

Mantle sources and differentiation of alkaline magmatic suite of Lages, Santa Catarina, Brazil

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Abstract: The alkaline-carbonatite district of Lages (Santa Catarina, Brazil) contains mafic-ultramafic and prevalent leucocratic bodies mainly composed of olivine melilitites, olivine nephelinites, basanites, phonotephrites, nepheline syenites and peralkaline phonolites. Kimberlitic pipe breccias and carbonatitic rocks are also present.

Petrography, mineral and bulk-rock chemistry and mass balance calculations show that differentiated leucocratic rock-types can be derived by fractional crystallization processes from basanitic magmas. Trace element and Sr-Nd isotopic data suggest metasomatized mantle sources for the primary magmas and variable crustal contamination for the more differentiated rock-types.

Key-words: igneous petrology, Sr-Nd isotopes, basanite-peralkaline phonolite, Brazil.

Introduction

Studies on the alkaline-carbonatite complexes of continental Brazil have been carried out by an Italian-Brazilian research team (Morbidelli *et al.*, 1986, 1991; Barbieri *et al.*, 1987; Gomes *et al.*, 1987, 1990; Brotzu *et al.*, 1989, 1994; Macciotta *et al.*, 1990; Beccaluva *et al.*, 1992). Among these, the Lages alkaline district has been recently investigated, as regards petrography, petrochemistry and mineral chemistry of the silicatic rock series (Traversa *et al.*, 1994).

The alkaline magmatic suite of southern Brazil, mainly comprising intrusive leucocratic rocks, is frequently associated with carbonatites and shows a clear tectonic control related to large-scale geological phenomena which started in late Jurassic times with continental break-up and drift (Ulbrich & Gomes, 1981; Herz, 1977). Five ancient cratonic areas are recognized in South America, separated by large sedimentary protobasins (*e.g.* Parana and Paranaiba troughs) which were already well accreted by late Precambrian times. This tectonic stability lasted up until the end of

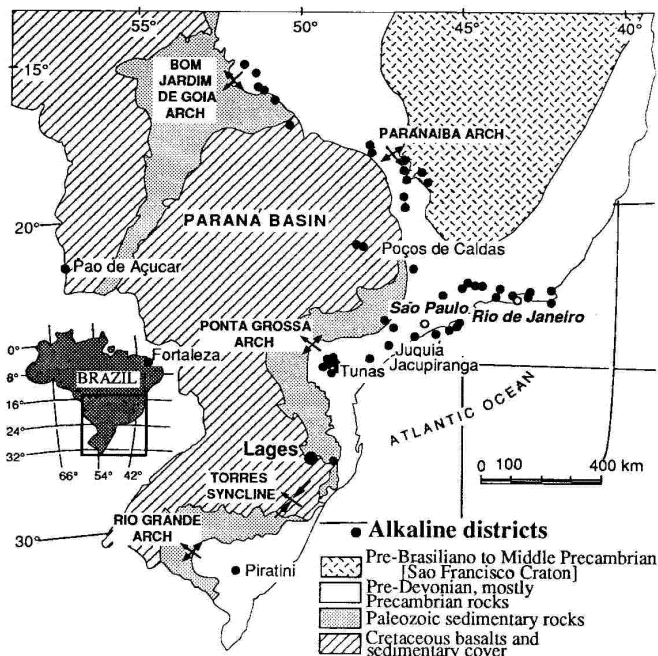


Fig. 1. Alkaline districts of southern Brazil (simplified after Ulbrich & Gomes (1981) and Gomes *et al.* (1990). Alkaline districts at the Paraguay border are indicated by the Pao de Açúcar occurrence.

the Jurassic when renewed faulting formed small continental basins. The large protobasin areas underwent subsidence up to the Late Cretaceous–Early Tertiary, with the accumulation of a 5000 m thick sedimentary succession. This new tectonic activity is associated with basaltic flood volcanism (140–120 Ma, Rocha-Campos *et al.*, 1988) which covered most of the Paraná Basin and other surrounding areas.

The Brazilian alkaline districts show two main structural positions, one at the Paraná Basin border, and the other as a NE-trending belt parallel to the Coast zone of São Paulo and Rio de Janeiro states (Fig. 1). The alkaline magmatism, cutting pre-Devonian basement or Paraná Basin sediments (*e.g.* Lages) is concentrated into distinct geographic areas and is attributable to tectonic features such as arches, flexures, fault zones and rifted areas. Of great importance are the NW-trending arch structures of Rio Grande do Sul, Ponta Grossa and Paranaíba and also the NNW-trending lineaments with rift tectonic features associated with the Bom Jardim de Goiás uplift.

Radiometric ages (Gomes *et al.*, 1990) show the periodicity of alkaline magmatism in southern Brazil characterized by four main phases. The

first, of Permo-Triassic age (250–240 Ma) developed at the Paraguay border (Pao de Açúcar district). The second phase (Jacupiranga and related massifs) yields an age of around 130 Ma, similar to that of the Paraná Basin magmatism, predating the opening of the South Atlantic Ocean (127 Ma being the oldest sea-floor anomaly; *cf.* Piccirillo *et al.*, 1988). A few occurrences in the Ponta Grossa Arch Province give an age of 110–100 Ma (third phase), while the youngest and most important phase (90–50 Ma), to which the Lages magmatism belongs (78–63 Ma, Scheibe, 1986), developed in several provinces, from south (Rio Grande do Sul Arch, Piratini) to north (Coastal province of São Paulo and Rio de Janeiro, Poços de Caldas Province and Minas Gerais-Goiás alkaline belt).

The Lages district is associated with the uplift of a large crustal block, the so-called “Lages Dome” (Paiva, 1933), bounded to the north and south by two main tectonic lineaments. For this dome structure (Santa Catarina Province), tectonic control by old NW-trending fault zones has been recognized (Scheibe, 1986). The domed character of the area is underlined by the concentric arrangement of sedimentary formations, making up the entire Gondwanan succession: from the fluvio-

lacustrine Permo-Carboniferous deposits, outcropping in the central part of the uplifted area, to the Triassic Botucatu sandstones, in the marginal zones of the Lages Dome, which is bordered to the west by the Paran basaltic traps.

In the context of Brazilian alkaline associations of Cretaceous age, the Lages complex is remarkable for the coexistence of mafic-ultramafic and leucocratic rock-types with carbonatites and kimberlitic diatreme breccias. The shallow level of intrusions with dominant hypabyssal-subvolcanic rocks is to be also noted.

The Lages magmatic suite is mainly composed of leucocratic types, while carbonatitic, kimberlitic and mafic-ultramafic rocks are strongly subordinate. These latter comprise olivine melilitites (OM), olivine nephelinites (ON) and minor basanites (BA), whereas the leucocratic rocks are represented by largely prevalent porphyritic (PPPh) and aphyric-subaphyric (PPh) peralkaline phonolites and minor nepheline syenites (NeSy).

Rare trachyphonolites (TrPh) and sporadic phonolithic tephrites (PhTe) are also present.

The mineralogy, clinopyroxene chemistry, incompatible element distribution and mass balance calculations preclude derivation by fractional crystallization of OM, ON and BA. On the other hand, fractional crystallization has been hypothesized between basanitic primary magmas and leucocratic rocks (Traversa *et al.*, 1994).

Petrology, Sr-Nd isotope data, and chemical mass balance calculations for mafic-ultramafic to leucocratic rocks are presented in the present study.

Petrography and geochemistry

Table 1 reports the mineralogy of the main rock-types. It is also suitable to highlight: the presence of monticellite in some OM; the large alkali feldspar megacrysts (up to 20 mm) characterizing many NeSy; the presence of unstable xenocrysts

Table 1. Mineralogical composition of Lages alkaline rocks.

		OM	ON	BA		PhTe		NeSy	PPPh	
				ph	gd	ph	gd		ph	gd
Sp	Cr ₂ O ₃	30.4–21.7	28.0–20.0							
	Al ₂ O ₃	32.5–27.4	43.8–53.9							
Ti-mt	ulv	24.8–19.6	69.2–38.3	58.2	+	24.4–24.2	+	38.4–20.6	+	
Ol	Fo	90.5–86.8	89.5–80.4	86.3–85.5	+					
Mel	CaO	36.7–33.7								
	Na ₂ O	2.7–4.8								
Bi	mg	0.77–0.76	0.85–0.69	0.84–0.81	0.64	0.59	0.74	0.77–0.48	(0.85–0.84)	
Cpx	mg	0.89–0.85	0.85–0.75	0.67	0.80	0.65–0.53	+	0.67–0.26	0.67–0.02	0.41–0.00
									(0.83–0.58)	
Ne	Na	76–67	78–66		+	83	+	90–82	83–75	87–74
	K	24–33	22–34			17		10–18	17–25	13–26
Af	Or				+		+	48.6–67.1	77.1–69.6	97.1–90.4
										65.9–48.6
										2.4–0.8
Kaer	mg							(0.56–0.52)	(+)	
Parg	mg					0.57	0.57	(0.49–0.43)		
Pl					+		+			
Ap		+	+		+			+	+	
Prv		+	+							
Ti								+	+	
Lc			+							
Kp			+							

Abbreviations: OM = olivine melilitite; ON = olivine nephelinites; BA = basanite; PhTe = phonotephrite; NeSy = nepheline syenite; PPPh = porphyritic peralkaline phonolite; ph = phenocryst; gd = groundmass; gd of PPPh refers also to groundmass composition of aphyric peralkaline phonolites; Sp = spinel; Ti-mt = titaniferous magnetite; Ol = olivine; Mel = melilitite; Bi = phlogopite and biotite; Cpx = clinopyroxene; Ne = nepheline; Af = alkali feldspar; Kaer = kaersutite; Parg = pargasite; Pl = plagioclase; Ap = apatite; Prv = perovskite; Ti = titanite; Lc = leucite; Kp = kalsilitite; oxides (Cr₂O₃ *etc.*) in wt%; ulv = ulvospinel %; mg = Mg/Mg+Fe²⁺; + = present; values in brackets refer to xenocrysts.

Table 2. Selected chemical analyses of Lages alkaline rocks.

	LM6 OM	PA1 OM	LM98 OM	LA70 ON	PA3 ON	LM115 ON	LM116 ON	PA4 BA	LA3 PHTe	LM53 NeSy	LM51 NeSy	LM99 PPPh	LM97 PPh	LM112 PPh	LM19 PPh	LM83 PPh
SiO ₂	38.28	34.23	35.34	40.15	40.25	41.75	41.57	44.62	46.10	55.81	56.23	54.94	57.09	59.23	57.93	58.37
TiO ₂	1.51	1.54	1.81	1.98	1.98	2.88	2.93	2.21	1.53	0.79	0.65	0.38	0.36	0.20	0.13	0.20
Al ₂ O ₃	9.29	8.29	9.71	11.30	10.85	11.50	11.45	12.08	17.55	20.18	19.98	21.03	19.97	20.80	20.95	20.88
Fe ₂ O ₃	2.58	4.10	3.14	5.37	4.91	4.36	4.62	4.44	4.00	1.15	1.49	1.21	2.29	1.32	1.34	1.30
FeO	6.10	5.42	5.74	4.69	5.24	6.10	5.92	5.35	3.48	3.02	1.52	1.22	0.70	0.62	0.64	0.58
MnO	0.18	0.17	0.21	0.16	0.15	0.17	0.17	0.14	0.14	0.15	0.14	0.12	0.11	0.21	0.17	0.30
MgO	17.47	18.42	14.18	14.53	13.17	10.74	10.38	12.56	3.95	1.51	0.48	0.16	0.37	0.05	0.05	0.04
CaO	14.59	16.65	18.32	13.25	12.29	12.88	12.59	8.06	7.24	2.39	1.87	0.78	0.89	0.76	0.76	0.46
Na ₂ O	3.16	0.87	2.96	2.00	4.90	3.73	4.00	3.19	6.06	7.02	6.90	9.22	10.67	9.89	10.87	11.91
K ₂ O	3.17	1.54	2.84	1.07	0.88	2.82	3.36	3.16	4.07	5.97	6.77	6.71	5.01	5.79	5.58	5.01
P ₂ O ₅	1.37	1.10	2.33	1.15	1.60	1.15	1.04	0.60	0.60	0.40	0.17	0.06	0.09	0.03	0.01	0.03
L.O.I.	2.24	6.95	3.41	3.86	3.21	1.93	1.97	3.04	4.90	0.34	3.28	3.08	2.55	0.97	1.57	0.92
Total	99.94	99.28	99.99	99.51	99.53	100.01	100.00	99.45	99.62	100.01	100.00	100.00	99.99	100.00	100.00	100.00
V	232	165	220	224	196	217	217	284	175	74	52	43	51	14	12	10
Cr	642	676	402	498	426	320	325	474	22	1	n.d.	n.d.	14	5	n.d.	n.d.
Co	54	54	40	50	49	44	45	50	24	7	4	3	5	2	2	n.d.
Ni	417	342	171	305	327	233	243	288	18	14	15	12	18	15	11	12
Zn	83	87	83	95	99	108	108	96	84	91	2998	77	94	147	133	195
Rb	92	64	100	39	45	85	92	43	79	122	115	125	122	168	203	296
Sr	1470	1910	1950	1370	1360	1650	1640	1010	1270	3730	4320	2200	310	108	30	19
BA	2290	1720	3210	1620	1970	1920	1940	1220	1660	2600	2990	1260	293	48	29	27
Zr	218	173	239	186	166	276	267	207	239	394	203	310	1840	840	685	1340
Pb	19	10	22	10	10	19	8	11	17	35	31	23	25	36	39	44
Nb	100	101	158	86	89	113	111	36	87	120	109	98	626	165	90	255
Y	30.04	31.00	45.72	25.00	26.00	25.49	25.85	22.00	22	29.28	29.09	21.03	7.27	26.47	16.34	45.27
La	140.95	123.60	167.06	88.30	89.60	91.48	94.74	65.50	94	151.70	147.57	130.58	21.28	183.03	146.69	174.63
Ce	266.25	213.80	314.63	148.30	150.30	175.22	178.14	121.40	176	246.49	231.57	186.75	42.84	264.55	169.25	287.46
Nd	85.43	88.20	115.32	63.10	65.80	69.08	71.47	55.00	--	75.05	67.12	39.98	13.01	50.76	25.62	61.43
Sm	14.55	14.90	19.03	10.90	11.80	12.08	12.20	9.40	--	11.09	10.46	5.75	2.23	6.50	3.48	8.50
Eu	4.40	4.10	5.52	3.00	3.10	3.40	3.45	2.50	--	2.77	3.41	1.60	0.63	1.35	0.90	1.30
Gd	9.59	10.90	13.44	7.80	8.60	8.29	8.47	6.50	--	7.21	6.73	3.93	1.60	4.32	2.45	5.72
Dy	5.32	6.10	8.43	4.50	5.10	5.01	5.04	4.00	--	4.65	4.23	2.82	1.21	3.17	1.54	3.77
Er	2.22	2.50	3.30	1.90	2.10	1.96	1.91	1.70	--	2.34	2.20	1.69	0.70	2.13	1.24	3.50
Yb	1.72	1.50	2.58	1.00	1.30	1.33	1.35	1.10	--	2.30	2.21	1.81	0.79	2.75	1.96	4.95
Lu	0.25	0.20	0.36	0.14	0.19	0.18	0.21	0.15	--	0.29	0.25	0.26	0.12	0.38	0.35	0.74
Or	--	--	--	6.32	5.20	--	--	18.67	24.05	35.28	40.00	39.65	29.60	34.21	32.97	29.60
Ab	--	--	--	0.43	0.08	--	--	8.00	9.48	25.59	27.94	17.13	32.46	34.70	31.17	35.08
An	1.80	14.17	4.82	18.70	5.01	6.31	3.36	9.31	8.67	5.92	3.55	--	--	--	--	--
Ac	14.69	7.14	13.16	--	--	13.07	15.57	--	--	--	--	--	--	--	--	--
Ne	14.48	3.99	13.57	8.93	22.42	17.10	18.33	10.29	22.64	18.32	16.49	29.09	22.95	21.70	24.66	24.06
Ac	--	--	--	--	--	--	--	--	--	--	--	3.52	6.63	3.82	3.88	3.76
Ns	--	--	--	--	--	--	--	--	--	--	--	0.75	1.85	1.07	2.53	3.96
Di	6.56	3.93	2.72	30.00	33.29	34.63	32.98	19.51	17.08	4.37	2.58	0.86	1.47	0.27	0.27	1.15
Ed	0.91	0.32	0.36	0.87	2.44	3.57	2.82	1.50	1.24	3.62	1.40	3.45	1.24	2.25	2.40	1.69
Wo	--	--	--	--	--	--	--	--	--	--	0.96	1.63	--	0.56	0.28	--
Fo	28.36	30.87	23.87	15.61	12.17	7.50	7.40	15.58	1.35	1.22	--	--	0.17	--	--	0.02
Pa	4.96	3.22	3.98	0.57	1.13	0.98	0.80	1.52	0.12	1.27	--	--	0.18	--	--	0.30
Cs	16.15	17.28	20.72	--	--	0.49	2.10	--	--	--	--	--	--	--	--	--
Mt	3.74	5.94	4.55	7.79	7.12	6.32	6.70	6.44	5.80	1.67	2.16	--	--	--	--	--
Tl	2.87	2.92	3.44	3.76	3.76	5.47	5.56	4.20	2.91	1.50	1.23	0.72	0.68	0.38	0.25	0.38
Ap	3.25	2.61	5.52	2.72	3.79	2.72	2.46	1.42	1.42	0.95	0.40	0.14	0.21	0.07	0.02	0.07
Mgv*	80.7	80.3	77.0	75.5	73.2	68.4	67.6	73.1	53.0	43.1	25.4	12.6	21.3	5.2	5.1	4.4

Major (wt%) and trace elements (ppm) were carried out by XRF; FeO by titration, loss on ignition (L.O.I.) by gravimetry; REE and Y by inductively coupled plasma (except for samples LA3 and LM36 by XRF); n.d. = not detected. Precision and accuracy for trace elements is better than 10%. For rock abbreviations see Table 1. Mgv* = (Mg/Mg+Fe²⁺) × 100 (Fe₂O₃/FeO = 0.15; analyses normalized to 100% on a volatile-free basis).

such as orthopyroxene in BA, kaersutite or pargasite in NeSy, melanite, kaersutite and phlogopite in PPPh. Phlogopite xenocrysts are very similar in composition to the phenocrysts of BA. Zoned diopside-agerine-augite phenocrysts of PPPh are considered as xenocrysts from less differentiated cognate melts, as proposed in the Laacher See rocks (Duda & Schmincke, 1978). PPPh and PPh are also characterized by pectolite-serandite series minerals (up to 24.4% of MnO). Ti-Zr phases such as eudialite-eucolite, neptunite, murmanite,

lavenite and astrophyllite are present in PPh in addition to fluorite and cryolite.

Selected analyses are generally representative of the main rock-types from which isotopic data were obtained and figure in Table 2, while all analysed rocks (Traversa *et al.*, 1994) are reported in Fig. 2. Lages rocks are all nepheline normative and show high ZREE and strong LREE/HREE fractionation. As regards leucocratic types, all PPPh and PPh show peralkaline affinity, the Al-patic Index (A.I.) ranging between 1.01 and 1.22,

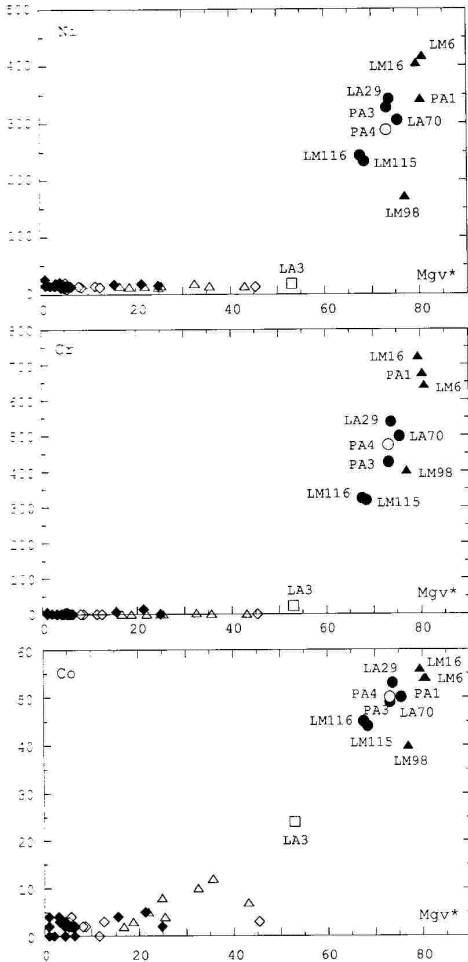


Fig. 2. Ni, Cr and Co vs. Mg^* ($Mg^* = Mg/(Mg+Fe^{2+})$; $Fe_2O_3/FeO = 0.15$, analyses normalized to 100% on a volatile-free basis) for the alkaline rocks of Lages. Solid triangle = OM; solid circle = ON; empty circle = BA; square = PhTe; empty triangle = NeSy; empty diamond = PPh; solid diamond = PPh.

while NeSy are dominantly alkaline or slightly peralkaline (A.I. 0.89–1.03). Mg^* values ($Fe_2O_3/FeO = 0.15$; analyses normalized to 100% on a volatile-free basis, according to Brey, 1978), as well as the Ni, Cr and Co abundances and distribution (Fig. 2), suggest the possible primary nature of some mafic-ultramafic rocks. At least one OM (LM98) and two ON (LM115 and LM116) (Fig. 2)

could represent more differentiated types. Nevertheless, least-squares mass balance calculations exclude low-pressure fractionation of the observed liquidus phases. However, it is noteworthy that a high-pressure evolution (*e.g.* from LA70 to LM115) linked to spinel (10.1 wt%), clinopyroxene (28.4 wt%) and orthopyroxene (9.1 wt%) fractionation ($Res^2 = 0.52$) could be possible among the ON. Lages rocks (Traversa *et al.*, 1994) with Mg^* values ranging for OM between 79.5 and 80.7, for ON between 73.2 and 75.5 and 73.1 for BA appear to represent liquids that have equilibrated with upper mantle peridotite (Brey, 1978; Frey *et al.*, 1978), and could thus be considered as primary magmas. Among the olivine melilitites from different parts of the world studied by Brey (1978), the types from South Africa are very similar in composition to the Lages rocks. The presence of monticellite is associated with the highest Mg^* values, while rocks with $Mg^* > 77$ are interpreted as containing olivine and melilite cumulates, even there is no textural evidence for cumulus processes in Lages OM. Olivines present in OM, ON and BA show Fo contents always lower than equilibrium olivines (Roeder & Emslie, 1970), probably due to the presence of CO_2 in the fluid phase, according to the experimental data of Brey & Green (1977).

Strontium and neodymium isotopes

Sr isotopic ratios were measured on a VG 54E Micromass spectrometer. Standard deviations are expressed as 2σ . Several determinations of standard NBS 987 $SrCO_3$ gave $^{87}Sr/^{86}Sr = 0.71024 \pm 2$. Nd isotope composition analyses were carried out following the chemical and spectrometric procedures described in Zindler *et al.* (1979). The measured $^{143}Nd/^{144}Nd$ ratios were corrected for fractionation to $^{146}Nd/^{144}Nd = 0.7219$ and normalized to the La Jolla Nd standard (1.5118 ± 2). Standard deviations are expressed as 2σ .

Strontium and neodymium isotopic ratios are reported in Table 3. The initial Sr ratios (Sr_i) (calculated for a mean age of 70 Ma), range between 0.70427 and 0.70577 (except 3 samples), as those of analogous alkaline associations derived from mantle magmas not significantly contaminated by crustal rocks. Three samples of PPh which have high to very high Sr_i values (from 0.71019 to 0.73106) could be interpreted as significantly modified by crustal components. However, as demonstrated below, the amount of crustal con-

Table 3. Strontium and neodymium isotopic ratios of Lages alkaline rocks.

		Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_m$	$^{87}\text{Sr}/^{86}\text{Sr}_i$ (70Ma)	$\epsilon_{\text{Sr}}(t)$
LM6	OM	92	1470	0.181	0.70445±2	0.70427	-2.1
PA1	OM	64	1910	0.097	0.70443±3	0.70433	-1.2
LM115	ON	85	1650	0.149	0.70477±3	0.70462	2.9
PA3	ON	45	1360	0.096	0.70466±2	0.70456	2.1
PA4	BA	43	1010	0.123	0.70445±2	0.70433	-1.3
LA3	PhTe	79	1270	0.180	0.70550±2	0.70532	12.8
LM1	NeSy	115	4320	0.077	0.70550±2	0.70542	14.3
LM53	NeSy	122	3730	0.095	0.70540±3	0.70530	12.6
LM99	PPPh	125	2200	0.164	0.70535±2	0.70519	10.9
LM112	PPh	168	108	4.503	0.71025±2	0.70577	19.2
LM36	PPh	221	15	42.65	0.76914±2	0.72672	316.7
LM97	PPh	122	310	1.139	0.70589±1	0.70476	4.8
LM83	PPh	296	19	45.10	0.77591±2	0.73106	378.2
LM19	PPh	203	30	19.59	0.72967±2	0.71019	81.9
LA62	Ca	4	2250	0.005	0.70428±2	0.70427	-2.0
		Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_m$	$^{143}\text{Nd}/^{144}\text{Nd}_i$ (70Ma)	$\epsilon_{\text{Nd}}(t)$
LM6	OM	14.55	85.43	0.103	0.51244±2	0.51239	-3.0
PA1	OM	14.9	88.2	0.102	0.51250±2	0.51245	-1.8
LM115	ON	12.08	69.08	0.106	0.51235±3	0.51230	-4.8
PA3	ON	11.8	65.8	0.108	0.51232±3	0.51227	-5.4
PA4	BA	9.4	55.0	0.103	0.51250±3	0.51245	-1.9
LM1	NeSy	10.46	67.12	0.094	0.51199±3	0.51195	-11.7
LM53	NeSy	11.09	75.05	0.089	0.51201±2	0.51197	-11.3
LM99	PPPh	5.75	39.98	0.087	0.51204±3	0.51200	-10.7
LM106	PPPh	5.54	42.39	0.079	0.51211±3	0.51207	-9.2
LM112	PPh	6.5	50.76	0.077	0.51210±2	0.51206	-9.4
LM97	PPh	2.23	13.01	0.103	0.51242±3	0.51237	-3.4
LM83	PPh	8.5	61.43	0.083	0.51192±3	0.51188	-13.0
LM19	PPh	3.84	25.62	0.090	0.51198±3	0.51194	-11.9

ϵ_{Sr} and ϵ_{Nd} values calculated using the following values for Bulk Earth (Bell & Blenkinsop, 1989): $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$; $^{87}\text{Rb}/^{86}\text{Sr} = 0.0827$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$; $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$.

tamination by strongly radiogenic Brazilian continental basement (average $^{87}\text{Sr}/^{86}\text{Sr} = 0.783$) is also rather limited for PPh. The samples showing

the highest Sr_i ratios are also very low in Sr and therefore were most susceptible to contamination from basement rocks.

OM, ON and BA, some of which (*e.g.* LM6, PA1, PA3 and PA4 of Table 3), approach the composition of primary magmas, show the lowest Sri values (between 0.70427 and 0.70462) probably reflecting small-scale heterogeneities in the mantle source. Differentiated rock-types, such as PhTe, NeSy and PPh (both porphyritic and sub-aphyric) show higher values; from 0.70519 to 0.70577, with only one PPh having Sri (0.70476) close to the mafic or ultramafic types.

The Sri value (0.70427) of the Fazenda Varela carbonatite suggests that these rocks may be generated from the same mantle source as the mafic and ultramafic magmas.

The majority of Sri data for Lages are included in the range of Brazilian alkaline complexes (0.703–0.706). In fact, more than 90% of analysed samples from Piratini, Morro Redondo, Fortaleza, Tunas, Juquiã, Passa Quatro and Poços de Caldas (Morbidelli *et al.*, 1991) are comprised within this range. Some Lages PPh have the highest Sri values (0.71019–0.73108) among the Brazilian alkaline magmatism. Rocks affected by crustal contamination (0.705–0.710) are also present at Juquiã (Beccaluva *et al.*, 1992), Tunas (Gomes *et al.*, 1987) and Fortaleza (Macciotta *et al.*, 1990).

Neodymium isotope data (Table 3) also support the mantle origin of the Lages suite. Present $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of silicic rocks range between 0.51232 and 0.51250 for mafic-ultramafic and between 0.51192 and 0.51242 for leucocratic types. As for Sri, only one PPh (LM97) has Nd_m close to the values of the mafic and ultramafic rocks. The carbonatite from Fazenda Varela shows the highest Nd_m value (0.51252). On the Sr-Nd isotopic plot (Fig. 3), the trend of Lages alkaline rocks lies

below and to the left of the main mantle array defined by MORB and Ocean Island Basalts, in particular those from the Atlantic Ocean. This feature also characterizes the carbonatites, and has been attributed to mantle metasomatism by CO_2 -rich fluids (Menzies & Wass, 1983).

Petrogenesis

In order to test the relations among the various rock-types, mass balance calculations on major elements were performed (Wright & Doherty, 1970) to evaluate a model of differentiation from primary magmas OM, ON and BA through PhTe and NeSy to PPh.

Mass balance results for the transition from BA (PA4) through PhTe (LA3) and NeSy (LM2) to PPh (LM112) are presented in Table 4. The rocks were selected taking into account the availability of core compositions of minerals (Traversa *et al.*, 1994) and the similarity of Sri values, considering that a Sri value can be attributed to LM2 analogous to those of LM1 and LM53. In fact, all three samples belong to the same intrusive stock and LM2 was collected near LM1. Apatite and titanite compositions used for least squares mass balance calculations represent average values from Jacupiranga rocks (Morbidelli *et al.*, 1986).

The predicted trace element concentrations, assuming Rayleigh's law, were calculated using distribution coefficients derived from the literature (listed in Table 5) and F values calculated above. Mass balance results for major element modelling show low Res^2 values (0.18 to 0.38), and the derived melts correspond 11–51% of parental basanitic liquid. A comparison of calculated with observed trace element data is quite satis-

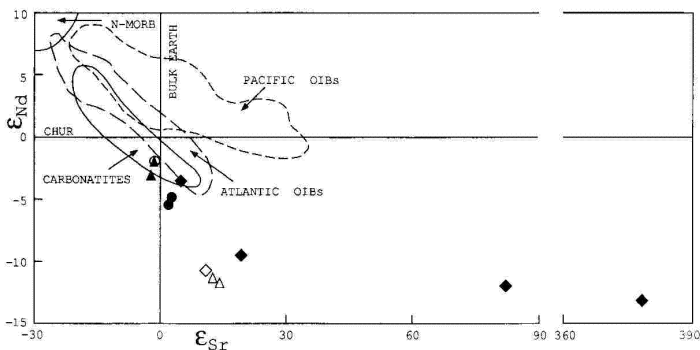


Fig. 3. Plot of $\epsilon_{\text{Nd}}(t)$ vs. ϵ_{Sr} for alkaline rocks of the Lages district. Symbols as in Fig. 2. Fields of MORBs, OIBs and young carbonatites (<40 Ma) are based on data from De Paolo (1978), Hart *et al.* (1986), Barreiro & Cooper (1987), Nelson *et al.* (1988) and summarized by Bell & Blenkinsop (1989).

Table 4. Mass balance calculations used to model variation from basanite to peralkaline phonolite in the Lages district.

	BA PA4		PhTe LA3		NeSy LM2		PPh LM112	
	obs.	calc.	obs.	calc.	obs.	calc.	obs.	
SiO ₂	46.47	49.07	48.86	58.06	58.02	59.74	59.90	
TiO ₂	2.30	1.91	1.61	.64	.63	.12	.20	
Al ₂ O ₃	12.59	18.52	18.61	20.74	20.48	20.89	21.03	
FeO _t	9.74	7.50	7.51	2.82	2.74	1.85	1.83	
MnO	.15	.18	.15	.08	.12	.14	.21	
MgO	13.10	4.12	4.19	.26	.38	.00	.05	
CaO	8.41	7.48	7.68	2.52	2.40	1.05	.90	
Na ₂ O	3.32	6.18	6.42	7.99	8.24	10.13	10.00	
K ₂ O	3.29	4.10	4.32	6.73	6.82	6.08	5.85	
P ₂ O ₅	.63	.94	.64	.16	.17	.00	.03	
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
F	1	.51		.24		.11		
Ol	10.46							
Bi	16.35							
Cpx	20.65		9.01		4.22			
Amph			30.30					
Ne			12.44		11.04			
Af					36.55			
Mt	1.16		.39		1.68			
Ap			1.32		.80			
Ti					.82			
Total	48.62		53.46		55.11			
Res ²	0.38		0.18		0.19			
	obs.	calc.	obs.	calc.	obs.	calc.	obs.	
V	284	185	175	50	49	15	14	
Cr	474	22	22	0	0			
Co	50	23	24	6	5	2	2	
Ni	288	18	18	14	14	15	15	
Zn	96	85	84	73	73	142	147	
Rb	43	76	79	125	117	170	168	
Sr	1010	1374	1270	2688	4370	108	108	
Ba	1220	1669	1660	3270	3247	56	48	
Zr	207	237	239	214	216	468	840	
Nb	36	63	87	109	109	161	165	
Y	22	21	22	20	20	26	26	
La	65	91	94	135	137	199	183	
Ce	121	183	176	177	175	263	265	

Calculated major and trace element values (calc.) are compared with observed values (obs.). F = weight fraction of residual liquid. Res² = sum of squares of differences between calculated and observed major element composition. Bi = biotite; Amph = amphibole; Mt = Ti-magnetite. Further mineral and rock abbreviations as in Table 1.

factory. The discrepancy for Sr in NeSy could be related to crustal contamination (see below) while the Zr contents in PPh are probably due to the highly incompatible behaviour of Zr also in titanite.

Mass balance calculations are on the whole in

good agreement with petrography, as well as mineral- and whole-rock chemistry, suggesting a link between basanite and peralkaline phonolites through crystal-liquid fractionation of liquidus phases of the different rock-types.

Table 5. Crystal/liquid distribution coefficients used to test the fractionation models. Abbreviations as in Table 4.

	Ol (1)	Ol (4)	Bi (1)	Amph (2)	Cpx (1)	Cpx (2)	Cpx (3)	Cpx (4)	Ne (2)	Ne (3)
r	1.3	0.04	0.35	5.6	4	4	4	0.7	0.0001	0.0001
Cr	1	1	10	3.1	17	33	0	2.76	0.0001	0
Co	2	2	8	7.5	3	4	30.9	2	0.066	0.066
Ni	39	17	1	0.8	5	10	15	3	0.0001	0.0001
Mn	1.8	1.59	1.846	2.67	2.6	2.6	0.24	0.5	0.0001	0.0001
Pb	0.0001	0.08	0.82	0.59	0.0001	0.284	0.284	0.28	1.5	1.5
Ir	0.1	0.1	1.2	0.02	1.51	0.001	0.001	2.8	0.001	0.24
Ca	0.002	0.1	3.2	0.15	0.02	0.02	0.388	2.5	0.42	0.42
Pr	0.06	0.06	3.3	2	1.2	5	0.05	1.5	0.5	0.005
Tb	0.01	0.01	0.9	2.2	0.01	0.2	0.3	1.2	0.2	0.2
Y	0.01	0.01	0.8	2	4.6	0.7	0.7	0.5	0.5	0.5
La	0.05	0.05	2.59	1	0.25	0.49	0.49	0.92	0.041	0.041
Ce	0.02	0.02	0.50	2.06	1.34	1.34	0.53	1.34	0.047	0.047

	Ne (4)	Af (3)	Mt (1)	Mt (2)	Mt (3)	Mt (4)	Ap (2)	Ap (3)	Ap (4)	Ti (3)
r	0.0001	0.1	63	63	112	16	0.0001	0.0001	0.0001	1.54
Cr	0.0001	0	40	300	0	43	0.4	0.4	0.2	0
Co	0.066	0.48	10	17	43	10	0.2	0.2	0.2	7.89
Ni	0.0001	0.14	15	15	15	15	0.3	0.3	0.3	0.0001
Mn	0.0001	0.013	15.56	15.56	7.59	15.56	0.0001	0.0001	0.0001	0.0001
Pb	1.5	0.97	0.001	0.47	0.47	0.72	0.04	0.04	0.004	0.0001
Ir	0.24	15.55	1	0.001	0.001	1	0.06	0.06	5	0.874
Ca	0.42	16.6	0.4	0.4	0.4	0.7	0.08	0.08	0.45	4.72
Pr	0.005	0.003	0.4	0.66	0.103	8	3	0.01	3	2.5
Tb	0.2	0.1	0.01	0.01	10.7	14	0.01	0.01	0.01	23
Y	0.5	0.01	0.15	0.20	0.20	0.17	40	30	30	29
La	0.041	0.31	2.90	2.90	2.90	2.90	14.4	1.5	16	19
Ce	0.047	0.04	0.90	0.90	0.90	0.90	24.3	18	16	25

(1) From BA to PhTe; (2) from PhTe to NeSy; (3) from NeSy to PPh; (4) from ON to PhTe.

Table 6. Mass balance calculations used to model variation from olivine nephelinite (ON) to phonotephrite (PhTe). Abbreviations as in Table 4.

	ON LM115	PhTe	LA3		ON LM115	PhTe	LA3
	obs.	calc.	obs.		obs.	calc.	obs.
SiO ₂	42.76	48.80	48.86	V	217	174	175
TiO ₂	2.95	1.35	1.62	Cr	320	21	22
Al ₂ O ₃	11.78	18.60	18.61	Co	44	26	24
FeO _t	10.26	7.56	7.51	Ni	233	18	18
MnO	.17	.19	.15	Zn	108	83	84
MgO	11.00	4.19	4.19	Rb	85	173	79
CaO	13.19	7.75	7.68	Sr	1657	1282	1270
Na ₂ O	3.82	6.20	6.42	Ba	1924	1911	1660
K ₂ O	2.89	4.89	4.32	Zr	276	245	239
P ₂ O ₅	1.18	.47	.64	Nb	113	84	87
Total	100.00	100.00	100.00	Y	25	22	22
F	1	.36		La	91	92	94
Ol	8.86			Ce	175	171	176
Cpx	36.53						
Nef	9.71						
Mt	6.52						
Ap	2.60						
Total	64.22						
Res ²	0.49						

Mass balance data show that intermediate PhTe could also derive from ON magmas (Table 6). Some trace element discrepancies (*e.g.* calculated to observed Rb and Ba differences) may be explained by the distribution coefficients used for nepheline, but the literature data for this mineral are very rare.

It follows that differentiated rock-types from Lages are compatible with fractional crystallization starting from nephelinitic or basanitic magmas.

Relations between OM and the other rock-types seem to be excluded. The transitions from OM to ON or BA, or PhTe, even if possible from a numerical viewpoint (Res^2 from 0.15 to 0.29), are not petrographically consistent because the solutions do not involve the liquidus phase melilite in the subtracted solid assemblages (66 to 77% of Mt+Ap+Prv+Ol+Mont+Ne), and also show an unrealistic quantity of both Mg-olivine (15–20%) and monticellite (28–34%).

A crystal fractionation trend from basanite to peralkaline phonolites has been proposed and tested for the Nyambeni range – East Kenya Plateau (Aurisicchio *et al.*, 1983; Brotzu *et al.*, 1983) as well as many other alkaline provinces worldwide. Similar trends were found by Kyle *et al.* (1992) using major element mass balance and trace element models for the basanite to anorthoclase phonolite suite of Mount Erebus (Ross Island, Antarctica), using lavas from Hut Point Peninsula and cores from the Dry Valley Drilling Project (Kyle, 1981). In the Laacher See district (Duda & Schminke, 1978; Schminke *et al.*, 1983; Worner & Schminke, 1984), nephelinite and basanite magmas are both considered primitive, with the basanitic magma giving rise to phonolite by the separation of amphibole and clinopyroxene deep in the crust.

Fig. 4 shows chondrite-normalized (Boynnton, 1984) REE patterns for Lages rocks; they are flat for OM, ON and BA and slightly to strongly concave upward from NeSy to PPh and PPh. MREE depletion is in accordance with the removal of amphibole and titanite during the differentiation leading to PPh. Almost all the samples lack a negative Eu anomaly.

Incompatible element concentrations normalized to the primordial mantle (Wood *et al.*, 1979) are plotted in Fig. 5. Average concentrations of Nb, Sr and P decrease from OM to ON and BA, while the elemental ratios show only small variations. Increasing degrees of partial melting may explain these relationships. This is also evident

from the relations between incompatible elements such as La and Ce (Fig. 6). The strong consistency between OM, ON and BA, in accordance with Sr and Nd isotopic compositions, indicates that all these rocks were derived from a similar mantle source. Leucocratic rocks show less consistent results, notably due to the behaviour of some elements very sensitive to late-stages fractionation.

The abundances of K_2O , P_2O_5 and ΣREE , as well as the strong LREE/HREE fractionation of the primary Lages magmas, suggest low degrees of partial melting and residual garnet as an important phase. However, the high Al_2O_3/TiO_2 ratios point to a higher proportion of ilmenite with respect to garnet in the residue. The relatively constant CaO/MgO ratios of primary OM, ON and BA from Lages and olivine melilitites worldwide (Brey, 1978) is compatible with the melting of pyrolite mantle in the stability field of dolomite (24–35 kbar; Brey, 1978; Wyllie, 1978, 1987).

Applied to the Lages suite, the experimental data of Brey & Green (1977) and Brey (1978) suggest that OM is derived from 5% partial melting at about 35 kbar, with CO_2 contents of over 7% in the source. ON and BA would correspond to slightly higher degrees of melting.

Normally, lower degrees of melting in equilibrium with increasingly jadeite-rich clinopyroxene are characterized by decreasing CaO/ Na_2O which reflects the diopside/jadeite ratio of coexisting clinopyroxene, provided that diopside and jadeite activities in the melt are approximately proportional to CaO and Na_2O concentrations (Frey *et al.*, 1978). Lages primary magmas are characterized by a reverse trend, with CaO/ Na_2O decreasing from OM to ON and BA. This behaviour, similar to that observed in the olivine nephelinite 2854 and olivine melilitite 2927 from Tasmania (Frey *et al.*, 1978), can be related to a dramatic reduction of diopside activity in the melt due to Ca bonding with $(CO_2)^{-}$.

The trend of incompatible elements normalized to Primordial Mantle and REE patterns for the possible primary magmas of Lages suggest an analogous metasomatized mantle source which underwent low degrees of melting, gradually increasing from OM through ON to BA. The mantle source, with respect to the primordial mantle, is enriched in many trace elements such as HFSE (Ti, P, Nb), LILE (Sr, K, Rb, ecc.) and LREE.

Frey *et al.* (1978) proposed 4 to 7% melting of the same pyrolite source to yield the olivine melilitites to olivine nephelinites and basanites in

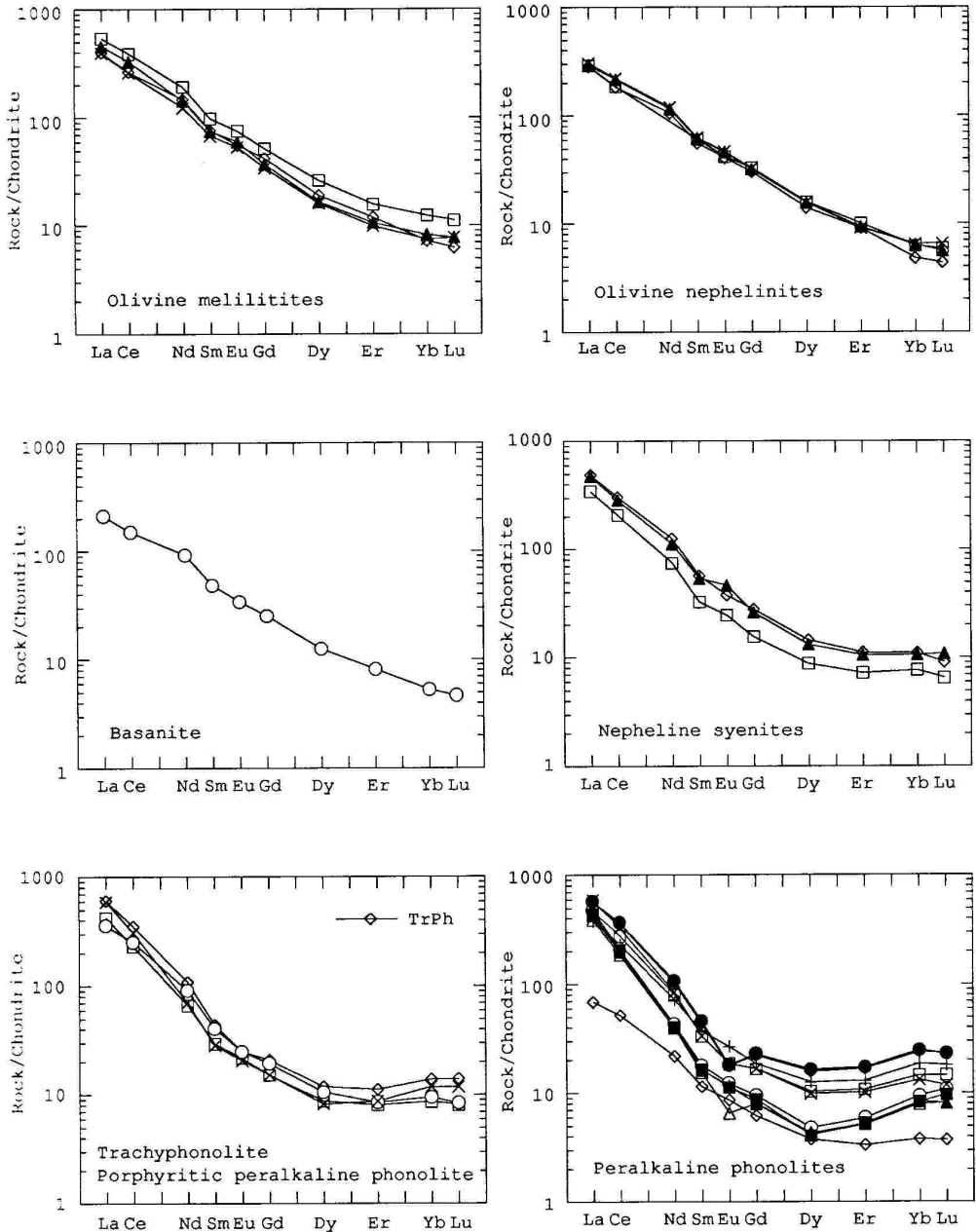


Fig. 4. Chondrite-normalized (Boynton, 1984) REE patterns for some representative rocks of the Lages district.

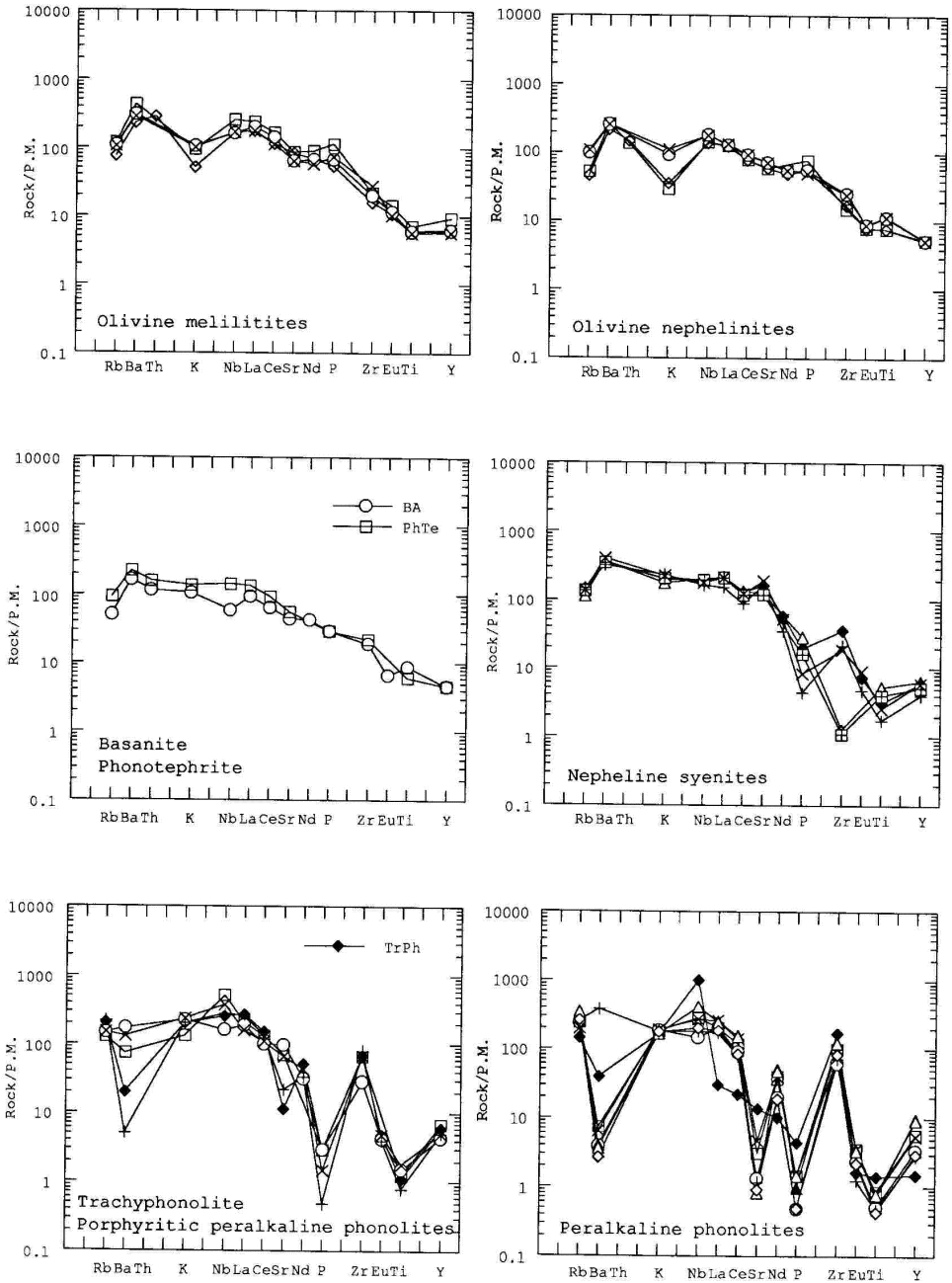


Fig. 5. Primordial mantle (P.M.) normalized (Wood *et al.*, 1979) incompatible element distribution for some representative rocks of the Lages district.

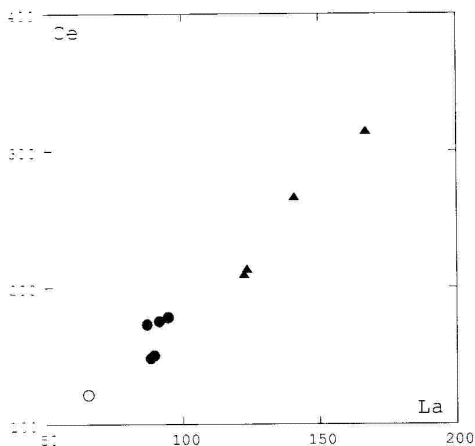


Fig. 6. Ce vs. La diagram for mafic-ultramafic rocks of Lages. Symbols as in Fig. 2.

the Tertiary to Recent volcanics of Victoria and Tasmania. The source would be enriched 6–9 times with respect to chondrites in strongly incompatible elements (Ba, Sr, Th, U, LREE), and less enriched (2.5–3 × chondrites) in moderately incompatible elements such as Ti, Zr, Hf, Y and HREE. Melting models for the Lages alkaline rocks have not yet been investigated and will be the subject of a forthcoming paper. Nevertheless, the comparison with Tasmanian rocks suggests higher metasomatic enrichment of Ba, Sr, and LREE in the peridotite source, for the Lages primary magmas. Analogous metasomatic processes have been recognized in the garnet peridotite source of Tertiary nephelinitic magmatism in Eastern Paraguay (Comin-Chiaramonti *et al.*, 1991). Otherwise, Mesozoic Kimberlites and related alkaline rocks of the Alto Paranaíba Province (Brazil) have been related to enriched garnet peridotite (Bizzi *et al.*, 1991, 1993). The metasomatic event could be connected to the thermal anomaly responsible for the Paraná Basin flood volcanism. In South Africa, metasomatic processes in the mantle source for the Kimberley magmatism occurred (90–150 Ma ago) after the peak of basaltic flood volcanism in the Karoo Province (ca. 190 Ma; Waters & Erlank, 1988).

The situation outlined for the Lages primary magmas is similar to that for the Oahu suite of the Honolulu Volcanics (Clague & Frey, 1982) and the Bathurst Island suite in the Canadian Arctic

(Mitchell & Platt, 1984). Clague & Frey (1982) consider that melilite-olivine nephelinites, olivine nephelinites, nepheline basanites and alkali basalts may all be primitive magmas derived from metasomatized garnet lherzolite, with the compositional differences of the magmas reflecting varying degrees of melting.

The success of the present fractional crystallization model in explaining the trace elemental trends of the Lages suite, the lack of evidence for simple magma mixing and the relations between SiO₂, K₂O, Rb, Ba, Sr, ΣREE and Sri suggest that the differences in Sri between mafic-ultramafic and leucocratic types, could be linked to crustal contamination during magma ascent and fractionation.

Since variability in trace-element concentrations can be explained largely by fractional crystallization alone, the extent of assimilation must have been comparatively small. In fact, the application of an assimilation and fractional crystallization model (AFC; De Paolo, 1981) shown in Table 7 and Fig. 7, shows that all leucocratic rocks of Lages have been affected by variable low degrees of crustal contamination. The comparison (Table 7) between calculated and measured Sri, Sr and Rb values is quite satisfactory. The measured Sri values of all leucocratic rocks are justified by slight crustal contamination (0.5–8%), of a basaltic magma by strongly radiogenic Brazilian continental basement (Projeto RadamBrasil, 1981, in Macciotta *et al.*, 1990). Also, the high Sri values of some PPh can be explained by low degrees of contamination, due to the high ⁸⁷Sr/⁸⁶Sr value of the contaminant and the very low Sr contents of PPh.

Even if mass balance results suggest that the leucocratic rocks of Lages may be derived by crystal-liquid fractionation processes from both basaltic and nephelinitic magmas, the presence in the differentiated types (NeSy and PPh) of biotite, amphibole and clinopyroxene xenocrysts – analogous to those crystallizing from basanites and tephrites – agrees better with a basaltic-tephritic liquid line of descent. The presence of kaersutitic amphibole and biotite in the subtracted solid assemblage of the Lages suite points to the role of pH₂O. Together with the absence of plagioclase, as indicated by the lack of negative Eu anomalies, this may suggest magmatic evolution deep in the crust, at least for basaltic to phonotephritic and nepheline syenites. Mass balance results among olivine nephelinites also reveal the possible role

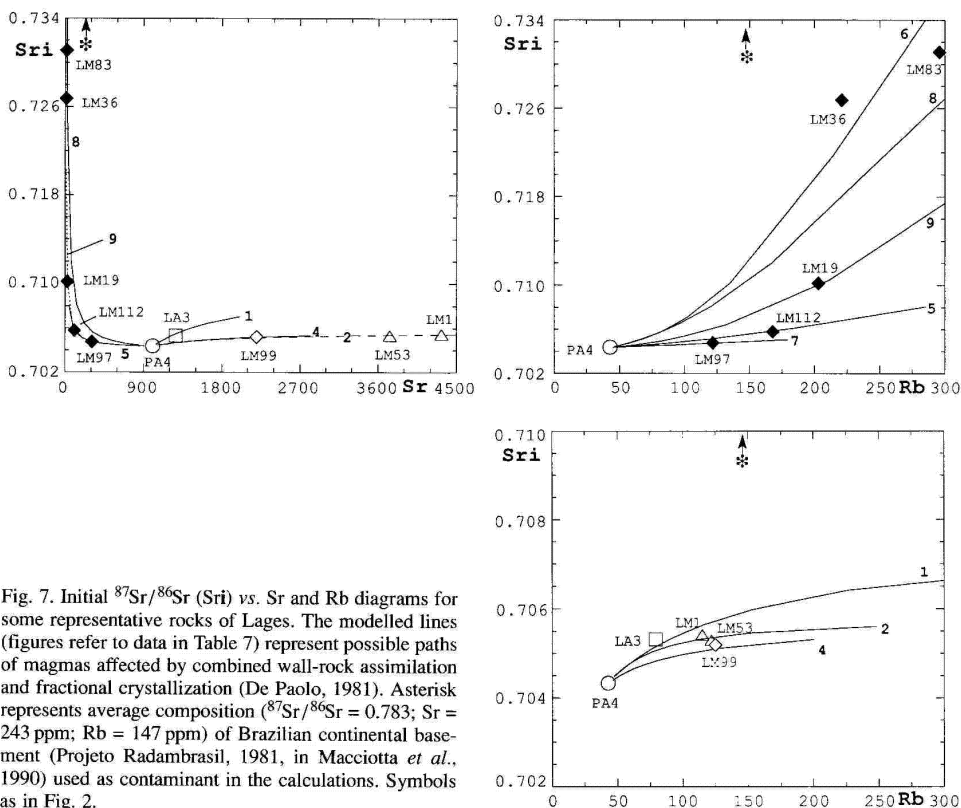


Fig. 7. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ (S_{ri}) vs. Sr and Rb diagrams for some representative rocks of Lages. The modelled lines (figures refer to data in Table 7) represent possible paths of magmas affected by combined wall-rock assimilation and fractional crystallization (De Paolo, 1981). Asterisk represents average composition ($^{87}\text{Sr}/^{86}\text{Sr} = 0.783$; $\text{Sr} = 243$ ppm; $\text{Rb} = 147$ ppm) of Brazilian continental basement (Projeto Radambrasil, 1981, in Macciotta *et al.*, 1990) used as contaminant in the calculations. Symbols as in Fig. 2.

Table 7. Combined wall-rock assimilation and fractional crystallization model (De Paolo, 1981).

		F	τ	D_{Sr}	D_{Rb}	S_{ri_m}	S_{ri_c}	S_{r_m}	S_{r_c}	Rb_m	Rb_c	
1	LA3	PhTe	0.51	0.08	0.66	0.10	0.70532	0.70533	1270	1237	79	90
2	LM1	NeSy	0.23	0.07	0.01	0.33	0.70542	0.70542	4320	4383	115	138
3	LM53	NeSy	0.26	0.065	0.03	0.23	0.70530	0.70531	3730	3767	122	143
4	LM99	PPPh	0.18	0.035	0.54	0.38	0.70519	0.70515	2200	2172	125	137
5	LM112	PPPh	0.11	0.01	2.01	0.38	0.70577	0.70591	108	106	168	174
6	LM36	PPPh	0.08	0.035	2.67	0.35	0.72672	0.72772	15	17	221	249
7	LM97	PPPh	0.11	0.005	1.54	0.53	0.70476	0.70474	310	303	122	123
8	LM83	PPPh	0.08	0.05	2.57	0.24	0.73106	0.73204	19	21	296	342
9	LM19	PPPh	0.10	0.015	2.53	0.33	0.71019	0.71043	30	30	203	211

Basanite PA4 is the initial magma composition used in the modelling. The contaminant used in the calculations is the Brazilian continental basement average composition ($^{87}\text{Sr}/^{86}\text{Sr} = 0.783$; $\text{Sr} = 243$ ppm; $\text{Rb} = 147$ ppm) (Projeto Radambrasil 1981, in Macciotta *et al.*, 1990). F = residual liquid fraction derived from the least squares mass balance calculations. τ = ratio between mass of wall rock assimilated/mass of fractionated phases, per time unit. D_{Sr} and D_{Rb} = bulk partition coefficients calculated from Rayleigh model, with F derived as above. m = measured and calculated values.

of high-pressure evolution of ultramafic magmas connected with solidification in the lithosphere before penetrating the crust. This magmatic environment also agrees with the lack of crustal contamination.

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