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PETROLOGY AND MINERAL CHEMISTRY OF THE ALKALINE DISTRICT OF LAGES, SC, BRAZIL

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ABSTRACT

The Lages alkaline district is characterized by prevalent leucocratic rocks and subordinate mafic-ultramafic types. The first group of rocks is represented by peralkaline phonolites and nepheline syenites and the second one by olivine melilitites, olivine nephelinites and basanites. Minor phonotephrites and trachyphonolites are also present. Melilite, Mg-olivine, monticellite, diopside to aegirine clinopyroxene, phlogopite to Mg-biotite, kaersutite to pargasite, Ti-magnetite and Cr-Al spinels, alkali feldspar and nepheline are the dominant phases. Leucite, kalsilite, perowskite and serandite-pectolite appear subordinate. Ti-Zr minerals of typical agpaitic occurrence also characterize the peralkaline phonolites. Major and trace element data point out the strongly alkaline, potassic character of the Lages association. Mg values, trace elements and REE distribution show the probable primary nature of many mafic-ultramafic rock-types. Petrography, mineral and whole-rock chemistry better agree with the derivation of peralkaline phonolites and nepheline syenites by fractional crystallization processes from a basanitic parent magma.

RESUMO

O distrito alcalino de Lages é constituído dominantemente de rochas leucocráticas, com tipos máfico-ultramáficos ocorrendo de forma subordinada. O primeiro grupo acha-se representado por fonolitos peralcalinos e nefelina sienitos, enquanto que o segundo por olivina melilititos, olivina nefelinitos e basanitos. Em pequena proporção encontram-se fonotefritos e traquifonolitos. Mineralogicamente, melilita, Mg-olivina, monticellita, clinopiroxênio (diopsídio a egirina), mica (flogopita a Mg-biotita), anfibólio (kaersutita a pargasita), Ti-magnetita e Cr-Al espinélio, feldspato alcalino e nefelina são as fases mais abundantes. Leucita, kalsilita, perowskita e serandita-pectolita aparecem subordinamente. Minerais ricos em Ti e Zr, típicos de ocorrências agpaíticas, estão presentes nos fonolitos peralcalinos. Elementos maiores e traços apontam para o caráter fortemente alcalino e filiação potássica das associações litológicas de Lages. Os valores de Mg, elementos traços e a distribuição das Terras Raras indicam a provável natureza primária de muitos litotipos máfico-ultramáficos. Dados petrográficos, mineralógicos e químicos (análises globais) são concordantes com a derivação dos fonolitos peralcalinos e nefelina sienitos por processos de cristalização fracionada a partir de um magma parental basanítico.

INTRODUCTION

This work is included within the Italo-Brazilian research program on alkaline and alkaline-carbonatite magmatism of continental Brazil (Morbidelli et al., 1986; Barbieri et al., 1987; Gomes et al., 1987; Brotzu et al., 1989; Gomes et al., 1990; Macciotta et al., 1990; Morbidelli et al., 1991; Beccaluva et al., 1992; Brotzu et al., 1992 and Morbidelli et al., 1993a, b). Preliminary geo-petrological data of the Lages district were provided by Scheibe et al. (1988), while geochronological data are found in Amaral et al. (1967), Teixeira (1969), Scheibe et al. (1985) and Sonoki & Garda (1988).

In this paper we present, on the basis of a new detailed sampling, petrography, major and trace element (including REE) analyses, and mineral chemistry on a representative set of the silicatic rocks of the district, with the aim to contribute for understanding their petrogenesis. The carbonatitic and kimberlitic rock-types will be discussed in a forthcoming paper.

GEOLOGICAL SETTING AND RADIOMETRIC AGES

The alkaline-carbonatitic district of Lages, bordered westward by the Paraná flood basalts (Piccirillo & Melfi, 1988), is connected to the uplift of a larger crustal block, the "Lages Dome", limited to the north by the Corupá and to the south by the Rio Engano lineaments. The Lages district is as large as any of the Brazilian alkaline provinces (Ulbrich & Gomes, 1981) because alkaline rocks are dispersed as relatively small outcrops in a wide area.

The Lages complex consists of many

shallow level intrusions, with dominant hypabyssal and volcanic rock-types, localized in the sedimentary Gondwanic sequences from the Permian Itararé beds to the Triassic Botucatu sandstone.

The alkaline rocks, in outcrops ranging from several km² to less than 1 m in width (dykes), occur as shallow intrusions throughout the dome structure. They display a roughly anular distribution, but are more concentrated along a 10 km wide, N60°E-trending belt in the eastern part of the district (Fig. 1).

Scheibe et al. (1984) assembled the Lages alkaline rocks into four groups: carbonatites and associated rocks, pipe breccias and kimberlites, leucocratic, and ultrabasic rocks.

The Fazenda Varela carbonatites, situated in the central part of the Lages Dome, have been investigated in some detail by Scheibe (1978, 1979) and Scheibe & Formoso (1982).

Pipe breccias and kimberlites in the Lages region are first reported by Oliveira (1927), and afterwards by Paiva (1933), Loczy (1968) and Arioli (1974); whereas the "Janjão kimberlite" (Scheibe, 1978) represents the first description of kimberlitic material in the district, occurring in the Guarujá area of the city of Lages. Geophysical data were interpreted by Svisero et al. (1985) and mineral chemistry was discussed by Scheibe & Svisero (1988) and Traversa et al. (in preparation), while brief descriptions of 35 occurrences of diatremes, pipe breccias and brecciated dykes were presented Scheibe (1986), and since then several new occurrences have been found.

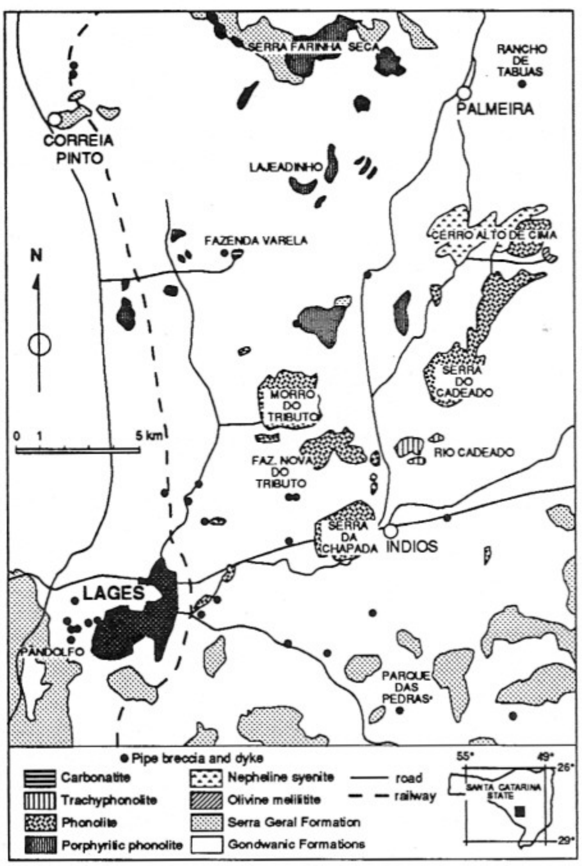

Figure 1 – Geologic sketch map of the Lages district (after Scheibe, 1986).

Leucocratic rocks include almost all of the about 50 km² total outcropping area of alkaline rocks. These are represented by nepheline syenites, trachyphonolites, porphyritic peralkaline phonolites and peralkaline phonolites (Fig. 1).

Basic and ultrabasic rocks consists of olivine melilitites, olivine nephelinites, basanites and phonotephrites. The most striking occurrence is a semianular dyke of olivine melilitite, about 50 wide, which can be seen in a quarry east of Cerro Alto de Cima. Other occurrences consist of matrix or fragments in pipe-breccias, or else small dykes, some of which were recently found also in the extreme south and in the northeastern part of the Lages quadrangle.

K/Ar and Rb/Sr determinations indicate a late Cretaceous age for the alkaline rocks of the district. On the basis of three K/Ar determinations on phonolitic rocks, Amaral et al. (1967) gave a "preferred age" of 65 Ma for the complex. These data, recalculated by Sonoki & Garda (1988), provide a mean age of about 68 Ma, as proposed for phonolites by Teixeira (1969).

Scheibe et al. (1985) present eleven new K/Ar determinations for the alkaline rocks from Lages. The results range from 63 to 78 Ma, and suggest an older age for the nepheline syenites relative to the phonolites, pipe breccias, olivine melilitites and the Janjão kimberlite (Fig. 2). K/Ar histogram indicates a mean age of 70 Ma. Notably, Rb/Sr whole-rock isochron (Scheibe et al., 1985) yielded an age of 82 $\pm$ 6 Ma and an initial $^{87}Sr/^{86}Sr$ ratio (R_0) of 0.7060 $\pm$ 0.0015, which is comparable with R_0 values of 0.7052-0.7056 $\pm$ 0.0014 determined for the studied porphyritic nepheline syenites.

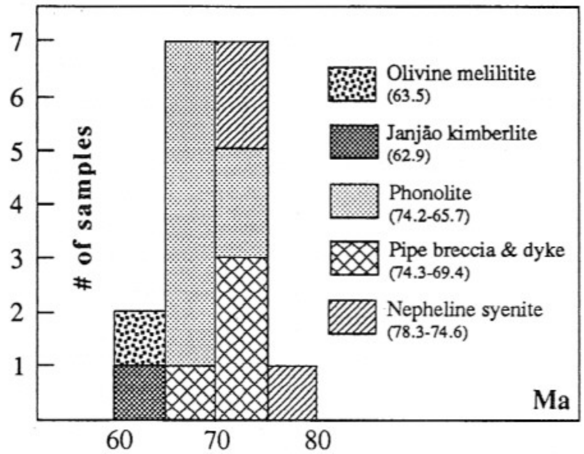

Figure 2 – Histogram of K-Ar ages for alkaline rocks of the Lages district. Data from Amaral et al. (1967), Sonoki & Garda (1988), Teixeira (1969) and Scheibe et al. (1985).

PETROGRAPHY

The main rock-types have been classified according to their petrography and chemistry, on the basis of TAS (Le Maitre, 1989) and R1-R2 (De La Roche et al., 1980) diagrams and those of Le Bas (1989) for basanites, nephelinites and melilitites. Location of the analysed samples are reported in the Appendix. Volcanic nomenclature (melilitites and nephelinites) has also been employed for hypabyssal rocks.

Olivine melilitites (OM)

They are hypabyssal rocks with fine-grained equigranular texture. Sometimes, olivine and phlogopite large crystals give the rock an inequigranular character. The main constituents, according to the crystallization sequence, are: Ti-magnetite (always included in the other minerals), euhedral well preserved Mg-olivine, zoned and corroded millimetric melilite, anhedral nepheline and poikilitic phlogopite. In the olivine melilitites from Lajeadinho, phlogopite appears as a transformation product of Mg-olivine. Accessory minerals include apatite and perowskite. Large reabsorbed crystals of diopside are rarely present. In some samples from Cerro Alto de Cima, monticellite accompanies Mg-olivine.

Rancho de Tábuas dyke has corroded and highly fractured olivine phenocrysts, spinel, and perowskite microphenocrysts in a matrix composed of phlogopite, nepheline, monticellite, and a greenish glass tending to melilitic composition.

Olivine nephelinites (ON)

All the analysed samples, except PA3, plot in the melanephelinites field of Le Bas (1989). These rocks exhibit a variable texture: from granular and inequigranular to porphyritic (dykes). Well-crystallized rocks are mostly constituted by euhedral olivine and light green zoned diopside frequently included in poikilitic nepheline. Leucite, kalsilite, interstitial phlogopite and Ti-magnetite are also present. Apatite and perowskite are accessory phases. The porphyritic rocks show basically the same paragenesis. Olivine is the most abundant phenocryst of these strongly porphyritic types; diopside is clearly subordinate; nepheline, Ti-magnetite, apatite, perowskite and, occasionally, melilite and leucite occur as microphenocrysts. Clinopyroxene, nepheline, phlogopite and sometimes glass are present in the groundmass, which may be partially replaced by zeolites and/or carbonates.

Basanite (BA)

Basanite is porphyritic; euhedral, well preserved olivines and phlogopites with reaction rims, as well as two-generations of zoned clinopyroxene, are the phenocrysts phases in a matrix composed by olivine, clinopyroxenes, phlogopite, Ti-magnetite, Ca-plagioclase, alkali feldspar, nepheline and interstitial calcite. Olivine-clinopyroxene intergrowths (with intergranular euhedral phlogopite) represent crystal-liquid reaction products of rare unstable orthopyroxene relicts.

Phonotephrite (PhTe)

It is represented by a weakly porphyritic rock with greenish to yellow-green diopside, brown amphibole, biotite and nepheline phenocrysts. Ocelli-like shaped nepheline is completely transformed in an aggregate of zeolite and calcite; Ti-magnetite microphenocrysts are also present. Clinopyroxene includes Ti-magnetite and apatite, while fresh nepheline, clinopyroxene, Ti-magnetite and apatite are found inside poikilitic brown amphibole. The groundmass is made up of clinopyroxene rods, zoned dark reddish to brownish-yellow biotite, brown amphibole, calcic plagioclase and Ti-magnetite set in a weakly zeolitized nepheline-alkali feldspar aggregate.

Nepheline syenites (NeSy)

From a textural viewpoint, coarse porphyritic syenites to medium grained microsyenites can be distinguished. Alkali feldspar, from large (up to 20 mm) zoned megacrysts to submillimetric laths, nepheline, and oscillatory-zoned, diopsidic-hedenbergitic to aegirine-augitic clinopyroxene are the dominant phases. Titanite, Ti-magnetite and apatite are always the early crystallized minerals. Sodalite, nosean, and unstable biotite and brown amphibole are sometimes present; the last two phases with corroded and oxidated rims. Groundmass of the porphyritic varieties may contain analcite and aegirinic clinopyroxene as microlites or rims around the mafic phenocrysts. Natrolite and carbonates can be present as alteration products.

Trachyphonolites (TrPh)

These rocks are subaphyric, with rare clinopyroxene, titanite, Ti-magnetite and sodalite microphenocrysts set in a trachytic groundmass made up by alkali feldspar laths, nepheline and interstitial analcite. Vesicles are sometimes filled with carbonates and catapleiite.

Porphyritic peralkaline phonolites (PPPh)

Porphyritic to strongly porphyritic in texture, these rock-types show zoned diopsidic-hedenbergitic to aegirinic clinopyroxene, alkali feldspar, sodalite and nepheline phenocrysts; Ti-magnetite, apatite and titanite are commonly in the form of microphenocrysts. In the phonolitic rocks of Farinha Seca, kaersutitic amphibole, included in clinopyroxene, large phenocrysts of titanite and Ti-magnetite are present. Biotite and melanite rarely occur and, like amphibole, exhibit corrosion and development of aegirinic rims. The groundmass consists of alkali feldspar, nepheline, aegirine, poikilitic pectolite and interstitial analcite. Natrolite and gibbsite are sometimes present as transformation products.

Peralkaline phonolites (PPh)

Even though they form large massifs, these rocks generally show aphyric to subaphyric fluidal texture with subparallel orientation of alkali feldspar and clinopyroxene needles. The late development of poikilitical and skeletal aegirine aggregates (from submillimetric to centimetric) gives to the rock a mottled aspect, especially at Morro do Tributo. Rare alkali feldspar, nepheline, sodalite and green clinopyroxene phenocrysts are found in the weakly porphyritic varieties, whereas Ti-magnetite, titanite and apatite occur as microphenocrysts. The rocks of Fazenda Nueva do Tributo show nodules made up by diopside and biotite; rare corroded biotite xenocrysts with the coronitic texture of aegirine needles are also present. The groundmass is made up of K- to Na-feldspars, nepheline, aegirine, skeletal or poikilitical manganoan pectolite and calcian serandite. Ti-Zr minerals of typical agpaitic occurrence include eudialite-eucolite, neptunite, murmanite, lavenite, astrophyllite. Fluorite and cryolite are also present.

MINERAL CHEMISTRY

More than 750 chemical mineral analyses were performed with JEOL microprobe equipped with EDS (LINK) and with ARL/SEMQ systems, using both natural and synthetic materials as standards. Element concentrations were obtained according to Bence & Albee (1968). All the investigated minerals were analysed from core to rim in order to check compositional zoning. In the Tables 1 to 9 are reported the representative mineral analyses, whereas Figures 3 to 7 include all the microprobe data.

Melilite

Melilite is present in variable amounts in the different OM outcrops. Its composition is quite uniform (Table 1) and corresponds to the volcanic and plutonic melilites (cf. El Goresy & Yoder, 1974). The mean values show slight enrichment of FeO (2.02 to 2.22) and Na_2O (3.60 to 3.99) and depletion of CaO (35.20 to 34.56) from core to rim. The melilites of the Cerro Alto de Cima (LM6, LM16) have cationic Na higher than Al, suggesting the presence of the ferrisodamelilite end-member (Nielsen, 1980). According to Velde & Yoder's (1977) synthetic system data, the homogeneous composition of the Lages melilites is

Table 1 – Microprobe compositions of representative melilites from the Lages OM rocks. c = core; r = rim. Atomic proportions are based on 14 oxygens.

	1	2	3	4	5	6
	LM98	LM98	LM6	LM6	LM16	LM16
	c	r	c	r	c	r
SiO_2	42.34	42.85	43.58	44.10	44.27	44.45
TiO_2	0.05	0.05	0.02	0.00	0.16	0.00
Al_2O_3	6.53	5.83	5.70	6.44	5.78	5.68
FeO	2.00	2.37	2.20	2.61	1.95	2.20
MnO	0.06	0.05	0.00	0.09	0.07	0.00
MgO	9.39	9.20	9.70	8.60	9.63	9.13
CaO	36.69	35.78	35.25	33.70	34.81	34.30
Na_2O	2.70	3.56	3.79	4.78	3.80	4.26
K_2O	0.16	0.11	0.05	0.18	0.13	0.16
Total	99.92	99.80	100.29	100.50	100.60	100.18
Si	3.8480	3.9038	3.9354	3.9701	3.9704	4.0054
Ti	0.0034	0.0034	0.0014	0.0000	0.0108	0.0000
Al	0.6994	0.6259	0.6066	0.6832	0.6109	0.6032
Fe^{2+}	0.1520	0.1805	0.1661	0.1965	0.1462	0.1658
Mn	0.0046	0.0039	0.0000	0.0069	0.0053	0.0000
Mg	1.2719	1.2492	1.3055	1.1539	1.2873	1.2262
Ca	3.5724	3.4922	3.4102	3.2502	3.3446	3.3112
Na	0.4757	0.6288	0.6635	0.8343	0.6607	0.7442
K	0.0185	0.0128	0.0058	0.0207	0.0149	0.0184
Total	10.0460	10.1006	10.0946	10.1157	10.0512	10.0743

in agreement with the constant amount of whole rock normative nepheline (15.9-13.6).

Olivine and monticellite

The representative analyses of Lages olivines (Table 2) show small compositional variations. Olivines from melilitites display Fo content between 90.5 and 86.8 with no (core-rim) noticeable variations, except for a slight CaO enrichment (mean values from 0.25 to 0.89). Olivine nephelinites are also characterized by crysolitic olivines (max $Fo_{89.5}$ and sometimes by normal zoning to $Fo_{88.5}$ to $Fo_{80.4}$). In the latter case, Fe0 enrichment is also accompanied by a CaO increase (0.30 to 0.93). Olivines from basanite are very homogeneous, with Fo values ranging between 86.3 and 85.5.

The monticellite from the olivine melilitites of Cerro Alto de Cima is also quite uniform in composition. MnO values are higher in monticellite (up to 0.82) than in olivine (up to 0.65).

Clinopyroxenes

All the rock-types from Lages contain variable amounts of clinopyroxene. Selected analyses are reported in Table 3. The adopted nomenclature is that proposed by I.M.A. (Morimoto et al., 1988) (Fig. 3). For the cations distribution between T, M_1 and M_2 sites, the ideal site occupancy suggested by Morimoto et al. (1988) has been taken into account.

Lages clinopyroxenes cover a very large compositional range, from diopside-hedenbergite to aegirine through aegirine-augite, sometimes present in the same sam-

Table 2 – Microprobe compositions of representative olivines (1-17) and monticellites (18-20) from the Lages rocks. 1-7, 18-20 = OM; 8-15 = ON; 16-17 = BA. c = core; r = rim. Atomic proportions are based on 4 oxygens. Mg* = $Mg/Mg+Fe^{2+}$.

	1	2	3	4	5	6	7	8	9	10
	PA1	PA1	LM98	LM6	LM6	LM16	LM16	LA70	LA70	LA29
	c	r	c	c	r	c	r	c	r	c
SiO_2	40.66	40.25	40.21	41.02	40.43	40.82	40.14	40.14	39.56	39.97
TiO_2	-	-	-	-	-	-	-	-	0.05	-
Al_2O_3	-	0.06	-	-	-	-	-	0.06	0.18	-
FeO	10.50	10.80	12.66	9.60	10.90	10.57	9.68	11.62	16.70	12.77
MnO	0.10	0.13	0.18	0.05	0.40	0.25	0.48	0.12	0.56	0.21
MgO	47.91	47.71	47.41	48.35	46.79	48.14	47.50	46.82	42.42	46.73
CaO	0.12	0.22	0.11	0.41	1.28	0.12	1.31	0.27	0.95	0.25
NiO	0.20	0.21	-	-	-	-	-	0.12	-	0.17
Cr_2O_3	-	-	0.02	0.16	-	-	-	-	-	-
Total	99.49	99.38	100.59	99.59	99.80	99.90	99.11	99.15	100.42	100.10
Si	1.0047	0.9984	0.9931	1.0079	1.0018	1.0044	0.9974	1.0012	1.0003	0.9940
Ti	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0010	0.0000
Al	0.0000	0.0018	0.0000	0.0000	0.0000	0.0000	0.0000	0.0018	0.0054	0.0000
Fe^{2+}	0.2169	0.2240	0.2614	0.1972	0.2259	0.2175	0.2011	0.2423	0.3531	0.2655
Mn	0.0021	0.0027	0.0038	0.0010	0.0084	0.0052	0.0101	0.0025	0.0120	0.0044
Mg	1.7644	1.7638	1.7452	1.7706	1.7281	1.7654	1.7591	1.7405	1.5987	1.7320
Ca	0.0032	0.0058	0.0029	0.0108	0.0340	0.0032	0.0349	0.0072	0.0257	0.0067
Ni	0.0040	0.0042	0.0000	0.0000	0.0000	0.0000	0.0000	0.0024	0.0000	0.0034
Cr	0.0000	0.0000	0.0004	0.0031	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	2.9953	3.0007	3.0067	2.9906	2.9982	2.9956	3.0026	2.9980	2.9961	3.0060
Mg*	0.8905	0.8873	0.8697	0.8998	0.8844	0.8903	0.8974	0.8778	0.8191	0.8671

Table 2 (conclusion)

	11	12	13	14	15	16	17	18	19	20
	PA3	LM115	LM115	LM116	LM116	PA4	PA4	LM6	LM16	LM16
	c	c	r	c	r	c	r	c	c	c
SiO_2	40.10	41.06	39.55	40.79	40.63	39.51	39.89	37.18	36.11	35.89
TiO_2	-	-	-	-	-	-	0.04	-	-	-
Al_2O_3	0.04	-	-	-	-	-	0.03	-	-	-
FeO	11.78	11.06	18.06	10.46	12.51	13.70	13.88	10.20	10.92	10.74
MnO	0.17	-	-	0.01	0.19	0.22	0.18	0.61	0.33	0.58
MgO	48.01	47.88	41.54	47.92	45.88	45.45	46.13	19.68	19.11	18.69
CaO	0.18	0.30	0.93	0.22	0.98	0.15	0.13	33.12	33.34	33.59
NiO	0.17	-	-	-	-	0.17	0.20	-	-	-
Cr_2O_3	-	0.01	0.04	-	-	-	-	0.04		
Total	100.45	100.31	100.12	99.40	100.19	99.20	100.48	100.83	99.81	99.49
Si	0.9892	1.0072	1.0066	1.0072	1.0075	0.9958	0.9929	1.0031	0.9905	0.9894
Ti	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0007	0.0000	0.0000	0.0000
Al	0.0012	0.0000	0.0000	0.0000	0.0000	0.0000	0.0009	0.0000	0.0000	0.0000
Fe^{2+}	0.2430	0.2269	0.3844	0.2160	0.2594	0.2887	0.2889	0.2301	0.2505	0.2476
Mn	0.0036	0.0000	0.0000	0.0002	0.0040	0.0047	0.0038	0.0139	0.0077	0.0135
Mg	1.7652	1.7505	1.5758	1.7636	1.6956	1.7074	1.7113	0.7913	0.7812	0.7680
Ca	0.0048	0.0079	0.0254	0.0058	0.0260	0.0041	0.0035	0.9573	0.9797	0.9921
Ni	0.0034	0.0000	0.0000	0.0000	0.0000	0.0034	0.0040	0.0000	0.0000	0.0000
Cr	0.0000	0.0002	0.0008	0.0000	0.0000	0.0000	0.0000	0.0009	0.0000	0.0000
Total	3.0102	2.9927	2.9930	2.9928	2.9925	3.0042	3.0059	2.9965	3.0095	3.0106
Mg*	0.8790	0.8853	0.8039	0.8909	0.8673	0.8554	0.8556	0.7747	0.7572	0.7562

Table 3 – Microprobe compositions of representative clinopyroxenes from the Lages rocks. 1-2 = OM; 3-6 = ON; 7-8 = BA; 9-10 = PhTe; 11-15 = NeSy; 16-22 = PPPh; 23-30 = PPh. c = core; r = rim; gm = groundmass; A, B = different crystals. Atomic proportions are based on 6 oxygens. Fe^{2+}/Fe^{3+} partitioning according to Papike et al. (1974).

	1	2	3	4	5	6	7	8	9	10
	LM6	LM6	LA70	LA70	LM115	LM115	PA4	PA4	LA3	LA3
	c	r	c	r	c	r	c	gm	c	r
SiO_2	53.98	54.45	51.54	49.77	48.11	53.63	50.21	50.87	45.45	47.17
TiO_2	1.63	0.46	1.58	1.18	2.69	1.33	0.48	0.71	1.99	1.75
Al_2O_3	0.13	-	1.95	4.70	4.72	0.19	2.31	2.19	5.69	6.25
FeO	4.72	3.45	5.75	6.77	5.30	5.08	10.78	6.69	13.00	10.05
MnO	0.19	0.09	0.20	0.16	-	0.14	0.17	0.12	0.64	0.30
MgO	15.60	16.56	14.23	12.56	13.80	15.21	12.73	15.63	8.50	10.72
CaO	21.64	23.70	24.73	22.71	24.07	23.12	22.30	22.09	21.68	22.31
Na_2O	1.61	0.98	0.39	1.44	0.59	0.91	0.68	0.52	1.44	1.15
Total	99.50	99.69	100.37	99.29	99.28	99.61	99.66	98.82	98.39	99.70
Si	1.9851	1.9899	1.9054	1.8462	1.7896	1.9828	1.8880	1.8946	1.7523	1.7697
Ti	0.0451	0.0126	0.0439	0.0329	0.0752	0.0370	0.0136	0.0199	0.0577	0.0494
Al	0.0056	0.0000	0.0850	0.2055	0.2069	0.0083	0.1024	0.0961	0.2585	0.2763
Fe^{3+}	0.0301	0.0443	0.0250	0.1399	0.0992	0.0000	0.1248	0.0937	0.2292	0.1691
Fe^{2+}	0.1150	0.0611	0.1527	0.0701	0.0656	0.1571	0.2141	0.1146	0.1899	0.1462
Mn	0.0059	0.0028	0.0063	0.0050	0.0000	0.0044	0.0054	0.0038	0.0209	0.0095
Mg	0.8551	0.9020	0.7841	0.6944	0.7651	0.8382	0.7134	0.8676	0.4884	0.5994
Ca	0.8526	0.9279	0.9794	0.9025	0.9592	0.9158	0.8983	0.8814	0.8955	0.8967
Na	0.1148	0.0694	0.0280	0.1036	0.0425	0.0652	0.0496	0.0375	0.1076	0.0836
Total	4.0093	4.0100	4.0097	4.0000	4.0034	4.0087	4.0096	4.0093	4.0000	4.0000

Table 3 (continuation)

	11	12	13	14	15	16	17	18	19	20
	LM53	LM53	LM2	LM2	LM2	LM99	LM99	LM99	LM99	LM106
	c	r	c	r	gm	c	r	gmA	gmB	r
SiO_2	45.29	48.00	47.97	49.11	50.86	46.56	44.71	48.26	48.52	45.02
TiO_2	1.43	0.67	2.26	1.80	1.08	1.86	1.03	1.18	2.57	1.55
Al_2O_3	5.69	1.93	6.29	4.94	3.95	5.57	4.24	1.96	1.16	5.58
FeO	14.90	20.09	9.69	10.71	14.83	9.69	20.09	20.30	26.39	14.73
MnO	0.80	2.38	0.30	0.52	1.34	0.22	2.42	2.23	2.22	0.61
MgO	7.30	4.41	10.79	9.89	7.32	11.05	3.91	4.43	0.11	8.19
CaO	20.39	14.75	20.72	21.28	18.11	21.85	18.83	12.97	3.55	20.16
Na_2O	2.00	4.76	1.17	1.20	2.24	1.52	2.41	5.69	10.69	2.02
Cr_2O_3	0.06	0.09	0.15	0.13	0.12	0.03	0.04	-	-	-
Total	97.86	97.08	99.34	99.58	99.85	98.35	97.68	97.02	95.21	97.86
Si	1.7613	1.9005	1.8084	1.8594	1.9447	1.7626	1.7915	1.8998	1.9364	1.7437
Ti	0.0418	0.0199	0.0641	0.0512	0.0311	0.0529	0.0310	0.0349	0.0771	0.0451
Al	0.2608	0.0901	0.2794	0.2204	0.1789	0.2485	0.2002	0.0909	0.0546	0.2547
Fe^{3+}	0.2820	0.4126	0.0567	0.0424	0.0329	0.2311	0.3240	0.4553	0.7272	0.3161
Fe^{2+}	0.2026	0.2526	0.2487	0.2966	0.4412	0.0757	0.3491	0.2130	0.1535	0.1610
Mn	0.0263	0.0798	0.0096	0.0167	0.0434	0.0071	0.0821	0.0743	0.0750	0.0200
Mg	0.4231	0.2602	0.6063	0.5581	0.4172	0.6235	0.2335	0.2599	0.0065	0.4728
Ca	0.8495	0.6257	0.8368	0.8632	0.7419	0.8862	0.8083	0.5470	0.1518	0.8365
Na	0.1508	0.3654	0.0855	0.0881	0.1660	0.1116	0.1872	0.4342	0.8271	0.1517
Cr	0.0018	0.0028	0.0045	0.0039	0.0036	0.0009	0.0013	0.0000	0.0000	0.0000
Total	4.0000	4.0095	4.0000	4.0000	4.0000	4.0000	4.0083	4.0093	4.0092	4.0016

Table 3 (conclusion)

	21	22	23	24	25	26	27	28	29	30
	LM106	LM106	LM97	LM97	LM97	LM97	LM112	LM112	LM88	LM25
	r	gm	c	r	gmA	gmB	c	r	gm	gm
SiO_2	50.08	50.86	48.90	50.45	50.64	50.46	46.04	48.94	50.35	50.50
TiO_2	0.68	1.72	1.66	1.14	1.67	1.27	1.55	0.76	0.72	0.91
Al_2O_3	0.88	1.39	5.49	1.67	0.88	0.83	4.06	1.63	1.01	1.07
FeO	27.35	26.83	4.86	12.81	17.67	26.65	15.66	22.77	27.41	27.05
MnO	0.98	0.76	0.09	0.59	0.76	0.04	2.62	3.43	1.00	1.06
MgO	0.29	-	13.42	10.20	7.33	1.29	6.83	1.53	0.60	0.33
CaO	4.89	2.61	23.80	17.15	11.54	3.51	18.89	10.31	2.29	4.39
Na_2O	10.44	11.71	0.80	3.83	6.40	11.26	2.42	7.27	11.72	10.61
Cr_2O_3	-	-	0.12	0.13	0.07	-	-	-	-	-
Total	95.59	95.88	99.14	97.97	96.96	95.31	98.07	96.64	95.10	95.92
Si	1.9787	1.9873	1.8127	1.9157	1.9504	1.9745	1.8027	1.9421	1.9761	1.9857
Ti	0.0202	0.0505	0.0463	0.0326	0.0484	0.0374	0.0456	0.0227	0.0212	0.0269
Al	0.0410	0.0640	0.2398	0.0747	0.0399	0.0383	0.1873	0.0762	0.0467	0.0496
Fe^{3+}	0.7609	0.7473	0.0961	0.2877	0.4190	0.7922	0.2800	0.5535	0.8504	0.7339
Fe^{2+}	0.1427	0.1294	0.0546	0.1191	0.1501	0.0798	0.2328	0.2021	0.0492	0.1555
Mn	0.0328	0.0252	0.0028	0.0190	0.0248	0.0013	0.0869	0.1153	0.0332	0.0353
Mg	0.0171	0.0000	0.7415	0.5773	0.4208	0.0752	0.3986	0.0905	0.0351	0.0193
Ca	0.2070	0.1093	0.9452	0.6977	0.4762	0.1471	0.7924	0.4383	0.0963	0.1849
Na	0.7997	0.8871	0.0575	0.2820	0.4779	0.8542	0.1837	0.5593	0.8917	0.8088
Cr	0.0000	0.0000	0.0035	0.0039	0.0021	0.0000	0.0000	0.0000	0.0000	0.0000
Total	4.0000	4.0000	4.0000	4.0095	4.0096	4.0000	4.0099	4.0000	4.0000	4.0000

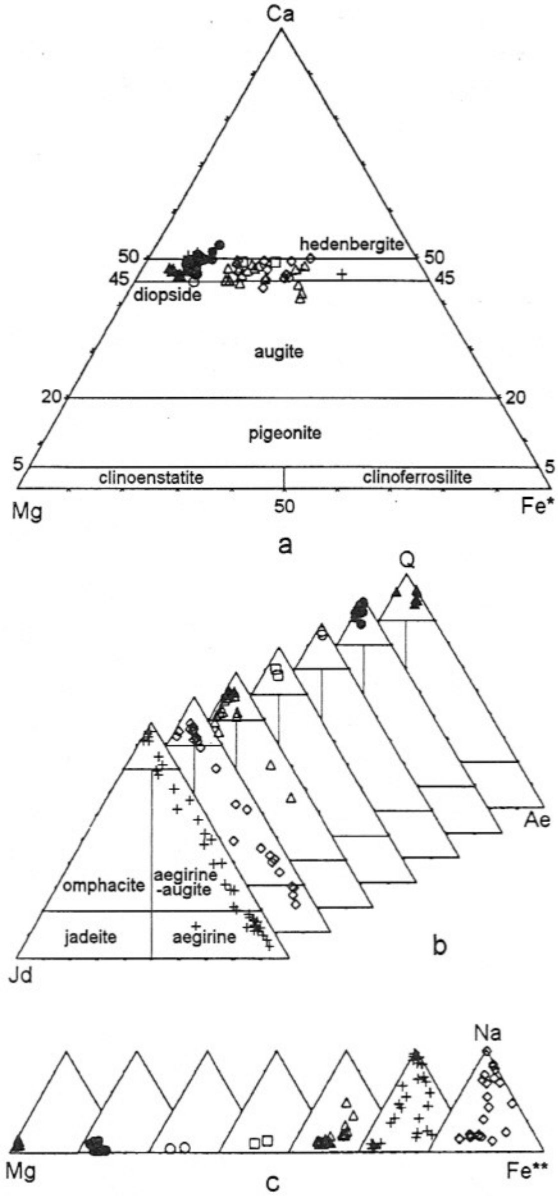

Figure 3 – Microprobe composition of clinopyroxenes from Lages alkaline rocks in the Ca-Mg-Fe** (Fe** = Fe^{2+} + Fe^{3+} + Mn) and Q-Jd-Ae classificative diagrams (Morimoto et al., 1988) (a,b) and Na-Mg-Fe** (Fe** = Fe^{2+} + Fe^{3+} + Mn - Na) diagram (c). Full triangle = OM; full circle = ON; empty circle = BA; square = PhTe; empty triangle = NeSy; empty rhombus = PPPh; cross = PPh.

ple (Fig. 3).

Only Cerro Alto de Cima olivine melilitites contain diopsidic clinopyroxene. Very limited zoning shows an opposite trend with respect to the evolved rock-types, Na_2O decreasing and CaO and MgO increasing from core to rim. From a structural viewpoint, it is relevant that both Al^{3+} and Fe^{3+} entry T sites, while Mg occupies only M1 sites and Mn^{2+} only M2 sites.

Also the clinopyroxenes from olivine nephelinites are represented by diopsidic types. Fe^{3+} is not always necessary to fill T sites, and Mn^{2+} occupies only M2 sites, except for three samples. Almost all diopsides of the olivine nephelinites are represented by aluminian and ferroan types, and are frequently titanian in the rims. Mean values testify slight variations from core to rim, sometimes of opposite sign in the different rocks.

Aluminian, ferrian and ferroan diopside is normally present in both basanite and phonotephrite. Limited zoning shows, core to rim, Na and Fe decrease and Mg increase. From the structural point of view, diopside of phonotephrite is distinguished by an excess of Al entering the M1 sites, while in basanite Fe^{3+} is necessary to fill T sites. Diopside from phonotephrite is also characterized by lacking in M1 cations partially balanced by Mn^{2+}.

Nepheline syenites show larger compositional variations, from diopside to hedenbergite and augite up to aegirine-augite. LM1 and LM2 samples have aluminian, ferroan, sometimes sodian diopside cores which evolve to ferroan omphacite and to sodian, ferroan, aluminian augite rims, respectively. Core to rim zoning shows Na_2O, FeO and SiO_2 increase and CaO, MgO and Al_2O_3 decrease. LM53 crystals present a sodian, ferrian aluminian hedenbergite core and an aegirine-augite rim with an intermediate portion with diopsidic character. So, Na_2O (2.11-1.16-5.67) and FeO (15.27-9.23-20.49) present an U shaped evolution, while MgO (6.94-11.08-4.43) and CaO (20.35-22.44-12.89) show an inverse trend. Clinopyroxenes from all nepheline syenites are characterized, like thoses one of phonotephrite, by an excess of Al entering the M1 sites. Only the terms from LM53 present Mn^{2+} in M1.

Clinopyroxenes from porphyritic and subaphyric peralkaline phonolites show the maximum compositional range from diopside up to almost pure aegirine (12.43% Na_2O) through hedenbergite and aegirine-augite (Fig. 3). These variations are not only found in different rocks, but also inside zoned crystals (cf. sample LM97, Table 3). Oscillatory zoning (Scheibe, 1986), according to Vieten (1980), could be explained by rhythmical PH_2O variations in the magmatic system. Different PH_2O and fO_2 values could also explain Na-Fe^{3+} enrichment trends (cf. Fig. 3c) in the porphyritic peralkaline phonolites (e.g. LM99) and peralkaline phonolites (e.g. LM97). Diopside and hedenbergite of phonolites are normally represented by aluminian, ferrian and sodian terms, while aegirine-augites are frequently titanian or manganoan. Phonolites are also characterized by Al excess in M1 sites; Mn^{2+} enters both M1 and M2.

Phlogopite and biotite

Phlogopite and Mg-biotite are important constituents of mafic and ultramafic rocks, and occur also in some leucocratic types. Representative analyses are reported in Table 4. Micas from olivine melilitites have a homogeneous composition and, according to Rock (1982), they can be classified as titaniferous phlogopites (Fig. 4). Al contents, except three samples, are relatively low, but enough to fill the tetrahedral sites. Most samples have small quantities of Al in octahedral sites (0.15 is the mean value of Al^{VI} of 40 samples). In Figure 4a they plot over the phlogopite-annite line.

Micas from olivine nephelinites plot over the phlogopite-Mg-biotite boundary (Fig. 4b) and have lower Al contents so that Al+Si is always less than 8 (7.77 mean value of 15 samples). The lack of Al^{VI}, balanced by higher Ti values in place of Al in octahedral sites, suggests the presence of Fe^{3+} in tetrahedral sites (titan-tetraferriphlogopite, according to Rock, 1982).

The phlogopites, as well as those from the more leucocratic terms, are characteristically Al-rich. Phlogopites from peralkaline phonolites of Fazenda Nova do Tributo (LM97) are very different from groundmass types of peralkaline phonolites of Rio do Cadeado (LM76), and resemble those characterizing the cores of basanitic rocks (Fig. 4). As previously stated, these phlogopites from the sample LM97 show evidence of instability, which manifests itself in a corroded form and in the presence of a mantle of small clinopyroxenes; these phlogopites probably represent xenocrysts from less evolved melts.

From the classificative viewpoint (Rock, 1982), micas from mafic rocks vary from titanphlogopites (basanite cores) to titanbiotites (groundmass of basanite and phenocrysts from phonotephrite); micas from peralkaline phonolites vary from titaniferous phlogopites to titaniferous biotites.

Amphibole

Amphiboles are present as rare xenocrysts in some nepheline syenites and phonolites, corroded and mantled by an aegirine-augitic rim, while in phonotephrite they are primary and well developed as both phenocrysts and groundmass phases. Representative analyses are listed in Table 5. Xenocrysts from phonolites have not been analysed. According to Leake (1978) and Rock & Leake (1984), amphiboles from nepheline syenite LM1 are classified as potassian kaersutite and those ones from phonotephrite and nepheline syenite LM2 as potassian titanian ferroan pargasites. Amphibole from phonotephrite has Mg values (0.57) similar to that of whole-rock (0.53; with Fe_2O_3/FeO = 0.15). In nepheline syenite, on the contrary, Mg values are much higher in the amphiboles (0.43-0.56) than in the total rocks (0.22-0.25), pointing out their probable xenocrystic nature referable to cogenetic, less evolved melts.

Oxides

Ti-magnetite and spinel representative analyses are reported in Table 6. Olivine nephelinites are characterized by highly titaniferous magnetite (Fig. 5) with ulvöspinel molecule (Ulv) between 57.4 and 69.2 (only a rim of LA70 has 38.3%). Basanite also has a high ulvöspinel value (58.2). Ti-magnetite from olivine melilitites and leucocratic rocks, on the contrary, have lower titanium contents (19.6 < Ulv < 24.8 and 14.3 < Ulv < 38.4, respectively). Cr_2O_3 contents, in both olivine melilitites and olivine nephelinites, are strongly variable, ranging from 0.10 to 12.04 and from 0.03 to 6.57, respectively. In mafic and leucocratic types they are always at low levels (0.02-0.08). MgO is also quite variable, being higher in olivine melilitites (3.84-8.47), intermediate in olivine nephelinites (2.21-4.58), basanite (3.73) and phonotephrite (1.38-2.07) and much lower (0-0.47) in nepheline syenites and peralkaline phonolites. MnO content follows an inverse pattern: it increases from olivine melilitites (0.43-1.06) to olivine nephelinites (0.78-1.54) and to mafic and leuco-

Table 4 – Microprobe compositions of representative phlogopites and biotites from the Lages rocks. 1-6 = OM; 7-10 = ON; 11-13 = BA; 14-15 = PhTe; 16-17 = NeSy; 18-20 = PPh. c = core; r = rim; gm = groundmass. Atomic proportions are based on 23 oxygens. Mg* = Mg/Mg + Fe^{2+}.

	1	2	3	4	5	6	7	8	9	10
	PA1	LM98	LM98	LM6	LM16	LM16	LA29	LM115	LM116	LM116
	c	c	r	c	c	r	c	c	c	r
SiO_2	36.24	37.80	39.06	39.96	39.73	40.66	37.42	44.11	40.60	40.36
TiO_2	6.68	2.15	2.34	3.45	2.13	1.96	4.57	4.70	3.78	5.72
Al_2O_3	8.39	11.91	11.02	13.12	12.42	11.81	16.22	5.98	8.60	7.25
FeO	6.72	6.84	7.37	6.31	4.94	5.76	6.13	10.08	10.45	12.42
MnO	0.12	0.11	0.10	-	0.04	-	-	0.05	-	0.07
MgO	21.85	23.29	22.97	23.24	24.17	23.96	20.02	19.86	19.91	15.55
CaO	3.83	0.04	0.02	-	-	1.09	0.04	0.01	-	-
Na_2O	0.44	0.09	0.12	0.35	0.18	0.35	0.37	1.68	0.55	3.16
K_2O	8.96	9.72	10.14	9.93	9.81	9.84	9.91	9.64	9.27	9.12
Cr_2O_3	-	-	-	-	-	-	0.27	0.05	-	-
BaO	-	-	-	0.93	1.99	0.99	-	1.63	1.63	0.31
Total	93.43	91.95	93.14	97.29	95.41	96.42	94.95	97.79	94.79	93.96
Si	5.7016	5.9247	6.0616	5.9199	6.0110	6.0788	5.6477	6.6563	6.3272	6.4125
Ti	0.8139	0.2534	0.2731	0.3843	0.2423	0.2203	0.5186	0.5333	0.4430	0.6834
Al	1.5556	2.2000	2.0154	2.2906	1.2145	2.0808	2.8850	1.0635	1.5795	1.3575
Fe^{2+}	0.8841	0.8965	0.9564	0.7817	0.6250	0.7201	0.7736	1.2719	1.3618	1.6501
Mn	0.0160	0.0146	0.0131	0.0000	0.0051	0.0000	0.0000	0.0064	0.0000	0.0094
Mg	5.1237	5.4408	5.3129	5.1315	5.4504	5.3389	4.5035	4.4668	4.6246	3.6823
Ca	0.6456	0.0067	0.0033	0.0000	0.0000	0.1746	0.0065	0.0016	0.0000	0.0000
Na	0.1342	0.0273	0.0361	0.1005	0.0528	0.1014	0.1083	0.4915	0.1662	0.9734
K	1.7982	1.9433	2.0073	1.8765	1.8933	1.8765	1.9079	1.8556	1.8428	1.8483
Cr	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ba	0.0000	0.0000	0.0000	0.0540	0.1180	0.0580	0.0000	0.0964	0.0995	0.0193
Total	16.6728	16.7073	16.6793	16.5390	16.6124	16.6495	16.3832	16.4492	16.4446	16.6362
Mg*	0.8528	0.8585	0.8475	0.8678	0.8971	0.8812	0.8534	0.7784	0.7725	0.6906

Table 4 (conclusion)

	11	12	13	14	15	16	17	18	19	20
	PA4	PA4	PA4	LA3	LA3	LAG3	LAG7	LM97	LM97	LM76
	c	r	gm	c	gm	c	r	c	r	gm
SiO_2	36.99	36.88	35.69	34.92	35.38	36.54	33.72	37.58	37.17	35.60
TiO_2	4.67	4.19	7.79	5.77	5.72	5.05	6.96	4.20	3.88	2.85
Al_2O_3	14.78	15.06	13.03	14.34	15.44	15.30	14.42	16.43	15.72	13.71
FeO	8.09	6.53	14.29	16.89	10.67	10.86	21.62	6.49	6.76	19.99
MnO	0.07	0.09	0.08	0.27	0.10	0.10	0.96	0.02	0.10	1.42
MgO	19.63	19.79	14.30	13.36	16.70	19.86	11.11	20.70	19.89	12.01
CaO	0.08	0.06	0.13	-	0.06	-	-	-	-	-
Na_2O	0.70	0.54	0.64	0.68	0.75	-	-	0.87	0.80	0.38
K_2O	7.31	9.49	8.73	8.53	8.79	9.04	8.51	9.38	9.39	9.64
NiO	0.11	0.13	-	-	-	-	-	0.02	-	-
Cr_2O_3	0.15	0.12	-	-	-	-	-	0.25	0.07	-
BaO	-	-	-	-	-	0.60	2.75	0.04	-	-
Total	92.58	92.88	94.68	94.76	93.61	97.35	100.05	95.98	93.78	95.60
Si	5.7135	5.7081	5.6306	5.5686	5.5375	5.1114	5.3357	5.6137	5.6920	5.7639
Ti	0.5424	0.4876	0.9241	0.6919	0.6732	0.5728	0.8281	0.4718	0.4468	0.3470
Al	2.6904	2.7470	2.4226	2.6949	2.8480	2.7197	2.6890	2.8924	2.8370	2.6160
Fe^{2+}	1.0449	0.8451	1.8851	2.2522	1.3964	1.3697	2.8606	0.8107	0.8656	2.7063
Mn	0.0092	0.0118	0.0107	0.0365	0.0133	0.0128	0.1287	0.0025	0.0130	0.1947
Mg	4.5191	4.5652	3.3625	3.1754	3.8957	4.4647	2.6202	4.6087	4.5397	2.8982
Ca	0.0132	0.0099	0.0220	0.0000	0.0101	0.0000	0.0000	0.0000	0.0000	0.0000
Na	0.2096	0.1620	0.1957	0.2102	0.2276	0.0000	0.0000	0.2520	0.2375	0.1193
K	1.4403	1.8736	1.7568	1.7351	1.7549	1.7393	1.7177	1.7873	1.8342	1.9909
Ni	0.0137	0.0162	0.0000	0.0000	0.0000	0.0000	0.0000	0.0024	0.0000	0.0000
Cr	0.0183	0.0147	0.0000	0.0000	0.0000	0.0000	0.0000	0.0295	0.0085	0.0000
Ba	0.0000	0.0000	0.0000	0.0000	0.0000	0.0355	0.1705	0.0023	0.0000	0.0000
Total	16.2147	16.4413	16.2102	16.3647	16.3566	16.4257	16.3505	16.4732	16.4743	16.6362
Mg*	0.8122	0.8438	0.6408	0.5850	0.7361	0.7652	0.4781	0.8504	0.8399	0.5171

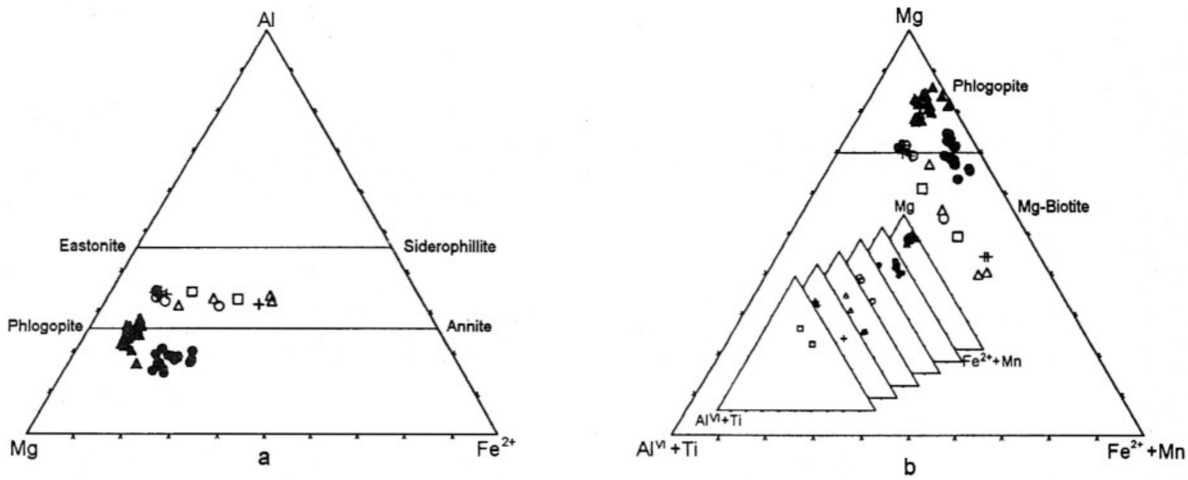

Figure 4 – Microprobe composition of phlogopites and biotites from Lages alkaline rocks in the Al-Mg-Fe^{2+} (a) and Mg-Al^{VI}+Ti-Fe^{2+}+Mn (b) diagrams (Rock, 1982). Symbols as in Fig. 3.

Table 5 – Microprobe compositions of representative amphiboles from the Lages rocks. 1-3 = PhTe; 4-6 = NeSy. c = core; r = rim; gm = groundmass. Atomic proportions are based on 23 oxygens. Mg* = Mg/Mg + Fe^{2+}.

	1 LA3 c	2 LA3 r	3 LA3 gm	4 LM1 c	5 LM2 c	6 LM2 r
SiO_2	38.72	37.93	38.29	39.27	38.33	38.93
TiO_2	3.56	3.69	3.58	4.53	3.40	4.26
Al_2O_3	13.89	13.55	12.95	13.40	13.38	12.49
FeO	14.87	14.59	14.91	13.98	18.68	16.21
MnO	0.22	0.27	0.29	0.34	0.92	0.47
MgO	10.86	10.71	11.10	10.17	7.95	8.85
CaO	11.96	11.65	11.96	11.38	11.32	11.38
Na_2O	2.28	2.28	2.36	2.74	2.91	2.72
K_2O	1.90	1.87	1.94	2.20	2.29	2.16
Total	98.26	96.54	97.38	98.01	99.18	97.47
Si	5.8440	5.8300	5.8535	5.9255	5.8740	5.9814
Ti	0.4040	0.4265	0.4115	0.5140	0.3918	0.4922
Al	2.4706	2.4545	2.3331	2.3829	2.4165	2.2616
Fe^{2+}	1.8767	1.8752	1.9060	1.7639	2.3937	2.0826
Mn	0.0281	0.0351	0.0375	0.0434	0.1194	0.0612
Mg	2.4430	2.4535	2.5291	2.2872	1.8159	2.0267
Ca	1.9339	1.9184	1.9588	1.8396	1.8585	1.8732
Na	0.6671	0.6794	0.6994	0.8015	0.8646	0.8102
K	0.3658	0.3666	0.3783	0.4234	0.4477	0.4233
Total	16.0332	16.0393	16.1073	15.9816	16.1820	16.0124
Mg*	0.5656	0.5668	0.5703	0.5646	0.4314	0.4932

Table 6 – Microprobe compositions of representative oxides from the Lages rocks. 1-6 = OM; 7-12 = ON; 13 = BA; 14-15 = PhTe; 16-17 = NeSy; 18-20 = PPPh. c = core; r = rim; gm = groundmass; A, B = different crystals. Atomic proportions are based on 32 oxygens. Fe_2O_3 and FeO* calculated on ulvöspinel basis (Carmichael, 1967).

	1	2	3	4	5	6	7	8	9	10
	PA1	PA1	PA1	LM98	LM98	LM16	LA70	LA70	LA29	LA29
	c	r	gm	A	B	A	c	r	c	r
SiO_2	0.16	0.16	0.12	-	-	0.16	0.11	-	0.22	0.17
TiO_2	1.10	8.51	6.67	8.41	8.61	6.77	0.84	12.96	0.70	0.74
Al_2O_3	32.49	2.56	6.66	0.49	8.93	0.09	35.93	3.36	43.84	43.46
FeO	18.06	67.13	63.02	80.99	68.62	79.61	16.56	65.31	18.38	18.56
MnO	0.28	0.43	0.52	1.06	1.02	0.65	0.19	0.78	0.26	0.20
MgO	16.85	8.47	7.87	3.96	8.20	3.84	16.50	4.58	17.59	17.61
NiO	0.16	0.13	-	-	-	-	0.17	0.10	0.17	0.23
Cr_2O_3	30.43	5.35	12.04	0.10	0.13	3.68	28.00	6.57	20.04	19.98
Total	99.53	92.74	96.90	95.01	95.51	94.80	98.30	93.66	101.20	100.95
Fe_2O_3	6.47	46.41	40.68	54.53	46.25	53.90	4.32	33.70	5.81	6.18
FeO*	12.24	25.37	26.42	31.92	27.00	31.11	12.67	34.99	13.15	13.00
Total*	100.18	97.39	100.98	100.47	100.14	100.20	98.73	97.04	101.78	101.57
Si	0.0370	0.0463	0.0330	0.0000	0.0000	0.0473	0.0254	0.0000	0.0479	0.0372
Ti	0.1911	1.8501	1.3777	1.8621	1.7744	1.5063	0.1459	2.8853	0.1147	0.1216
Al	8.8459	0.8723	2.1560	0.1700	2.8843	0.0314	9.7785	1.1724	11.2555	11.1936
Fe^{3+}	1.1244	10.0969	8.4073	12.0829	9.5390	12.0006	0.7512	7.5071	0.9528	1.0162
Fe^{2+}	2.3645	6.1336	6.0684	7.8593	6.1877	7.6971	2.4466	8.6627	2.3955	2.3757
Mn	0.0548	0.1053	0.1210	0.2643	0.2368	0.1629	0.0372	0.1956	0.0480	0.0370
Mg	5.8020	3.6500	3.2221	1.7379	3.3496	1.6935	5.6792	2.0211	5.7115	5.7362
Ni	0.0297	0.0302	0.0000	0.0000	0.0000	0.0000	0.0316	0.0238	0.0298	0.0404
Cr	5.5582	1.2230	2.6148	0.0233	0.0282	0.8609	5.1123	1.5380	3.4517	3.4524
Total	24.0077	24.0076	24.0003	23.9998	23.9999	24.0000	24.0077	24.0060	24.0074	24.0102
Ulv %	4.08	24.81	19.58	23.27	23.61	19.79	3.11	38.26	2.93	2.86

Table 6 (conclusion)

	11	12	13	14	15	16	17	18	19	20
	LA29	LM115	PA4	LA3	LA3	LM2	LM2	LM99	LM106	LM106
	gm	A	A	c	r	c	r	A	c	r
SiO_2	0.14	0.11	0.15	0.26	0.11	0.79	-	0.27	0.03	0.11
TiO_2	20.40	22.04	21.46	8.32	8.52	12.00	6.99	4.60	6.25	5.67
Al_2O_3	1.30	0.87	1.37	1.69	2.09	0.57	0.71	0.24	1.28	1.21
FeO	69.62	69.66	73.23	82.46	82.91	75.26	82.04	87.59	83.90	83.99
MnO	0.89	0.70	-	1.10	1.17	4.17	1.75	1.74	1.79	1.90
MgO	3.55	3.50	3.73	2.07	1.38	-	0.42	-	0.41	0.47
NiO	-	0.08	0.06	0.09	-	-	-	-	-	-
Cr_2O_3	0.85	0.03	-	-	-	-	-	0.05	0.02	0.03
Total	96.75	96.99	100.00	95.99	96.18	92.79	91.91	94.49	93.68	93.38
Fe_2O_3	28.53	26.73	29.61	52.22	51.49	41.20	52.97	62.37	54.99	55.88
FeO*	43.95	45.61	46.59	35.47	36.58	38.19	34.38	31.47	34.42	33.71
Total*	99.61	99.67	102.97	101.22	101.34	96.92	97.22	100.74	99.19	98.98
Si	0.0410	0.0323	0.0425	0.0765	0.0324	0.2464	0.0000	0.0814	0.0092	0.0337
Ti	4.4926	4.8601	4.5706	1.8415	1.8899	2.8143	1.6424	1.0430	1.4361	1.3057
Al	0.4487	0.3007	0.4573	0.5863	0.7266	0.2095	0.2615	0.0853	0.4610	0.4367
Fe^{3+}	6.2871	5.8979	6.3100	11.5669	11.4289	9.6686	12.4541	14.1509	12.6440	12.8769
Fe^{2+}	10.7634	11.1844	11.0346	8.7305	9.0231	9.9600	8.9832	7.9347	8.7949	8.6326
Mn	0.2208	0.1739	0.0000	0.2742	0.2923	1.1015	0.4631	0.4443	0.4632	0.4928
Mg	1.5496	1.5298	1.5747	0.9082	0.6067	0.0000	0.1956	0.0000	0.1867	0.2145
Ni	0.0000	0.0189	0.0137	0.0213	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cr	0.1968	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000	0.0119	0.0048	0.0073
Total	24.0001	24.0049	24.0033	24.0054	23.9999	24.0003	23.9998	23.7516	23.9999	24.0002
Ulv %	57.44	61.59	58.24	24.29	24.40	38.43	20.64	14.23	18.24	16.90

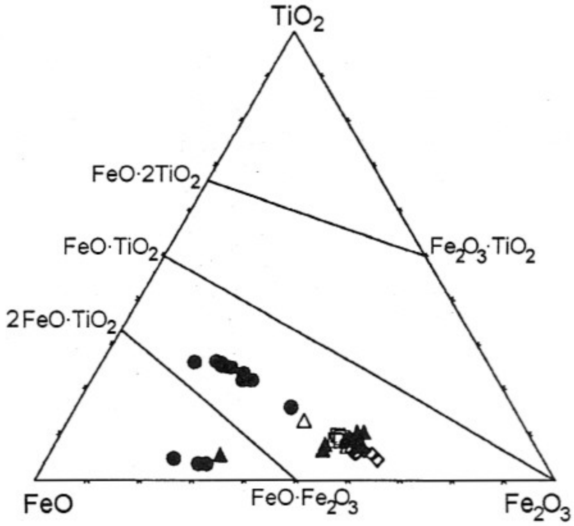

Figure 5 – Microprobe composition of magnetites and spinels from Lages alkaline rocks in the TiO_2-FeO-Fe_2O_3 diagram. Symbols as in Fig. 3.

cratic rocks (1.10-4.17).

Cr-Al spinels are present as distinct brown crystals, sometimes corroded and jacketed by Ti-magnetite, in olivine melilitites and olivine nephelinites. Cr_2O_3 contents range between 20.0 and 30.4 and are inversely correlated with Al_2O_3 (43.8-32.5). MgO contents are similarly high (16.0-17.6), attesting the primitive character of these magmas.

Feldspars

Representative analyses of alkali feldspar are listed in Table 7. Figure 6 shows that intermediate sanidine compositions (between 50 and 80% K + Ba) characterize basanite, phonotephrite and nepheline syenites, in the last ones frequently coexisting with almost pure K-sanidine in the groundmass. The highest values of An (max. 7.09%) are present in the large zoned phenocrysts from porphyritic nepheline syenite. Core to rim and groundmass evolution, evaluated from all microprobe data average values, respectively, shows a decrease in CaO (from 0.54 to 0.32) and Na_2O (from 4.56 to 3.76) and an increase in K_2O (from 9.56 to 10.88). BaO remains almost constant.

Intermediate sanidine compositions also characterize many paralkaline phonolites (Fig. 6), where crystals of almost pure sanidine and albite, frequently with extreme compositions, are ubiquitous and associated in the groundmass.

Nepheline, leucite and kalsilite

Representative analyses of Lages feldspathoids are listed in Table 8. Nepheline characterizes all lithotypes while leucite and kalsilite are present only in olivine nephelinites.

Nepheline compositions are quite variable; rim and groundmass data often show higher Q values than cores, emphasizing the lack of correlation between Q and crystallization temperatures. Interstitial nephelines from ultrabasic rocks have similar compositions with a medium to high potassium content, from $Na_{76}K_{24}$ to $Na_{67}K_{33}$ (olivine melilitites) and from $Na_{78}K_{22}$ to $Na_{68}K_{34}$ (olivine nephelinites) with no or very low Q indicating a close relation to the nature of the host rock.

Nephelines from phonotephrite and leucocratic rocks are normally present both as phenocrysts and in the groundmass and always show (with the exception of non-porphyritic peralkaline phonolites) an excess of Q (1.34-10.60) and lower K content: $Na_{38}K_{17}$ in phonotephrite; from $Na_{90}K_{10}$ to $Na_{82}K_{18}$ in nepheline syenites; from $Na_{86}K_{14}$ to $Na_{77}K_{23}$ in porphyritic peralkaline phonolites; and from $Na_{87}K_{13}$ to $Na_{77}K_{23}$ in peralkaline phonolites.

Iron contents are higher in nephelines from the ultrabasic rocks (average FeO = 1.12) than in leucocratic terms (average FeO = 0.59). Only a peralkaline phonolite (LM97) shows values (average FeO = 1.46) similar to those of less evolved rocks pointing out the role of fractional crystallization processes.

The composition of leucite does not depart significantly from the ideal formula: Si/Al ratio is close to 2/1, and Na replacement is very limited (Na_2O: 0.28-0.52). The iron content is also low, as expected.

Kalsilite shows almost pure composition (Na_4K_{96}).

Perowskite

Small dark brown perowskite crystals characterize the olivine melilitites and olivine nephelinites ultramafic rocks. Representative analyses are reported in Table 9.

Table 7 – Microprobe compositions of representative alkali feldspars from the Lages rocks. 1 = BA; 2 = PhTe; 3-8 = NeSy; 9-13 = PPPh; 14-20 = PPh. c = core; r = rim; gm = groundmass; A, B = different crystals. Atomic proportions are based on 32 oxygens.

	1	2	3	4	5	6	7	8	9	10
	PA4	LA3	LM1	LM1	LM1	LM1	LM2	LM2	LM106	LM106
	gm	gm	c	r	gmA	gmB	gmA	gmB	c	r
SiO_2	61.40	62.50	62.86	65.50	65.13	64.34	65.39	64.53	65.48	65.04
Al_2O_3	20.11	21.28	20.33	19.02	18.46	18.47	18.76	18.59	18.85	18.72
FeO	1.90	0.40	0.27	0.26	0.08	-	0.15	-	0.14	0.17
CaO	0.18	0.18	1.26	0.33	0.00	0.16	0.15	-	-	-
Na_2O	2.78	4.38	4.71	4.45	3.54	0.31	3.75	0.42	3.53	2.69
K_2O	12.61	10.41	8.12	10.16	11.76	16.27	11.31	16.21	11.81	12.99
BaO	-	-	2.30	0.21	0.09	0.11	0.13	0.16	0.01	-
Total	98.98	99.15	99.85	99.93	99.06	99.66	99.64	99.91	99.82	99.61
Si	11.4457	11.4812	11.5610	11.8970	11.9807	11.9548	11.9440	11.9548	11.9451	11.9423
Al	4.4179	4.6069	4.4064	4.0714	4.0019	4.0444	4.0383	4.0587	4.0525	4.0508
Fe^{3+}	0.2962	0.0614	0.0415	0.0395	0.0123	0.0000	0.0229	0.0000	0.0214	0.0261
Ca	0.0359	0.0354	0.2483	0.0642	0.0000	0.0318	0.0294	0.0000	0.0000	0.0000
Na	1.0047	1.5599	1.6794	1.5670	1.2624	0.1117	1.3279	0.1508	1.2484	0.9576
K	2.9985	2.4393	1.9050	2.3540	2.7594	3.8562	2.6352	3.8306	2.7481	3.0425
Ba	0.0000	0.0000	0.1657	0.0149	0.0065	0.0080	0.0093	0.0116	0.0007	0.0000
Total	20.1988	20.1842	20.0072	20.0080	20.0232	20.0069	20.0070	20.0066	20.0163	20.0193
Ab wt%	23.78	37.26	42.36	37.91	30.12	2.63	31.95	3.58	29.97	22.87
An wt%	0.90	0.90	6.64	1.65	0.00	0.80	0.75	0.00	0.00	0.00
Or wt%	75.32	61.84	51.00	60.44	69.88	96.57	67.30	96.42	70.03	77.13

Table 7 (conclusion)

	11 LM106 gmA	12 LM106 gmB	13 LM106 gmC	14 LM112 gmA	15 LM112 gmB	16 LM112 gmC	17 LM88 gmA	18 LM88 gmB	19 LM25 gmA	20 LM25 gmB
SiO_2	64.62	65.61	68.18	64.65	66.66	68.29	64.95	68.17	64.43	68.32
Al_2O_3	18.62	18.84	19.51	18.41	18.86	19.50	18.38	19.61	18.43	19.35
FeO	0.20	0.35	0.10	0.18	0.02	0.17	0.15	0.25	0.11	0.23
CaO	-	-	0.09	-	-	-	-	-	0.02	-
Na_2O	0.88	4.02	11.66	0.34	5.66	11.64	1.00	11.68	0.46	11.68
K_2O	15.64	11.14	0.16	16.35	8.67	0.22	15.45	0.13	16.17	0.14
BaO	-	-	-	-	-	-	-	0.13	-	-
Total	99.96	99.96	99.70	99.93	99.87	99.82	99.93	99.97	99.62	99.72
Si	11.9367	11.9314	11.9565	11.9703	12.0040	11.9618	11.9860	11.9351	11.9621	11.9764
Al	4.0535	4.0377	4.0321	4.0172	4.0025	4.0254	3.9973	4.0461	4.0325	3.9975
Fe^{3+}	0.0309	0.0532	0.0147	0.0279	0.0030	0.0249	0.0231	0.0366	0.0171	0.0337
Ca	0.0000	0.0000	0.0169	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0000
Na	0.3151	1.4173	3.9642	0.1220	1.9760	3.9528	0.3578	3.9645	0.1656	3.9694
K	3.6852	2.5841	0.0358	3.8616	1.9915	0.0492	3.6369	0.0290	3.8295	0.0313
Ba	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0089	0.0000	0.0000
Total	20.0213	20.0238	20.0201	19.9990	19.9770	20.0140	20.0011	20.0203	20.0107	20.0084
Ab wt%	7.46	34.07	98.61	2.89	48.31	98.70	8.48	99.23	3.91	99.17
An wt%	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.10	0.00
Or wt%	92.54	65.93	0.95	97.11	51.59	1.30	91.52	0.77	95.99	0.83

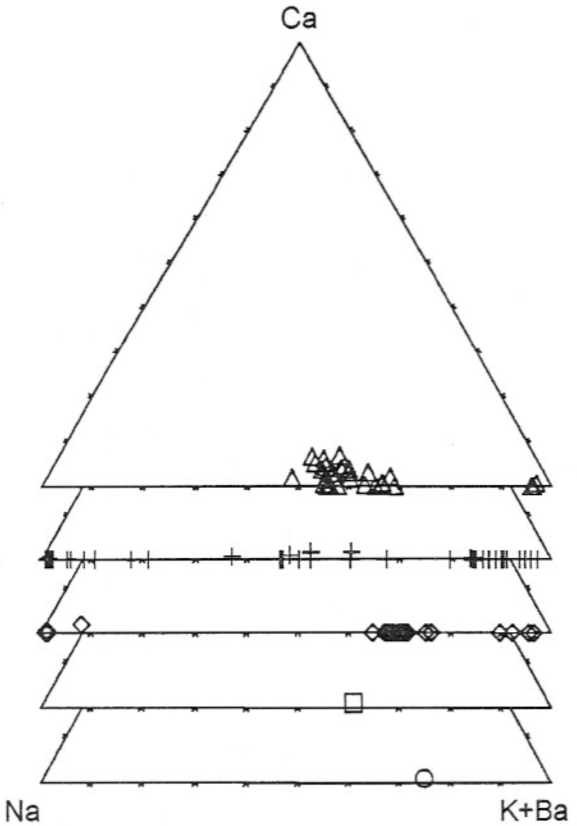

Figure 6 – Microprobe composition of alkali feldspars from Lages alkaline rocks in the Ca-Na-K+Ba diagram. Symbols as in Fig. 3.

The composition is quite uniform. Due to the significant presence of Nb, La and Ce, the perowskites approach the knopite and dysanalyte varieties.

Pectolite-serandite

Representative analyses are given in Table 9. Minerals of the pectolite-serandite series, along with aegirine, formed in the late crystallization stages of peralkaline phonolites. Pectolites from Lageadinho and Chapada (Fig. 7) plot between pectolite and schizolite (manganoan pectolite), while from peralkaline phonolites of Tributo, lying between schizolite and serandite types, can be classified as calcian serandite, a mineral rarely reported in the literature (Schaller, 1955; Takeuchi et al., 1976).

PETROCHEMISTRY AND PETROGENESIS

Major and trace elements were carried out by XRF, FeO by titration, loss on ignition (LOI) by gravimetry and REE by inductively coupled plasma. Precision and accuracy for trace elements are better than 10%.

Selected whole-rock compositions and CIPW parameters are reported in Table 10.

Alkali-silica (Fig. 8) diagram points to the strongly alkaline character of the Lages association.

Three main groups of silicatic rocks are present: ultramafic (OM and ON), mafic (BA) and leucocratic (NeSy, PPPh and PPh), the last one clearly prevailing. The intermediate rock-types are represented only by PhTe (LA3), so that the suite resembles other provinces mentioned by Barker et al. (1987), Le Bas (1978, 1987) and Brey (1978) in which melilititic, nephelinitic, basanitic and phonolitic rocks are associated.

All OM samples show high levels of normative leucite and calcium orthosilicate (Cs) related to strong undersaturation and abundant modal melilite. Only three ON have small values of Cs, in accordance with the previously reported low presence of modal melilite. All analysed Lages rocks are nepheline normative. Agpaitic Index (A.I.) ranges between 0.89 and 1.03 in NeSy, 1.01 and 1.22 in PPPh, and 1.08 and 1.21 in PPh, highlighting the prevalent peralkaline character of leucocratic types.

All Lages rocks but one (LM97, REE_{tot} = 88) show high values of total REE (650-302; average 424), and strong fractionation of LREE/HREE (La/Lu from 631 to 177; average 437). PPh present the lowest La/Lu ratios of the suite due to fractionation processes.

Petrography, mineral chemistry and whole-rock compositions suggest that the three groups of mafic-ultramafic rocks (OM, ON and BA) cannot be considered as linked by fractional crystallization processes. Their Mg normalized values (Brey, 1978) ranging from 0.68 to 0.82, and Ni, Cr, and Co abundances are in agreement with the primary nature of many Lages mafic-ultramafic magmas.

Variation diagrams (Figs. 9 and 10) indicate that the different leucocratic magmas can have been generated by fractional crystallization processes from BA and/or ON types. In general D.I.* is positively correlated with SiO_2, Al_2O_3 and Na_2O, whereas FeO_{tot}, MgO, CaO and P_2O_5 show a negative correlation. Such variations are in accordance with olivine, clinopyroxene,

Table 8 – Microprobe compositions of representative nephelines (1-18), leucites (19) and kalsilites (20) from the Lages rocks. 1-2 = OM; 3-4, 19-20 = ON; 5 = PhTe; 6-10 = NeSy; 11-14 = PPPh; 15-18 = PPh. c = core; r = rim; gm = groundmass. Atomic proportions are based on 32 oxygens for nepheline and kalsilite and on 6 oxygens for leucite.

	1	2	3	4	5	6	7	8	9	10
	LM6	LM6	LM115	LM115	LA3	LM1	LM1	LM1	LM2	LM2
	c	r	c	r	A	c	r	gm	c	r
SiO_2	40.55	40.54	40.64	41.30	45.32	42.08	45.10	45.71	45.30	44.82
Al_2O_3	33.74	33.76	34.12	32.93	31.87	35.48	32.44	32.00	31.78	31.73
FeO	1.05	1.16	0.45	1.24	0.34	0.35	0.35	0.80	0.42	0.41
MnO	0.11	-	-	-	-	-	-	-	-	-
CaO	-	-	-	-	0.16	0.44	0.08	0.03	0.13	0.11
Na_2O	15.63	16.34	15.54	14.34	15.78	17.63	16.59	16.44	15.89	16.64
K_2O	8.59	7.82	7.85	9.46	5.02	3.12	5.38	4.75	5.18	4.85
BaO	-	0.17	-	-	-	-	-	-	-	-
Total	99.67	99.79	98.60	99.27	98.49	99.10	99.94	99.73	98.70	98.56
Si	7.9713	7.9535	8.0163	8.1429	8.7325	8.0695	8.6118	8.7072	8.7245	8.6616
Al	7.8165	7.8056	7.9315	7.6516	7.2370	8.0184	7.3001	7.1837	7.2132	7.2265
Fe^{3+}	0.1726	0.1903	0.0742	0.2044	0.0548	0.0561	0.0559	0.1274	0.0676	0.0663
Mn	0.0183	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ca	0.0000	0.0000	0.0000	0.0000	0.0330	0.0904	0.0164	0.0061	0.0268	0.0228
Na	5.9567	6.2149	5.9426	5.4813	5.8947	6.5544	6.1415	6.0713	5.9330	6.2343
K	2.1540	1.9570	1.9751	2.3792	1.2338	0.7632	1.3104	1.1542	1.2726	1.1956
Ba	0.0000	0.0131	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	24.0895	24.1345	23.9397	23.8594	23.1859	23.5520	23.4361	23.2499	23.2378	23.4070

Table 8 (conclusion)

	11	12	13	14	15	16	17	18	19	20
	LM73	LM99	LM106	LM106	LM97	LM19	LM88	LM25	LM116	LM116
	gm	gm	c	r	gm	gm	gm	gm	A	A
SiO_2	47.91	41.95	43.64	45.28	48.79	46.13	44.51	44.87	55.44	37.93
TiO_2	-	0.04	-	-	-	-	-	-	-	-
Al_2O_3	30.44	34.82	32.93	31.55	28.96	30.96	31.67	32.38	22.31	31.39
FeO	0.77	0.09	0.91	0.32	1.06	0.10	0.63	0.89	0.40	1.20
MnO	-	-	-	-	0.07	-	-	-	-	-
CaO	0.04	-	-	-	-	-	-	0.07	-	0.56
Na_2O	17.00	16.09	17.04	14.68	16.95	14.24	16.42	15.43	0.28	0.72
K_2O	4.11	7.38	5.48	7.27	4.01	7.73	5.22	6.19	21.69	27.99
BaO	-	-	-	-	0.02	-	-	-	0.39	0.55
Total	100.27	100.37	100.00	99.10	99.86	99.16	98.45	99.83	100.51	100.34
Si	9.0322	8.0902	8.3799	8.7497	9.2297	8.9006	8.6301	8.5939	2.0151	7.9737
Ti	0.0000	0.0058	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Al	6.7630	7.9138	7.4521	7.1848	6.4563	7.0399	7.2366	7.3087	0.9556	7.7768
Fe^{3+}	0.1214	0.0145	0.1461	0.0517	0.1677	0.0161	0.1021	0.1425	0.0121	0.2110
Mn	0.0000	0.0000	0.0000	0.0000	0.0112	0.0000	0.0000	0.0000	0.0000	0.0000
Ca	0.0081	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0144	0.0000	0.1261
Na	6.2133	6.0158	6.3436	5.4995	6.2163	5.3267	6.1722	5.7294	0.0197	0.2934
K	0.9884	1.8155	1.3423	1.7920	0.9676	1.9025	1.2910	1.5123	1.0056	7.5057
Ba	0.0000	0.0000	0.0000	0.0000	0.0015	0.0000	0.0000	0.0000	0.0056	0.0453
Total	23.1264	23.8555	23.6639	23.2777	23.0503	23.1859	23.4321	23.3013	4.0137	23.9320

Table 9 – Microprobe compositions of representative perowskites (1-2) and pectolite-serandite (3-6) from the Lages rocks. 1 = OM; 2 = ON; 3 = PPPh; 4-6 = PPh. A, B = different crystals; gm = groundmass. Atomic proportions are based on 24 oxygens for perowskite and on 18 oxygens for pectolite-serandite.

	1	2	3	4	5	6
	LM16	LM115	LM106	LM19	LM88	LM88
	A	A	gm	gm	gmA	gmB
SiO_2	-	-	53.82	52.00	51.69	50.99
TiO_2	54.82	55.54	-	0.18	0.19	-
Al_2O_3	0.30	-	1.37	-	0.09	-
FeO	1.28	0.93	0.17	0.95	0.66	0.97
MnO	-	-	5.87	7.15	19.63	24.39
MgO	-	-	-	0.07	0.01	-
CaO	37.89	36.34	26.48	26.73	15.71	11.95
Na_2O	0.55	0.77	9.77	8.92	9.40	9.22
K_2O	-	-	0.74	-	0.10	-
SrO	-	0.55	-	-	-	-
Total	94.84	94.13	98.22	96.00	97.48	97.52
Si	0.0000	0.0000	6.3117	6.3027	6.3284	6.3216
Ti	7.9038	8.0636	0.0000	0.0164	0.0175	0.0000
Al	0.0678	0.0000	0.1893	0.0000	0.0130	0.0000
Fe^{2+}	0.2052	0.1501	0.0167	0.0963	0.0676	0.1006
Mn	0.0000	0.0000	0.5830	0.7340	2.0354	2.5609
Mg	0.0000	0.0000	0.0000	0.0126	0.0018	0.0000
Ca	7.7832	7.5170	3.3269	3.4709	2.0606	1.5872
Na	0.2044	0.2882	2.2213	2.0960	2.2311	1.2161
K	0.0000	0.0000	0.1107	0.0000	0.0156	0.0000
Sr	0.0000	0.0616	0.0000	0.0000	0.0000	0.0000
Total	16.1645	16.0805	12.7596	12.7289	12.7710	12.7864

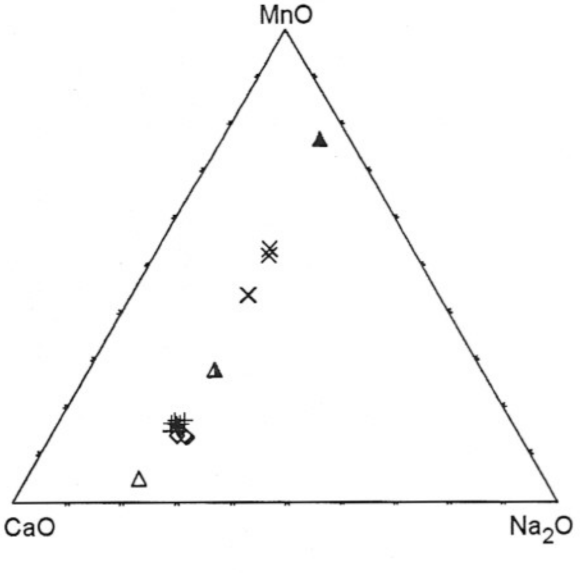

Figure 7 – Microprobe composition of pectolite and serandite from Lages alkaline rocks in the MnO-CaO-Na_2O diagram. Rhombus = pectolites from PPPh of Lajeadinho (LM106); cross = pectolites from PPh of Chapada (LM19, LM25); transverse cross = calcian serandites from PPh of Tributo (LM88); empty triangle = fibrous pectolite from NeSy (Deer et al., 1963); half empty triangle = manganoan pectolite (schizolite) from NeSy (Deer et al., 1963; full triangle = serandite (Takeuchi et al., 1976).

Table 10 – Major (wt %) and trace element (ppm) content and CIPW norms for selected Lages alkaline rocks. 1-4 = OM; 5-9 = ON; 10 = BA; 11 = PhTe; 12-16 = NeSy; 17 = TrPh; 18-20 = PPPh; 21-30 = PPh. A.I. = Agpaitic Index = (Na_2O + K_2O)/Al_2O_3 mol. %; D.I.* = Differentiation Index = Qz + Or + Ab + Ne + Lc + Kp + Ac + Ns.

	1 PA1 OM	2 LM98 OM	3 LM6 OM	4 LM16 OM	5 LA70 ON	6 LA29 ON	7 PA3 ON	8 LM115 ON	9 LM116 ON	10 PA4 BA
SiO_2	34.23	35.34	38.28	37.45	40.15	39.18	40.25	41.75	41.75	44.62
TiO_2	1.54	1.81	1.51	1.44	1.98	2.45	1.98	2.88	2.93	2.21
Al_2O_3	8.29	9.71	9.29	8.98	11.30	11.64	10.85	11.50	11.45	12.08
Fe_2O_3	4.10	3.14	2.58	2.76	5.37	4.63	4.91	4.36	4.62	4.44
FeO	5.42	5.74	6.10	6.42	4.69	5.84	5.34	6.10	5.92	5.35
MnO	0.17	0.21	0.18	0.20	0.16	0.16	0.15	0.17	0.17	0.14
MgO	18.42	14.18	17.47	17.04	14.53	13.88	13.17	10.74	10.38	12.56
CaO	16.65	18.32	14.59	15.17	13.25	12.86	12.29	12.88	12.59	8.06
Na_2O	0.87	2.96	3.16	3.48	2.00	3.55	4.90	3.73	4.00	3.19
K_2O	1.54	2.84	3.17	3.02	1.07	1.73	0.88	2.82	3.36	3.16
P_2O_5	1.10	2.33	1.37	1.52	1.15	1.08	1.60	1.15	1.04	0.60
L.O.I.	6.95	3.41	2.24	2.51	3.86	2.36	3.21	1.93	1.97	3.04
Total	99.28	99.99	99.94	99.99	99.51	99.36	99.53	100.01	100.00	99.45
V	165	220	232	302	224	266	196	217	217	284
Cr	676	402	642	723	498	538	426	320	325	474
Co	54	40	54	56	50	53	49	44	45	50
Ni	342	171	417	404	305	342	327	233	243	288
Zn	87	83	83	83	95	99	99	108	108	96
Rb	64	100	92	89	39	70	45	85	92	43
Sr	1910	1950	1470	1460	1370	1230	1360	1650	1640	1010
Ba	1720	3210	2290	2110	1620	1630	1970	1920	1940	1220
Th	27	-	-	-	14	11	13	-	-	11
Zr	173	239	218	302	186	229	166	276	267	207
Pb	10	22	19	12	10	8	10	19	8	11
Nb	101	158	100	104	86	101	89	113	111	36
Y	31	45.72	30.04	28.13	25	25	26	25.49	25.85	22
La	123.6	167.06	140.95	122.5	88.3	87	89.6	91.48	94.74	65.5
Ce	213.8	314.63	266.25	209.85	148.3	173	150.3	175.22	178.14	121.4
Nd	88.2	115.32	85.43	74	63.1	-	65.8	69.08	71.47	55
Sm	14.9	19.03	14.55	13.24	10.9	-	11.8	12.08	12.2	9.4
Eu	4.1	5.52	4.4	3.93	3	-	3.1	3.4	3.45	2.5
Gd	10.9	13.44	9.59	8.88	7.8	-	8.6	8.29	8.47	6.5
Dy	6.1	8.43	5.32	5.14	4.5	-	5.1	5.01	5.04	4
Er	2.5	3.3	2.22	2.08	1.9	-	2.1	1.96	1.91	1.7
Yb	1.5	2.58	1.72	1.55	1	-	1.3	1.33	1.35	1.1
Lu	0.2	0.36	0.25	0.25	0.14	-	0.19	0.18	0.21	0.15
Or	0.00	0.00	0.00	0.00	6.32	0.00	5.20	0.00	0.00	18.67
Ab	0.00	0.00	0.00	0.00	0.43	0.00	0.08	0.00	0.00	8.00
An	14.17	4.82	1.80	0.00	18.70	10.72	5.01	6.31	3.36	9.31
Lc	7.14	13.16	14.69	13.99	0.00	8.02	0.00	13.07	15.57	0.00
Ne	3.99	13.57	14.48	15.91	8.93	16.27	22.42	17.10	18.33	10.29
Ac	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00
Di	3.93	2.72	6.56	4.82	30.00	24.35	33.29	34.63	32.98	19.51
Ed	0.32	0.36	0.91	0.74	0.87	1.93	2.44	3.57	2.82	1.50
Di	4.25	3.07	7.47	5.57	30.87	26.29	35.73	38.19	35.79	21.02
Fo	30.87	23.87	28.36	28.17	15.61	16.31	12.17	7.50	7.40	15.58
Fa	3.22	3.98	4.96	5.50	0.57	1.64	1.13	0.98	0.80	1.52
Ol	34.09	27.85	33.32	33.67	16.18	17.95	13.30	8.47	8.20	17.10
Cs	17.28	20.72	16.15	18.05	0.00	3.89	0.00	0.49	2.10	0.00
Mt	5.94	4.55	3.74	3.97	7.79	6.71	7.12	6.32	6.70	6.44
Il	2.92	3.44	2.87	2.73	3.76	4.65	3.76	5.47	5.56	4.20
Ap	2.61	5.52	3.25	3.60	2.72	2.56	3.79	2.72	2.46	1.42
A.I.	0.37	0.82	0.93	1.00	0.39	0.66	0.83	0.80	0.89	0.72
D.I.*	11.12	26.73	29.17	29.97	15.69	24.29	27.70	30.16	33.90	36.96

Table 10 (continuation)

	11 LA3 PhTe	12 LM61 NeSy	13 LM54 NeSy	14 LM53 NeSy	15 LM1 NeSy	16 LM60 NeSy	17 LM80 TrPh	18 LM99 PPPh	19 LM67 PPPh	20 LM106 PPPh
SiO_2	46.10	50.45	53.48	55.81	56.23	57.57	60.06	54.94	54.01	55.88
TiO_2	1.53	1.34	0.84	0.79	0.65	0.44	0.28	0.38	0.45	0.20
Al_2O_3	17.55	17.87	19.31	20.18	19.98	20.42	19.75	21.03	19.59	21.04
Fe_2O_3	4.00	3.01	2.13	1.15	1.49	1.00	1.01	1.21	3.41	2.25
FeO	3.48	3.20	2.28	3.02	1.52	1.26	1.07	1.22	0.92	0.76
MnO	0.14	0.18	0.18	0.15	0.14	0.12	0.19	0.12	0.25	0.23
MgO	3.95	1.62	1.00	1.51	0.48	0.21	0.13	0.16	0.17	0.09
CaO	7.24	6.32	4.21	3.67	2.39	1.98	1.49	1.87	1.27	1.03
Na_2O	6.06	7.29	7.38	7.02	6.90	7.48	7.74	9.22	9.92	9.78
K_2O	4.07	5.26	5.79	5.97	6.77	6.96	5.99	6.71	7.02	6.05
P_2O_5	0.60	0.59	0.43	0.40	0.17	0.09	0.06	0.06	0.03	0.01
L.O.I.	4.90	2.87	2.97	0.34	3.28	2.48	2.22	3.08	2.97	2.67
Total	99.62	100.00	100.00	100.01	100.00	100.01	99.99	100.00	100.01	99.99
V	175	143	82	74	52	34	15	43	63	24
Cr	22	1	3	1	-	-	-	-	-	-
Co	24	12	10	7	4	2	-	3	2	2
Ni	18	14	18	14	15	14	14	12	14	16
Zn	84	96	84	91	2990	69	113	77	119	184
Rb	79	95	110	122	115	124	174	125	126	186
Sr	1270	2820	3630	3730	4320	3720	259	2200	1480	498
Ba	1660	2660	2860	2650	2990	2360	148	1260	966	38
Th	15	-	-	-	-	-	-	-	-	-
Zr	239	14	259	394	203	237	730	310	730	869
Pb	17	18	24	35	31	27	31	23	38	46
Nb	87	121	108	120	109	100	154	98	227	169
Y	22	31	24	29.98	29.09	19.44	29.11	21.03	24.24	24.48
La	94	153	156	151.7	147.57	106.79	187.71	130.58	110.01	183.66
Ce	176	252	234	246.49	231.57	167.5	284.44	186.75	202.39	247.55
Nd	-	-	-	75.05	67.12	44.78	65.18	39.98	54.79	42.39
Sm	-	-	-	11.09	10.46	6.35	8.56	5.75	7.87	5.54
Eu	-	-	-	2.77	3.41	1.8	1.83	1.6	1.83	1.52
Gd	-	-	-	7.21	6.73	4.01	5.44	3.93	5.02	3.95
Dy	-	-	-	4.65	4.23	2.83	3.82	2.82	3.4	2.65
Er	-	-	-	2.34	2.2	1.52	2.36	1.69	1.79	1.83
Yb	-	-	-	2.3	2.21	1.6	2.89	1.81	1.98	2.48
Lu	-	-	-	0.29	0.35	0.21	0.45	0.26	0.27	0.38
Or	24.05	31.08	34.21	35.28	40.00	41.13	35.40	39.65	41.48	35.75
Ab	9.48	15.36	22.83	25.59	27.94	29.10	42.87	17.13	9.60	22.40
An	8.67	0.50	2.46	5.92	3.55	1.59	1.46	0.00	0.00	0.00
Ne	22.64	25.09	21.46	18.32	16.49	18.52	12.25	29.09	28.21	28.24
Ac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.50	9.87	6.51
Ns	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	2.57	0.19
Di	17.08	8.70	5.37	4.37	2.58	1.13	0.70	0.86	0.91	0.48
Ed	1.24	2.84	2.58	3.62	1.40	1.85	1.92	3.45	2.65	2.81
Di	18.32	11.54	7.96	7.99	3.98	2.98	2.62	4.31	3.57	3.29
Wo	0.00	5.27	2.43	0.00	0.96	1.72	1.04	1.63	0.82	0.53
Fo	1.35	0.00	0.00	1.22	0.00	0.00	0.00	0.00	0.00	0.00
Fa	0.12	0.00	0.00	1.27	0.00	0.00	0.00	0.00	0.00	0.00
Ol	1.47	0.00	0.00	2.49	0.00	0.00	0.00	0.00	0.00	0.00
Mt	5.80	4.36	3.09	1.67	2.16	1.45	1.46	0.00	0.00	0.00
Il	2.91	2.54	1.60	1.50	1.23	0.84	0.53	0.72	0.85	0.38
Ap	1.42	1.40	1.02	0.95	0.40	0.21	0.14	0.14	0.07	0.02
A.I.	0.82	0.99	0.95	0.89	0.93	0.97	0.97	1.07	1.22	1.08
D.I.*	56.17	71.54	78.51	79.18	84.44	88.75	90.52	90.12	91.74	93.10

Table 10 (conclusion)

	21 LA97 PPh	22 LM76 PPh	23 LM19 PPh	24 LM112 PPh	25 LM3 PPh	26 LM46 PPh	27 LM88 PPh	28 LM25 PPh	29 LM83 PPh	30 LM37 PPh
SiO_2	57.09	59.91	57.93	59.23	57.88	58.54	58.21	58.87	58.37	58.66
TiO_2	0.36	0.22	0.13	0.20	0.26	0.12	0.19	0.10	0.20	0.11
Al_2O_3	19.97	20.11	20.95	20.80	20.93	20.99	21.02	21.17	20.88	20.85
Fe_2O_3	2.29	1.01	1.34	1.32	1.51	1.31	1.36	1.40	1.30	1.71
FeO	0.70	0.82	0.64	0.62	0.55	0.67	0.50	0.53	0.58	0.36
MnO	0.11	0.22	0.17	0.21	0.25	0.17	0.30	0.17	0.30	0.18
MgO	0.37	0.06	0.05	0.05	0.06	0.01	0.04	0.03	0.04	0.04
CaO	0.78	0.96	0.76	0.89	0.39	0.70	0.45	0.65	0.46	0.71
Na_2O	10.67	9.68	10.87	9.89	11.19	11.18	11.70	10.84	11.91	11.16
K_2O	5.01	5.51	5.58	5.79	4.80	5.46	5.02	5.32	5.01	5.33
P_2O_5	0.09	0.03	0.01	0.03	0.05	0.01	0.02	0.01	0.03	0.01
L.O.I.	2.55	1.48	1.57	0.97	2.12	0.84	1.19	0.93	0.92	0.88
Total	99.99	100.01	100.00	100.00	99.99	100.00	100.00	100.02	100.00	100.00
V	51	12	12	14	14	13	11	9	10	11
Cr	14	-	-	5	-	-	-	-	-	-
Co	5	2	2	2	2	4	-	3	-	3
Ni	18	13	11	15	13	15	11	19	12	16
Zn	94	142	133	147	196	130	185	139	195	147
Rb	122	208	203	168	196	219	289	222	296	222
Sr	310	71	30	108	65	27	19	32	19	21
Ba	293	55	29	48	54	2860	30	45	27	20
Zr	1840	1080	685	840	1160	787	1330	741	1340	911
Pb	25	35	39	36	45	35	45	36	44	49
Nb	626	175	90	165	298	111	254	108	255	123
Y	7.27	27.74	16.34	26.47	34.54	13.62	46.98	14.48	45.27	14.4
La	21.28	143.8	146.69	183.03	116.14	120.09	177.9	136.77	174.63	130.97
Ce	41.84	223.32	169.25	264.55	187.52	148.9	295.02	162.4	287.46	158.22
Nd	13.01	48.03	25.62	50.76	43.27	23.56	64.36	24.23	61.43	24.24
Sm	2.23	6.5	3.48	6.5	7.17	2.99	8.97	3.19	8.5	3.15
Eu	0.63	1.37	0.9	1.35	1.97	0.48	1.33	0.83	1.3	0.85
Gd	1.6	4.32	2.45	4.32	4.83	2.05	5.93	2.27	5.72	2.09
Dy	1.21	3.32	1.54	3.17	4.07	1.35	5.26	1.32	5.07	1.39
Er	0.7	2.26	1.24	2.13	2.73	1.08	3.61	1.11	3.5	1.09
Yb	0.79	3.03	1.96	2.75	3.87	1.66	5.14	1.73	4.95	1.74
Lu	0.12	0.47	0.35	0.38	0.58	0.26	0.74	0.31	0.74	0.26
Or	29.60	32.56	32.97	34.21	28.36	32.26	29.66	31.44	29.60	31.50
Ab	32.46	39.68	31.17	34.70	36.85	32.91	34.84	35.14	35.08	33.72
Ne	22.95	17.92	24.66	21.70	23.88	24.19	24.56	23.91	24.06	23.75
Ac	6.63	2.92	3.88	3.82	4.37	3.79	3.93	4.05	3.76	4.95
Ns	1.85	1.36	2.53	1.07	2.05	2.96	3.34	1.83	3.96	2.62
Di	1.47	0.32	0.27	0.27	0.20	0.05	0.17	0.16	0.15	0.21
Ed	1.24	2.92	2.40	2.25	1.21	2.54	1.68	2.11	1.69	1.53
Di	2.71	3.24	2.67	2.52	1.41	2.59	1.85	2.28	1.84	1.75
Wo	0.00	0.37	0.28	0.56	0.00	0.21	0.00	0.24	0.00	0.61
Fo	0.17	0.00	0.00	0.00	0.04	0.00	0.02	0.00	0.02	0.00
Fa	0.18	0.00	0.00	0.00	0.31	0.00	0.21	0.00	0.30	0.00
Ol	0.35	0.00	0.00	0.00	0.35	0.00	0.22	0.00	0.33	0.00
Il	0.68	0.42	0.25	0.38	0.49	0.23	0.36	0.19	0.38	0.21
Ap	0.21	0.07	0.02	0.07	0.12	0.02	0.05	0.02	0.07	0.02
A.I.	1.15	1.09	1.14	1.08	1.13	1.16	1.17	1.11	1.20	1.16
D.I.*	93.49	94.44	95.21	95.50	95.51	96.12	96.33	96.36	96.47	96.53

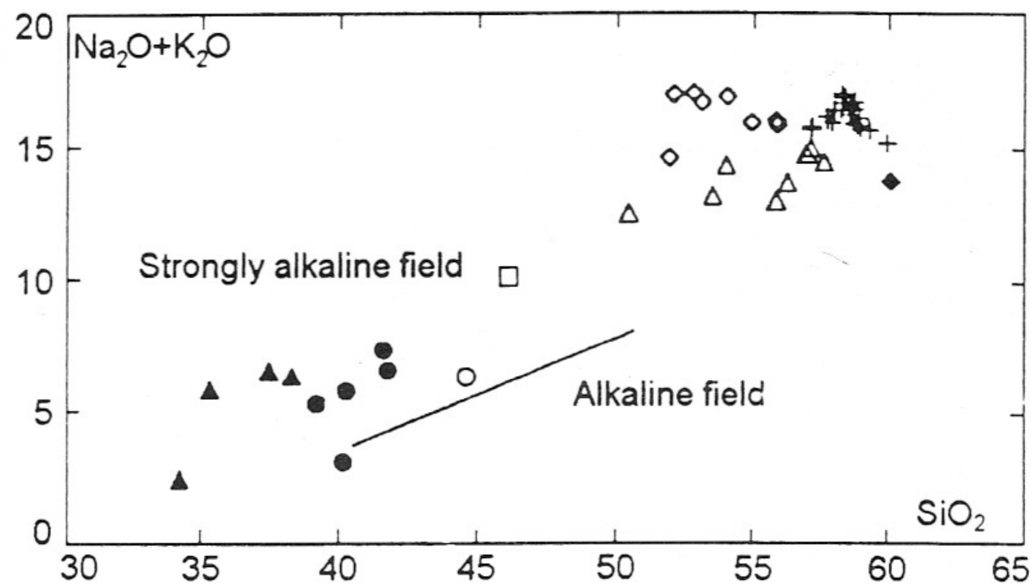

Figure 8 - Alkali-silica diagram of Lages alkaline rocks; field boundary according to Saggerson & Williams (1964). Symbols as in Fig. 3.

Ti-magnetite and apatite removal in the first steps of differentiation, followed by nepheline and finally by K-feldspar. This is particularly suggested by the K_2O, Ba and Sr increase up to about D.I.* = 90 and by the successive abrupt fall. Petrography and chemistry would also indicate the presence, among the cumulus phases, of phlogopite, amphibole and titanite, in some steps of the fractionation leading to peralkaline phonolites. Petrographic characters also point to the possible role of nepheline as liquidus phase in ON magmas.

The evolution lines are in accordance with the presence in many leucocratic rocks of minerals (biotite, amphibole, clinopyroxene and nepheline) generated from less evolved cogenetic melts.

Chondrite-normalized (Wood et al., 1979) REE field patterns of Lages silicatic rocks (Fig. 11) exhibit profile linear for OM, ON and BA and slightly to strongly concave for leucocratic types, the last one probably connected to fractionation of amphibole and titanite. REE patterns are in agreement with a primitive nature of OM, ON and BA and would suggest different degrees of partial melting from a homogeneous metasomatized source.

Bulk-rock chemistry, mineral chemistry and petrography would exclude evolved terms related to OM magmas.

The virtual absence of clinopyroxene as liquidus phase in Lages OM can be explained, on the basis of the experimental system 2Wo+Qz-Ne-Fo (Yoder, 1979), by the predominance of Fo+Ne components. The evolution of such liquids by the early crystallization of olivine leads to the subsequent cotectic crystallization of nepheline or melilite, together with olivine. The presence of phlogopite is evidence of high PH_2O and at the same time a complicating factor respect to the simplified experimental system. The relations for ON, in the same system, indicate that clinopyroxene and finally nepheline will form, after olivine, at the invariant point, in agreement with the observed petrographic data.

The links by fractional crystallization model, between basanites and peralkaline phonolites, has been checked in many alkaline volcanic complexes, such as Nyambeni Range in Kenya (Aurisicchio et al., 1983; Brotzu et al., 1983); Mount Erebus, Antarctica (Kyle et al., 1992); and Laacher See District, Germany (Worner & Schmincke, 1984). The same evolutive trend was also confirmed for the studied alkaline districts of Brazil, such as: Piratini, RS (Barbieri et al., 1987); Fortaleza, CE (Macciotta et al., 1990) and Juquiá, SP (Beccaluva et al., 1992).

Finally it must be noted that in PA4 basanite primary calcite has been found. This could suggest a CO_2-rich magma and a genetic relation of the Lages carbonatites with a basanitic parent as in the Juquiá alkaline-carbonatitic complex (Beccaluva et al., 1992).

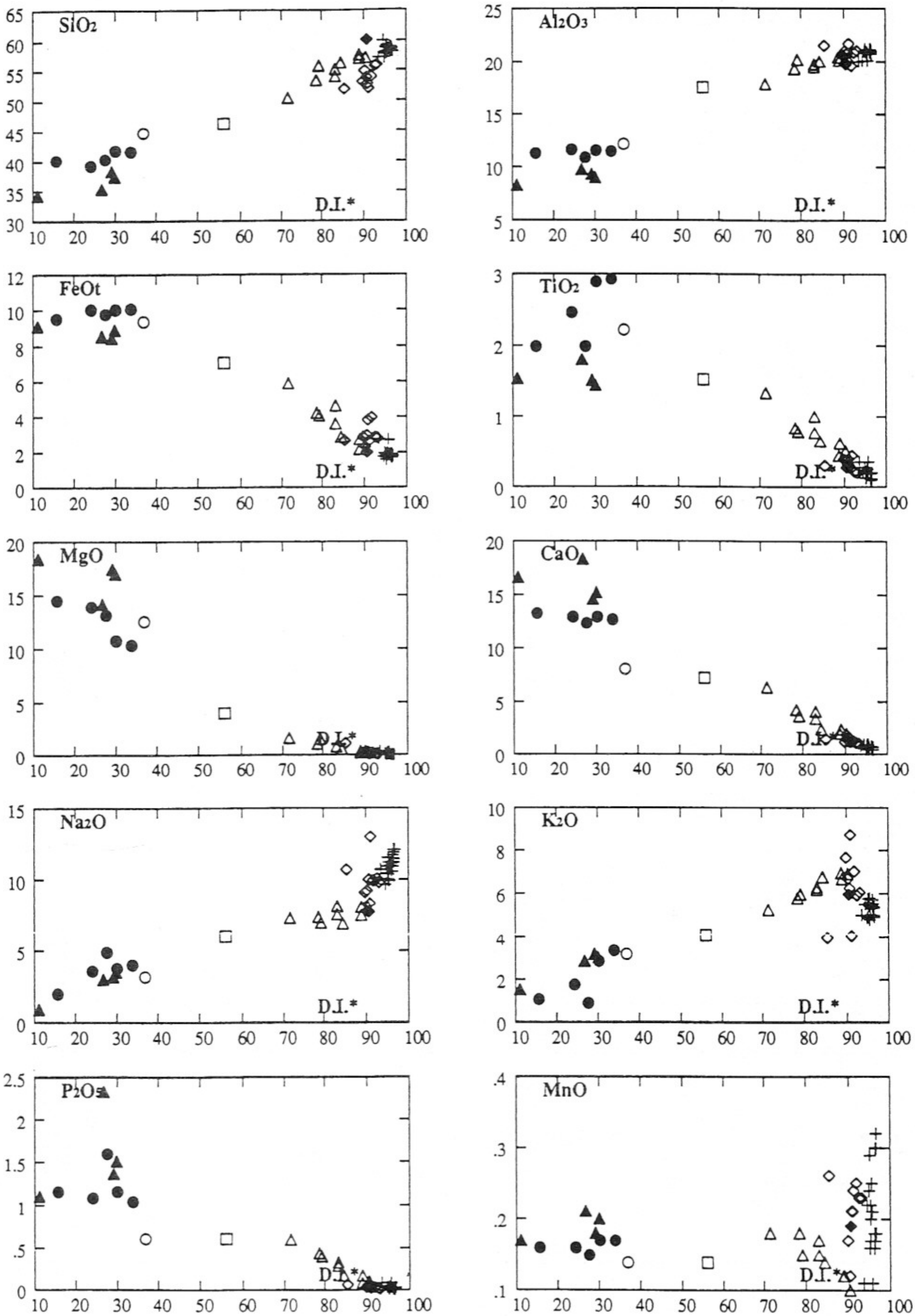

Figure 9 – Major elements vs. D.I.* diagrams for Lages alkaline rocks. Symbols as in Fig. 3.

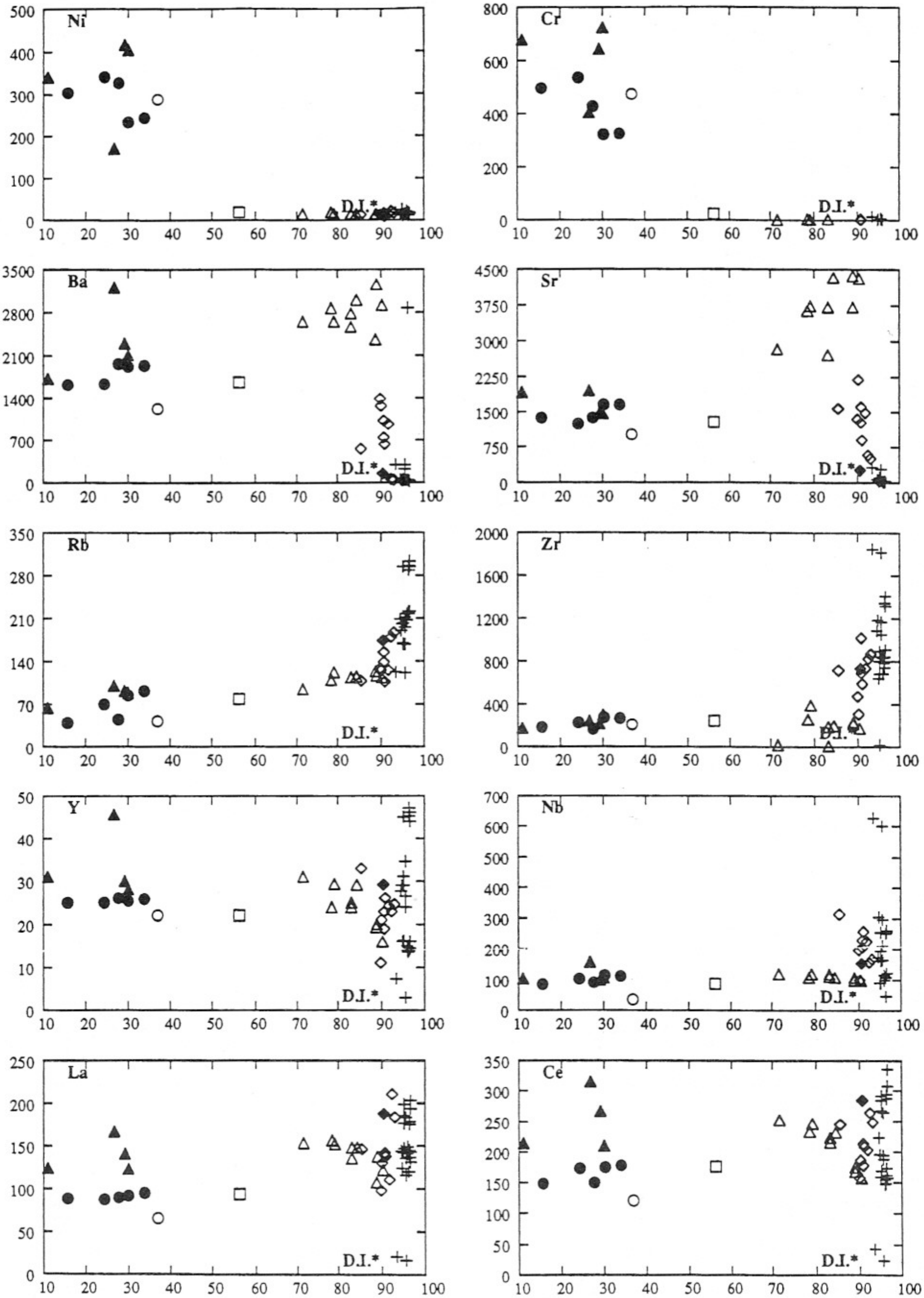

Figure 10 – Trace elements vs. D.I.* diagrams for Lages alkaline rocks. Symbols as in Fig. 3.

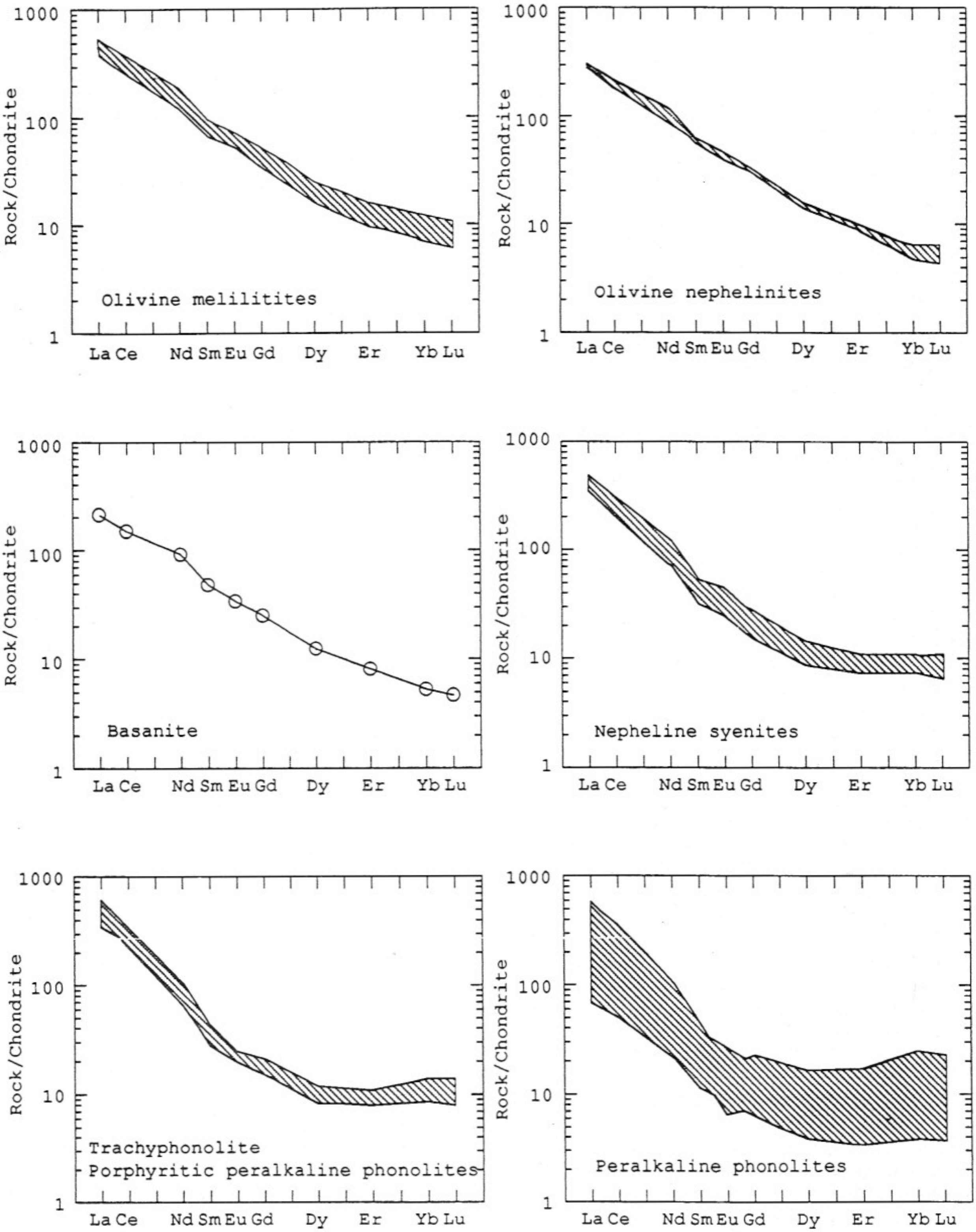

Figure 11 – Field patterns of chondrite-normalized (Boynton, 1984) REE for Lages alkaline rocks.

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APPENDIX

Olivine melilitites: PA1 - Rancho de Tábuas; LM6 and LM16 - Cerro Alto de Cima; LM98 - Palmeira.

Olivine nephelinites: LM115 - Chapada NW; LM116 - Chapada NE; LA29 - Parque das Pedras; LA70 - Pandolfo; PA3 - Rancho de Tábuas.

Basanite: PA4 - South Lages.

Phonotephrite: LA3 - East Lages.

Nepheline syenites: LM1, LM2, LM53, LM54, LM58, LM60, LM61 and LM63 - Cerro Alto de Cima.

Trachyphonolite: LM80 - Rio do Cadeado.

Porphyritic peralkaline phonolites: LM99, LM101 and LM103 - Serra da Farinha Seca; LM105 and LM106 - Lajeadinho; LM64, LM67 and LM73 - São Roque.

Paralkaline phonolites: LM111, LM112 and LM114 - Serra do Cadeado; LM3 and LM5 - Cerro Alto de Cima; LM93 and LM97 - Fazenda Nova do Tributo; LM19, LM23, LM24, LM25, LM27, LM36, LM37, LM38 and LM46 - Chapada; LM83, LM87, LM88, LM94 and LM95 - Tributo; LM76 - Rio do Cadeado.