Proterozoic Thermochronologic Implications from $^{40}Ar/^{39}Ar$ and K-Ar Dating of the Campo Belo Metamorphic Complex, Southern São Francisco Craton, Brazil

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ABSTRACT

Four $^{40}Ar/^{39}Ar$ step-heating analyses, performed on Archean rocks of the Campo Belo complex, Minas Gerais state, yielded results in agreement with 24 K-Ar dates already available for the study area. Integrated interpretation of these results is compared with typical argon blocking temperatures of both biotites and amphiboles dated, as well as with the geologic scenario of the southern part of the São Francisco Craton and the adjacent Brasilia marginal belt, therefore providing better understanding of the regional thermal history.

The resulting K-Ar and $^{40}Ar/^{39}Ar$ cooling patterns are diagnostic of a progressive isotopic rejuvenation of the Campo Belo complex during the Proterozoic. The oldest $^{40}Ar/^{39}Ar$ and K-Ar dates, in the range 2,100-1,900 Ma and 1,790-1,760Ma, are related to successive uplift of the basement structures due to evolution of the Transamazonian Mineiro belt and tectonism that originated the Espinhaço rift, respectively. The emplacement of plutonic rocks into the Archean Piumhi greenstone at ~1,127, ~726 and 635Ma (U-Pb ages) compares well with K-Ar dates on the basement rocks within the SW edge of the Craton, among 1,280 and 740 Ma. Although these radiometric data broadly support a Neoproterozoic age for the collision of the Brasilia belt, the oldest dates also suggest that a Mesoproterozoic tectonic reactivation may have occurred in the southern end of the São Francisco Craton.

Key words: $^{40}Ar/^{39}Ar$ geochronology, São Francisco Craton, Proterozoic tectonics.

INTRODUCTION

In recent years, $^{40}Ar/^{39}Ar$ geochronological studies dealing with different geological topics have increased in South America due to cooperative programs with foreign laboratories (EUA, France), as summarized below:

i) dating of dike swarms, alkaline massifs and flood volcanism (Renne *et al.*, 1990b, 1992, 1993; Teixeira, 1990; Teixeira *et al.*, 1996a; Montes Lauar *et al.*, 1994, 1995) that have provided better understanding of the timing of fracturing episodes, and constraints for the ages of paleomagnetic poles in the Proterozoic (e.g. D'Agrella Filho *et al.*, 1990);

ii) thermochronology of Precambrian metamorphic terrains (Renne *et al.*, 1989, 1990b; Onstott *et al.*, 1989; Sletten, 1989) with implications for tectonic reconstructions; and

iii) thermochronology and evolution of shear zones (Lambert de Figueiredo, 1992).

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Detailed account and geological applications of the $^{40}Ar/^{39}Ar$ tool can be found in Faure (1986), McDougall & Harrison (1988) and Hanes (1991). Up to date research based on $^{40}Ar/^{39}Ar$ interpretation (i.e., using lasers and stepwise heating approach which provides errors as low as 0.3%) includes routine age determinations of individual mineral grains with identification of heterogeneous argon zoning (e.g., Onstott & Peacock, 1987; Phillips & Onstott, 1988), dating of deformation episodes (e.g., Dunlap *et al.*, 1991; Goodwin & Renne, 1991), diagenetic K-feldspar overgrowths (Girard & Onstott, 1991), timing of weathering processes (e.g., Vasconcelos *et al.*, 1992, 1994), and provenance studies of detrital micas from sedimentary rocks (e.g., Renne *et al.*, 1990a), among other applications.

Because of the wide versatility of the $^{40}Ar/^{39}Ar$ method the Geochronological Research Center of the Institute of Geosciences (USP) will set up the first $^{40}Ar/^{39}Ar$ laboratory in Brazil, in 1996. This project which is technically supported by the Berkeley Geochronology Center (USA) has been recently granted by the Research Council of the state of São Paulo – FAPESP. Therefore, in the near future the $^{40}Ar/^{39}Ar$ dating method is expected to become increasingly valuable for understanding the thermal history of the Brazilian Precambrian shield, in addition to the knowledge of the widely used Rb-Sr, Sm-Nd, U-Pb and K-Ar dates.

This paper presents the first $^{40}Ar/^{39}Ar$ step-heating analyses performed on Archean gneissic rocks from the Campo Belo metamorphic complex for which a detailed geochronological framework based on SHRIMP U-Pb, Sm-Nd, Rb-Sr, Pb-Pb data is already available (Teixeira *et al.*, 1996b,c). The new radiometric results are used to constrain the polyphase thermochronology of the metamorphic rocks of this complex and to provide insights for the interpretation of the K-Ar mineral dates (Teixeira, 1985) available for the area.

GEOLOGICAL SETTING

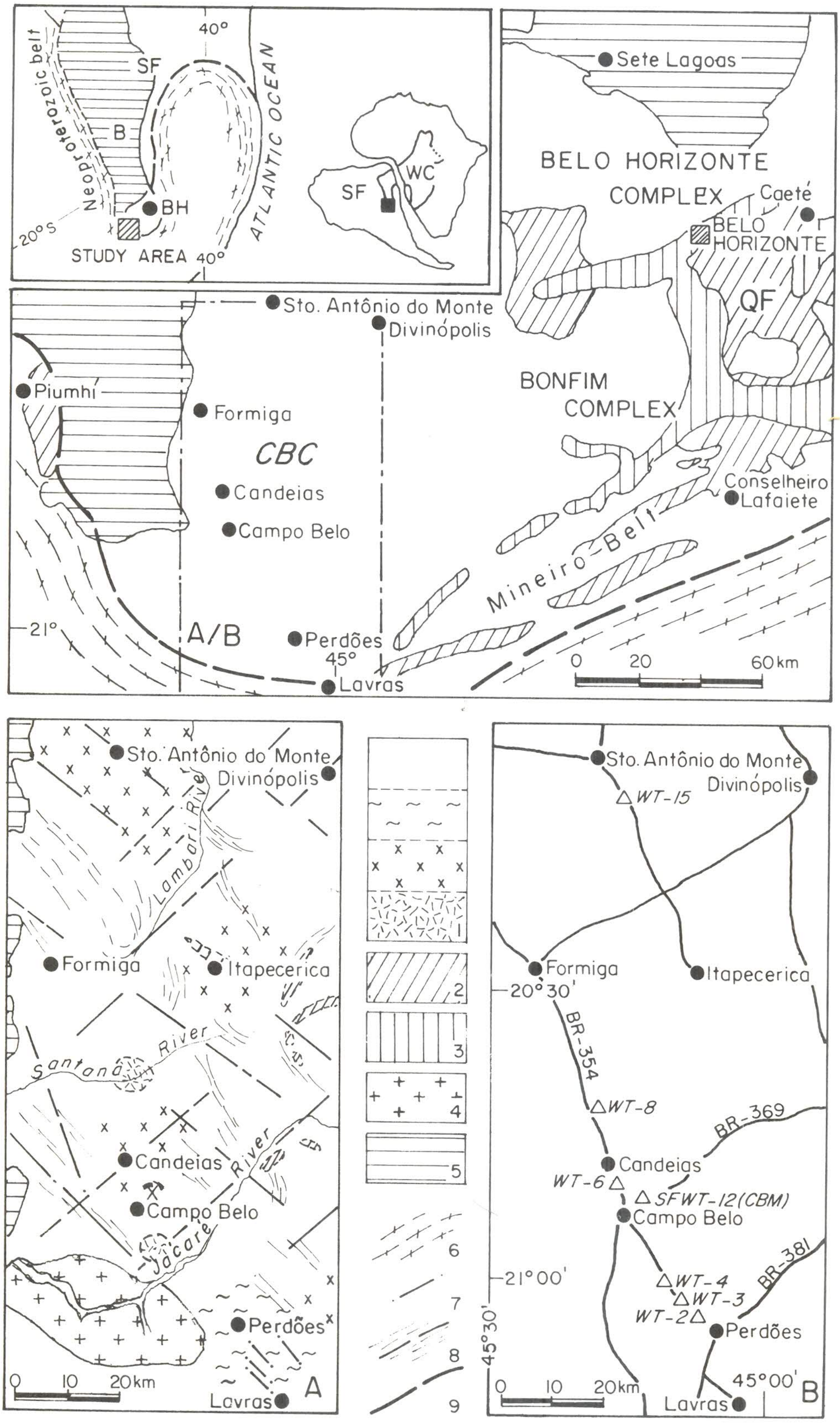
The Campo Belo complex (CBC) is one of the oldest recognized Archean metamorphic terrains within the southern part of the São Francisco Craton, according to the available geochronological knowledge. This Complex crops out in area of *ca.* 55 × 160 km (Fig. 1) in the western side of the region, where it is overlaid by the Bambuí platform cover of Neoproterozoic age. Nevertheless the field relations between the CBC and the adjacent Belo Horizonte and Bonfim metamorphic complexes (Carneiro, 1992; Noce, 1995) are unknown due to the deep erosion level of the crust and lack of additional detailed isotopic studies in the rock-units exposed between these complexes.

The CBC consists of medium- to high grade orthogneisses, granitoids, migmatites, metavolcano-sedimentary and ultramafic rocks, and amphibolites, further intruded by basic-noritic dikes. The CBC shows a polyphase crustal evolution summarized by a sequence of episodes as follows (Teixeira *et al.*, 1996b,c):

EARLY PRIMITIVE CRUSTAL EVOLUTION

It is shown by the relict age on zircon crystals from the Campo Belo migmatite (3,204 ± 12 Ma; SHRIMP U-Pb on zircon). This stage represents the first recognized emergence of continental crust in the southern end of the São Francisco Craton. Additional isotopic evidence comes from the 3.12

Fig. 1 — Geological outline of the southern part of the São Francisco Craton showing the Campo Belo (CBC), Belo Horizonte and Bonfim Archean metamorphic complexes (1), supracrustal sequences (2 = Archean greenstone belts; 3 = Paleoproterozoic Minas Supergroup); and the Paleoproterozoic Mineiro belt. QF = Quadrilátero Ferrífero area. The insert shows the investigated area in the Craton (SF) which is surrounded by Neoproterozoic mobile belts, including the Brasilia belt (6 = dashed, oriented lines). Heavy dashed line (9) is the limit between the Craton and the fold belts marginal to it (Alkmin *et al.*, 1995). Fig. 1A — Main geologic units in the Campo Belo Archean metamorphic complex: 1: gneiss migmatite terrain (unmarked); granulite (~); amphibolite (chaotic dashes); syn-to-late-tectonic granitoid terrane (×). 2: Archean supracrustal relicts (oblique lines). Proterozoic units exposed in the area: 4 = Ponto Mendes granite (+); 5 = Neoproterozoic Bambuí Group (horizontal lines). 7 = dikes; 8 = salient structures and trends of metamorphic foliation of the CBC. Adapted from Teixeira (1985). Fig. 1B — Main roads and localities of the investigated area showing the location of the $^{40}Ar/^{39}Ar$ age determinations.


40°
SF
B
BH
Neoproterozoic belt
20°S
STUDY AREA
40°
ATLANTIC OCEAN
SF
WC
Sete Lagoas
BELO HORIZONTE
COMPLEX
Caeté
BELO
HORIZONTE
QF
BONFIM
COMPLEX
Conselheiro
Lafaiete
Mineiro-Belt
Sto. Antônio do Monte
Divinópolis
Piumhi
Formiga
CBC
Candeias
Campo Belo
21°
A/B
Perdões
45°
Lavras
0 20 60km
Sto. Antônio do Monte
Divinópolis
Lambari River
Formiga
Itapecerica
Santana River
Candeias
River
Campo Belo
Jacaré
Perdões
0 10 20km
Lavras
A
1
2
3
4
5
6
7
8
9
Sto. Antônio do Monte
Divinópolis
WT-15
Formiga
Itapecerica
20°30'
BR-354
WT-8
BR-369
Candeias
WT-6
SFWT-12(CBM)
Campo Belo
21°00'
WT-4
WT-3
WT-2
BR-381
Perdões
45°30'
0 10 20km
45°00'
Lavras
B

Ga U-Pb age (upper intercept U/Pb discordia; Machado & Schrank, 1989) obtained for a mafic sill in the Piumhí greenstone belt.

Major Tectonomagmatic Event

It is dated at 3,068 ± 19 Ma (SHRIMP U-Pb zircon age). It consists of juvenile orthogneisses, according to their slightly positive ε_{Nd} values and Pb mantle like single stage μ_1 parameter of Pb-Pb whole rock isochron and $T_{(DM)}$ ages up to 3.07 Ga. Formation of granitic rocks at 2,881 ± 54 Ma (Rb-Sr isochron; Teixeira *et al.*, 1996b) might form part of this event. Their genesis appears to have involved addition of new crust and reworking of older material accompanying subduction-like related igneous processes, as suggested by the ε_{Nd} values between –1.21 to +1.55.

Migmatite Episode

It is dated at 2,839 ± 17 Ma (SHRIMP U-Pb zircon age). This interpretation agrees with field observations showing that both the CBC orthogneisses and granitoids were partly submitted to migmatization. Available ε_{Nd} values (t_0 = 2.84 Ga; see above) for the granitoids suggest mantle derived components predominated in their formation.

Archean Cratonization Stage

It is illustrated by emplacement of basic-noritic dikes (Sm-Nd isochron age of 2,697 ± 65 Ma; Pinese *et al.*, 1995, 1996), representing a major extension phase in association with the tectonic stabilization of the CBC. These dikes have sharp contacts discordant in relation to the metamorphic foliation of the host country rocks, indicating their emplacement into a rigid crust.

Late Archean Tectonic Overprint (2,650-2,540 Ma)

It is evidenced by the resetting of Pb-Pb and Rb-Sr whole rock isotope data in granitoids, granulites and basic-noritic dikes (see above), long after their primary crystallization. Such resetting suggests the existence of a regional overprinting episode during which transportation of low-temperature fluids have played an important role in inducing isotopic disturbance of both the Rb-Sr and Pb-Pb systematics. In the southern part of the São Francisco Craton, within the Belo Horizonte and Bonfim complexes, granitic plutonism took place similarly between 2,650-2,540 Ma ago (e.g., Romano *et al.*, 1991; Noce, 1995).

Final Tectonic Episode

It is related to a regional re-heating of the CBC rocks occurred when the Transamazonian orogeny was active in the adjacent Mineiro belt, of Paleoproterozoic age. The subsequent cooling is demonstrated by K-Ar apparent ages between 2,000 and 1,800 Ma (Teixeira & Canzian, 1994), widely distributed within the Southern São Francisco Craton.

SAMPLING COLLECTION AND ANALYTICAL PROCEDURE

The $^{40}Ar/^{39}Ar$ dates (sampled WT-8, WT-7.1, WT-5 and WT-3A2; Table I) have been performed on selected rocks from the CBC for which previous K-Ar mineral apparent ages are available (Teixeira, 1985). All the samples were taken from the BR-354 roadcut between Formiga and Perdões (Fig. 1B; see reference numbers in Table II).

The common lithologies that occur in the Formiga-Perdões region are amphibolite grade banded gneisses of granodioritic (e.g., WT-7.1) to tonalitic (e.g. WT-8, 5) composition, granitoids, amphibolites and hornblendites (e.g., WT-3A2) and granulites. The gneisses exhibit granoblastic to lepido-nemato-granoblastic textures, and consist primarily of hornblende, biotite, quartz, twinned oligoclase, and rare insterstlcial microcline. Perthytic microcline is characteristic of sample WT-8 only, whereas WT-5 is distinct, because it does not contain amphibole. The accessory minerals in the gneisses are: opaque minerals, apatite, epidote, allanite (sometimes in metamitic relicts) and zircons. The observed two populations of zircons (clear hypidiomorphic and zoned metamitic crystals) support the geochronological interpretation of a

TABLE I
Comparative K-Ar and $^{40}Ar/^{39}Ar$ dates on the CBC rocks.

Sample/mineral	K-Ar age (error) *Ma*	*Tg* age *Ma*	Preferred date *Ma*	Preferred date type	Ref. no.
WT-3A2 /hornblende	2,559 (123)	2,134 (7)	2,300 (25)	T*p*	1
WT-7.1/biotite	1,998 (60)	1,910 (8)	1,945 (8)	T*p*	11
WT-8/biotite	2,041 (61)	2,027 (9)	2,040 (9)	T*p*	8
WT-5/biotite	1,511 (45)	1,506 (8)	—	—	21

T*p* is the plateau date calculated for the gas fractions indicated. T*g* is the total gas $^{40}Ar/^{39}Ar$ apparent age, calculated from the sum of all Ar released during step heating, corrected for atmospheric Ar. T*g* ages and preferred date type abbreviations, as shown in Fig. 2, presented with 1σ uncertainties. The errors for T*g* and T*p* include uncertainty in the J-value, the age of the standart and the interference corrections. Reference numbers are plotted in Fig. 3.

TABLE II
K-Ar analytical data of selected rocks from the CBC (Teixeira, 1985).
Figure 1b presents the geographic situation of the samples.

*Ref. no.	Lab no.	Sample/ (mat.)	rock	%K	$^{**40}Ar_{rad}$	% $^{40}Ar_{atm}$	Age (error) *Ma*
1	4851	WT-3A2 (hornbl.)	amphibolite	0.173	37.76	5.10	2,559 (125)
2	4475	WT-17A (hornbl.)	gneiss	1.795	288.90	0.60	2,161 (162)
3	4474	WT-17A1 (biot.)	gneiss	6.967	987.60	0.53	1,996 (60)
4	4467	WT-17C (biot.)	gneiss	6.892	921.90	1.04	1,926 (58)
5	4462	WT-18 (biot.)	gneiss	6.687	1,068.00	0.99	2,144 (64)
6	4456	WT-12B (hornbl.)	amphibolite melanosome	0.787	119.20	11.19	2,077 (62)
7	4457	WT-12A (biot.)	gneiss	0.725	83.90	6.04	1,763 (82)
8	4441	WT-8 (biot.)	gneiss	5.399	794.50	1.23	2,041 (61)
9	5486	SF/WT-14A (biot.)	gneiss	3.887	568.69	1.89	2,036 (61)
10	4593	WT-16 (biot.)	gneiss	7.059	1,003.00	0.70	1,999 (60)
11	4440	WT-7.1 (biot.)	gneiss	6.917	982.40	1.08	1,998 (60)
12	4458	WT-14 (biot.)	gneiss	6.194	848.40	0.57	1,954 (59)
13	4498	WT-21 (biot.)	gneiss	5.785	767.20	0.74	1,917 (57)
14	5459	AP/WT-9ACK (biot.)	gneiss	6.517	850.58	1.67	1.898 (57)

(to be continued)

TABLE II (Continuation)

*Ref. no.	Lab no.	Sample/ (mat.)	rock	%K	$^{**40}Ar_{rad}$	% $^{40}Ar_{atm}$	Age (error) *Ma*
15	4461	WT-15D2 (biot.)	gneiss	5.941	773.60	2.04	1,896 (60)
16	4718	JD-4 (biot.)	gneiss	6.754	842.80	2.34	1,845 (55)
17	3471	PS-17p (hornbl.)	migmatite	0.665	83.80	12.40	1,826 (24)
18	4510	WT-19.1 (biot.)	gneiss	3.431	407.10	1.15	1,789 (54)
19	5554	AP/WT-10D (biot.)	gneiss	5.457	645.95	1.62	1,785 (53)
20	1092	MG-321 (biot.)	gneiss	6.670	776.70	0.30	1,767 (50)
21	4592	WT-5 (biot.)	gneiss	4.594	421.90	7.09	1,511 (45)
22	5509	SF/WT-10.2A (hornbl.)	gneiss	2.324	161.71	2.26	1,278 (38)
23	5513	SF/WT-10.2A (biot.)	gneiss	4.494	291.61	1.16	1,183 (35)
24	4722	JD-3 (biot.)	gneiss	6.963	246.20	5.00	737 (22)

Minerals: biot. = biotite; hornbl: hornblende. *Reference numbers as plotted in Figure 2.
$^{**40}Ar_{rad} \times 10^{-6}$ (*cc*STP/g).

polyphase evolution for the CBC (see previous section).

Sample WT-5 exhibits weak (local) deformation evidenced by the undulatory extinction in quartz, and biotite kink bands, as well as subordinate chlorite formed from the biotite, and epidote from saussurite either at the edges or along fractures of the plagioclase. Sample WT-7.1 was weakly affected by a hydrothermal episode, as suggested by local equilibrium between the biotite, quartz and opaque minerals, coupled with the existence of chlorite and local carbonatization and chlorization of the amphibole.

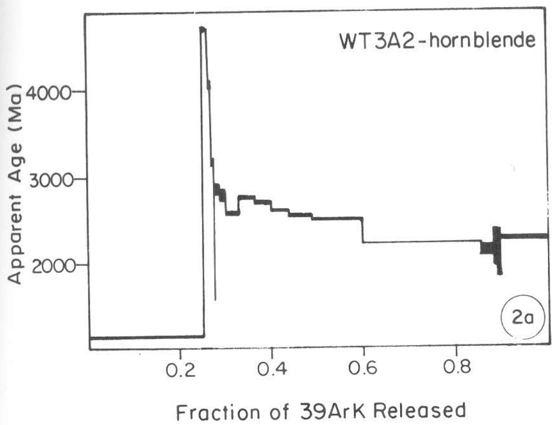
Sample WT-3A2 is a pristine hornblendite with rare accessory opaque minerals, showing equigranular, poligonal granoblastic texture. Scarce films of oxide may be present in the hornblende. Biotite is absent in the two thin sections available for this rock.

The $^{40}Ar/^{39}Ar$ age determinations were performed in the argon lab at the Department of Geological and Geophysical Sciences of the Princeton University (USA) during 1988, under the sponsorship of a NSF/CNPq cooperative program. All the samples were irradiated at the McMaster University research reactor in Hamilton, Ontario (Canada). The irradiated samples were then transferred to quartz boats and were degassed to remove any possible argon contamination.

The hornblende (100% pure) and three biotite concentrates (>95% pure) were analyzed (Tabs. I, III, IV, V, VI). The $^{40}Ar/^{39}Ar$ apparent age spectra (Fig. 2) were derived from incremental heating between 320 and 1200°C using procedures outlined by Onstott & Peacock (1987).

RESULTS AND DISCUSSION

The $^{40}Ar/^{39}Ar$ hornblende date obtained for WT-3A2 is difficult to interpret because of the excess argon contamination in the low temperature steps (Fig. 2a). In addition, the low ages at the beginning of the spectrum correlates with low $^{37}Ar/^{39}Ar_K$ (Fig. 2), indicating the separate was



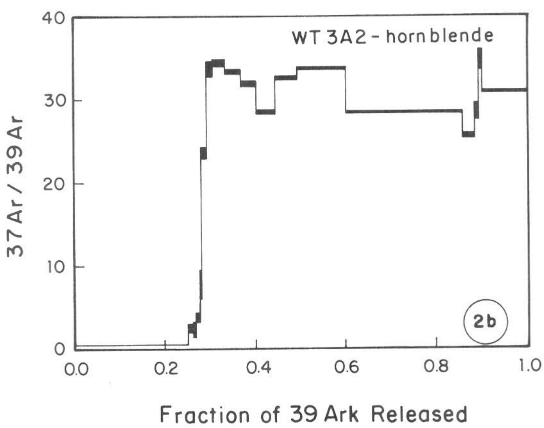


Fig. 2a — Plot of $^{40}Ar/^{39}Ar$ apparent age *vs.* fraction of argon released for sample WT-3A2. Fig. 2b — Plot of $^{37}Ar/^{39}Ar$ *vs.* Fraction of 39ArK released (sample WT-3A2).

contaminated by a K-rich phase which degasses at low temperatures. The petrographic studies, however, do not reveal the presence of biotite (see above). The 1,146 Ma age of the first temperature step (Tab. III) is probably the maximum estimate of the age of resetting of such unknown K-rich phase. Because of the presence of excess argon contamination, interpretation of the rest of the spectrum is uncertain (Fig. 2a), and therefore we consider the *ca.* 2.3 Ga plateau as a minimum age. However, this interpretation appears to be consistent with the 2,559 ± 123 Ma K-Ar apparent age (Tab. I) that means an integrated total release date. In any case the $^{40}Ar/^{39}Ar$ age is clearly older than rocks of the Transamazonian cycle, although, it may also reflect partial overprinting of Archean ages by the Transamazonian event.

Two of the $^{40}Ar/^{39}Ar$ biotite analyses show good plateaus, although these exhibit an overprint by a younger episode in the lowest temperature steps (Figs. 3a,b; Tabs. IV, V). These ages, 1,945 ± 8 Ma (WT-7) and 2,040 ± 9 Ma (WT-8), are in agreement within error with the K-Ar biotites ages (Tab. I): 1,998 ± 60 Ma and 2,041 ± 61 Ma, respectively. The concordance among the dates suggests that all the other K-Ar biotite dates available in the area (Tab. II, Fig. 4) are geologically significant, and therefore they provide constraints for the thermal history of the CBC (see further discussion).

The third biotite (WT-5) yielded a very disturbed spectrum (Fig. 3c) with an integrated date of 1,506 ± 8 Ma. Again, the K-Ar apparent age for the same sample is similar (1,511 ± 11 Ma; Tab. I). However the oldest date of the 11 step (1,878 Ma; Table VI), is probably the minimum estimate of the cooling age of WT-5. This sample was isotopically disturbed by a younger episode, as suggested by the apparent age (~1,200 Ma; Fig. 3c) from the lowest temperature steps, the precise age of which cannot be defined because the $^{37}Ar_{Ca}/^{39}Ar_{K}$ is too high for a pure biotite. In other words this isotopic feature suggests rejuvenation is mainly due to alteration of the WT-5 biotite, in agreement with both the petrographic characteristics of this sample (see previous section) and the low K content of the biotite (4.59%).

As already stated, the new $^{40}Ar/^{39}Ar$ biotite ages agree well with the K-Ar biotite dates from the same rocks. In addition, when minerals are heated above their argon blocking temperatures for a sufficiently long time, they are outgassed completely and can subsequently be used to tectonic inferences. Therefore the K-Ar age determinations in the CBC (Tab. II) are geologically significant, and they can be useful to delineate the regional thermal history of this part of the São Francisco Craton.

Figures 4 and 5 present a regional scenario regarding the thermal history based on the K-Ar and $^{40}Ar/^{39}Ar$ dates in the area. The most representative and widely distributed age pattern in the CBC falls in the range 2,160 and 1,830 Ma (Fig. 4). It is exemplified by two hornblendes from gneisses near the localities of Formiga (2,080 Ma)

TABLE III
$^{40}Ar/^{39}Ar$ analytical data sample WT3A2 hornblende.

T°C	f_1 × 10	f_2	Atmos. (%)	Cum. $^{40}Ar^*$	Cum. $^{39}Ar_K$	× 10^5	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{38}Ar_{Cl}/^{39}Ar_K$	Age (Ma) ± 1 S.D.
600	-.003	.001	36.5	.091	.251		.008	.526	.088	1146 ± 13
700	-.016	.007	3.8	.149	.263		.077	2.420	.182	4684 ± 38
750	-.015	.126	.4	.169	.268		.815	2.258	.189	4068 ± 75
800	-.024	.377	.4	.184	.276		.816	3.754	.133	3165 ± 58
850	-.051	.496	1.4	.186	.279		.205	7.766	.188	1902 ± 358
900	-.155	.252	3.9	.202	.289		.076	3.493	.306	2861 ± 54
930	-.223	.677	2.3	.222	.302		.130	33.554	.389	2789 ± 60
960	-.228	1.301	1.4	.256	.329		.205	34.271	.401	2576 ± 22
980	-.221	.520	3.0	.309	.364		.100	33.229	.399	2757 ± 19
995	-.211	.923	1.7	.357	.399		.173	31.773	.380	2696 ± 18
1010	-.188	.677	2.2	.411	.439		.134	28.389	.377	2603 ± 18
1025	-.216	1.251	1.5	.472	.487		.203	32.480	.366	2540 ± 20
1045	-.223	1.334	1.5	.606	.598		.201	33.589	.364	2487 ± 10
1065	-.188	1.826	1.1	.733	.727		.262	28.320	.334	2209 ± 9
1080	-.188	2.488	.8	.859	.856		.355	28.319	.334	2208 ± 10
1095	-.168	.278	6.5	.884	.883		.045	25.489	.338	2108 ± 56
1110	-.188	.076	19.0	.891	.891		.016	28.410	.337	2144 ± 223
1131	-.230	.043	30.2	.898	.898		.010	34.564	.434	2073 ± 278
1175	-.204	.567	3.7	1.000	1.000		.081	30.773	.388	2244 ± 27

Integrated age = 2134 ± 7 Ma.

Note: $f_1 = 1/[1-(^{37}Ar/^{39}Ar)_{Ca}/(^{37}Ar/^{39}Ar)_m]$, and $f_2 = f_1[1-(^{36}Ar/^{39}Ar)_{Ca}/(^{36}Ar/^{39}Ar)m]$, where $()_{Ca}$ = isotope ratio of argon extracted from irradiated calcium salts (values cited in Onstott & Peacock, 1987) and where $^{40}Ar^*/^{39}Ar_K = (^{40}Ar/^{39}Ar)_m (1-f_1)-(295.5(^{36}Ar/^{39}Ar)_m(1-f_2)-(^{40}Ar/^{39}Ar)_K$ $()m$ = isotope ratio of argon extracted from irradiated unknown.

Uncertainty for $^{40}Ar^*$ and $^{39}Ar_K$ volumes are ± 5%.

Cum. $^{39}Ar_K$ and Cum. $^{40}Ar^*$ = cumulative fractions of $^{39}Ar_K$ and $^{40}Ar^*$ released in each step.

Age (Ma) = the age calculated using the following decay constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.961 \times 10^{-10}$ yr^{-1}; $^{40}K/K$ = 0,01167 atom % (Steiger & Jäger, 1977).

The quoted error is one standard deviation (S.D.) and does not include the error in the J-value, the standard error, or the error in the interference corrections.

Integrated date = the date and error calculated from the sum total gas from all steps; the error includes the error in J-value.

Plateau date = the data and error calculated from the sum total gas from those steps, the ages of which fall within 2 S.D. of each other; the error includes the error in J-value.

$J = 2.3255 \times 10^{-2} \pm 1.6116 \times 10^{-4}$.

TABLE IV

$^{40}Ar/^{39}Ar$ analytical data for sample WT-7 biotite.

T°C	f_1 x10^2	f_2 x10	Atmos. (%)	Cum. $^{40}Ar^*$	Cum. $^{39}Ar_K$ x10^5	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{38}Ar_{Cl}/^{39}Ar_K$	Age (Ma) ± 1 S.D.
580	-.263	.160	2.7	.061	.074	.011	.405	.125	1693 ± 3
680	-.090	.251	.5	.308	.312	.060	.139	.141	1953 ± 1
730	-.112	.382	.4	.460	.462	.072	.172	.137	1924 ± 1
760	-.109	.410	.4	.558	.558	.080	.168	.139	1943 ± 2
790	-.163	.463	.5	.593	.591	.062	.251	.137	1977 ± 4
820	-.116	.165	.9	.624	.620	.031	.179	.138	1972 ± 5
860	-.188	.261	1.0	.669	.664	.030	.289	.138	1942 ± 3
800	-.061	.124	.7	.714	.708	.043	.094	.139	1944 ± 4
940	-.127	.171	1.0	.761	.753	.029	.195	.137	1946 ± 4
1040	-.123	.143	1.2	.864	.858	.024	.189	.136	1885 ± 2
1100	-.063	.040	2.3	1.000	1.000	.013	.098	.130	1864 ± 2

Integrated age = 1910 ± 8 Ma.

Plateau age = 1945 ± 8 Ma.

Note: $f_1 = 1/[1-(^{37}Ar/^{39}Ar)_{Ca}/(^{37}Ar/^{39}Ar)_m]$, and $f_2 = f_1[1-(^{36}Ar/^{39}Ar)_{Ca}/(^{36}Ar/^{39}Ar)m]$, where $()_{Ca}$ = isotope ratio of argon extracted from irradiated calcium salts (values cited in Onstott & Peacock, 1987) and where $^{40}Ar^*/^{39}Ar_K = (^{40}Ar/^{39}Ar)_m(1-f_1)-(295.5(^{36}Ar/^{39}Ar)_m(1-f_2)-(^{40}Ar/^{39}Ar)_K$ $()m$ = isotope ratio of argon extracted from irradiated unknown.

Uncertainty for $^{40}Ar^*$ and $^{39}Ar_K$ volumes are ± 5%.

Cum. $^{39}Ar_K$ and Cum. $^{40}Ar^*$ = cumulative fractions of $^{39}Ar_K$ and $^{40}Ar^*$ released in each step.

Age (Ma) = the age calculated using the following decay constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.961 \times 10^{-10}$ yr^{-1}; $^{40}K/K$ = 0,01167 atom % (Steiger & Jäger, 1977).

The quoted error is one standard deviation and does not include the error in the J-value, the standard error, or the error in the interference corrections.

Integrated date = the date and error calculated from the sum total gas from all steps; the error includes the error in J-value.

Plateau date = the data and error calculated from the sum total gas from those steps, the ages of which fall within 2 S.D. of each other; the error includes the error in J-value.

and Cláudio (2,160 Ma), and 12 biotites that show apparent ages between 2,040 and 1,840 Ma.

The 2.16-1.80 Ga time interval is typical for the Transamazonian cycle in the southern part of the São Francisco Craton during which the Mineiro belt (2.20-1.90 Ga) was formed (e.g., Teixeira & Figueiredo, 1991). This belt, characterized by granodioritic to granitic substratum and supracrustal units, including BIFs (Minas Supergroup), developed EW to NE oriented structures that further overprinted the margins of the Archean continent adjacent to it. Tholeiitic dikes (1,900 Ma; Rb-Sr whole rock isochron; Pinese *et al.*, 1995) emplaced into the adjacent Archean crust (e.g., near Lavras; CBC) during the cratonization stage of the Mineiro belt that caused also isotopic rejuvenation of the K-Ar and $^{40}Ar/^{39}Ar$ dates cited above.

The amphibole and biotite dates, mostly between 2,100 and 1,900 Ma within the error, indicate that these samples cooled rapidly, as illustrated by the hatched field in Figure 5. Tectonically, this implies that the area was subject to rapid uplift and cooling acting as a stable foreland at the time of the tectonomagmatic evolution of the adja-

TABLE V

$^{40}Ar/^{39}Ar$ analytical data for sample WT-8 biotite.

T°C	f_1 x10^3	f_2	Atmos. (%)	Cum. $^{40}Ar^*$	Cum. $^{39}Ar_K$ x10^6	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{38}Ar_{Cl}/^{39}Ar_K$	Age (Ma) ± 1 S.D.
500	-.668	.010	5.5	.020	.014	.005	1.027	.130	2501 ± 6
550	-.163	.016	2.4	.044	.058	.013	.251	.034	1346 ± 3
590	-.125	.583	0.0	.063	.078	1.015	.192	.046	1973 ± 4
620	-.108	.058	.2	.095	.111	.119	.167	.046	1981 ± 3
660	-.043	.313	0.0	.149	.166	1.598	.066	.046	1985 ± 2
690	-.033	.017	.2	.207	.223	.123	.050	.052	2044 ± 2
705	-.029	.446	0.0	.246	.261	3.514	.045	.052	2051 ± 2
720	-.036	2.180	0.0	.277	.290	14.158	.056	.052	2071 ± 3
740	-.029	1.423	0.0	.306	.319	11.176	.045	.046	2039 ± 3
760	-.053	.371	0.0	.330	.342	1.614	.081	.046	2038 ± 4
780	-.057	.248	0.0	.352	.362	1.047	.088	.053	2099 ± 4
810	-.095	1.232	0.0	.371	.380	3.167	.146	.051	2110 ± 5
845	-.130	.057	.3	.395	.403	.104	.201	.053	2085 ± 3
885	-.133	8.871	0.0	.432	.437	16.037	.205	.056	2097 ± 3
925	-.088	.100	.1	.497	.499	.268	.136	.058	2074 ± 2
965	-.150	50.912	0.0	.581	.580	78.700	.231	.063	2052 ± 2
1000	-.219	.376	.1	.681	.678	.396	.337	.071	2040 ± 2
1030	-.249	.171	.2	.773	.768	.158	.384	.073	2037 ± 2
1060	-.377	.026	1.9	.890	.895	.015	.580	.073	2046 ± 2
1120	-.106	.013	1.0	.966	.969	.029	.162	.052	2024 ± 3
1140	-.192	.033	.7	.991	.993	.041	.295	.054	2090 ± 10
1170	-.534	.028	1.9	1.000	1.000	.016	.821	.060	2304 ± 40

Integrated age = 2027 ± 9 Ma.

Plateau age = 2040 ± 9 Ma.

Note: $f_1 = 1/[1-(^{37}Ar/^{39}Ar)_{Ca}/(^{37}Ar/^{39}Ar)_m]$, and $f_2 = f_1[1-(^{36}Ar/^{39}Ar)_{Ca}/(^{36}Ar/^{39}Ar)m]$, where $()_{Ca}$ = isotope ratio of argon extracted from irradiated calcium salts (values cited in Onstott & Peacock, 1987) and where $^{40}Ar^*/^{39}Ar_K = (^{40}Ar/^{39}Ar)_m(1-f_1)-(295.5(^{36}Ar/^{39}Ar)_m(1-f_2)-(^{40}Ar/^{39}Ar)_K$ $()m$ = isotope ratio of argon extracted from irradiated unknown.

Uncertainty for $^{40}Ar^*$ and $^{39}Ar_K$ volumes are ± 5%.

Cum. $^{39}Ar_K$ and Cum. $^{40}Ar^*$ = cumulative fractions of $^{39}Ar_K$ and $^{40}Ar^*$ released in each step.

Age (Ma) = the age calculated using the following decay constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.961 \times 10^{-10}$ yr^{-1}; $^{40}K/K$ = 0,01167 atom % (Steiger & Jäger, 1977).

The quoted error is one standard deviation and does not include the error in the J-value, the standard error, or the error in the interference corrections.

Integrated date = the date and error calculated from the sum total gas from all steps; the error includes the error in J-value.

Plateau date = the data and error calculated from the sum total gas from those steps, the ages of which fall within 2 S.D. of each other; the error includes the error in J-value.

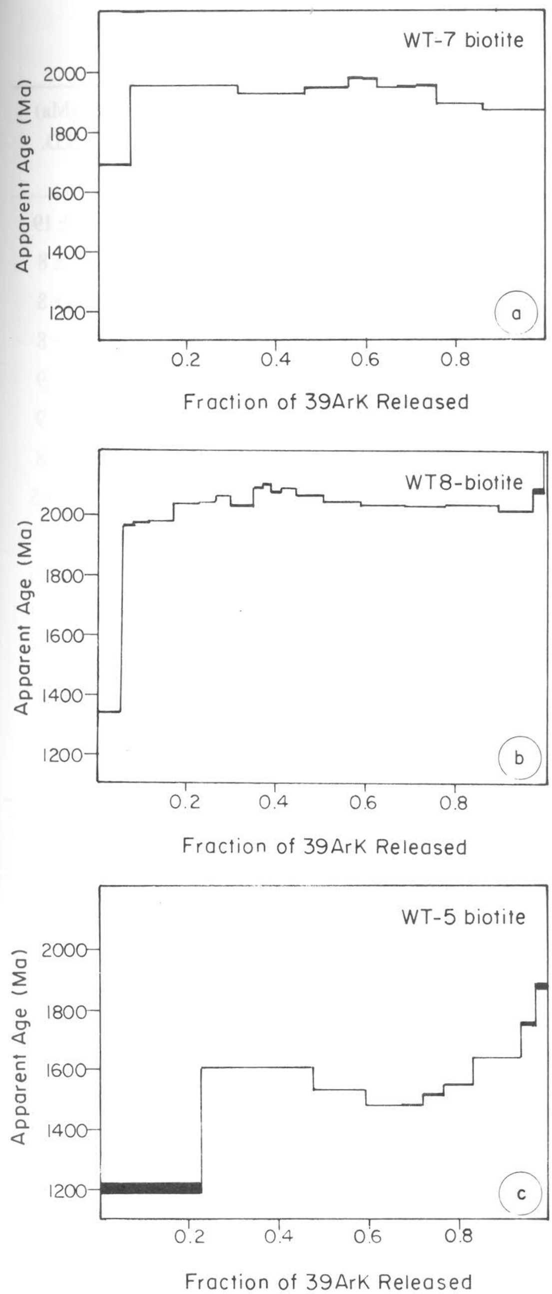


Fig. 3a,b,c — Plot of $^{40}Ar/^{39}Ar$ apparent age *vs.* fraction of argon released for samples WT-7.1, WT-8 and WT-5.

cent Mineiro belt. Furthermore, the distinctly older apparent age and sample #1 (~2,300 Ma; hornblende; see Figs. 4, 5) suggests partial argon outgassing of a pre-Transamazonian crust, in agreement with the model proposed for the CBC.

Seven biotites and one amphibole reveal K-Ar results younger than the cooling age pattern typical of the Transamazonian cycle (Teixeira, 1985). Four of these biotite dates, in the range 1,790 and 1,760 Ma (samples #18, 19, 20, 23; Tab. II; Figs. 4, 5), distributed in the Bom Despacho-Santo Antônio do Monte-Formiga-Itapecerica region, western side of the CBC, are not comparable within error with the slightly older biotite dates (i.e., >1.90 Ga) also reported for CBC gneisses located eastward. We interpret these dates to result from a further argon outgas probably associated with a late uplift of the western part CBC crust. Low temperature fluids probably participated in the uplift regime, as suggested by the common presence of chlorite and low potassium contents of the biotites (%K between 5.46 and 0.72) dated between 1,790-1,760 Ma. It is noteworthy that such a peculiar K-Ar age pattern is comparable to that reported for gneissic rocks in the eastern zone of the Transamazonian Itabuna belt, northern part of the Craton (Teixeira & Figueiredo, 1991; Teixeira & Canzian, 1994). Moreover, this pattern agrees well with the age of a major rifting event – the Espinhaço system – dated at 1.75 Ga ago, according to U-Pb zircon ages on basal volcanics of this system (e.g., Brito Neves *et al.*, 1979; Machado *et al.*, 1989; Babinski *et al.*, 1994; Schobbenhaus *et al.*, 1994).

Additional biotite dates obtained on gneissic rock of the CBC, all of them located in the SW sector of the study area, have yielded the following results: *ca.* 1.510 Ma (biotite already discussed; south of Campo Belo), 1,280/1,180 Ma (Boa Esperança) and 740 Ma (biotite; NW of Lavras). The 1,280 Ma K-Ar hornblende date (sample #22; Tab. II), reported for the Boa Esperança granitoid, implies that a Mesoproterozoic overprinting episode took place in the study area and this reached 500 ± 50°C (Teixeira & Canzian, 1994), the blocking temperature of this mineral for argon diffusion (Hanes, 1991). Additional evidence for such a Mesoproterozoic event in supported by the 1,180 Ma biotite K-Ar age of the same granitoid (sample #23, Tab. II), as well as by an interbedded and folded gabbro dated at 1,127 Ma (U-Pb age, 1.2% discordant; zircon core fragments; Machado &

TABLE VI

$^{40}Ar/^{39}Ar$ analytical data for sample WT-5 biotite.

T°C	f_1 $x10^3$	f_2 x10	Atmos. (%)	Cum. $^{40}Ar^*$	Cum. $^{39}Ar_K$ $x10^3$	$^{40}Ar/^{36}Ar$	$^{37}Ar_{Ca}/^{39}Ar_K$	$^{38}Ar_{Cl}/^{39}Ar_K$	Age (Ma) ± 1 S.D.
600	-1.500	.355	10.3	.163	.224	.287	2.305	.077	1205 ± 19
680	-.189	.384	.9	.436	.472	3.240	.291	.061	1606 ± 8
720	-.181	.542	.7	.556	.590	4.421	.279	.056	1530 ± 8
750	-.155	.766	.4	.634	.669	6.947	.238	.048	1479 ± 8
780	-.214	.664	.7	.680	.716	4.367	.329	.047	1481 ± 9
815	-.346	.574	1.2	.726	.762	2.439	.532	.057	1516 ± 9
855	-.227	.532	.8	.793	.827	3.546	.349	.068	1550 ± 8
890	-1.697	15.944	.2	.796	.829	14.381	2.607	.079	1574 ± 65
930	-.239	.259	1.6	.913	.932	1.804	.367	.067	1639 ± 8
1030	-.638	.158	6.0	.956	.966	.493	.981	.063	1754 ± 10
1080	-.385	.136	3.9	.988	.989	.760	.593	.059	1878 ± 14
1130	-.462	.054	11.9	.996	.996	.248	.710	.040	1704 ± 62
1170	-.023	.001	33.1	.999	.998	.098	.036	.025	1461 ± 222
1200	-.034	0.000	69.6	1.000	1.000	.042	.053	.010	1166 ± 634

Integrated age = 1506 ± 8 Ma.

Note: $f_1 = 1/[1-(^{37}Ar/^{39}Ar)_{Ca}/(^{37}Ar/\ ^{39}Ar)_m]$, and $f_2 = f_1[1-(^{36}Ar/^{39}Ar)_{Ca}/\ (^{36}Ar/^{39}Ar)m]$, where $()_{Ca}$ = isotope ratio of argon extracted from irradiated calcium salts (values cited in Onstott & Peacock, 1987) and where $^{40}Ar^*/^{39}Ar_K = (^{40}Ar/^{39}Ar)_m\ (1-f_1)-(295.5(^{36}Ar/^{39}Ar)_m(1-f_2)-(^{40}Ar/^{39}Ar)_K$ $()m$ = isotope ratio of argon extracted from irradiated unknown.

Uncertainty for $^{40}Ar^*$ and $^{39}Ar_K$ volumes are ± 5%.

Cum. $^{39}Ar_K$ and Cum. $^{40}Ar^*$ = cumulative fractions of $^{39}Ar_K$ and $^{40}Ar^*$ released in each step.

Age (Ma) = the age calculated using the following decay constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}\ yr^{-1}$; $\lambda_\beta = 4.961 \times 10^{-10}\ yr^{-1}$; $^{40}K/K$ = 0,01167 atom % (Steiger & Jäger, 1977).

The quoted error is one standard deviation and does not include the error in the J-value, the standard error, or the error in the interference corrections.

Integrated date = the date and error calculated from the sum total gas from all steps; the error includes the error in J-value.

Plateau date = the data and error calculated from the sum total gas from those steps, the ages of which fall within 2 S.D. of each other; the error includes the error in J-value.

Schrank, 1989), intrusive into the Archean Piumhí greenstone belt.

The group of younger (<1.79 Ga) apparent biotite dates when compared to the relatively older K-Ar results available for the CBC rocks (see above) can be additionally interpreted taking into consideration the argon blocking temperatures of this mineral, estimated at 300 ± 50°C (e.g., Hanes, 1991), therefore providing delineation of the "isotherms" plotted in Fig. 4. These "isotherms" may represent a hypothetical contour age transition between the Transamazonian cooling age and adjacent Meso and Neoproterozoic patterns related to either tectonic and magmatic episodes recognized within the Craton and marginally to it.

The Neoproterozoic episodes, typical of the Brasilia collision belt, have overprinted the Bambuí Group, in the outcroping area that overlays the

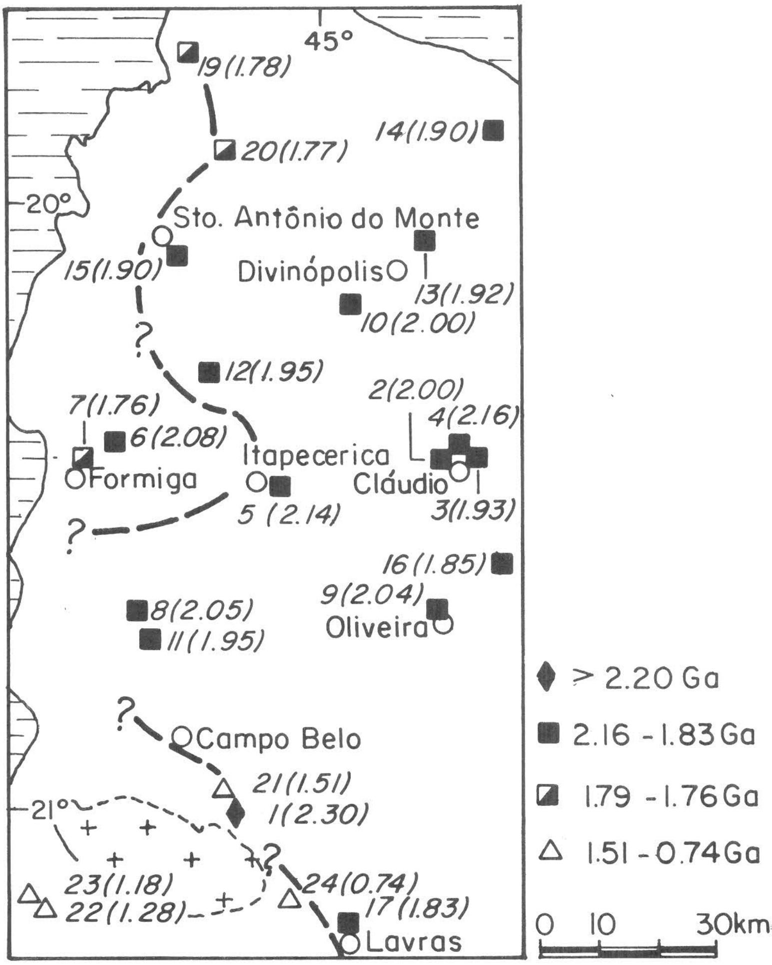


Fig. 4 — Contour apparent age map based on the K-Ar and $^{40}Ar/^{39}Ar$ dates on biotites and amphiboles from the country rocks of the CBC. Dashed heavy lines represents hypothetical "isotherms" (~300°C). Geological units as in Fig. 1 (reference numbers are in Table II).

western part of the CBC (e.g., Alkmin *et al.*, 1995). This Neoproterozoic tectonics would explain therefore the heterogeneous K-Ar dates obtained in the western and southwestern sectors of the CBC, in particular the 740 Ma biotite date (Fig. 4). Also, during such a collision, the Piumhí greenstone was uplift and thrust over the Bambuí Group (Valeriano, 1992), and intruded by granite sheets (~726 Ma) and trachyte bodies (635 ± 2 Ma; 1.7% discordant; single crystals abraded), according to U-Pb zircon dates (Machado & Schrank, 1989).

Finally, in the Archean Bonfim and Belo Horizonte complexes, in the Quadrilátero Ferrífero area (Fig. 1), K-Ar biotite dates on the country rocks are between 1,400 and 700 Ma (Carneiro, 1992; Noce, 1995), which is broadly compatible with the late thermal history described for the CBC. According to Teixeira *et al.* (1987) the K-Ar isotopic rejuvenation in the Quadrilátero Ferrífero area was influenced by extensive thrusting and deformation episodes related to Neoproterozoic events that took place marginally to the Craton. From the above, the apparent K-Ar and $^{40}Ar/^{39}Ar$ dates in the southern end of the São Francisco Craton appear to be diagnostic of a progressive isotopic rejuvenation phenomenum during the Proterozoic (Transamazonian, Espinhaço and Brasiliano events) from the center towards the bor-

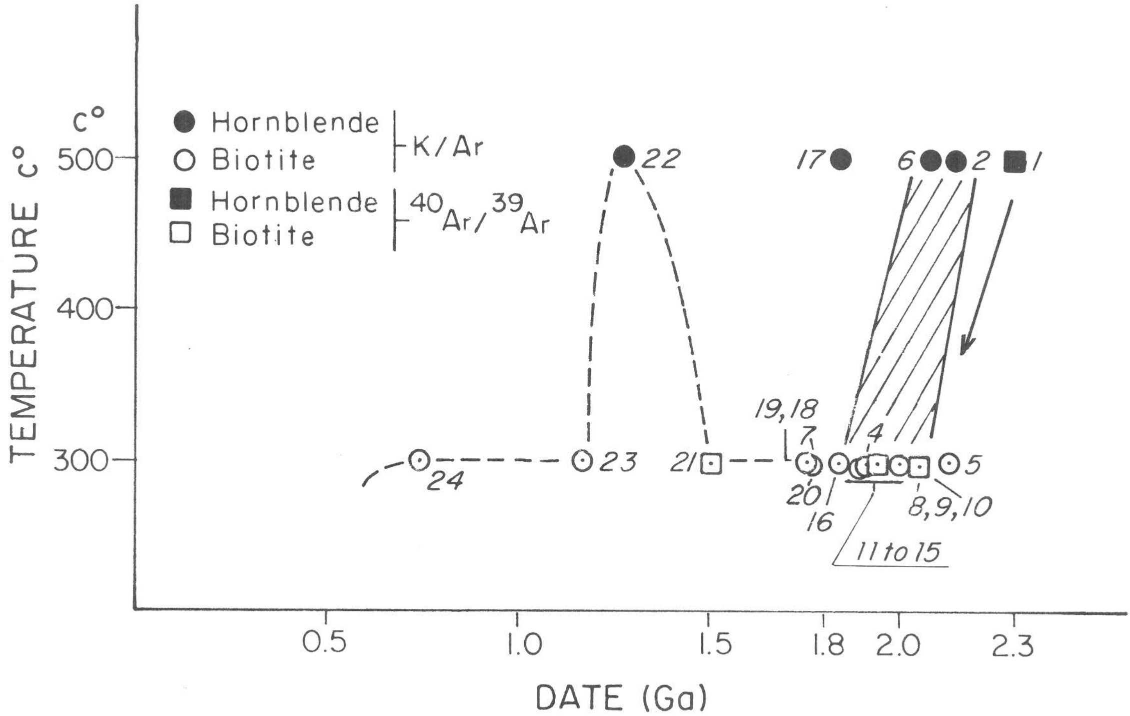


Fig. 5 — Regional shape of the thermal history of the CBC based on the K-Ar and $^{40}Ar/^{39}Ar$ dates. Delimitated field indicates the major regional cooling of the area. The arrow illustrates a probably partial argon outgassing path of the pre-Transamazonian crust. Dashed line shows the polyphase thermal evolution of the rocks located in the W and SW sides of the CBC.

ders of an Archean domain (Teixeira *et al.*, 1996b,c). This geochronologic picture probably results from the overprinting of Proterozoic tectonomagmatic processes, the youngest of which developed marginally to the São Francisco Craton.

SUMMARY AND CONCLUSIONS

Interpretation of four $^{40}Ar/^{39}Ar$ and 24 K-Ar dates on amphibole and biotite from the Archean CBC provides better understanding of the regional thermal history, and allow recognition of tectonic relationships with the Proterozoic tectonomagmatic events which took place in the São Francisco Craton and its margins, as summarized below:

1. The majority of the apparent ages are between 2,160-1,830 Ma, indicating their association with the evolution of the Transamazonian cycle. During this cycle the Mineiro mobile belt (e.g., Teixeira & Figueiredo, 1991) developed marginally to the Archean crust (Campo Belo, Belo Horizonte and Bonfim complexes), in the southern end of the São Francisco Craton. Compared with the northern part of the Craton that exhibits also an equivalent period of time for the regional cooling, as recorded by the concordance of hornblende and biotite $^{40}Ar/^{39}Ar$ dates (e.g., Sletten, 1989; Teixeira & Canzian, 1994), the more likely scenario is that uplift of most of the continental mass occurred at the end of the Transamazonian cycle. In particular for the investigated area the thermal history recorded on most of the K-Ar and $^{40}Ar/^{39}Ar$ dates suggests a rapid exhumation of the substratum during the end of the Paleoproterozoic (~1,800 Ma).

2. A group of rejuvenated dates in the CBC (1,790-1,760 Ma; 1,510-740 Ma) is characteristic of the western and southwestern sides of the CBC. The preferential distribution of the 1,790-1,760 Ma dates suggests a progressive late-uplift of the continental crust, interpreted to be related with balance of the cratonic mass accompanying extensional tectonics and the collapse of the Espinhaço rift

(1.75 Ga) within the proto-São Francisco Craton. The younger rejuvenated results (1,510-740 Ma) suggest a tectonic relationship with Meso- and Neoproterozoic episodes that took place marginally to the Craton. The geologic features associated with such thermal overprints are the tectonic reactivation of the Piumhí greenstone belt in association with intrusive plutonism (1,127 Ma; 726 Ma; 635 Ma), and deformation of the Bambuí platform cover, westward from the CBC. Coupled with the analogous Meso- and Neoproterozoic K-Ar apparent age patterns reported for medium to high grade terranes in the Quadrilátero Ferrífero area (Carneiro, 1992; Noce, 1995) the resulting picture suggests that the latest isotopic rejuvenation of the K-Ar systematic has a genetic relationship with the Neoproterozoic collision belts that surrounded the southern end of the São Francisco Craton.

3. Finally, considering the typical argon blocking temperature of biotites (~ 300°C) it may be assumed that reactivation of basement structures of the Craton under a "warm" regime, due to the tectonomagmatic evolution of the marginal belts, was the major cause for regional isotopic rejuvenation of part of the $^{40}Ar/^{39}Ar$ and K-Ar dates. Therefore these dates are useful for constraining the concept of "tectonic stability" of a cratonic domain, and together with additional criteria of investigation (e.g., structures) have important bearing for establishing the boundary between the São Francisco Craton and the surrounding collision belts.

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