Cryogenian U-Pb (SHRIMP I) zircon ages of anorthosites from the upper sequences of Niquelândia and Barro Alto Complexes, Central Brazil

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Abstract The Niquelândia Complex comprises two main superposed sequences dipping westward: the lower (LS), at the eastern, and the upper (US), at the western part of the body. The Complex is either interpreted as a single body, or as two distinct unrelated layered massifs. New SHRIMP U-Pb determinations on igneous zircon grains of anorthosites from Niquelândia US and from the upper portion of the Barro Alto Complex indicate crystallization ages of 833 ± 21 Ma and 733 ± 25 Ma, respectively, thus supporting Cryogenian Neoproteroic ages for the igneous crystallization of the US unit of Niquelândia and for the Barro Alto anorthosites.

Keywords: Niquelândia, Barro Alto, anorthosites, U-Pb geochronology, Central Brazil.

Resumo *Idades U-Pb (SHRIMP I) Criogenianas dos anortositos das seqüências superiores dos Complexos de Niquelândia e Barro Alto, Brasil central.* O Complexo de Niquelândia é formado por duas seqüências superpostas mergulhando para W: a inferior (LS) a leste, e a superior (US) na parte oeste do corpo. O complexo é interpretado como sendo uma intrusão única, ou como composto por duas intrusões distintas e não relacionadas. Novas determinações isotópicas efetuadas pelo método SHRIMP U-Pb em grãos de zircão ígneos de anortositos da unidade US de Niquelândia, e da porção superior do Complexo de Barro Alto indicaram idades de cristalização de 833 ± 21 Ma e 733 ± 25 Ma, respectivamente. Tais dados implicam na atribuição de idades Neoproterozóicas do Criogênico para a cristalização ígnea da unidade US de Niquelândia e para os anortositos de Barro Alto.

Palavras-chave: Niquelândia, Barro Alto, anortositos, geocronologia U-Pb, Brasil Central.

INTRODUCTION The Niquelândia (NQC) and Barro Alto (BAC) Complexes, in central Brazil, are among the largest anorogenic stratiform layered intrusions in the world. They belong to a 350 km long discontinuous, north-trending chain of mafic-ultramafic massifs, which also includes the northern Cana Brava (CBC) Complex and are located at the western side of the São Francisco craton, bordered by the Brasília Belt, in the Tocantins Province (Fig.1).

These bodies are of great geologic and economic significance to Brazil. The Niquelândia Complex is the principal Ni mining area, whereas the Barro Alto complex has huge reserves of laterite-hosted-Ni. The Cana Brava Complex hosts the largest asbestos mine in Brazil. All three bodies have been investigated for their potential to host platinum group element mineralization.

The main aim of this paper is to discuss new SHRIMP isotopic U-Pb zircon analyses from anorthosites of the upper units of the Niquelândia and Barro Alto complexes, in order to contribute to a better knowledge of the ages of the complexes, which are particularly significant for the tectonic evolution of the Tocantins Province and the western border of the São Francisco craton.

GEOLOGICAL OVERVIEW The NQC and the two other associated complexes are recognized as stratiform intrusions (Rivalenti *et al.* 1982, Girardi *et al.*1986, Feininger *et al.* 1991, Ferreira Filho *et al.* 1992, 1994, Oliveira & Jost 1993, Correia 1994).

NQC is constituted of two main superposed sequences dipping westward: the lower (LS) at the eastern, and the upper (US) at the western part of the complex. LS consists of a basal gabbro zone (BGZ), made of gabbros and some interlayered pyroxenites and peridotites, a basal peridotite zone (BPZ), a layered ultramafic zone (LUZ), formed of pyroxenites with minor interlayered peridotites and gabbros, and the lower gabbro zone (LGZ). Two chromitite horizons (cm to dm thick) occur in the LUZ zone (see Fig. 1, in Girardi *et al.* 1986, for details). LGZ is composed of melanocratic to leucocratic gabbros (plagioclase, augite, hypersthene, with minor and variable amounts of ilmenite, magnetite, sulphide and apatite), and some thin layers of websterite and peridotite close to the base of the zone. Cumulate igneous textures are locally well preserved. Mylonitic textures are common, associated with discrete shear zones. Amphibole appears before the middle portion of LGZ and increases in proportion upwards. The top of this layer, formerly called "hydrous zone" by Girardi *et*

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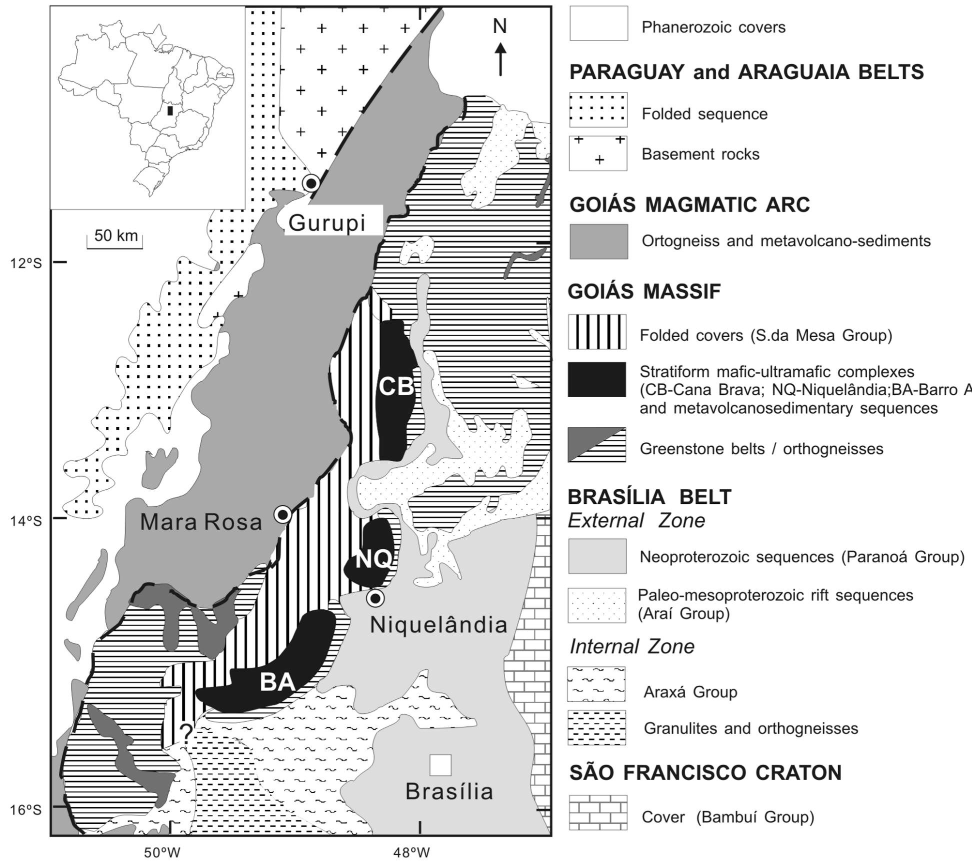

Figure 1 - Geological map of central-eastern part of the Tocantins Province (modified after Pimentel et al. 2004a).

al. (1986), due to the enrichment in biotite, hornblende, apatite, zircon, incompatible elements and LREE, is here designated "LGZ top zone", as proposed by Correia *et al.* (1996). At this level, biotite appears together with quartz, hornblende and orthopyroxene as major mineral phases, whilst apatite and zircon are significant components in several samples. The peculiar mineralogy of the gabbros of this zone is mainly due to the interaction with abundant country-rocks xenoliths, including quartzites, schists, calc-silicate rocks and gneisses.

US comprises two zones: the upper gabbroic zone (UGAZ) and the upper amphibolite zone (UA). UGAZ is composed of gabbro, anorthosite and some clinopyroxenite layers near its top. Cumulate textures (plagioclase and olivine cumulus, orthopyroxene intercumulus) and ophytic textures are quite common, as are corona textures derived from reaction between plagioclase and primary mafic phases (Candia *et al.* 1989). In the anorthosites, hornblende is the main mafic phase. UA lithotypes are layered amphibolite (hornblende, plagioclase, clinopyroxene, opaque minerals, ± garnet). Some anorthosites occur at its base.

US is bordered by the Mesoproterozoic Indaianópolis metavolcano-sedimentary sequence, whereas LS is in tectonic contact with Paleoproterozoic granite-gneiss terrains.

Although the preservation of primary igneous structures and mineral assemblages are common, the effects of a high temperature re-equilibration formerly attributed to a slow sub-solidus event (Girardi *et al.* 1986), and later ascribed to granulite-amphibolite facies metamorphism (Ferreira Filho *et al.* 1998), are important features.

The age and the stratigraphy of the complex are controversial. According to Girardi *et al.* (1986), the Niquelândia body represents a single igneous complex. Following this model, Correia *et al.* (1996), using SHRIMP U-Pb data in the LGZ top zone and the Re-Os systematic in LUZ, obtained an Re-Os age of 2.0 Ga for the LS sequence, interpreted as the crystallization age of the entire Complex. U-Pb ages of 780 Ma, 1000-1400 Ma, and 1600-1880 Ma from the concordia were interpreted as probable periods of tensional relaxing due to extensional rifting in the area. Ferreira Filho *et al.* (1994) analyzed zircon grains from two rocks (CF 03, a diorite from LS, and CF-04, a quartz-rich mylonitic rock within gabbros of US) by conventional U-Pb method. The result was a poorly constrained discordia, where the upper intercept (1.56 Ga) was interpreted as the crystallization age of the complex. The authors attributed an age of 794 Ma to the metamorphism. Ferreira Filho & Pimentel (2000) proposed that LS and US constitute two distinct layered complexes, yielding ages of 2.0 Ga (LS) and 1.35 Ga (US). However, the last age originated from poorly defined Sm-Nd isochrons as mentioned by Pimentel *et al.* (2004b). The interval 770-795 Ma was interpreted as the period of high-grade metamorphism of both units. Pimentel *et al.* (2004b) using SHRIMP U-Pb zircon ages from the same samples (CF-03 and CF-04) formerly studied by Ferreira Filho *et al.* (1994), and Sm-Nd data from Ni-376 (a gabbronorite of LS) concluded that LS and US yield respective igneous crystallization ages of 0.79 and 1.25 Ga.

The Barro Alto Complex (BAC) is an elongated, arch-shaped body. The northeastern part, according to Girardi *et al.* (1981), is composed of: 1) a Basal Zone consisting of metagabbros and amphibolites, 2) an Ultramafic Zone made of serpentinized metaperidotites, 3) an Anorthositic Zone composed of metagabbros and pyrigarnites and 4) an Upper Zone containing ophitic and blastophitic gabbros. Similarly to NQC, these units dip westward and are bordered to the east and to the west, respectively by Paleoproterozoic granite-gneiss terrains and the metavolcanic-sedimentary sequence of Juscelândia (Moraes *et al.* 2003).

The first geochronological data of BAC and its country rocks consist of K-Ar and Rb-Sr analyses (Hasui & Almeida 1970, Souza 1983), which were discussed and summarized by Cordani & Hasui (1975). The spread of obtained ages is very large (4000 to 500 Ma) and their significance remains controversial due to analytical and sampling uncertainties.

According to Moraes & Fuck (2000), BAC underwent granulite facies metamorphism. The mafic-ultramafic assemblage is composed mainly of gabbronorite, with minor amounts of dunite, peridotite, gabbro, anorthosite and banded clinopyroxene-garnet-amphibolite. Acid granulites and high-grade metasedimentary rocks included as lenses into the mafic-ultramafic suite were considered as part of the complex (Fuck *et al.* 1989). Two Rb-Sr isochron ages, the first originated from felsic granulites collected inside the complex (1330±66 Ma), and the second (1266±17 Ma) related to gneissic country rocks from the Juscelândia metavolcano-sedimentary sequence at its western border were interpreted as related to metamorphism of those units, probably due to the continental collision between Goiás massif and the Neoproterozoic metamorphic units on its eastern border (Uruaçuano cycle, ca. 1.100-1.200 Ma, Hasui & Almeida 1976). Suita *et al.* (1994) obtained the first U-Pb conventional zircon data for BAC. They analyzed zircons from a quartz-diorite sample and interpreted the U-Pb upper concordia intercept of 1.72-1.73 Ga as the minimum igneous age for the Barro Alto complex. They also reported U-Pb ages of 1.29-1.35 Ga (upper intercept) and 0.77-0.82 Ga (lower intercept) from a pegmatitic gabbro of the complex. The upper intercept age was interpreted as a period of mafic magmatism related to the Uruaçuano cycle, or perhaps post-Barro Alto magmatism. The lower intercept age was attributed to the last metamorphic event during Brasiliano times. Correia *et al.* (1999) analysed zircon grains by U-Pb (SHRIMP II) methodology from an acid granulite containing quartz, cordierite, sillimanite, plagioclase and mesopertite, collected at the western border of the complex, close to the bimodal Juscelândia metavolcano-sedimentary sequence; and a high grade metagranite located in central-northern part of the massif. These samples displayed respectively two groups of $^{207}Pb/^{206}Pb$ concordant ages of 1286 ± 13 Ma and 1302 ± 32 Ma, interpreted as a Mesoproterozoic metamorphic overprint on older protoliths.

NEW U-Pb SHRIMP RESULTS The analyses were performed on zircon grains from two anorthosites: one from Niquelândia (NQ-1552: 95% labradorite and minor amounts of green hornblende, epidote, scapolite and zircon; subhedral granoblastic texture; epidote locally euhedral in apparent equilibrium with plagioclase and hornblende; grain size between 0.5-3 mm) and the other from Barro Alto (BA-1541: 92% labradorite and minor amounts of hornblende, epidote and zircon; texture predominantly subhedral granoblastic, partially sheared; relicts of the original subophitic texture still preserved; grain size between 0.9-4 mm). NQ-1552 and BA-1541 are located at S 14°22'01"- W 48°31'58" and S 15°05'17"-W49°02'25" respectively.

The radiometric analyses (Tables 1 and 2) were carried out at the Australian National University at Canberra, using SHRIMP I, according to the procedures presented by Compston *et al.* (1984), Williams (1998) and Stern (1998). The CZ3 standard was used for the isotopic corrections and calculation of element concentrations. Lead concentration corrections were based on the isotopic common Pb composition at the approximate time of rock formation (Cumming & Richards 1975). The ages were calculated using the decay constants and the $^{238}U/^{235}U$ ratio value recommended by Steiger & Jäger (1977). The isotope data were processed using the Isoplot Ex program (Ludwig 2001).

The cathodoluminescence images (Fig. 2) for both samples display a pale-gray homogeneous zircon pattern. Only few grains show clearly thin overgrowths and oscillatory growth zonation.

The results are plotted in Tera-Wasserburg diagrams, which show that the zircon populations in both samples have different ages. BAC (BA-1541) and NQC (NQ 1552) anorthosites yielded 733 ± 25 Ma and 833 ± 21 Ma, respectively (Fig. 3).

DISCUSSION Pimentel *et al.* (2004b) published SRHIMP data on zircons from samples CF-04 (a quartz rich mylonite from a shear zone cutting gabbros, at the base of US, close to the limit of the LS top zone) and CF-03 (a diorite from LS top zone); and Sm-Nd data from Ni-376 (a gabbronorite from LS top zone).

Zircon crystals from both CF-03 and CF-04 display inherited cores bordered by overgrowth rims. Based on analysis of these rims and regions with oscillatory zoning from sample CF-03, the authors proposed a concordia age of 797 ± 10 Ma, as representative of the igneous crystallization of the LS unit of Niquelândia. The Sm-Nd results from Ni-376 were not conclusive.

Sample CF-04 displayed zircon cores varying from 0.76 to 1.25 Ga. Based on four $^{207}Pb/^{206}Pb$ discordant analyses the authors interpreted the upper intercept

Table 1 - SHRIMP I zircon data from NQ-1552 sample

Label	Grain Type	U/ppm	Th/U	Pb*/ppm	204/ppb	207Pb/206Pb	238U/206Pb	Age 6/38(Ma)	%Disc.
NQ1552 – corrected for common Pb using measured 204Pb (C&R model 800 Ma)									
NQ-1.1	e, h, p, fr	52.1	0.65	7	0	0.06523±0.00209	7.98497±0.24957	761±22	-3
NQ-2.1	m, pr, p, h	52.1	0.59	7	1	0.06814±0.00123	7.74906±0.30720	782±29	-10
NQ-3.1	c, h, p, r	66.4	0.72	12	2	0.07242±0.00154	6.11241±0.17098	977±25**	-2
NQ-4.1	e, h, p, eq	53.7	0.64	8	1	0.07023±0.00190	7.23063±0.24482	835±27	-11
NQ-5.1	e, h, b, fr, r	22.9	0.38	3	0	0.07598±0.00260	6.99232±0.25536	862±30	-21
NQ 6.1	e,h,p,r	1.3	0.07	0	0	0.12628±0.03118	7.43020±1.25236	814±130**	***
NQ-7.1	c, h, p, eq	48.4	0.65	8	0	0.07515±0.00173	6.81116±0.24965	883±30	-18
NQ-8.1	c, h, p, fr	14.1	0.09	2	0	0.07456±0.00559	7.58327±0.36786	799±37	-24
NQ-9.1	c, h, p, pr	35.7	0.43	5	0	0.06799±0.00227	7.51284±0.26367	806±27	-7
NQ-10.1	e, ov, os, pr	29.2	0.46	4	1	0.06888±0.00283	7.16440±0.22686	842±25	-6
NQ-11.1	c, h, p, eq	43.0	0.69	6	1	0.06769±0.00202	7.52480±0.26993	804±27	-6

Legend: c-core; e-end; m-middle; h-homog., p-pale, b-bright, r-round, pr-prismatic, eq-equant, fr-fragment, ov-overgrowth, os-oscil. zoning; * = radiogenic lead ** = data not included in the weigthted average *** high discordant data

Table 2 - SHRIMP I zircon data from BA-1541 sample

Label	Grain Type	U/ppm	Th/U	Pb*/ppm	204/ppb	207Pb/206Pb	238U/206Pb	Age 6/38(Ma)	%Disc.
BA1541 corrected for common Pb using measured 204Pb (C&R = 750 Ma)									
BA-1.1	c, h, p, fr	20.5	0.65	3	0	0.06462±0.00431	8.30021±0.32343	733±27	-4
BA-2.1	e, h, p, fr	9.2	0.71	1	1	0.05469±0.01158	8.13756±0.38479	747±33	***
BA-3.1	c, h, b, fr	11.4	0.55	1	1	0.05973±0.00653	8.21627±0.35312	740±30	25
BA-4.1	e, p, pr	13.1	0.46	2	0	0.06745±0.00452	7.58177±0.36379	799±36**	-7
BA-5.1	c, pr, b	8.8	0.49	1	1	0.06095±0.00591	8.37734±0.52434	727±43	14
BA-6.1	e, b, fr	33.9	0.70	4	0	0.06578±0.00226	8.39453±0.31542	726±26	-10
BA-7.1	c, h, b, r	6.6	0.26	1	1	0.05038±0.01421	8.37159±0.42791	727±35	***

Legend: c-core; e-end; h-homogeneous, p-pale, b-bright, r-round, pr-prismatic, fr-fragment
* = radiogenic lead ** = data not included in the weigthted average *** high discordant data

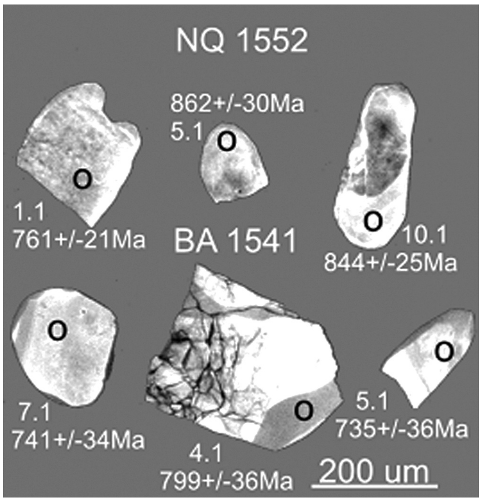

Figure 2 - Selected cathodoluminescence images of zircon grains from NQ-1552 and BA-1541 samples. Black circles indicate the analyzed areas.

age of 1248 ± 23 Ma as the igneous crystallization of the US unit of Niquelândia.

These interpretations and also the crystallization age proposed by Correia *et al.* (1996) and Correia (2001) are questionable due to the abundant country-rock xenoliths, which contaminate the LS top zone. The crustal contamination caused by the assimilation of these rocks by the intrusive magma possibly accounts for the particular geochemical characteristics of gabbros and diorites of this zone (see previous section). Both samples CF-03, and mainly CF-04, seem to be close to the limit between LS and US (see Fig. 3 in Pimentel *et al.* 2004b). Moreover CF-04 contains kyanite, which indicates contamination probably by metasediments. Therefore, it is not possible to distinguish between those zircon grains that came from the intrusion from the ones originated from the country-rocks. Thus, the age of 1248 ± 23 Ma may have no relationship with the igneous crystallization of the Niquelândia complex. In addition, the 1.35 Ga Sm-Nd isochron from leucogabbros (Ferreira Filho & Pimentel 2000) does not help to support the Mesoproterozoic age for US. It is poorly defined, as mentioned by Pimentel *et al.* (2004b), and also might be the result of mixing lines.

Petrographic studies and individual grain observation of the zircon populations from samples BA-1541 and NQ-1552 display morphological igneous

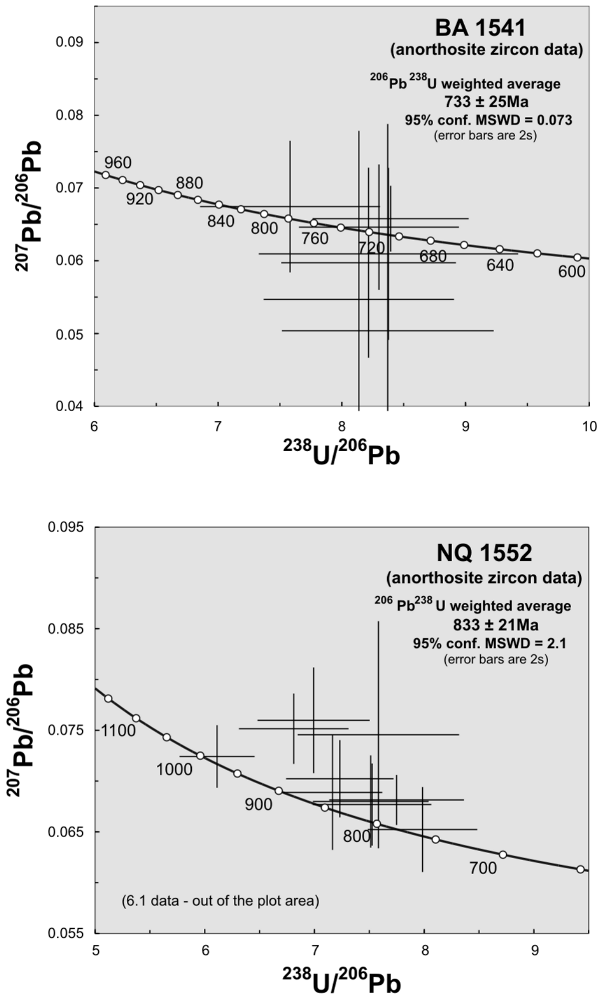

Figure 3 - Tera-Wasserburg plots for NQ 1552 and BA 1541 anorthosites zircon analysis

characteristics. All the individual crystals preserved from fragmentation are prismatic. The occasional faint-rounded fragments differ from the typical spherical shaped metamorphic zircon. Moreover, cathodoluminescence images (see Fig. 2) confirm the igneous features: inherited old cores inside newly formed borders are absent in the zircon grains, as well as different zones displaying discontinuous oscillatory growth. Some grains show only very thin and localized overgrowths on the borders, which were avoided during SHRIMP I analysis. Besides, irregular shaped grains or crystals devoid of oscillatory growths are common in deep crystallized igneous mafic rocks.

Therefore the resulting ages should reflect the time of zircon crystallization of BA-1541 and NQ-1552 samples. The absence of inherited cores does not support previous interpretations, which suggest a Mesoproterozoic age for the rocks from the upper units of NQC.

The morphological characteristics, the internal structure, homogeneity, and the predominant high Th/U ratios (see Table 1) of the NQ-1552 anorthosite zircon crystals indicate that 833 ± 21 Ma can be interpreted as the crystallization age of the US unit of the Niquelândia complex. The εNdT of this sample is + 3.5, which indicates the influence of a previous depleted mantle source on the origin of the parental melt (Girardi *et al.* 2006a, 2006b).

Th/U ratios, morphological and structural features of the BA-1541 anorthosite zircons are similar to those of the NQ-1552 sample (Fig. 2, Table 2). Therefore the obtained data (733 ± 25 Ma) can be associated to the crystallization age of the upper portion of BAC. However the stratigraphy of the massif is debatable and further studies are necessary to set up the geochronology of the whole Complex. On the other hand side, taking into account this reinterpretation on the age of the NQC upper sequence, and the geological and petrologic similarities of the bi-modal metavolcano-sedimentary sequences of Juscelândia and Indaianópolis, the 1286 ± 13 Ma and 1302 ± 32 Ma U-Pb determinations by Correia *et al.* (1999), previously attributed to the Mesoproterozoic metamorphism of the complex, are now interpreted as related to age of the protoliths of the acid granulites included into the layered complex during the mafic-ultramafic intrusion.

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