

# Limeira and Indaiá Intrusions, Minas Gerais

By

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## INTRODUCTION

The Limeira and Indaiá intrusions, approximately 1.5 km apart, occur 20 km north of Monte Carmelo and 25 km west of Coromandel. (Fig. 1) The intrusions are emplaced into possible Archaen basement rocks consisting of granitic gneisses and schists. Within the region are mica schists and quartzites of the Proterozoic Araxá Group (Barbosa et al. 1970). Two separate bodies occur at each location and consist of chemically and petrographically distinct rocks which have similar isotopic signatures.

Previous brief descriptions of these intrusions, including geophysical aspects, have been provided by Svisero et al. 1980, 1984; Svisero and Haralyi 1984; Haralyi and Svisero 1984.

## LIMEIRA INTRUSION

The Limeira intrusion covers approximately 3.5 ha. The major portion is kimberlitic in nature and has a slightly elongated surface expression (200 m x 175 m) (Limeira I). Small spinel-bearing mantle xenoliths are common in this rock. A knoll, or hill, roughly 75 m in diameter occurs about 150 m immediately north of Limeira I and is formed by a fine grained alkalic rock (Limeira II). Surrounding Limeira II on all but the north side is a thin margin of fine grained breccia similar in constitution to Limeira II. (Fig. 2a)

## INDAIÁ INTRUSION

The Indaiá intrusion is 3.2 ha in size and consists of a relatively flat area of kimberlitic rock (Indaiá I) 200 m maximum size, similar to Limeira I and also containing

xenoliths, plus an associated satellite intrusion (Indaiá II) which forms a knoll about 90 m in diameter (Fig. 2b). The rock constituting Indaiá II is identical to that of Limeira II.

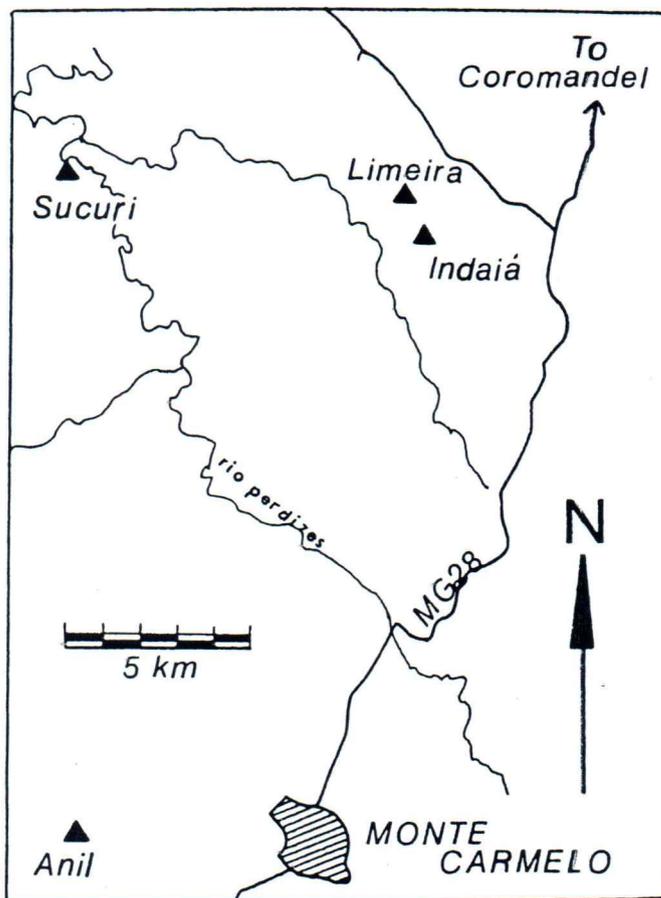


Figure 1 - General location map of the Limeira and Indaiá intrusions.

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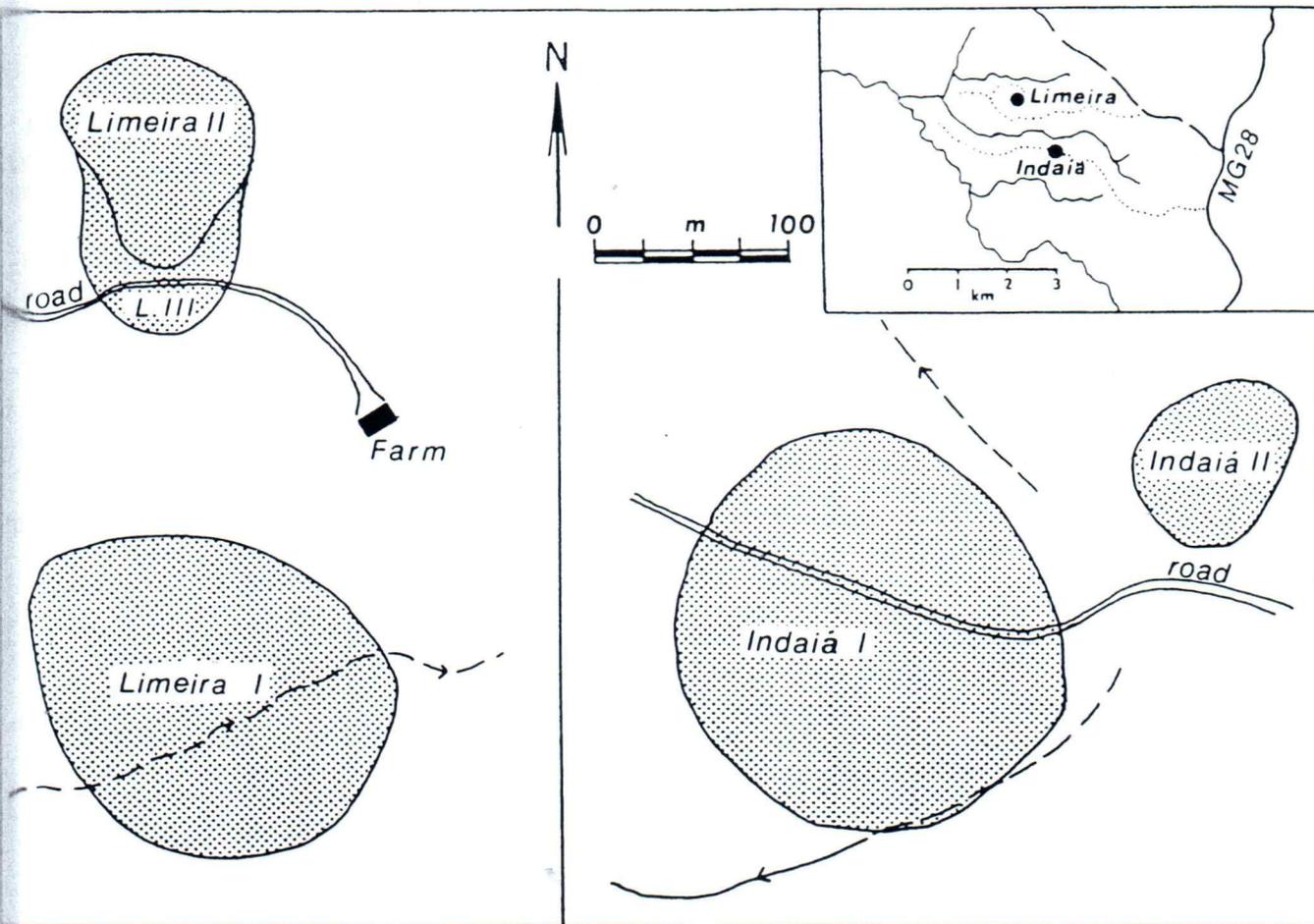


Figure 2 – General outline and relationship of the Limeira I and II, and the Indaiá I and II intrusions. The rock into which the intrusions were emplaced is mainly granites and granitic schists.

## CHEMISTRY

Bulk analyses of the rocks in the Limeira and Indaiá intrusions are provided in Table 1. In both major and minor oxides Limeira I and Indaiá I are similar but different to Limeira II and Indaiá II, which themselves are similar to each other.

Limeira I and Indaiá I are compositionally equivalent to kimberlite (Table 1). Mineralogical variation in modal olivine and calcite is the most likely cause of the slight variation in MgO and CaO between the two intrusions whereas the difference in Na<sub>2</sub>O may be attributed to inhomogeneity in sampling (Mitchell 1986). Both rocks are undersaturated and ultrabasic (SiO<sub>2</sub> 28 wt.%) with Al<sub>2</sub>O<sub>3</sub> contents of 2 wt.%, [Na<sub>2</sub>O/K<sub>2</sub>O] and (Na<sub>2</sub>O + K<sub>2</sub>O)/Al<sub>2</sub>O<sub>3</sub>, and the rocks are miassic.

The satellite intrusions (Limeira II and Indaiá II) are chemically distinct to Limeira I and Indaiá I and kimberlites in general. They are mildly potassic and contain significantly more SiO<sub>2</sub> (42 wt. %), Al<sub>2</sub>O<sub>3</sub> (7 wt. %) and (Na<sub>2</sub>O and K<sub>2</sub>O), but less MgO, P<sub>2</sub>O<sub>5</sub> and possibly FeO than their larger neighbors. Chemically Limeira II and Indaiá II resemble ugandite (Holmes 1956).

Table 1 – Chemical analyses of rocks constituting the Limeira and Indaiá intrusions, Minas Gerais.

	Limeira I	Indaiá I	Limeira II	Indaiá II
SiO <sub>2</sub>	29.2	27.3	42.4	41.5
TiO <sub>2</sub>	2.62	2.54	2.71	2.99
Al <sub>2</sub> O <sub>3</sub>	1.87	2.09	7.44	6.90
Cr <sub>2</sub> O <sub>3</sub>	0.42	0.38	0.21	0.15
FeO	10.1	10.5	8.77	9.55
MgO	28.3	26.6	13.1	13.5
CaO	11.3	13.2	12.5	12.8
Na <sub>2</sub> O	0.76	0.25	2.30	1.40
K <sub>2</sub> O	0.96	0.74	2.69	2.04
P <sub>2</sub> O <sub>5</sub>	2.13	2.61	1.36	1.42

Rare Earth Element contents when normalized to chondrite values show a similar distribution pattern for all four rocks (Fig. 3). The pattern shows an enrichment in LREE similar to many other alkalic rocks, including kimberlites and lamproites.

## PETROGRAPHY

*Limeira I and Indaiá I:* These rocks appear to be hypabyssal macrocrystal kimberlites consisting of rounded macrocrysts and subhedral phenocrysts of

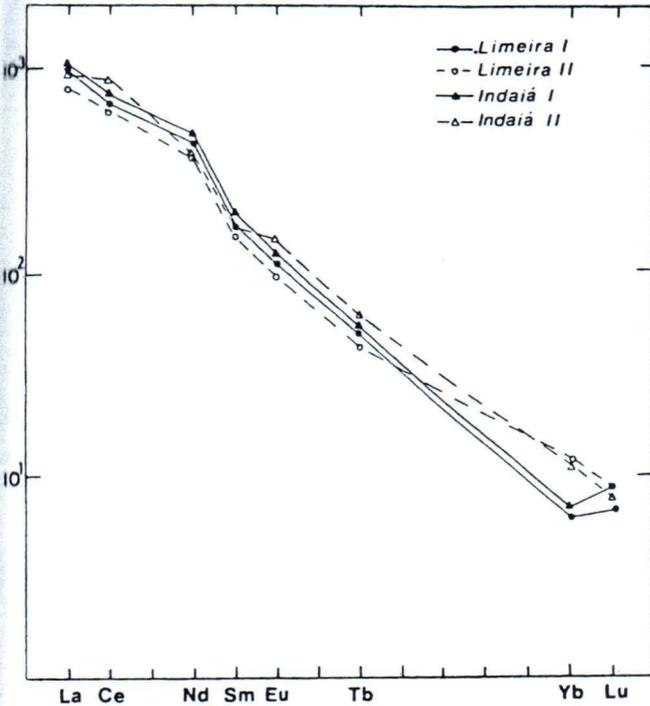


Figure 3 - Rare Earth Element abundances relative to chondrite model for Limeira and Indaiá rocks.

olivine, macrocrysts of green diopside, Mg-ilmenite, altered phlogopite and chromite, set in a groundmass of serpentine, calcite, perovskite, apatite, monticellite and spinel. This assemblage is typical of Group I kimberlites (Smith 1983). Small xenoliths of dunite, harzburgite, and spinel lherzolite are common (Meyer 1988) and display the mineralogical effects of metasomatism similar to xenoliths from kimberlites in southern Africa (Erlank et al. 1987). In addition to the above xenoliths, clasts (5 mm) of calcite occur. Garnets, having compositions similar to those from kimberlite, have been reported from concentrate.

*Limeira II and Indaiá II:* These rocks consist of macrocrysts and microphenocrysts of olivine in a fine grained, flow textured groundmass of small thin clinopyroxene laths, in which larger spinels, perovskite, apatite and Mg-ilmenite are present. Small plates of phlogopite in the groundmass poikilitically enclose pyroxene, spinel and perovskite. Also present are irregular schlieren which consist of low alumina clinopyroxene and rectangular plates of nepheline in a yellow-brown intersertal glass. The schlieren appear to be the result of magma flow. They resemble clasts which have been drawn-out, and pyroxene laths in the groundmass flow around the schlieren in a somewhat trachytic type of texture.

## MINERAL CHEMISTRY

Representative analyses of most minerals are presented in Tables 2, 3, 4 and 5.

Table 2 - Representative analyses of minerals in Limeira I and Indaiá I.

	Olivine		Ilmenite		Mica		Ilmenite		Spinel			
	1	2	3	4	5	6	7	8	9	10	11	12
SiO <sub>2</sub>	39.60	39.70	37.10	38.00	42.50	42.20	0.24	0.05	0.24	0.26		
TiO <sub>2</sub>	0.00	0.05	0.06	0.07	1.64	1.07	52.90	51.90	52.30	14.60	25.12	13.12
Al <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.04	0.05	10.20	10.02	0.14	0.47	0.20	0.89	0.86	1.91
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.03	0.01	0.01	0.23	0.10	2.13	2.16	2.46	2.79	2.60	2.57
FeO	11.20	15.40	2.97	2.95	6.41	7.02	30.40	30.50	28.70	63.80	50.55	61.95
MgO	48.50	45.20	24.70	25.40	24.00	23.10	12.90	12.70	14.10	13.40	17.83	18.32
CaO	0.04	0.09	33.40	33.20	0.00	0.00	0.07	0.22	0.05	0.17	1.15	0.28
MnO	0.20	0.20	0.57	0.67	0.02	0.04	0.54	0.61	0.71	1.26	1.21	1.20
NiO	0.29	0.23	0.11	0.07	0.00	0.10	0.00	0.25	0.03	0.13		
Na <sub>2</sub> O	0.00	0.00	0.00	0.07	0.35	0.28	0.00	0.14	0.18	0.26		
K <sub>2</sub> O	0.02	0.01	0.01	0.04	10.10	10.40	0.00	0.05	0.00	0.02		
P <sub>2</sub> O <sub>5</sub>			0.15									
Total	99.85	100.91	99.12	100.53	95.45	94.33	99.32	99.05	98.97	97.58	99.32	99.35

Analyses: 1, 3, 7, 9, 10 are from Limeira I and 2, 4, 5, 6, 8, 11 and 12 from Indaiá I

**Table 3** – Representative perovskite analyses from Limeira I and II.

	1	2	3	4
SiO <sub>2</sub>	0.08	0.03	0.05	0.01
TiO <sub>2</sub>	54.30	54.80	53.50	53.70
FeO	1.45	1.39	2.02	2.30
CaO	35.90	36.50	37.60	37.40
SrO	0.44	0.45	0.55	0.52
La <sub>2</sub> O <sub>3</sub>	1.21	0.99	0.81	0.95
Ce <sub>2</sub> O <sub>3</sub>	3.00	2.90	2.48	2.74
Nd <sub>2</sub> O <sub>3</sub>	1.14	1.03	1.02	1.02
Sm <sub>2</sub> O <sub>3</sub>	0.08	0.00	0.00	0.03
Gd <sub>2</sub> O <sub>3</sub>	0.37	0.30	0.22	0.30
Nb <sub>2</sub> O <sub>5</sub>	0.70	0.66	0.32	0.32
Total	98.67	99.05	98.57	99.29

Analyses 1 and 2 from Limeira I; Analyses 3 and 4 from Limeira II.

**Table 4** – Representative analyses of minerals in Limeira II and Indaiá II.

	Olivine		Pyroxene		Mica		Spinel			
	Core 1	Rim 2	3	4	5	6	7	8	9	10
SiO <sub>2</sub>	41.10	42.00	52.60	51.90	38.30	38.40				
TiO <sub>2</sub>	0.07	0.09	1.04	1.66	5.73	6.10	13.81	4.55	3.83	15.60
Al <sub>2</sub> O <sub>3</sub>	0.06	0.00	0.32	0.54	11.10	11.00	1.16	3.86	3.98	0.96
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.00	0.13	0.08	0.00	0.03	3.34	53.09	44.30	1.00
FeO	8.31	11.20	4.03	4.89	5.54	5.67	63.07	27.04	40.50	75.73
MgO	50.00	47.80	16.30	15.40	21.80	21.60	11.85	10.91	5.96	4.53
CaO	0.09	0.18	23.90	22.70	0.00	0.00	4.19	0.1	0.18	0.28
MnO	0.14	0.16	0.08	0.21	0.06	0.08	1.19	0.6	0.97	1.08
NiO	0.44	0.29	0.00	0.03	0.04	0.01				
Na <sub>2</sub> O	0.06	0.06	0.86	1.10	0.28	0.31				
K <sub>2</sub> O	0.00	0.00	0.07	0.01	8.79	9.00				
BaO					4.01	3.18				
F					2.95	2.76				
Total	100.27	101.78	99.33	98.52	98.60	98.14	98.61	100.5	99.72	99.18

Analyses 1, 2, 3, 5, 7, 8 are from Limeira I; 4, 6, 9, 10 are from Indaiá II.

**Table 5** – Representative analyses of glass, nepheline and diopside in schlieren in Limeira II and Indaiá II

	Glass		Nepheline	Diopside	
	1	2	3	4	5
SiO <sub>2</sub>	40.30	42.10	41.60	53.30	53.50
TiO <sub>2</sub>	1.41	2.22	0.02	0.93	0.77
Al <sub>2</sub> O <sub>3</sub>	9.56	10.40	29.30	0.37	0.18
Cr <sub>2</sub> O <sub>3</sub>	0.05	0.00	0.00	0.05	0.09
FeO	17.60	15.40	3.91	3.87	3.81
MgO	11.20	9.75	0.54	16.30	16.50
CaO	1.22	0.77	0.00	24.20	23.80
MnO	0.41	0.45	0.01	0.16	0.14
NiO	0.02	0.00	0.02	0.04	0.00
Na <sub>2</sub> O	0.24	0.12	15.10	1.05	0.76
K <sub>2</sub> O	6.06	4.66	8.97	0.03	0.03
BaO	0.04	0.05	0.01	0.00	0.00
F	0.06	0.00	0.01	0.00	0.00
Total	88.17	85.92	99.49	100.30	99.58

## 1. Limeira I and Indaiá I

**Olivine:** Macrocrystal olivine (2 - 6 mm) is usually angular whereas olivine grains between 1 and 0.15 mm are often euhedral. There appears to be no difference in Mg/[Mg + Fe] between macrocrystal and microphenocrystal olivine and all range between 0.92 and 0.84; similar to the range for olivine in the spinel xenoliths. Minor element contents are low and TiO<sub>2</sub> contents range from 0 to 0.07 wt.%, the higher values occurring in olivine with lower MgO. Olivine constitutes about 30 - 35 % of the rock.

**Mica:** Macrocrysts of phlogopite up to 1.5 mm in size occur but for the most part have been pseudomorphed by calcite and serpentine although occasional cores remain. TiO<sub>2</sub> and FeO contents are generally lower and higher respectively when compared with mica in the xenoliths. No mica was recognized in the groundmass.

**Ilmenite:** Magnesian ilmenite (12 - 18 wt.% MgO, 2 - 4 wt.% Cr<sub>2</sub>O<sub>3</sub>) is common and ranges in size between 1 and 0.1 mm. Most grains appear rounded but when examined in detail have ragged margins due to replacement by perovskite and spinel.

**Spinel:** Orange red angular macrocrysts of aluminous magnesian chromite are present. These differ in chemical composition to the ubiquitous spinels that are present in the groundmass. These latter spinels average 0.05 mm in size and may be either euhedral or rounded; no atoll spinels have been recognized. Compositionally spinel has Al<sub>2</sub>O<sub>3</sub> 2 wt.%, MgO 11 - 14.3 wt.% and TiO<sub>2</sub> 6 - 19 wt.%. The cores of some grains often have higher Cr<sub>2</sub>O<sub>3</sub> than the margins (40 wt.% versus 1 wt.%), but TiO<sub>2</sub> and FeO<sub>T</sub> are the reverse. The overall trend of spinels is similar to trend I of Mitchell (1986) and is from titanian chromites to magnesian ulvospinel - ulvospinel - magnetite (MUM) at Mg/[Mg + Fe] of 0.3 and 0.4 for Limeira I and Indaiá I respectively.

**Perovskite:** Perovskite, 0.05 to 0.1 mm, is a groundmass phase and occurs both as euhedral grains with a rhombic of rectangular shape and as small fragments. It has high concentrations of La, Ce and Nd (Table 3).

**Monticellite:** Monticellite occurs in the groundmass as small lath shaped crystals 0.1 mm in size. FeO varies between 2.5 to 4 wt. % and rarely up to about 9 wt. %.

## 2. Limeira II and Indaiá II

In contrast to Limeira I and Indaiá I both Limeira II and Indaiá II are much finer grained.

**Olivine:** Olivine phenocrysts are generally between 0.5 and 0.25 mm in size and are usually angular in shape. Some have a large clear central core surrounded by a mantle. Irregular brownish/yellow blebs occur at the junction between core and mantle. Olivine in Limeira II have cores with Mg/[Mg + Fe] of 0.92 and margins of

0.88, whereas in Indaiá II the cores and margins are 0.87 and 0.90 respectively. In Indaiá II olivine also occurs as small (0.05 mm) anhedral grains and have compositions similar to the margins of the larger phenocrysts.

**Clinopyroxene:** The major groundmass phase in both Limeira II and Indaiá II is clinopyroxene which occurs as a mass of felty lath shaped crystals (0.005 mm wide by 0.05 mm long) often showing a flow texture. The clinopyroxene is diopside in composition with relatively high contents of TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Na<sub>2</sub>O. Pyroxene with lower contents of Al<sub>2</sub>O<sub>3</sub> also occurs in association with glass and nepheline in the irregular schlieren which are a feature of both these rocks.

**Mica:** Mica occurs as irregular to rectangular plates, up to 0.5 mm in size (average 0.2 mm), of phlogopite that poikilitically enclose groundmass pyroxene, spinel, and perovskite. Compositionally similar mica occurs as plates enclosing nepheline and clinopyroxene in the schlieren with glass. The phlogopite has a high TiO<sub>2</sub> content of about 7 wt.%, Al<sub>2</sub>O<sub>3</sub> of 11 wt.%, and Mg/[Mg + Fe] of 0.86. BaO and F are also important constituents.

**Spinel:** Spinel occurs as a groundmass phase and occurs in grains that are small and irregular (0.02 to 0.1 mm). Cores are equivalent to titanian magnesian chromites and may be replaced in whole or part by mantles of titanomagnetite containing minor ulvospinel. There is possibly a compositional gap between core and mantle. These spinels appear to be highly evolved and contain between 1 and 2 wt.% MnO, and Fe/[Fe + Mg] of about 0.9).

**Perovskite:** Perovskite, in the same size range as spinel (0.02 to 0.1 mm), has high contents of HREE. However, on average La, Ce and Nd, as well as Nb, occur in lower concentrations than the perovskite in Limeira I and Indaiá I (Table 3).

**Schlieren:** A feature of Limeira II and Indaiá II are schlieren in which occur pyroxene, nepheline, mica and glass. The pyroxene is diopside and is low in Al<sub>2</sub>O<sub>3</sub> (ca. 0.3 wt.%) and TiO<sub>2</sub> (ca. 1.0 wt.%) compared with diopside laths which forms the felty groundmass. Nepheline occurs as square to rectangular grains and contains about 9 wt.% K<sub>2</sub>O and 5.5% Fe<sub>2</sub>O<sub>3</sub>. The associated yellow-brown glass is ultrabasic in composition (SiO<sub>2</sub> 41 wt.%) and contains MgO (10 wt.%), FeO (16 wt.%), Al<sub>2</sub>O<sub>3</sub> (10 wt.%) and K<sub>2</sub>O (6 wt.%). CaO contents are generally less than 1 wt.% (Table 5).

## ISOTOPE CHEMISTRY

Whole rock Rb/Sr and Nd/Sm isotopic data have been obtained (Fig. 4). Limeira I and Indaiá I have initial <sup>87</sup>Sr/<sup>86</sup>Sr values of 0.705 and Limeira II and Indaiá II have 0.706. The initial <sup>143</sup>Nd/<sup>144</sup>Nd value is the same for

all rocks and is 0.5122. Although chemically and mineralogically Limeira I and Indaiá I are equivalent to Group I kimberlites, the isotopic signature based on Sr and Nd systematics falls between Group I and Group II (Smith 1983). Limeira II (and probably Indaiá II), also falls between Group I and Group II kimberlites.

All rocks have been derived from a slightly enriched source relative to bulk earth, and interestingly lie within or close to the envelope (Fig. 4) defined by data for high phosphorus and titanium (HPT) Parana basalts.

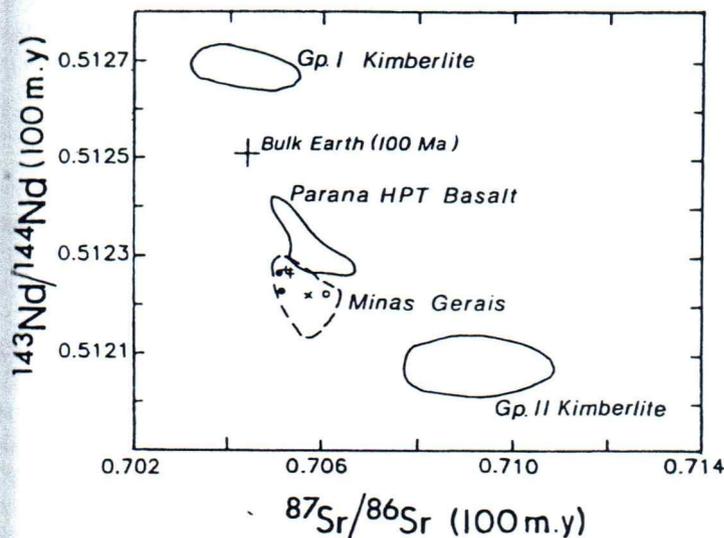


Figure 4 -  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  values for some rocks from Minas Gerais. Solid circles - Limeira and Indaiá I; Open circle - Limeira II; + 's - Pantano; X - Canas.

## XENOLITHS

Xenoliths occur in Limeira I and Indaiá I but are rare to absent in the satellites intrusions Limeira II and Indaiá II. The xenoliths are small (0.5 to 5 cm) and consist of dunite, harzburgite and lherzolite. To date only spinel-bearing xenoliths have been found - no garnet-bearing ones have been discovered.

Texturally the xenoliths include coarse granular, mosaic-porphroclastic and mosaic (Harte 1977); the latter consisting entirely of neoblasts of olivine. A number of the xenoliths shows evidence of mineral replacement and alteration equivalent to the patent (Dawson 1984) and modal (Harte 1983) metasomatism and similar to that recorded in xenoliths from kimberlites in southern Africa (Erlank et al 1986). Representative mineral analyses are presented in Table V.

One of the commonest minerals occurring in the xenoliths is phlogopite. In some of the xenoliths this mineral has the textural and chemical characteristics of primary metasomatic mica (Carswell 1985). In other

xenoliths the mica is replacing diopside and enstatite, preferentially before olivine. Finally, phlogopite also occurs with magnesian chromite in symplectic intergrowths of two distinct types. One is in the form of the classic "fingerprint" texture whereas the second consists of a "nest" of plates of phlogopite and associated chromite. This latter texture appears to be most common in olivine-rich xenoliths (dunites and harzburgites). Often associated with the phlogopite/spinel intergrowths is a greenish metasomatic diopside which is enriched in Na, Al and Cr relative to other diopside that is a primary constituent of the original rock. In one xenolith aggregates of spinel, mica and monticellite are present.

## SUMMARY

Chemically, petrographically and mineralogically the Limeira I and Indaiá I intrusions resemble Group I kimberlites but isotopically (Sr and Nd systematics) they are distinct from both Group I and Group II kimberlites. The satellite intrusions, Limeira II and Indaiá II although having similar isotopic signatures to Limeira I and Indaiá I are chemically different to any known kimberlite. However, bulk chemical analyses of these rocks are comparable to ugandite from Katwe, in the Toro-Ankole volcanic field, Uganda, (Holmes 1956; Holmes and Harwood, 1932). The presence of K-bearing nepheline in Indaiá II lends credence to this association.

Mineralogically Limeira II and Indaiá II contain several similar minerals (i.e olivine, Mg-ilmenite, pyroxene, perovskite, spinel) to the larger intrusions (Limeira I and Indaiá I). However, the schlieren which contain glass and nepheline are unique to Limeira II and Indaiá II and are absent in Limeira I and Indaiá I. Many of the other small intrusions in western Minas Gerais also contain similar assemblages of minerals and similar isotopic signatures but differ in petrographic characters. It is possible that many of the intrusions are genetically related and form a continuum of rock chemistries and petrographic types. It is possible that in western Minas Gerais exists a province of kamafugitic rocks. The source of the magmas may be similar to that of the HPT Paraná basalts (115-140 m.y.) which pre-date the intrusions, although radiometric ages for the intrusions are limited. The relationship, if any, of the major carbonatites (ca. 80-85 m.y.) in the area to the intrusions also needs clarification and further investigations are warranted.

## ACKNOWLEDGEMENTS

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