Review Article

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Carbonatites from the southern Brazilian Platform: A review. II: Isotopic evidences

Abstract: Early and Late Cretaceous alkaline and alkaline–carbonatitic complexes from southern Brazil are located along the main tectonic lineaments of the South America Platform. Calcium-, magnesium-, and ferrocarbonatites are well represented and frequently associated even in the same complex. Primary carbonates present significant variations in C–O isotopic compositions, which are mainly due to isotope exchange with H_2O–CO_2-rich hydrothermal fluids, whereas fractional crystallization or liquid immiscibility probably affects the $\delta^{18}O$ and $\delta^{13}C$ values by no more than 2‰. Our isotope exchange model implies that the most significant isotopic variations took place in a hydrothermal environment, e.g., in the range 400–80°C, involving fluids with the CO_2/H_2O ratio ranging from 0.8 to 1. Sr–Nd–Pb isotope systematics highlight heterogeneous mixtures between HIMU and EMI mantle components, similar to the associated alkaline rocks and the flood tholeiites from southern Brazil. In spite of the strong variation shown by C–O isotopes, Sr–Nd–Pb–Os isotopic systematics could be related to an isotopically enriched source where the chemical heterogeneities reflect a depleted mantle "metasomatized" by small-volume melts and fluids rich in incompatible elements. These fluids are expected to have promoted crystallization of K-rich phases in the mantle, which produced a veined network variously enriched in LILE and LREE. The newly formed veins (enriched component) and peridotite matrix (depleted component) underwent a different isotopic evolution with time as reflected by the carbonatites. These conclusions may be extended to the whole Paraná–Etendeka system, where isotopically distinct parent magmas were generated following two main enrichment events of the subcontinental lithospheric mantle at 2.0–1.4 and 1.0–0.5 Ga, respectively, as also supported by Re–Os systematics. The mantle sources preserved the isotopic heterogeneities over a long time, suggesting a nonconvective lithospheric mantle beneath different cratons or intercratonic regions. Overall, the data indicate that the alkaline–carbonatitic magmatism originated from a locally heterogeneous subcontinental mantle.

1 Introduction

Southern Brazil is part of the Paraná–Etendeka Province (PAEP) [1] characterized by the emplacement of Early Cretaceous tholeiitic flood basalts and dyke swarms, 129–133 Ma aged [1–6], and alkaline and alkaline–carbonatite complexes of Early Cretaceous to Paleogene age [8–12]. The alkaline and alkaline–carbonatitic complexes formed mainly along tectonic structures (Figure 1) active at least since Early Mesozoic, and up to the present day, as indicated also by the distribution of the earthquakes in southern Brazil [13].

Almost all the carbonatites from southern Brazil are restricted to continental areas. The criteria by which a carbonate-rich rock is considered to be a true carbonatite are difficult to apply with confidence. Although not conclusive, the following characteristics are the strongest clues, especially when they are observed together [14]: (1)

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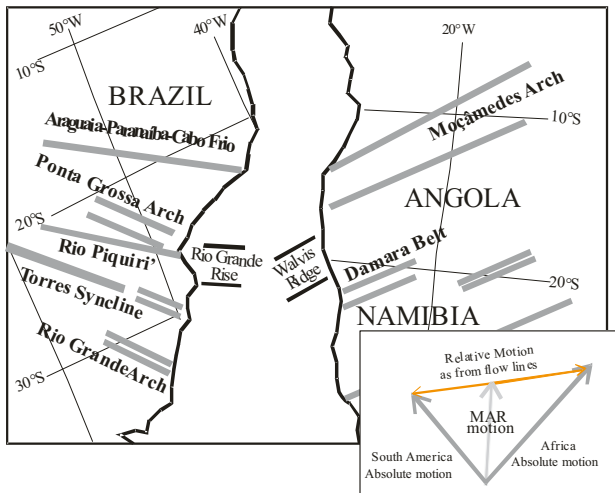
Figure 1: Main tectonic structures in the Paraná–Angola–Namibia (PAN) system (South American and African plates, Western Gondwana at about 110 Ma; modified after [20]) and corresponding to the main alignments of the alkaline and alkaline-carbonatitic complexes. Inset: Qualitative vector diagram showing the relationships between absolute plate motions, relative motions, and the development of the mid-Atlantic ridge (MAR) as depicted in the figure [21].

field evidences, e.g., subcircular or suboval or ring structures of alkaline complexes with carbonatite body occupying the inner part; (2) association with melilite- or nepheline-bearing rocks; (3) calcite with >1 wt% SrO; (4) presence of perovskite, pyrochlore, F-REE-carbonates, and apatite with high silica content (e.g., >2 wt%); (5) enrichment in Sr, Ba, Nb, U, Th, and rareearth elements (with high LREE vs HREE fractionation) and depletion of other incompatible elements (e.g. K, Rb, Zr, Hf, and Ti) relative to mantle and continental crust [15]; (6) $^{87}Sr/^{86}Sr$ initial ratios similar to those of the associated silicate alkaline rocks [16]; (7) stable isotopes (O–C) in the "primary carbonatitic box" [17,18] or following well-distinct isotopic fractionation trends [19].

Taking into account the above criteria, this article summarizes field and geological evidences and geochemical characteristics in terms of C–O and Sr–Nd–Pb–Re–Os isotopic data of alkaline–carbonatitic complexes and occurrences in and around the Paraná Basin in southern Brazil, in particular, and in the Paraná–Angola–Namibia (PAN) system in general [20]. In the context of the long-standing controversy about the exact mechanism that produced the South Atlantic igneous province [22], our results give new important information that allows one to interpret the geodynamic framework of the whole Mesozoic magmatism of the southern Brazilian Platform, in alternative to the

mainstream model based on the involvement of a deep mantle plume in magma genesis processes in the region. Notably, noble gases isotopic data suggest that the source (s) are similar to other mantle-derived magmas (e.g., HIMU and MORB) and that the carbon of carbonatites is unlikely to be subduction-related carbon, and supports a picture of C−O fractionation starting from mantle-derived sources, in ametasomatized subcontinental lithospheric mantle (SCLM) based on Sr−Nd−Pb isotope systematic [20,23−25].

The structure of this article will follow the same structure as the first part (Speziale et al., this issue) in that the different carbonatitic occurrences are grouped on the basis of petrographic associations [26] as magmatic carbonatites [27,28], hydrothermal carbonatites, and occurrences with unusual geometric relationship.

(1) Magmatic carbonatites
  (A) Occurrences associated with rock types of the urtite-ijolite-melteigite series, without the presence of extrusive nephelinites (Brazil, Vale do Ribeira: Anitápolis, Ipanema, Itapirapuã, Jacupiranga, Mato Preto, and Juquiá; Goiás: Caiapó and Morro do Engenho; Paraguay: Cerro Sarambí and Sapucai).
  (B) Occurrences only with olivinites and pyroxenites as ultramafitites (±syenites) as Salitre I and Serra Negra, and with glimmerites as Araxá, Catalão I, Catalão II, and Salitre II.
  (C) Occurrences with intrusive rocks containing melilite, as Tapira and Lages.
(2) Hydrothermal carbonatites: those produced at temperatures ≤375°C (e.g., Barra do Itapirapuã, Cerro Chiriguelo, Cerro Manomó).
(3) Occurrences with unusual geometric relationships: a small number of occurrences in the form of small dykes or ocelli in alkaline silicate rocks (e.g., Vallemí, Cerro Canãda, Cerro E Santa Elena, Itanhaém; cf. Speziale et al., this volume).

2 C−O isotopes

A compilation of the C−O isotopic data for calcite and dolomite-ankerite ($\delta^{18}O$‰ vs V-SMOW and $\delta^{13}C$‰ vs PDB-1) is given in Table 1. The C−O isotope compositions of the studied carbonatites appear to be in general agreement with a magmatic origin from supercrytical fluids with $CO_2/H_2O \approx 0.2–0.6$ molar ratios and temperatures ranging from ~800°C to 400°C (i.e., from

Table 1: Representative C−O isotopic ratios in δ‰ notation for calcite and dolomite/ankerite (sometimes coexisting) in carbonatites from the Brazilian Platform. Analytical methods and uncertainties on the values reported in this table can be found in [29]. The locations of the sampling areas [30,31] are reported in detail following the references relative to the single localities: PARAGUAY: Cerro Sarambí, [32,33]; Cerro Cañada, [20,34,35]; Cerro E Santa Elena, [20,34,35]; Sapucai, [34,36]; Cerro Chiriguelo, [29,36]; Valle-mí, [16,37]. BRAZIL: Anitápolis, [38]; Ipanema, [39]; Itapirapuã, [40]; Jacupiranga, [36,41–44]; Juquiá, [45]; Salitre, [46,47]; SerraNegra, [48]; Araxá, [49]; Catalão I, [50,51]; Catalão II, [52]; Tapira, [31,53]; Mato Preto, [53]; Lages, [36,54]; Barra do Itapirapuã, [36]; Limeira, [36,42]; Itanhaém, [55]; Caiapó, [56] Morro do Engenho, [56,57]; Santo Antònio da Barra, [58]

PARAGUAY

Sample	δ18O‰ Cc	δ13C‰ Cc	δ18O‰ Dol/Ank	δ13C‰ Dol/Ank	Sample	δ18O‰ Cc	δ13C‰ Cc	δ18O‰ Dol/Ank	δ13C‰ Dol/Ank	Sample	δ18O‰ Cc	δ13C‰Cc	δ18O‰ Dol/Ank	δ13C‰ Dol/Ank
Cerro Sarambí					Cerro Chiriguelo					Cerro Chiriguelo				
SA-90	21.68	−5.68	—	—	3,407	17.87	−7.01	—	—	3,433	18.71	−5.34	—	—
SA-91	17.11	−10.37	—	—	3,408	18.14	−5.97	—	—	3,434	11.22	−6.52	—	—
SA-95	14.96	−5.68	—	—	3,409	14.14	−6.30	—	—	3,435°	11.53	−7.77	—	—
GL-SA	—	—	7.04	−8.61	3,410	23.33	−4.71	—	—	3,435b	14.94	−6.25	—	—
SA-958	14.89	−6.40	—	—	3,411	15.93	−5.48	—	—	3,436	12.51	−7.07	—	—
Cerro Cañada					3,412	17.76	−4.98	—	—	3,440	—	—	22.91	−4.10
PS-245	6.90	−8.50	—	—	3,413	16.21	−5.80	—	—	3,442	11.76	−8.08	—	—
PS245B	11.4	−6.3	11.1	−5.5	3,414	17.56	−5.75	—	—	3,443	13.07	−6.49	—	—
Cerro E Santa Elena					3,416	16.53	−6.40			Valle-mí				
PS-524	16.09	−7.76	16.31	−7.34	3,417	16.38	−4.98	—	—	VM-1	8.53	−7.30	—	—
Sapucai					3,418	15.56	−6.74	—	—	STE-A	17.12	−7.68	—	—
PS-72	—	—	14.47	−5.63	3,419	19.44	−3.97	—	—	STE-B	17.96	−7.30	—	—
PS-72A	—	—	14.00	−6.54	3,420	15.45	−6.98	—	—	STE-D	18.30	−6.96	—	—
PS-72B	14.77	−6.54	14.05	−6.83	3,422	13.48	−7.26	—	—	STE-E	18.03	−7.75	—	—
PS-94	16.70	−7.37	—	—	3,423	18.04	−6.89	—	—	VM-1	8.53	−7.30	—	—

BRAZIL

Sample	δ18O‰ Cc	δ13C‰ Cc	δ18O‰ Dol/Ank	δ13C‰ Dol/Ank	Sample	δ18O‰ Cc	δ13C‰ Cc	δ18O‰ Dol/Ank	δ13C‰ Dol/Ank	Sample	δ18O‰ Cc	δ13C‰ Cc	δ18O‰ Dol/Ank	δ13C‰ Dol/Ank
Anitápolis					Salitre					Lages				
SAN-1	7.55	−7.24	8.24	−7.07	C-1	8.8	−6.2	C-1	8.8	SB05	17.87	−0.51	16.45	−0.46
SAN-2°	7.94	−7.34	8.51	−6.93	C-4	9.3	−6.9	C-4	9.3	SB05A	—	—	15.69	−1.78
SAN2-B	7.89	−7.29	—	—	Serra Negra					SB05B	—	—	16.59	−0.24
SAN-3	7.53	−7.26	8.17	−7.02	LG-03-70	8.23	−6.18	—	—	SB17	—	10.37	−4.29	
SAN-4	7.63	−7.27	8.11	−7.00	LG-14-28	7.23	−6.91	—	—	SB20	—	—	8.99	−5.76
SAN-5	8.08	−7.16	8.39	−6.80	LG-06-32	7.28	−7.35	—	—	FV24	—	—	23.91	−3.02
SAN-6A	—	—	10.12	−6.89	LG-13-126	7.24	−6.54	—	—	LG-1-4	—	—	21.19	−1.66
SAN-8	10.38	−6.82	—	—	LG-20-91	—	—	8.50	−5.95	Barra do Itapirapuã				
SAN-11	7.55	−7.38	8.04	−7.21	LG-32-63	—	—	13.89	−4.84	5-13.0	—	—	8.40	−5.70
SAN-12	7.47	−7.15	8.19	−6.78	LG-38-46	—	—	8.86	−5.81	5-79	9.06	−5.82	10.0	−5.19
SAN-13	7.52	−7.37	7.45	−7.25	Araxá					5-98	8.42	−6.92	9.08	−6.35
SAN-14	7.50	−7.15	8.22	−6.78	AR-891	—	—	14.0	−6.1	5-256	9.09	−6.43	9.60	−5.94
Ipanema					AR-892	—	—	12.6	−7.2	6-20	—	—	9.13	−5.76
I19-2	7.67	−7.02	—	—	AR-893	11.5	−6.3	9.5	−5.8	6-30	—	—	8.76	−6.22

Table 1: Continued

					BRAZIL									
Sample	$\delta^{18}O$ ‰ Cc	$\delta^{13}C$ ‰ Cc	$\delta^{18}O$ ‰ Dol/Ank	$\delta^{13}C$‰ Dol/Ank	Sample	$\delta^{18}O$ ‰ Cc	$\delta^{13}C$ ‰ Cc	$\delta^{18}O$ ‰ Dol/Ank	$\delta^{13}C$‰ Dol/Ank	Sample	$\delta^{18}O$ ‰ Cc	$\delta^{13}C$ ‰ Cc	$\delta^{18}O$ ‰ Dol/Ank	$\delta^{13}C$‰ Dol/Ank
IP-1	23.62	5.38	—	—	ARX-90-1AS	9.7	−7.2	—	—	6-66	—	—	9.23	−5.71
Itapirapuã					ARX-90-2B	10.0	−6.9	11.1	−6.0	6-78.8	—	—	10.19	−3.69
IT-28	8.12	−6.63	9.13	−6.04	ARX-90-3B	10.4	−7.1	11.4	−6.3	6-95	—	—	8.63	−6.44
IT-29	8.75	−7.08	—	—	ARX-90-4B	13.8	−4.8	10.7	−3.5	6-99.7	—	—	8.73	−6.52
6,220	13.26	−1.66	—	—	ARX-90-5B	10.0	−7.0	—	—	6-110	—	—	9.81	−6.04
6,221	14.61	0.38	15.95	0.99	AR	12.5	−6.8	—	—	5-170.7	—	—	9.72	−5.42
6,222	8.26	−6.25	—	—	AR-891	—	—	14.0	−6.1	Weakly Overprinted				
6,223	10.04	−4.52	—	—	Catalão I					1-18.8	—	—	9.0	−5.8
6,224	12.36	−1.06	—	—	C1-1	8.2	−6.0	8.2	−6.9	1-30.5A	12.5	1.80	13.5	1.1
6,225	13.19	−2.41	—	—	C1CB02	9.9	−6.2	10.9	−6.9	1-32.5	7.67	−6.91	8.64	−6.19
6,227	10.19	−5.84	12.60	−4.98	C1C4	10.75	−5.79	—	—	1-33.45	—	—	9.4	−5.4
6,228	13.11	−0.56	—	—	CTTTW	9.6	−7.0	—	—	1-37.4	6.00	−7.10	6.7	−6.4
6,229	9.77	−0.57	—	—	13E-1º	13.3	−6.5	11.4	−5.0	1-39.3	8.08	−6.48	9.0	−5.78
−62.2	10.68	−3.45	11.88	−2.74	13E-2A	14.6	−6.4	10.2	−5.4	1-57.6	7.00	−6.80	7.9	−6.1
−70.0	18.90	−0.70	—	—	13E-3A	19.3	−6.2	20.4	−4.2	2-72.4	—	—	8.84	−6.13
−77	11.32	−1.91	13.00	−1.30	C3-2B	12.5	−5.3	9.9	−4.8	3-67.4B	13.1	1.2	13.7	1.5
−84	12.64	−0.41	—	—	CAT1	8.45	−6.97	8.03	−6.17	3-183.4	8.27	−6.77	9.26	−6.0
−93.1	—	—	13.06	−0.63	CAT2	8.03	−6.47	8.51	−5.97	5-160.5	8.8	−6.35	9.36	5.99
−119.3	12.49	−0.81	13.31	−0.45	CAT3	8.23	−6.85	8.15	−6.01	5-230	9.88	−5.38	10.55	−4.90
−130	13.00	−3.96	—	—	Catalão II					2-72.4	—	—	8.84	−6.13
Jacupiranga					C2	9.36	−6.03	9.6	−7.0	3-67.4B	13.1	1.2	13.7	1.5
JM-1	8.00	−6.3	—	—	C2A2	9.21	−5.68			Limeira				
JM-2	7.48	−6.07	8.12	−5.03	C2A15	8.49	−5.96	—	—	1A (M)	23.69	−5.97	—	—
JM-6A	8.12	−5.03	8.41	−4.59	C2A17	8.68	−5.97	—	—	1B (M)	23.62	−6.07	—	—
JM 12B	9.38	−4.12	9.51	−3.80	C2A19	8.46	−5.97	—	—	1C (M)	23.80	−5.61	—	—
JM 15	8.62	−5.15	9.20	−4.8	C2A21	8.69	−6.00	—	—	1M	23.42	−6.13	—	—
JC-11	7.50	−6.40	—	—	C2B17	9.48	−6.16	—	—	2M	22.94	−6.50	—	—
JC-18	8.10	−6.39	—	—	C2B18	8.74	−5.90	—	—	3M	23.91	−6.89	—	—
JC 26	7.30	−6.20	7.1	−5.8	C2B19	9.13	−6.35	—	—	Itanhaém				
JC 27	—	—	7.7	−5.9	C2B22	10.75	−5.79	—	—	IA-1	15.0	−4.3	—	—
JC 44	9.60	−5.8	7.3	−6.1	C1C4	9.36	−6.03	—	—	IA-2	11.6	−5.5	17.0	−2.6
JC 46	7.70	−6.4	8.1	−5.6	Tapira					Caiapó				
JC 99	10.05	−6.39	—	—	T-1	9.9	−6.8	11.1	−5.9	CR-09	12.3	−7.0	—	—
JC 100	7.48	−6.07	7.6	−5.71	S22-4B	10.0	−6.7	13.9	−4.9	Morro do Engenho				
JC 101	8.12	−5.03	8.41	−4.59	S22-11-C	9.9	−6.8	11.1	−5.9	ME-C	11.7	−7.8	—	—
JC 102	9.38	−4.12	9.51	−3.80	S22-5B	15.4	−5.6	15.6	−5.8	Santo Antônio da Barra				
JC 103	8.62	−5.15	9.2	−4.8	S22-8F	9.7	−6.8	—	—	SAB-12	8.83	−6.10	8.99	−5.77
JP 881	7.4	−5.8	7.2	−5.7	TP90-1-C	10.0	−5.3	11.9	−3.7					
JP 882	7.7	−6.5	7.5	−6.3	TP90-1-D	9.7	−6.2	10.6	−5.0					
HB-005	—	—	7.1	−5.8	TAP-1	12.89	−6.61	12.95	−5.92					
HB-010	—	—	7.7	−5.9	Mato Preto			11.88	−2.74					
HB-011	9.38	−4.12	—	—	44	10.68	−3.45							

Table 1: Continued

	BRAZIL													
Sample	$\delta^{18}O$ ‰ Cc	$\delta^{13}C$ ‰ Cc	$\delta^{18}O$ ‰ Dol/Ank	$\delta^{13}C$‰ Dol/Ank	Sample	$\delta^{18}O$ ‰ Cc	$\delta^{13}C$ ‰ Cc	$\delta^{18}O$ ‰ Dol/Ank	$\delta^{13}C$‰ Dol/Ank	Sample	$\delta^{18}O$ ‰ Cc	$\delta^{13}C$ ‰ Cc	$\delta^{18}O$ ‰ Dol/Ank	$\delta^{13}C$‰ Dol/Ank
Juquiá					46	11.32	−1.91	13.0	−1.3					
S16C	16.58	−7.57	15.83	−7.20	49	12.49	−0.81	13.31	−0.45					
S25	15.68	−7.60	16.13	−7.27	51	14.61	0.38	15.91	0.95					
S26A	16.42	−7.84	16.64	−7.27	56	10.19	−5.84	12.6	−4.98					
S26B	15.68	−8.02	16.64	−7.45	59	8.91	−6.09	9.05	−5.75					
1A	14.39	−6.31	14.19	−5.78	60	8.76	−6.12	8.94	−5.78					
2A	14.50	−5.82	14.19	−5.32	Lages									
3A	13.90	−6.39	13.59	−5.78	SB02	−	−	15.18	−1.66					
4A	13.79	−5.95	13.59	−5.32	SB03	17.35	−1.0	15.82	−1.55					

orthomagmatic to pegmatitic environment; cf. [59]). Primary carbonates of alkaline rock types and associated carbonatites show significant variations in C–O isotope compositions [16,19,20,36,42]. The main trends of $\delta^{18}O$ and $\delta^{13}C$ fractionation appear to be controlled by the depth of emplacement of the carbonatites. Weathering and groundwater fluids are locally important, as well as meteoric water, which yielded samples strongly enriched in light carbon due to contamination by a biogenic component [16,27,60]. Oxygen and carbon isotopic compositions of individual minerals from selected alkaline–carbonatitic complexes in the Brazilian Platform are reported in Table 2.

Carbonatite complexes worldwide display large compositional ranges of oxygen and carbonisotopic ratios in the carbonate phases [17,29,67–71]. In the studied carbonatites, the $\delta^{18}O$ values cover a wide interval from about 5 to 25‰ vs V-SMOW notation [69], but about 50% of the analyses fall into a narrow field between 6 and 10‰. The variation of $\delta^{13}C$ is more restricted, i.e., 91% of $\delta^{13}C$ values fall in the range between −2‰ and −8‰ vs PDB-1 notation [69]. Ranges of $\delta^{18}O$ and $\delta^{13}C$ between 6 and 10‰ and between −4 and −8‰, respectively, are considered to reflect primary carbonatites [17,18]. Different emplacement levels (i.e., deep-seated, up to near surface, or near-surface environments [72]) and superimposed primary and secondary processes are all believed to play an important role in the isotopic variations. These may be related to (1) isotopic compositional differences in the source, (2) fractionation processes during the magmatic evolution, (3) loss of fluids during decompression at the time of emplacement, (4) crustal contamination, and (5) post-magmatic, and deuteric-groundwater processes.

Most of the large variations in heavy oxygen of the carbonatites from the southern Brazilian Platform could be explained by the interaction with hydrothermal fluids, whereas the variations in heavy carbon may be associated with both primary (i.e., isotopic composition of parental magma) and secondary (i.e., hydrothermal re-equilibration) processes [17,68,69]. Determining the extent of primary versus secondary variations of oxygen and carbon isotopic ratios in carbonatites has important implications for evaluating the geochemical characteristics of the source regions, and may be useful for deciphering the nature of the subcontinental mantle [16,37].

In order to address some of these problems, we apply to the whole set of investigated carbonatites a model of isotopic C–O fractionation (see [36] and references therein). In fact (1), the carbonatitic complexes from the southern Brazilian Platform are among the most intensively studied in the worldwide literature; (2) a large number of C–O isotopic and radiogenic data are available for these occurrences ([26] and references therein); (3) the current interpretation of the isotopic data from the individual sites is controversial as to the role of primary processes versus crustal contamination.

$\delta^{18}O$‰ (V-SMOW) and $\delta^{13}C$‰ (PDB-1) data for the carbonates in the carbonatites from the southern Brazilian Platform display both typical values of primary carbonatites along with higher $\delta^{18}O$ and $\delta^{13}C$ values for a number of samples (Figures 2–5). Enrichments in heavy isotopes are interpreted in terms of heterogeneity in the mantle source [70], or contamination by host rocks [71], or magmatic – hydrothermal evolution of the carbonatite at a shallow level [16,19,29]. $\delta^{18}O$ and $\delta^{13}C$ for sedimentary carbonates and groundwater calcite are in the range
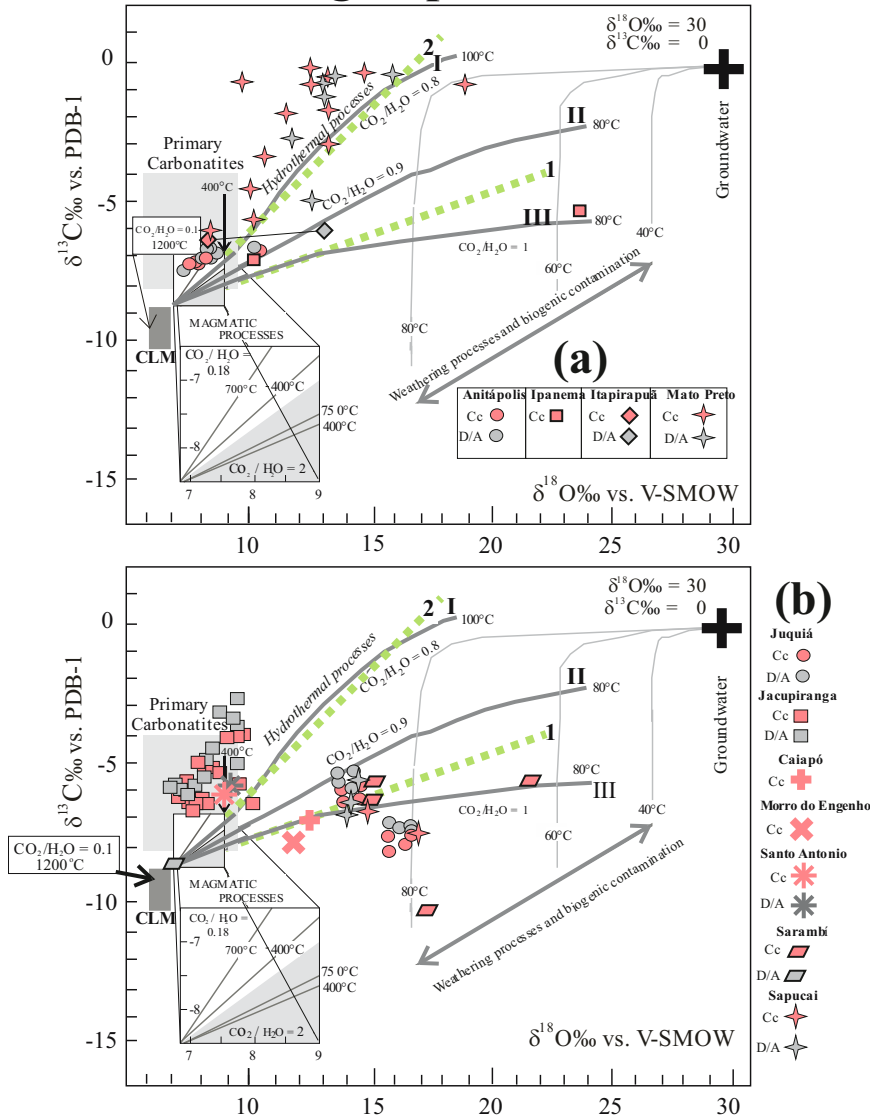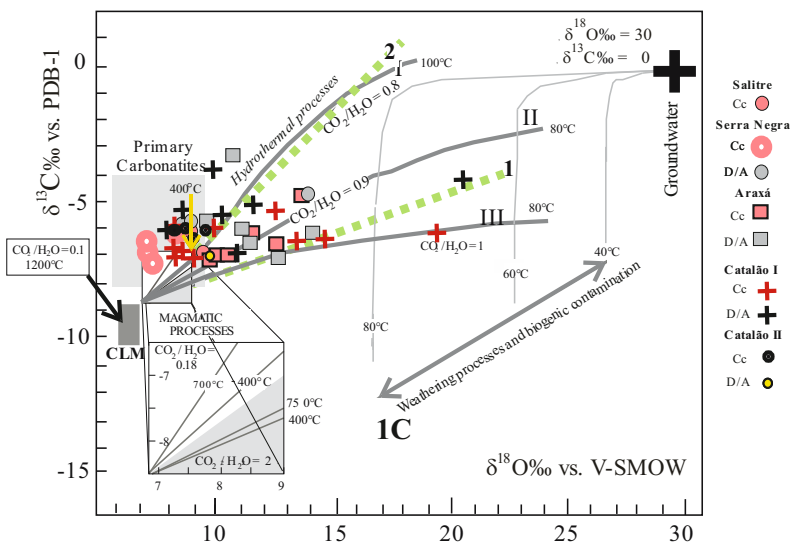
Figure 2: Group-A magmatic carbonatites (cf. also Figure 3a, (b). Evolution of the C–O isotopic compositions (δ‰ notation) in the carbonatitic complexes (cf. also Table 2): (a) Anitápolis, Ipanema, Itapirapuã, Mato Preto; (b) Juquiá, Jacupiranga, Caiapó, Morro do Engenho, Santo Antônio da Barra, Cerro Sarambí, Sapucai. Magmatic conditions: 1,200–400°C; hydrothermal environment: I case of fluid with $CO_2/H_2O = 0.8$, II case of $CO_2/H_2O = 0.9$, and III case of $CO_2/H_2O = 1.0$ (cf. [16,36] and references therein). Low temperature conditions: biogenic component with temperature 40–80°C; arbitrary starting compositions of groundwater: $\delta^{18}O = 0$, $\delta^{13}C = 30$‰ (cf. [17,73,74]). CLM: continental lithospheric mantle [75]. **1** and **2**: regression lines from field and borehole samples, respectively. Primary carbonatites after [17,18] Cc: calcite, D/A: dolomite ankerite.

20 to 30‰ and 20 to 24‰, and −4 to +5‰ and −6 to −4‰, respectively. It should be noted that marbles from southern Brazil show $\delta^{18}O$ and $\delta^{13}C$ ranges from 16 to 23‰ and from −4 to +3‰, respectively [20]. There are two main trends of isotopic C–O variations in the carbonatites from southern Brazil: (I) a trend characterized by a positive increase of both $\delta^{18}O$ and $\delta^{13}C$ (e.g.,

Anitápolis, Mato Preto, and Jacupiranga, Figure 2a and b; Lages, Figure 3b) and (II) a trend of $\delta^{18}O$ increase and $\delta^{13}C$ decrease (e.g., Juquiá, Figure 2b).

At the Cerro Chiriguelo carbonatitic complex (Figure 4a), two main linear trends are apparent: the first one defined by carbonatitic samples and primary carbonate of silicate rocks from bore-holes [16], while the second one

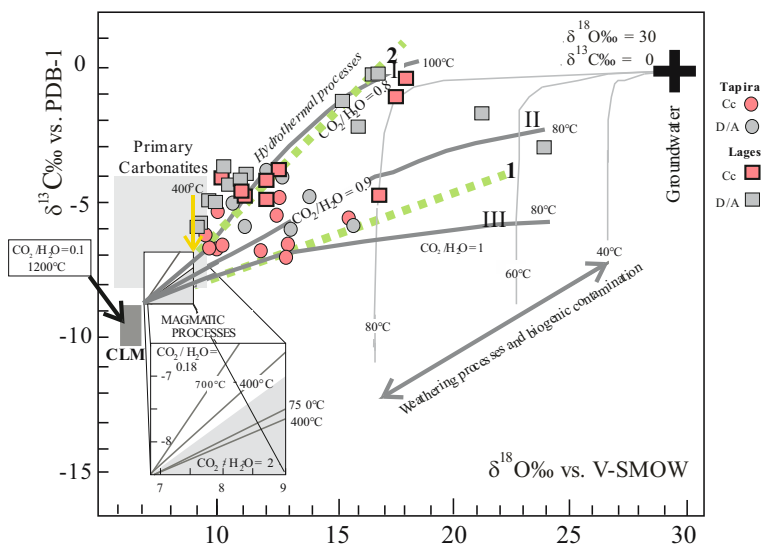# Magmatic carbonatites
group-B

group-C

Figure 3: Group B and C magmatic carbonatites (cf. Figure 2). **1B**: Salitre, Serra Negra, Araxá, Catalão I, Catalão II; **1C**: Tapira, Lages. For other symbols and notations, see Figure 2.

represents carbonatitic specimens sampled near to or at the topographic surface, or carbonatitic lava flows. The extrapolations of the two trends intersect at $\delta^{18}O$ = 7.5‰ and $\delta^{13}C$ = −8.5‰, similar to the values obtained for primary carbonate phases of an ijolite from Cerro Cañada in Central Paraguay, i.e., $\delta^{18}O$ = 6.9‰ and $\delta^{13}C$ = −8.5‰, respectively. Additional data for silicates, oxides, and carbonates associated in *ocelli* from Cerro E Santa Elena and Cerro Cañada ijolitic rocks (Figure 5) or silicate-oxide-carbonate phases in Jacupiranga complex and also

apatite-calcite pairs in Jacupiranga and Juquiá carbonatites, respectively [36,61], are all reported in Table 2 along with calculated temperatures of isotopic equilibria.

Concluding, the observed large C–O isotopic variations are mainly due to isotope exchange between carbonates and H_2O–CO_2 rich fluids, while magmatic processes, i.e., fractional crystallization or liquid immiscibility probably affect the $\delta^{18}O$ and $\delta^{13}C$ values by no more than 2‰. The isotope exchange model implies that the main isotopic variations occurred at low
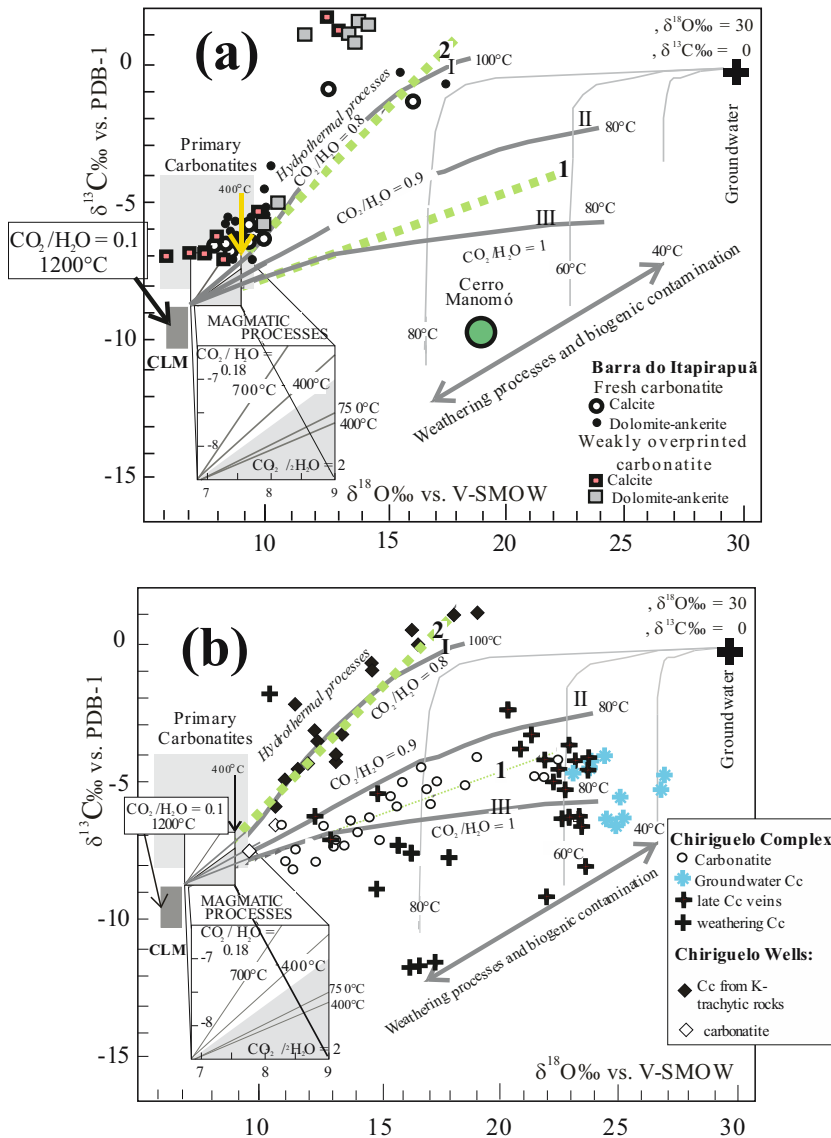
Hydrothermal Carbonatites

Figure 4: Hydrothermal carbonatites. (a) Barra do Itapirapuã, Cerro Manomó; (b) Cerro Chiriguelo. For other symbols and notations, see Figure 2.

temperatures, in a hydrothermal environment, e.g., in the range 400–80ºC, involving fluids with a CO_2/H_2O molar ratio ranging from 0.8 to 1, as proposed by [36], based on their thermodynamic model of C–O isotopic evolution.

3 Sr–Nd isotopes

The carbonatites from the southern Brazilian Platform usually show the same initial isotopic ratios, $^{87}Sr/^{86}Sr$ (Sr_i) and $^{143}Nd/^{144}Nd$ (Nd_i), as the associated alkaline

rocks, even in the late stages of fluid-rock re-equilibration (i.e., hydrothermal environment), as concluded by [16,19]. Initial ratios relative to Sr–Nd isotopes and model ages of carbonatites are reported in Table 3.

In Brazil (Figure 6a), the Early Cretaceous carbonatites have Sr_i between 0.70425 and 0.70595 and Nd_i between 0.51213 and 0.51280 (mean Sr_i = 0.70527 ± 0.00034 and mean Nd_i = 0.51224 ± 0.00011; cf. [1]). Late Cretaceous complexes yield the following Sr_i and Nd_i mean values, respectively: Alto Paranaíba Igneous Province (APIP), Sr_i = 0.70527 ± 0.00036 and Nd_i = 0.51224 ± 0.00006 ([76–78] and references therein);

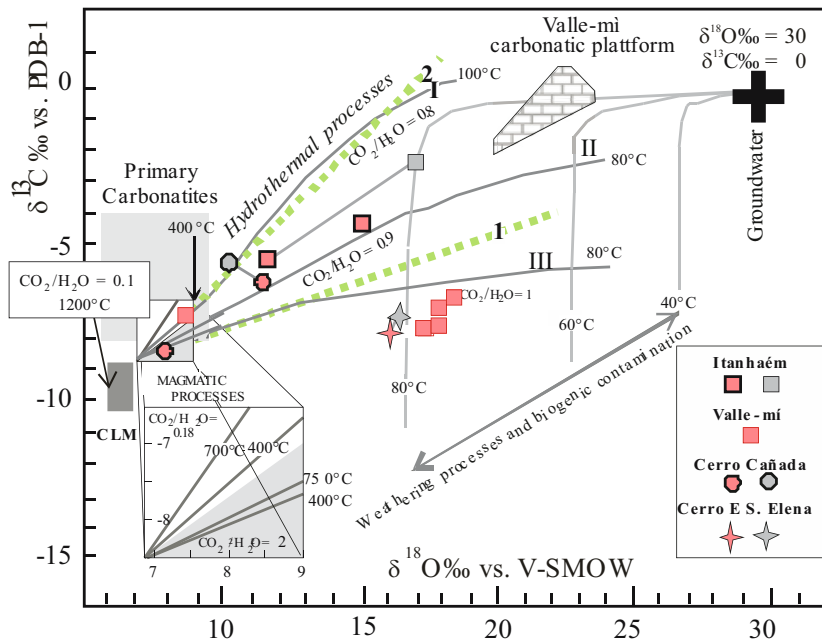# Occurences with unusual geometric relationships

Figure 5: Carbonatites with unusual geometric relationships. C–O isotopic evolution of the carbonatites from Itanhaém, Cerro Santa Elena, Cerro Cañada, and Valle-mi. Data for Valle-mí carbonate platform are from [35]. Other symbols and notations are the same as in Figure 2.

Taiúva-Cabo Frio and Serra do Mar, Sr_i = 0.70447 ± 0.00034 and Nd_i = 0.51252 ± 0.00008 [79]; Lages, Sr_i = 0.70485 ± 0.00053 and Nd_i = 0.51218 ± 0.00022 [54,80]. It should be noted that the alkaline–carbonatite magmatism shows trends similar to those of the Cretaceous tholeiites from southern Brazil and from Walvis Ridge and Rio Grande Rise (fields H-Ti, L-Ti, UCA, LCA, and RGR; cf. [81,82]).

In eastern Paraguay (Figure 6b), specimens from the Early Cretaceous K-alkaline rocks (both pre- and post-Early Cretaceous tholeiitic magmatism) and associated carbonatites yield Sr_i and Nd_i within the ranges 0.70612–0.70754 and 0.51154–0.51184, respectively. These are distinct from the values obtained for the Late Early Cretaceous (Misiones, MIS, province) to Paleocene Na-alkaline rocks (Asunción province, ASU), i.e., Sr_i = 0.70362–70524 and Nd_i = 0.51225–0.51277. In Figure 6b, the carbonatites and associated K-alkaline rocks show Sr_i and Nd_i values similar to the low Nd array of [83] and to the Paraguay array of [84].

The Sr–Nd isotopic ratios of alkaline and alkaline–carbonatite complexes plotted in Figure 6 appear to follow a well-defined array involving depleted and enriched mantle components. Both the Early and Late Cretaceous Brazilian alkaline–carbonatite complexes vary from close to the HIMU to the enriched quadrant, fitting the fields of the uncontaminated low-Ti and high-Ti tholeiites from the Paraná Basin, that is those unaffected by crustal magma contamination processes [1,16,19,99].

The isotopically Sr-enriched rocks (e.g., eastern Paraguay alkaline–carbonatite complexes) are not easily explained by crustal contamination, since this requires high percentages of crustal components in a mixing process (up to 90%; [99]). On the contrary, we stress that the oxygen isotope data suggest a primary, mantle-derived origin for silicate phases: whole-rock $\delta^{18}O$ data for the potassic rocks yielded +5.45 to +5.91‰ (vs V-SMOW), which are consistent with the values for its mineral constituents, clinopyroxene (+4.85 to +5.20‰) and biotite (+3.96 to +5.54‰), and the expected mantle values (cf. Table 3). On the whole, the Na-rocks, close to the BE, and the K-rocks, typically high in radiogenic Sr worldwide, represent the range of virtually uncontaminated source magmas. The same combination of different isotopic data can be a key to

Table 2: Measured isotope compositions in δ‰ notation of silicates, oxides, apatite, and calcite in some alkaline and alkaline-carbonatitic complexes from the Brazilian Platform

Cerro E Santa Elena (ijolite)	$\delta^{18}O$‰ (V-SMOW)	$\delta^{13}C$‰		$\times 10^{-6} K^2$		Ref.	T (°C)
				A	B		
Clinopyroxene[a]	4.85		Cpx-Ol	1.24	0	1	852
Olivine[a]	3.87		Cpx-Mt	4.03	0	2	808
Magnetite[a]	1.40		Cpx-Amph	0.478	−0.30	2	746
Amphibole[a]	4.69		Cc-Cpx	2.37	0	3	908
Biotite[a]	4.62		Cc-Mt	5.91	0	3	798
Calcite[a]	6.55	−8.90	Average				822 ± 61
			Biot-Amph	2.33	+0.60	1	799
			Cc-Biot	1.84	0	4	703
			Biot-Cpx	−0.57	+0.60	1	556
			Biot-Mt	−0.092	+0.30	2	510
			Average				642 ± 133
Cerro Cañada (ijolite)							
Clinopyroxene[b]	5.20		Cpx-Ol	1.24	0	1	1,202
Olivine[b]	4.63		Cc-Cpx	2.37	0	3	908
Biotite[b]	5.54		Biot-Cpx	−0.57	+0.60	1	1,208
Calcite[b]	6.90	−8.50	Cc-Biot	1.84	0	4	890
Jacupiranga (carbonatite)			Average				1,052 ± 180
Clinopyroxene[a]	4.20		Cpx-Mt				858–890
Magnetite[c]	1.05		Cc-Mt	5.91	0	3	675–706
Magnetite[c]	1.23		Cc-Biot	1.84	0	4	436–458
Biotite[c]	3.96		Biot-Cpx	−0.57	0.60	1	551
Calcite[c]	7.40	−6.58	Cc-Cpx	2.37	0	3	560–558
Calcite[c]	7.62	−6.68	Range				440–890
Juquiá (carbonatite)							
Apatite[b]	14.11 ± 1.87	−6.60 ± 0.39	Cc-Ap	1.60	0	5	863
Calcite[b]	12.35 ± 2.34	−6.87 ± 0.81					

Abbreviations: Cpx, clinopyroxene; Ol, olivine; Mt, magnetite; Amph, amphibole; Biot, biotite; Cc, calcite; Ap, apatite. Calculated isotopic temperatures based on fractionation of oxygen isotopes in mineral pairs according to the general equation $1000\ln\alpha = A(10^6 T^{-2}) + B$, where A and B are coefficients of the equation and T is the absolute temperature (cf. [62]). References: (1) [63]; (2) [64,65]; (3) [65]; (4) [66]; (5) [67]. The uncertainties are about 0.05‰ (1 σ) for both carbon and oxygen (cf. [29]).
[a] Unpublished data. [b] Ref. [30] and [31]. [c] Ref. [61].

interpret the sources of alkaline and ultra-alkaline magmatism in complex geodynamic settings, such as the Italian ultrapotassic volcanic province [102–106].

In summary, the data support the view that the carbonatites and alkaline rocks from eastern Paraguay, mainly ranging in composition from a depleted component to the BE, may represent the end members of virtually uncontaminated source magmas from subcontinental mantle segments variously affected by "metasomatic s.l." processes at earlier times [99].

4 Nd-Model ages

Studies relative to the initial $^{143}Nd/^{144}Nd$ ratios from Precambrian terrains suggest that the mantle that

produced continental crust has evolved with Sm/Nd ratios higher than that of CHUR (chondritic uniform reservoir; cf. [62,107]). For this reason, model ages for the continental crustare usually calculated with reference to the depleted mantle reservoir (DM: $^{143}Nd/^{144}Nd$ = 0.513151, $^{147}Sm/^{144}Nd$ = 0.2188) rather than CHUR and they are expressed as T^{DM} model ages.

Although the Nd model ages do not reflect the true ages of the sources, being a function of the Sm/Nd fractionation during the melting and magma differentiation [108], they may provide a notional estimate of the time when a major metasomatic event may have occurred, as a function of the different geochemical characteristics of the different sectors of Brazil and Paraguay.

Applying the T^{DM} (Nd) model ages on the whole Paraná system (PS) (e.g. [31,109]), we observe that: (1) in

Table 3: Sr–Nd isotopes initial ratios and model ages of carbonatites from the southern Brazilian Platform. References as in Table 1 and Figure 6

A

Magmatic carbonatites

	Anitápolis	Ipanema	Itapirapuã		Jacupiranga		
Sample N	SAN1;14;49;12–78;11–101;16A	SAN 13	IT 28	119.2	HB 005	HB 010	HB 011
	Early Ca–carbonatite N = 4	Late Mg–Ca–carbonatite	Ca–Fe–carbonatite	Ca–carbonatite	Ca–Fe–carbonatite	Ca–Fe–carbonatite	Ca–carbonatite
Rb–Sr(R_0)							
$^{87}Sr/^{86}Sr$	0.70595(1)	0.70594	0.70446	0.70673	0.70497	0.70492	0.70497
Sm–Nd(R_0)							
$^{147}Nd/^{144}Nd$	0.51219(5)	0.51222	0.51249	0.51169	0.51254	0.51253	0.51254
εSr	20.6(1)	19.8	1.09	33.7	6.0	5.4	6.0
εNd	–7.0(0.6)	–4.8	–0.15	–15.4	1.4	1.2	1.4
T^{DM}(Ma)	1.281(53)	1397	663	2164	708	708	719

	Mato Preto					Juquiá				Sapucai
Sample N	I-119.3	I-84.0	II-77.0	III-62.2	III-622	S16C	S25	S26A	S26B	Carbonate Fraction (dolomite 24.3 wt%)
	Ca–carbonatite	Ca–carbonatite	Ca–carbonatite	Fe–carbonatite	Ca–carbonatite	Ca–Mg–carbonatite	Carbonatite	Ca–Mg–carbonatite	Ca–Mg–carbonatite	
Rb–Sr(R_0)										
$^{87}Sr/^{86}Sr$	0.70495	0.70472	0.70473	0.70473	0.70487	0.70556	0.70551	0.70531	0.70515	0.70717
Sm–Nd(R_0)										
$^{147}Nd/^{144}Nd$	0.51253	0.51270	0.51266	0.51256	0.51249	0.51255	0.51246	0.51252	0.51255	0.51131
εSr	4.70	1.44	1.56	1.55	3.51	17.2	16.5	13.7	11.4	34.17
εNd	–0.33	2.90	2.19	0.33	01.19	1.6	–0.2	1.2	1.6	–22.7
T^{DM}(Ma)	1,095	680	671	647	599	744	924	781	750	1,845

	Caiapó	Morro do Engenho	Santo Antônio da Barra	Cerro Sarambi			Sapucai
Sample N	CR-09 Ca-Carbonatite	ME-C Ca-Carbonatite	SAB-12Ca-Mg-Carbonatite	Glimmerite-Carbonatite.Whole rock	Carbonate Fraction (dolomite)	Carbonate Fraction (calcite 7%)	PS72 Sap. Whole rock. Phonotephrite
Rb–Sr(R_0)							
$^{87}Sr/^{86}Sr$	0.70497	0.70497	0.70520	0.70746	0.70745	0.70746	0.70700
Sm–Nd(R_0)							
$^{147}Nd/^{144}Nd$	0.51254	0.51254	0.51255	0.51157	0.51157	0.51156	0.51171
εSr	6.0	6.0	9.4	44.33	44.26	44.30	34.7
εNd	1.4	1.4	1.5	–17.42	–17.39	–17.64	–14.8
T^{DM}(Ma)	742	742	769	1,574	1,739	1,669	1,884

Table 3: Continued

B

Sample N	Araxá	Catalão I					Catalão II		
	AR 893 Phlogopite-bearing Mg-Carbonatite	C1-L 1250 Mg-Ca-Carbonatite	C1CB02 Mg-Ca-Carbonatite	C1C4 Ca-Mg-Carbonatite	C2-AA165907 Ca-Carbonatite	C2A2 Ca-Carbonatite	C2B19 Ca-Carbonatite	C2B18 Phlogopite-bearing Fe-Carbonatite	C2B17 Ca-Carbonatite
Rb–Sr(R_0)									
$^{87}Sr/^{86}Sr$	0.70499	0.70563	0.70565	0.70529	0.70468	0.70524	0.70510	0.70512	0.70517
Sm–Nd(R_0)									
$^{147}Nd/^{144}Nd$	0.51222	0.51221	0.51225	0.51214	0.51229	0.51225	0.51219	0.51226	0.51224
εSr	5.60	8.96	8.89	8.13	2.54				
εNd	−5.66	−6.12	−6.07	−7.7	−6.44	−5.5	−6.70	−5.2	−5.7
T^{DM}(Ma)	1,044	1,207	1,032	1,140	873	896	1,082	994	986

C

Sample N	Tapira		Lages			
	T1 Ca-carbonatite	T2 Ca-carbonatite	SB05A;SB05B Fe-carbonatite N = 2	SB02 Fe-carbonatite	SB10 Si-phlogopite carbonatite	SB11 phlogopite-bearing carbonatite
Rb–Sr(R_0)						
$^{87}Sr/^{86}Sr$	0.70531	0.70539	0.70626(2)	0.70596	0.70612	0.70609
Sm–Nd(R_0)						
$^{147}Nd/^{144}Nd$	0.51219	0.51221	0.51208(1)	0.51210	0.51208	0.51204
εSr	10.05	11.08	19.2(2)	19.21	23.24	21.01
εNd	−6.33	6.98	−8.5(0.4)	8.50	−9.01	−9.42
T^{DM}(Ma)	911	987	1,558(48)	1,319	1,558	1,454
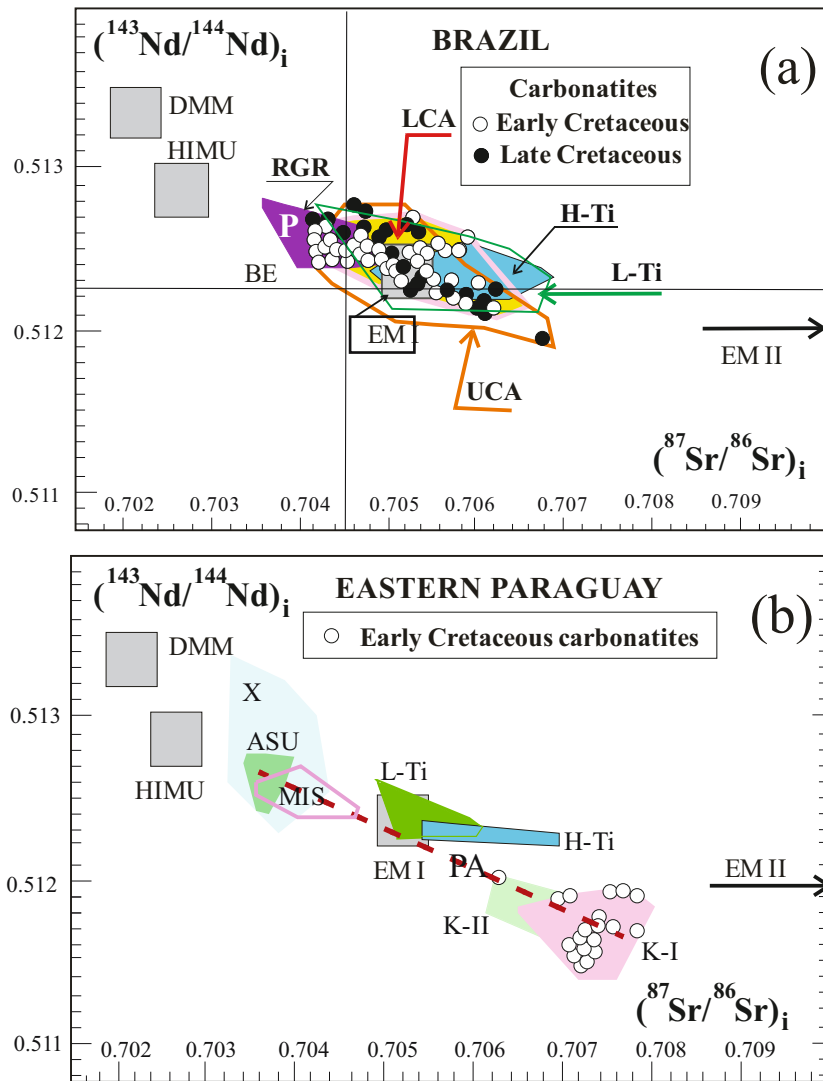
Figure 6: Initial $^{87}Sr/^{86}Sr$ (Sr_i) vs initial $^{144}Nd/^{143}Nd$ (Nd_i) correlation diagrams for carbonatites of the southern Brazilian Platform compared with basalts and andesi-basalts with MgO $\geq$ 4 wt% and $Sr_i \leq 0.7065$, i.e., those believed to be poorly crustally contaminated or uncontaminated [2]. (a) Brazil: L-Ti, H-Ti, Lower or Early Cretaceous high- and low-Ti flood tholeiites and alkaline complexes, respectively; UCA and RGR, Upper or Late Cretaceous alkaline complexes and Rio Grande Rise rock types; P, Paleocene alkaline complexes from Serra do Mar. Data sources: Early Cretaceous: [41,53,80,82,85–91]; Late Cretaceous: [24,76,78,79,86,89,92–95]; Paleocene: [79,96]. (b) Paraguay; Early Cretaceous: K-I and K-II, potassic alkaline complexes, pre- and post-tholeiites, respectively; H-Ti and L-Ti, high- and low-Ti tholeiitic basalts and andesi-basalts, respectively; late Early Cretaceous: MIS, sodic alkaline magmatism from Misiones province; Paleocene: ASU, sodic alkaline magmatism from Asunción and X, associated mantle xenoliths. PA: Paraguay array. Data sources: [16,30,31,84,90,97–100]. DMM, HIMU, EMI, and EMII are approximation of mantle end members taken from [101].

the South American Platform, H-Ti flood tholeiites and dykes mainly range between 0.8 and 2.4 Ga; (2) L-Ti flood tholeiites span between 0.8 and 2.7 Ga; (3) the pre-tholeiitic potassic rocks mainly vary from 0.8 to 2.5 Ga; (4) early Cretaceous syn- and post-tholeiitic alkaline and carbonatitic magmatism range from 0.6 and 0.9 Ga; (5) Late Cretaceous alkaline rocks and carbonatites vary between 0.6 and 0.9 Ga [12,31].

If the comparison is made between eastern Paraguay (at the western margin of the south Brazilian Platform)

and the eastern end of the Brazilian Platform [31,110], we observe that: (1) T^{DM} of pre-tholeiitic K-alkaline rocks from eastern Paraguay display two main peaks at 1.1 Ga (Valle-mí, Apa Block) and at 1.4 Ga (Amambay region), respectively; (2) the post-tholeiitic K-alkaline complexes and dykes from central Paraguay (ASU) show a mean T^{DM} of 1.7 Ga [84]; (3) the associated high-Ti tholeiitic basalts have T^{DM} ranging from 0.9 to 1.4 Ga. On the other hand, the low-Ti tholeiites exhibit model ages varying from 0.7 to 2.8 Ga, with T^{DM} increasing from north to
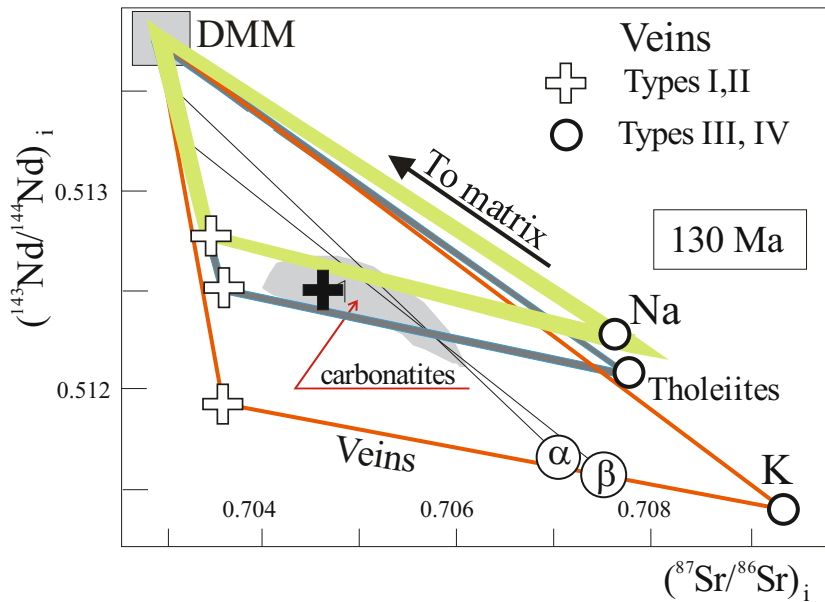
Figure 7: Calculated subcontinental upper mantle (SCUM) isotopic composition at 1.8 Ga, projected to 130 Ma. Parental melts with various Rb/Sr and Sm/Nd ratios are assumed for potassic and sodic rocks from Paraguay (symbol "K" and "Na," respectively [20,34,35,100]) and tholeiitic basalts ("tholeiites" of [2]). The compositions of metasomatites formed from a single metasomatizing melt vary with the evolution of the melt. Consequently, the veins will define a trend of shallow slope, and mixing curves between vein and matrix will define an array toward the matrix (cf. α and β regression lines). Model DMM: Rb = 0, Sr = 0.133, Sm = 0.314, Nd = 0.628; +: present-day Bulk Earth: $^{87}Sr/^{86}Sr$ = 0.70475, $^{87}Rb/^{86}Sr$ = 0.0816, $^{143}Nd/^{144}Nd$ = 0.512638, $^{147}Sm/^{143}Nd$ = 0.1967; $(Rb/Sr)_{diopside}$: $(Rb/Sr)_{melt} \approx$ 0.125, $(Sm/Nd)_{diopside}$: $(Sm/Nd)_{melt} \approx$ 1.5; K: Rb/Sr = 0.0957, Sm/Nd = 0.1344; Na: Rb/Sr = 0.0732, Sm/Nd = 0.2295; Th: Rb/Sr = 0.0733, Sm/Nd = 0.2082 (cf. Figure 8 and 15 of [84] and [20], respectively). Metasomatic veins are classified after [113].

south and from west to east; (4) the Na-alkaline rocks display T^{DM} mean values of 0.6 Ga (Na-ASU, Paleocene) and 1.0 Ga (Misiones, late Early Cretaceous, respectively, [34,35]). The youngest model ages are those of the Late Cretaceous alkaline outcrops from the Brazilian Mato Preto carbonatite (Ponta Grossa Arch: 0.58 ± 0.08 [40]). On the other hand, the Early Cretaceous carbonatites of Barra do Itapirapuã and Jacupiranga (Ponta Grossa Arch) show T^{DM} of 0.7 ± 0.2 Ga.

Thus, the range of model ages in the southern Brazilian Platform (cf. Figure 9 of [12]) suggests that the corresponding Paleozoic, Cretaceous, and Paleogene magmas are derived from subcontinental lithospheric mantle modified by metasomatic processes (probably involving asthenospheric components) since Neoarchean to Neoproterozoic times [1,20,34,35,110].

In summary, the overlapping of isotopic compositions and/or model ages of different igneous rocks (i.e., high- and low-Ti tholeiites, K- and Na-alkaline rocks and carbonatites) cannot be accidental and suggests sampling of ancient reservoirs formed at the same time from the same subcontinental upper mantle (SCUM). Either in case of heterogeneity induced by recycled crust in the mantle [111,112], or of variably veined material in the SCUM [113], or

both, it is clear that magma genesis involved ancient lithospheric mantle reset at well-defined isotopic ranges.

A Proterozoic lithospheric mantle with veins of amphibole/phlogopite-carbonate-lherzolite and amphibole-lherzolite + CO_2 fluid (type III and IV veins of [113]) may well account for the magmatism of the southern Brazilian Platform (Figure 7). This scenario is compatible with Pb isotope data indicating a mantle source of ca. 1.8 Ga for the Paraná high-Ti tholeiites (see Pb isotopes section) and with the age of formation of much of the crust of southern Brazil (2 Ga; cf. [114]).

5 Pb isotopes

The available Pb isotopic data for the alkaline–carbonatite complexes and tholeiites from the PS are reported in Table 4 and plotted in Figure 8a and b. The figures show patterns compatible with mixing processes mainly involving HIMU and EMI end members, and subordinately DMM and EMI, as well as crustal s.l. components (e.g., EMII). It should be noted that all the rock types lie to the right of the 132 Ma geochron for the whole

Table 4: Representative Pb isotopic ratios (measured and initial ratios) of carbonatites from the southern Brazilian Platform. Data sources as in Table 1

Brazil	Measured			Age Ma	Initial		
	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Barra do	18.627	15.605	39.123	115	18.232	15.598	38.922
Itapirapuã	18.763	15.618	39.147		18.495	15.612	39.011
	18.426	15.528	38.808		18.159	15.538	38.593
Ipanema	17.617	15.477	37.938	125	17.451	15.467	37.612
Itanhaém	17.489	15.418	37.879	129	17.262	15.406	37.473
Itapirapuã	17.887	15.362	38.141	109	17.750	15.398	37.845
	17.262	15.453	38.019	131	17.26	15.45	38.00
	17.254	15.457	37.881		17.25	15.46	37.87
Jacupiranga	17.273	15.457	37.970		17.27	15.45	37.90
	17.140	15.445	37.800		17.10	15.44	37.70
	18.256	15.446	38.170		17.464	15.407	37.769
	17.049	15.380	37.610		17.048	15.38	37.606
	17.954	15.430	38.791		17.326	15.399	37.755
	18.191	15.448	40.320		17.47	15.413	38.049
Juquiá	17.585	15.440	39.405	132	17.42	15.42	38.19
	17.787	15.432	38.379		17.453	15.415	38.18
Anitápolis	17.394	15.432	38.479	129	17.37	15.43	38.34
	17.491	15.453	39.375		17.41	15.45	38.21
	17.415	15.46	38.468		17.38	15.46	38.27
Paraguay							
Valle-mí	20.310	15.658	38.9676	138.7	19.968	15.641	38.589
Cerro Chiriguelo	17.333	15.521	37.608	137.9	17.033	15.506	37.465
	18.821	15.434	38.288		18.501	15.574	38.152
Cerro Sarambí	18.821	15.434	38.290	139.6	18.490	15.56	38.07
Sapucai	17.859	15.518	37.916	126.4	17.702	15.511	37.852
Cerro Cañada	17.865	15.632	38.222	124.6	17.624	15.620	37.915
Cerro E Santa Elena	17.435	15.435	37.796	127	17.200	15.424	37.373

Paraná–Etendeka system ([115], except for the post-tholeiitic K-rocks from eastern Paraguay that plot close to the 132 Ma geochron (Figure 8a).

Carbonatites from southern Brazil and eastern Paraguay plot close to the EMI/DMM-HIMU mixing lines for both Pb–Sr and Pb–Nd [31], different from Mid-Atlantic Ridge (MAR) basalts and Ocean island basalts (OIB), which define trends between the DMM and HIMU mantle components.

This observation seems to confirm the advantages in using carbonatite over silicate rocks, as indicators of mantle sources, because of their rapid ascent to the surface conditions, and buffering against crustal assimilation due to their high Sr, Nd, and Pb concentrations in the liquids.

The available Pb isotopic data indicate that any model proposed for the evolution of the HIMU and EMI end members must be consistent with the following constraints: (1) HIMU and EMI are not restricted to the oceanic environment; (2) end members are variously associated in space as a function of the various protoliths; (3) mantle regions with HIMU and EMI isotope characteristics can generate a wide variety of silicate melts, including melts enriched in CO_2 [116]; (4) Na-alkaline rock types are systematically grouped together in fields well distinct from the K-alkaline fields in Paraguay; (5) even the Na-alkaline rock types from the Central Rift of the sub-Andean system (Late Cretaceous; cf. [117]) fit the Triassic to Neogene analogues from eastern Paraguay (cf. [35]).

Some authors as [11,79,115] postulated that the Early Cretaceous alkaline–carbonatitic and tholeiitic magmatism and the Late Cretaceous alkaline and alkaline–carbonatitic magmatism from Alto Paranaíba-Serra do Mar (southern Brazil) would reflect the variable contributions of the asthenospheric mantle components related to the Tristan da Cunha and Trindade plumes, respectively. On the contrary, other authors [1,16,99,110] suggested that the alkaline and alkaline–carbonatitic magmatism in the
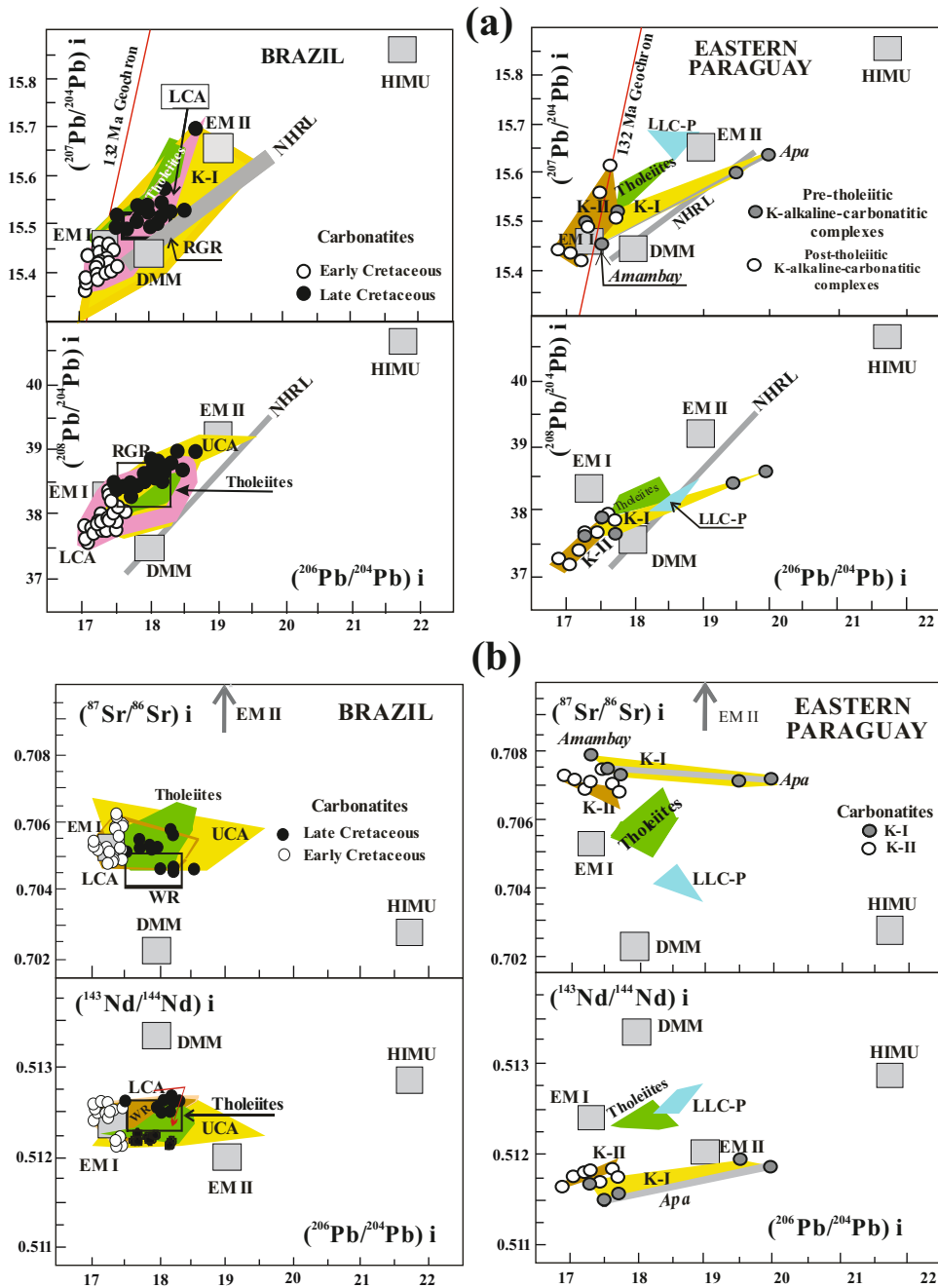
Figure 8: (a) $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ (initial ratios) for rock types from southern Brazil and eastern Paraguay. (b) $^{206}Pb/^{204}Pb$ (initial ratios) vs Sr_i and Nd_i. Brazil: Lower (or Early) Cretaceous (LCA) and Upper (or Late) Cretaceous (UCA) alkaline magmatism, respectively; RGR, Rio Grande Rise; eastern Paraguay: K-I and K-II pre- and post-tholeiitic potassic alkaline magmatism (Early Cretaceous), respectively; LLC-P, late Lower (or Early) Cretaceous and Paleocene magmatism. Data sources: Table 4. Other data sources, as in Figure 6. NHRL (North Hemisphere Reference Line) after [124]; 132 Ma geochron of [115].

examined rock types originated from lithospheric mantle sources without appreciable contribution of plume-derived materials.

On the basis of geochemical and geophysical data, [6,7,118] proposed that the genesis of the tholeiites in the Paraná-Tristan da Cunha system mainly reflects melting of heterogeneous subcontinental mantle reservoirs, and that the geochemical and isotopic signatures of the Walvis Ridge and Rio Grande Rise basalts may be explained by contamination through detached continental lithospheric mantle left behind during the continental break-up processes.

Table 5: Rb, Sr, Sm, Nd, Re, and Os concentrations and isotopic initial ratios of selected samples from the Alto Paranaíba Igneous Province and one sample from Lages (notional ages 85 and 75 Ma, respectively). Analytical methods and data sources: [20,24,25] and references therein

	Kimberlites								Glimmerites		
	Limeira		Tres Ranchos		Pantano	Salitre			Santa Rosa	Verdiana	Canas
ppm											
Rb	114	94	48	38	183	124	21.1	132	333	1,161	144
Sr	2,540	2,215	1,811	2,927	2,029	2,267	1,450	1,070	1,668	1,771	1,632
Sm	30.3	42	23.5	43	24.9	25.6	20.0	42.9	22	22	22.2
Nd	224.6	312	208.4	348	195.1	186	116.5	324.8	160	162	165
Pb	11	15	19.5	13	9.2	12	13	13.2	23.2	16.4	17.4
U	4	28	7.1	8	6.4	18	8.2	11.4	4.3	4.8	4.3
Th	23	41	29.6	42	25.4	40	25	30.9	18.2	20.9	20.9
ppb											
Re	0.418	0.315	1.992	0.2173	0.2170	0.3347	0.7192	1.3135	1.101	6.33	2.23
Os	1.612	1.221	1.982	1.2624	0.8080	1.1646	1.9271	1.4295	0.518	0.582	0.609
$^{187}Re/^{188}Os$	1.334	1.2313	4.845	0.6227	1.2960	1.3344	1.8619	4.4295	10.46	54.14	18.07
Initial ratios											
$^{87}Sr/^{86}Sr$	0.70528	0.70543	0.70493	0.70514	0.70532	0.70540	0.70541	0.70505	0.70564	0.70624	0.70595
$^{143}Nd/^{144}Nd$	0.51225	0.51222	0.51228	0.151227	0.51225	0.51220	0.51230	0.51223	0.51219	0.51218	0.51218
$^{206}Pb/^{204}Pb$	17.84	21.48	18.67	18.11	17.84	21.44	17.86	19.35	17.22	17.24	17.24
$^{207}Pb/^{204}Pb$	15.49	15.66	15.53	15.51	15.47	15.74	15.61	15.58	15.39	15.41	15.40
$^{208}Pb/^{204}Pb$	38.25	39.73	38.18	38.61	39.21	39.67	38.92	38.40	37.78	37.76	37.81
$^{187}Os/^{188}Os$	0.113338	0.12679	0.12138	0.11986	0.12618	0.12861	0.11721	0.12456	0.27471	0.30452	0.26677

`he Early Cretaceous alkaline magmatism from the southern Brazilian Platform appears to be related to heterogeneous mantle sources spanning from time-integrated HIMU and enriched mantle components (Figure 8). According to [119], for example, relatively low $^{206}Pb/^{204}Pb$ and high $^{207}Pb/^{204}Pb$ compositions could be related to delamination of pyroxenite restites formed by anatexis of the initial basaltic crust in Archean–Proterozoic times. The alkaline magmatism from Brazil and Paraguay mimics, in terms of isotopic compositions, the coeval flood tholeiites. We stress that, in general, the enriched isotopic signatures of the Early Cretaceous alkaline magmatism decreases from West (Paraguay) to East (Brazil and SE continental margins). We observe a similar decreasing trend as a function of the age of the magmatism in Paraguay and Brazil from Early-Late Cretaceous to Paleogene. These results suggest that the magmatism is related to both large- and small-scale heterogeneous mantle sources. It should be noted that, according to [79], the APIP (Alto Paranaíba Igneous Province) would be the inland surface expression of the "dogleg" track left by the Trindade plume. However, in terms of Sr–Nd–Pb isotopes, the contribution, if any, of the asthenospheric components related to that plume is difficult to account for.

Overall, the data are consistent with a thermally eroded metasomatic SCLM and/or delaminated lithospheric materials stored for long time in the transition zone or deeper mantle in Archean–Proterozoic times [26]. The important role of the Tristan plume claimed by [115] is not apparent. Therefore, we agree with [6,7] that the hypothesis of asthenospheric plumes for the magmatism from PS is not compelling, while a deep mantle thermal anomaly, corresponding to positive geoid anomaly and low seismic velocity (e.g., [120,121]), may have been its possible heat source based on reconstructions of the position of the South American lithospheric plate in the Cretaceous [7,20,122,123].

6 Some notes on the Re–Os isotopic system

Although carbonatites are not suitable materials for the analysis of Re–Os and platinum group elements ([125,126] and references therein), many carbonatitic complexes from southern Brazil are strictly associated with mafic-ultramafic high-K rocks with kamafugitic and kimberlitic affinity, e.g., in the Rio Verde-Iporá (Goiás), Alto Paranaíba (Minas Gerais), and Lages (Santa Catarina) areas (Late Cretaceous magmatism). Some
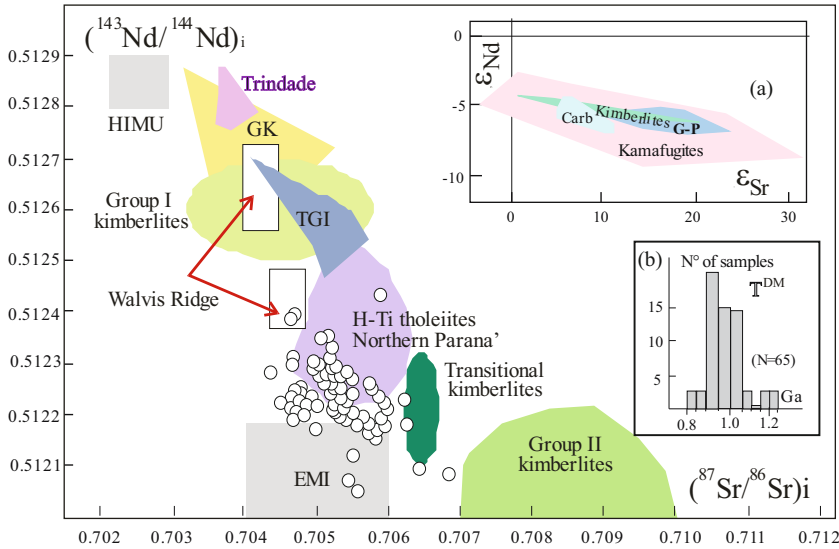
Figure 9: $^{87}Sr/^{86}Sr$ vs. $^{144}Nd/^{143}Nd$ initial ratios for rock types from Alto Paranaíba. GK, Gibeon kimberlites [131]; TGI, Tristan da Cunha, Inaccessibile and Gough islands [132,133]; Other data sources: [24,77,78,86,89,92–95,129,130,134–136]. Inset (a), time-integrated ε_{Sr} vs ε_{Nd} correlation diagrams; Inset (b), hystogram relative to Nd model ages (T^{DM}) for Alto Paranaíba alkaline and carbonatite rocks (T^{DM} values: calculation of model ages relative to a depleted reservoir, $^{143}Nd/^{144}Nd = 0.513114$ and $^{147}Sm/^{144}Nd = 0.222$: cf. [62].

authors [24,25,71,90,127] provided some Re, Os, and platinoids data for rocks from the APIP (cf. Figure 1 of [128]), with the aim to develop a petrogenetic model regarding the kamafugitic–kimberlitic magmatism and associated carbonatites. For this purpose, this section presents a brief review for the main APIP rock types, i.e., kimberlites, kamafugites, phlogopite-rich peridotites, glimmerites, and associated carbonatites, in order to compare the Sm–Nd–Pb isotope results with the available Re–Os data.

Representative trace element compositions and isotope ratios are listed in Table 5. $^{87}Sr/^{86}Sr$ vs $^{143}Nd/^{144}Nd$ initial ratios are plotted in Figure 9. The APIP rock types straddle the field of the high-Ti tholeiites of the Northern Paraná Basin (Early Cretaceous) and are intermediate between the Kimberlites I and the Kimberlites II of [129,130].

In general, the high concentrations of the most incompatible elements (IEs) in all the APIP alkaline rocks [128] suggest that the effects of crustal contamination on the Sr–Nd isotopic system were negligible and that the parental magma compositions are more likely produced by mantle-enriched sources affected by variable degrees of metasomatism. The data, plotted in time-integrated ε-notations, are widespread mainly in the enriched quadrant, with εSr and εNd extending in the ranges from –4 to 31 and from –2.5 to –9, respectively. The field relative to the kamafugitic rock types contains all the other lithologies (inset a of Figure 9), i.e., kimberlites, glimmerites, mica

peridotites, and carbonatites. The almost constant value of the Sm/Nd ratio in the APIP rocks ($^{147}Sm/^{144}Nd = 0.085 \pm 0.009$; [31]) suggests that the Nd model age is indicative of the main metasomatic event affecting the lithosphere beneath the Alto Paranaíba region [128]. Model ages T^{DM} (calculated with respect to the depleted mantle; cf. [31]) for the whole APIP population (65 samples; cf. inset b of Figure 9) average to 1.0 ± 0.1 Ga.

The initial isotopic compositions displayed on $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ vs $^{208}Pb/^{204}Pb$ diagrams (Figure 10a) define essentially linear arrays that are subparallel to both the Early Cretaceous tholeiites from the Paraná Basin [89,135] and the Northern Hemisphere Reference Line (NHRL; [124]). A possible explanation for the Pb isotope behavior is that the data represent a secondary isochron, giving an apparent age of 2.5 Ga, suggesting an Archean–Proterozoic mantle source, as already pointed out by [114] for the tholeiites from the Paraná Basin. Alternatively, the observed trends are due to the mixing of different mantle components. Notably, some kimberlites approach the HIMU mantle component.

Overall, the APIP alkaline rock types and associated carbonatites plot in the field of the Brazilian Late Cretaceous alkaline–carbonatite complexes. The latter contains the fields of all the magmatic rock types from the Paraná Basin (i.e., Early Cretaceous flood tholeiites and alkaline–carbonatite complexes (cf. [31] and Figure 8). In particular, the APIP extends from EMI and DMM to EMII mantle components, overlapping the field of the
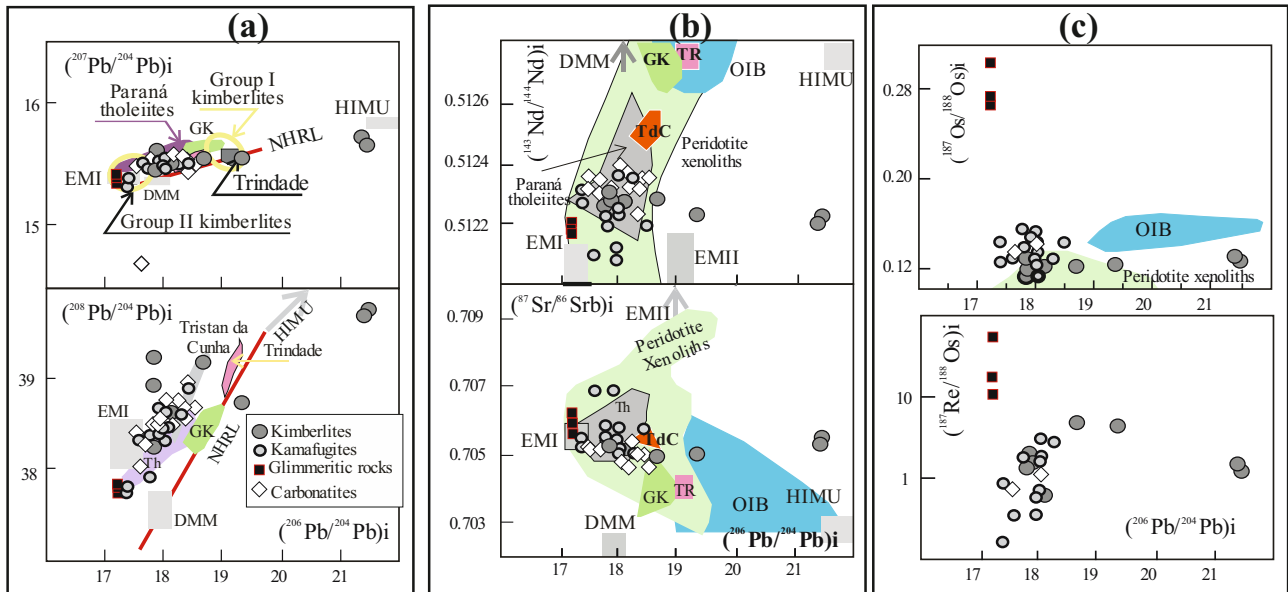
Figure 10: Pb, Nd–Sr and Re–Os isotopic ratios of samples from the Alto Paranaíba (Table 5). (a): $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ and vs $^{208}Pb/^{204}Pb$, initial ratios; (b): $^{206}Pb/^{204}Pb$ vs $^{143}Nd/^{144}Nd$ and vs $^{87}Sr/^{86}Sr$ initial ratios; (c): $^{206}Pb/^{204}Pb$ vs $^{187}Os/^{188}Os$ and $^{187}Re/^{188}Os$ isotopic signatures (initial ratios). HIMU, DMM EMI, and EMII components, as defined by [137] and by [138]; Group I and Group II kimberlites, OIB, Ocean island basalts, and peridotite xenoliths, after [129,130,139]; Paraná tholeiites ("uncontaminated" high-Ti tholeiites after [99] and references therein); TR, Trindade, [135,136]; TdC, Tristan da Cunha-Gough-Inaccessible [133]. GK, Gibeon kimberlites [131]. NHRL: North Hemisphere Reference Line [124].

Tristan da Cunha volcanics (Figure 10). Considering the diagrams $^{206}Pb/^{207}Pb$ vs $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}$ Nd (initial ratios) of Figure 10b, it should be noted that most of the APIP rocks are in the field of the peridotite xenoliths, except for some kimberlites; the latter show lower radiogenic Nd with respect to the Late Cretaceous kimberlites from Gibeon [131].

The Re–Os isotope systematics does not allow a clear distinction among the different rock types. Kimberlites have Re and Os between 0.32 and 1.99 ppb, and 0.81 and 1.98 ppb (av. 0.69 ± 0.64 and 1.43 ± 0.40 ppb, respectively). On the other hand, $^{187}Os/^{188}Os$ initial ratios vary within a small range, i.e., from 0.11 to 0.13 (av. 0.122 ± 0.005). Kamafugites show Re and Os from 0.06 to 0.38 ppb and from 0.12 to 1.76 ppb (av. 0.156 ± 0.140 and 0.672 ± 0.526 ppb, respectively) and have $^{187}Os/^{188}Os$ initial ratios ranging from 0.11 to 0.15 (av. 0.134 ± 0.013). The glimmerites that present the highest $^{187}Os/^{188}Os$ (av. 0.295 ± 0.043) and $^{187}Re/^{188}Os$ (av. 13.98 ± 3.83) ratios are well distinct from the other groups (Figure 10).

Rhenium depletion (TRD) model ages (based on Re–Os isotopes) range between 1.39 and 1.64 Ga, thus setting a minimum Re age of the source region protolith [25] showing an older event with respect to the APIP Nd model age (1.0 ± 0.1). Notably, these model ages are in the same range of the Paraguay alkaline–carbonatite

rocks (1.1–1.7 Ga). The cluster of isotopic data seems to indicate old lithospheric sources.

Arguments in favor of lithospheric sources for the APIP magma types are also postulated by [24,127], by comparing the Re-depletion ages of the kimberlites with Nd-depleted mantle model ages of all their analyzed rock types. The Os isotope data for the APIP rock types are indicative of lithospheric mantle sources for the kimberlites ($^{187}Os/^{188}Os$ ratios 0.11 to 0.13) that were variously Re depleted, probably at Neoarchean to Mesoproterozoic times. These lithospheric sources experienced LILE enrichment by fluid/melt metasomatism at ~1 Ga, probably during the mobile belt formation along the western border of the São Francisco craton. Kamafugites have radiogenic $^{187}Os/^{188}Os$ ratios (up to 0.15) suggestive of source veins that appear to have been stabilized in the lithospheric mantle in the Meso- to Neoproterozoic.

Finally, it should be stressed that Carlson et al. [24] proposed that the Os isotope compositions, coupled with Sr–Nd–Pb isotope systematics, most likely represent the influence of delaminated Brazilian lithospheric mantle mixed into mantle circulation beneath the South Atlantic and are not related to the plume(s) activity commonly attributed to the APIP magmatism (cf. [77]). As matter of fact, geoid anomaly maps and regional seismic tomography studies are supporting a non-plume-related heat

source for the magmatism from southern Brazil and eastern Paraguay [7,110]. The hotspot tracks of Walvis Ridge and Rio Grande Rise, as well as the Victória-Trindade chain, rather than reflecting continuous magmatic activity induced by mantle plumes beneath the moving lithospheric plates might instead reflect the accommodation of stresses in the lithosphere during rifting, similar to the general mechanism proposed by [140,141].

7 Concluding remarks

The isotopic data show that magmatism from the southern Brazilian Platform requires heterogeneous mantle sources, also in terms of radiogenic isotopes, probably related to metasomatic s.l. processes that occurred between Neoarchean and Neoproterozoic times, as also confirmed by Re–Os systematics on mafic-ultramafic rock types associated with the alkaline–carbonatitic complexes.

The areal distribution of magmatism suggests that the time-integrated isotopic enrichment of carbonatites and associated alkaline rocks decreases from west (eastern Paraguay) to east (southern Brazil), concomitantly with the decreasing age of the magmatism (Early to Late Cretaceous). This supports the view that the alkaline–carbonatitic magmatism originated from large- to small-scale heterogeneous subcontinental mantle. Sr–Nd–Pb–Os isotope data yield clear evidences that HIMU and EMI mantle components were important in the genesis of the magmatism in the southern Brazilian Platform. We speculate that a viable mechanism could involve passive rifting, asthenosphere upwelling, and consequent melting of a metasomized (fluid-bearing) subcontinental lithospheric mantle.

All the results indicate that asthenospheric components derived from mantle plumes (i.e., Tristan da Cunha and Trindade hot spots; cf. [142]) did not significantly contribute to the genesis of the alkaline–carbonatitic magmatism, consistent with the conclusions reached by [2,7,90,99] for the petrogenesis of the Paraná flood tholeiites. This confirms that the exact mechanism that produced the South Atlantic igneous province and its relationship with the South Atlantic opening are still an open question (e.g., [22] and reference therein).

Regional thermal anomalies in the mantle, mapped by geoid and seismic tomography, are supporting a non-plume-related heat source for the Paraná magmatic province according to [7,110,118]. The hotspot tracks of Walvis Ridge and Rio Grande Rise, as well as the Victória-Trindade chain, might be the manifestation of accumulation of stresses due to small-scale lithospheric convection associated with rifting rather than continuous magmatic activity induced by mantle plumes beneath the moving lithospheric plates.

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