igneous rocks (Piuzana et al., 2003a). This is suggested also by the initial isotopic compositions and inheritance patterns displayed by the mafic rocks around the Anicuns area. To the west of the gravimetric discontinuity, mafic rocks are pristine, and present positive ε_{Nd}(T) values, whereas mafic rock associations towards the east display evidence of contamination of the original magmas with older crust. For instance, the Gongomé intrusion has very high initial Sr isotopic ratio (0.7153) (Winge, 1995), rocks of the Santa Bárbara de Goiás Complex have inherited zircon grains of possible Mesoproterozoic age, and the Goianira-Trindade layered intrusion has a Sm-Nd isochron age of ca. 621 Ma with an ε_{Nd}(T) value of 0.0 (M.M. Pimentel, unpublished results).

Based on the field, geochronological, isotopic and regional geophysical data, we suggest that the supracrustal sequence exposed in the Anicuns area might represent a fore-arc or back-arc sequence, marking the tectonic boundary between the Goiás Magmatic Arc and the westernmost exposures of the former São Francisco continental plate.

Table 2.2 Summary of SHRIMP U-Pb data for sample JHL-14.

Grain Spot	U ppm	Th ppm	^{206*}Pb/^{204}Pb	$^{(1)206}$Pb/^{238}U Age	1σ err	$^{(1)207}$Pb/^{206}Pb Age	1σ err	% Dis cor dant	Total ^{238}U/^{206}Pb	% err	Total ^{207}Pb/^{206}Pb	% err	$^{(1)207*}$Pb/^{206*}Pb	% err	$^{(1)207*}$Pb/^{235}U	% err	$^{(1)206*}$Pb/^{238}U	% err	err corr
JHL14-1.2	106	73	15783.1	919.9	20.5	934	43	1	6.51	2.4	0.0711	1.2	0.0702	2.1	1.48	3.2	0.1534	2.4	0.749
JHL14-2.2	78	44	697.7	924.7	21.5	1069	169	16	6.32	2.5	0.0954	4.3	0.0750	8.4	1.60	8.8	0.1542	2.5	0.285
JHL14-7.1	40	21	1687.8	907.0	21.9	616	66	-32	6.55	2.6	0.0689	2.0	0.0603	3.1	1.26	4.0	0.1511	2.6	0.644
JHL14-8.1	84	64	4273.3	894.6	20.7	824	49	-8	6.69	2.5	0.0699	1.5	0.0666	2.4	1.37	3.4	0.1489	2.5	0.724
JHL14-8.2	57	28	6831.3	900.2	21.1	886	78	-2	6.66	2.5	0.0707	1.8	0.0686	3.8	1.42	4.5	0.1499	2.5	0.554
JHL14-9.1	154	173	16895.6	887.4	19.5	862	30	-3	6.77	2.4	0.0686	1.1	0.0678	1.4	1.38	2.8	0.1476	2.4	0.853
JHL14-10.1	55	23	3675.1	921.0	21.9	825	59	-10	6.48	2.5	0.0705	1.9	0.0666	2.8	1.41	3.8	0.1536	2.5	0.669
JHL14-11.1	91	44	15761.0	900.0	23.0	838	42	-7	6.67	2.7	0.0679	1.5	0.0670	2.0	1.38	3.4	0.1498	2.7	0.802
JHL14-12.1	61	26	9215.4	881.9	20.8	887	53	1	6.81	2.5	0.0702	1.8	0.0686	2.6	1.39	3.6	0.1466	2.5	0.702
JHL14-13.1	177	107	10935.8	889.2	20.5	858	32	-3	6.75	2.5	0.0690	1.2	0.0677	1.5	1.38	2.9	0.1479	2.5	0.850
JHL14-14.1	122	74	16378.4	867.9	19.4	935	28	8	6.93	2.4	0.0711	1.3	0.0702	1.4	1. 40	2.8	0.1441	2.4	0.865
JHL14-15.1	407	184	32739.6	868.5	18.6	879	16	1	6.93	2.3	0.0688	0.7	0.0684	0.8	1.36	2.4	0.1442	2.3	0.950
JHL14-16.1	322	150	12026.6	867.6	19.3	880	18	1	6.93	2.4	0.0696	0.8	0.0684	0.9	1.36	2.5	0.1441	2.4	0.940

(1) Common Pb corrected using measured ^{204}Pb.

Error in Standard calibration was 1.11% (not included in above errors but required when comparing data from different mounts).

Table 2.3 Summary of ID-TIMS U-Pb data for the mafic rocks.

Sample/ Fraction	Size (mg)	U ppm	Pb ppm	Th ppm	Pb^{206}/Pb^{204}	Pb^{207*}/Pb^{235}	(pct)	Pb^{206*}/U^{238}	(pct)	Correl. Coeff. (rho)	Pb^{207*}/Pb^{206*}	(pct)	Pb^{206*}/U^{238} Age	$Pb^{207}/^{*}U^{235}$ Age	$Pb^{207}/^{*}Pb^{206*}$ Age	(Ma)	Quant.
JHL 15 D13 [1]	0.025	46.8	66.5	43.5	380.55	1.251	2.44	0.134	2.34	0.965	0.0677	0.63	810	824	859	13	1
JHL 15 D14 [1]	0.039	64.2	9.3	27.9	798.54	1.282	1.18	0.136	1.15	0.973	0.0679	0.27	826	837	867	5.6	1
JHL 15 18 [1]	0.019	86.2	13.5	57.3	586.29	1.351	1.63	0.144	1.57	0.969	0.0677	0.39	870	868	861	8.3	2
JHL 15 19[1]	0.035	107.5	16.4	31.1	1476.53	1.336	0.59	0.143	0.53	0.921	0.0677	0.23	861	861	861	4.8	3
JHL 23 E15[2]	0.021	137.0	23.1	51.8	274.52	1.258	2.05	0.137	1.83	0.903	0.0663	0.88	831	827	816	18	1
JHL 23 D2[2]	0.034	29.7	4.3	32.0	390.89	1.137	1.55	0.124	1.45	0.944	0.0663	0.51	755	771	818	11	1
JHL 23 D3[2]	0.021	85.5	9.4	51.8	392.39	0.928	2.15	0.101	2.03	0.951	0.0668	0.66	618	667	934	14	1
JHL 26B E12[2]	0.030	89.5	15.3	36.2	271.24	1.310	1.93	0.142	1.87	0.971	0.0668	0.46	856	850	833	9.7	1
JHL 26B D2[2]	0.034	44.1	6.8	32.0	616.34	1.250	1.09	0.136	1.01	0.933	0.0666	0.39	822	823	826	8.2	1
JHL 26B D5[2]	0.041	40.7	6.3	26.5	650.57	1.250	0.95	0.135	0.85	0.910	0.0668	0.39	820	823	832	8.2	2
JHL 26B 2[2]	0.042	76.3	10.5	25.9	410.15	1.140	2.01	0.122	1.95	0.974	0.0678	0.45	742	773	864	9.5	1
JHL 26B 1[2]	0.037	85.5	11.7	29.4	267.45	1.070	2.17	0.114	2.02	0.931	0.0676	0.79	699	738	857	16	1
JHL 19 12[3]	0.022	137.8	16.9	49.4	215.02	0.847	2.73	0.101	2.30	0.867	0.0606	1.36	622	623	627	29	4
JHL 19 11[3a]	0.013	166.6	18.7	83.7	402.37	0.839	2.07	0.101	1.88	0.921	0.0603	0.80	619	618	615	17	1
JHL 19 15[3a]	0.019	106.4	11.8	57.2	453.26	0.850	1.85	0.102	1.77	0.966	0.0601	0.47	626	624	617	10	2
JHL 22C 5[3b]	0.020	78.1	9.1	54.4	448.34	0.847	1.39	0.102	1.18	0.865	0.0602	0.69	626	623	610	15	2
JHL 22C 2[3b]	0.036	87.6	9.2	30.2	621.76	0.848	1.26	0.102	1.17	0.939	0.0602	0.43	627	623	610	9.4	1
JHL 04 D10[3c]	0.017	83.8	9.4	64	332.46	0.862	2.54	0.103	2.48	0.981	0.0603	0.48	636	631	614	10	1
JHL 04 D6[3c]	0.016	99.4	11.4	68	465.10	0.856	1.72	0.103	1.15	0.714	0.0601	1.20	633	628	609	26	1
JHL 04 D9[3c]	0.029	77.0	8.5	37.5	432.70	0.842	2.11	0.101	1.66	0.819	0.0601	1.21	623	620	606	26	1
JHL 04 D9[3c]	0.144	199.8	19.2	7.5	5232.00	0.783	0.33	0.094	0.25	0.782	0.0602	0.20	581	587	610	4.4	1
SB 01 D[3c]	0.038	60.02	6.4	28.6	1468.10	0.860	0.49	0.102	0.41	0.847	0.0615	0.26	625	633	658	5.6	1
SB 01 L[3c]	0.041	120.6	13.2	26.5	689.68	0.970	1.39	0.109	1.37	0.985	0.0641	0.23	670	688	746	5	1
SB 01 19[3c]	0.072	97.7	9.5	15.1	938.38	0.790	0.83	0.096	0.69	0.853	0.0596	0.43	593	592	588	9.4	2
AMB 15 M[4a]	0.033	95.7	10.9	32.9	630.48	0.851	2.79	0.102	2.68	0.963	0.0602	0.74	629	625	612	16	1
AMB 15 O[4a]	0.031	61.3	6.7	35.1	487.56	0.858	2.07	0.102	1.93	0.941	0.0607	0.69	629	629	629	15	1
AMB 01 4[4b]	0.025	215.7	32.8	43.5	1417.10	1.290	0.71	0.138	0.62	0.869	0.0676	0.35	838	843	856	7.3	1
AMB 01 3[4b]	0.024	71.2	11.3	45.3	1281.10	1.320	0.59	0.142	0.39	0.704	0.0675	0.42	858	857	855	8.8	1
AMB 01 2[4b]	0.019	165.7	25.4	109.9	1007.80	1.300	1.39	0.140	1.32	0.951	0.0676	0.43	844	848	858	8.9	1

[1]- Córrego da Boa Esperança Sequence; [2]- Anicuns-Itaberaí Sequence; [3a]- Anicuns-Santa Bárbara Suíte - Córrego Seco Complex (intrusive in Córrego da Boa Esperança Sequence); [3b]- Anicuns-Santa Bárbara Suíte - Córrego Seco Complex (intrusive at Anicuns Itaberaí Sequence); [3c]- Anicuns-Santa Bárbara Suíte - Santa Bárbara de Goiás Complex; [4a]- Americano do Brasil Layered Complex; [4b]- Americano do Brasil Layered Complex – country rock.

Table 2.4 Sm-Nd results for the mafic rocks.

	Sm	Nd	$^{143}Nd/^{144}Nd$ (±2SE)	$^{147}Sm/^{144}Nd$	$\varepsilon_{(0)}$	$\varepsilon_{(T)}$	T_{DM}(Ga)
JHL01[1]	6.16	29.40	0.512517(±5)	0.1266	-2.3	--	0.92
JHL 09[1]	2.11	6.42	0.512876(±10)	0.1991	4.6	--	--
JHL13[1]	6.60	30.52	0.512524(±17)	0.1308	-2.2	--	0.95
JHL14[1]	2.12	9.25	0.512542(±6)	0.1387	-1.9	+4.4	1.01
JHL15[1]	2.64	9.95	0.512713(±6)	0.1603	1.5	+5.5	0.94
JHL18[1]	6.50	29.23	0.512500(±6)	0.1297	-2.7	--	0.98
JHL23[2]	3.44	13.94	0.512612(±6)	0.1493	-0.5	+4.4	1.02
JHL24[2]	4.27	15.95	0.512663(±10)	0.1620	0.5	--	0.11
JHL 26b[2]	3.21	17.01	0.512401(±6)	0.1142	-4.6	+4.4	0.98
JHL19[3a]	2.54	10.86	0.512540(±19)	0.1412	-1.9	+1.8	1.05
JHL22a[3b]	1.27	6.29	0.512374(±10)	0.1226	-5.1	--	1.11
JHL22b[3b]	5.28	22.84	0.512538(±5)	0.1398	-1.9	--	1.04
JHL22c[3b]	4.05	16.93	0.512566(±6)	0.1447	-1.4	+2.6	1.05
JHL 4a[3c]	4.83	20.14	0.512542(±7)	0.1450	-1.9	+2.2	1.10
JHL 4b[3c]	3.99	16.05	0.512587(±6)	0.1503	-1.0	--	1.09
SB 01[3c]	1.84	6.65	0.512652(±8)	0.1671	0.3	+2.6	1.26

[1]- Córrego da Boa Esperança Sequence; [2]- Anicuns Itaberaí Sequence; [3a]- Anicuns-Santa Bárbara Suíte - Córrego Seco Complex (intrusive in Córrego da Boa Esperança Sequence); [3b]- Anicuns-Santa Bárbara Suíte - Córrego Seco Complex (intrusive in Anicuns Itaberaí Sequence); [3c]- Anicuns-Santa Bárbara Suíte - Santa Bárbara de Goiás Complex.