GEOCHEMISTRY AND GEODYNAMIC IMPLICATIONS OF THE ANITÁPOLIS AND LAGES ALKALINE-CARBONATITE COMPLEXES, SANTA CATARINA STATE, BRAZIL

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RESUMO *GEOQUÍMICA E IMPLICAÇÕES GEODINÂMICAS DOS COMPLEXOS ALCALINO-CARBONATÍTICOS DE ANITÁPOLIS E LAGES, SANTA CATARINA* O complexo de Anitápolis representa um stock do Cretáceo Inferior (~132 Ma) intrusivo em rochas gnáissicas-graníticas proterozóicas (570–630 Ma). Compõe-se de piroxenitos cumuláticos, quantidades menores de nefelina sienitos e ijolitos, além de escasos diques de composição nefelínica. Carbonatitos formam um pequeno corpo e abundantes diques e veios dispersos. O complexo de Lages (70–77 Ma) é formado de inúmeras intrusões rasas, brechas de chaminé e diques concêntricos, que se espalham dentro de uma proeminente estrutura de domo encaixada em sedimentos Permianos e Triássicos. Consiste em fonolitos peralcalinos e nefelina sienitos e, subordinadamente, de rochas ultramáficas (melilitito, olivina nefelinito, basanita e tefrito). Outros tipos petrográficos importantes são brechas kimberlíticas e carbonatitos. Quimicamente, os carbonatitos de Anitápolis são Ca-carbonatitos, enquanto os de Lages correspondem a Fe-carbonatitos. Os padrões de distribuição dos elementos incompatíveis e das terras raras para ambos os carbonatitos são também distintos. Os isótopos $d^{18}\text{O}$ and $d^{13}\text{C}$ obtidos em carbonatitos de Anitápolis revelam composição de cristalização primária, enquanto os de Lages exibem grande dispersão dos valores $d^{18}\text{O}$. Os dados de isótopos radiogênicos indicam que os carbonatitos e as rochas silicáticas associadas apresentam valores Sr e Nd similares, variando, no entanto, quanto à fonte de tipos empobrecidos a enriquecidos. As idades modelo Nd (t_{DM}) para Anitápolis (K) e Lages (K) são, respectivamente, de $1,3 \pm 0,1$ Ga e $1,2 \pm 0,2$ Ga. Contudo, os dados sugerem que as rochas de Lages parecem ter sido afetadas por dois eventos mantélicos metassomáticos distintos durante o Proterozóico. Considerações sobre as implicações geodinâmicas do magmatismo alcalino e alcalino-carbonatítico são feitas com base em modelos que diferem daqueles da pluma mantélica.

Palavras-chave:

ABSTRACT The Early Cretaceous (~132 Ma) Anitápolis stock is made up of cumulate pyroxenites, minor nepheline syenites and ijolites and scarce dykes of nephelinitic composition. Carbonatites form a small body, but are also widespread as dykes and veins. The complex is entirely surrounded by Late Proterozoic granitic-gneissic rocks (570–630 Ma). The Late Cretaceous (70–77 Ma) Lages complex constitutes a prominent dome structure underlined by a concentric arrangement of Permian to Triassic sediments. It consists mainly of peralkaline phonolites and nepheline syenites with subordinate ultramafic rocks (melilitite, olivine nephelinite, basanite and tephrite). Other important rock-types are kimberlitic breccias and carbonatites as a minor intrusion. Chemical data suggest that the Anitápolis carbonatites are essentially Ca-carbonatites and the Lages ones Fe-carbonatites. Normalized IE and REE diagrams for both carbonatites display different patterns. $d^{18}\text{O}$ and $d^{13}\text{C}$ isotopes for the Anitápolis carbonatites plot near the primary carbonatite box, whereas the Lages rocks point to a large spreading of $d^{18}\text{O}$ values. Radiogenic isotope data indicate that the carbonatites and the associated silicate rocks present similar Sr and Nd values, spanning from time integrated depleted to enriched types. Nd-model ages for the Early (Anitápolis) and Late Cretaceous (Lages) carbonatites are 1.3 ± 0.1 Ga and 1.2 ± 0.2 Ga, respectively, but the Lages rocks seem to have been affected by two different Proterozoic mantle metasomatic events. Considerations on the geodynamic implications of the alkaline and alkaline-carbonatitic magmatism are made on the basis of models other than mantle plume.

Keywords: alkaline-carbonatite complexes, geochemistry, O-C-Sr-Nd isotopes, Santa Catarina State, Brazil.

INTRODUCTION The Paraná Basin, part of the Paraná-Angola-Etendeka Province (PAEP, cf. Comin-Chiaramonti *et al.* 1999), is characterized by Early Cretaceous flood tholeiites, sills and dyke swarms (Piccirillo & Melfi 1988) occurring in close association with alkaline and alkaline-carbonatitic complexes of Early to Late Cretaceous age (Morbideilli *et al.* 1995, Alberti *et al.* 1999). The emplacement of the alkaline and alkaline-carbonatitic complexes, in and around the PAEP, took place along tectonic lineaments (Fig. 1), which have been active at least since Early Mesozoic (Fig. 1) and probably up to the present day, as shown by the distribution of earthquakes in southeastern Brazil (Berrocal & Fernandes 1996). Recently, Molina & Ussami (1999) have registered a clear correlation

between geoid anomalies and magmatic/tectonic features along southeastern Brazil and Uruguay: particularly in the eastern part of Santa Catarina State a positive 4 m-amplitude geoid anomaly is defined relating to: 1) Early Cretaceous tholeiitic dyke swarms from the Florianópolis area (129–119 Ma; Raposo *et al.* 1998); 2) Early Cretaceous alkaline-carbonatitic complex of Anitápolis (132 Ma; Sonoki & Garda 1988); 3) Late Cretaceous alkaline-carbonatitic complex of Lages (76 Ma; Traversa *et al.* 1996).

Notably, the Florianópolis dykes have approximately N-S attitude and lie parallel to the coast, whereas the Anitápolis and Lages complexes are emplaced along the almost E-W-trending Uruguay lineament (Fig. 1).

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Tholeiitic and alkaline-carbonatitic magmatism have been considered a marker of the subcontinental lithospheric mantle (SCLM; cf. Comin-Chiaramonti *et al.* 1997a,b, 1999, Marques *et al.* 1999). It is interesting to note that Gibson *et al.* (1999) have suggested that the PAEP Late Cretaceous magmatism would represent the widespread effect of the Trindade plume at the SCLM basis, channelled up to Lages latitude; if it is the case, also the Late Cretaceous alkaline bodies found in the Piratini area in the southern Brazil (Rio Grande Arch; Barbieri *et al.* 1987) would be related to that model.

This study attempts to assess the geochemical relationships between the spatially associated Early and Late Cretaceous alkaline-carbonatite magmatism along the Uruguay lineament

and its significance in relation to the South Atlantic plume(s) puzzle.

GEOLOGICAL BACKGROUND

The Anitápolis complex crops out in a circular depression of about 6 km² and is made up of phlogopite pyroxenites and apatite-biotite-pyroxenites, surrounded by ijolites and nepheline syenites, intruding Late Proterozoic granitic-gneissic rocks (570-630 Ma; Furtado 1989) (Fig. 2). Scarce melanephelinite and nephelinite dykes cross cut the complex. A dyke-like carbonatitic core of about ten square meters occurs in the center of the depression in contact with phlogopite pyroxenites. Carbonatite dykes and veins are widespread, having been found noticeably in association with the pyroxenites. Field volume estimates for the main lithologies of the complex are 60% of cumulate rock-types, 39% of ijolite + nepheline syenite and about 1% of carbonatite.

K/Ar data indicate an approximate age (131-132 Ma, cf. Sonoki & Garda 1988) to that of the Jacupiranga and Juquiá alkaline-carbonatitic complexes (Morbiddelli *et al.* 1995).

Figure 1 – Distribution of the alkaline and tholeiitic magmatism in the Paraná-Angola-Etendeka Province (after Alberti *et al.*, 1999, modified).

Figure 2 – Simplified geological map of the region of Anitápolis and Lages. Inset: Anitápolis complex. Data sources: Furtado (1989) and Scheibe (1986).

The Lages outcrops, lying about 100 km to the E of Anitápolis, cover an area of approximately 50 km². They are associated with a dome structure underlined by a concentric arrangement of Permian to Triassic sediments (Traversa *et al.* 1994). The Lages igneous rocks occur as shallow intrusions, pipe breccias and dykes displaying an annular arrangement throughout the dome structure (Fig. 2) and are mainly constituted of peralkaline phonolites and nepheline syenites with subordinate amounts of melilitite, olivine nephelinite, basanite, tephrite, carbonatite and kimberlite (Scheibe 1986, Traversa *et al.* 1994).

K/Ar ages range from 70 Ma (Sonoki & Garda 1988) to 77 Ma (Gibson *et al.* 1999), whereas a whole-rock errorchron yielded a value of 82 ± 6 Ma (Scheibe *et al.* 1985).

SAMPLING AND ANALYTICAL PROCEDURES The analyzed rocks were mostly selected from drill cores (Anitápolis: Indústria de Fosfato Catarinense; Lages: Cimenvale Co.), but surface samples were also investigated.

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 from mixed HF-HClO₄ digestion under pressure in a 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 carbonatite composition was also determined by X-ray diffraction methods, in order to establish the amounts of dolomite/ankerite and calcite. Oxygen and carbon isotopic compositions on carbonates were obtained by reacting the samples with 100% H₃PO₄ at 25°C. The released CO₂ was subsequently analyzed on a Finnigan Mat Delta S mass spectrometer and its oxygen isotopic composition was 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 by using the double extraction techniques described by Epstein & Taylor (1967). The sample powders were ground to grain size fractions ranging between from 100 to 200 mesh. The CO₂ 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 conventional δ ‰ units, the reference standards being PDB-1 for carbon and V-SMOW for oxygen.

⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd 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 (2s), ⁸⁶Sr/⁸⁸Sr normalized to 0.1194; La Jolla standard gave 0.511856 ± 0.000015 (2s). Nd isotopic ratios were normalized for within-run fractionation to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. Standard deviations of the isotopic ratios are expressed at 95% confidence level as 2s of the mean value. The e_r Sr-Nd notations were calculated using the following values for the Bulk Earth: ⁸⁷Sr/⁸⁶Sr = 0.7045, ⁸⁷Rb/⁸⁶Sr = 0.827, ¹⁴³Nd/¹⁴⁴Nd = 0.512638 and ¹⁴⁷Sm/¹⁴⁴Nd = 0.1967.

Selected analyses (major and trace elements) are given in Tables 1 and 2 (nomenclature: carbonatites after Woolley & Kempe 1989; silicate rocks after De La Roche *et al.* 1980). The

isotopic values are listed in Tables 3 and 4.

PETROGRAPHICAL OUTLINES **Anitápolis** The prevailing (early) carbonatites are texturally coarse to medium-grained and allotriomorphic, and whitish. The main minerals are calcite, apatite and subordinate Fe-dolomite. Layers and/or patches of apatite, magnetite, phlogopite and altered olivine are noticeable. Olivine also appears as an accessory phase along with pyrochlore, sulphides and occasional baddeleyite.

Late carbonatite veins are only recognized in drill cores (Furtado 1989), the rocks being fine to coarse-grained, allotriomorphic to hypidiomorphic in texture, and pink-greyish. They are composed of calcite and subordinate Mg-ankerite, quartz, apatite and phlogopite; accessories include RE fluorcarbonates (ancylite, bastnaesite), alstonite, fersmite, magnetite, pyrite and galena.

The ultramafic rocks (mostly phlogopite-pyroxenites and apatite-biotite-pyroxenites) are fine to very coarse (pegmatoid) in size and display cumulus texture with variable orthocumulus minerals: clinopyroxene (diopside to augite), mica (chiefly tetraferriphlogopite), apatite and magnetite. Alkali feldspar (Or 79-90 wt%), nepheline (Ks > 30 wt%) and carbonates (mainly calcite and ankeritic dolomite) are intercumulus phases. Titanite, amphibole, pyrrhotite, calcopyrite and pyrite are also frequent. The apatite-biotite pyroxenites are characterized by the presence of carbonate "ocelli" where clinopyroxene, alkali feldspar and nepheline are found mantled by a biotite shell, indicating local increase of alkaline hydrous fluid activity.

The alkaline rocks (nepheline syenites and subordinate ijolites) have medium to coarse-grained and hypidiomorphic to heterogranular texture, and contain variable amounts of idiomorphic clinopyroxene (augite to ferriaugite), biotite and magnetite (25 ± 12 , 9 ± 5 and 2 ± 1 vol%, respectively). Alkali feldspar (Or 87 ± 4 wt%) and nepheline (Ks 35 ± 11 wt%) are the main felsic phases (28 ± 15 and 26 ± 20 vol%, respectively), and apatite, titanite, pyrrhotite and carbonates occur as accessory phases. Nephelinite dykes are porphyritic in texture with phlogopite phenocrysts and microphenocrysts of diopside, olivine and opaques set in a hypohyaline groundmass.

Gibson *et al.* (1999) also reported the occurrence of nephelinite dykes near São Paulo dos Pinhais and Rio Branco, not too far from the Anitápolis alkaline complex (see Table 3).

Lages Early carbonatites are represented by medium-grained, hypidiomorphic and brownish rocks consisting of Mg-ankerite and calcite with alkali feldspar xenocrysts and accessory apatite, quartz, pyrochlore and pyrite. Locally, concentrations of tetraferriphlogopite are present. On the other hand, late carbonatites bear abundant veins and patches of barite and RE fluorcarbonates (synchysite).

Kimberlitic diatreme breccias (Scheibe 1986) are characterized by angular fragments of various rock-types (carbonatite, dunite, nepheline syenite, leucitite, tholeiitic basalt) and minerals (phlogopite, diopside, garnet, ilmenite, magnetite and zircon) set in a strongly altered groundmass. In particular, the tholeiitic basalts have hypohyaline and microporphyritic texture with plagioclase, augite, pigeonite and opaques as pheno- and microphenocrysts; leucititic rocks are made of pheno- and microphenocrysts of leucite, phlogopite, diopsidic clinopyroxene set in a glassy-carbonatitic (Mg-ankerite) groundmass.

Table 1 - Selected analyses of Ca-carbonatites and associated silicate rocks from Anitápolis.

Sample wt%	SAN 1. Ca-carb	SAN 14-49 Ca-carb	SAN 12-78 Ca-carb	SAN 11- 101 Ca-carb	SAN 2N Phlogopite pyroxenite	SAN 8 Apatite- biotite pyroxenite	SAN 24 Ijolite	SAN 25 Nepheline syenite	SAN 6A Mela nephelinite
SiO ₂	0.31	0.20	2.45	1.20	38.19	33.57	40.61	44.88	38.54
TiO ₂	0.01	0.01	0.06	0.05	1.93	3.40	3.49	3.31	2.61
Al ₂ O ₃	0.21	0.02	0.01	0.09	6.12	7.60	14.56	18.91	10.97
FeO _t	0.08	2.59	2.03	2.95	13.59	11.80	9.99	8.14	10.61
MnO	0.07	0.08	0.23	0.22	0.22	0.17	0.19	0.18	0.19
MgO	1.55	2.30	4.13	1.83	14.15	13.78	6.64	2.15	10.00
CaO	53.59	51.25	49.36	52.15	12.73	15.47	11.34	8.44	10.93
Na ₂ O	0.05	0.16	0.34	0.01	1.66	0.71	2.71	4.08	2.94
K ₂ O	0.49	0.78	0.07	0.02	3.30	4.55	4.95	5.48	4.14
P ₂ O ₅	0.48	1.31	2.37	2.89	1.45	6.34	1.46	0.63	0.96
L.O.I.	42.06	40.13	38.72	38.25	4.98	2.18	2.81	2.66	6.93
p.p.m.									
Rb	3.2	6.1	6.5	6.9	104.6	213.7	124.5	103.0	107.9
Ba	1051.8	950.6	1579.4	1120.6	1758.3	3800.0	2357.5	1300.0	2509.0
Th	5.6	3.5	10.2	4.2	6.9	1.2	5.1	8.2	3.3
Nb	5.2	8.9	7.8	10.4	26.2	22.8	54.3	67.1	28.6
Ta	1.4	0.5	1.5	1.8	1.9	1.8	2.7	3.1	1.3
Sr	2462.3	2982.9	6848.5	4462.3	616.2	954.7	724.5	677.2	397.9
Hf	0.4	0.4	1.8	0.8	6.9	3.6	5.4	7.1	3.5
Zr	15.8	7.7	46.2	15.5	188.9	146.2	213.3	307.9	117.7
Y	43.7	18.8	45.9	42.9	16.4	56.1	33.4	15.2	29.1
La	67.13	41.20	125.38	48.57	42.15	116.08	47.66	29.71	59.76
Ce	142.32	90.30	286.66	106.45	90.52	243.64	103.77	67.37	98.65
Pr	16.80	12.24	29.17	14.44	11.16	26.77	13.46	10.15	14.89
Nd	69.62	47.54	115.73	53.49	46.70	104.32	54.73	42.31	73.22
Sm	13.78	9.43	21.33	9.44	9.07	19.71	10.59	8.31	16.80
Eu	3.99	2.53	6.51	3.91	2.78	5.41	2.89	2.22	3.04
Gd	12.57	7.91	19.83	8.90	8.05	15.74	8.38	6.42	13.90
Tb	1.87	1.35	2.37	1.59	1.37	2.22	1.29	1.03	2.30
Dy	9.62	7.67	11.63	9.04	7.67	10.59	5.97	4.45	13.19
Ho	1.74	1.39	2.44	1.64	1.39	1.92	1.13	0.87	2.25
Er	4.81	3.17	5.80	3.74	3.67	5.00	2.83	2.11	5.46
Tm	0.63	0.56	0.81	0.67	0.54	0.74	0.41	0.30	0.73
Yb	3.74	3.09	4.83	3.48	3.31	4.37	2.38	1.70	2.79
Lu	0.59	0.44	0.65	0.51	0.47	0.61	0.34	0.25	0.38

The silicate rocks are classified by Traversa *et al.* (1994) as olivine melilitite, olivine nephelinite, basanite, tephrite-phonotephrite, nepheline syenite and phonolitic rock-types (trachyphonolite, phonolite and peralkaline phonolite).

Olivine melilitite shows fine-grained equigranular to inequigranular texture with pheno- and microphenocrysts and groundmass minerals consisting of olivine (Fo 87-91 mol %), phlogopite, melilite, nepheline (Ks = 29 wt%), diopsidic clinopyroxene and Ti-magnetite, and apatite and perovskites as accessory phases. Olivine nephelinite (melanephelinite) has inequigranular to porphyritic texture with pheno- and/or micro-phenocrysts of olivine, diopside, opaques, perovskite, apatite and melilite and groundmass of olivine (Fo 89-90 mol%), diopside, nepheline (Ks = 33 wt%), Ti-magnetite, phlogopite, leucite, kalsilite, apatite and perovskite. Basanite is porphyritic with olivine, phlogopite and clinopyroxene phenocrysts set in a groundmass composed of olivine, clinopyroxene, phlogopite, Ti-magnetite, plagioclase, alkali feldspar and nepheline. Tephrite and phonotephrite are weakly porphyritic

with diopside, amphibole, and nepheline phenocrysts, and Ti-magnetite microphenocrysts, set in a groundmass showing the same constituents and plagioclase. Nepheline syenite is coarse to medium-grained and porphyritic with large megacrysts of alkali feldspar (Or 73 wt% as average), nepheline (Ks 17 wt% as average), diopsidic to aegirinaugitic clinopyroxene, biotite, Ti-magnetite, apatite and titanite. Phonolite is weakly porphyritic to strongly porphyritic with phenocrysts of alkali feldspar (Or 70-75 wt%), nepheline (Ks up to 27 wt %), aegirinic clinopyroxene, titanite, ± biotite and melanite. The groundmass is made of glass, alkali feldspar (Or 65-95 wt%), nepheline (Ks up to 25 wt%) and aegirinic clinopyroxene.

GEOCHEMICAL RESULTS The analyzed carbonatites plot into two main groups in the CaO-MgO-(FeO+MnO) wt% diagram (Fig. 3): Ca-carbonatites (Anitápolis) and Fe-carbonatites (Lages).

It should be noted that by using the concept of carbonatite "stage" (cf. Wall & Mariano 1996) based on mineral consti-

Table 2 - Selected analyses of early and late carbonatites (I and II, respectively) and associated silicate rocks from Lages.

Sample wt%	SB 05 Fe-carb (I)	SB 02 Fe-carb (II)	SB 10-61.0 Si-carb (I)	SB 11-24.4 Phlogopite carb (I)	SB 09 Leucititic xenolith	SB 07 L-Ti Thol. basalt xenolith	SB 08 Tephrite
SiO ₂	2.53	1.46	32.50	26.01	31.50	48.99	44.71
TiO ₂	0.05	0.04	0.44	0.37	0.59	1.76	1.50
Al ₂ O ₃	0.87	0.83	12.11	8.18	20.73	13.87	16.46
FeO _t	10.28	17.74	10.06	11.61	3.69	12.92	6.36
MnO	1.06	2.39	0.54	0.66	0.16	0.20	0.16
MgO	14.16	12.72	0.35	6.12	2.15	6.35	5.02
CaO	34.27	29.41	19.77	17.37	11.36	9.32	9.40
Na ₂ O	0.02	0.02	0.07	0.19	0.59	2.50	3.78
K ₂ O	0.26	0.20	3.69	5.76	17.89	0.38	3.99
P ₂ O ₅	0.03	0.04	0.54	0.05	0.41	0.24	0.65
L.O.I. p.p.m.	35.33	33.16	18.83	22.39	10.52	1.86	7.27
Rb	6.1	3.5	78.3	394.0	1078.0	9.4	105.5
Ba	951.0	13528.0	1756.0	581.5	6940.0	161.0	2202.0
Th	3.5	5.0	8.9	6.0	480.5	2.1	27.8
U	1.4	0.8	2.0	1.2	119.1	0.4	6.4
Nb	8.9	8.4	26.2	4.8	25.2	8.2	65.1
Ta	1.5	2.0	2.0	0.7	1.9	0.6	4.1
Sr	2983.0	8057.0	616.2	5237.0	4243.0	183.0	1650.0
Hf	0.4	0.1	6.9	1.9	1.9	3.3	8.7
Zr	7.7	14.3	188.9	59.1	203.0	123.0	385.0
Y	18.8	45.5	16.4	59.3	24.2	29.5	23.6
La	41.20	2569.00	42.15	106.44	1109.00	12.55	104.68
Ce	90.31	5236.00	90.52	223.75	2260.00	28.20	173.74
Pr	12.24	767.00	11.16	26.90	137.30		17.37
Nd	47.54	2184.00	46.70	103.19	354.33	19.75	57.51
Sm	9.43	375.60	9.07	17.74	73.23	4.28	8.22
Eu	2.53	80.11	2.78	6.81	20.58	1.51	2.20
Gd	7.91	225.32	8.05	17.78	48.17		6.45
Tb	1.35	12.69	1.37	2.45	5.16	0.81	0.94
Dy	7.67	56.91	7.67	13.47	23.17		4.09
Ho	1.39	9.39	1.40	2.42	3.86		0.40
Er	3.17	22.45	3.67	6.04	7.39		1.28
Tm	0.56	2.34	0.54	0.86	0.79		0.22
Yb	3.09	8.72	3.31	4.89	4.17	2.83	1.49
Lu	0.44	0.86	0.61	0.57	0.42	0.44	0.15

tuents only the Anitápolis carbonatites may be considered as "early" carbonatites (prevailing Ca-carbonatites containing apatite and magnetite), whereas the Lages carbonatites appear on the whole as "late" carbonatites (prevailing iron-rich dolomite or ankerite carbonatites containing baryte, fluorite, RE minerals, U-Th minerals, quartz or chalcedony).

The silicate rocks associated with the carbonatites, excluding those showing alteration products such as cancrinite, secondary carbonates, zeolites, clay minerals and so on, belong to the potassic suites (Morbideilli et al., 1995) and range from strongly potassic to "transitional" rock-types (inset of Fig. 3).

Trace elements Abundance patterns for the incompatible elements (IE) and REE, normalized to the primitive mantle and to the chondrites (Sun & Mc Donough 1989, and Boynton 1984, respectively), are presented in figures 4 and 5 (Anitápolis and Lages, respectively).

Mantle normalized Anitápolis early Ca-carbonatites have positive spikes of Sr-P, Sm, Eu and Tb, and negative ones of Nb, K, Hf-Zr and Ti. The late carbonatites (cf. Furtado 1989) are ten or more times enriched with Ba-Th-U-Nb and La-Ce,

Nd, Eu, Y-Yb compared to the early analogues, and present a negative Sr-P anomaly. The associated alkaline rocks (ijolites, nepheline syenites and nephelinite dykes) display a more "flattened" behaviour, characterized by a positive K spike. The cumulate rocks (mainly phlogopite pyroxenites and apatite-biotite pyroxenites) overlap to some extent the field of the former rocks, showing positive anomalies of P, Eu and Tb.

In the [REE]_N diagrams, the cumulate rocks fall roughly into the same range of the early carbonatites, but have lower LREE, (La/Yb)_N = 13.3 ± 6.6 (pyroxenites) vs. 13.5 ± 4.3 (early carbonatites), whereas the ijolites to nepheline syenites and nephelinites present the lowest LREE, with (La/Yb)_N = 13.2 ± 1.3 and negative Eu anomaly (Eu/Eu* = 0.65 ± 0.24). The late carbonatites have (La/Yb)_N = 3.0 and are strongly REE-enriched.

On the whole, the Anitápolis complex (mass balance calculation and trace elements modelization, not shown) is consistent with about 70% of cumulate rocks, 29% of ijolite + nepheline syenite and 1% of carbonatite.

[I.E.]_N diagram for Lages early Fe-carbonatites present positive spikes of Ba, La, Nd-Sm and Tb, and negative ones of

Table 3 - Isotopic data and main mineral assemblage for the carbonatites and associated silicate rocks from Anitápolis (notional age: 132 Ma). Additional data: (*) Toyoda et al. (1995); (**) Gibson et al. (1999).

			ppm	d‰ _{alk-ant}	d‰ _{calc}	ppm	ppm	Measured	132 Ma	ppm	ppm	Measured	132 Ma			Ma	Main mineralogy		
	Lan	(La/Yb) _N	S REE	¹⁸ O	¹³ C	¹⁸ O	¹³ C	Rb	Sr	⁸⁷ Sr/ ⁸⁶ Sr	R ₀	Sm	Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	R ₀	eSr	eNd	T _{DMT}	
CARBONATITES																			
Bore-holes																			
SAN 14-49	133	9	229	8.21	-6.69	7.5	-7.15	6.1	2983	0.705952 (8)	0.7059	9.43	47.54	0.512281 (8)	0.51218	19.8	-5.7	1339	cc, ap, phl, (af)
SAN 12-78	405	17.5	633	8.19	-6.78	7.47	-7.15	6.48	6849	0.705953 (6)	0.706	21.33	115.7	0.512279 (7)	0.51222	19.9	-5.6	1237	cc, dol, ap, phl
S-83.6 (F)	1803	2.99	3800									180.2	672.6						cc, Mg-ank, phl, fcc, ap, op
SAN 11-101	157	9.4	266	8.04	-7.21	7.55	-7.38	6.87	4462	0.705952 (6)	0.7059	9.44	53.49	0.512259 (7)	0.51213	19.8	-6.7	1266	cc, dol, ap, (qz)
Surface samples																			
AP 891 (T)	400	20.7	679			9	-6.7	0	4000	0.706151 (6)	0.7062	36.1	150			22.7			cc, ap, op
SAN 1	217	12.1	352	8.24	-7.07	7.65	-7.24	3.22	2462	0.705947 (10)	0.7059	13.78	69.62	0.512262 (8)	0.51222	19.8	-6	1365	cc, dol, ap
SAN 2	222	11.4	368	8.51	-6.93	7.94	-7.34	272	1739	0.706779 (8)	0.7059	14.75	72.33	0.512278 (8)	0.51217	19.6	-5.8	1391	cc, ap, dol, op, af, phl
SAN 13	343	14.7	538	7.65	-7.25	7.52	-7.37	114	7194	0.706029 (8)	0.7059	22.12	103.2	0.512332 (10)	0.51222	19.8	-4.8	1397	cc, dol, op, phl
SILICATE ROCKS																			
SAN 2N Phlogopite pyroxenite	136	8.6	229	8.01	-7	7.89	-7.26	105	616	0.706830 (10)	0.7059	9.07	46.7	0.512278 (11)	0.51215	19.6	-6.2	1350	px, phl, op, ap, cc
SAN 6A Melanephelinite (dyke)	331	17.3	502	10.12	-6.89	10.02	-7.15	826	798	0.711471 (5)	0.7059	18.86	101.4	0.512333 (10)	0.51224	18.5	-4.5	1172	phl, px, ol, op, glass, dol, ap
SAN 8 Apatite-biotite pyroxenite	375	17.9	560	11.05	-6.43	10.38	-6.82	214	955	0.707139 (11)	0.7059	19.71	104.3	0.512290 (6)	0.51219	19.5	-5.4	1254	ap, biot, px, op, cc
Nephelinite (G) (dyke)**	103	13.4	150					111	1082	0.70678 (7)	0.7062	6.04	33.4	0.51220 (7)	0.51211	23.8	-7.1	1322	biot, px, ol, af, ne, op
Nephelinite (G) (dyke)**	153	16	205					120	834	0.70736 (7)	0.7066	6.61	38.8	0.51225 (7)	0.51216	28.8	-6	1185	biot, cpx, ol, af, ne, op
SAN 24 Jiolite	154	13.5	256	7.99	-6.65	7.51	-7.17	125	724.5	0.706836 (9)	0.7059	10.59	54.73	0.512286 (11)	0.51218	19.3	-5.5	1295	px, phl, af, ne, op, ap, cc
SAN 25 Nephelinite syenite	96	11.8	148			8.98	-7.1	103	677	0.706751 (10)	0.7059	8.31	42.31	0.512285 (10)	0.51218	19.6	-5.6	1317	af, ne, px, biot, op

Abbreviations: af = alkali feldspar; am = amphibole; ank = ankerite; ap = apatite; ba = barite; biot = biotite; cc = calcite; ccpx = Ca-clinopyroxene; dol = dolomite; fcc = fluorocarbonates; fl = fluorite; kp = kalsilite; lc = leucite; mel = melilitite; ne = nephelinite; op = opaque; phl = phlogopite; pig = pigeonite; pl = plagioclase; prv = perovskite; px = pyroxene; qz = quartz; sph = titanite; str = strontianite.

Table 4 - Isotopic data and main mineral assemblage for Lages carbonatites (+, early carbonatites; *, late carbonatites), associated silicate rocks (notional age: 76 Ma), and xenoliths from pipes. Additional data: S, Scheibe (1986); C, Carlson et al. (1996); T, Traversa et al. (1996); G, Gibson et al. (1999). Abbreviations as in Table 3.

	Lan	(La/Yb) _N	ppm SREE	ppm ¹⁸ O	d ¹⁸ O _{calc} - ¹⁸ O _{carb}	ppm ¹⁸ O	d ¹⁸ O _{calc} - ¹⁸ O _{carb}	ppm Rb	ppm Sr	Measured ⁸⁷ Sr/ ⁸⁶ Sr	76Ma R ₀	ppm Sm	ppm Nd	Measured ¹⁴³ Nd/ ¹⁴⁴ Nd	76 Ma R ₀	eSr	eNd	Ma T _{DM}	Main mineralogy
CARBONATITES																			
Bore-holes																			
(S)FV-14*				16,67	-3,09														
(S)FV-24*				23,91	-3,02														
(S)FV-26+				11,24	-7,15														dol, cc, ba, fcc
(S)FV-32*	10335	275	12294	12,43	-2,44														ank, cc, ba, fcc
(S)FV-33*				11,44	-5,27														ank, cc, fcc, ap
(S)LG-1/2-64.5*	54461	813	41833	10,63	-4,26														ank, ba, fcc
(S)LG-1/4*				21,19	-1,66														ank, ba, fcc
(S)LG-1/6+				8,95	-4,38														ank, ba, fcc
(S)LG-1/8-101.4+				9,74	-4,07	9,02	-4,48												ank, cc, ba, fcc
(S)LG-1/10-109.8*	2752	82	3478	9,26	-4,89	8,64	-5,27												ank, cc, ba, ap
(S)LG-1/12-123.8+				9,11	-4,89	8,38	-5,3												ank, cc, phl, ap
(S)LG-3/5-34.3*	6952	484	8561																cc, ank, fcc, ba
(S)LG-3/8-27.9*	1623	339	2268																ank, cc, ba, phl
SB10-61+	136	8,59	229	17,45	-4,56			78,3	616,2	0.706240 (5)	0.7058	9,07	46,7	0.512100 (4)	0.51214	17,48	-9,72	1576	ank, cc, ba, phl
SB11-24.4+	343	14,7	537	11,12	-3,94	12,54	-3,9	394	5237	0.705887 (9)	0.7057	17,74	103,2	0.512229 (9)	0.51218	14,76	-7,08	1222	ank, cc, phl, ap
SB14-60+	286	14,7	377			10,92	-4,54	10,39	3738	0.706101 (6)	0.7061	10,95	60,16	0.512112 (6)	0.51204	21,01	-9,42	1454	cc
SB15-20+	331	17,3	494	9,59	-4,67			3,8	4879	0.706946 (7)	0.7069	18,86	86,96	0.511969 (5)	0.5119	33,09	-12,95	1718	ank
SB16-28.34+	375	17,9	561	10,17	-4,2	10,19	-3,86	155,64	954			19,71	104,3						ank, cc, phl
SB17-34.38+	405	17,5	634	10,37	-4,29			6,48	6849			21,33	115,7						ank
SB18-50*	7500	206	11157	10,55	-4,33			236,3	3937	0.706263 (9)	0.7062	358,7	2086	0.512232 (6)	0.51218	20,77	-7,02	1218	ank, phl, ap
SB19-80*	1105	89,9	1243	24,84	-3,24	22,73	-4,76	120,85	1094			38,43	158,2						ank, cc, ap
SB20-85*	1297	88,3	1431	8,99	-5,76			1,9	1544	0.706126 (5)	0.7061	42,84	185,9	0.512151 (13)	0.51208	21,43	-8,94	1910	ank
Surface samples																			
SB-02*	8287	199	11550	15,18	-1,66			3,52	8057	0.705967 (13)	0.706	375,6	2184	0.512156 (5)	0.5121	19,21	-8,5	1319	ank, ba, fcc
SB-03+	157	9,4	275	15,82	-1,55			6,87	4462			16,44	53,49						ank
SB-05+	133	9	229	16,45	-0,46			6,1	2983	0.706263 (10)	0.7063	9,43	47,54	0.512138 (11)	0.51208	23,34	-9,01	1558	ank

Table 4 (cont.)

			ppm	ppm	ppm	Measured	76Ma	ppm	ppm	Measured	76Ma	eSr	eNd	Ma	Main mineralogy
	Lav	(La/Yb) _N	S REE	Rb	Sr	⁸⁷ Sr/ ⁸⁶ Sr	R ₀	Sm	Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	R ₀			T _{DM}	
SILICATE ROCKS															
SB-08 Tephrite	338	47,4	379	105,47	1650	0.705111 (9)	0.70491	8,22	57,51	0.512434 (8)	0.51236	4,28	-2,91	826	phl, px, op, ne, glass
(C) Chapada Tephrite	326	54	388	76,7	1881	0.705285 (9)	0.70516	9,74	63,04	0.512405 (9)	0.51236	7,82	-3,54	907	px, pl, biot, af, op, glass
(G) B162 Ol-melilitite	329	25,7	448	58	1639	0.70462 (1)	0.70451	11,82	76,2	0.51244 (1)	0.51239	-1,45	-2,86	867	px, mel, ol, op, biot, ne, prv, ap
(G) B161 Ol-melilitite	532	33	596	96	1810	0.70472 (1)	0.70455	18,87	105	0.51243 (1)	0.51238	-0,82	-3,2	997	px, mel, ol, op, biot, ne, prv, ap
(T) LM6 Ol-melilitite	455	55,3	548	92	1470	0.70445 (2)	0.70425	14,55	85,43	0.51244 (2)	0.51239	-5,07	-2,95	936	px, mel, ol, op, biot, ne, prv, ap
(T) PA1 Ol-melilitite	400	55,7	492	64	1910	0.70443 (3)	0.70433	14,9	88,2	0.51250 (2)	0.51245	-4,07	-2,95	851	px, mel, ol, op, biot, ne, prv, ap
(G) B169 Melanephelinite	277	24,6	364	78	1941	0.70439 (1)	0.70426	11,7	66,3	0.51252 (1)	0.51247	-4,93	-1,43	858	px, ol, op, biot, ne, lc, ap, kp, prv
(G) B168 Melanephelinite	292	26,9	385	87	1648	0.70443 (1)	0.70427	11,42	65,9	0.51250 (1)	0.51245	-4,92	-1,8	870	px, ol, op, biot, ne, lc, ap, kp, prv
(T) PA3 Ol-nephelinite	289	46,5	356	45	1360	0.70466 (2)	0.70456	11,8	65,8	0.51232 (2)	0.51227	-0,78	-5,34	1147	px, ol, op, biot, ne, lc, ap, kp, prv
(T) LM115 Ol-nephelinite	295	46	384	85	1650	0.70477 (3)	0.70461	12,08	69,08	0.51235 (3)	0.5123	-0,03	-4,73	1079	px, ol, op, biot, ne, lc, ap, kp, prv
(G) B166 Ol-nephelinite	260	25,7	336	80	1353	0.70547 (1)	0.70529	10,2	61,2	0.51220 (1)	0.51215	9,55	-7,61	1227	px, ol, op, biot, ne, lc, ap, kp, prv
(T) PA4 Basanite	211	40,1	281	43	1010	0.70445 (2)	0.70431	9,4	55	0.51250 (3)	0.51245	-4,18	-1,79	859	px, ol, op, biot, ol, pl, af, ne, glass
(T) LM-1 Nepheline syenite	476	45	491	115	4320	0.70550 (2)	0.70542	10,46	67,12	0.51199 (3)	0.51194	11,42	-11,65	1418	ne, af, cpx, biot, op, ap, sph, ann
(T) LM-53 Nepheline syenite	489	44,5	520	122	3730	0.70540 (3)	0.7053	11,09	75,05	0.51201 (2)	0.51197	9,74	-11,21	1342	ne, af, cpx, biot, op, ap, sph, ann
(T) LM97 Peralkaline phonolite	69	18,2	87	122	310	0.70589 (1)	0.70466	2,23	13,01	0.51242 (3)	0.51237	0,69	-3,35	967	glass, ne, af, px, ap, sph
(T) LM-99 Peralkaline phonolite	421	48,6	387	125	2200	0.70535 (2)	0.70517	5,75	39,98	0.51204 (3)	0.512	7,96	-10,6	1283	glass, ne, af, px, ap, sph
XENOLITHS															
SB-07 L-Ti tholeiitic basalt (130 Ma)	40,48	2,99	75	9,4	183	0.705596 (11)	0.70532	4,28	19,75	0.512353 (10)	0.51224	10,96	-4,47	1383	glass, glass, pl, cpx, op, pig
SB-09 Leucite	3577	179	4047	1078	4243	0.705916 (7)	0.70512	73,23	354,3	0.512132 (17)	0.51207	7,24	-9,18	1651	glass, cc, lc, px, phl, op

Th, P, Hf-Zr, Ti and Y. The large range shown by the elements U-Nb-Ta-K reflects the local concentrations of uranpyrochlore, alkali feldspar and tetraferriphlogopite. The late carbonatites are systematically enriched with Ba, Th, La-Ce, Nd-Sm and Tb in comparison to the early analogues. Leucititic xenoliths from pipes containing large carbonatitic fragments display the same enrichment pattern (plus K) as the late carbonatites, probably reflecting the presence of carbonatitic material. However, these leucititic xenoliths differ considerably from the cognate tholeiitic xenoliths (L-Ti basalt) which present a more flattened tendency and I.E. and REE contents similar to those of the low-TiO₂ Early Cretaceous Paraná basalts (Fig. 5; cf. also Marques *et al.* 1989).

The alkaline rocks from the complex show [I.E.]_N and [REE]_N roughly in the same range as the early carbonatites, except for some leucocratic rock-types (peralkaline phonolites) having strongly Nb and Zr positive spikes and the lowest (La/Yb)_N values. The ratio numbers for the whole suite of rocks are: 13.6 ± 4.0, early carbonatites; 289 ± 238, late carbonatites; 179, leucitite; 3.0, L-Ti tholeiitic basalt; 36.1 ± 12.5, olivine melilitite + melanephelinite + basanite; 47.7 ± 4.4, tephrite + nepheline syenite; and 35.3 ± 16.7, peralkaline phonolite.

Traversa *et al.* (1996) suggested that I.E. trends and REE patterns of the "primitive" rock-types (i.e. olivine melilitite, melanephelinite, basanite) are consistent with a metasomatized mantle source, enriched with HFSE, LILE and LREE in respect to the primitive mantle, which suffered relatively low degree of partial melting of wet layers (e.g. 4-10%; cf. also Comin-Chiaramonti *et al.* 1997a), gradually increasing from olivine melilitite to basanite. Moreover, the Lages alkaline rocks are also consistent with petrogenetic models involving crystal-liquid fractionation from mafic magmas, through tephrite-phonotephrite, to peralkaline phonolites (Traversa *et al.* 1994). Some of the more evolved rocks could also be linked to crustal contamination during magma ascent and fractionation processes (Traversa *et al.* 1996).

Stable isotopes: Oxygen and Carbon In the Early Cretaceous Ca-carbonatites from Anitápolis where Fe-dolomite or Mg-ankerite are coupled with prevailing calcite, ¹⁸O and ¹³C isotopes lie within a very restricted range close to the "primary" magmatic carbonatite box, and tend to fit a straight line along with the Juquiá carbonatites (Fig. 6; cf. Walter *et al.* 1995). Isotopic values are in the same range as those shown by the carbonates from the associated silicate rocks (e.g. phlogopite pyroxenite and ijolite; cf. Table 3). The data suggest crystallization temperatures starting close to magmatic conditions (Fig. 7). Mass balance equations for oxygen and carbon of early carbonatites are consistent with a carbonatitic liquid formed under nearly closed conditions and varying within a temperature interval from about 700°C to 400°C, according to the equation CO₂ + H₂O → CO₃²⁻ + 2H⁺ (Wyllie 1989; Speziale *et al.* 1997). If this is the case, the Anitápolis early carbonatites may represent a type of parental unfractionated carbonatite magma from which the composition of Juquiá Mg-carbonatites could be obtained by fractionating of about 70-80% calcite (Fig. 7; cf. Beccaluva *et al.* 1992).

The Late Cretaceous Fe-carbonatites from Lages are characterized by a large spreading of d¹⁸O values (av. 13.55‰ ± 5.15‰) coupled with a relatively narrow d¹³ variation (av. -3.98 ± 1.40‰). Notably, all the late carbonatites tend to shift towards the meteoric calcite and sedimentary carbonate fields

(Fig. 6). This behaviour may be indicative of the action of groundwater weathering and/or of biogenic contamination, other than hydrothermal processes (Castorina *et al.* 1997).

Strontium and Neodimium isotopes The Ca-carbonatites from Anitápolis have Sr_i and Nd_i values in the same range as those of the associated silicate rock-types (Fig. 8A), i.e. Sr_i = 0.70597 ± 0.00008, Nd_i = 0.51219 ± 0.00004 (carbonatite) vs. Sr_i = 0.70605 ± 0.00026, Nd_i = 0.51217 ± 0.00004 (alkaline rocks and cumulates), supporting a common parent magma hypothesis for both sets of rocks. Correlations between stable and radiogenic isotopes are not apparent (inset of Fig. 8A). Only a sample (Ap 891, Table 3, cf. Toyoda *et al.* 1995) shows relatively high Sr_i and low d¹⁸O‰ (0.70615 and 9.0, respectively), but possible crustal contamination effects are not evident.

The Fe-carbonatites from Lages have Sr_i = 0.70622 ± 0.00032 and Nd_i = 0.51209 ± 0.00009 similar to the values found for the Anitápolis Ca-carbonatites, but with a major Nd_i spread (Fig. 8B). No apparent positive correlation between oxygen isotopes and Sr_i is indicated (inset of Fig. 8B), in spite of the weathering evidence and the "late" emplacement of the carbonatites. It should be noted that the silicate rocks of the complex are quite variable in composition, thus, making it difficult to suppose a direct link with the carbonatites: in fact, the silicate rocks spread from Sr_i = 0.70425 and Nd_i = 0.51247 (melanephelinite) to Sr_i = 0.70542 and Nd_i = 0.51192 (nepheline syenite). Moreover, some peralkaline phonolites display a crustal signature (Sr_i up to 0.73106 and Nd_i = 0.51188; not shown in this paper; sample LM 83, Table 3, cf. Traversa *et al.* 1996). On the other hand, the isotopic ratios of some peralkaline phonolites (e.g. LM112, Table 3, cf. Traversa *et al.* 1996) approach those of the carbonatites and therefore these latter rocks may have originated by immiscibility from a carbonate-rich liquid. Also according to Traversa *et al.* (1996), since even leucocratic rocks appear to have been formed by crystal fractionation processes starting at mafic types, the

Figure 3 – Classification of the carbonatite samples, according to Woolley & Kempe (1989). Inset: classification of the associated alkaline rocks (cf. Comin-Chiaramonti & Gomes, 1996).

Figure 4 - Anitápolis: Trace and RE elements normalized to the primitive mantle and to the chondrites (Sun & McDonough 1989, and Boynton 1984, respectively).

Figure 5 - Lages: Trace and RE elements normalized to the primitive mantle and to the chondrites (Sun & McDonough, 1989, and Boynton, 1984, respectively).

Figure 6 - Stable O-C isotope compositions for the investigated samples. Data sources for Açungui Group, meteoric calcite and Juquiá are from Fassbinder (1996), Alcover Neto et al. (1995) and Comin-Chiaramonti (unpublished data), respectively. PCB: primary carbonatite box, after Taylor et al. (1967) and Keller & Hoefs (1995).

extent of crustal assimilation is assumed to be relatively small; this is also supported by ACF models, indicating that the leucocratic rocks were affected by less than 8% crustal contamination. Finally, it is noticeable that some analyzed xenoliths from a Lages pipe, i.e. a leucite and a tholeiitic basalt, lie in the same isotopic range as that obtained from the alkaline rocks and low-Ti tholeiites of the area, respectively (Table 2, cf. Piccirillo & Melfi 1988).

ANITÁPOLIS ALKALINE-CARBONATITIC COMPLEX

Figure 7 - (A) Plot of $\delta^{18}\text{O}_{\text{dolomite-calcite}}$ vs. $\delta^{13}\text{C}_{\text{dolomite-calcite}}$ for coexisting pairs in the Anitápolis early carbonatites and associated alkaline rocks. Equilibrium lines, metamorphic and magmatic-hydrothermal, are from Sheppard & Schwartz (1970) and Deines (1989), respectively. (B) isotopic fractionation model (Speziale et al. 1997, Castorina et al. 1997). I, magmatic evolution; II, fluid related hydrothermal recrystallization; $f = (A-b)/A$ is the residual fraction of the fluid, defined by the equations:

$$2A\delta^{18}\text{O}(\text{CO}_2)^{\text{initial}} + B\delta^{18}\text{O}(\text{H}_2\text{O})^{\text{initial}} = 2a\delta^{18}\text{O}(\text{CO}_2) + 3b\delta^{18}\text{O}(\text{carbonate}) + c\delta^{18}\text{O}(\text{H}_2\text{O})$$

and

$$A\delta^{13}\text{C}(\text{CO}_2)^{\text{initial}} = a\delta^{13}\text{C}(\text{CO}_2) + b\delta^{13}\text{C}(\text{carbonate})$$

where a , b , c are CO_2 , CO_3^{2-} and H_2O molar

concentrations in the fluid-mineral system at the time t . A and B are the initial CO_2 and H_2O molar concentrations, respectively, in the magmatic fluid at "i" before crystallization of the carbonate (i.e., fixed A , from $\text{CO}_2/\text{H}_2\text{O}$ initial molar ratio, B is defined). From the above equations the concentration values of the various components can be defined at each time "t" as $b = A - a$ and $c = B - b$ (see Speziale et al. 1997 for detailed explanation).

Figure 8 - (A) Carbonatites and associated silicate rocks from Anitápolis in terms of initial isotopic ratios of Sr-Nd. Inset represents initial $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}\text{O}$ plot of carbonatites and other rock-types. (B) Carbonatites and associated silicate rocks from Lages in terms of initial isotopic ratios of Sr-Nd. Inset represents initial $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}\text{O}$ plot of carbonatites. Additional data sources are from Traversa *et al.* (1996) and Gibson *et al.* (1999).

SIGNIFICANCE OF THE RADIOGENIC ISOTOPES

In spite of the large variations in petrographic features, distribution of incompatible elements and O-C isotopes, the radiogenic isotopes of the investigated carbonatites are in the same range as those shown by the associated alkaline rocks, especially the nepheline syenites or phonolites. It also should be noted that in general the carbonatites from the whole Paraná-Angola-Etendeka Province (PAEP) have Sr_i and Nd_i values similar to those presented by the associated alkaline silicate rocks, even the samples more affected by hydrothermal processes, spanning from time integrated depleted (Angola and Namibia) to enriched types (Paraguay and Uruguay; Alberti *et al.* 1999, Kirkstein *et al.* 2000). This magmatism overlaps the subcoeval PAEP flood tholeiites and, on the whole, the data strongly suggest that the PAEP magmatism is related to large and small-scale heterogeneous subcontinental mantle variously "contaminated" by ancient metasomatic processes (Comin-Chiaromonte *et al.* 1997a,b). Yet to be registered the time-integrated depleted signature of the Trindade Island is similar to that shown by the Angola and Namibia alkaline-carbonatitic magmatism of Early Cretaceous (and Late Cretaceous) age, but different from that (EMI to B.E. signature) related to the Late Cretaceous analogues in Brazil (Alto Paranaíba, Ponta Grossa Arch and Lages). The alkaline magmatism of Tristan da Cunha, Gough and Inaccessible inlands, and Walvis Ridge have B.E.-EMI Sr-Nd isotopic characteristics which are distinct or partly overlap those of the Early Cretaceous alkaline-carbonatitic (and tholeiitic) magmatism. Therefore, the contribution of the asthenospheric components derived from the Tristan da Cunha plume is not appreciable (Comin-Chiaromonte *et al.* 1999).

Hawkesworth *et al.* (1986) interpreted the EMI signature of the Etendeka basalts as resulting from the melting of ancient lithospheric mantle which, in the case of Walvis Ridge (WR2 basalts), is found as remnant within the shallow oceanic asthenosphere following the opening of the South Atlantic. Alternatively, this signature may result from the contamination of the oceanic mantle by ancient continental lithospheric mantle that was eroded from the base of the lithosphere at the time of the continental break-up (Milner & Le Roex 1996).

Assuming that Sm/Nd was not substantially modified by melting and magma differentiation, Nd-model ages provide a broad estimate as to the time when a "metasomatic" event may have occurred. Early Cretaceous and Late Cretaceous carbonatites from the Ponta Grossa Arch display average model ages (0.64 ± 0.08 and 0.65 ± 0.07 Ga, respectively) similar to those of the Early Cretaceous (and Late Cretaceous) alkaline-carbonatitic complexes from Angola and Namibia (Fig. 9; cf. Alberti *et al.* 1999, and therein references); Early Cretaceous Anitápolis carbonatites (Santa Catarina State, along Uruguay lineament) have an average model age of 1.3 ± 0.1 Ga, intermediate between the H-Ti and L-Ti tholeiites from the PAEP; finally, Late Cretaceous Lages carbonatites (Santa Catarina State, along the same Uruguay lineament) show a large broad variation with an average model age of 1.2 ± 0.2 Ga. However, the bimodal distribution (mafic rocks: 0.9 ± 0.1 Ga; peralkaline phonolites + carbonatites: 1.4 ± 0.1 Ga) seems to indicate the presence of two different mantle metasomatized sources as suggested by Traversa *et al.* (1996). In this scenario the model ages of Lages carbonatites tend towards the ancient model ages of alkaline complexes from Paraguay and Uruguay

(~1.5 and 1.7 Ga, respectively).

DISCUSSION AND CONCLUSIONS The link with the geodynamic processes which led to the opening of the South Atlantic Ocean is crucial to the magma genesis. According to Nüberg & Müller (1991), the sea-floor spreading in the South Atlantic at Paraná Basin latitude was initiated at ~125-127 Ma (Chron M4). To the north of the Walvis-Rio Grande ridges (latitude >28°), the onset of oceanic crust would be younger (~113 Ma; Chang *et al.* 1988). The Anitápolis alkaline-carbonatitic complex (and in general the Early Cretaceous analogues from Angola, NW Namibia, Ponta Grossa Arch, Paraguay and Uruguay) is subcoeval with the main flood tholeiites of the Paraná Basin and, therefore, occurred during the early stages of rifting, before the continental separation. On the other hand, the Florianópolis dyke swarms approach the time of sea-floor spreading (~120 Ma). The Late Cretaceous Lages alkaline-carbonatite rocks (and the analogues from Ponta Grossa Arch, Serra do Mar, Taiúva-Cabo Frio Lineament, Alto Paranaíba, Iporá, Namibia) correspond to a more advanced stage of the Africa-South America continental separation.

The debate concerning the origin of these types of magmatism with respect to plate tectonics is still opened and a subject of controversy, and various models have been proposed invoking the presence of mantle plume/hot spots (up to 16; Stefanick & Jurdy 1984) or of shallow thermal anomalies (Holbrook & Kelemen 1993). However, even considering the large degree of flexibility permitted in the plume concept (such as composition, temperature, size and depth of origin, adoption of any number of hot spots), this model cannot account for all occurrences of the types of volcanic occurrences (see Smith & Lewis 1999, for a general discussion). Gibson *et al.* (1999) suggested that the Late Cretaceous Lages magmatism, located more than 1000 km to the south of the postulated center of the Trindade plume, was induced by high temperature melts channelling away southwards from the thick keels of the São Francisco craton, without considering other occurrences of Late Cretaceous alkaline rocks (e.g. Piratini in the Rio Grande do Sul State) and the mechanical barriers formed by the "second order plate boundaries" ("wet plumes"; e.g. Ponta Grossa Arch, Rio Piquiri and Rio Uruguay lineaments; Comin-Chiaramonti & Gomes 1996).

A more convincing model is thought to be that proposed by Smith & Lewis (1999). The forces acting on plates with differential angular velocity and the presence of volatile-rich mantle sources (wet spot) would drive the rifting to occur parallel to the pre-existing N-S sutures, i.e. "Adamastor Ocean", in the South Atlantic basin (Fig. 10). Intraplate alkaline and alkaline-carbonatitic magmatism occurs where second order sutures (e.g. Alto Paranaíba Arch, Ponta Grossa-Moçamedes Arch, Uruguay lineament, Damara Belt) intersect the axis of major rifting, indicating an erosion and cycling of continental mantle towards the ridge axis by local convection taking the form of transverse rolls.

In southern Brazil, the alkaline and alkaline-carbonatitic magmatism is concentrated in regions affected by a positive geoid anomaly (Molina & Ussami, 1999) that may refer to dense (and warm), very deep material. Moreover, the different westwards angular velocity of lithospheric fragments in South American plate, defined by the second order plate boundaries, may favour the decompression and melting of the variously metasomatized (wet spot) portion of the lithospheric mantle

Figure 9 - Synoptical Nd model-ages relative to the Early Cretaceous and Late Cretaceous alkaline-carbonatitic and carbonatitic complexes from the Paraná-Angola-Etendeka Province. For data sources see Comin-Chiaramonti *et al.* (1999).

Figure 10 - Forces acting on plates in rotational model illustrated by the present South Atlantic basin (after Smith & Lewis 1999, modified). Major rifting occurs parallel to the X-X' pre-existing suture. Intraplate volcanism follows the second order sutures (e.g. PG-MO: Ponta Grossa-Moçamedes Arch, UR: Rio Uruguay lineament; DM: Damara Belt). MAR: Mid Atlantic Ridge; SA: South America plate; AF: African plate; RGR: Rio Grande Rise; WR: Walvis Ridge; TdC: Tristan da Cunha; T: Trindade. F_{CD} : continental drag; F_{RP} : ridge push; F_{SU} : trench suction. F, Florianópolis; A, Anitápolis; L, Lages.

with different isotopic imprint and at different times (cf. also Comin-Chiaromonti *et al.* 1999).

This scenario may explain the presence of Late Cretaceous to Tertiary sodic magmatism in the Paraná-Angola-Etendeka Province (Fig. 1), even up to the Eastern Paraguay where there is evidence of active rifting structures (Comin-Chiaromonti *et al.* 1999). In this case, the thermal perturbations may be channeled along the second order plate boundaries, as pictured by the hypocenters of earthquakes in South America (Berrocal

& Fernandes 1996).

Acknowledgements Special thanks are due to M. Ernesto, L. Marques, N. Ussami and E. Molina for helpful discussions and suggestions. This research was supported by grants from Italian (CNR, MURST 60%, COFIN 98) and Brazilian (FAPESP, Proc. 97/01210-4) agencies. To two anonymous referees of RBG for the suggestions to the original.

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Manuscrito A-1204

Recebido em 10 de janeiro de 2001

Revisão dos autores em 15 de janeiro de 2002

Revisão aceita em 20 de janeiro de 2002