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Sr AND Pb ISOTOPIC EVOLUTION OF GRANITOIDS IN THE SÃO PAULO REGION, BRAZIL

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ABSTRACT In this paper, we report Rb-Sr and Pb isotopic data bearing on the age and origins of the granitic intrusions in the São Paulo area. The Morro Azul, Itu, and Nazaré Paulista granites define Rb-Sr whole rock isochron dates of 525 ± 30, 590 ± 10, and 790 ± 32 Ma, together with initial $^{87}Sr/^{86}Sr$ ratios of 0.711 ± 0.0006, 0.7066 ± 0.0004, and 0.7132 ± 0.005, respectively. The Bragança Paulista and Cantareira granitoids yield preliminary whole rock Rb-Sr isochronic ages around 800 and 650 Ma respectively. In addition we report Pb isotopic analyses of feldspar separates from those massifs and the Moinho granitoid. The feldspar Pb analyses plot close to the evolution curve for the orogene in the plumbotectonics models, between 1,200 and 650 Ma. Most of the feldspar Pb data plot below the orogene curve in the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram, and above it in the $^{208}Pb/^{204}Pb$ diagram, implying significant contributions from older lower continental crust. The Nazaré Paulista data plot towards the upper crust curve. The combined evidence of Rb-Sr and Pb isotopic data suggests that the Moinho Intrusion is probably the oldest of the granites studied (Ca 1.200 Ma) and Morro Azul, the youngest (Ca 550 Ma). The main granitic activity in the São Paulo area is of Late Proterozoic age. Significant contributions to the parent magmas of the granites were derived by melting in the lower crust.

RESUMO Neste trabalho foram realizadas análises isotópicas Rb-Sr e de Pb em granitóides da região de São Paulo com o objetivo de se determinar tanto suas idades como suas fontes magmáticas. Os granitóides de Morro Azul, Itu, e Nazaré Paulista indicaram, pelos diagramas isocrônicos Rb-Sr em rocha total as idades de 525 ± 30, 590 ± 10 e 790 ± 32 Ma, com razões iniciais de 0,7113 ±0,0006, 0,7066 ± 0,0004 e 0,7132 ± 0,0005, respectivamente. Já os corpos de Bragança Paulista e Cantareira sugeriram idades isocrônicas Rb-Sr preliminares da ordem de 800 e 650 Ma. Adicionalmente, foram também realizadas análises isotópicas de Pb em feldspatos separados dos granitos acima citados e também do granitóide do moinho. Os pontos relativos a essas análises, quando plotados nos diagramas de plumbotectônica, situaram-se próximos à curva de evolução do Pb para ambientes orogênicos, entre 1.200 e 650 Ma. Muitos dos feldspatos caíram abaixo da curva orogênica no diagrama Pb^{207}/Pb^{204} versus Pb^{206}/Pb^{204} e acima dela no diagrama Pb^{208}/Pb^{204} versus Pb^{206}/Pb^{204}, o que sugere uma importante contribuição de material proveniente da crosta continental inferior na composição dos magmas parentais desses granitóides, cuja única exceção seria o corpo de Nazaré Paulista, que se supõe formado a partir de fusão parcial da costa continental superior. O uso combinado dos isotópos de Sr e Pb sugere que o granitóide do Moinho seria o mais velho dos corpos estudados com idade da ordem de 1.200 Ma, e o Morro Azul o mais novo, com cerca de 550 Ma. A principal atividade granítica na região de São Paulo seria no Proterozóico Superior sendo os magmas parentais desses granitóides formados predominantemente por fusão parcial da crosta continental inferior.

INTRODUCTION In this paper we report the results of Rb-Sr whole-rock isochron dating and Pb isotopic analyses of feldspars in several granitic intrusions of the São Roque, Piracaia, Itapira, and Amparo geologic domains in the São Paulo region. The studied intrusions are Bragança Paulista (nº 1 in figure 1), Nazaré Paulista (nº 2), Moinho (nº 3), Morro Azul (nº 4), Cantareira (nº 5), and Itu (nº 6). Our aim in carrying out these analyses has been to determine both age of the granitoids and the origin of their parent magmas.

The combined use of initial $^{87}Sr/^{86}Sr$ ratios and initial Pb isotopic compositions (estimated from feldspar Pb analyses) is a powerful petrogenetic tool, capable of distinguishing among granites which have been derived by reworking of older continental crustal material, including the distinction between upper and lower crustal sources, and those which represent juvenile additions of material to the continental crust, derived from sources in the mantle or from subducted basaltic rocks.

Sr ISOTOPIC EVOLUTION Rb-Sr analytical data for the samples of the granitic rocks are listed in table 1 and plotted in figures 2, 3, and 4. The isochron for the Morro Azul Granite (four points) forms as well defined linear array with a slope corresponding to 523 ± 27 Ma with a $^{87}Sr/^{86}Sr$ initial ratios of 0.7113 ± 0.0006 (Fig. 2). The Rb-Sr data for the Itu Granite indicated an age of 590 ± 10 Ma with an initial ratio of 0.7066 ± 0.0004 (Fig. 3). The Rb-Sr analytical for the Nazaré Paulista Granite define an isochron line with age of 790 ± 32 Ma and initial $^{87}Sr/^{86}Sr$ ratio of 0.7132 ± 0.0005 (Fig. 4).

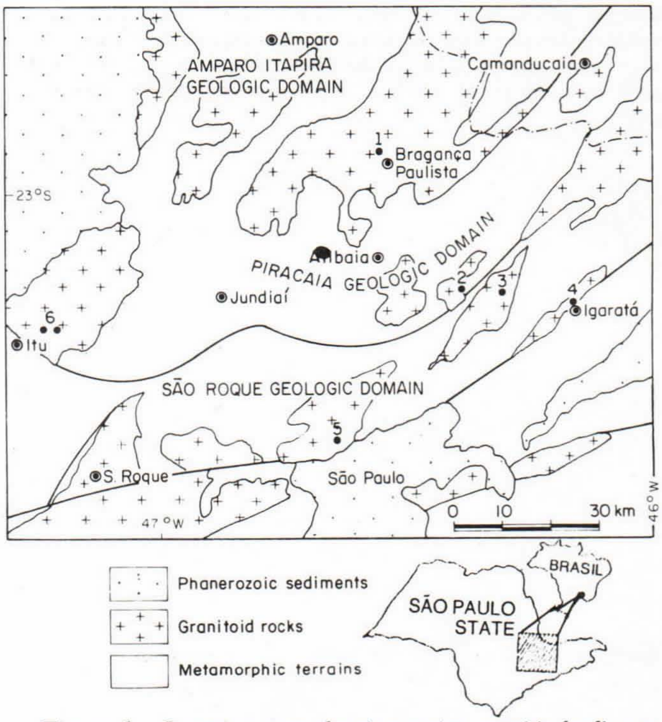

Figure 1 – Location map showing major granitic bodies and samples studied (after Machado Filho et. al. 1983 modified)

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The Rb-Sr whole-rock isochron results indicate that granitic activity in the region of São Paulo took place over a time interval spanning at least 250 Ma, from 790 to 530 Ma. However, the Pb/Pb whole rock isochron data for the Moinho intrusion (1,225 $\pm$ 350 Ma; Fig. 5), although rather imprecise, suggest an even longer time span for the granitic activity.

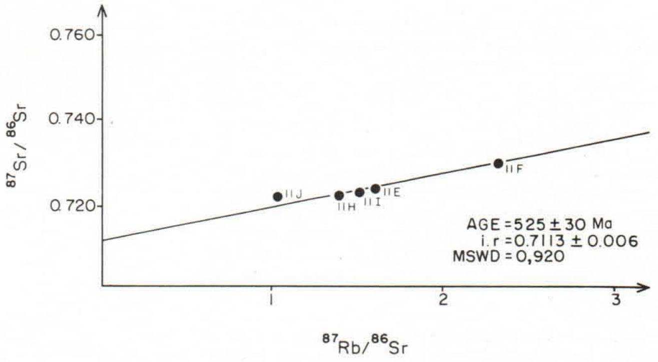

Figure 2 – Rb-Sr isochron diagram for Morro Azul granitoids

Initial $^{87}Sr/^{86}Sr$ ratios for the granites studied range from 0.7066 $\pm$ 0.0004 (Itu) up to 0.7132 $\pm$ 0.0005 (Nazaré Paulista). The initial ratio of the Morro Azul, Bragança Paulista, and Cantareira granitoids (Tassinari in prep.) fall inside the range stated above. Thus, it is clear that all the analised granites have initial ratios plotting well above any estimates of Sr isotope evolution curves for the bulk earth, undepleted mantle sources, strongly implying major contributions to their parent magmas from continental crustal sources. Figure 6 is a Sr isotope evolution diagram illustrating the evolution of the São Paulo granitoids in relation to the evolution model proposed for the upper mantle by Peterman (1979) and for the bulk earth. The crustal growth lines are based on average $^{87}Sr/^{86}Sr$ ratios for individual granitic bodies.

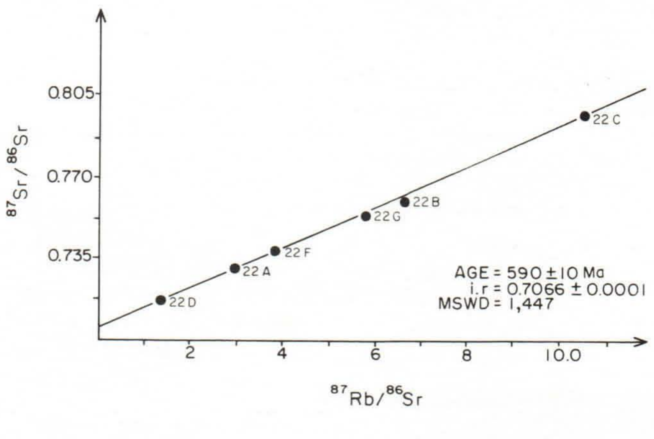

Figure 3 – Rb-Sr isochron diagram for Itu granitoids

The $^{87}Sr/^{86}Sr$ evolution line for Bragança Paulista and Cantareira granites extrapolates back to an intersection with the bulk earth evolution line at ca 1,6 Ga. This date may be taken as a minimum age for the crustal source of those granitoids, since the processes of anatexis would usually increase the Rb/Sr ratio of a melt relative to its source material.

Pb ISOTOPIC EVOLUTION The internal geochemical differentiation of the continental crust produces lower continental crust depleted in U and Th with U/Pb ratio much lower than the upper mantle, and upper continental crust with U and Th enriched relative to Pb. The upper mantle presents lower concentrations of U, Th, and Pb than crustal reservoirs, but its U/Pb ratio lies between those of the upper and lower continental crust. Keeping this difference in mind, the plumbotectonics model of Doe & Zartman (1979) and Zartman & Doe (1981) provides useful information about the magmatic sources of the granitic rocks.

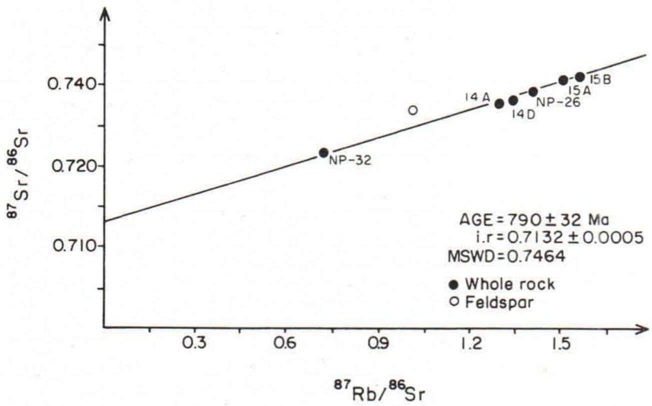

Figure 4 – Rb-Sr isochron diagram for Nazaré Paulista granitoids

Pb isotopic compositions of feldspars from the São Paulo granitoids (Tab. 2) are plotted in the $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagrams (Figs. 7 and 8). Pb isotope evolution, taken from the *Plumbotectonics model,* for average upper continental crust (U), lower continental crust (L), upper mantle (M), and orogene (O) are also shown. Tick-marks on the isotopic evolution curves are placed at 400 Ma intervals, and all curves terminate at the compositions predicted by the model for the present day. The plumbotectonics evolution curve for the orogene is an attempt to model the interaction between the major long-lived reservoirs of U, Th, and Pb, namely the upper mantle and the upper and lower continental crust. The orogenic environment

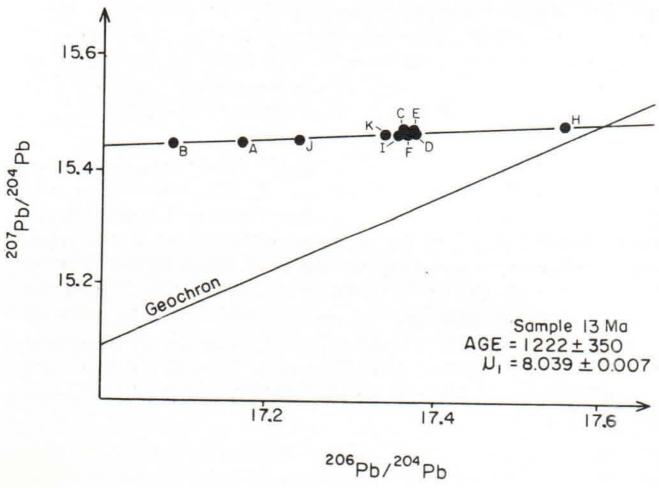

Figure 5 – Pb/Pb isochronic diagram for the Moinho granitoids

is the place where occurs the new crust generation, in plate tectonic terms, at subduction zones.

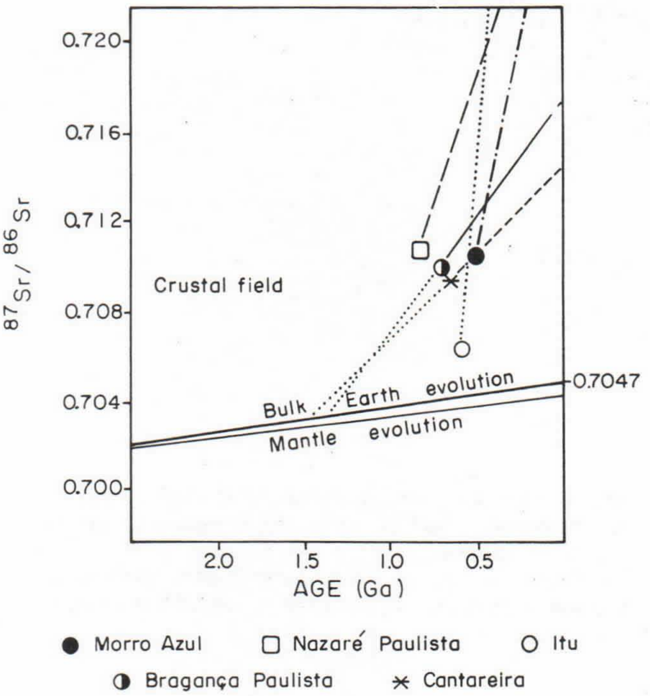

Figure 6 – Sr isotopic evolution diagram

Table 1 – Rb-Sr analyses in whole rock

Granitoid	Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Rb$	$^{87}Sr/^{86}Sr$
Nazaré P.	NP26B	212.9	435.6	1.418	0.7294
Nazaré P.	NP32	108.6	434.8	0.724	0.7215
Nazaré P.	14A	143.0	318.1	1.304	0.7275
Nazaré P.	15A	139.9	265.9	1.526	0.7309
Nazaré P.	15B	147.7	272.8	1.571	0.7310
Nazaré P.	14D	131.6	284.0	1.344	0.7280
M. Azul	11E	168.4	305.5	1.598	0.7235
M. Azul	11F	245.1	302.4	2.351	0.7288
M. Azul	11H	165.3	342.3	1.400	0.7215
M. Azul	11I	142.5	265.8	1.554	0.7228
M. Azul	11J	165.7	469.9	1.022	0.7213
Itu	22A	111.2	108.1	2.984	0.7310
Itu	22B	109.8	47.7	6.696	0.7601
Itu	22D	107.0	232.8	1.322	0.7179
Itu	22F	129.0	97.1	3.857	0.7399
Itu	22G	188.1	112.1	4.875	0.7474
Itu	22C	104.6	29.0	10.540	0.7967

* The Rb-Sr isochronic ages have been calculated using a decay constant of Rb = $1{,}42 \times 10^{-11}$ yr^{-1}

In figure 7 ($^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$), it is evident that the feldspars Pb analyses plot on or below the orogene curve at compositions corresponding to model ages between ca 1,200 Ma (Moinho Granitoid) and ca 800 Ma (Nazaré Paulista and Bragança Paulista granitoids). The Morro Azul and Cantareira bodies are the two intrusions which plot most clearly below the orogene curve. The Nazaré Paulista feldspar has the highest $^{207}Pb/^{204}Pb$ ratio of any of the granitoids analysed in this study, and the data plot towards the upper crust curve.

Table 2 – Pb-isotopic analyses of feldspars and whole rock

Granitoid	Sample	Mat.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Cantareira	1C	Flsp	17.454	15.555	37.492
Morro Azul	11D	Flsp	17.353	15.502	37.466
Morro Azul	11.2	Flsp	17.154	15.506	37.308
Moinho	13K	Flsp	16.915	15.486	37.089
Moinho	13.2	Flsp	17.146	15.521	37.339
Nazaré Paulista	14.A	Flsp	17.520	15.593	37.542
Bragança Paulista	16.H	Flsp	17.431	15.572	37.428
Bragança Paulista	17.A	Flsp	17.456	15.572	37.441
Moinho	13.A	WR	17.205	15.499	37.714
Moinho	13.B	WR	17.121	15.497	37.821
Moinho	13.C	WR	17.405	15.516	37.694
Moinho	13.D	WR	17.407	15.512	37.851
Moinho	13.E	WR	17.406	15.516	37.801
Moinho	13.F	WR	17.398	15.519	38.174
Moinho	13.H	WR	17.592	15.534	37.898
Moinho	13.I	WR	17.396	15.515	37.904
Moinho	13.J	WR	17.274	15.503	37.708
Moinho	13.K	WR	17.378	15.516	37.672

In figure 8 ($^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) all the feldspars plot above the orogene curve, again between the ca 1,200 Ma and the 800 Ma marks. These model age indications, however, should not be regarded as definitive geochronological constraints: they are reported principally to demonstrate reasonable agreement with other age constraints and may thus help to authenticate the petrogenetic interpretation which follows.

In figure 7 the interpretation of data lying below the orogene is ambiguous, allowing either upper mantle or lower continental crust as a source of some of the Pb in the São Paulo granitoids. On the other hand, figure 8 shows no ambiguity and identifies the lower continental crust as a significant source of the Pb in these granites. For the Nazaré Paulista granite the observations in figure 7 suggest that the contribution from lower crustal sources was substantially less than for other granitoids considered in this study.

ADDITIONAL INFORMATION RELATING TO THE GRANITOIDS Usually these granites exhibit batholithic sizes and tectonic contacts with the surrounding metamorphic assemblages.

Petrological and structural studies on these granites are already available in the literature (Hasui *et al.* 1978, Wernick 1982, 1984, Carneiro 1983, Campos Neto *et al.* 1983, 1984, Janasi & Ulbrich 1985).

The mineralogical compositions and the main petrographic types found in the massifs are summarized as follow:

- *Bragança Paulista:* Microcline, plagioclase, biotite, hornblende, zircon, apatite and quartz (granodiorites, quartz-diorites, and 3B-granites).
- *Nazaré Paulista:* Microcline, quartz, oligoclase garnet, muscovite, biotite, zircon, apatite, and opaques (3A and 3B granites).
- *Moinho:* Microcline, oligoclase, plagioclase, quartz, biotite, and opaques (granodiorites).
- *Morro Azul:* Quartz, microcline, oligoclase, andesine, and biotite (diorites up to granites, but granodiorites are predominant).
- *Cantareira:* Microcline megacristals, quartz, plagioclase, biotite, and opaques (granodiorites).
- *Itu:* Microcline, oligoclase, quartz, biotite, turmaline, garnet, and topaz (granite).

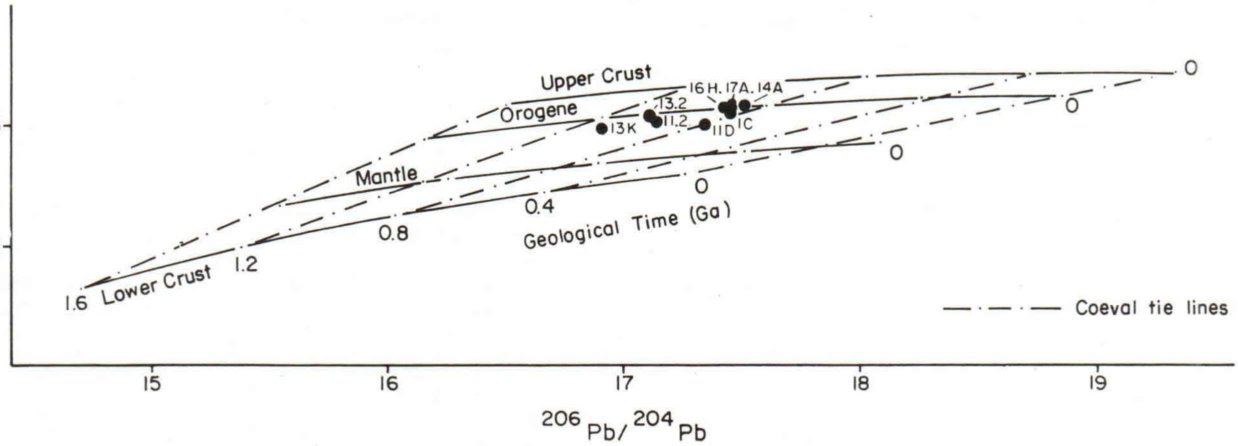

Figure 7 – Plumbotectonics constraints on the origins of granitoids

EXPERIMENTAL PROCEDURES Rb and Sr concentrations were determined by X-Ray fluorescence and separations were made using ion exchange methods described in Kawashita (1972). Sr samples were loaded onto Ta monofilaments for mass spectrometry, and the Sr isotopic analyses were made on VarianMat TH-5 mass spectrometer. The measured $^{87}Sr/^{86}Sr$ ratios have been normalized to $^{86}Sr/^{88}Sr = 0.1194$.

Feldspars were extracted using Frantz eletromagnetic separation, heavy liquids, and hand picking. Pb was extracted

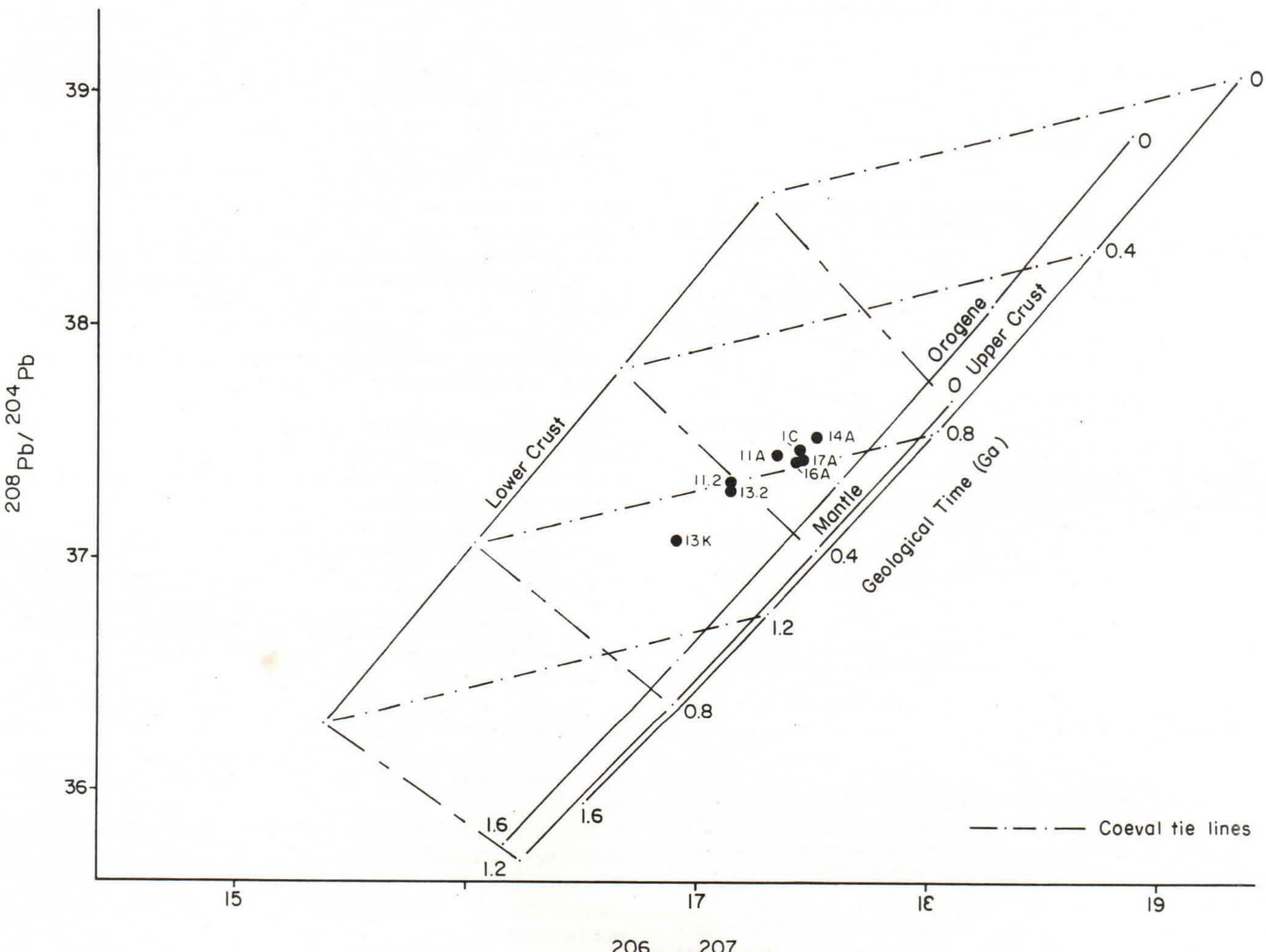

Figure 8 – Plumbotectonics constraints on the origins of granitoids

by the double electrodeposition method of Arden & Gale (1974) and in some samples ion exchange methods. Pb samples were loaded onto Re filaments for mass spectrometry. All Pb isotopic measurements were run on a fully automated VG-Isomass 54E mass spectrometer. The Pb isotope ratios were corrected for mass fractionation using a factor of – 0.114% a.m.u. determined on NBS 981 standard.

CONCLUSIONS The main conclusions concerning the petrogenesis of the individual granitoid intrusions can be summarized as follow:

1. The isotopic composition of Pb in the Bragança Paulista feldspars suggests a major contribution from ancient lower crust to the parent magma, and the Sr isotope evolution line for this granitoid indicates ca 1,600 Ma as a minimum age for the crustal source.

2. In figure 6, the extrapolated Nazaré Paulista Sr isotope evolution line has a lower intersection age on the bulk earth evolution line at ca 1,200 Ma. This date may be taken as a minimum age for the crustal source. The combined evidence of Rb-Sr and Pb isotopic data suggests that the Nazaré Paulista intrusion is derived by partial melting of upper continental crust. This conclusion is consistent with field observations – it is a garnet-bearing granitoid, emplaced into metassediments – and its includes numerous metassedimentary xenoliths, many in an advanced stage of digestion. In this regard it differs markedly from Bragança Paulista, in which the xenoliths are mainly deformed mafic rocks. Consequently an upper crustal source for much of the Nazaré Paulista parent magma is indicated.

3. For the Moinho Granitoid, both the Pb/Pb whole-rock isochron and the plumbotectonics $^{207}Pb/^{206}Pb$ model age of the least radiogenic feldspar Pb imply a formation age of ca 1,200 ma. (However, this date is not well constrained). A significant ancient lower crustal contribution is again indicated by the feldspar Pb data in figure 8.

4. Morro Azul has a very steep Sr isotope evolution line, which extrapolates back to intersect the bulk earth evolution line at a date only slightly older than the granitoid itself (ca 650 Ma) to set the minimum age of the source of the parent magma. However, feldspar Pb data for this granitoid clearly require a significant contribution from ancient lower crustal sources. Thus, an origin predominantly by deep crustal reworking is indicated notwithstanding the poorly constrained initial $^{87}Sr/^{86}Sr$ ratio for this intrusion.

5. The Cantareira granitoid is dated at 640 $\pm$ 8 Ma by the U-Pb method on zircons (Tassinari & Van Schmus, in prep.). The feldspar Pb isotopic composition for this intrusion suggests a significant contribution from the lower continental crust.

6. For the Itu intrusion there are no Pb isotope data available yet, but its initial $^{87}Sr/^{86}Sr$ ratio of 0.7066 $\pm$ 0.0004 is consistent with an origin similar to most of the other São Paulo granitoids discussed above, *i.e.* derivation substantially from lower crustal sources. We therefore conclude that this area of granitic activity in the vicinity of the city of São Paulo represents the site of major deep crustal reworking during the upper proterozoic.

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