PENECONTEMPORANEOUS SYENITIC-PHONOLITIC AND BASIC-ULTRABASIC-CARBONATITIC ROCKS AT THE POÇOS DE CALDAS ALKALINE MASSIF, SE BRAZIL: GEOLOGIC AND GEOCHRONOLOGIC EVIDENCE

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ABSTRACT The large Poços de Caldas alkaline massif, southheastern Brazil, is constituted mainly by felsic rocks (nepheline syenites, phonolites and subvolcanic tinguaites), associated with volcaniclastic basic-ultrabasic deposits. Critical appraisal of earlier K/Ar, Rb/Sr and microchemical ages (microprobe Th-U-total Pb determinations), combined with geological and paleomagnetic informations, can limit more adequately the age interval for the massif. A critical appraisal of the existing K/Ar data limit the age interval for the felsic rocks between 64 and 83 Ma, with a median value of 77 Ma. Earlier Rb/Sr data for various nepheline syenites result in isochron ages between 89±8 and 83±21 Ma (whole rock), while more recent determinations show 79±7 Ma (internal isochron), with initial ratio of 0.70511±0.00001. Nepheline syenites strongly affected by hydrothermal alteration were dated at 76±2 Ma (Rb/Sr isochron), i.r. 0.7053±0.0002. A phlogopite lamprophyre in the uranium open pit Osamu Utsumi mine yielded phlogopite Ar-Ar ages of 76±1-2 Ma, close to a microprobe Th-U-total Pb age of thorite, 79±3 Ma, found in carbonatite veins associated with lamprophyric-pyroxenitic dikes emplaced within nearby basement gneisses. These geochronologic data, together with geological-structural information and published magnetization directions, indicate that the felsic rocks were emplaced during a short time interval of perhaps 1-2 Ma, during the reverse 33r Campanian magnetization event (dated between 83 and 79.1 Ma). The vocaniclastic basic-ultrabasic deposits were emplaced, at least in part, during the following 33n magnetization event. All basic-ultrabasic occurrences in the district (the Vale do Quartel rocks, phlogopite lamprophyre dike in the open pit, pyroxenitic-carbonatitic dikes) seem to be related, and are in part somewhat younger than the felsic rocks or penecontemporaneous to them, partly accompanying the hydrothermal and mineralization event in the massif.

Keywords: Poços de Caldas, geochronology, hydrothermal alteration, normal-reverse magnetizations.

RESUMO O maciço alcalino Poços de Caldas, SP-MG, sudeste do Brasil, é formado principalmente por rochas félsicas (fonolitos, tinguaitos subvulcânicos e nefelina sienitos), com rochas básicas-ultrabásicas vulcanoclásticas associadas. A avaliação de dados geocronológicos K/Ar, Rb/Sr e, em parte, microquímicos (dados Th-U-Pb total por microssonda), aliados a dados geológicos e paleomagnéticos, permite limitar mais adequadamente o intervalo de idades possível para o maciço. Uma análise crítica dos dados K/Ar existentes apontam para um intervalo entre 64 e 83 Ma para a maioria das rochas félsicas, com valor mediano próximo a 77 Ma. As primeiras datações Rb/Sr para variedades de nefelina sienitos resultaram em isócronas com idades entre 89±8 e 83±21 Ma (rocha total), enquanto medições mais novas e confiáveis indicam 79±7 Ma (isócrona interna), com razão inicial de 0.70511±0.00001. Nefelina sienitos fortemente afetados por alteração hidrotermal foram datados em 76±2 Ma, r.i. 0.7053±0.0002. Diques de flogopita lamprófiro da cava Osamu Utsumi de urânio apresentam idades Ar-Ar em flogopitas próximas a 76±1-2 Ma. Torita presente em veios carbonatíticos encaixados em gnaisses vizinhos do embasamento, associados a diques máfico-ultramáficos lamprofíricos-piroxeníticos, resultam em idades microquímicas Th-U-Pb total de 79±3 Ma. Estas datações, junto com informações geológico-estruturais e direções de magnetização da literatura, sugerem que as rochas félsicas do maciço se colocaram em intervalo de idades reduzido, da ordem de 1 a 2 Ma, durante o evento Campaniano 33r de magnetização reversa (datado entre 83 e 79.1 Ma). Os depósitos vulcanoclásticos máfico-ultramáficos do Vale do Quartel, com magnetização normal, invadiram pelo menos em parte durante o evento 33n. A alteração hidrotermal e mineralizações associadas ocorreram imediatamente após a colocação das rochas félsicas. As ocorrências básicas-ultrabásicas do distrito (Vale do Quartel, lamprófiro na cava, diques piroxeníticos-carbonatíticos) parecem estar relacionadas entre si, e são em parte penecontemporâneos às rochas félsicas, ou as sucedem imediatamente, acompanhando de perto os processos hidrotermais e mineralizadores.

Palavras-chave: Poços de Caldas, geocronologia, alteração hidrotermal, magnetizações normal-reversa.

INTRODUCTION The Poços de Caldas alkaline massif, already known from early studies (e.g., Derby in 1887, Machado in 1888, cf. Ellert 1959), is the largest of many Brazilian alkaline occurrences, which are mostly distributed along the eastern and northeastern rim of the Paraná Basin (e.g., Ulbrich & Gomes 1981, cf. Fig. 1). The massif was mapped by Ellert, Björnberg and Coutinho (cf. map in Ellert 1959), by geologists of the Brazilian uranium agencies Nuclebrás and CNEN (e.g., Utsumi *et al.* 1971) and as part of the research programs of the University of São Paulo (e.g., Ulbrich & Ulbrich 1992, Fig. 2). Although the literature about the massif is rather abundant, many questions are still unanswered, especially those referring to petrogenesis and age of emplacement of the different magmatic rocks.

PETROGRAPHIC COMPOSITION OF THE PREDOMINANT ROCKS The massif is mainly composed by felsic rock types, with K-feldspar, nepheline and sodic pyroxene (to aegirine) as main minerals, associated with a wide variety of accessory phases. The main rocks are fine-grained to aphanitic dark greyish-green tinguaites (subvolcanic phonolites), together with violet-greyish partly amygdaloidal phonolites. Several bodies of nepheline syenites are observed as independent intrusions within tinguaites, usually showing medium- to coarse-grained textures, in strong contrast to the texture of their host rocks. The nepheline syenites are divided into agpaitic and intermediate-miaskitic varieties, on account of the presence (or absence) of typical "agpaitic" minerals, especially eudyalite, which in some syenites is a rock-forming phase. Over 25 different nepheline syenites facies can be

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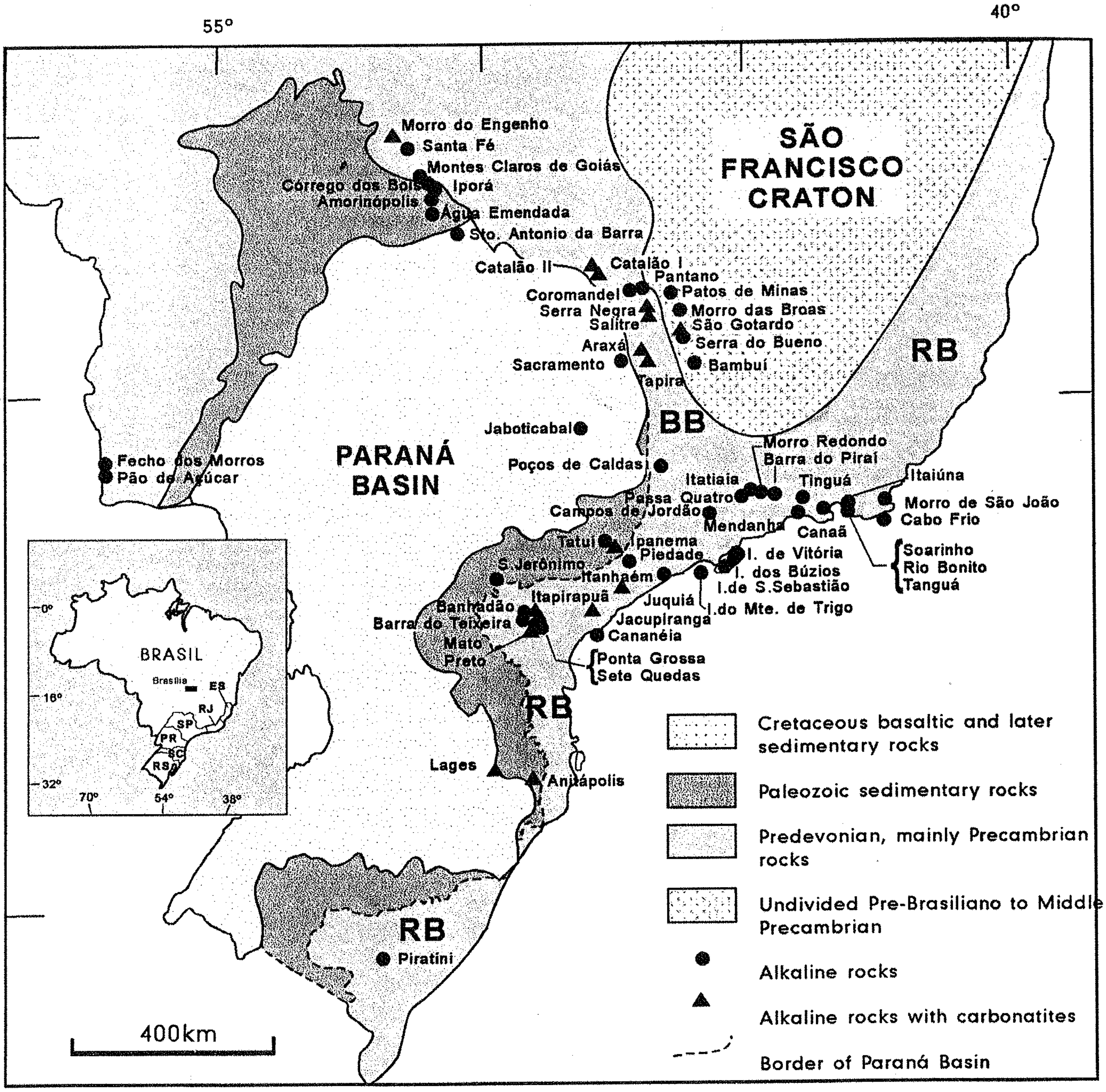

Fig. 1 - Alkaline occurrences in southern Brazil (Ulbrich & Gomes 1981).

recognized, based on differences in mineral content, grain size, color index and textural-structural features. The conspicuous Vale do Quartel is a large N-S trending curved strip of volcaniclastic basic-ultrabasic rocks (breccias, tuffs, agglomerates; some remnants of lava flows), flanked on both sides mostly by erosion-resistant tinguaites. Quartz arenites, showing large cross-stratification of eolian origin and attributed to the Botucatu Formation, are observed especially in the NW and SW quarters of the district (Ellert 1959, Bjoernberg 1959, Ulbrich & Ulbrich 1992, Fig. 2).

A late hydrothermal alteration is responsible for the district's mineralizations, in some cases strongly enhanced by supergene enrichment (e.g., zircon and caldasite occurrences, the U-Zr-Mo ore bodies of the Campo Agostinho and the open pit Osamu Utsumi uranium mine). It may also be, in part, responsible for the Th-REE Morro do Ferro supergene deposit, since this occurrence is positioned within hydrothermally altered rocks.

The *main point* to be discussed in this paper is the existence of approximately coeval intermediate and basic-ultrabasic-carbonatitic magmatisms in the district. All known radiometric ages are also tested, against structural, petrographic and geologic observations. Error estimates and numerical spread of ages, as reported in the literature, are usually of the order of several Ma or even tens of Ma, and may be in strong contradiction with these observations. Of course, the ages themselves

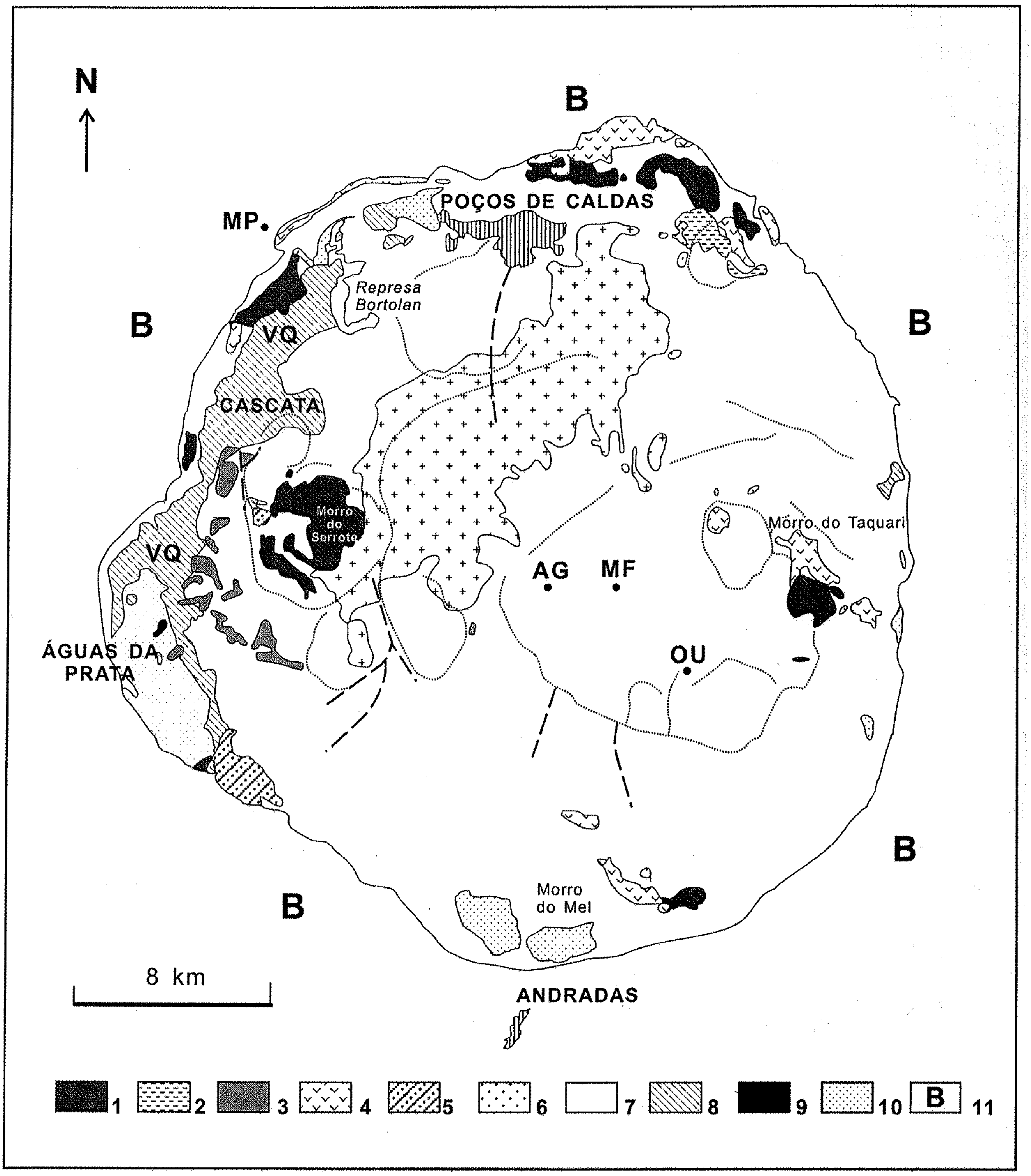

Fig. 2 - Geologic and structural outline of the Poços de Caldas alkaline massif. 1. Agpaitic nepheline syenites (NeS); 2. NeS with pseudoleucites; 3. Porpyritic NeS; 4. Grey NeS; 5. Biotite-bearing NeS; 6. NeS, Pedreira facies; 7. Tinguaites and phonolites, undifferentiated; 8. Volcaniclastic deposits (to the W, the Vale do Quartel strip); 9. Diabase; 10. Sandstones and related sediments; 11. B, undifferentiated basement. AG: Campo do Agostinho; MF: Morro do Ferro; MP: Minas Pedras quarry; OU: Osamu Utsumi uranium mine; VQ: Vale do Quartel. Faults as thicker traces, "circular structures" as dotted lines. Simplified geology, after Ulbrich & Ulbrich (1992).

can be critically examined. Another argument is to place the accepted ages in confrontation with data on magnetic polarity reversals.

STRUCTURAL OUTLINE OF THE MASSIF The topographic and lithologic features, showing prominent tinguaite ridges, suggest that the massif represents the upper part of a caldera-like structure, with early appearance of tinguaites as ring dikes, followed by collapse and the intrusion of the inner tinguaites and some outpouring of phonolites, culminating with the late intrusion of most nepheline syenites (Ellert, 1959).

More recent studies (cf. summary in Ulbrich & Ulbrich 1992) in general confirm these interpretations. Nepheline syenites, in particular, are almost always later rocks, invading as several independent batches of alkaline magmas and crystallizing within the tinguaite envelope. Geologic observations show that the miaskitic-intermediate nepheline syenites are somewhat older than the more evolved agpaitic varieties. Many elongated nepheline syenite bodies are confined to the rim areas, a preferred site for the intrusion of these magmas and an indirect evidence for the existence of "ring structures"; the northern-rim fluorite-bearing grey nepheline syenite is clearly an incomplete ring dike (Fig. 2).

Some "circular" structures within the district (Paradella & Almeida F° 1976) are, in part, the topographic expression of subvolcanic domes (Ulbrich & Ulbrich 1992). In some instances, they were the preferred site for the location of hydrothermal alteration, such as the large circular structure limiting an area of over 100 Km^2, which contains the Campo do Agostinho and Osamu Utsumi ore bodies and the supergene Th-REE mineralization at Morro do Ferro (Fig. 2).

INTERVAL OF INTRUSIONS Structures reminiscent of commingling features, found as cm- to dm-sized ovoidal to somewhat irregular tinguaitic enclaves within nepheline syenites, are observed in several outcrops, especially in quarries and road cuts along the borders of the Pedreira nepheline syenite facies (Fig. 2).

Commingling features, as explained in the literature on granites and associated rocks (e.g., Didier & Barborin 1991), are usually taken as indicative of the coexistence of different magmas. Therefore, at least some nepheline syenites invaded at a time when their tinguaite hosts were still in a partly liquid state, or at least still very hot, suggesting a rapid sequence of intrusive events.

DEPTH OF CRYSTALLIZATION The Poços de Caldas tinguaites crystallized at shallow depths at the NE border of the large Paraná Basin under a cover of quartz arenites of the Botucatu Formation, which were previously intruded by diabase dikes and sills of the basaltic Serra Geral Formation (Ellert 1959, Ulbrich & Ulbrich 1992). The tinguaites invaded as mostly liquid magmas, since their textures are indicative of rapid cooling or even chilling: they are mostly aphyric and aphanitic or very fine-grained, a texture acquired by crystallization against the much cooler, more permeable and fractured cover sandstones. The *liquidus* temperatures for phonolite magmas, ranging from >870°C at 1 Kb H_2O pressure to 1130°C at 1 atm H_2O pressure (Sood 1981), are therefore representative of the intrusion temperatures of the tinguaites.

The Poços de Caldas nepheline syenites crystallized more or less at the same depth of intrusion of most tinguaites, about 3 to 5 Km and a $P(H_2O)$ of about 1 Kb (Ulbrich & Ulbrich 1992). The coarse texture was acquired by slow cooling, with retention of volatiles (as suggested by the presence of volatile-bearing accessory minerals and a widespread deuteric alteration to zeolites and cancrinites), indicating that the host tinguaites were still very hot during the intrusion of the nepheline syenite magmas. The extremely agpaitic lujavrites show a large liquidus-solidus interval, between 870 and 425°C at 1 Kb $P(H_2O)$ (around 855 and 625°C for the miaskitic varieties; Sood 1981; see also geothermometric data in Ulbrich 1993). The observed contacts of the several nepheline syenite bodies, against tinguaites, are always sharp.

THE POÇOS DE CALDAS BASIC-ULTRABASIC OCCURRENCES The most abundant basic-ultrabasic rocks are found as rounded blocks, in the agglomerates, breccias and tuffs in the elongated Vale do Quartel (Fig. 2). The described rocks are of various types (Ellert 1959, Ulbrich & Ulbrich 1992), including some rather rare fragments of the "porphyritic" facies of nepheline syenite, which appears as several small bodies within the tinguaites flanking the Vale do Quartel (Fig. 2). A few horizontal lava flows are also recognized as more uniform dm- to m-thick horizons, probably representing fragments of earlier flows disrupted by the general fragmentation episode (cf. Garda 1990, Ulbrich & Ulbrich 1992). Some of the pyroxene-bearing phenocrystic rocks were classified as ankaratrites (Ellert 1959, Ulbrich & Ulbrich 1992). Thompson *et al.* (1998) also refer to blocks of feldspar-free pyroxene leucitites. These volcaniclastic rocks are, at least in part, airfall deposits (Ellert 1959, own observations).

Geologic observations clearly indicate that all larger volcanic events, the world over, are simultaneously accompanied by the intrusion of shallow and deeper-seated plutonic bodies: the history of such an extrusive-intrusive igneous event may in fact be the sum-total of hundreds, if not thousands, of short-lived individual episodes.

How do the Vale do Quartel rocks fit into this general framework? The explanation, in earlier publications, was that these rocks are the preserved remnants of the initial volcanism that represent, together with the amygdaloidal phonolites, a part of the old volcanic superstructure of the Poços de Caldas "volcano" (Ellert 1959, Ulbrich & Ulbrich 1992). This interpretation can no longer be totally accepted, on account of the following aspects: a) the phonolites can be interpreted as the extrusive counterparts of the intrusive Poços de Caldas tinguaites and nepheline syenites, but no intrusive equivalents to the basic-ultrabasic volcaniclastic Vale do Quartel types are found, at the present level of erosion, in the district; b) the Vale do Quartel is the topographic expression of an easily eroded, structurally weak zone within the district; c) the "porpyritic nepheline syenite" is found as (rather rare) fragments in the agglomerates.

The best explanation is that the Vale do Quartel deposits represent, at least in part, the product of younger pyroclastic events, combined with the surface eruption of lavas. Therefore, at *least* part of the volcaniclastic Vale do Quartel rocks are somewhat younger than the surrounding tinguaites.

Ultramafic rocks are also observed in the Osamu Utsumi open pit as inclined and altered lamprophyre dikes (thickness between a few dm and 1-2 m) with rather fresh dark mica phenocrysts. The rocks show an altered matrix with a pale to moderate lilac color. A single fresh dike of a phlogopite lamprophyre is observed, with mica phenocrysts in a dark-greenish groundmass (Garda 1990, Ulbrich & Ulbrich 1992, Schorscher *et al.* 1991). A "carbonate-apatite lamprophyre" was recovered from a bore-hole (Schorscher *et al.* 1991, Waber *et al.* 1992). The lamprophyres are somewhat older (e.g., the altered dikes) or clearly younger than the hydrothermal event (the fresh dike); for an alternative explanation, see Schorscher & Shea (1992).

Another occurrence of ultramafic rocks was recently found in the Minas Pedras quarry, within regional high-grade gneisses of the Caconde Complex (Fig. 2). Several fresh silico-carbonatitic rocks of alnöitic affinity (dikes, veins, breccias, a meter-sized plug) are associated with late veins of hydrothermal origin, the last ones showing assemblages constituted by carbonate, phlogopite, apatite, fluorite and aegirine. The presence of a composite ultramafic dike with enclaves of angular cm-sized tinguaite fragments, each with a thin alteration rim, shows that the tinguaites were older than the ultrabasic occurrences; at the very most, both magmas may have coexisted, the tinguaites being chilled by the invasion of the cooler, volatile-rich, ultrabasic dikes (Vlach *et al.* 1996, 1998, Ulbrich *et al.* 1998).

The various basic-ultrabasic rocks found in the Vale do Quartel and in the Osamu Utsumi open pit were loosely identified as ankaratrites, kamafugites, lamproites and ultramafic lamprophyres (Ellert 1959, Schorscher *et al.* 1991, Waber *et al.* 1992, Shea 1992, Thompson *et al.* 1998, Vlach *et al.* 1998, Ulbrich *et al.* 1998).

A few of the already mentioned commingled enclaves of tinguaites, found in the contact area of the Pedreira nepheline syenites, have inclusions of mm-sized irregular pyroxenitic inclusions, with salitic pyroxene as main mineral: hence, these pyroxenitic "enclaves within enclaves" were older than, or perhaps even contemporaneous with, the host tinguaite.

These geologic observations show that alkaline basic to ultrabasic magmas coexisted, and in part outlasted, the intrusion of the phonolitic-syenitic Poços de Caldas magmas. The presence in this massif of minor amounts of carbonatitic rocks is documented by their coexistence with ultrabasic types at the Minas Pedras occurrence. The point about the existence of carbonatites in the district was already made by the interpretation of Schorscher & Shea (1992) as an explanation for the Th-REE concentration and the presence of magnetite dikes at the Morro do Ferro (Fig. 2).

HYDROTHERMAL AND DEUTERIC ALTERATIONS

Most rocks in the district present some type of high-temperature deuteric alteration (felsic minerals partly substituted by cancrinite, zeolites, etc.; growth of late aegirine; presence of fluorite, etc.). The product of hydrothermal alteration, on the other hand, is a highly fractured, buff-grey to beige-colored rock, locally known as "potassic rock" (*rocha potássica*) on account of its high K_2O content (for details on mineralogy and chemistry of alteration, cf. Garda 1990, Waber 1992, Waber et al. 1992). The presence of hot springs in Poços de Caldas indicates that low-temperature alteration is still going on at depth, probably controlled by the larger than average geothermal gradient in this U-Th-K- bearing district. The bauxites and laterite soils formed at the expense of fresh felsic rocks, on the other hand, are conspicuously different from the hydrothermally altered rocks (for details, cf. Schulmann *et al.* 1997).

The proposed model for the hydrothermal alteration and mineralization events is based on the processes envisaged for porphyry copper deposits in granites, a result of both physical and chemical interactions: shattering of country rocks by a second boiling mechanism in and above the cupolas of crystallizing magma chambers, followed by cooling through the circulation of hydrothermal cells, mainly composed of supercritical water-rich solutions (e.g., Burnham 1979, Garda 1990, Ulbrich & Ulbrich 1992, Sawkins 1990). The significant point about this interpretation is that the fracturing episode launching the hydrothermal alteration is one of the finishing subvolcanic events, and therefore intimately linked with the emplacement and cooling of the whole massif: radiometric dating of both the intrusive and hydrothermal events by presently known methods should show overlapping ages.

GEOCHRONOLOGICAL DATA A great number of K-Ar and Rb-Sr data were accumulated in the last 40 years for the Poços de Caldas massif, but the age of the district is still a subject of debate. A more careful discussion of the available figures is therefore appropriate.

The known K-Ar data for the Poços de Caldas rocks are reproduced in Table 1 (cf. also Fig. 3). The ages, with a range from 89.3 to 54.2 Ma, point to an age gap of about 35 Ma for the whole magmatism, far too high to be accepted as a reasonable estimate for the interval of magmatic activity. This large gap is also strongly contradicted by the cited observations on contacts, texture, and structure, all in favor of a much shorter magmatic history.

The K-Ar histogram shows a simple mean of 73.7±8.6 (2σ) Ma and a median of 75.5 Ma (for the entire data set of 40 measurements). A discussion about the possible explanations for the large age variations is necessary. The rather widespread deuteric recrystallization present in the rocks affected feldspars, nephelines and the mafic minerals, clearly adding several elements (Na, Zr, Mn, Fe, etc.) and leaching out others, such as Mg, Ca, Sr, etc. (cf. Garda 1990). The typical hydrothermal alteration, on the other hand, added H_2O and K to the rocks, and leached out mainly Ca and Mg. The two processes enhance the loss of radiogenic Ar, so that both whole-rock and K-feldspar ages may turn out to be younger than expected. Most of the older ages (>85 Ma; Table 1) also have to be rejected, since they come from samples with low K contents or with high atmospheric ^{40}Ar, or both, including the measurements on the "amphibole" (?) fractions; the only exception is the JB-PC 10 ankaratrite, with an apparently "good" age of 89.3 Ma. Two biotites from nepheline syenites, with measured K_2O contents equivalent to those of fresh biotites, yield apparently "good" ages of about 82.5 Ma, somewhat higher than the other "acceptable" K-Ar dates. It is difficult to evaluate these 3 older ages (instrumental conditions?); no error indications are given (Table 1).

Based on these observations, a reduced set with 22 samples is selected, by exclusion of the data obtained from K-feldspars and "amphiboles", and also of those with high atmospheric ^{40}Ar (Table 1, Fig. 3). This set shows a mean of 75.6±6.8 (2σ) Ma and a median at 76.6 Ma.

The above treatment of the known K-Ar ages suggests that the Poços de Caldas magmatism took place between ~64 to ~83 Ma, a narrower range than the 89.3 to 54.2 Ma interval. Thompson *et al* (1998) and Thomaz Filho & Rodrigues (1999)

Table 1 - K-Ar ages of rocks from the Poços de Caldas massif

	Sample Nr.	Rock type	Mineral/WR	% K_2O	^{40}Ar atm (%)	Age Ma (error)	Ref
1	JB PC 12	W rim NeS	Biotite	9.43	15.3	82.3	1
2	KA 1832	W rim NeS	Biotite	9.37	20.3	82.7	2
3	JB PC 38	Tinguaite	WR	8.69	37.5	76.9	1*
4	JB PC 38	Tinguaite	WR	8.69	34.5	75.0	1*
5	JB PC 24	Tinguaite	WR	7.93	13.1	78.2	1
6	Berk6241	Tinguaite	WR	8.65	11.1	65.4 (1.6)	1
7	UC624 1	Tinguaite	WR	8.56	6.4	64.3	1
8	UC6241a	Tinguaite	WR	8.53	7.6	66.0	1
9	JB PC 10	Ankaratr.	WR	5.14	15.1	89.3	2
10	JB PC 17	Ankaratr.	WR	5.17	7.9	78.4	2
11	JB PC 28	Phonolite	WR	7.75	19.70	77.1	2
12	JB PC 29	Phonolite	WR	6.10	19.4	77.5	2
13	JB PC 36	N rim ting	WR	6.55	9.0	82.0	2
14	JB PC 31	S tinguaite	WR	7.74	10.6	82.4	2
15	KA1821	S tinguaite	WR	8.35	24.3	82.9	2*
16	KA1820	Tinguaite	WR	8.26	15.6	76.0	2
17	JA1820R	Tinguaite	WR	8.26	7.3	75.7	2
18	JB PC 5	Tinguaite	WR	8.42	20.0	74.9	2
19	JB PC 53	N rim ting	WR	8.46	7.0	71.1	2
20	JB PC 44	N rim ting	WR	8.47	5.0	74.5	2
21	JB PC 48	N rim ting	WR	8.28	5.4	74.2	2
22	JB PC 51	N rim ting	WR	8.78	6.2	65.4	2
23	KA1822	Pedr. NeS	KF	11.93	15.0	63.6	2*
24	KA1833	Grey NeS	KF	16.39	11.0	61.2	2*
25	KA1833R	Grey NeS	KF	13.39	47.7	61.7	2*
26	KA1829	Lujavrite	KF	15.84	7.8	62.3	2*
27	KA1826	N rim ting	WR	12.09	28.2	54.2	2*
28	VL3.1161	NeS	Pyroxene	0.13	71.5	85.5 (15.1)	3*
29	MZ	Phonolite	WR	7.31	21.57	86.5 (1.2)	3*
30	RAA 414	NeS	Amphibole?	0.70	39.21	75.4 (3.0)	3*
31	RAA 420	NeS	Amphibole?	0.57	74.24	82.5 (6.6)	3*
32	RAA 416	NeS	KF	10.39	6.52	78.2 (1.8)	3*
33	RAA 419	NeS	KF	13.96	7.60	75.5 (1.4)	3*
34	RAA 419	NeS	KF	13.96	15.05	72.4 (1.3)	3*
35	RAA 418	Tinguaite	WR	11.20	5.73	78.0 (1.3)	3
36	RAA 418	Tinguaite	WR	11.20	6.77	81.0 (1.1)	3
37	RAA 417	Tinguaite	WR	7.59	5.73	66.3 (4.0)	3
38	RAA 413	NeS	Amphibole?	1.05	41.38	66.2 (2.0)	3*
39	RAA 415	NeS	Amphibole?	0.65	44.07	54.3 (1.7)	3*
40	RAA 415	NeS	KF	11.09	31.13	71.7 (2.5)	3*

NeS: nepheline syenite; WR: whole rock; KF: K feldspar. Asterisks mark the excluded data (cf. text and Fig. 3). The K content of 0.508%, sample JB PC 29, as stated in Sonoki & Garda (1988), should read "K 5.08%". References: (1), Amaral et al. (1967); (2), Bushee (1974); (3) unpublished data, São Paulo Geochronology Center. All ages converted to Steiger & Jaeger's newer decay constants (cf. compilation in Sonoki & Garda 1988). W & N rim, S, Pedr., Grey: refer to western & northern rim, southern, Pedreira NeS facies, grey NeS facies (northern rim). Samples 28 to 40: no localization indicated.

made similar evaluations of K-Ar ages. The first authors propose a magmatic interval between 80 and 85 Ma for Poços de Caldas, while the last authors choose 74.6 Ma as the "best mean".

The first Rb-Sr isochron dating of Poços de Caldas nepheline syenites was presented by Kawashita *et al.* (1984), more recently followed by new information (Shea 1992, Table 2). Isochronic ages and initial ratios were here recalculated with the use of the IsoPlot software (Ludwig 1988); all results refer to a 95% confidence level (for original ages, cf. cited references).

An isochron age of 83±21 Ma was calculated for whole-rock data of samples from the lujavrite-khibinite body at the northern rim of the massif (samples 1-5, Table 2), with (^{87}Sr/

$^{86}Sr)_i$ = 0.7052±0.0003, MSWD= 0.52. Whole rock data for samples of the grey and fluorite-bearing nepheline syenites (samples 7-11, Table 2) yield 88.5±8.1 Ma, initial ratio = 0.7054±0.0002, MSWD = 0.44 (data for samples 1-14 obtained by K. Kawashita, Table 2; cf. Kawashita et al. 1984). Both are considered true isochrons, on petrographic-structural grounds and probability of data fit; errors, however, are high. A reference isochron for samples 1-11 gives an age of 86.1±6.5 Ma, initial ratio = 0.7051±0.0002, MSWD= 0.57. All results are equivalent, within error levels.

The determinations cited in Shea (1992) for the Pedreira nepheline syenite facies (samples 15-18, Table 2) give an errorchron with 72(±79!) Ma. An internal isochron for the NS-7 samples (analysis 18-23, Table 2) yields 78.6±6.6 Ma, initial ratio = 0.70511±0.00001, MSWD= 1.3 (own calculations); Shea (1992) reports 77.9±6.2 (2σ) Ma, i.r. 0.70512±0.00002, MSWD= 0.88, calculated with the McIntyre model I regression. The result of 78.6 Ma is considered the best age for the main nepheline syenite magmatism. Data for the hydrothermally altered nepheline syenite from the F4 borehole in the Utsumi open pit mine (samples 24-35, Table 2) result in an age of 75.6±2.2 Ma, initial ratio = 0.7053±0.0002, MSWD= 1.3, and probability of fit value of 21% (own calculations); Shea (1992) cites an age of 75.8±2.4 (2σ) Ma, i.r. 0.7053±0.0002, MSWD= 1.08. The exclusion of samples 32 to 35, not well aligned in the $^{87}Rb/^{86}Sr$ vs. $^{87}Sr/^{86}Sr$ plot, results in a better isochron, with an age of 76.8±2.6 Ma, initial ratio = 0.7053±0.0002, MSWD= 0.49 and probablity of fit of 84% (own calculations, samples 24 to 31). The hydrothermally altered nepheline syenite samples present a large increase in the $^{87}Rb/^{86}Sr$ ratios, when compared with the fresh rocks, a fact that is explained by the increase in K and/or leaching of Sr, determined by the hydrothermal event. Shea (1992) points out that the alteration has completely reset the Rb-Sr system, immediately after magma emplacement and cooling. In fact, the ages identifying crystallization and alteration, based on Shea's data, cannot be separated within a 95% confidence level; the initial ratios of both isochrons are also similar, again

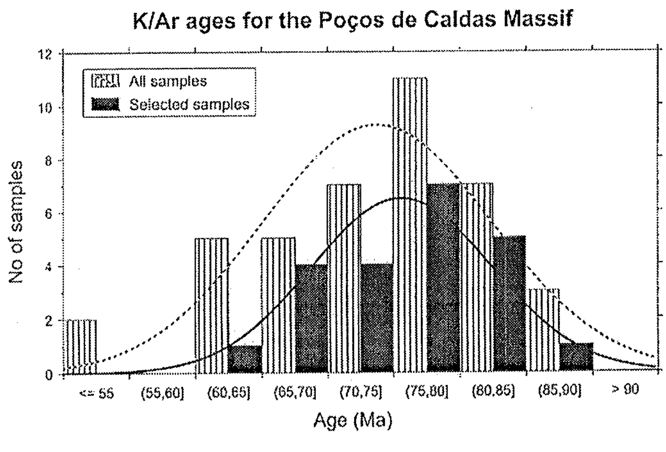

Figure 3 - Histogram of K-Ar ages for Poços de Caldas rocks (Table 1). Mean value for the "all samples" curve (N= 40) is 73.7 (±8.6, 2σ) Ma, that for "selected samples" (N=22) is 75.6 (±6.8, 2σ) Ma. The selected sample set excludes alkali feldspar samples, and the amphibole, pyroxene and whole rock ages with over 20% atmospheric ^{40}Ar content. Data in Sonoki & Garda (1988).

pointing to a very small time interval between emplacement and hydrothermal events.

$^{40}Ar/^{39}Ar$ plateau ages of the phenocrystic and matrix phlogopites of the phlogopite lamprophyre dike in the Osamu Utsumi mine are, respectively, 75.7±0.6 (2s) and 76.2±1.6 (2σ) Ma (Shea 1992). These ages are statistically identical to the isochronic ones of the altered nepheline syenites, indicating that the hydrothermal alteration, the related mineralizations and the emplacement of these basic-ultrabasic dikes were all roughly coeval, at least in the Osamu Utsumi mine (cf. also Shea, 1992).

The dikes occuring at the Minas Pedras quarry were dated with the Th-U-total Pb microprobe dating technique on thorite, an ubiquitous phase found in the Minas Pedras carbonatitic veins. Although most grains are metamictic, some cores are preserved, showing high optical birrefringence and high electron backscattering. The procedures for the thorite dating are similar to the ones developed for monazite, as described in Vlach & Gualda (2000); the instrumental setup was 15 kV, 50 nA and 10 mm for accelerating voltage, beam current and beam diameter. The best Th, U and Pb analytical results for thorite are listed in Table 3. The individual spot ages vary between 82 and 76 (±11 Ma, 95% confidence level), with a weighted mean of 79±3.5 Ma.

The above discussion brackets the eruption of the felsic Poços de Caldas rocks between 75-76 and about 83 Ma. Better geochronologic constraints can only be achieved with more detailed dating. Even so, paleomagnetic data can help to define more closely the ages of the magmatic event.

REVERSE AND NORMAL MAGNETIZATIONS Montes Lauar *et al.* (1995) used paleomagnetic techniques to study several alkaline massifs in southeastern Brazil (Poços de Caldas, Itatiaia, Passa Quatro, Ilha de São Sebastião). Virtual geomagnetic poles and normal or reverse magnetizations were determined in 73 Poços de Caldas samples, mostly tinguaites-phonolites and nepheline syenites, some sandstones, and also samples of the Vale do Quartel basic-ultrabasic lava flows. All Poços de Caldas tinguaites-phonolites and nepheline syenites show reverse polarity, while the three succesfully studied Vale do Quartel samples (out of five that were collected) present normal polarity. The samples, or sampling procedure, of the Vale do Quartel rocks are not clearly described in Montes Lauar et al. (1995, cf. also Montes Lauar 1988). The present topographic level of the Vale do Quartel is the result of the original volcanic-subvolcanic activity and significant vertical movements: e.g., a subsidence of at least 500 m is registered at the northern end of the Valley, where the cover sandstones crop out at 1100-1200 m, in contrast with the altitude of 1400 to over 1600 m at the closeby northern topographic tinguaite rim. It seems probable that the only rocks that still preserve their original attitudes in the Vale do Quartel are the remnants of lava flows found in a horizontal position. With these precautions in mind, the polarity data can now be compared with absolute ages and the time-polarity scale.

The most recent ages on magnetic reversals (Cande & Kent 1994) show that the Late Campanian reverse 33r polarity episode lasted from about 83 Ma to 79.1 Ma, while the following younger 33n normal episode lasted till 73.6 Ma (Fig. 4).

The previously cited K-Ar ages point to a general interval of 76 to 83 (±5-6) Ma for the ages of the Poços de Caldas

Table 2 - Rb-Sr determinations in rocks of the Poços de Caldas massif.

	Samp.	Rock type	Mineral/WR	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ (error)	$^{87}Sr/^{86}Sr$ (error)	$^{87}Sr/^{86}Sr$ init (error)
1	P47	Khibinite	KF	413.3	627.9	1.905 (54)	0.70747 (20)	0.70533 (21)
2	P11	Khibin.^{A}	WR	316.7	965.9	0.949 (27)	0.70641 (42)	0.70535 (42)
3	P 224	Khibinite	WR	323.5	1139.8	0.821 (23)	0.70593 (24)	0.70500 (34)
4	P 215	Khibinite	WR	191.3	1112.8	0.494 (14)	0.70585 (11)	0.70530 (11)
5	P 223	Lujavrite	WR	216.9	2678.2	0.216 (6)	0.70538 (18)	0.70514 (18)
6	P 224	NeS	KF	400.7	557.1	2.084 (59)	0.70786 (32)	0.70552 (33)
7	P220	Grey NeS	WR	576.8	1167.0	1.430 (40)	0.70680 (9)	0.70520 (10)
8	P 525	NeS^B	WR	532.3	424.7	3.628 (103)	0.70958 (9)	0.70551 (15)
9	P 432	Grey NeS	WR	289.5	722.8	1.159 (33)	0.70648 (4)	0.70518 (6)
10	P 176	Grey NeS	WR	617.8	691.0	2.588 (73)	0.70828 (8)	0.70538 (12)
11	P 205	Grey NeS	WR	593.6	1104.7	1.555 (44)	0.70708 (6)	0.70534 (8)
12	P 205	Grey NeS	KF	605.9	735.3	2.385 (67)	0.70813 (6)	0.70545 (10)
13	P 371	NeS^C	WR	173.9	1814.2	0.277 (8)	0.70477 (3)	0.70446 (3)
14	P 384	NeS	WR	152.0	2824.6	0.156 (41)	0.70518 (13)	0.70500 (13)
15	NS 1	NeS	WR	170.0	2130	0.2309	0.705335 (7)	0.705079 (15)*
16	NS 4	NeS	WR	162.0	2902	0.1614	0.705274 (8)	0.705095 (12)*
17	NS 6	NeS	WR	148.8	3263	0.1319	0.705250 (7)	0.705104 (12)*
18	NS 7	NeS	WR	159.5	2865	0.1610	0.705309 (8)	0.705131 (12)*
19	NS 7	NeS	Sphene?	8.88	5038	0.00510	0.705121 (11)	
20	NS 7	NeS	Sphene?	14.13	6242	0.00655	0.705133 (10)	
21	NS 7	NeS	Aegirine	0.648	291.2	0.00644	0.705105 (12)	
22	NS 7	NeS	KF	229.4	2605	0.2547	0.705398 (8)	
23	NS 7	NeS	Nephel.	12.89	186.5	0.2000	0.705326 (12)	
24	1A-A	Alt. NeS	WR	418.3	174.9	6.924	0.712807 (9)	
25	1A-A	Alt. NeS	WR	419.1	171.6	7.071	0.712898 (8)	
26	1A-C	Alt. NeS	WR	419.6	172.7	7.034	0.712889 (9)	
27	1A-E	Alt. NeS	WR	434.3	184.7	6.807	0.712635 (14)	
28	1A-H	Alt. NeS	WR	420.0	168.4	7.222	0.713119 (15)	
29	1A-L	Alt. NeS	WR	435.7	240.6	5.241	0.710941 (11)	
30	1A-N	Alt. NeS	WR	439.6	194.5	6.543	0.712308 (7)	
31	1A-P	Alt. NeS	WR	422.4	204.4	5.983	0.711740 (9)	
32	1AA	Alt. NeS	WR	426.3	205.2	6.013	0.711768 (12)	
33	1AC	Alt. NeS	WR	432.9	229.3	5.464	0.711229 (11)	
34	1AE	Alt. NeS	WR	423.1	203.2	6.027	0.711900 (8)	
35	1AE	Alt. NeS	WR	437.0	209.0	6.051	0.711878 (7)	

For abbreviations, see Table 1. Superscripts: **A,** pegmatoid facies; **B,** fluorite-bearing grey NeS; **C,** numbers 13 to 23 are samples from the Pedreira NeS facies; initial ratios marked with (*) are calculated for an age of 78 Ma (Shea 1992), others with 79 Ma (cf. Conclusions). Samples 24 to 35 are from the F4-413 bore hole core samples. *References*: samples 1 to 14: unpublished data, obtained by K.Kawashita on a VG-54 single-collector mass spectrometer at the University of Pará in Belem (cf. text and Kawashita et al. 1984); 15 to 35: Shea (1992). Lujavrite-khibinite body, northern rim, samples 1 to 5: 83±21 Ma, i.r.= 0.7052±0.0003; northern rim grey NeS, samples 7 to 11: 88.5±8.1 Ma, i.r. 0.7054±0.0002. Hydrothermalized NeS, samples 24 to 32: 75.6±2.23 Ma, i.r. = 0.7053±0.0002. NS-7 NeS, mineral and whole-rock isochron, samples 18 to 23: 78.6±6.6 Ma, i.r. 0.70511±0.00001; ages and errors calculated for 2s intervals with the IsoPlot software.

phonolites, tinguaites and syenites, with a median value of 76.6 Ma, while Rb-Sr as well as Ar-Ar determinations show ages around 76 to 79 Ma. The reverse polarity presented by the felsic intermediate rocks, together with the discussed ages, indicate that their intrusion took place, most probably, during the 33r Campanian polarity event.

The agglomerates and associated volcaniclastic basic-ultrabasic Vale do Quartel rocks are, at least in part, somewhat younger than the surrounding tinguaites, as discussed. Therefore, they either fall towards the end of the 33r Campanian polarity event or, if the normal polarity findings in the Vale do Quartel lavas are meaningful, more properly at the beginning of the 33n event (< 79.1 Ma; cf. Fig. 4).

THE RELATIONSHIP BETWEEN THE SYENITIC-PHONOLITIC MAGMATISM AND THE BASIC-ULTRABASIC ROCKS IN POÇOS DE CALDAS The intrusion periods of the felsic and the basic-ultrabasic rocks at

Table 3 - Th, U, and Pb contents and ages for thorite from carbonatite veins, Minas Pedras quarry, Poços de Caldas.

No.	Spot ID	Th (error)	U (error)	Pb (error)	Spot age (error), Ma
1	C11, cv	65.16(0.47)	0.67(0.04)	0.235(0.034)	79(11)
2	C11, c	65.19(0.48)	0.57(0.04)	0.243(0.034)	82(11)
3	C11, i	64.38(0.47)	0.55(0.03)	0.229(0.034)	78(11)
4	C11,i	64.98(0.47)	0.51(0.04)	0.235(0.034)	79(11)
5	C11, r	65.33(0.48)	0.48(0.04)	0.231(0.033)	78(11)
6	C10, c	67.22(0.49)	0.55(0.04)	0.237(0.034)	77(11)
7	C10, i	65.27(0.48)	0.42(0.04)	0.230(0.034)	77(11)
8	C10, i	64.76(0.47)	0.49(0.04)	0.238(0.034)	80(12)
9	C10,.i	64.97(0.47)	0.65(0.04)	0.233(0.033)	79(11)
10	C15, n	66.19(0.48)	0.43(0.04)	0.244(0.034)	81(11)
11	C15, i	65.85(0.48)	0.45(0.04)	0.243(0.034)	81(11)
12	C15, i	64.71(0.47)	0.47(0.04)	0.223(0.040)	76(12)
12	C15, i	64.71(0.47)	0.47(0.04)	0.223(0.040)	76(12)

Values are given in wt %. Analytical errors (95% confidence level) refer to counting statistics only and were normally propagated to the age results. The weighted mean gives 79.0±3.2 Ma.

Poços de Caldas overlap, as shown especially by the presented geologic and structural arguments. A discussion about the possible genetic relationships between both magmatic events is thus necessary, although much isotopic and geochemical information about the Poços de Caldas rocks is still missing.

The chemical data for the lamprophyre dike in the open pit (Schorscher *et al.* 1991, Waber *et al.* 1992) and for the ultrabasic Minas Pedras dikes (Ulbrich *et al.* 1998) reveal similarities between both: they are potassic or even ultrapotassic, show high contents of Ti and of several incompatible elements, and present a rather low mg number, mostly less than 0.60 (about 0.68 in only two samples). The rocks crystallized, therefore, from evolved liquids of more primitive magmas, since the cited mg values are not within the range expected for primary melts directly derived from mantle protoliths (e.g., Eggler 1989). They are also broadly similar to some of the potassic basic-ultrabasic rocks of the Paranaiba and Serra do Mar provinces (Gibson *et al.* 1996, Thompson *et al.* 1998), although associated carbonatites were not cited in the last occurrences.

Recent petrologic models consider that the source for most continental basic-ultrabasic and also phonolitic magmas are either a relatively enriched subcontinental lithospheric mantle or the convecting mantle, or a mixture of both (e.g., Le Roex & Lanyon 1998, Thompson et al. 1998). The initial $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope ratios, calculated for T = 79 Ma, of the analysed Poços de Caldas ultrabasic dikes are more primitive than those of the Poços de Caldas phonolites and syenites, the respective e parameters varying between $(-0.2) < \varepsilon_{Nd} < (+0.4)$ and $(-1.5)\ \varepsilon_{Sr} < (+3.0)$ for the first rocks (Vlach *et al.* 1998) and between $(-3.0) < \varepsilon_{Nd} < (-4.6)$ and $(+6.5) < \varepsilon_{Sr} < (+11.0)$ for the latter (Shea 1992); only one pyroxenite sample from the Minas Pedras quarry shows a high e_{Sr} of about 16. These values suggest that the ultrabasic magmas came from more primitive, and possibly carbonated, lithospheric mantle sources. A model by Thompson et al. (1998) proposes that the initial impact of the Trindade mantle plume is responsible for the Poços de Caldas magmatism, contributing with OIB-type melts. No unique choice as to the relative importance of all the possible mantle and crustal contributions can be set up with the presented data set. However, it seems that the source rocks for these two contrasted but overlapping intrusive events, responsible for the felsic and basic-ultrabasic rocks, are different; the corresponding liquids cannot be simply related by magmatic differentiation.

The normal depleted mantle model of De Paolo (1988) yields T_{DM} ages within the range of 580-750 Ma for all Poços de Caldas felsic samples, while the analysed basic-ultrabasic rocks always present ages that are younger by about 100-150 Ma. This age interval points to a possible lithospheric mantle enrichment event (in part related to the Brasiliano orogenic cycle?), but could also be explained by the contrasting geochemistry of the mantle sources and/or different degrees of melting (Vlach et al., work in progress).

CONCLUSIONS The present discussion leads to the following conclusions:

1) The entire history of a magmatic event, including hydrothermal alteration and mineralizations, can usually be broadly reconstructed solely from geological and structural observations. Not unfrequently, available geochronologic ages are in contradiction with inferences drawn from these observations.

2) Outcrops within the Poços de Caldas massif and around its perimeter indicate that two different magmatic events took place, one comprising the emplacement of the predominant intermediate undersaturated felsic rocks (tinguaites, phonolites and equivalent syenites), the other characterized by the presence of much smaller amounts of basic to ultrabasic volcanic and dike rocks, in part also accompanied by minor carbonatite occurrences.

3) The ages for the predominant Poços de Caldas intermediate rocks were constrained, by the best published K-Ar geochronology, between ~64 and ~83 Ma. In addition, geologic observations indicate that phonolites, tinguaites and nepheline syenites were emplaced in a continuous and rapid sequence, lasting perhaps not over 1-2 Ma; the error intervals for the cooling ages of all these rocks should overlap. It is suggested

that the Poços de Caldas intermediate magmas were emplaced at an age around 79 Ma, in accordance with a recent Rb-Sr isochron dating of 78.6±6.6 Ma of a nepheline syenite (recalculated from data in Shea 1992, his age: 77.9±6.2 Ma).
4) The Poços de Caldas tinguaites, phonolites and nepheline syenites all show reverse polarization, which places the eruption event most likely within the 33r Campanian geomagnetic polarity event, dated between 83 and 79.1 Ma, as suggested by the discussed ages. There is a minor age discrepancy here, suggesting that the passage of the 33r to the 33n event may have occurred at a slightly younger date than 79.1 Ma (Fig. 4).
5) The basic-ultrabasic volcaniclastic Vale do Quartel rocks, showing little or no biotite, are notoriously difficult to date; they outlasted, at least in part, the emplacement of the Poços de Caldas felsic rocks, as shown by structural relationships and the presence of some nepheline syenite blocks in the agglomerates. The normal magnetic polarity shown by the studied Vale do Quartel basic-ultrabasic lavas is to be expected if the volcaniclastic event is somewhat younger than the flanking tinguaites, erupting at least in part within the 33n Campanian polarity episode (< 79.1 Ma).
6) Petrographic and geologic arguments, together with radiometric dating, constrain the age interval of at least part of the basic-ultrabasic magmatism. The oldest remnants of "alkaline" pyroxenites are found as minute inclusions in tinguaite enclaves, that represent material either older than, or coeval with, the tinguaite (³79.1 Ma). The Vale do Quartel explosive

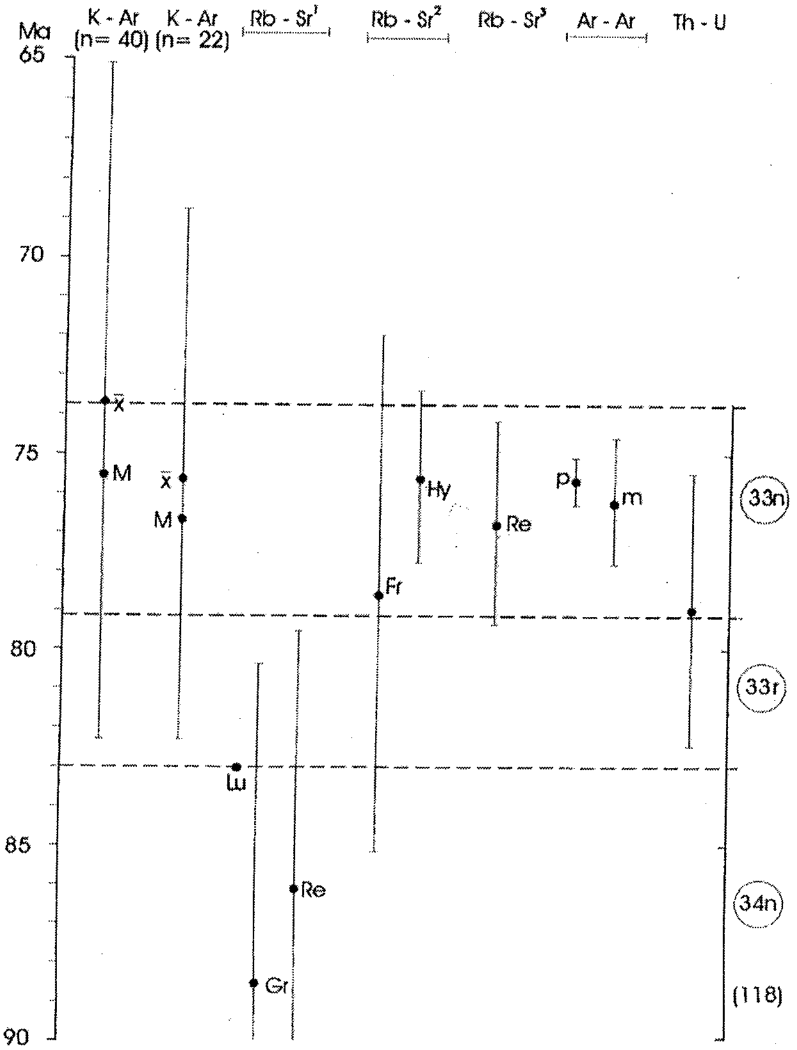

Figure 4 - Magnetic polarity reversals and ages of the Poços de Caldas rocks. 33n interval: 73.6-79.1 Ma; 33r interval: 79.1-83.0 Ma; 34n interval: 83-118 Ma;'x, M: mean and median values for the K-A ages. Rb-Sr^1, Lu, Gr,Re: Rb-Sr isochron ages for the lujavrite-khibinite (Lu) bodies and the northern grey (Gr) nepheline syenites (data in Table 2); Re is a reference age for all data. Rb-Sr^2, Fr, Hy: respectively, fresh and hydrothermally altered nepheline syenites (data in Table 2 from Shea, 1992). Rb-Sr^3, Re: reference isochron (hydrothermal alteration) calculated with data from Shea (1992), this text. p, m: phlogopite Ar-Ar ages of phenocrysts and matrix crystals, respectively. Th-U: age of thorite with the microprobe technique (Table 3). Uncertainty bars (not represented for the Lu age) are for $\pm 2\sigma$.

event is, at least in part, younger than 79 Ma. The youngest registered age for the basic-ultrabasic magmatism, 76±1-2 Ma, is given by the Ar-Ar dating of the phlogopite in the fresh lamprophyre dike of the Osamu Utsumi mine. Additional data (ages, Sm-Nd and Rb-Sr isotopic information) are needed for the Vale do Quartel rocks.

7) The age for the hydrothermal alteration is ^{3}76 Ma, constrained by the Ar-Ar age of 76±1-2 Ma of micas in the Osamu Utsumi fresh lamprophyre, emplaced within hydrothermally altered rocks, and the Rb-Sr isochron age of 76.6±2.6 Ma for an altered syenite. There should not be any meaningful age difference between the alteration episode and the emplacement of the cited lamprophyre dike in the Utsumi open pit.

8) CO_2-rich and siliceous ultrabasic magmas were closely associated, as shown by the Minas Pedras occurrence. The existence of carbonatites had already been proposed to explain the emplacement of the magnetite dikes and the original nature of the rocks from which the Th-REE mineralization at Morro do Ferro was derived (Schorscher & Shea 1992, Waber *et al.* 1992).

Acknowledgments The authors thank FAPESP, the São Paulo Science Foundation, and CNPq, the Brazilian Federal Research Council, for support granted for field and laboratory work (to H.H.U. and K.K.) during the development of work related to the Poços de Caldas magmatism and mineralizations, and the staff of the CEPEGEO, the São Paulo Geochronology Center, and the Geochronology Lab at the University of Pará at Belem, for data acquisition. To two anonymous reviewers of RBG for their suggestions to the manuscript.

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Manuscrito A-1185
Recebido em 04 de outubro de 2000
Revisão dos autores em 25 de janeiro de 2002
Revisão aceita em 28 de janeiro de 2002