GEONOMOS 8 (1): 15-23

GEOCHRONOLOGY OF THE QUADRILÁTERO FERRÍFERO: A REVIEW

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RESUMO

Os estudos geocronológicos, especialmente com o uso do método U-Pb, tem sido fundamentais para o conhecimento da evolução arqueana do Quadrilátero Ferrífero. A região registra a atuação de diversos eventos magmáticos e tectono-metamórficos, entre 2860 e 2600 Ma. A datacão de rochas vulcânicas félsicas em *ca.* 2772 Ma permite balizar a idade do Greenstone Belt Rio das Velhas. Tais vulcanitos félsicos parecem posicionar-se próximo ao topo da sucessão basal do greenstone belt. Não se conhece a ocorrência de rochas vulcânicas datáveis nas unidades supracrustais proterozóicas do Quadrilátero Ferrífero, de forma que suas idades de deposição podem apenas ser inferidas através das análises de zircões detríticos. A atuação da Orogenia Transamazônica na região encontra-se bem registrada, por meio da datação de corpos granitóides e eventos de metamorfismo entre 2120-2040 Ma.

INTRODUCTION

Archean terrains of the Quadrilátero Ferrífero comprise a granite-greenstone belt association (Rio das Velhas Supergroup; Dorr *et al*. 1957) surrounded by granite-gneiss complexes. The Rio das Velhas Supergroup basal unit (Nova Lima Group) consists of a volcano-sedimentary sequence hosting the main gold deposits of the Quadrilátero Ferrífero, which is covered by the dominatly quartzitic Maquiné Group. The granite-gneiss terrains comprise several complexes or domes (Herz 1970): Belo Horizonte to the north of Quadrilátero Ferrífero, Caeté to the northeast, Bação in the centre, and Bonfim to the west. The Paleoproterozoic Minas Supergroup tectonically overlies the Archean units 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. The Piracicaba Group is characterized by interbedded quartzite and phyllite containing carbonatic lenses. Its upper unit (Sabará Formation) is composed of chlorite schists, phylites, graywackes, conglomerates, quartzites and rare iron formation (Fig. 1).

Geochronological research in the Quadrilátero Ferrífero, mainly based on U-Pb dating of zircon, titanite and monazite, has disclosed a polyciclic Archean evolution comprising many magmatic and metamorphic episodes. It has also stressed the role played by Proterozoic events like the *ca.* 2.1 Ga Transamazonian Orogeny.

A large set of geochronological determinations is available for the granite-gneiss-migmatite terrains of the Quadrilátero Ferrífero and surrounding areas. On the other hand, only three volcanic rocks of the greenstone belt have been dated so far, resulting in poorly contrained time limits for this unit. Proterozoic supracrustal sequences are devoid of volcanic rocks and their deposition ages have been essentially indicated by detrital zircon dating (Table 1).

U-BEARING MINERAL AGES (ID-TIMS; PB-PB EVAPORATION AND LP-ICPMS)

Archean TTG gneiss and migmatite

Banded TTG gneiss, exhibiting migmatization features, makes up the largest proportion of the crystalline basement of the Quadrilátero Ferrífero. In the Belo Horizonte Dome, north of the Quadrilátero Ferrífero, U-Pb analyses were carried out on a migmatitic gneiss displaying tightly folded leucossome layers up to 0.5 m thick. Three zircon fractions from a leucosome sample define a discordia line (23% probability of fit) with the upper intercept at 2860+14/-10 Ma. A fourth single zircon fraction yields a $^{207}Pb/^{206}Pb$ minimum age of 2923 Ma (2.3% discordant). This is interpreted as an inherited zircon from the gneiss. Both the leucosome and a less-migmatized gneiss sample from the same outcrop contain titanite; that from the leucosome is concordant at 2041±5 Ma, whilst two titanite fractions from the gneiss yield minimum ages of 2312 Ma and 2227 Ma, defining a discordia with a poorly-constrained upper intercept at 2847+81/-77 Ma.

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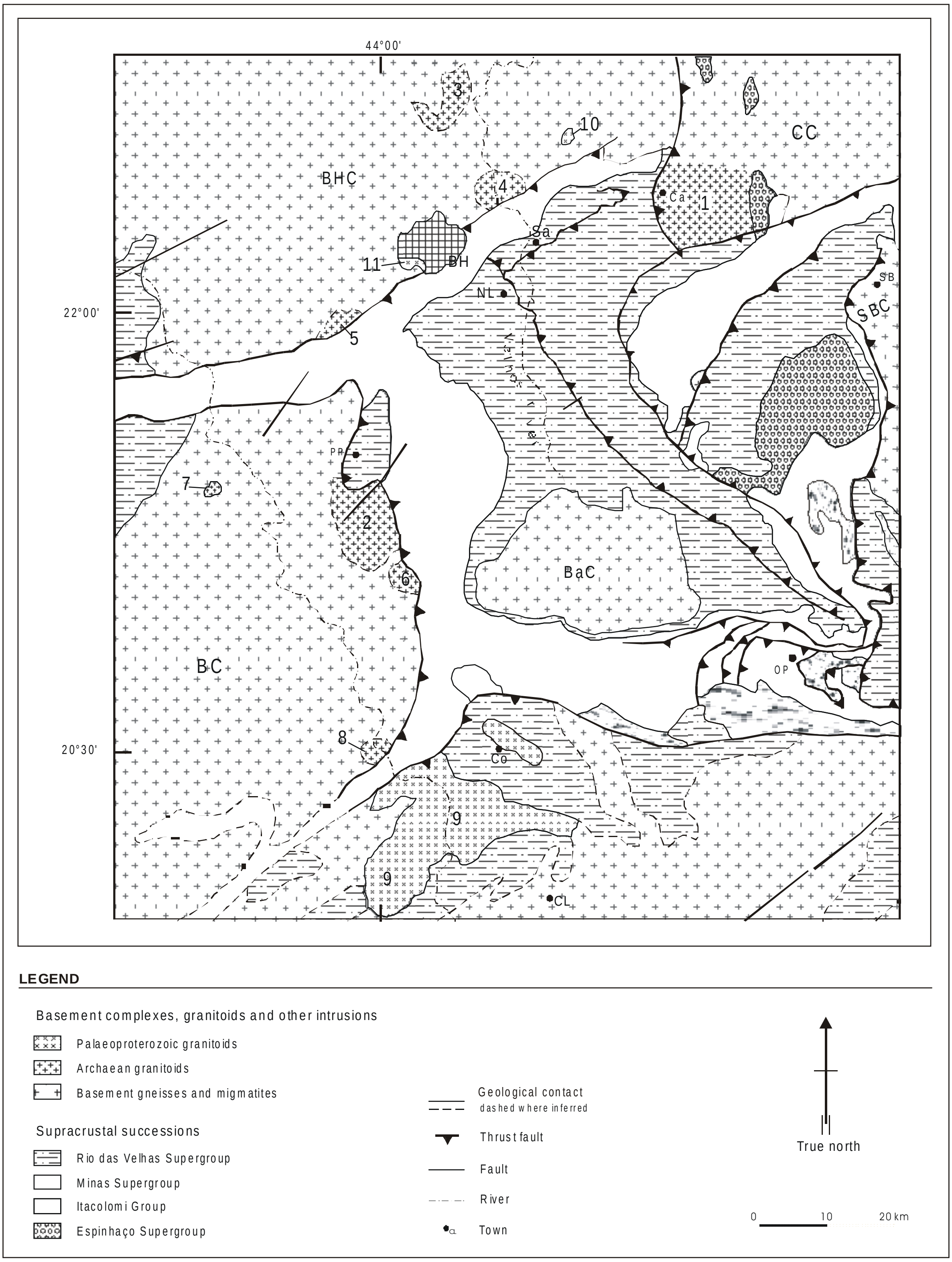

Figure 1: Simplified geological map of the Quadrilátero Ferrífero showing the basement complexes, the main granitoids and intrusive bodies (after Noce 1995).

Basement complexes: BHC - Belo Horizonte; BC - Bonfim; CC - Caeté; BaC - Bação; and SBC - Santa Bárbara complexes. Archaean granitoids: 1 - Caeté granodiorite; 2 - Samambaia tonalite; 3 - Santa Luzia granite; 4 - General Carneiro granite; 5 – Ibirité granodiorite; 6 - Mamona granodiorite; 7 - Brumadinho granite; 8 – Salto do Paraopeba granite. Palaeoproterozoic granitoids: 9 - Alto Maranhão tonalite; 10 - Córrego do Brumado granite; 11 - Morro da Pedra granite. Towns: BH - Belo Horizonte; Ca - Caeté; CL - Conselheiro Lafaiete; CoC - Congonhas do Campo; NL - Nova Lima; OP - Ouro Preto; PP - Piedade do Paraopeba; SB - Santa Bárbara.

Figura 1: Mapa geológico simplificado do Quadrilátero Ferrífero apresentando os complexos do embasamento, os principais granitóides e corpos intrusivos (segundo Noce 1995).

It can be concluded that migmatization occurred at 2860+14/-10 Ma, forming zircon and titanite. During the Transamazonian Orogeny, titanite in the leucosome was completely reset at 2041±5 Ma, whilst titanite in the gneiss was partially reset (Noce *et al*., 1998). A similar titanite age of 2059±6 Ma was obtained from an amphibolite enclave within a migmatitic gneiss of the Bação Dome, located at the center of the Quadrilátero Ferrífero (Machado *et al*., 1992). On the other hand, a titanite fraction from a sheared banded gneiss of the eastern part of the Caeté Dome (NE of the Quadrilátero Ferrífero) is 3.5% discordant with a $^{207}Pb/^{206}Pb$ age of 2555 Ma (Noce, 1995), probably indicating the same process of partial lead loss as proposed above.

A sample from TTG gneiss of the Bonfim Dome, west of the Quadrilátero Ferrífero, contains zircon prisms with core and overgrowth, yielding the following U-Pb ages: a single overgrowth is concordant at 2772±6 Ma whilst a single core is 1.1% discordant with a $^{207}Pb/^{206}Pb$ age of 2920 Ma (Machado and Carneiro, 1992). There is a striking coincidence between $^{207}Pb/^{206}Pb$ ages for inherited zircon from leucossome layer in the Belo Horizonte Dome and zircon core from the Bonfim gneiss. In both cases, a minimum age of 2920 Ma is indicated for the gneiss protoliths. On the other hand, the 2860 Ma metamorphic episode is not recorded in the Bonfim Dome, but rather a younger one at 2772 Ma.

A mylonite-gneiss from the Bação Dome contains a rather uniform zircon population, seven of which were analysed by the Pb evaporation method. The wide variation of $^{207}Pb/^{206}Pb$ ages precludes the determination of a plateau age, but one of the zircons gives a mean age of 2972±56 Ma, assumed as a minimum crystallization age for the gneiss (Endo, 1997). This agrees well with the minimum magmatic crystallization ages obtained for the gneiss from Belo Horizonte and Bonfim domes.

Archean granitoid plutons

The older sialic crust, represented by TTG banded gneiss, was intruded by granitoids of variable composition, comprising foliated and poorly- to unfoliated types, and ranging from veins to large bodies. U-Pb dating of many intrusions has disclosed three granitic magmatic episodes during the Neoarchean, at *ca*. 2780-2760 Ma, 2720-2700 Ma, and 2600 Ma.

The Caeté granodiorite is a large body located in the northeastern Quadrilátero Ferrífero. Three zircon fractions from this rock yield an age of crystallization of 2776+7/-6 Ma, whilst a rutile from the same sample is 11% discordant and gives a minimum age of 2391 Ma (Machado *et al*., 1992). The rutile age probably indicates incomplete resetting during the Transamazonian Orogeny.

The Samambaia tonalite is a calc-alkaline and metaluminous intrusion (Carneiro, 1992) comprising two plutons cropping out within the Bonfim Dome. Two zircon fractions from each pluton were analysed; one single zircon is concordant at 2779±3 Ma and, together with the other three fractions, define a discordia (44% probability of fit) with an upper intercept at 2780+3/-2 Ma (Machado and Carneiro, 1992). A titanite fraction is concordant at 2774±6 Ma, revealing a different pattern from the Belo Horizonte and other gneissic domes to the east, where the Transamazonian Orogeny induced severe lead loss on titanites, or even total resetting.

Northwest of the Quadrilátero Ferrífero the Mateus Leme pluton is a well-foliated, granitic- to granodioritic, calc-alkaline and metaluminous intrusion (Romano, 1989, Heineck, 1997). Five unabraded zircon fractions from a granite sample are highly discordant but define a discordia line with an upper intercept at 2755+14/-13 Ma (Romano, 1989; Romano *et al*., 1991).

Two intrusions related to the second granitic magmatism are found within the Bonfim Dome. The calc-alkaline Brumadinho granite (Carneiro, 1992) comprises weakly foliated and folded dykes that crosscut the N-S regional foliation of TTG-gneiss. Three zircon fractions from one of the granitic dykes are 3 to 12% discordant and lies on a discordia line with a poorly-defined upper intercept at 2703+24/-20 Ma, assumed as the best estimate for the age of the dyke (Machado and Carneiro, 1992). The Mamona granite is coarse-grained to porphyritic, and seems to postdate the Archean deformational events that affected the Bonfim Dome (Noce *et al*., 1996). According to Lacerda *et al*. (1996) it can be classified as a post-collisional subalkaline granite. Two zircon fractions from the granite are slightly discordant with $^{207}Pb/^{206}Pb$ ages of 2717 Ma and 2715 Ma whilst a third fraction is concordant at 2721±3 Ma, assumed as the crystallization age of the intrusion (Machado *et al*. 1992).

Granitic plutons intruding the migmatized TTG gneiss of the Belo Horizonte Dome fall into the 2720-2700 Ma interval, but are strongly foliated contrasting with the less-deformed, contemporaneous plutons of the Bonfim Dome. A sample from the calc-alkaline and slightly peraluminous Santa Luzia granite yields three zircon analyses which are between 9% and 17% discordant, and define a discordia (56% probability of fit) with the upper intercept at 2712+5/-4 Ma, taken as the age of crystallisation of the granite (Noce *et al*., 1998). A less precise intrusion age is available for the Ibirité granodiorite; four zircon fractions define a discordia with an upper intercept at 2698±18 Ma (Chemale Jr. *et al*., 1993). Four fractions of titanite from the Santa Luzia granite which underwent variable abrasion times are discordant with $^{207}Pb/^{206}Pb$ ages between 2328 Ma and 2212 Ma. The analyses do not define a discordia but are compatible with this rock having undergone Transamazonian metamorphism, which has partially reset the titanite (Noce *et al*., 1998).

The Capelinha trondhjemite is a small, foliated pluton located to the northwest of the Quadrilátero Ferrífero. Three zircon fractions are 12% to 80% discordant, plotting on a discordia with the upper intercept at 2714±2 Ma (Oliveira, 1999). Two other fractions composed of metamict zircons plot below the

Unit	Rock-type	Location	Mineral or rock dated	Dating method	Age (Ma)	Interpretation	Reference
Archean TTG gneiss and migmatite							
Belo Horizonte dome	migmatite (leucossome)	North of the QF	zircon	U-Pb	2923*[2]	minimum age of migmatite protolith	Noce *et al.* (1998)
Belo Horizonte dome	migmatite (leucossome)	North of the QF	zircon	U-Pb	2860+14/-10*[3]	migmatization age	Noce *et al.* (1998)
Belo Horizonte dome	migmatite	North of the QF	titanite	U-Pb	2041±5*[1]	metamorphic resetting	Noce *et al.* (1998)
Bação dome	gneiss	Center of the QF	zircon	Pb-Pb evaporation	2972±56	minimum magmatic age	Endo (1997)
Bação dome	amphibolite	Center of the QF	titanite	U-Pb	2059±6*[1]	metamorphic age	Machado *et al.* (1992)
Caeté dome	gneiss	NE of the QF	titanite	U-Pb	2555*[2]	partial resetting	Noce (1995)
Bonfim dome	gneiss	West of the QF	zircon core	U-Pb	2920*[2]	minimum age of gneiss protolith	Machado and Carneiro (1992)
Bonfim dome	gneiss	West of the QF	zircon overgrowth	U-Pb	2772±6*[3]	metamorphic resetting	Machado and Carneiro (1992)
Archean granitoid plutons							
Caeté granodiorite		NE of the QF	zircon	U-Pb	2776+7/-6*[3]	magmatic age	Machado *et al.* (1992)
Caeté granodiorite		NE of the QF	rutile	U-Pb	2391*[2]	partial resetting	Machado *et al.* (1992)
Samambaia tonalite		West of the QF	zircon	U-Pb	2780+3/-2*[3]	magmatic age	Machado and Carneiro (1992)
Samambaia tonalite		West of the QF	titanite	U-Pb	2774±6*[1]	magmatic age	Machado and Carneiro (1992)
Mateus Leme granite		NW of the QF	zircon	U-Pb	2755+14/-13*[3]	magmatic age	Romano *et al.* (1991)
Brumadinho granite		West of the QF	zircon	U-Pb	2703+24/-20*[3]	magmatic age	Machado and Carneiro (1992)
Mamona granite		West of the QF	zircon	U-Pb	2721±3*[1]	magmatic age	Machado *et al.* (1992)
Santa Luzia granite		North of the QF	zircon	U-Pb	2712+5/-4*[3]	magmatic age	Noce *et al.* (1998)
Santa Luzia granite		North of the QF	titanite	U-Pb	2328/2212*[2]	partial resetting	Noce *et al.* (1998)
Ibirité granodiorite		North of the QF	zircon	U-Pb	2698±18*[3]	magmatic age	Chemale Jr. *et al.* (1993).
Capelinha trondhjemite		NW of the QF	zircon	U-Pb	2714±2*[3]	magmatic age	Oliveira (1999)
Salto Paraopeba granite		SW of the QF	zircon	U-Pb	2612±5*[3]	magmatic age	Noce *et al.* (1998)
Caio Martins granodiorite		NW of the QF	zircon	U-Pb	2593±8*[3]	magmatic age	Romano *et al.* (1991)
Bação dome (granite stocks and veins)		Center of the QF	zircon	Pb-Pb evaporation	2682±43/ 2567±8	minimum magmatic age	Endo (1997)
Rio das Velhas Greenstone Belt							
Nova Lima Group	felsic volcanic	Piedade Paraopeba	zircon	U-Pb	2772±6*[1]	magmatic age	Machado *et al.* (1992)
Nova Lima Group	felsic volcanic	Piedade Paraopeba	zircon core	U-Pb	2883±6*[1]	zircon inheritance	Machado *et al.* (1992)
Nova Lima Group	felsic volcanic	Caeté	zircon	U-Pb	2776+23/-10*[3]	magmatic age	Machado *et al.* (1992)
Nova Lima Group	felsic volcanic	Caeté	zircon	U-Pb	3029*[2]	zircon inheritance	Machado *et al.* (1992)
Nova Lima Group	mafic volcanic	Caeté	rutile	U-Pb	2580*[2]	minimum age of hydrotermal alteration and gold mineralization	Noce (1995)
Nova Lima Group	graywacke	Caeté	23 detrital zircons	Pb-Pb LA-ICPMS	3539±34 -2996±38	age of sediment source	Machado *et al.* (1996)
Nova Lima Group	graywacke	Caeté	4 detrital zircons	U-Pb	3232 -2900*[2] 3198±6*[1]	age of sediment source	Machado *et al.* (1996)
Nova Lima Group	graywacke	Caeté	monazite	U-Pb	2850*[2] 2921±3*[1]	age of sediment source	Schrank and Machado (1996b)
Nova Lima Group	graywacke	Cuiabá	monazite	U-Pb	2857±1*[1]	age of sediment source	Schrank and Machado (1996b)
Nova Lima Group	sandstone	Carrapato	zircon	U-Pb	1808±4*	reset age	Schrank and Machado (1996b)

Table 1: U-bearing mineral ages (ID-TIMS; Pb-Pb evaporation and LA-ICPMS) - cont.

3590±7*4

Unit	Rock-type	Location	Mineral or rock dated	Dating method	Age (Ma)	Interpretation	Reference
Proterozoic granitoid rocks and pegmatites							
Alto Maranhão tonalite		South of the QF	titanite	U-Pb	2124±1*3	magmatic age	Noce *et al.* (1998)
Belo Horizonte dome	granite stock	North of the QF	monazite	U-Pb	2045*2	magmatic age	Noce *et al.* (1998)
Bação dome	pegmatite veins	Center of the QF	monazite	U-Pb	2030/2022*2	magmatic age	Machado *et al.* (1992)
Minas Supergroup and Itacolomi Group							
Moeda Formation	quartzite	different locations in the QF	185 detrital zircons	LA-ICPMS	2606±47 -3257±58	age of sediment source	Machado *et al.* (1996)
Sabará Formation	graywacke	West of Belo Horizonte	zircon	U-Pb	2164±13*1 2131±5*1 2125±4*1	age of sediment source	Machado *et al.* (1992, 1996)
Itacolomi Group	quartzite in the QF	different locations	131 detrital zircons	LA-ICPMS -3120±207	2059±58	age of sediment source	Machado *et al.* (1996)

*1 concordant mineral age
*2 discordant mineral age ($^{207}Pb/^{206}Pb$ age)
*3 upper intercept age
*4 lower intercept age

Table 1: U-bearing mineral ages (ID-TIMS; Pb-Pb evaporation and LA-ICPMS)

discordia line.

In the southwestern part of the Quadrilátero Ferrífero, a calc-alkaline and peraluminous granitic intrusion, the Salto do Paraopeba granite, is present. It is in general isotropic and medium- to fine grained. It yielded large and flattened zircon prisms fractured across their lenght suggesting the absence of cores. Two prisms were broken, abraded and the four fragments analysed separately. The analyses are 3% to 19% discordant and define a discordia (87% probability of fit) with an upper intercept at 2612±5 Ma, taken as the age of crystallisation of the granite (Noce *et al*., 1998). The late Archean granitic magmatism includes another pluton located to the northwest of the Quadrilátero Ferrífero, the Caio Martins granodiorite. Three highly discordant unabraded zircon fractions from this rock define a discordia with an upper intercept at 2593±8 Ma (Romano, 1989; Romano *et al*., 1991).

The Bação Dome was also affected by Neoarchean granitic magmatism as is indicated by less-precise, Pb-evaporation zircon ages. Three samples from granite bodies and a dyke yield plateau ages ranging from 2682±43 Ma to 2567±8 Ma (Endo, 1997).

Proterozoic granitoid rocks and pegmatites

A large Paleoproterozoic tonalite intrusion of metaluminous composition occurs to the south of the Quadrilátero Ferrífero intruding a greenschist sequence correlated with the Nova Lima Group. The Alto Maranhão tonalite contains euhedral zircons devoid of visible cores. Two analyses yield minimum ages of 2130 Ma and 2166 Ma, 0.8% and 4% discordant respectively, indicating the presence of inheritance in the tonalite. Three titanite analyses define a discordia (97% probability of fit) with an upper intercept age of 2124±1 Ma taken as the age of crystallisation of the pluton (Noce *et al*., 1998).

A slightly foliated granite stock within the Belo Horizonte Dome contains monazite that yields a $^{207}Pb/^{206}Pb$ age of 2045 Ma (2.3% discordant), which indicates a minimum crystallization age for the granite (Noce *et al*., 1998). This age agrees well with monazite U-Pb data from pegmatite veins of the Bação Dome. Two pegmatite veins, one intrusive into migmatitic gneiss and the other intruded along the schistosity of Nova Lima rocks, yield $^{207}Pb/^{206}Pb$ ages of 2030 Ma (1.3% discordant) and 2022 Ma (4.4% discordant), respectively (Machado *et al*., 1992). The intrusion of small granite stocks and pegmatite veins at 2045-2030 Ma, together with titanite growth and/or resetting at 2059-2041 Ma, is associated with amphibolite-facies metamorphism and restricted production of anatectic melts during the latter stages of the Transamazonian Orogeny (Machado *et al*., 1992, Noce *et al*., 1998).

Rio das Velhas Greenstone Belt

The lower portion of the Nova Lima Group is predominantly composed of mafic- to ultramafic volcanics and chemical sediments, including very restricted felsic volcanic rocks. Two samples of these rocks come from close areas south of Caeté, northeast of the Quadrilátero Ferrífero. One sample contains very small and coreless zircon prisms that could not be properly abraded, resulting in discordant analyses. Nevertheless, three fractions define a discordia with an upper intercept of 2776+23/-10 Ma (Machado *et al*., 1992). The other sample yielded only two zircon grains, which are 0.8% discordant with a minimum age of 3029 Ma (Machado *et al*., 1992). In the same area, rutiles were extracted from sheared mafic volcanics displaying hidrothermal alteration and gold mineralization. A single fraction is highly discordant (24%) and yields a $^{207}Pb/^{206}Pb$ age of 2580 Ma (Noce, 1995), thus suggesting an Archean age for gold mineralization in the area.

At Piedade do Paraopeba, west of the Quadrilátero Ferrífero, an isolated tectonic slice of the Nova Lima Group is positioned between the Minas Supergroup and gneisses of the Bonfim Dome. Similarly to the Caeté region, felsic volcanic rocks occurs as very subordinate layers within a sequence composed of mafic- to ultramafic volcanics and thin BIF (Noce *et al*., 1992), suggesting a stratigraphic correlation. One sample from the felsic volcanics yielded a mixed zircon population, some of them with visible cores. An analysis of two coreless grains is concordant at 2772±6 Ma, and one core physically separated from the overgrowth is concordant at 2883±6 Ma (Machado *et al*., 1992).

The more precise age of 2772±6 Ma seems to be the best estimate for felsic volcanism within the lower portion of the Nova Lima Group, while zircon of 2883 Ma and 3029 Ma could represent inherited grains. This also points to the presence of an older continental crust in the Quadrilátero Ferrífero during greenstone belt evolution, which is confirmed by the detrital zircon data discussed below.

Geochronological studies of sedimentary rocks of the Nova Lima Group resulted in a complex age pattern (Machado *et al*., 1996, Schrank and Machado, 1996a,b). Two graywacke samples are from a turbidite sequence overlying basaltic komatiites, located to the west of the Nova Lima district. One sample was collected 5 km north of the Carrapato deposit; LP-ICPMS analysis of 23 detrital zircons yield $^{207}Pb/^{206}Pb$ ages ranging from 3539±34 Ma to 2996±38 Ma and a mode at 3.2-3.1 Ga. Another four grains were analysed by U-Pb TIMS; three are discordant with minimum ages between 3232 Ma and 2900 Ma and one is concordant at 3198±6 Ma (Machado *et al*., 1996). Three detrital monazites were also analysed by U-Pb TIMS; two grains are discordant with minimum ages around 2850 Ma and one is concordant at 2921±3 Ma. The other sample was from the northern limb of the Cuiabá Mine antiform, and contained monazite concordant at 2857±1 Ma (Schrank and Machado, 1996b).

A sediment layer trapped between two basaltic flows that hosts the Carrapato de Cima gold deposit was also sampled. It contains zircons with no detrital features and displaying core and overgrowth. Analysis of two cores and one overgrowth define a discordia (42% probability of fit) with an upper intercept age of 1808±4 Ma, and a lower intercept of 590±7 Ma (Schrank and Machado, 1996b).

There is also available data for sediments from the Morro Velho Mine, presented by Schrank and Machado (1996a) One sample comes from a turbidite sequence that hosts the mineralized "lapa seca" unit, containing zircon and monazite. A fraction composed of two small and subrounded zircons is 2.7% discordant with a minimum age of 3126 Ma. Two euhedral grains are slightly discordant, yielding minimum ages of 2777 Ma (0.1% discordant) and 2776 Ma (0.7% discordant). A $^{207}Pb/^{206}Pb$ age of 2278 Ma (7.2% discordant) was obtained for a zircon with clear detrital features and displaying a monazite inclusion. A fraction of small and rounded monazite yields a minimun age of 2068 Ma (13.1% discordant), whilst a single euhedral grain is 2.7% discordant with a minimum age of 1875 Ma. A sample of the "lapa seca" unit also contains detrital zircon and monazite. Two zircon grains yield $^{207}Pb/^{206}Pb$ ages of 2771 Ma (0.5% discordant) and 2748 Ma (11.5% discordant), and one monazite is concordant at 2705±1 Ma.

A sample of quartzite of the upper Maquiné Group yields the following U-Pb zircon ages: three are concordant at 3261±2 Ma, 2898±3 Ma and 2877±3 Ma, while two others give minimum ages of 3006 Ma and 2913 Ma (Machado *et al*., 1996). The same sample contained euhedral monazite that yield $^{207}Pb/^{206}Pb$ ages of 2020 Ma (3.3% discordant) and 1989 Ma (2% discordant, Schrank and Machado, 1996b).

The main conclusions that arise from the geochronological data of the Rio das Velhas greenstone belt are:

1) The main source-area for the Rio das Velhas sediments seems to be the TTG-crust formed at multiple episodes after *ca*. 3500 Ma, that culminated in a extensive metamorphic/magmatic event at 2880-2850 Ma. The latter is constrained not only by detrital zircon and monazite ages (2877±3 Ma and 2857±1 Ma), but also by the 2883±6 Ma age of a zircon core from the Piedade do Paraopeba felsic volcanic, and the migmatization of Belo Horizonte gneiss at 2860+14/-10 Ma.

2) Felsic volcanism at 2772±6 Ma is related to the final stages of evolution of the predominantly mafic- to ultramafic lower volcanic sequence of the Nova Lima Group, and represents the best age constraint for the greenstone belt. The volcanic sequence was also a source for some directly overlying sediments, as indicated by the presence of detrital zircons dated at 2777-2771 Ma. One of these sedimentary layers contains detrital monazite dated at 2705±1 Ma. It is uncertain if this age dates a sediment source or, more likely, isotopic resetting of monazite during widespread plutonic activity at 2720-2700 Ma. Thus, the upper sedimentary sequence of the Nova Lima Group was deposited after 2772 Ma, but there are no age data

limiting the completion of deposition. There is also no age data limiting the onset of Maquiné sedimentation.

3) Isotopic resetting and/or crystallization of monazite at *ca.* 2068-2020 Ma must be associated to metamorphic overprint during the Transamazoniam Orogeny, in agreement with titanite and monazite ages from gneiss and pegmatites.

Post-Transamazonian events are recorded by one monazite age at *ca.* 1875 Ma and zircon ages at 1808±4 Ma and 590±7 Ma. Schrank and Machado (1996a) also report a monazite discordia line for Au-quartz vein from the Passagem de Mariana Gold Mine, with upper and lower intercepts at 1843±4 Ma and 462±4 Ma, respectively. A monazite minimum age of 596 Ma was obtained by Noce (1995) for quartz veins cutting across the Engenho Fault at the southern edge of the Quadrilátero Ferrífero. Those ages may be broadly related to two major events: the Espinhaço rifting and the evolution of the Brasiliano/Pan-African Araçuaí-Ribeira Belt. Both events played a secondary role in the evolution of the Quadrilatero Ferrífero, and regional temperatures associated to them were low, as indicated by the scarcity of U-Pb data and also by other isotopic systems (see below). As a consequence, zircon and monazite growth and/or resetting were probably associated to low-temperature processes restricted to narrow shear zones, as proposed by Noce (1995) and Schrank and Machado (1996b).

Minas Supergroup and Itacolomi Group

The majority of age data regarding these metasedimentary units are LA-ICPMS $^{207}Pb/^{206}Pb$, detrital zircon ages. Six quartzite samples from the basal Moeda Formation, Minas Supergroup, were collected from different areas of the Quadrilátero Ferrífero, the number of analysed zircons amounting to 185. Ages range from 2606±47 Ma to 3257±58 Ma, the younger one providing a maximum age for the onset of Minas sedimentation (Machado *et al.* 1996a). This is in agreement with the idea that sedimentation must post-date the intrusion of the *ca.* 2600 Ma, late Archean granites (Noce, 1995).

A quartzite of the Cercadinho Formation and a graywacke of the Sabará Formation, respectively the basal and upper units of the Piracicaba Group, were also analysed. Archean rocks were the only source for the Cercadinho quartzite and the main one for the Sabará graywacke, but the latter also includes Paleoproterozoic zircons. Three euhedral zircons yields concordant U-Pb ages of 2164±13 Ma, 2131±5 Ma and 2125±4 Ma (Machado *et al.*, 1992, 1996a), the latter being coincident with the 2124±1 Ma intrusion age for the Alto Maranhão tonalite. Paleoproterozoic detrital zircons predominate in the overlying Itacolomi Group, and its deposition is limited by a minimum age of 2059±58 Ma for the youngest grain (Machado *et al.* 1996a). It can be concluded that Sabará and Itacolomi units were supplied with sediments derived from magmatic rocks originated during the Transamazonian Orogeny. According to Machado *et al*. (1996a), both units may represent the filling of a foreland basin.

OTHER AGES (PB-PB, RB-SR, K-AR, SM-ND)

Rb-Sr and K-Ar Ages

Rb-Sr whole rock ages and K-Ar mineral ages are remarkably incoherent in the Quadrilátero Ferrífero. For example, samples of the Alto Maranhão tonalite 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). Another example comes from the Bonfim dome, where the *ca.* 2700 Ma Brumadinho granite and its host-rock, the TTG-gneiss, yield contrasting Rb-Sr whole-rock ages of 2219±80 Ma and 982±91 Ma (Carneiro, 1992). Fluid circulation through reactivated shear zones during post-Transamazonian events may be the cause of widespread disturbance of Rb-Sr isotopic systems, resulting in meaningless ages (Carneiro and Teixeira, 1992).

Despite many local discrepancies, K-Ar mineral ages as a whole become progressive younger from west to east. Biotite ages at about 550-500 Ma largely predominates at the far east part of the Quadrilátero Ferrífero (e.g. Cordani *et al.*, 1980), what is atributted to isotopic resetting during the Brasiliano orogeny. For most of the region, biotite ages display a wide range between 1800 Ma and 500 Ma (e.g. Teixeira, 1985, Romano, 1989, Carneiro, 1992, Noce, 1995). The same pattern is found for the more reliable hornblende ages. Data for the Bonfim dome to the west cluster at the 2150-1950 Ma interval (Carneiro, 1992), reflecting the metamorphic overprint of the Transamazonian orogeny, while along the eastern border of the Quadrilatero Ferrífero hornblende ages are similar to biotite ages at the 550-500 Ma interval (Cordani *et al*, 1980, Noce, 1995).

Mafic dykes are a common feature in the Quadrilátero Ferriífero, making up dense dyke swarms specially to the west and nortwest. K-Ar dating has disclosed multiple episodes of dyke emplacement (e.g. Teixeira *et al.*, 1988). Pre-2.1 Ga dykes are amphibolites and were isotopically reset during the Transamazonian Orogeny, precluding the stablishment of emplacement ages. However, field relations indicate that at least part of these bodies are Archean in age (Carneiro, 1992). The post-Transamazonian dykes may preserve their igneous textures, and K-Ar hornblende and plagioclase ages cluster at 1.75-1.55 Ga and 1.2-0.6 Ga (Teixeira *et al.*, 1988). The best estimate for the age of magmatic crystallization of the first set of mafic bodies is a baddeleyte U-Pb age of 1714±5 Ma for a dyke occurring to the west of Belo Horizonte (Silva *et al.*, 1995). For the younger set, a dyke from the Bonfim Dome yields a hornblende K-Ar age of 1006±46 Ma (Carneiro, 1992). Consequently, there is a correlation between these mafic bodies and two major extensional episodes, that is the

Espinhaço rift opening at *ca.* 1.7-1.8 Ga, and the Araçuaí basin opening at *ca.* 1.0-0.9 Ga.

Pb-Pb Ages

Pb isotopic studies are rare, resulting in few mineral and whole-rock isochron ages that generally present large errors. Of great importance in terms of the geologic evolution of the Quadrilátero Ferrífero is a whole-rock age on dolomites of the Gandarela Formation, Minas Supergroup, obtained by Babinski *et al.* (1995). Samples were taken from the central part of the Gandarela Syncline, which is a low-strain area, and the dolomites display laminated stromatolitic structures. The isochron age is 2420±19 Ma, and it gives a minimun depositional age for the Gandarela Formation that probably approaches the true one (see discussion in Renger *et al*. 1994 and Babinski *et al*. 1995). A second Pb-Pb isochron for a dolomite lense within the Fecho do Funil, south of the Bação Dome, yields an age of 2110±110 Ma suggesting isotopic re-equilibration due to Transamazonian metamorphism (Babinski *et al*. 1995).

In the Itabira District, northeast of the Quadrilátero Ferrífero, a thick iron-formation unit of the Minas Supergroup displays bands of jacutinga (hydrothermally-altered iron-formation) hosting Pd-Au orebodies associated with hematite- and quartz-rich veins (Olivo *et al*. 1996). Analyses of quartz, gold and hematite associated to the alteration process define an isochron age of 1830±100 Ma tentatively correlated to the Transamazonian orogenesis (Olivo *et al*. 1996). However, there are other isotopic data suggesting a *ca.* 1.8 Ga regional event of hydrothermal alteration postdating Transamazonian metamorphism (*e.g.* the zircon and monazite ages of Schrank and Machado, 1996a,b). A Pb-Pb amphibole isochron of 1804±110 Ma obtained for a pegmatite intruded into the Moeda Formation was also associated to a hydrothermal event (Noce, 1995).

Sm-Nd Ages

Nd isotopic compositions are available for four TTG-gneiss samples from the Bonfim and Belo Horizonte domes, and T_{DM} ages range from 3.38 Ga to 3.03 Ga. Because crystallization U-Pb ages are not available for these rocks, $e_{Nd(t)}$ was calculated for t=main metamorphic event (migmatization), yielding negative values of -0.7 to -2.2 (Noce, 1995, Teixeira *et al*., 1996). The data suggest that these TTG-gneiss protoliths have an extended crustal residence time.

Granitoid plutons crystallized at 2780-2700 Ma yields T_{DM} ages of 3.10-2.78 Ga, and their $e_{Nd(t)}$ range from -0.3 to -3.1 (Romano, 1989, Teixeira *et al*., 1996). It implies that the plutons were mainly derived from the older sialic crust with some contribution of mantle-derived material.

Nd isotopic data for the 2125 Ma Alto Maranhão tonalite points to a Paleoproterozoic mantelic source (T_{DM} = 2.27 Ga, $e_{Nd(t)}$ = +1.1), and may indicate oceanic crust consumption during the Transamazonian orogeny (Noce *et al*., 1999).

A metamorphic aureole developed along the contact between the Sabará Formation and the Belo Horizonte dome, and this process has been associated to the Transamazonian orogenic collapse (Alkmim and Marshak, 1998). Analyses of garnet from a Sabará pelite yields a Sm-Nd isochron of 2095±65 Ma (Marshak *et al*. 1997), that falls within error in the 2065-2030 Ma U-Pb ages for titanite and monazite.

FINAL REMARKS

The great deal of geochronological data that have been obtained for the Quadrilátero Ferrífero, especially by way of dating U-bearing minerals, largelly improved our knowledge about its geological evolution. However, some key questions are still open. Despite many efforts, lack of suitable material for analysis has precluded the precise dating of mineralization events. The same is true regarding deposition ages of sequences like the Maquiné Group, Minas Supergroup and Itacolomi Group, which seems to be devoid of volcanic rocks. Also, more data are needed to identify more accurately the role of Proterozoic orogenic cicles in the structural evolution of the Quadrilátero Ferrífero.

ACKNOWLEDGMENTS

I would like to thank Franciscus J. Baars for his usefull comments on the manuscript.

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