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GEOLOGIC EVOLUTION OF THE SERRA DOS CARAJÁS, PARÁ, BRAZIL

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ABSTRACT The Serra dos Carajás is located in southern Pará, in the region between the Araguaia and Xingu rivers, and has been regarded very recently as the most promising and potentially interesting metallogenic province in South America. In order to characterize its geologic evolution, a geochronological program was carried out by a cooperative effort of Docegeo and the CPGeo-USP, with the help of structural, petrologic and geological information.

In the region, a polymetamorphic basement occurs in which gneisses and related rocks are associated to the supracrustal rocks of the Salobo Formation. The iron formations and low grade metamorphics of the Grão-Pará Group overlie the basement, and are covered by the sedimentary rocks of the Rio Fresco Formation. Post-orogenic and cratogenic granites occur, cutting through all the above mentioned units.

The granitic rocks indicated Rb-Sr whole rock ages up to 1,850 m.y., K-Ar determinations on micas from the metamorphic indicated that the regional cooling occurred at about 1,950 m.y., after the main events of the Transamazonian orogeny. Some transamazonian results were also obtained on micaceous schists of the Salobo Formation. However, several analytical points, in a Rb-Sr isochron diagram, indicated a Late Archean age for their main metamorphic episode.

INTRODUCTION The Serra dos Carajás region is located in southern Pará, in the area between the Araguaia and Xingu rivers (Fig. 1). It has been regarded recently as the most promising and potentially interesting metallogenic province in South America.

This work deals with the geotectonic evolution of the Serra dos Carajás. This region is part of the Amazonian Central Province (Cordani *et al.*, 1979), which is composed of archean rocks, in part remobilized in the Transamazônico Orogenic Cycle.

Three successive episodes of continental accretion had been established for the Amazonian Craton, the first in the 2,200-1,800 m.y. (Maroni-Itacaiúnas Mobile Belt), the second in the 1,750-1,400 m.y. age range (Rio Negro-Juruena Mobile Belt), and the third at about 1,400-1,000 m.y. (Rondonian Mobile Belt) (Cordani *et al.*, *op. cit.*).

The geotectonic evolution here presented is based on the available geochronological dates, with the aid of structural, petrologic and geological information. The new age determinations used in this paper were obtained by a cooperative effort of Docegeo-Rio Doce Geologia e Mineração S.A. and the Geochronological Research Center of Universidade de São Paulo (CPGeo-USP).

The Rb-Sr whole-rock age determinations were interpreted in isochron diagrams, and the measured Sr^{87}/Sr^{86} ratios have been normalized to $Sr^{86}/Sr^{88} = 0.1194$. The Rb-Sr ages have been calculated using a decay constant of $\lambda Rb = 1.42 \times 10^{-11}\ yr^{-1}$.

The K-Ar age determinations were carried out in whole rock and/or separated mineral, such as biotite, plagioclase, and amphibole. Constants employed in the age calculations were $\lambda K_{total} = 0.581 \times 10^{-10}\ yr^{-1}$; $\lambda k = 4.962 \times 10^{-10}\ yr^{-1}$; $Ar^{38}/Ar^{36} = 295.5$; and $K^{40} = 0.0116\%\ K_{total}$.

A total of 54 age determinations, of which 27 are here presented for the first time, has been considered for the interpretation attempted in this work.

GEOLOGIC SETTING The Serra dos Carajás region in the southeastern part of the Amazonian Craton (Almeida, 1978), is situated at the boundary area of the Amazônia Central Province and Maroni-Itacaiúnas Province (Cordani *et al.*, 1979).

The basement rocks are mainly migmatites, schists, granites, gneisses, and other granitoid rocks. The metamorphism is generally within upper amphibolite facies, although granulite facies mineralogy is sometimes recorded. This complex can be divided into high-grade granite-gneiss terrains and medium grade granitic rocks typical of a mobile belt environment.

High-grade granite-gneiss terrains are located in the southern area, within the Amazonian Central Province. They have a history dating back to 2,600 to 2,900 m.y., or more, and are surrounded by younger Proterozoic metamorphic belts. At least in part, they constitute a basement upon which greenstone belts developed.

Low grade metasedimentary and metavolcanic associations occur in the same area. Ultramafic metalavas (talc schists), cherts, and banded iron formation overlie the granite-gneiss terrain. Metadacitic and metarhyolitic lavas, as well as basic metavolcanics, talc-chlorite schists, clastic-siltic sediments, greywackes and sandstones are also reported in the region.

High-grade metasediments are found in the Carajás area, are included in the Salobo Formation. They consist mainly of gneisses, banded iron formations, amphibolites, schists (plagioclase, amphibole, biotite, quartz, garnet), and metamorphic rocks with cordierite.

The basement rocks are overlain with angular unconformity by a metamorphic sequence, named Grão-Pará Group (Beisiegel *et al.*, 1973), which is subdivided into three units: the lower paleovolcanic sequence of metabasites, the Carajás Formation with itabirites and the upper paleovolcanic sequence consisting of metabasite with some

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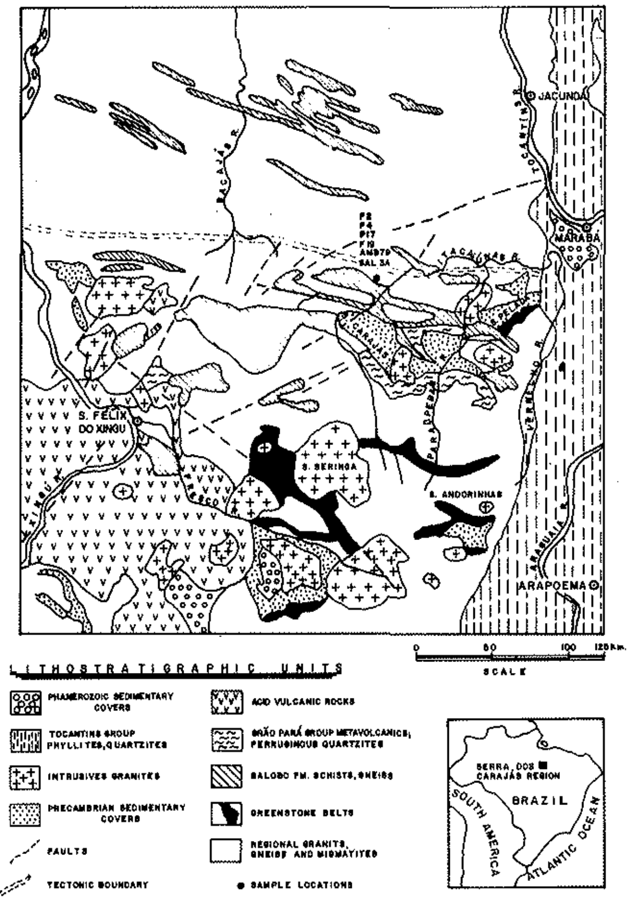

Figure 1 – Regional geology of the Serra dos Carajás area

interbedded layers of iron formation. The Carajás Formation is strongly laminated, with quartz, magnetite and hematite as dominant minerals, and is cut by mafic sills and dikes.

Acid volcanic rocks and the clastic sedimentary rocks of the Rio Fusco Formation overlie the Grão-Pará Group, or its basement. The Gorotire Formation overlie these volcanic rocks and consists mainly of sandstone, siltstone, shale and conglomerate intercalations. Near its contacts with volcanic and granitic rocks, the sediments have undergone slight contact metamorphism.

Various granitic bodies occur in this region. The most important acid plutonic rocks are the Serra da Seringa Granite, the Carajás Granite and other small circular subvolcanic bodies of alaskitic composition, named by Silva *et al.* (1975) Velho Guilherme Granites. These small bodies include rocks varying from granitic to granodioritic composition, and exhibit greisenized zones with cassiterite, fluorite, and topaz.

All the rock units described above are cut by dikes which show no evidence of metamorphism. These dikes range in composition from diabase to andesite porphyry.

The structure of the Serra dos Carajás region is very complex, the main fold axes being west-east, plunging both towards east and west. This structural trend is truncated by the north-south trends of the epimetamorphic rocks of the Tocantins Group, in the easternmost part of the area.

GEOCHRONOLOGY In the southern part, within the Amazonian Central Province, the major rock units are granite-greenstone terrains, represented by schists associated to granodioritic, dioritic and granitic rocks.

Rb-Sr analytical data for samples of the granitic rocks are listed in Table 1 and plotted in Fig. 2. In the isochron plot five points form a well defined linear array with a slope corresponding to 2,750 m.y. and with a Sr^{87}/Sr^{86} intercept of 0.701. This initial Sr^{87}/Sr^{86} ratio coincides with the estimated value for the contemporaneous upper mantle, as deduced from plausible upper mantle evolution models (Faure and Powell, 1972), and, in our view, this late archean age could correspond to the formation of the granite-greenstone terrains, during a major episode of continental accretion.

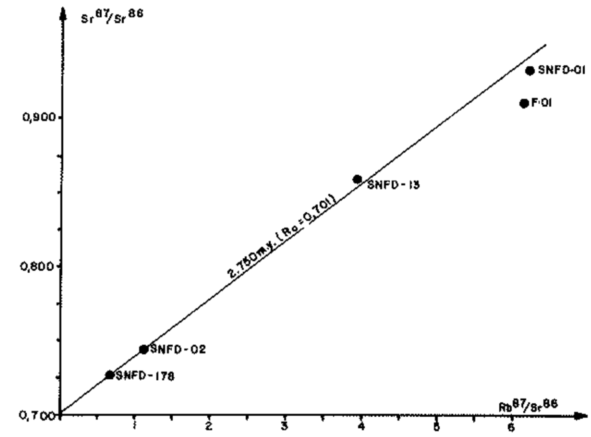

Figure 2 – Isochron diagram for granite-greenstone terrains

The K-Ar results obtained on minerals from rocks of this unit (Table 2) are younger than the Rb-Sr whole rock values. The apparent K-Ar ages exhibit a scatter with limiting values of 2,200-1,750 m.y., although some apparent ages are older (3,300 m.y. and 2,400 m.y.). Thus the K-Ar ages indicate that at least part of the region was affected by events of the Transamazonian orogenic cycle.

Twelve whole-rock samples of schists of the Salobo Formation have now been analyzed by the Rb-Sr method (Table 3). In the isochron diagram of Fig. 3, the analytical

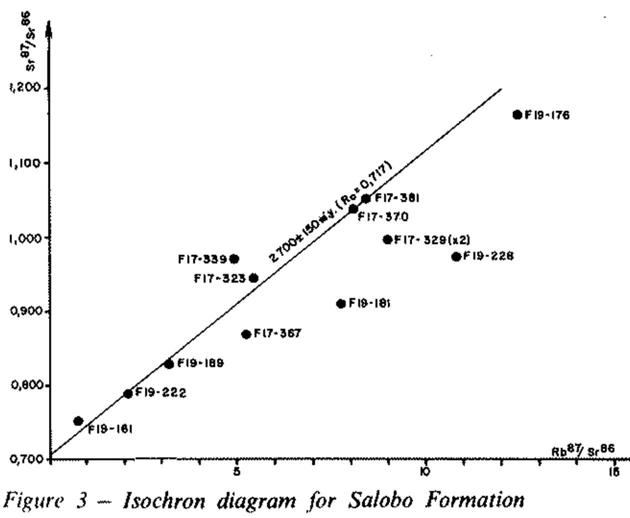

Figure 3 – Isochron diagram for Salobo Formation

Table 1 – Rb-Sr whole rock age of granite-greenstone terrains

Sample*	Rb(ppm)	Sr(ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Rock	Ref.
SNFD 178	83.1	354.3	0.68	0.7268	Granodiorite	4
SNFD 02	145.3	395.7	1.07	0.7471	Granodiorite	4
SNFD 13	217.5	160.3	3.99	0.8599	Granite	4
SNFD 01	246.6	115.9	6.22	0.9347	Granite	4
F 01	315.5	150.9	6.18	0.9116	Gneiss	1

*Samples from Serra do Inajá, approx. 300 km S of Serra dos Carajás
1 – Silva *et al.* (1974); 4 – Cunha *et al.* (1981).

Table 2 – K-Ar ages of granite-greenstone terrains

Sample	Rock	Material	%K	Ar^{40} rad × 10^{-3} cc STP/g	$\%Ar_{atm}$	Age (m.y.)	Ref.
485AZ196.1*	Diorite	Amphibole	0.54	0.092	4.11	2,230 ± 59	4
F 01*	Gneiss	Biotite	6.99	0.786	2.78	1,727 ± 72	1
JW-03**	Gneiss	Biotite	7.57	0.918	1.26	1,813 ± 40	1
TT-26**	Amphibol.	Whole rock	0.15	0.053	26.0	3,283 ± 113	3
BS-23**	Gneiss	Biotite	6.29	0.012	0.5	2,409 ± 70	3
TT-4**	Amphibol.	Amphibole	0.68	0.106	8.4	2,130 ± 78	3

*Samples from Serra do Inajá. **Samples are localized in Gomes *et al.* (1975).
1 – Silva *et al.* (1974); 3 – Gomes *et al.* (1975); 4 – Cunha *et al.* (1981).

Table 3 – Rb-Sr whole rock age determination on Salobo Formation

Sample*	Rb(ppm)	Sr(ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Rock	Ref.
F17-323	109.3	59.3	5.41	0.9477	Schist	2
F17-329	198.4	18.40	17.96	1.2820	Schist	2
F17-339	60.4	37.00	4.85	0.9763	Schist	2
F17-367	125.8	70.8	5.22	0.8711	Schist	2
F17-370	136.7	45.1	8.03	1.0040	Schist	2
F17-381	127.7	45.5	8.40	1.0500	Schist	2
F19-161	13.5	47.9	0.82	0.7506	Schist	2
F19-181	114.2	43.4	7.77	0.0985	Schist	2
F19-189	135.4	129.3	3.07	0.8306	Schist	2
F19-222	108.6	152.2	2.08	0.7879	Schist	2
F19-228	117.0	32.00	10.86	0.9725	Schist	2
F19-176	131.0	31.80	12.44	1.1637	Schist	2

*Location shown on Fig. 1
2 – Docegeo/CPGeo-USP

points exhibit considerable dispersion, nevertheless six points seem to define a linear array with 2,700 ± 150 m.y. (initial $Sr^{87}/Sr^{86} = 0.717$). This age can be associated in our view, to the main metamorphic episode affecting the metasedimentary rocks. The high Sr^{87}/Sr^{86} ratio obtained for this reference isochron indicates sedimentary origin.

The analytical point F-17-339 is located significantly above the isochron, and five analytical points are located below it. In our view, this suggests chemical mobility, caused by the younger tectono-thermal events, such as the Transamazonian orogeny.

K-Ar determinations on rocks of the Salobo Formation, obtained on micas, are concordant, within the experimental error, with ages around 1,950 m.y. old (Table 4). These ages represent the tectonic stabilization epoch, which is confirmed by the K-Ar dates obtained by Gomes *et al.* (1975) in additional samples of the area.

The plagioclases of the samples F-19-222 and F-19-276 yielded K-Ar results younger than the micas, which can be explained by some loss of radiogenic argon by continuous diffusion at low temperatures, a fact which is normal for low retentivity material.

The boundary between the Maroni-Itacaiúnas Mobile Belt and the granite-greenstone terrain is located in the northern edge of Serra dos Carajás, with an eastern-western trend, as shown in Fig. 1. This boundary is based essentially on the geochronological results, and should be regarded as tentative, since it could not be observed in the field.

The structural trends of both geochronological provinces are parallel and the supracrustal rocks were probably eroded, in the northern part, thus precluding any correlation.

The granitic rocks of the northern part, within the Maroni-Itacaiúnas Mobile Belt were sampled along the Bacajás and Itacaiúnas rivers.

Table 4 – K-Ar ages of Salobo Formation

Sample*	Rock	Material	%K	Ar^{40**}_{rad}	$\%Ar^{40}_{atm}$	Age(m. y.)	Ref.
F17-347	Schist	Biotite	6.003	0.917	8.45	1,971 ± 27	2
F17-381	Schist	Biotite	6.704	0.891	1.88	1,920 ± 53	2
F19-222	Schist	Feldspar	1.281	0.101	1.53	1,358 ± 31	2
F19-176	Schist	Feldspar	0.758	0.086	1.67	1,740 ± 27	2
F19-176	Schist	Biotite	4.928	0.646	1.53	1,903 ± 35	2
F19-222	Schist	Biotite	6.036	0.822	0.40	1,948 ± 32	2
SAL-3AF1	Schist	Amphibole	1.679	0.227	2.10	1,940 ± 45	2
Am9-79	Schist	Muscovite	7.940	1.113	1.30	1,983 ± 47	2
1097	Schist	Muscovite	7.620	1.101	0.70	2,022 ± 73	2

*Location shown on Fig. 1; $^{**}x_{10}^{-3}$ *(ccSTP/g)*
2 – Docegeo/CPGeo-USP

The Rb-Sr determinations for this mobile belt are listed in Table 5 and plotted in Fig. 4. Their Rb-Sr analytical data have been fitted to the 2,000 m.y. isochron line. This age

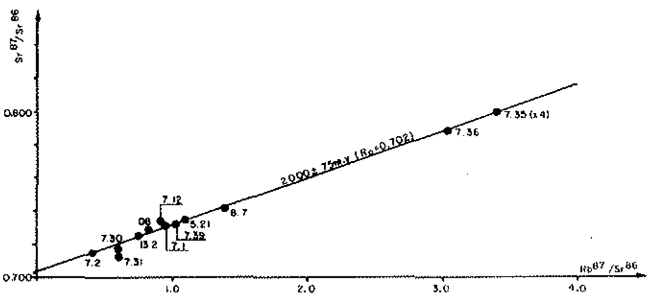

Figure 4 – Isochron diagram for the the granitic rocks of Maroni--Itacaiúnas Mobile Belt

value corresponds to an important period of rock formation, which falls within the Transamazonian orogenic cycle. The low Sr^{87}/Sr^{86} initial ratio of 0.702 suggests that this terrain is formed by granitic magma mantle derived, and which could not have been resulted by reworking of much older crust.

Gomes *et al.* (1975) using amphibolites, granites, gneisses and migmatites of this geotectonic unit, obtained an age, around 2,000 m.y. by K-Ar analysis. This age represents, in our view, the main tectonic stabilization event of the northern region.

For the Grão-Pará Group, Gomes *et al.* (*op. cit.*) reported five K-Ar age determinations obtained on rocks of the metavolcanic sequences associated with iron formations. These samples suffered substantial argon loss, and the oldest K-Ar result of 1,905 ± 59 m.y. may be close to the time of the regional metamorphism of the Grão-Pará Group. Other four results, around 950 m.y., seem to be geologically meaningless.

The pos-tectonic granitic intrusions are mostly, to the south and southwest of the Serra dos Carajás. Some of these bodies have been dated by Silva *et al.* (1974), by the Rb-Sr whole rock method, with calculated ages [with $(Sr^{87}/Sr^{86})_0 = 0.705$] of about 1,700 m.y. for the Serra da Seringa bodie and 1,433 ± 43 for the Velho Gilherme Granite. The same authors present a K-Ar result for the Serra da Seringa Granite of 1,810 m.y. Gomes *et al.* (1974) gave a K-Ar age for the Serra dos Carajás Granite of 1,800 m.y.

The Rb-Sr whole-rock age determinations on these undeformed granites are listed in Table 6. The analytical points are plotted in the isochron diagram of Fig. 5, and defined an isochron line with age of 1,700 ± 45 m.y. and initial Sr^{87}/Sr^{86} ratio of 0.710. This age value is taken as the approximate age of emplacement in this area, possibly corresponding to a post-tectonic phase of the Transamazônico orogenic cycle.

The initial ratio Sr^{87}/Sr^{86}, although not precisely controlled in Fig. 5, seems to indicate a derivation of such granitic massifs from previously existent crustal material.

Table 5 – Rb-Sr whole rock age of the granitic of Maroni-Itacaiúnas Mobile Belt

Sample	Rb(ppm)	Sr(ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Rock	Ref.
AG-7.1*	252.5	750.0	0.9750	0.7321	Granite	1
AG-7.2*	107.6	815.0	0.3820	0.7153	Granite	1
AA-132*	84.0	326.0	0.7460	0.7242	Granite	1
JW-08*	83.8	286.1	0.8480	0.7289	Migmatite	1
CN-521*	122.8	298.4	1.1910	0.7336	Migmatite	1
AA-7.30*	36.4	178.1	0.600	0.7182	Granitic	3
AA-7.31*	56.5	268.0	0.618	0.7132	Granitic	3
AA-7.39*	32.4	90.8	1.048	0.7303	Granitic	3
AA-7.36*	119.0	115.0	3.05	0.7885	Granitic	3
AA-7.35*	310.0	68.5	13.80	1.093	Granitic	3
AA-8.7*	120.0	247.0	1.424	0.7407	Granitic	3
AA-7.12*	60.8	186.0	0.961	0.7330	Granitic	3

*Samples are localized in Gomes *et al.* (1975)
1 – Silva *et al.* (1974) 3 – Gomes *et al.* (1975)

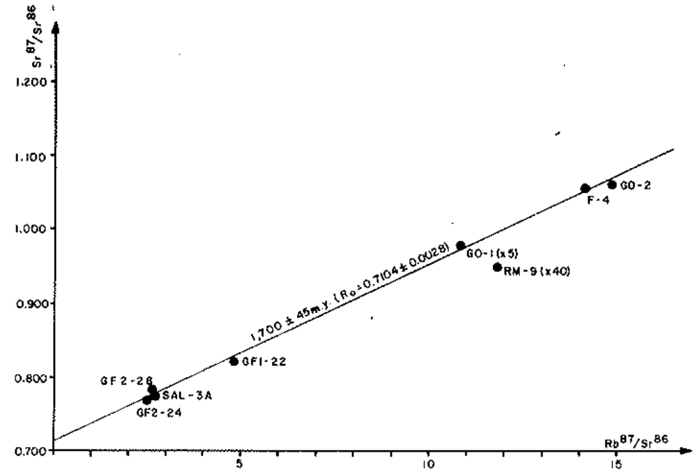

Figure 5 – Isochron diagram for post-tectonic granites

CONCLUSIONS The geochronological pattern of the Serra dos Carajás region indicates a southern part in which Archean granite-greenstone terrains were identified, and a northern part in which a Transamazônico mobile belt was emplaced. The Grão-Pará Group, located at the boundary of these units, is here interpreted as a marginal basin, in which sediments and volcanic rocks were deposited and metamorphosed during the geotectonic evolution of the Maroni-Itacaiúnas Mobile Belt.

The Sr isotopic composition, in the granitic rocks of the region suggests that irreversible chemical differentiation of the mantle, starting in the Archean has produced new continental, sialic crust, in several episodes. During these "Continental Accretion-differentiation superevents" (Moorbath and Taylor, in press), juvenile sial derived from the mantle, jointly with some reworking of older continental crust, produced the magmatic components of the granitic-greenstone terrain, and later the bulk of the Maroni-Itacaiúnas Province.

It can be noted that in this accretion process, the continental growth seems to have predominated over reworking of older sialic crust.

The younger precambrian sedimentary rocks, associated with volcanics, and intrusive post-tectonic granites, represented post-orogenic deposits and cratogenic magmatic activity, affecting the cratonized unit, long after the Transamazônico orogeny.

Based on the geochronological dates, the geologic evolution can be summarized as follows:

1,700 m.y.	Post-tectonic intrusive granites
1,800 m.y.	Deposition of sediments (Gorotire Formation). Extrusion of acid volcanic rocks
1,900 m.y.	Deposition and metamorphism of Grão-Pará Group in a marginal basin
2,000 m.y.	Formation of migmatites, granites and gneisses, within the Maroni-Itacaiúnas Mobile Belt
2,700 m.y.	Regional metamorphism of the Salobo Formation
2,750 m.y. (or slightly older)	Formation of Granite Greenstone terrains

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Table 6 – Rb-Sr whole rock age of the post-tectonic granites

Sample	Rb(ppm)	Sr(ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Age(m.y.)	Ref.
GO-1*	338.1	17.80	54.4	2.089	1,760 ± 41	1
GO-2*	199.0	38.70	14.8	1.061	1,670 ± 62	1
Rm-9	447.0	2.63	472	10.41	1,420 ± 62	1
GFI-22	116.1	71.7	4.74	0.819	1,630 ± 70	3
GF2-24	104.2	120.3	2.52	0.7712	1,780 ± 130	3
F-2	197.5	34.9	17.12	1.1641	1,860 ± 60	3
F-4	204.6	43.3	14.16	1.0601	1,750 ± 50	3
SAL-3A	196.4	220.0	2.60	0.7756	1,880 ± 80	3
CF2-26	123.8	133.9	2.70	0.7792	1,850 ± 100	3

* Samples are localized in Gomes *et al.*, (1975)
1 – Silva *et al.* (1974); 3 – Docegeo/CPGeo-USP.

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