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MATO PRETO ALKALINE-CARBONATITE COMPLEX: GEOCHEMISTRY AND ISOTOPE (O-C, Sr-Nd) CONSTRAINTS

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ABSTRACT

The Late Cretaceous (70-72 Ma) alkaline-carbonatitic complex of Mato Preto is basically composed of silicate rocks and carbonatites. Early Ca-carbonatites are the dominant type whereas late Fe-carbonatites are less common. Normalized IE diagrams indicate that the late carbonatites tend to be more enriched in La, Ce, Eu and Tb with respect to the early. Only 23% of the analized samples have $\delta^{13}C$ *and* $\delta^{18}O$ *values within or close to the primary carbonatite box, the enrichment of both heavy carbon and oxygen being explained by low temperature events.* Sr_i *and* Nd_i *isotopic ratios for both carbonatites present relatively narrow variations (0.70475-0.70482 and 0.51254-0.51257, respectively) and in the conventional* ε^t *Sr vs.* ε^t *Nd diagram the Mato Preto rocks plot into the field of the Serra do Mar Province and close to the Bulk Earth composition.*

RESUMO

O complexo de Mato Preto (70-72 Ma) compõe-se de rochas silicáticas e carbonatitos. Ca-carbonatitos são as rochas dominantes, enquanto Fe-carbonatitos tardios são menos comuns. Diagramas multi-elementares normalizados indicam que os carbonatitos tardios tendem a ser mais enriquecidos em La, Ce, Eu e Tb quando comparados aos iniciais. Somente 23% das amostras analisadas apresentaram valores de $\delta^{13}C$ *e* $\delta^{18}O$ *dentro do campo de carbonatitos primários, sendo o enriquecimento de carbono e oxigênio pesados explicado por eventos de temperaturas mais baixas. As razões isotópicas* Sr_i *and* Nd_i *variam, respectivamente, no intervalo 0.70475-0.70482 e 0.51254-0.51257, e, no diagrama* ε^t *Sr vs.* ε^t*, os carbonatitos de Mato Preto plotam no campo da Província da Serra do Mar e próximo à composição média da Terra.*

INTRODUCTION

The Mato Preto alkaline-carbonatitic complex, tectonically controlled by the Ponta Grossa Arch, is intruded into Meso- to Neoproterozoic metasediments of the Açungui Group and the Neoproterozoic Três Córregos granite (Fig. 1). It shows little topographic expression, is intensely weathered and has been investigated in detail for uranium prospection in two small areas (Lapido Loureiro & Tavares, 1983).

The intrusion consists mainly of silicate rocks and carbonatites, being the former represented by phonolites and nepheline syenites and subordinate ijolites, alkali gabbros, alkali basalts and lamprophyres. The carbonatites are found in two distinct areas, i.e. "Mato Preto I" (mainly carbonatitic breccia with abundant K-feldspar clasts and carbonatitic veins) and "Mato Preto II" (the main carbonatitic body), in the southwestern and northwestern sides of the complex, respectively (Lapido Loureiro & Tavares, 1983).

K/Ar data show ages between 70.2 ± 4.8 and 71.7 ± 4.7 Ma (Sonoki & Garda, 1988), placing Mato Preto complex as the latest Cretaceous alkaline event associated with Ponta Grossa Arch. This event, also including Barra do Teixeira plug and other small phonolitic bodies in the area, is assumed to be 60 Ma later than the Early Cretaceous alkaline-carbonatite magmatism (e.g. Jacupiranga, Juquiá) and tholeiitic volcanism (lava flows, sills and dykes) related to Paraná Basin (Piccirillo & Melfi, 1988; Morbidelli *et al.,* 1995). The nearby alkaline occurrences of Itapirapuã (also bearing carbonatitic rocks; Gomes, 1970) and Tunas (Gomes *et al.*, 1987) probably correspond to an intermediate magmatic pulse (100-110 Ma, cf. Gomes *et al.*, 1990).

The geochemical features of the complex will be illustrated and the radiogenic Sr-Nd isotopes will be compared to the magmatism from the Paraná-Angola-Namibia Province.

ANALYTICAL METHODS

More than 20 specimens were selected for investigation mostly deriving from surface sampling and subordinately from drill cores.

Major and trace elements were determined on pressed powder discs by a PW1400 XRF spectrometer (Rh as target tube). REE plus Th, U, Hf and Ta were analyzed by ICP-MS (Perkin Elmer Elan 5000) in solutions obtained by mixed HF-$HClO_4$ digestion under pressure in sealed teflon vessel, following the procedure outlined by Alaimo & Censi (1992). The overall precision and accuracy for the major and trace elements including the REE are better than 2% and 15%, respectively.

The oxygen and carbon isotopic compositions on carbonates were obtained by reacting the samples with 100% H_3PO_4 at 25°C. The released CO_2 was subsequently analyzed in a Finnigan Mat Delta S mass spectrometer and its oxygen isotopic composition has been corrected to calcite and dolomite (or ankerite) by applying the fractionation factors 1.01025 and 1.0111, respectively, according to Santos & Clayton (1995). Since most of the samples contain both calcite and ankeritic dolomite/ankerite, they were analyzed using the double extraction techniques described by Epstein & Taylor (1967). The sample powders were prepared with grain size fractions ranging from 100 to 200 mesh. The CO_2 corresponding to calcite and dolomite/ankerite was extracted after 1 hour and between 24 and 384 hours after reaction, respectively. The isotopic results are given in terms of usual δ‰ units, the reference standards being PDB-1 for carbon and V-SMOW for oxygen.

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic ratios were measured on a MAT 262 multicollector mass spectrometer, following Ludwig (1987). The average value of NBS 987 standard during data acquisition was 0.710220 ± 0.000012 (2σ), $^{86}Sr/^{88}Sr$ normalized to 0.1194; La Jolla standard gave 0.511856 ± 0.000015 (2σ). Nd isotopic ratios were normalized within-run fractionation to $^{146}Nd/^{144}Nd = 0.7219$. Standard deviations of the isotopic ratios are expressed at 95% confidence level as 2σ of the mean value. The ε^t Sr-Nd notations were calculated using the following values for the Bulk Earth: $^{87}Sr/^{86}Sr = 0.7045$, $^{87}Rb/^{86}Sr = 0.827$, $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$. Additional data: lamprophyre (Gibson *et al.,* 1999); metalimestones and metadolostones (Fassbinder, 1996).

PETROGRAPHY

The carbonatite samples from the main body (Mato Preto II) are medium to fine Ca-carbonatites and vary from white to grey. The texture is xenomorphic seriate with prevailing calcite and subordinate ankerite, as well as magnetite, apatite, pyrochlore and RE fluorcarbonates as accessories. K-feldspar xenocrysts are widespread and locally abundant. The textural relationships show at least two dif-

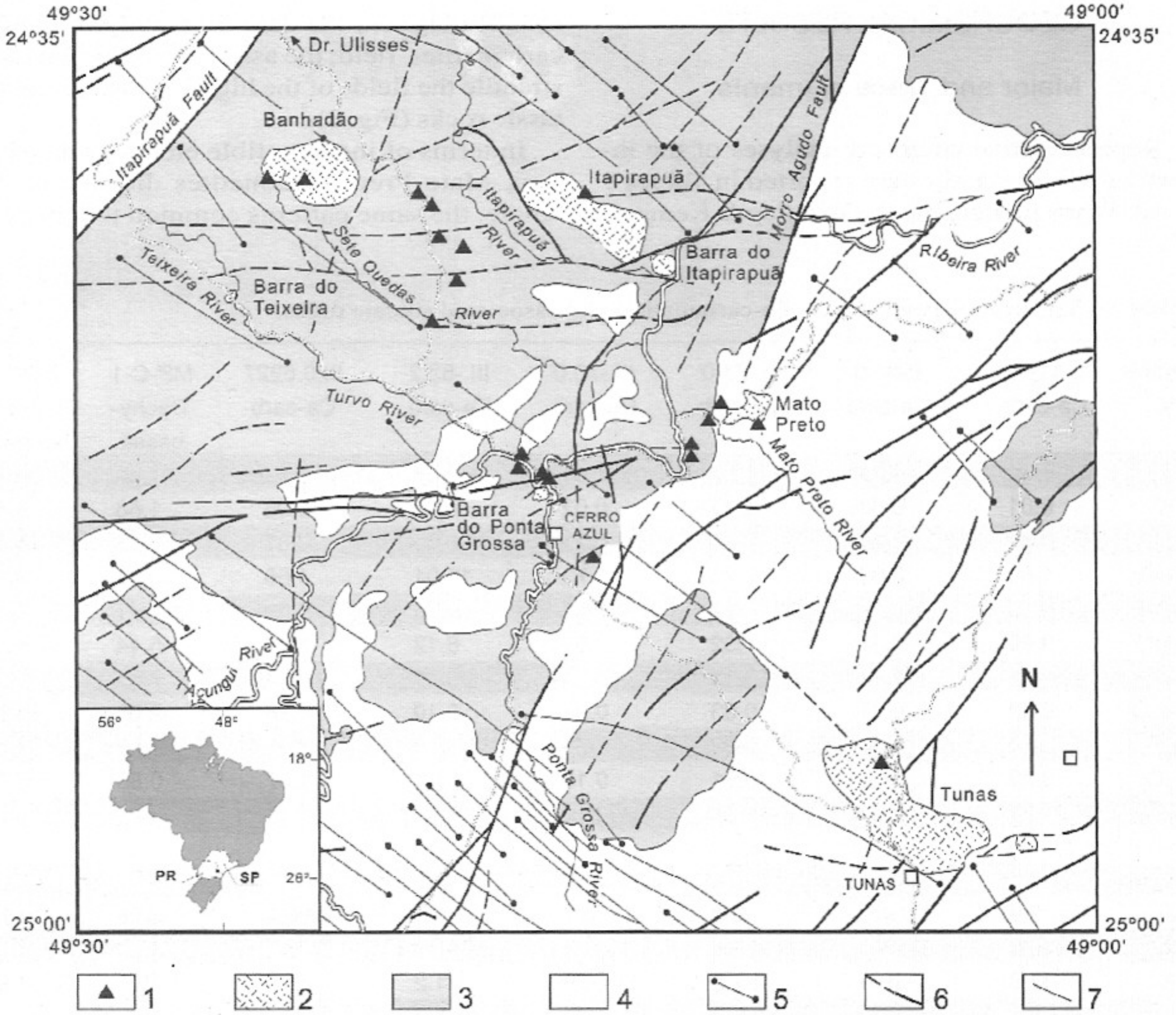

Figure 1 – Simplified geological map of Mato Preto region (after Vasconcellos & Gomes, 1998). Legends: 1 and 2, alkaline occurrences (dykes, plugs, stocks); 3, Upper Precambrian-Cambrian rocks (Três Córregos granite included); 4, Middle to Upper Precambrian metaigneous and metasedimentary rocks (Açungui Group included); 5, faults, as suggested by diabase dykes; 6 and 7, covered and well-defined dykes, respectively.

ferent stages: early Ca-carbonatites and late Fe-carbonatites with minor amounts of Ca-carbonatites. Late millimetric veins of quartz, fluorite, barite and RE fluorcarbonates cut the carbonatitic rocks.

Fe-carbonatites are rare and occur as centimetric veins (Mato Preto I) and dykes (Mato Preto II). They are medium to fine-grained and are typically brownish. The texture is inequigranular, xenomorphic to hypidiomorphic, and the mineralogy consists of dominant ankerite and subordinate calcite, in addition to RE fluorcarbonates, pyrochlore, opaques, barite, quartz and fluorite as accessory phases.

The main silicate rocks are medium to fine-grained *nepheline syenites* (Lapido Loureiro & Tavares, 1983), allotriomorphic in texture and with dominant alkali feldspar and nepheline. Aegirine-augite, opaques and biotite are less abundant, whereas apatite, sphene and monazite constitute the chief accessories. *Alkali gabbros* and *ijolites* are also present. *Lamprophyre* (following Gibson *et al.*, 1999; picritic alkali basalt?) and *trachybasalt* dykes, occasionally extending for about 5 km^2, cross cut the complex. The latter rocks are weakly porphyritic in texture and contain pheno- and microphenocrysts of clinopyroxene, olivine, biotite, nepheline, amphibole, plagioclase and opaques set in a hypohyaline to hypocrystalline groundmass.

Fenitized rocks are widespread over the complex (Ruberti, 1998) and generally show cataclastic texture with recrystallizated alkali feldspar grains and microfractures filled with amphiboles, aegirinic clinopyroxenes and carbonates.

GEOCHEMICAL RESULTS

Major and Trace elements

Representative chemical analyses of the investigated carbonatites are reported in Tables 1 and 2. When plotted into the Woolley & Kempe's (1989) diagram, the data lie mainly in the Ca-carbonatites field; the associated alkaline rocks straddle the fields of the highly potassic and potassic rocks (Fig. 2).

In terms of incompatible elements distribution, Mato Preto carbonatites display, on the whole, the same patterns common to other car-

Table 1 – Selected analyses of Ca-, Fe-carbonatites and associated silicate rocks.

Sample	I.-119.3	I.-84.0	II.-77.0	III.-70.0	III.-62.2	III.0.6227	MP-C-1	MP-C-2
wt%	Ca-carb	Ca-carb	Ca-carb	Ca-carb	Fe-carb	Ca-carb	Trachy-basalt	Nepheline syenite
SiO_2	0.30	0.23	0.52	1.91	2.28	3.22	47.49	58.21
TiO_2	0.01	0.01	0.11	0.02	0.11	0.06	1.68	0.80
Al_2O_3	0.23	0.14	0.21	0.21	0.59	0.81	16.63	18.65
FeO_t	1.81	0.92	2.23	1.73	10.01	4.56	8.67	3.47
MnO	0.19	0.19	0.22	0.21	0.73	0.39	0.21	0.08
MgO	0.99	0.33	1.32	0.51	6.12	1.49	5.44	0.86
CaO	54.35	54.83	53.13	55.01	39.21	49.74	7.15	1.96
Na_2O	0.03	0.01	0.03	0.01	0.10	0.06	2.05	5.64
K_2O	0.10	0.07	0.09	0.31	0.58	1.09	5.59	7.87
P_2O_5	0.52	0.17	0.51	0.16	0.28	1.67	0.85	0.30
L.O.I.	41.27	43.15	41.38	40.16	38.89	36.40	3.21	1.62
p.p.m.								
Rb	2.9	4.3	6.8	10.2	1.6	189.4	36.8	140.7
Ba	175.0	3798.0	1133.8	449.1	8378.0	2226.0	1639.0	2136.0
Th	44.8	19.9	81.5	146.6	811.2	1178.0	16.4	15.2
U	3.3	3.0	5.0	30.2	71.0	122.3	3.0	
Nb	251.0	384.0	22.9	95.1	315.2	25.1	147.0	80.3
Ta	9.4	18.7	0.8	6.3	11.8	1.4	6.1	3.1
Sr	8735.0	2134.0	8758.0	1053.2	3693.0	4652.0	2014.0	1391.0
Hf	2.9	7.7	0.2	3.7	2.4	4.9	5.9	13.3
Zr	45.9	123.0	22.9	182.8	122.9	177.9	221.0	537.0
Y	74.3	121.0	191.8	225.2	96.4	673.0	26.9	19.7
La	198.10	164.60	240.50	3686.00	852.00	1112.00	116.01	123.33
Ce	377.00	461.40	716.90	6510.00	1577.00	1808.00	213.08	195.40
Pr	44.30	69.51	101.01	581.12	154.60	232.90	23.70	
Nd	155.80	340.80	461.30	883.70	350.10	948.10	74.51	59.15
Sm	25.80	73.37	91.35	174.30	52.31	79.04	11.41	9.06
Eu	8.23	22.63	22.20	56.79	17.00	24.99	3.32	2.64
Gd	25.04	76.23	70.56	161.39	48.33	87.59		
Tb	3.74	12.01	8.27	23.12	6.91	14.44	1.37	1.09
Dy	17.27	67.28	39.92	85.85	30.15	90.03	8.21	6.50
Ho	2.81	12.33	6.70	9.70	5.13	18.23	1.40	
Er	7.31	24.85	16.04	26.49	10.36	46.97	3.92	3.10
Tm	1.07	2.83	2.57	3.80	1.73	6.92	0.42	
Yb	4.78	10.22	8.49	22.62	11.29	34.09	2.48	1.96
Lu	0.42	1.53	2.20	3.34	1.80	5.71	0.33	

Table 2 – CaO-MgO-FeO% (by X-ray diffraction methods, only for carbonatite samples), chondrite normalized La and La/Yb, total REE, Rb, Sr, Sm and Nd contents (ppm), O-C isotopic data, measured and initial (notional age: 70 Ma) isotopic Sr and Nd ratios, ε^{t} notations, and mineralogical assemblages for the samples from Mato Preto alkaline-carbonatite complex.

CARBONATITE ROCKS	wt%					ppm	δ‰-ank		δ‰alc		ppm	ppm	Measured		ppm	ppm	Measured				
	CaO	MgO	FeO	LaN	(La/Yb)N	SREE	^{18}O	^{13}C	^{18}O	^{13}C	Rb	Sr	$^{87}Sr/^{86}Sr$	R_0	Sm	Nd	$^{143}Nd/^{144}Nd$	R_0	εSr	εNd	Main mineralogy
Bore-hole samples																					
-62,2	70	11	19	2748	85,9	3064	11,88	-2,74	10,68	-3,45	1,59	3693	0.704729 (6)	0,70473	52,31	350,1	0.512606 (12)	0,51256	1,55	0,33	cc, ank, ba, qz, (fcc)
-70	96	1	3	11890	109,9	12067			18,9	-0,7	10,21	1055			174,3	883,7					cc, fcc, (fl); qz
-77	93	2	5	776	19,1	1717	13	-1,3	11,32	-1,91	6,78	8758	0.704731 (8)	0,70473	91,35	461,3	0.512715 (10)	0,51266	1,56	2,19	cc, ank, ap
-84	97	1	2	531	10,9	1265			12,64	-0,41	4,14	2134	0.704726 (9)	0,70472	73,37	340,8	0.512756 (11)	0,5127	1,44	2,9	cc, ap
-93,1	97	1	2	2275	29,7	3795		13,06	-0,63	4,34	9095			201,15	785,4						cc, str, (ap), (phl),
-119,3	95	2	3	639	27,9	846	13,31	-0,45	12,49	-0,81	2,91	8735	0.704951 (11)	0,70495	35,8	155,8	0.512577 (12)	0,51253	4,7	-0,33	cc ank, ap
Surface samples																					
6220	97	0	3	1643	10,9	2199			13,26	-1,66	2,44	2186			71,64	457					cc, ap
6221	84	6	10	3003	50,4	3390	15,91	0,95	14,61	0,38	2,57	1972	0.705329 (11)	0,70533	60,04	449,6	0.512582 (19)	0,51255	10,03	-0,06	cc, ank, ap, (phl), (qz)
6222	99	0	1	552	7,6	1155			8,26	-6,25	2,33	1752	0.704971 (12)	0,70497	36,79	272,1	0.512589 (5)	0,51255	4,94	0,07	cc, qz
6223	96	1	3	954	39,7	1324			10,04	-4,52	4,2	5238			19,91	260,1					cc, ap, qz
6224	96	1	3	975	34,4	1049			12,36	-1,06	3,33	4444	0.704449 (6)	0,70444	26,35	227,8	0.512551 (10)	0,51252	-2,44	-0,56	cc, ap
6225	98	0	2	1130	31,3	1074			13,19	-2,41	1,58	3693	0.704867 (12)	0,70486	22,15	163,8	0.512525 (16)	0,51249	3,5	-1,18	cc, ap
6227	88	3	9	3587	22	4421	12,6	-4,98	10,19	-5,84	189,44	4652	0.704983 (15)	0,70487	79,04	948,1	0.512510 (20)	0,51249	3,51	-1,19	cc, ank, phl, san, qz,
6228	99	0	1	2523	43	2306			13,11	-0,56	0,75	1015			47,5	570,1					cc, (ap), (qz)
6229	98	0	2	1175	26,9	1552			9,77	-5,77	2,13	2163	0.704729 (16)	0,70472	19,44	233,2	0.512625 (26)	0,5126	1,52	-1,05	cc, ap
SILICATE ROCKS																					
93SOB185(G) 'Lamprophyre' (picritic alkali basalt)				400	31,9	477					40	2324	0.70500 (1)	0,70495	12,2	79,3	0.51260 (1)	0,51258	4,71	0,19	?
MP-C-1 Trachybasalt				374	31,5	463			13,18	-1,35	36,8	2014	0.704925 (7)	0,70487	11,41	74,5	0.512543 (9)	0,5125	3,6	-0,92	px, pl, af, phl, glass
MP-C-2 Nepheline syenite				398	42,4	416					140,7	1391	0.705191 (9)	0,7049	9,06	59,15	0.512585 (7)	0,51254	3,99	-0,1	af, ne, px, am, op, sph,
AÇUNGUI GROUP																					
Metalimestones and metadolostones											0,10	428	0.71048 (37)	0,71048	0,28	3,84	0.511717 (31)	0,5117	83,2	-16,6	
Três Córregos Granite																					
Granite											168,4	868	0,716724	0,71617	4,56	29,82	0,511265	0,51122	164	-25,8	
Fenite											328	2412	0.71472 (1)	0,71433	8,4	57,7	0.51146 (1)	0,51142	138	-22	

Abbreviations (alphabetical order):

af = alkali felspar; am = amphibole; ank = ankerite; ap= apatite; ba = barite; cc = calcite; fcc = fluorocarbonates; fl = fluorite; ne = nepheline; op = opaques; phl = phlogopite; pl = plagioclase; px = pyroxene; qz = quartz; sph = sphene; str = strontianite.

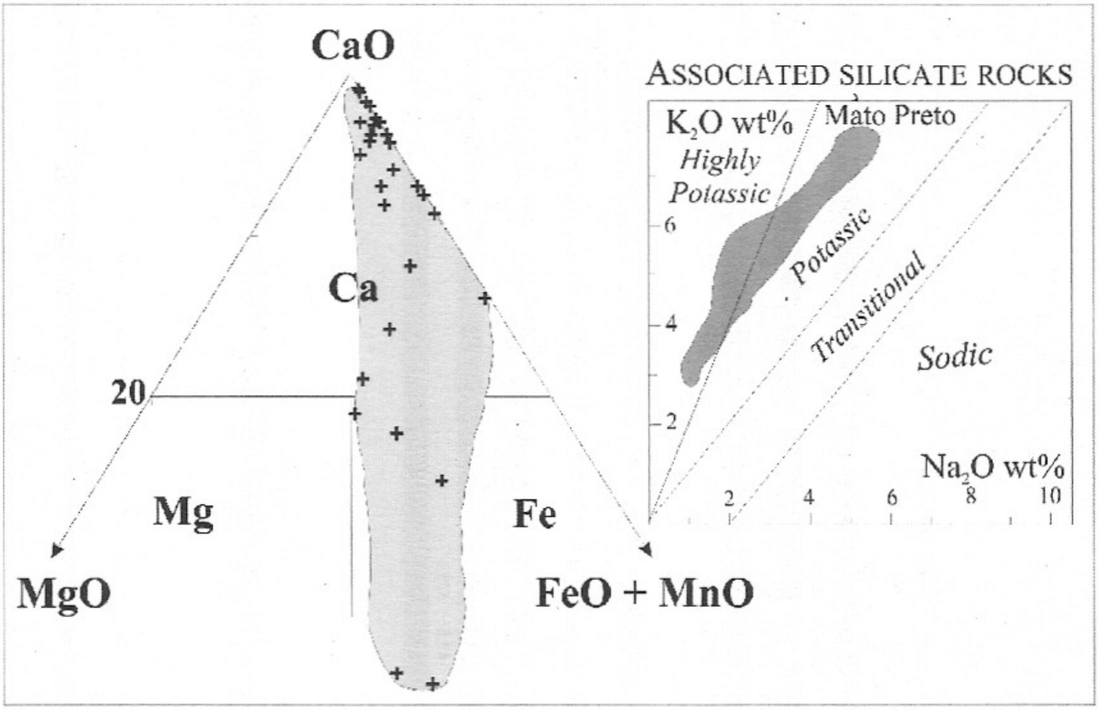

Figure 2 – Classification of the carbonatite samples according to Woolley & Kempe (1989). Inset: classification of the associated alkaline rocks after Comin-Chiaramonti & Gomes (1996).

bonatites from the area (e.g. Barra do Itapirapuã; cf. Ruberti, 1998) which are characterized by the presence of positive anomalies of Th-U, La-Ce, Nd-Sm, Eu and Tb, and negative ones of Nb, K, Hf, Zr and Ti (Fig. 3a). The associated dykes (lamprophyre and trachybasalt) and intrusive rocks (nepheline syenite) present Th-U depletion and K-positive spike in general. Notably, there are no clear differences between early Ca- and late Fe-carbonatites, the latter being slightly more enriched with La, Ce, Eu and Tb (Fig. 3a).

Chondritic normalization shows wide REE ranges, the early and late Ca-carbonatites having $(La/Yb)_N = 51 \pm 22$ and 254 ± 184, respectively, whereas the value of the late Fe-carbonatites is 124 ± 24. Lamprophyre and trachybasalt dykes and nepheline syenite give $(La/Yb)_N$ values of 68 ± 1 and 91, respectively.

Oxygen and Carbon isotopes

Ninety five per cent of the analyzed population (including additional data after Santos & Clayton, 1995) contain calcite and 20% show calcite associated with Mg-ankerite. Mg-ankerite is the main phase in about 10% of the samples. The isotopic data (Table 2), expressed as δ‰ notation, are illustrated in Figure 4. They fit a straight line ($\delta^{13}C‰ = 1.16$, $\delta^{18}O‰ = 16.14$, $r^2 = 0.77$), which correlates to that shown by Barra do Itapirapuã carbonatites (Ruberti et al., 2001, in press), but, in this case, only 23% of the carbonate samples (compared to 79% in Barra do Itapirapuã) plot within or close to the primary carbonatite box.

Fe-dolomite alteration (Mg-ankerite), by groundwater, may be related to the low-temperature hydrothermal cycles (200-80°C; cf. inset of Fig. 4 and Speziale *et al.*, 1997), responsible for massive fluorite deposits formation in the complex (Santos *et al.,* 1996). In general, as suggested by Santos & Clayton (1995), the "addition" of carbonates from the metasedimentary country rocks (e.g. Açungui Group: $\delta^{18}O‰$ and $\delta^{13}C‰$ ranges 16.1 to 28.5 and -4.4 to 2.5, respectively, after Fassbinder, 1996) to the system seems to be unnecessary to explain the presence of samples considerably enriched with both heavy oxygen and carbon (cf. Speziale *et al.*, 1997: these authors developed a diffusive equation system showing that the isotopic re-equilibration is only due to hydrothermal carbonatitic fluids), except for two samples that tend towards or overlap the metasedimentary carbonate field (Fig. 4).

Strontium and Neodimium isotopes

The Sr and Nd isotopic ratios (Table 2 and Fig. 5) display in general relatively narrow variations: early carbonatites (N = 4) have initial $^{87}Sr/^{86}Sr$ (Sr_i) and $^{143}Nd/^{144}Nd$ (Nd_i) = 0.70475 ± 0.00023 and Nd_i = 0.51254 ± 0.00005, respectively, whereas the late carbonatites (N= 7) contain Sr_i = 0.70482 ± 0.00027 and Nd_i = 0.51257 ± 0.00008. These data clearly overlap the range of the associated silicate rocks (Sr_i = 0.70491 ± 0.00004, Nd_i = 0.51257 ± 0.00008).

There is a relatively poor correlation (r^2 = 0.72; cf. inset of Fig. 5) between the late carbonatites and carbonatic rocks of the Açungui Group in terms of Sr_i vs. $\delta^{18}O$‰. A possible contamination of Mato Preto carbonatites by carbonatic metasediments, as proposed by Santos & Clayton (1995), is not apparent from the Sr_i and Nd_i mixing curves (Fig. 5). Only the fenitic rocks are strongly believed to represent an isotopic mixture of granitic and carbonatitic components (Fig. 5). As already emphasized by Speziale *et al.* (1997), the observed O-C isotope variations are consistent with low tempera-

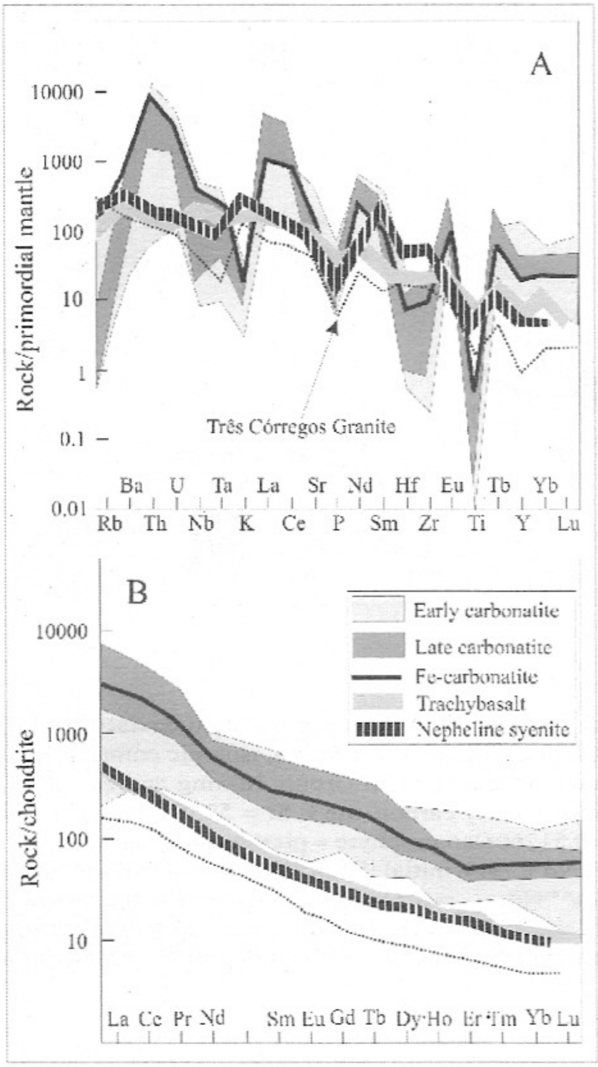

Figure 3 – Trace elements normalized to the primordial mantle (Sun & McDonough, 1989) (A). REE chondrite normalized (Boynton, 1984) for carbonatites and associated alkaline rocks from Mato Preto (B). The behaviour of Três Córregos granite is also shown for comparison.

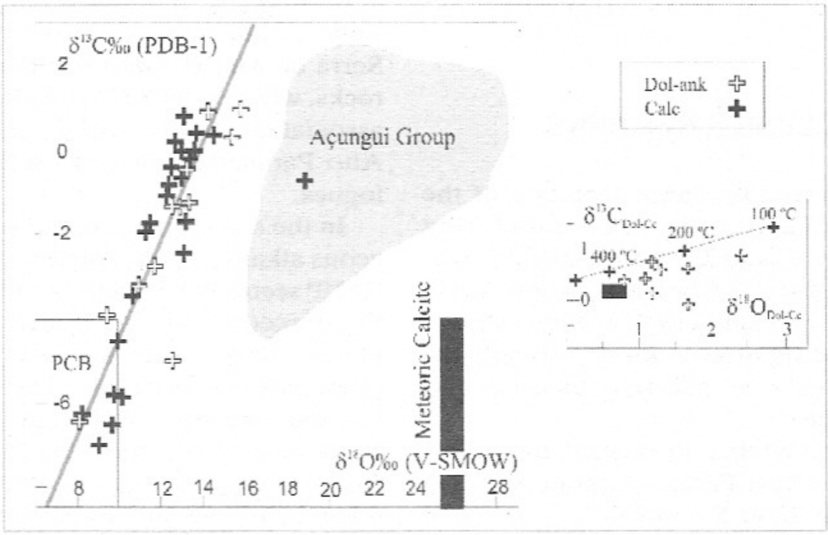

Figure 4 – Stable O-C isotope compositions for the carbonatite samples with additional data from Santos & Clayton (1995). Primary carbonatite box (PCB) after Taylor *et al.* (1967) and Keller & Hoefs (1995). Data sources for Açungui Group and meteoric calcite are from Fassbinder (1996) and Alcover Neto *et al.* (1995), respectively. Inset: $\delta^{13}C$ - $\delta^{18}O$ low-temperature isotopic fractionation (Sheppard & Schwartz, 1970).

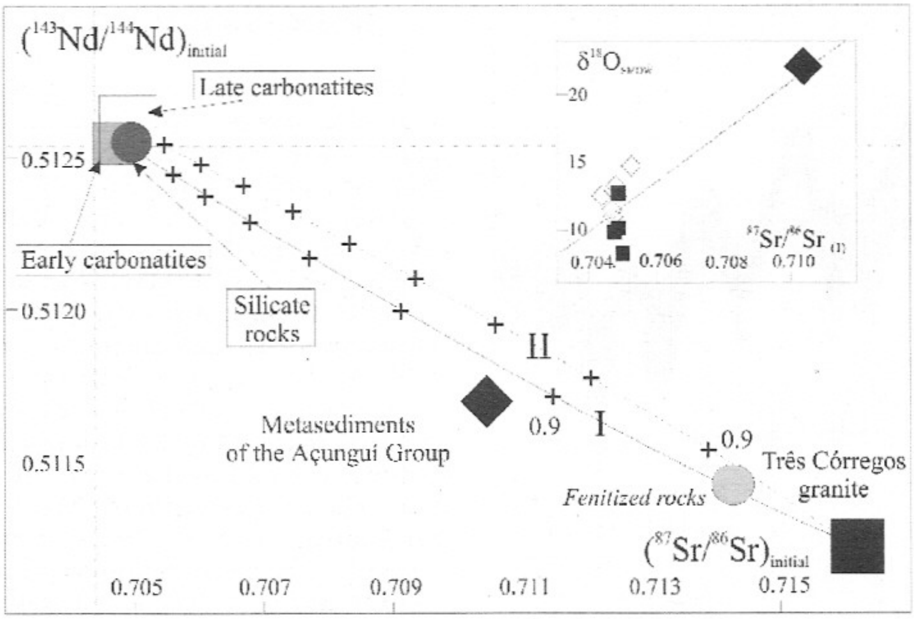

Figure 5 – Fields of carbonatites and associated silicate rocks (average values ± standard deviations) from Mato Preto alkaline-carbonatite complex in terms of initial isotopic ratios of Sr-Nd, isotopic composition of Três Córregos granite, fenitized rocks and metasediments of the Açungui Group. Mixing curves between isotopic composition of carbonatites {starting compositions, early carbonatite I: Sr = 5238 ppm, initial (70 Ma) $^{87}Sr/^{86}Sr = 0.70444$, Nd = 155.8, initial $^{143}Nd/^{144}Nd = 0.51260$; lamprophyre = picritic alkali basalt (Gibson *et al.*, 1999) II: Sr = 2014 ppm, initial $^{87}Sr/^{86}Sr = 0.70495$, Nd = 79.3, initial $^{143}Nd/^{144}Nd = 0.51260$} and granite (Sr = 868 ppm, $^{87}Sr/^{86}Sr_{120\,Ma} = 0.71617$, Nd = 29.82, $^{143}Nd/^{144}Nd_{120\,Ma} = 0.51122$) are shown with thicks spaced at 10%. Inset represents initial $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ plot of carbonatites (full square, early carbonatites; open diamond, late carbonatite) and average values of carbonatic metasediments of the Açungui Group (large full diamond).

ture fractionation rather than contamination by the assimilation of crustal/supracrustal sequences.

CONCLUSIVE REMARKS

Even considering the large variation of the incompatible elements and also the enrichment with both heavy O and C, the radiogenic isotopes for Mato Preto carbonatites (both early and late) are in the same range as those shown by the associated alkaline rocks, specifically the lamprophyre (alkali picritic basalt) and nepheline syenite.

It should be noted that, in general, the carbonatites from the whole Paraná-Angola-Namibia Province (PANP) have Sr_i and $Nd_{i\ similar}$ to those of the associated alkaline rocks, even in samples which have strongly experienced hydrothermal processes (Alberti *et al.*, 1999 and therein references).

In the conventional ε^t Sr–ε^t Nd isotope diagram (Fig. 6), the Late Cretaceous (LC) Mato Preto carbonatites represent an extension of the Serra do Mar (Brazil) and Blue Hill (Namibia) rocks, whereas the LC Lages Fe-carbonatites and associated alkaline rocks generally conform to Alto Paranaíba Igneous Province (APIP) analogues.

In the same diagram, the whole Early Cretaceous alkaline-carbonatite magmatism from the PANP seems to be related to heterogeneous mantle source(s) spanning from time-integrated depleted (Angola and Namibia) to enriched types (Paraguay and Uruguay). This magmatism overlaps the subcoeval PANP flood tholeiites in terms of radiogenic isotopes. On the whole, the data strongly suggest that the PANP magmatism is related to large and small-scale heterogeneous subcontinental mantle, variously "contaminated" by ancient metasomatic processes (Comin-Chiaramonti *et al.*, 1997a,b). Notably, the time integrated depleted signature of the Trindade Is-

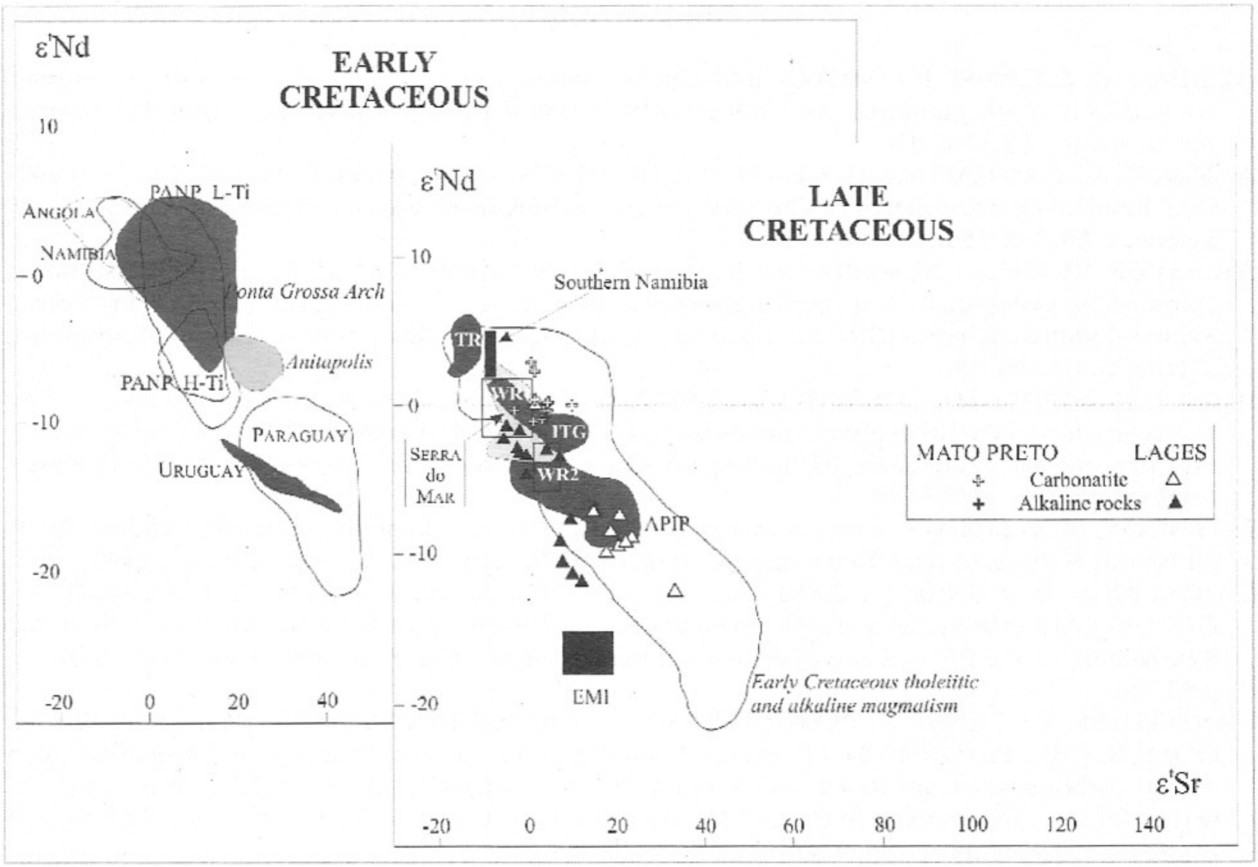

Figure 6 – Synoptical ε^tSr-ε^tNd time-integrated diagrams for the Late Cretaceous Mato Preto rocks compared with subcoeval K-alkaline-carbonatitic associations from Lages (Santa Catarina State), Alto Paranaíba (APIP), Taiúva-Cabo Frio lineament-Serra do Mar (Serra do Mar) and Blue Hills (Southern Namibia (Kurszlaukis *et al.*, 1999). Early Cretaceous: alkaline-carbonatite complexes from Brázil (Ponta Grossa Arch and Anitápolis), compared to alkaline-carbonatitic associations from Angola, Namibia, Paraguay and Uruguay and also with tholeiites of the Paraná-Angola-Namibia Province (PANP, "uncontaminated low-Ti and H-Ti tholeiites", i.e. measured $^{87}Sr/^{86}Sr < 0:706$). Post-Mesozoic magmatism (ITG, Inacessible, Tristan da Cunha and Gough; WR1 and WR2, Walvis Ridge) are also shown. Data sources: Comin-Chiaramonti *et al.* (1991, 1992, 1995, 1997a,b); Bizzi *et al.* (1994); Castorina *et al.* (1994, 1996, 1997); Gibson *et al.* (1995); Fontignie & Schilling (1996) and therein references; Traversa *et al.* (1996); Milner & Le Roex (1996) and therein references; Le Roex & Lanyon (1998) and therein references; Muzio *et al.*, 1998; Smithies & Marsh (1998); Thompson *et al.* (1998); Kirstein *et al.* (2000). DMM, EMI and EMII components as given in Zindler & Hart (1986).

land (TR, Fig. 6) is similar to that shown by Angola and Namibia alkaline-carbonatitic rocks of Early and Late Cretaceous age, but different from that (BE to EMI signature) of the Late Cretaceous analogues of Alto Paranaíba (APIP), Mato Preto and Lages.

The same diagram (Fig. 6) shows that the alkaline magmatism of Tristan da Cunha, Gough and Inaccessible islands, and Walvis Ridge have BE–EMI Sr-Nd isotopic characteristics which are distinct or partly overlap those of the Early Cretaceous alkaline-carbonatitic (and tholeiitic) magmatism. Therefore, it is also possible to conclude that the contribution of asthenospheric components to Tristan da Cunha and Trindade plumes was not appreciable.

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