U-Pb ARCHAEAN GEOCHRONOLOGY OF THE SÃO FRANCISCO CRATON (EASTERN BRAZIL)

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ABSTRACT The results of U-Pb age determinations performed on zircons and sphenes of Archaean metamorphic rocks from three regions of the São Francisco Craton are compared with previous Rb-Sr ages. In the southern Barbacena area and in the Bação Complex (Quadrilátero ferrífero), the U-Pb results are in agreement with the Rb-Sr Archaean ages but successive episodic Pb losses during Middle and Late Proterozoic events prevent from obtaining a precise age value for the first metamorphic stage. In the State of Bahia, the zircons of the granulites from the Jequié cratonic Complex (> 2700 Ma) show the influence of a 2400 Ma event whose geological significance is discussed. In the eastern Itabuna area, the zircons of the granulites yield an age of 2100 Ma confirming the strong influence of the Transamazônico event in the Salvador-Juazeiro mobile belt.

RESUMO Os resultados das determinações de idade U-Pb efetuadas em zircões e titanitas e rochas metamórficas arqueanas de três regiões do Cráton do São Francisco são comparadas com idades Rb-Sr. Na região sul de Barbacena e no Complexo Bação (Quadrilátero Ferrífero) os resultados U-Pb estão em concordância com as idades arqueanas Rb-Sr, mas perdas episódicas sucessivas durante eventos no Proterozóico Médio e Superior impedem a obtenção de um valor preciso de idade para o primeiro estágio metamórfico. No Estado da Bahia, os zircões procedentes dos granulitos do Complexo Cratônico de Jequié (>2700 Ma) exibem a influência de um evento de 2400 Ma, cujo significado geológico é discutido. Na área de Itabuna mais a leste, os zircões dos granulitos fornecem uma idade de 2100 Ma, confirmando a forte influência do evento transamazônico no cinturão móvel de Salvador – Juazeiro.

INTRODUCTION In Eastern Brazil the Precambrian terranes (Fig. 1) consist of two main structural units: (i) the São Francisco Craton and (ii) the N-S Ribeira belt which extendes between this craton and the Atlantic coast.

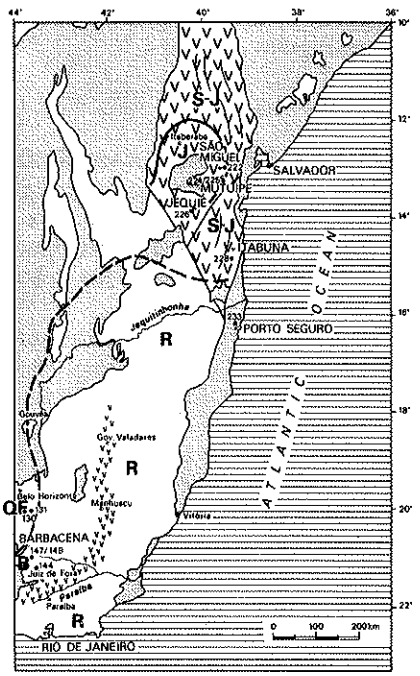
Several authours and most recently Cordani & Brito Neves (1982) have presented syntheses on the geological evolution of that well documented region.

In a few words, the São Francisco Craton is composed of large areas of Archaean greenstone-granite and granulites terranes as well as of Lower Proterozoic supracrustal belts. This "basement" is partly covered by moderately folded and metamorphosed Middle and Late Proterozoic sediments; it is unaffected, except in its border zone, by the Brasiliano (600-800 Ma) thermal overprint which characterizes the Ribeira belt.

The Ribeira belt consist of two superimposed mobile belts with similar N-S structural trends and metamorphic zoning generated by two tectonometamorphic events dated at *ca* 2000 Ma (Transamazônico orogeny) and *ca* 600 Ma (Brasiliano orogeny). The Lower Proterozoic Salvador-Juazeiro mobile belt extending nortwards in eastern Bahia can be correlated with the first one.

The various metamorphic and crystalline rocks, including granulitic types, which constitute the Ribeira belt might presumably be the synorogenic equivalents of the Proterozoic gently folded supracrustal and sedimentary rocks which, in the São Francisco Craton, overlie the Archaean Basement, as well as reworked portions of this basement.

Numerous Rb-Sr and K-Ar geochronological data have been published on the São Francisco Craton and the adjacent Ribeira mobile belt. This paper is focused on U-Pb zircon data from these areas. U-Pb ages for the granitic gneisses of the southern part of the São Francisco Craton (especially the Barbacena area and the Quadrilátero ferrí-



— — — Boundary between the Sao Francisco Craton and the Ribeira belt.
Northern part of the Sao Francisco Craton (Bahia).
J : Jequié Complex (Archaean)
S-J : Salvador-Juazeiro mobile belt (Transamazonian), including the Itabuna block
V V V : Medium to high grade terrains of Bahia
Southern part of the Sao Francisco Craton (Minas Gerais)
Q F : Quadrilatero ferrifero basement (Archaean)
B : Barbacena area (Archaean)
Ribeira mobile belt
R : Ribeira mobile belt (Brasiliano : Late Precambrian-Paleozoic)
v v v : High grade terrains of the Paraiba belt (transamazonian) within the Ribeira belt.

Fig. 1 – Geological sketch map of Eastern Brazil and location of samples

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fero) are merely in agreement with the Rb-Sr age determinations. For the Bahia granulitic domain (including rocks from both the cratonic area and the Salvador-Juazeiro mobile belt) the U-Pb ages yield complementary informations which are to be taken into account in the elaboration of the geological history of this region.

ANALYTICAL METHODS The zircons were dissolved under high pressure in a mixture of hydrofluoric and nitric acids (Krogh 1973). The sphenes were dissolved in the same acid mixture at atmospheric pressure.

A combined spike $^{208}Pb+^{235}U$ has been used in all cases. Lead has been extracted on ion-exchange columns. The common lead contamination during the chemical preparation of the zircons does not exceed 10ng.

The Pb isotope ratios were measured on single Re filament with a FINNINGAN MAT 260 mass spectrometer (Belgian Centre of Geochronology) by the H^3PO_4-silica gel technique (Cameron *et al.* 1969). Mass fractionation is 1.3 ± 0.3‰ by a.m.u. on the basis of repeated analyses of the NBS 981 Pb standard.

Pb and U concentrations were measured with a VARIAN TH5 Mass Spectrometer and are given with a precision better than 2%.

The U-Pb isotopic analyses of zircons (and two sphenes) are reported in Table 1, the corresponding Concordia diagrams are drawn on Figures 2, 3 and 4.

SOUTHERN PART OF THE SÃO FRANCISCO CRATON

Area of Barbacena Previous geochronological studies (Delhal *et al.* 1969, Cordani *et al.* 1973) have shown the existence of three superimposed tectonometamorphic events dated at 2900 Ma, 2100 and 600 Ma in Southeastern Brazil.

In the Barbacena area, tonalitic to granitic gneisses dated at 2880 ma By a 6 points Rb-Sr whole rock isochron, form the southernmost zone of the São Francisco Craton. These gneisses are in contact to the south with the Juiz de Fora granulites, themselves followed southwards by the Paraíba do Sul granulites which are part of the Ribeira mobile belt, and which were dated at 2100 Ma by both Rb-Sr (whole rock isochrons) and U-Pb (zircons) methods (Delhal *et al.* 1969).

It is noteworthy that, in the isochron diagram included in the mentioned work by Cordani *et al.* 1973, several specimens of the Juiz de Fora granulites plot above the Paraíba 2100 Ma isochron so that it is possible to include them either in the 2900 Ma isochron of the Barbacena gneisses with a rather low $^{87}Sr/^{86}Sr$ isotopic initial ratio (0.706) or in isochrons with higher initial rations (~0.715), parallel to the 2100 Ma reference isochron of the Paraíba granulites. In both cases the original Archaean age of the Juiz de Fora rocks seems well stablished but this leaves questionable the age (Archaean of Lower Proterozoic) of their granulite facies metamorphism.

On the other hand, the fact some whole rocks from Barbacena and Juiz de Fora plot also on, or close to, the Paraíba isochron shows the rather strong influence of the 2100 Ma event producing some Rb and/or Sr mobility in the total rocks which did not remain as closed systems. The influence of the 600 Ma event is weaker; though widespread in the Barbacena and Juiz de Fora areas, it is only recorded by Rb-Sr and K-Ar mineral ages.

In the Barbacena area, U-Pb data have been obtained (Delhal *et al.* 1976) on the zircon and on the sphene of a large specimen of an adamellitic gneiss (JD 144), and on zircons from two different portions of an heterogenous migmatitic gneiss (Am 147 and Am 149) (Tab. 1 and Fig. 2).

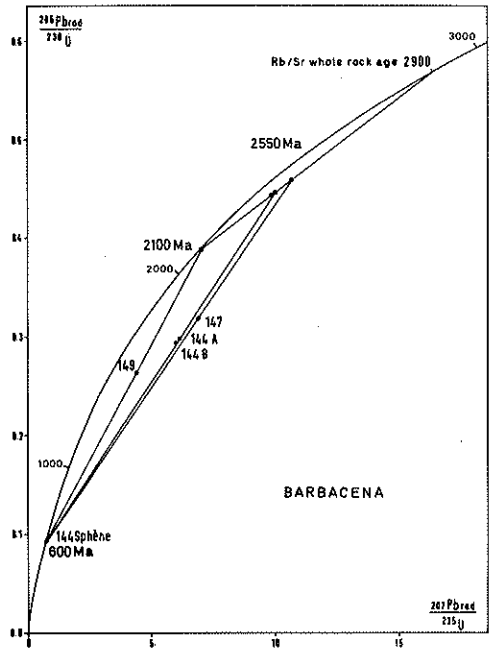

Figure 2 – Concordia plot for zircons and sphene of gneisses from Barbacena

The sphene yields nearly concordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages at *ca* 600 Ma, indicating the crystallization or recrystallization of the mineral during the Brasiliano orogeny or a total loss of radiogenic lead at that time.

On a Concordia graph (Fig. 2) the zircon fractions plot in a triangle whose summits correspond to 600 Ma, 2100 Ma and 2550 Ma. The geological meaning of this 2550 Ma figure is difficult to assess in such polymetamorphic areas. This value might be considered as a minimum age for the zircon crystallization.

According to models of polyepisodic Pb losses (Pasteels & Deutsch 1971, Allegre *et at.* 1974) the disposition of the data points on the Concordia graph is compatible with two episodic lead losses, at 2100 Ma and 600 Ma, affecting zircons crystallized at 2900 Ma (the Rb-Sr whole rock age), assuming that the first loss was much stronger than the second one.

Quadrilátero ferrífero In a recent paper, Teixeira (1982) reviewed all the available Rb-Sr and K-Ar geochronological data; two main events at 3000-2750 Ma and 2100 Ma (the Minas orogeny) are distinguished. Furthermore, some Rb/Sr data on minerals and most of the K/Ar ages reflect the overprint of the Brasiliano event (600 Ma). In the so called "eastern region" of this area, two gneisses (samples JD 130 and JD 131) from the Bação complex were dated (Delhal & Ledent, unpublished results) by the U-Pb method applied to zircon and sphene (Tab. 1).

Table 1 - U-Pb isotopic analyses of zircons and sphenes

N°	Fraction	Concentration (ppm) U	Pb tot.	Pb rad.	Isotopic composition (%) ^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	Apparent ages (Ma) 2 σ $^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$
Barbacena area											
JD. 144	Zircon A	319	113	110	0.030	73.01	11.31	15.65	0.150305 2349 ± 10	0.2979 1681 ± 30	6.1737 2001 ± 25
JD. 144	Zircon B	368	137	124	0.110	70.11	11.91	17.86	0.147991 2323 ± 10	0.2938 1660 ± 30	5.995 1975 ± 25
JD. 144	Sphene	130	21,1	13.9	0.424	56.52	9.571	33.48	0.059978 603 ± 75	0.0934 576 ± 13	0.7724 581 ± 39
Am 147	Zircon tot.	787	285	267	0.081	77.11	13.12	9.693	0.156761 2421 ± 15	0.3178 1779 ± 33	6.8690 2095 ± 24
Am 149	Zircon tot.	1117	309	298	0.048	82.88	10.63	6.444	0.120430 1963 ± 15	0.2640 1510 ± 29	4.3837 1709 ± 25
Baçao Complex											
JD. 130	Zircon A	654	277.6	267.6	0.0486	68.3725	11.0613	20.5175	0.152658 2375 ± 5	0.3323 1850 ± 33	6.9944 2111 ± 21
JD. 130	Zircon B	770.6	236.0	226.9	0.0563	78.589	11.913	9.441	0.142226 2255 ± 5	0.2760 1571 ± 29	5.4124 1887 ± 20
JD. 131	Zircon tot.	797.7	277.2	273.3	0.019	79.621	13.777	6.538	0.170196 2559 ± 10	0.3201 1790 ± 32	7.5077 2174 ± 19
JD. 131	Sphene	149.3	45.15	39.29	0.174	70.550	12.433	16.842	0.144102 2277 ± 20	0.2364 1368 ± 26	4.697 1767 ± 21
Jequié Complex											
JD. 222 Sao Miguel	A NM3°	462.2	139.7	130.9	0.0843	74.241	12.657	13.018	0.155949 2412 ± 14	0.255149 1465 ± 27	5.486626 1899 ± 22
id.	B M10°	1436.4	29.12	17.30	0.5458	51.607	13.893	33.954	0.128416 2076 ± 80	0.009742 63 ± 4	0.172511 162 ± 10
JD. 224 Mutuipe	A NM1°	174.4	83.93	83.22	0.0114	73.176	11.167	15.647	0.150597 2353 ± 8	0.407872 2205 ± 38	8.469722 2283 ± 19
id.	B M6° + M8°	200.8	82.00	77,9	0.0666	74.023	11.922	13.989	0.149430 2340 ± 10	0.345138 1911 ± 35	7.111487 2126 ± 23
JD. 225 D Mutuipe	M8°	892	143.6	140.2	0.0322	78.709	10.374	10.885	0.126339 2047 ± 15	0.146175 879 ± 17	2.546479 1285 ± 18
JD. 226 Jequié	NM 1,5 A, 5°	1064.7	288.3	268.8	0.0908	74.9746	11.6324	13.3023	0.139278 2218 ± 10	0.230589 1338 ± 13	4.428436 1718 ± 13
id.	M 1,5 A, 10°	1949.4	384.8	306.1	0.2749	63.9412	11.2675	24.5164	0.118171 1929 ± 9	0.134782 815 ± 8	2.196241 1180 ± 8
Itabuna Complex											
JD. 228 Itabuna	50-100μ	1000.4	309.31	309.09	0.0010	79.926	10.515	9.558	0.131394 2117 ± 15	0.287157 1627 ± 29	5.202626 1853 ± 19
id.	>50μ	616.1	245.8	244.7	0.0056	79.5256	10.3762	10.0927	0.129548 2092 ± 7	0.368229 2021 ± 17	6.577766 2056 ± 10
JD. 233 Porto Seguro	50-100 μ	245.3	63.90	62.46	0.0303	78.2636	10.9657	10.7410	0.134990 2165 ± 10	0.235271 1362 ± 25	4.379254 1708 ± 17
id.	>50 μ	321.5	126.2	115.0	0.1190	75.4128	11.7102	12.7580	0.134447 2157 ± 15	0.333784 1857 ± 22	6.187929 2003 ± 32

$\lambda^{238}U = 1{,}55125.10^{-10}.a^{-1}$; $\lambda^{235}U = 9{,}8485.10^{-10}.a^{-1}$; $^{238}U/^{235}U = 137{,}88$. Common lead used for correction : $^{206/204}$: 18,6; $^{207/204}$: 15,7; $^{208/204}$: 38,9.

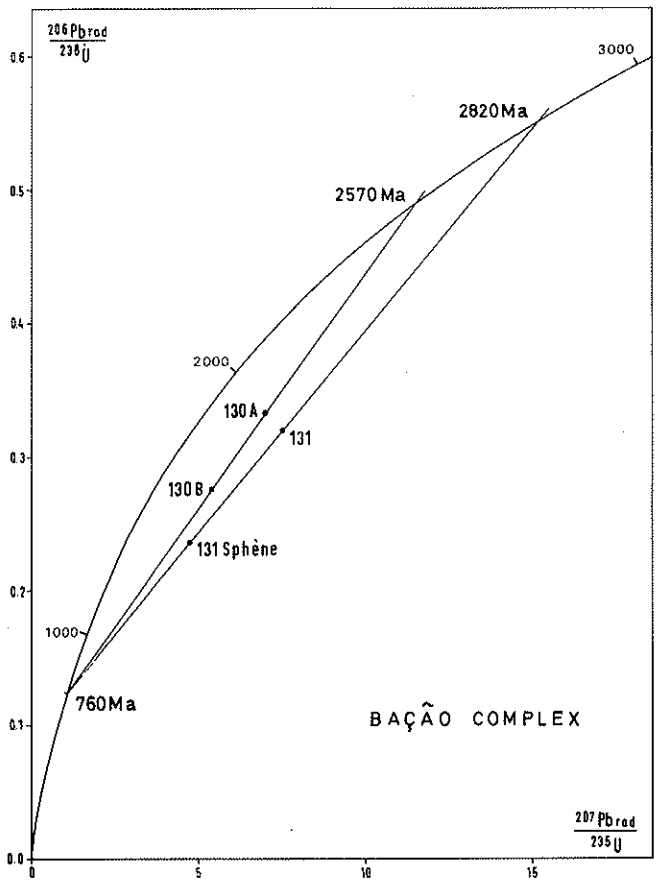

Figure 3 – Concordia plot for zircons and sphene of gneisses from the Bação Complex

The Rb-Sr data for these two specimens fall between the 2750 Ma and the 2100 Ma reference isochrons of Teixeira and are interpreted by him as representing a partial Sr isotopic rehomogenenization by the Transamazônico (2100 Ma) event.

The two fractions (A and B) of zircon JD 130 define a chord intersecting Concordia at 760 Ma and 2750 Ma, while the zircon and the sphene JD 131 define a chord intersecting Concordia at 760 Ma and 2820 Ma (Fig. 3).

The same lower intercept at 760 Ma for both specimens may be interpreted as reflecting an episodic Pb loss in relation with the Brasiliano event. The dispersion of the points towards upper intercepts should be interpreted as resulting from the influence of the 2100 Ma event, as suggested by the Rb/Sr results.

Owing to the existence of two successive events at *ca* 2100 Ma and *ca* 760 Ma, the four points of the two specimens are located in a 760-2100-2820 Ma triangle, and 2820 Ma is to be considered as a minimum age for the gneisses of the Bação Complex.

Conclusion In both areas, Barbacena and Quadrilátero ferrífero, the U-Pb geochronological pattern is very similar and agrees with the Rb-Sr data. The same geological evolution is recorded: the Archaean (≥ 2800 Ma) mainly granitic basement was affected by a medium-grade metamorphism during the Minas orogeny (~ 2100 Ma) and less influenced (mineral ages) by the Brasiliano thermal overprint (600 Ma).

NORTHERN PART OF THE SÃO FRANCISCO CRATON: HIGH GRADE TERRAINS OF SOUTHEASTERN BAHIA

Numerous papers have been recently published (see especially the Rev. Bras. Geoc. vol. 12, 1982) about the Bahia high-grade metamorphic terrains comprising the Jequié Complex surrounded by the Caraíba-Paramirim Complex to the North and West, and by the Salvador-Itabuna Complex to the East.

According to Cordani & Brito Neves (1982), the Jequié Complex is an Archaean "cratonic fragment" within the Salvador – Juazeiro mobile belt, while the Itabuna Complex belongs to this mobile belt, of Transamazônica age. In the works of Figueiredo (1982a) and Brito Neves *et al.* (1980) the high grade terrain of Itabuna is considered to be formed by different rocks in origin, petrology and geochronology from those of the Jequié Complex.

In a petrographic and geochemical description of the Bahia granulites, Oliveira *et al.* (1982) consider the Salvador-Itabuna Complex as a tectonic block of the Jequié Complex, intensively reworked during the Proterozoic Transamazônico cycle.

The Jequié Complex (block) Rb-Sr whole rock isochrons obtained on granulites from different areas (Mutuípe, Jequié, Itaberaba) of the Jequié Complex (or "Jequié block" *in* Oliveira *et al.* 1982) yield poorly defined age indications scattering from 3200 Ma to 2400 Ma, which have been grouped by Cordani & Iyer (1979) into three main periods i.e. > 3000 Ma, 2750 Ma (the so called Jequié event) and 2400 Ma, the metamorphic transformation of the whole complex into granulites being attributed to the 2750 Ma Jequié event.

The granulites dated at 3200 Ma in the area of Mutuípe are therefore considered (Cordani &Iyer 1979, Brito Neves *et al.* 1980) as being a very old nucleus in which the original Rb-Sr isotopic system has been preserved in spite of the profound mineralogical transformation occuring during the high-grade 2750 Ma event. On the contrary, in other areas of the same block, the granulites dated at 2400 Ma by Rb-Sr isochrons with high Sr isotopic initial ratios are interpreted tentatively as 2750 Ma old granulites mineralogically preserved but isotopically rehomogenized by a thermal event at 2400 Ma. Other authors (Mascarenhas & Sá 1982) prefer to consider this latter value as an apparent age resulting from the partial resetting of Archaean granulites during the 2100 Ma Transamazônico orogeny. However there is no Rb-Sr whole rockages much younger than 2400 Ma in the Jequié Complex and the certain but slight influence of the 2100 Ma event is only recorded by K/Ar ages of biotite and amphibole (Cordani & Iyer 1979).

Several granulitic rocks from the Jequié Complex, namely two from Mutuípe (JD 224 and JD 225), one from São Miguel (JD 222), one from Jequié (JD 226) have been dated by the U-Pb method on zircons (Tab. 1 and Fig. 4). The samples were collected in the areas where ages from 3160 Ma (Mutuípe) to 2700 Ma (Jequié) had been obtained by Rb-Sr. The Rb-Sr apparent ages measured on the total rocks of the same specimens from which the zircons were separated, when calculated with a mean initial ratio of 0.705,

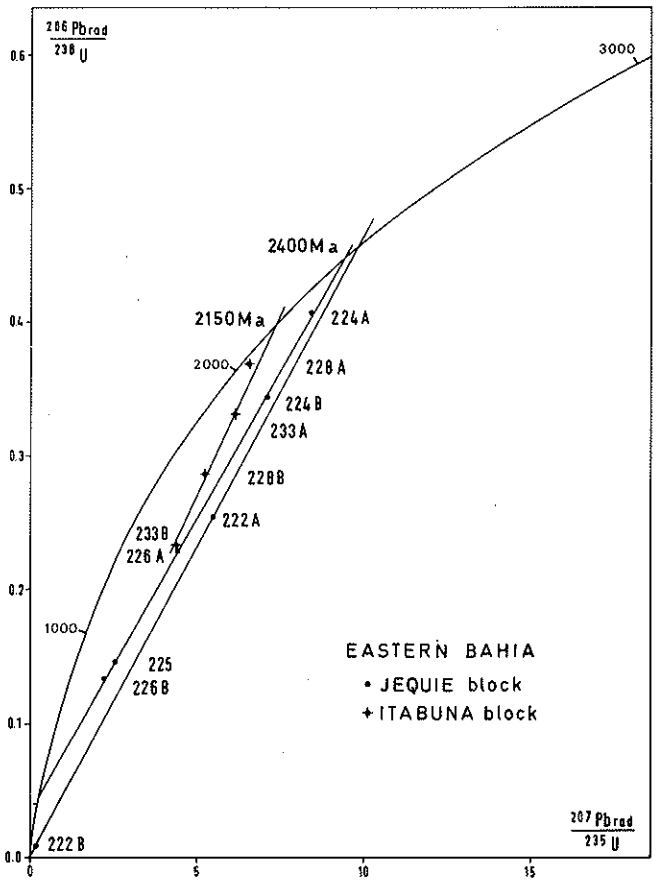

Figure 4 – Concordia plot for zircons from eastern Bahia

yielded ages between 2700 Ma and 2400 Ma (Cordani, unpublished results).

The A and B fractions of specimens JD 224, JD 226 and JD 222 define separate Discordia chords with upper intercepts on Concordia of 2355 Ma, 2390 Ma and 2425 Ma respectively. Four of these fractions (JD 224 A and B, JD 226 A and B) and the single fraction JD 225 are aligned on a chord with computed upper and lower intercepts of 2377 ± 28 Ma and 346 ± 28 Ma respectively. Fractions JD 222 A and B are not aligned on this five points array but they define a subparallel chord which gives an upper intercept of 2425 Ma, similar within the limits of experimental errors.

The linear array of the chord defined by the five zircon fractions is good (MSWD = 0,33) which seems to preclude the existence of an important episodic Pb loss at 2100 Ma; this is supported by the weak influence of this event as previously recognized by the other geochronological methods. One may therefore conclude that the 2400 Ma figure corresponds to a geologically significative event. The zircons being originally older than 2400 Ma, as it is demonstrated by the Rb-Sr ages of their host rocks, this age represents that of a complete resetting of the isotopic clock of the zircons.

The lower intercept (346 Ma) of the Discordia defined by five fractions has no geological significance and must be considered as the expression of an essentially continuous Pb loss.

The Salvador-Itabuna Complex (block) The granulites of the Itabuna area yield Rb-Sr ages roughly aligned along a 2400 Ma regression line which is interpreted tentatively (Brito Neves *et al.* 1980) as the influence of the Transamazônico event (2000 Ma) on Archaean rocks (2700 Ma).

In the Salvador area, most of the results (21 on 27 points) are grouped an isochron of about 2000 Ma with a Sr isotopic initial ratio of 0.705. Two interpretations have been proposed recently:

- These rocks result from a Sr isotopic rehomogenization process affecting Archaean rocks at 2100 Ma (Brito Neves *et al.* 1980); unclear chemical migrations have been proposed to explain the rather low initial ratio.
- These rocks were formed and granulitized during the 2100 Ma cycle (Cordani & Brito Neves 1982, Figueiredo 1982).

The U-Pb results confirm the importance of the Transamazônico orogeny in the granulitic terrain of the Itabuna area and also in the granito-gneissic region of Itapebi-Porto Seguro located just to the south of the Itabuna Complex. Indeed, the two zircon fractions of a granulite from Itabuna (JD 228 A and B) define a chord intersecting Concordia at *ca* 2100 Ma and the two fractions (JD 233 A and B) of a granito-gneiss from Porto Seguro yield an upper intersection age of 2150 Ma.

Discussion In the Jequié Complex, the age of the high-grade metamorphic event is not precisely known but all the isochrons of Archaean granulites, yielding ages between 3200 and 2700 Ma, have Sr isotopic initial ratios clearly higher than 0.702 (the highest probable mantle value 2900 Ma ago) indicating that these granulites result from the reworking and isotopic rehomogenization of rocks much older than 3000 Ma.

The presence in the vicinity of the granulitic complex of granitic to tonalitic gneisses without granulitic mineralogy and dated up to 3500 Ma (Mascarenhas & Sá 1982) makes this explanation very likely.

Besides, the cyrstalline nature, and therefore the low water content of the precursors have prevented extensive remelting in the high-grade conditions; this could therefore explain the undepleted character of those granulites (Figueiredo 1982, Iyer *et al.* 1984) and probably also the lack of isotopic homogenization of the Rb-Sr system between the different parts of the Complex during the metamorphism.

If this view is correct, we suggest in order to better define the age of the granulite metamorphism to date carefully selected samples which on the basis of field and petrological evidences could be interpreted as resulting from dry anatexis during this granulite metamorphism.

In the present state of the geochronological data, the dispersion of the ages seems to result from their computation from heterogeneous material corresponding to a mixture of undifferenciated early Archaean paleosome partially or completely rejuvenated and of Archaean neosome (granulitic melt), both being partially influenced by a 2400 Ma old event whose exact nature is still unknown. This 2400 Ma age, yielded by some total rocks (Rb-Sr isochrons with high initial ratios) and also by the zircons of the rocks giving older Rb-Sr ages, deserves to be considered as a

meaningful young age limit in the history of the Jequié Complex. All these data concordant around, and not lower than, 2400 Ma could indeed hardly be interpreted as mixed ages resulting from the influence of the 2000 Ma Transamazônico orogenic event on the Archaean granulites. They appear on the contrary to correspond to the age of a complete resetting of the zircons and of a rehomogenisation, or loss of Sr, for a part of the rocks.

Three interpretations might be formulated regarding the 2400 Ma old event:

- After the granulite facies metamorphism which took place during the Archaean, between 3200 and 2700 Ma, the whole complex remained deeply buried at such high temperatures that the radiogenic lead was continuously loss from the zircons until about 2400 Ma corresponding to the uplift at the beginning of the Transamazônico cycle.
- The granulitic metamorphic event is 2400 Ma old; it affected Archaean rocks and produced from area to area incomplete Sr isotopic rehomogenization resulting in a series of ill defined Rb-Sr whole rock isochrons with relatively high isotopic initial ratios.
- 2400 Ma is the age of a discrete thermal event without tectonometamorphic and magmatic manifestations but sufficient to influence the zircon U-Pb and some of the whole rock Rb-Sr systems.

From 2400 Ma, the Jequié Complex remained isotopically closed for Sr and Pb systems (only the K-Ar systems were still open) constituting an area of rigid lithosphere with a continental upper crust, while, in opposition, the Salvador Itabuna Complex, in the Salavador-Juazeiro mobile belt, has obviously been influenced by the 2000 Ma orogeny. However, the age (Archaean or Transamazônico) of the granulite metamorphism in this latter region remains controversial.

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MANUSCRITO
Recebido em 19 de novembro de 1984
Revisão aceita em 01 de abril de 1985

Colocar os eventos geológicos em sua posição no tempo e perspectiva apropriada na interpretação da história da terra representa a meta de grande parte do pensamento geológico.

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