U-Pb geochronology of gneisses and granitoids in the Quadrilátero Ferrífero (Southern São Francisco Craton): age constraints for Archean and Paleoproterozoic magmatism and metamorp...

Article *in* Revista Brasileira de Geociencias · March 1998

DOI: 10.25249/0375-7536.199895102

Wilson Teixeira
University of São Paulo

U-Pb GEOCHRONOLOGY OF GNEISSES AND GRANITOIDS IN THE QUADRILÁTERO FERRÍFERO (SOUTHERN SÃO FRANCISCO CRATON): AGE CONSTRAINTS FOR ARCHEAN AND PALEOPROTEROZOIC MAGMATISM AND METAMORPHISM

CARLOS MAURÍCIO NOCE*, NUNO MACHADO AND WILSON TEIXEIRA*****

RESUMO *GEOCHRONOLOGIA U-Pb DE GNAISSES E GRANITÓIDES DO QUADRILÁTERO FERRÍFERO {CRATON DO SÃO FRANCISCO MERIDIONAL): IDADE DO MAGMATISMO E METAMORFISMO ARQUEANO E PALEOPROTEROZÔICO* Determinações U-Pb foram realizadas em gnaisses e granitóides do Quadrilátero Ferrífero, porção sul do Craton do São Francisco. O Complexo Belo Horizonte representa um segmento de crosta arqueana, composto principalmente por gnaisses bandados do tipo TTG, afetados por migmatização. Este evento de migmatização foi datado em 2860+14/-10 Ma. Plutons graníticos, de derivação crustal, são intrusivos nos gnaisses e um deles apresenta idade U-Pb em zircão de 2712+5/-4 Ma. A intrusão de um pequeno corpo granítico, datada em 2612+37-2 Ma, marca o último evento magmático arqueano registrado no Quadrilátero Ferrífero. O conjunto de determinações geocronológicas disponíveis para o Quadrilátero Ferrífero permite estabelecer um quadro evolutivo para a crosta arqueana. O principal período de geração crustal ocorreu entre 3,0-2,9 Ga, conforme sugerido pela assinatura isotópica do Nd para os gnaisses TTG. Após este período, a progressiva amalgamação de blocos continentais ocasionou intenso retrabalhamento da crosta primitiva, associado a diversos episódios de granitogênese e a deposição de seqüência do tipo greenstone belt. Uma extensa área cratônica foi consolidada após 2,6 Ga, sendo recoberta por sedimentos plataformais. A intrusão do Tonalito Alto Maranhão ocorreu em 2124±l Ma. Este corpo possui assinatura isotópica juvenil e associa-se à Orogênese Transamazônica. Titanita do gnaisse TTG e leucossoma alinham-se em uma discórdia, com intercepto inferior em 2041±5 Ma, definindo o pico metamórfico deste evento.

Palavras-chaves:

ABSTRACT U-Pb analyses were carried out on gneisses and granitoids from the Quadrilátero Ferrífero area, in the southern São Francisco craton. The Belo Horizonte complex represents a segment of Archaean crust principally composed of migmatized banded TTG-type gneisses. Migmatization event took place at 2860+14/-10 Ma. Granitic plutons intruded in the complex are crust-derived and one of them yielded a zircon age of 2712+5/-4 Ma. The emplacement of a small granitic pluton at 2612+37-2 Ma defines the youngest Archaean magmatic event in the Quadrilátero Ferrífero. This set of geochronological determinations together with published data allows the establishment of a fairly accurate framework for the evolution of the Archaean crust in the Quadrilátero Ferrífero. The main period of crust generation at 3.0 to 2.9 Ga is indicated by Nd isotopic signature of TTG gneisses. The evolutionary trend followed the progressive amalgamation of continental blocks, associated with intensive reworking of the primitive crust, renewed events of granitoid emplacement and greenstone belt deposition. An extensive cratonic area consolidated at *ca.* 2.6 Ga and was subsequently covered by stable-shelf sediments. The Alto Maranhão pluton was emplaced at 2124±1 Ma. This tonalitic intrusion represents an isotopically juvenile body related to the Transamazonian Orogeny. Titanite of the TTG-gneiss and leucosome align in a discórdia with a lower intercept at 2041 ±5 Ma defining the metamorphic peak of this event.

Keywords:

INTRODUCTION The Quadrilátero Ferrífero (Iron Quadrangle) is a *ca.* 7000 km^2 area in the southern São Francisco craton in Brazil, comprising a Neoarchean greenstone belt surrounded by older gneiss complexes and overlain by a Paleoproterozoic sedimentary succession, all of them affected by the *ca.* 2.0 Ga Transamazonian Orogeny. The Quadrilátero Ferrífero provides an opportunity to investigate several aspects of crustal evolution, from greenstone belt-gneiss terrain relationships to Paleoproterozoic basin formation and orogenesis. In this paper we report the ages of important gneiss and granitoid units and consider their significance in the evolution of the area.

Precise U-Pb dating of zircon, titanite and monazite disclosed new magmatic and metamorphic events in the Quadrilátero Ferrífero. A large set of geochronological determinations is now available for this area. Therefore, a chronology of geologic events has been established as discussed hereafter.

GEOLOGICAL SETTING AND PREVIOUS GEOCHRONOLOGY Archean terranes of the Quadrilátero Ferrífero comprise a granite-greenstone belt association surrounded by granite-gneiss complexes (Fig. l)..The former is included in the Rio das Velhas Supergroup (Dorr *etal.* 1957), the basal unit of which (Nova Lima Group) consists of a volcano-sedimentary sequence hosting the main gold deposits of the Quadrilátero Ferrífero. Two felsic volcanic rocks of the Nova Lima Group have been dated at 2772±6 Ma and 2776+237-10 Ma (U-Pb data in Machado *et al* 1992). Tpnalitic-granodioritic intrusions associated with the formation of the greenstone belt yielded U-Pb ages of 2776+77-6 Ma and 2780+37-2 Ma (Caeté and Samambaia intrusions; Machado *et ai.* 1992; Machado & Carneiro 1992). These syn-volcanic intrusions occur at the margins of the greenstone belt and are partially or totally emplaced into the granite-gneiss complexes surrounding the greenstone belt.

The granite-gneiss terranes comprise several complexes (Herz 1970): Belo Horizonte to the north of Quadrilátero Ferrífero, Caeté to the northeast, Bação in the center, and Bonfim to the west (Fig. 1). The northern sector of the Bonfim complex is well known in geological detail supported by U-Pb data. The main unit is a banded gneiss, locally migmatized

* Centro de Pesquisa Prof. Manuel Teixeira da Costa, Instituto de Geociências, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, 31270-901 Belo Horizonte (MG), Brazil, e-mail: noce@dedalus.lcc.ufmg.br
** GEOTOP-Sc. de Ia Terre, Université du Quebec à Montreal, CP 8888, Succ. Centre-Ville, Montreal, Qc H3C 3P8 Canada
*** Instituto de Geociências, Universidade de São Paulo, CP 11348,05422-970 São Paulo (SP), Brazil

(Carneiro 1992). The gneiss has a minimum age of 2920 Ma and underwent remobilization during greenstone belt formation at 2772±6 Ma and tonalitic intrusion at 2780+3/-2 Ma (Machado & Carneiro 1992). 2703+24/-23 Ma granitic dykes crosscutting the regional foliation (Machado & Carneiro 1992) represents the youngest Archaean event recorded in the Bonfim Complex.

The Transamazonian Orogeny *(ca.* 2.0 Ga) resulted in remobilization in the B ação Complex as shown by U-Pb ages of 2059±6 Ma and *ca.* 2030 Ma for titanitc and monazite from an amphibolite and an undeformed pegmatite (Machado *etal.* 1992).

The Proterozoic Minas Supergroup tectonically overlies the Archaean units (Fig. 1) and comprises the Caraça, Itabira, and Piracicaba groups (Dorr 1969). The Caraça Group is composed predominantly of quartzites and phyllites. The Cauê Formation, at the base of the Itabira Group, comprises mainly Lake Superior-type banded iron formation, whilst the Gandarela Formation, at the top of the group, is composed of dolomitic carbonates with stromatolites, and was probably deposited at 2420±19 Ma (Pb-Pb whole-rock isochron; Babinski *etal.* 1995). Interbedded quartzite and phyllite containing carbonatic lenses characterize the Piracicaba Group. Its upper unit (Sabará Formation) is composed of chlorite schists, phylites, graywackes, conglomerates, quartzites, and rare iron formation. The maximum age for the deposition of the Sahara Formation is 2125±4 Ma, the age of detrital zircon from a graywacke (Machado *etal.* 1992).

STUDY AREA The Belo Horizonte granite-gneiss complex The Belo Horizonte complex is located to the north of the Quadrilátero Fern'fero (Fig. 1). The dominant rock type is a migmatitic banded gneiss with schlicrcn and stromatic structures and mafic enclaves, and is hereafter referred to as the Belo Horizonte gneiss. The foliation varies from N-S to NNE-WSE, dips 40-60° to W and WNW, and is broadly coeval with migmatization as indicated by leucosomes both parallel and secant to the regional foliation. Nebulitic leucosomes may also preserve relicts of the foliation. Some locations display a transposed older foliation.

Chemical analyses of the least migmatized gneisses yielded a predominantly trondhjemitic composition (Noce *et al.* 1997). Biotite is the main mafic mineral (up to 5-10%) whilst hornblende is rare. Most rocks display granoblastic or mylonitic textures.

The Belo Horizonte gneiss was intruded by granitoids ranging from pegmatitic veins to large bodies that can be divided into foliated and weakly or non foliated types. The former comprises the Santa Luzia and General Carneiro plutons (Fig. 1), which are generally homogeneous, post-date migmatization, and consists of calc-alkaline and slightly peraluminous granites. The Morro da Pedra and Córrego do Brumado (Fig. 1) are smaller peraluminous granite intrusions slightly foliated. The former is the only intrusive body known to intersect the Minas Supergroup. It is a 400mx700m intrusion outcropping within the Sabará Formation and considered intrusive, although contacts are not exposed (Pomerene 1964).

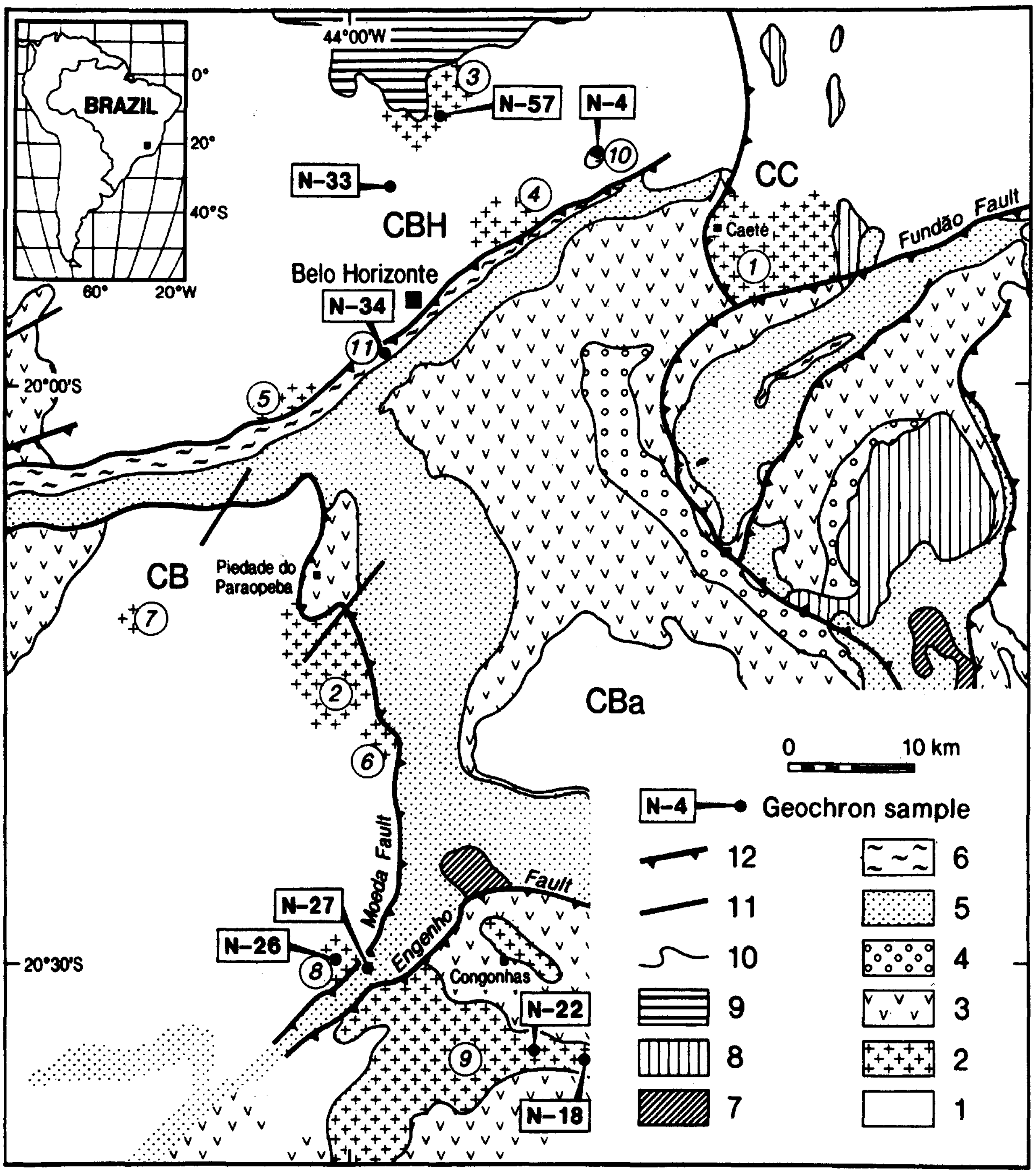
Granitoids of the southern Quadrilátero Fern'fero

In the southern Quadrilátero Fern'fero, the Minas Supergroup is separated from the other units by the Engenho and Moeda faults (Fig. 1). To the west of the latter occurs a gneiss complex composed of banded migmatitic gneisses similar to those of the Bonfim and Belo Horizonte complexes. A small granitic pluton (Salto do Paraopeba granite, Fig. 1) is intrusive into the gneisses and is partially overlain by the Moeda Formation of the Minas Supergroup. The Salto do Paraopeba granite is leucocratic and composed of quartz, microcline, oligoclase, and minor biotite. It is weakly deformed except for narrow shear zones that display strong grain comminution. Close to the contact between the granite and the supracrustal rocks, four tabular pegmatites are intruded into the quartzite layering. The pegmatites are 10-50 cm wide, pervasively kaolinized, foliated and boudinaged.

South of the Engenho fault, the greenstone sequences of the Nova Lima Group were intruded by the Alto Maranhão pluton (Fig. 1, Sad *et al.* 1983). This tonalitic intrusion is generally well foliated. The main components are oligoclase, quartz, biotite, and amphibole in a granoblastic texture. It is mctaluminous and can be classified as I type according to the scheme of Chapell & White (1974).

GEOCHRONOLOGY Analytical methods U-Pb measurements were performed in the Centre de Recherche en Gcochimie Isotopique et en Géochronologie (GEOTOP) of the Université du Quebec à Montreal. Crystal selection, chemistry, mass spectrometry, and data treatment broadly followed previously described procedures (Davis 1982, Krogh 1973, 1982, Machado *et al.* 1996a). For zircon analyses, blanks are below 10 pg Pb and 2 pg U. For titanite and monazite, maximum blanks are 15 pg Pb and 5 pg U. The highest analytical uncertainty of the two Pb/U ratios was used for error representation in figures 2 and 3. The uncertainty in Pb/ Pb was calculated with an error propagation routine which takes into consideration the analytical precision of the measured isotopic ratios. The isotopic composition of initial common Pb was calculated using the model of Stacey & Kramers (1975). Uncertainties are listed (Table 1) and represented (Figs. 2 and 3) at the l sigma level. Ages are quoted at the 95% confidence interval.

Results *BELO HORIZONTE COMPLEX* Two samples of the Belo Horizonte gneiss (N-33A, N-33B) were collected for U-Pb geochronology. Sample 33A is representative of the migmatitic gneiss with thin leucosome layers, and 33B is from a 0.5 m wide felsic leucosome occurring in the axial plane of a tight fold. Zircons from the first sample were too small and altered to yield reliable results and were not analyzed. The leucosome yielded a small amount of zircon of high magnetic susceptibility and pervasive white alteration precluding a rigorous typological examination. The least altered zircon type consists of pink euhedral 3:1 prisms devoid of obvious cores. In order to remove or weaken the altered portions, a selection of crystals of this type was submitted to HF attack, monitored under a binocular microscope, and subsequently abraded. One of the three zircon fractions treated that way is concordant at 2860±17 Ma (33B-3J whilstthe other two are 11% discordant and yield similar $^{207}Pb/^{206}Pb$ ages of 2823 Ma and 2813 Ma (33B-1 and 33B-2). The three analyses define a discórdia line (23% probability of fit) with the upper intercept at 2860+147-10 Ma (Table 1, Fig. 2a). The only zircon recovered from the least magnetic fractions is distinctly reddish, lower in U contents (75ppm vs.103-165 ppm for the previous zircons) and yielded a $^{207}Pb/^{206}Pb$ minimum age of 2923 Ma (2.3% discordant, analysis 33B-4). This is interpreted as an inherited zircon from the gneiss. Both rocks contain dark brown titanite; the one from the leucosome being concordant at 2041 ±5 Ma (33B-5) whilst two abraded titanite fractions from the gneiss are 4-6% discordant and yielded minimum ages of 2312 Ma and 2227 Ma (33A-1 and 33A-2, Table 1, Fig. 2a). The three titanite analyses define a discórdia with an upper intercept at 2847+81/-77 Ma, similar to the zircon age for the leucosome (2860+14/-10 Ma). It can be concluded that migmatization occurred at 2860 Ma forming zircon and titanite. During the Transamazonian Orogeny titanite in the leucosome was completely reset at 2041 Ma whilst titanite in the gneiss was partially reset.



(1) Caeté granodiorite
(2) Samambaia
(3) Santa Luzia
(4) General Carneiro
(5) Ibirité
(6) Mamona
(7) Brumadinho
(8) Salto do Paraopeba
(9) Alto Maranhão
(10) Córrego do Brumado
(11) Morro da Pedra

Figure 1 - Geology of the Quadrilátero Ferrífero (modifiedfrom Dorr 1969). Granitoid bodies are numbered at the figure bottom. Sample numbers are displayed inside rectangles. Legend: 1 = granite-gneiss complexes (CBH = Belo Horizonte complex; CC = Caeté complex; CBa = Bação complex; BC = Bonfim complex); 2 = Archaean and Paleoproterozoic granitoid bodies. Rio das Velhas Supergroup: 3 = Nova Lima Group; 4 = Maquine Group. Minas Supergroup: 5 - Caraça, Itabira and lower Piracicaba groups; 6 = Sahara Formation. 7 = Itacolomi Group. Meso and Neoproterozoic units: 8 - Espinhaço Group; 9 = Bambui Group. 10 = geologic contact; 11 = vertical or undetermined faults; 12 = thrust faults.

Figura 1 - Geologia do Quadrilátero Ferrífero (modificado de Dorr 1969). Corpos de granitóides estão numerados ao pé da figura. Números das amostras estão localizados no interior dos retângulos. Legenda: 1 = complexos granito-gnáissicos (CBH = Complexo Delo Horizonte; CC = Complexo Caeté; CBa = Complexo Bação; BC = Complexo Bonfim); 2 = granitóides arqueanos e paleoproterozóicos. Supergrupo Rio das Velhas: 3 = Grupo Nova Lima; 4 = Grupo Maquine. Supergrupo Minas: 5 = grupos Caraça, Itabira e Piracicaba Inferior; 6 = Formação Sabará. 7 = Grupo Itacolomi. Unidades meso e neoproterozóicas: 8 = Grupo Espinhaço; 9 = Grupo Bambuí. 10 = contato geológico; 11 = falhas verticais ou indeterminadas; 12 = falhas de empurrão.

The same sample of the leucosome layer (33B) together with another sample of the migmatitic gneiss (331) were analyzed by the Sm-Nd method (Noce 1995). £Nd values for t=2.86 Ga are slightly negative (-1.2 and -1.6) suggesting that the protholiths are not significantly older than the inherited zircon minimum age of 2922 Ma. This is in agreement with the gneiss Sm-Nd model age (TDM) of 2.97 Ga.

The Santa Luzia granite (N-57) yielded pink, euhedral and small zircon prisms and fragments with variable amounts of white alteration. The relatively small grain size precluded long abrasion times. Three analyses (57-1, 57-2 and 57-3) are between 9% and 17% discordant and define a discórdia (56% probability of fit) with the upper intercept at 2712+5/-4 Ma (Table 1, Fig. 2b) taken as the age of crystallization of the granite. Four fractions of titanite which underwent variable abrasion times are discordant with $^{207}Pb/^{206}Pb$ ages between 2328 Ma and 2212 Ma (57-4 to 57-7, Table 1, Fig. 2b). The analyses do not define a discórdia and lie close to but below an hypothetical line between 2712 Ma and 2041 Ma, possibly due to recent lead loss which could not be eliminated by abrasion. The results are, however, compatible with this rock having undergone Transamazonian metamorphism that has partially reset the titanite. Zircons from the General Carneiro granite are very small, pervasively altered, and thus were not analyzed.

The Morro da Pedra granite (N-34) yielded very altered zircons of small size. A few pink and colorless zircon grains displayed a thick whitish cover; these were treated with HF and abraded as previously described. Two analyses were performed, one on the pink (analysis 34-1) and the other on the colorless type (34-2). Both analyses are discordant and yield minimum ages of 2682 Ma and 2770 Ma (Table 1, Fig. 2c), the former being associated with a large error due to a high content of common Pb. These results do not define the

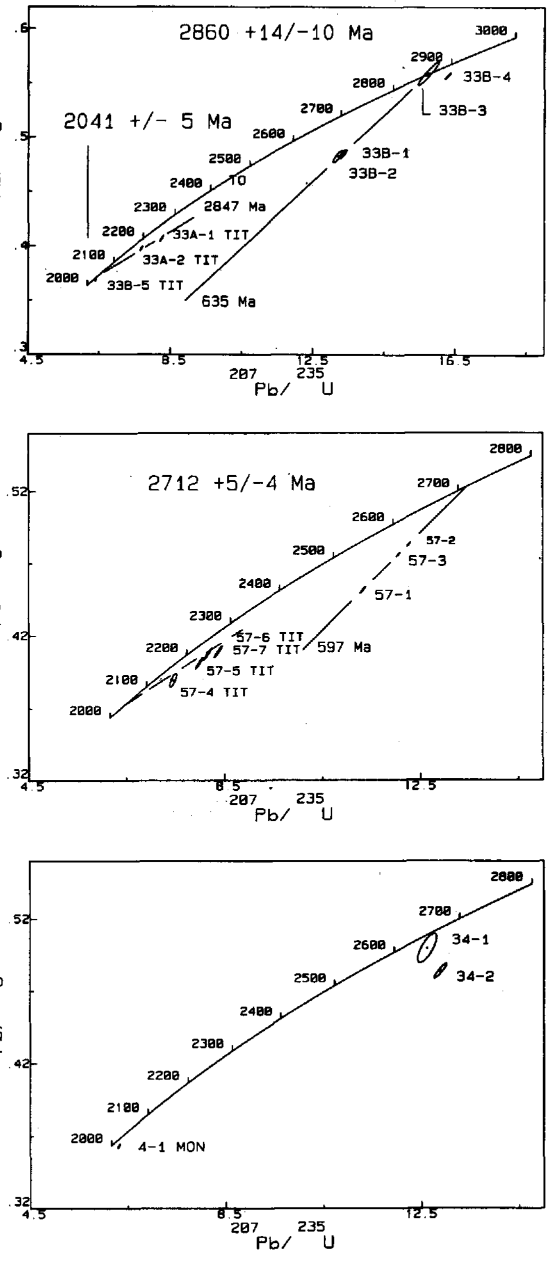


Figure 2 - (a) concórdia diagram for a migmatitic gneiss (sample 33A) and a leucossome (sample 33B) from the Belo Horizonte complex, (b) concórdia diagram for the Santa Luzia granite, (c) concórdia diagram for the Morro da Pedra granite (sample 34) and Córrego Brumado granite (sample 4).
Figura 2 - (a) diagrama concórdia de um gnaisse migmatítico (amostra 33A) e um leucossoma (amostra 33B) do Complexo Belo Horizonte, (b) diagrama concórdia do Granito Santa Luzia, (c) diagrama concórdia do Granito Morro da Pedra (amostra 34) e do Granito Córrego Brumado (amostra 4).

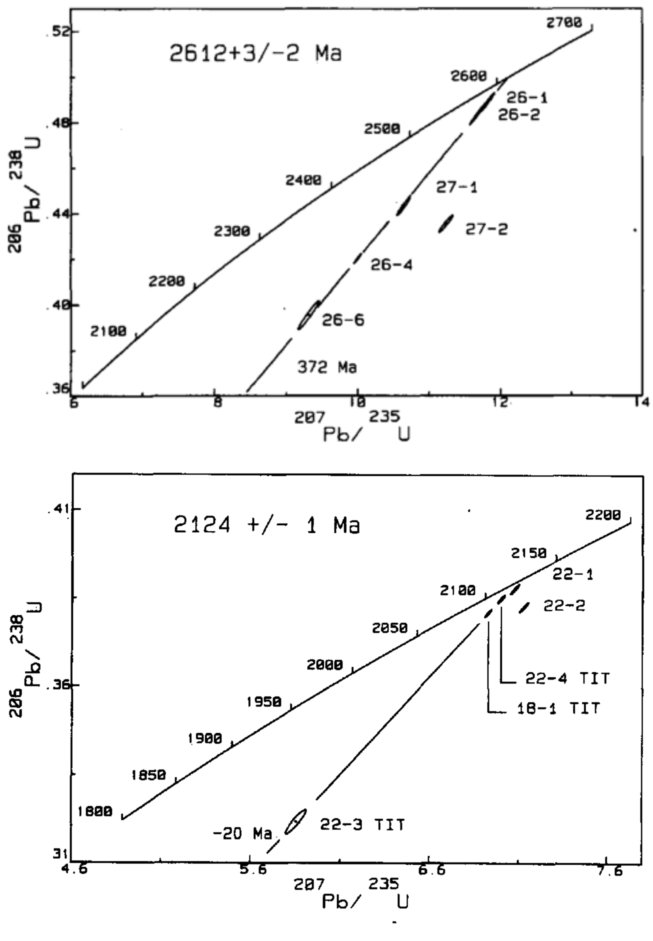


Figure 3 - (a) concórdia diagram for the Salto do Paraopeba granite (sample 26) and a pegmatite (sample 27). (b) concórdia diagram for the Alto Maranhão batholith (samples 18 and 22).
Figura 3 - (a) diagrama concórdia do granito Salto do Paraopeba (amostra 26) e um pegmatito (amostra 27). (b) diagrama concórdia do batólito Alto Maranhão (amostras 18 e 22).

Table 1 - U-Pb results

SAMPLE				CONCENTRATIONS			ATOMIC RATIOS								AGES (Ma)		
Sample no.	Min. [*]	#grains	Weight (mg)	Uranium (ppm) [#]	Pb rad (ppm) [#]	Pb comm. (pg) [**]	206Pb/204Pb [##]	208Pb/206Pb [***]	206Pb/238U [***]	±	207Pb/235U [***]	±	207Pb/206Pb [***]	±	206Pb/238U	207Pb/235U	207Pb/206Pb
Belo Horizonte Gneiss (Field numbers N-33A and N-33B)																	
33B-1	Z	3	0,006	103	57	36	543	0,1251	0,48490	0,29	13,346	0,38	0,19962	0,200	2549	2704	2823
33B-2	Z	4	0,011	106	59	37	973	0,1435	0,48235	0,43	13,196	0,50	0,19842	0,300	2537	2694	2813
33B-3	Z	15	0,009	164	108	70	761	0,1668	0,55922	0,87	15,747	0,93	0,20423	0,290	2863	2861	2860
33B-4	Z	1	0,005	75	47	41	331	0,0997	0,55713	0,24	16,303	0,26	0,21223	0,055	2855	2895	2923
33B-5	T	40	0,155	185	81	592	1139	0,2476	0,36878	0,14	6,399	0,16	0,12585	0,045	2024	2032	2041
33A-1	T	42	0,184	181	109	518	1660	0,5708	0,40688	0,33	8,249	0,34	0,14705	0,059	2201	2259	2312
33A-2	T	30	0,196	187	106	751	1233	0,5125	0,39757	0,25	7,674	0,26	0,13999	0,075	2158	2194	2227
Santa Luzia Granite (Field number N-57)																	
57-1	Z	8	0,010	167	94	61	785	0,263	0,45131	0,15	11,325	0,25	0,18199	0,061	2401	2550	2671
57-2	Z	16	0,019	84	49	6	8576	0,2322	0,48288	0,14	12,264	0,15	0,18420	0,045	2540	2625	2691
57-3	Z	13	0,015	85	49	10	3831	0,221	0,47578	0,14	12,046	0,15	0,18363	0,043	2509	2608	2686
57-4	T	50	0,536	103	67	2193	631	0,8079	0,38932	0,20	7,449	0,47	0,13878	0,370	2120	2167	2212
57-5	T	30	0,346	141	97	1824	671	0,8369	0,40099	0,43	7,985	0,50	0,14443	0,100	2174	2229	2281
57-6	T	15	0,204	151	108	1351	600	0,8683	0,40903	0,43	8,373	0,50	0,14847	0,100	2210	2272	2328
57-7	T	20	0,254	162	111	1939	558	0,7945	0,40744	0,45	8,158	0,50	0,14522	0,100	2203	2249	2290
Morro da Pedra Granite (Field number N-34)																	
34-1	Z	2	0,007	130	82	303	108	0,2722	0,4995	0,53	12,617	0,77	0,18320	0,670	2612	2651	2682
34-2	Z	5	0,007	143	85	104	307	0,2325	0,4837	0,41	12,889	0,50	0,19325	0,200	2544	2672	2770
Córrego do Brumado Granite (Field number N-04)																	
4-1	M	4	0,009	3241	7489	763	888	6,2167	0,36331	0,14	6,319	0,20	0,12614	0,093	1998	2021	2045
Salto do Paraopeba Granite (Field number N-26)																	
26-1	Z	1	<0.001	347	199	37	300	0,1916	0,4887	0,42	11,813	0,44	0,17531	0,080	2565	2590	2609
26-2	Z	1	<0.001	268	150	11	773	0,1717	0,4837	0,50	11,679	0,50	0,17511	0,067	2543	2579	2607
26-4	Z	1	0,003	215	101	22	799	0,1267	0,4202	0,24	9,998	0,26	0,17256	0,055	2261	2435	2583
26-6	Z	1	<0.001	183	86	33	153	0,2051	0,3954	0,76	9,311	0,79	0,17080	0,177	2148	2369	2566
Salto do Paraopeba Pegmatite (Field number N-27)																	
27-1	Z	2	<0.001	386	201	53	218	0,1883	0,4431	0,40	10,637	0,43	0,17409	0,110	2365	2492	2597
27-2	Z	7	0,002	255	130	34	430	0,1761	0,4354	0,40	11,231	0,43	0,21400	0,115	2330	2543	2677
Alto Maranhão Batholith (Field numbers N-22 and N-18)																	
22-1	Z	3	0,004	371	157	13	2768	0,1326	0,38779	0,17	7,078	0,18	0,13237	0,052	2113	2121	2130
22-2	Z	20	0,014	139	57	13	3663	0,1127	0,38256	0,17	7,129	0,18	0,13516	0,054	2088	2128	2166
22-3	T	55	0,217	156	52	4504	165	0,0996	0,31717	0,45	5,775	0,50	0,13205	0,200	1776	1943	2125
22-4	T	40	0,162	75	29	784	391	0,0236	0,38493	0,13	7,001	0,15	0,13192	0,059	2099	2112	2124
18	T	40	0,188	201	92	561	1623	0,2722	0,38083	0,13	6,927	0,15	0,13192	0,044	2080	2102	2124

Notes:

* - *Z-zircon; T- titanite; M-monazite.*
# - Concentrations are known to 2% for sample weights of 0.4mg, 10%-20% for sample weights below 0.020mg (for sample weights below the sensitivity of the microbalance, shown as <0.001, the concentrations listed are maximum values
** - Total common Pb present corrected for Pb in spike.
- Measured ratio, corrected for fractionation only.
*** - Ratios corrected for spike, fractionation, blank and initial common Pb. Precision is reported in % at 1 sigma

age of the rock and are tentatively interpreted as minimum ages of zircon inheritance.

The Córrego do Brumado granite (N-4) also contains zircons that are unsuitable for geochronological analyses. Monazite yielded a $^{207}Pb/^{206}Pb$ age of 2045 Ma (2.3% discordant, Table 1, Fig. 2c) which is taken as the minimum crystallization age for the granite.

The slight deformation present in the Morro da Pedra and Córrego do Brumado granites, together with the similarity of their chemical compositions, suggest that they may be approximately coeval. If this is the case, they were emplaced during the peak of Transamazonian metamorphism.

SOUTHERN QUADRILÁTERO FERRÍFERO The Salto do Paraopeba granite (N-26) yielded flattened 3:1 zircon crystals, fractured across their length suggesting the absence of cores. Two prisms were broken, abraded and the four fragments analyzed separately. The analyses are 3-19% discordant and define a discórdia (87% probability of fit) with an upper intercept at 2612+3/-2 Ma (Table 1, Fig. 3a), taken as the age of crystallization of the granite.

The pegmatites (N-27) intruded into the quartzites of the Minas Supergroup contain a very small amount of heavy minerals. Analysis 27-1 was performed on two small pink euhedral fragments and analysis 27-2 on seven similar grains from a more magnetic fraction. The analyses are 11 % and 14% discordant and yield $^{207}Pb/^{206}Pb$ ages of 2597 Ma and 2677 Ma (Table 1, Fig. 3a). Analysis 27-1 plots on the discórdia defined for the Salto do Paraopeba granite and may suggest that the pegmatite is coeval with the granite. However, analysis 27-2 clearly indicates the presence of inherited zircons in the pegmatite and it is not possible to decide if 27-1 also represents inherited zircon. Therefore, it can only be stated that the maximum age for the crystallization of the pegmatite is probably 2612 Ma.

Zircons from the Alto Maranhão pluton (N-22, N-18) are pink, euhedral and devoid of visible cores. Two analyses yield minimum ages of 2130 Ma and 2166 Ma (analyses 22-1 and 22-2, 0.8% and 4% discordant, respectively) indicating the

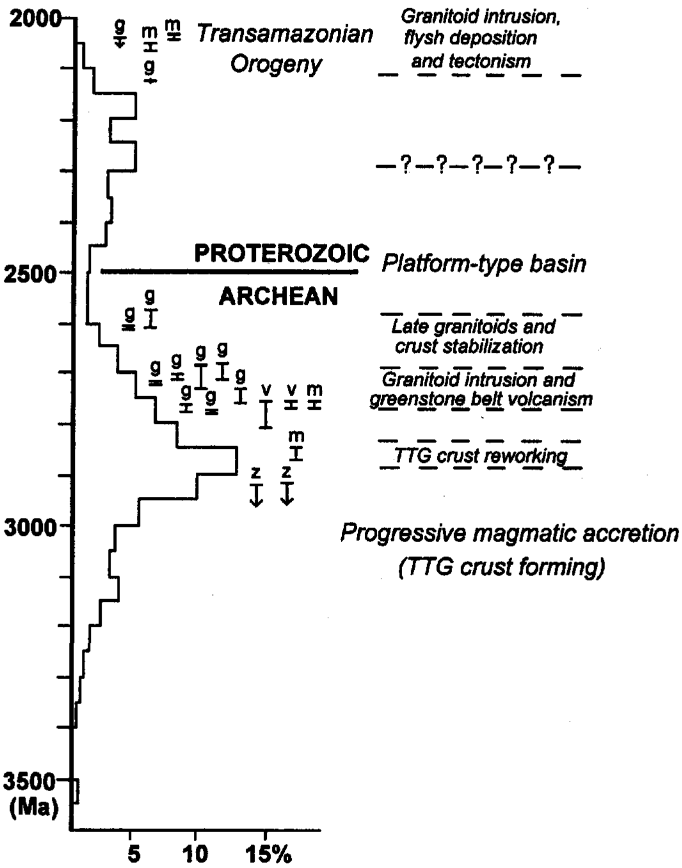


Figure 4 • Summary of the U-Pb ages for the Quadrilátero Ferrífero and the main events they represent (U-Pb ages from Romano et al. 1991, Machado et al. 1992, Machado & Carneiro 1992, Chemale et al. 1993). The histogram to the left represents detrital zircon age distribution, amounting to 449 zircons from Archaean and Proterozoic clastic units of the Quadrilátero Ferrífero (after Machado et al. 1996b). Legend: g. granitoid pluton, v. volcanic rock, in. metamorphic age, z. minimum age of inherited zircon.
Figura 4 - Resumo das idades U-Pb do Quiadrilátero Ferrífero e os principais eventos que representam (idades U-Pb obtidas por Romano et al. 1991, Machado et al. 1992, Machado & Carneiro 1992, Chemale et al. 1993). O histograma da esquerda representa a distribuição de idades de zircão detrítico, totalizando 449 zircões de unidades elásticas arqueanas e proterozóicas do Quadrilátero Ferrífero (seg. Machado et al. 1996b). Legenda: g. plútons de granitóioides, v. rochas vulcânicas, m.idade do metamorfismo, z. idade mínima de zircão herdado.

presence of inheritance in the tonalite. Two titanite fractions yield identical $^{207}Pb/^{206}Pb$ ages of 2125 Ma and 2124 Ma (22-3 and 22-4,1.4% and 19% discordant). One titanite fraction analysis from another sample (N-18) is 2.4% discordant and yields an identical $^{207}Pb/^{206}Pb$ age of 2124 Ma. The three titanite analyses define a discórdia (97% probability of fit) with an upper intercept age of 2124±1 Ma (Table 1, Fig 3b) taken as the age of crystallization of the pluton.

Sample N-18 yields a Nd model age (TDM) of 2.2 Ga (Noce 1995), similar to the age of crystallization, and a positive £Nd value of+1.1 suggesting that the tonalitic magma could be largely mantle derived. However, the presence of inherited zircon indicates a small degree of crustal assimilation by the magma.

GEOLOGICAL IMPLICATIONS AND CONCLUSIONS A summary of U-Pb data for the Quadrilátero Ferrífero is shown in figure 4, where magmatic and metamorphic episodes are compared to a detrital zircon age histogram. The histogram is based on more than 400 detrital zircons from clastic units of the Rio das Velhas greenstone belt, Minas Supergroup and Itacolomi Group, and ages were obtained by Laser-ablation-ICPMS and isotope dilution (Machado *et ai.* 1996b). The presence of 3.5-3.0 Ga continental crust in the Quadrilátero Ferrífero is only suggested by detrital zircon dating. The age distribution of detrital zircon increases after 3.0 Ga, probably reflecting an increase in crust-growth processes. The peak at 2900-2850 Ma coincides with geological events recorded in the Belo Horizonte, Campo Belo and Gouveia complexes (Machado *et al.* 1989, Teixeira *et al.* 1998). This tectonothermal event probably affected the entire pre-existing continental crust in a manner similar to that proposed by Choukroune *et al.* (1995).

The migmatization event at 2860+14/-10 Ma in the Belo Horizonte complex affected a TTG-type gneiss which protholith is at least 2922 Ma and probably not older than 3.0 Ga. During this event, the gneiss was strongly deformed and developed the regional N-S low angle foliation also found in the northern sector of the Bonfim complex (Carneiro 1992) and, more generally, to the west of the Quadrilátero Ferrífero.

Archaean events after 2860 Ma were episodic, short-lived, and could be related to a progressive accretion of crustal blocks reaching final cratonization at *ca.* 2600 Ma. The best-characterized event in the Quadrilátero Ferrífero took place in the 2780-2700 Ma time interval. Felsic volcanism dated at 2776-2772 Ma was coeval with granitoid emplacement at 2780-2776 Ma in the northern (Caeté granodiorite) and western (Samambaia tonalites) margins of the greenstone belt (Machado *et al.* 1992, Machado & Carneiro 1992). Less extensive and crust-derived granitoids occurring in the Belo Horizonte and Bonfim complexes represents further magmatic activity. In the former, foliated granitoids were dated at 2712+5/-4 Ma (the Santa Luzia and possibly the General Carneiro granite) and at 2698±18 Ma (U-Pb age of Ibirité granodiorite; Chemale *et al.* 1993). In the Bonfim complex, the Mamona granodiorite was dated at 2721 ±3 Ma (Machado *et al.* 1992), and the Brumadinho granite at 2703+24/-20 Ma (Machado & Carneiro 1992).

The youngest Archaean granitoids found in the Quadrilátero Ferrífero area are the Salto do Paraopeba granite (2612+3/-2 Ma) and the Caio Martins granite (259318 Ma, Romano *et al.* 1991).

Other Archaean cratons such as the Yilgarn of Western Australia, the Superior Province of Canada and the Kaapvaal and Zimbabwe cratons of southern Africa show similar kinds of broadly contemporaneous events at 2.8-2.6 Ga, which may reflect the formation of a supercontinent, or supercontinents, at this time (Myers 1995). Different tectonic environments have been proposed for Neoarchean greenstone belt formation and final cratonization. In the Superior Province, greenstone belts like the Abitibi evolved largely in an oceanic environment (Corfu 1993) and island-arc accretion played a major role in continental growth (Card 1990). In the Quadrilátero Ferrífero, older continental crust was a major source for greenstone belt sediments (Machado *et al.* 1996b), and cratonization was probably accomplished by amalgamation of a number of microcontinents.

Cratonic conditions and the absence of magmatic activity prevailed in the 2.6-2.4 time interval (see Fig. 4). The lower succession of the Minas Supergroup, consisting of fluvial sandstones and stable-shelf pelites, iron formation, ferruginous dolomites and dolomites, represents an Archaean-Paleoproterozoic cratonic cover. Its maximum age is defined by the emplacement of *ca.* 2600 Ma granitic plutons *(e.g.* Salto do

Paraopeba granite) while dolomitic rocks overlying the Cauê Iron Formation yielded a Pb-Pb whole-rock isochron of 2420±19 Ma (Babinski *el al* 1995). The Transvaal Supergroup in the Kaapvaal craton, and the Hamersley Group in the margins of the Pilbara craton, are similar to the lower Minas Supergroup. Both units are broadly time equivalent and were deposited after 2.68 Ga (Cheney 1996, Sumner & Bowring 1996). Their minimum age is not well constrained, but reported U-Pb ages for the Brockman Iron Formation (Hamersley Group) and the Griquatown Iron Formation (Transvaal Supergroup) are, respectively, 2470±4 Ma and 2432±31 Ma (Cheney 1996).

Source rocks for 2.4-2.2 Ga detrital zircons (Fig. 4) have not been found in the Quadrilátero Ferrífero and geologic events at this period remain highly speculative. A collisional belt developed at the margins of the former Archaean platform after 2.2 Ga. The flysch-like sediments of the Sahara Formation clearly mark a complete change both in depositional environment and source of sediments from those represented in the older units of the Minas Supergroup (Dorr 1969). The striking coincidence between the 2125±4 Ma age for the youngest zircon found in the Sahara Formation (Machado *et ai.* 1992) and the 2124± 1 Ma age of the Alto Maranhão pluton indicates that the flysch sedimentation and the igneous activity during the Transamazonian Orogeny are contemporaneous.

Transamazonian metamorphism is recorded in the Belo Horizonte gneiss by titanite ages of 2041+5 Ma and by the emplacement of granitic stocks at *ca.* 2045 Ma, in agreement with titanite and monazite ages of 2060-2030 Ma for amphibolite and pegmatite in the Bação Complex (Machado *et al.* 1992).

Rb-Sr whole-rock ages and K-Ar mineral ages are remarkably incoherent in the Quadrilátero Ferrífero. For example, samples of the Alto Maranhão pluton from the same locations sampled for U-Pb analyses (2124±1 Ma) yielded K-Ar biotite ages of 1000±22 Ma and 730±25 Ma and Rb-Sr whole-rock ages of 664±80 and 484±37 Ma (Noce 1995). Isotopic disturbance of Sr and Ar systems must be related to post-Transamazoniam events, especially the Braziliano Orogeny *(ca.* 600 Ma). This event probably played a minor role in the structural evolution of the Quadrilátero Ferrífero, inducing the reactivation of former structures especially in the eastern part of the area.

Acknowledgments Field and laboratory work in Brazil were supported by FAPEMIG (Minas Gerais) and FAPESP (Sao Paulo). The personnel of CPGeo (São Paulo) and CPMTC (Universidade Federal de Minas Gerais) are thanked for technical support. F. Robert and R. Lapointe are thanked for sustained technical support and Michelle Laithier for map drawing. The UQAM geochronology laboratory is supported by infrastructure grants from NSERC (Canada) and FCAR (Quebec). N.M. acknowledges support from NSERC (Canada).

REFERENCES

Babinski, M.; Chemale, F.; Van Schumus, W.R. 1995. The Pb/Pb age of the Minas Supergroup carbonate rocks, Quadrilátero Ferrífero, Brazil. *Precambrian Research,* 72:235-245

Card, K.D. 1990. A review of the Superior Province of the Canadian Shield, a product of Archean accretion. *Precambrian Research,* 48:99-156

Carneiro, M.A. 1992. *O Complexo Metamórfico Bonfim Setentrional (Quadrilátero Ferrífero, Minas Gerais): Litoestratigrafia e evolução geológica de um segmento de crosta continental do Arqueano.* Inst. de Geociências, Universidade de São Paulo, São Paulo, Tese de Doutoramento, 233 p.

Chapell, B.W.; White, A.J.R. 1974. Two contrasting types of granites. *Pacific Geology, 8:113-114*

Chemale., P.; Babinski, M.; Van Schumus, W.R. 1993. U/Pb dating of granitic-gneissic rocks from the Belo Horizonte and Bonfim complexes, Quadrilátero Ferrífero (Brazil): Report for CNPq and NSF-EAR Project on São Francisco Craton Margin Transect Project, 16 p. (unpubl.).

Cheney, E.S. 1996. Sequence stratigraphy and plate tectonics significance of the Transvaal succession of southern Africa and its equivalent in Western Australia. *Precambrian Research,* 79:3-24

Choukroune, P.; Bouhallier, H.; Arndt, N.T. 1995. Soft lithosphere during periods of Archaean crustal growth or crustal reworking. In M.P. Coward & A.C. Ries (eds.) *Early Precambrian Processes.* London, Geological Society Special Publication, n. 95,67-86

Corfu, F. 1993. The evolution of the southern Abitibi greenstone belt in light of precise U-Pb geochronology. *Economic Geology,* 88:1323-1340

Davis, D.W. 1982. Optimum linear regression and error estimation applied to U-Pb data. *Canadian Journal of Earth Sciences,* 19:2141 -2149

Dorr II, J.V.N. 1969. Phisiographic, stratigraphic and structural development of the Quadrilátero Ferrífero, Minas Gerais, Brazil. *U.S. Geological Survey Professional Paper,* 641-A: I -110

Dorr II, J.V.N.; Gair, J.E.; Pomerene, J.G.; Rynearson, G.A. 1957. *Revisão da estratigrafia pré-cambriana do Quadrilátero Ferrífero.* Rio de Janeiro, DNPM-DFPM, 31 p. (Avulso 81)

Herz, N. 1970. Gneissic and igneous rocks of the Quadrilátero Ferrífero, Minas Gerais, Brazil. *U.S. Geological Survey Professional Paper,* 641-8:1-58

Krogh, T.E. 1973. A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determination. *Geochimica et Cosmochimica Acia,* 37:488-494

Krogh, T.E. 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. *Geochimica et Cosmochimica Ada,* 46:637-649

Machado, N.; Schrank, A.; ABREU, F.R.; KNAUER, L.G.; ALMEIDA-ABREU, P.A. 1989. Resultados preliminares da geocronologia U-Pb na Serra do Espinhaço Meridional. In: SBG/Núcleo Minas Gerais, Simp. Geol. de Minas Gerais, 5, Belo Horizonte, *Anais,* l -4

Machado, N.;Carneiro, M.A. 1992. U-Pb evidence of late Archean tectono-thermal activity in the southern São Francisco shield, Brazil. *Canadian Journal of Earth Sciences,* 29:2341-2346

Machado, N.; Noce, C.M.; Ladeira, E.A.; Belo de Oliveira, O.A. 1992. U-Pb geochronology of Archean magmatism and Proterozoic metamorphism in the Quadrilátero Ferrífero, southern São Francisco Craton, Brazil. *Geological Society of America Bulletin,* 104:1221 -1227

Machado, N.; Valladares, C.; Heilbron, M.; Valeriano, C. 1996a. U-Pb geochronology of the central Ribeira Belt (Brazil) and implications for the evolution of the Brazilian Orogeny. *Precambrian Research,* 79:347-361

Machado, N.; Schrank, A.; Noce, C.M.; Gauthier, G. 1996b. Ages of detrital zircon from Archean-Paleoproterozoic sequences: Implications for Greenstone Belt setting and evolution of a Transamazonian foreland basin in Quadrilátero Ferrífero, southeast Brazil. *Earth and Planetary Science Letters,* 141:259-276

Myers, J.S. 1995. The generation and asembly of an Archaean supercontinent: evidence from the Yilgarn craton, Western Australia. In M.P. Coward & A.C. Ries (eds.) *Early Precambrian Processes.* London, Geological Society Special Publication, n. 95, p. 143-154.

Noce, C.M. 1995. *Geocronologia dos eventos magmáticos, sedimentares e metamórficos na região do Quadrilátero Ferrífero, Minas Gerais.* Inst. de Geociências, Universidade de São Paulo, São Paulo, Tese de Doutoramento, 129 p.

Noce, C.M.; Teixeira, W.; Machado, N. 1997. Geoquímica dos gnaisses TTG e granitóides neoarqueanos do Complexo Belo Horizonte, Quadrilátero Ferrífero, Minas Gerais. *Revista Brasileira de Geociências,* 27:25-32

Pomerene, J.B. 1964. Geology of Belo Horizonte, Ibirité and Macacos quadrangles. *U.S. Geological Survey Professional Paper,* 341-D:l-84

Romano, A.W.; Bertram!, J.M.; Michard, A.; Zimmermann, J.L. 1991. Tectonique tangentielle et décrochements d'age Protérozoique inférieur (orogenèse transamazonienne, environ 2000 Ma) au Nord du "Quadrilátero ferriíere" (Minas Gerais, Brésil): *Complex Rendus de l'Academic dês Sciences de Paris,* 313:1195-1200

Sad, J.H.G.; Pinto, C.P.; Duarte, C.L. 1983. Geologia do distrito manganesífero de Conselheiro Lafaiete, MG. In: SBG/Núcleo Minas Gerais, Simp. Geol. de Minas Gerais, 2, Belo Horizonte, *Amiix,* 259-270

Stacey, J.S.; Kramers, J.D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters,* 26:207-221

Sumner, D.Y.; Bowring, S.A. 1996. U-Pb geochronologic constraints on deposition of the Campbellrand Subgroup, Transvaal Supergroup, South Africa. *Precambrian Research,* 79:25-35

Teixeira, W.; Cordani, U.G.; Nutman, A.; Sato, K. 1998. Polyphase Archean evolution in the Campo Belo metamorphic complex, Southern São Francisco, Brazil: SHRIMP U-Pb zircon evidence. *Journal of South American Earth Sciences* (in press).

Manuscrito A-954
Recebido em 28 de janeiro de 1998
Revisão dos autores em 14 de abril de 1998-05-03
Revisão aceita em 15 de abril de 1998