The Serra do Bueno potassic diatreme: a possible hypabyssal equivalent of the ultra-mafic alkaline volcanics in the Late Cretaceous Alto Paranaíba Igneous Province, SE Brazil

S. A. Gibson, R. N. Thompson

Department of Geological Sciences, University of Durham, Durham, DH1 3LE, UK

O. H. Leonardos

Departmento de Geoquimica e Recursos Minerais, Instituto de Geociencias, Universidade de Brasilia, 70910 Brasilia DF, Brazil

S. E. Turner

Department of Earth Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA, UK

J. G. Mitchell

Department of Physics, The University, Newcastle upon Tyne, Newcastle NE1 7RU, UK

AND

A. P. Dickin

Department of Geology, McMaster University, 1280 Main Street West, Hamilton, Ontario, L8S 4M1, Canada

Abstract

Cretaceous, strongly alkaline mafic igneous provinces occur around the margins of the Ordovician to Cretaceous Paraná sedimentary basin of southern Brazil. The Serra do Bueno diatreme is situated in the southern portion of the largest of these alkaline provinces, the Alto Paranaíba Igneous Province in Minas Gerais. The well-exposed diatreme crops out close to the south-west surface limit of the São Francisco craton and is adjacent to several other poorly exposed ultramafic alkaline pipes, previously described variously as kimberlites (Barbosa, 1991) and lamproites (Ramsay and Tompkins, in press). The diatreme has two distinct facies: (1) a crater facies dominated by lapilli tuffs; and (2) a magmatic hypabyssal facies formed by a relatively fresh ultramafic (MgO = 15 wt.%) potassic (K_2O/Na_2O = $\sim$1.5) intrusion that contains xenoliths of meta-sediments, feldspathic gneiss and dunite. It is massive and porphyritic, with large olivine phenocrysts (Fo_{87}) and smaller crystals of diopside ($Ca_{50}Mg_{44}Fe_6$), phlogopite, perovskite, ilmenite and zeolites in a fine-grained groundmass that contains altered leucite and up to 20% devitrified glass. The Serra do Bueno intrusion shows a strong enrichment in light relative to heavy rare earth elements, with La/Yb of $\sim$85. Its initial $^{87}Sr/^{86}Sr$ (0.705176) and $^{143}Nd/^{144}Nd$ (0.512312) isotopic ratios are similar to those of other intrusions (e.g. Limeira 2) and lavas (e.g. Presidente Olegário) in the Alto Paranaíba Igneous Province. This suggests that these Late Cretaceous alkaline magmas were all derived from a similar source, predominantly within the sub-continental lithospheric mantle.

Laser $^{40}Ar/^{39}Ar$ analyses have yielded an isochron of 90 $\pm$ 4 Ma for the Serra do Bueno intrusion. This age is higher than the corresponding K/Ar bulk-rock age for the same sample but similar to K/Ar

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ages determined on mica separates from both intrusive and extrusive rocks in the Alto Paranaíba Igneous Province.

KEYWORDS: diatreme, potassium, alkaline volcanics, Serra do Bueno, Brazil.

Introduction

ULTRAMAFIC alkaline rocks, such as kimberlites and lamproites, are characteristic of magmas generated within and adjacent to the cratonic regions of the earth's continental lithosphere. The low temperature, volatile-rich melts forming these rocks are volumetrically insignificant, but they typically exhibit extreme enrichments of incompatible trace elements. This feature, together with their low liquidus temperature and small volumes, makes them less susceptible than other magma types to open-system post-genesis processes, such as crustal contamination. The current general concensus is that they are derived by heating and/or thinning of the sub-continental lithospheric mantle (e.g. Ellam and Cox, 1991; Gibson *et al.*, 1993; Hawkesworth *et al.*, 1986; Marsh, 1987; Peate *et al.*, 1990; Thompson *et al.*, 1990). As such they are important geochemical indicators of the lithospheric melts that are thought by many investigators to dominate the incompatible element and Sr, Nd and Pb isotope chemistry of continental flood basalts (e.g. Carlson, 1991; Ellam and Cox, 1991; Hawkesworth *et al.*, 1988; McDonough, 1990).

During the Cretaceous, alkaline magmatism was widespread in southern Brazil and Paraguay, around the margins of the Paraná Basin. This long-lived major structure has a history of multiphase extension between Late Ordovician and Late Cretaceous times (Zalan *et al.*, 1987). Recently, the emphasis on Cretaceous magmatism in this area has tended to concentrate on the vast outpourings of tholeiitic magma that comprise the Paraná flood basalts, the Serra Geral Formation (e.g. Bellieni *et al.*, 1986; Piccillero *et al.*, 1988; Hawkesworth *et al.*, 1988; Peate *et al.*, 1990), whose distribution seems to have been controlled by the lithospheric 'thinspot' of the Paraná sedimentary basin (Thompson and Gibson, 1991). In Brazil and Paraguay the alkaline magmas both pre- and post-date the eruption of the Paraná flood basalts. The largest region of Brazilian Cretaceous alkaline magmatism is in Alto Paranaíba Igneous Province (APIP) of Minas Gerais and Goias (Fig. 1). This province is composed of a wide range of magma types (Svisero *et al*, 1984; Leonardos and Meyer, 1991) ranging from carbonatites (e.g. Tapira, Araxá) to kimberlites (e.g. Limeira, Indaiá and Três Ranchos) and ultramafic potassic rocks (e.g. Presidente Olegário). These outcrop as dykes, pipes, diatremes, lava flows and pyroclastic deposits. Serra do Bueno is located in the southern portion of the province, in the Bambuí region close to several Cretaceous ultramafic potassic pipes (Almeida, Boa Esperança, Cana Verde, Inga and Quarteis; Barbosa *et al.*, 1970). Detailed published descriptions of the petrology of individual units of the APIP are uncommon. Here we give the first account of an important locality at the southern end of the region.

General geology

The Serra do Bueno diatreme is located 200 km west of Belo Horizonte, Minas Gerais (Fig. 1). It forms a roadside outcrop for a distance of approximately 100 m, beside the BR262, 22 km east of the junction with the BR354 (46°03′ 19°43′; Fig. 2). The diatreme is located in the southern portion of the APIP which covers an area of 10^5 km^2, extending from Coromandel in the north to Bambuí in the south (Fig. 1). This province is closely associated with the Alto Paranaíba arch which is a structural and gravity high that developed during the Cretaceous (Costa and Sad, 1968). The arch separates the Paraná Basin to the south-west from the São Franciscan Basin to the north-east and is defined by large northwest/southeast trending tholeiitic dykes,similar in composition to the basalts of the Serra Geral Formation (our unpubl. data)

The ultramafic alkaline rocks in the Bambuí region are situated close to the present day, southwest surface limit of the Archaean São Francisco craton (Fig. 1). Although the western boundary of this craton is not at all well-defined, due to masking by Proterozoic rocks, gravity studies by Almeida *et al.* (1980) and Pires (1986) suggest that the whole of the APIP lies well within the limits of the craton. This is reinforced by the recent discovery of a garnet lherzolite xenolith in the west of the province, at Três Ranchos, which appears to have equilibrated at depths of around 150 km (Leonardos *et al.*, 1993).

Field characteristics

The Serra do Bueno diatreme is emplaced into flat-lying green and red metamorphosed sandstones and shales of the Proterozoic Bambuí

Group (Fig. 3). The igneous structure is separated from the surrounding country rocks by sharp discordant contacts. The good exposure at this locality has allowed us to identify two different facies within the diatreme:

(1) Tuffaceous deposits that are rather weathered. These show evidence of parallel stratification but no signs of cross-stratification. The layers are typically between 50–70 cm thick and composed of rounded lapilli 1–2 cm in diameter. Relics of serpentinized olivines are also present amongst the lapilli. Some layers contain larger clasts up to 8 cm in diameter. These deposits are similar to those observed in the crater facies of ultramafic vents (Dawson, 1980; Lorenz, 1985; Smith and Lorenz, 1989).

(2) A dominantly magmatic hypabyssal facies consisting of a dyke-like structure which cross-cuts the adjacent tuffaceous deposit to the west and Bambuí Group sediments to the east (Fig. 3). The intrusion appears to have been emplaced asymmetrically with respect to the overall structure of the diatreme. It is relatively fresh and is formed by a massive, ultramafic, porphyritic rock that has large olivine phenocrysts and very small phlogopites. Xenoliths of

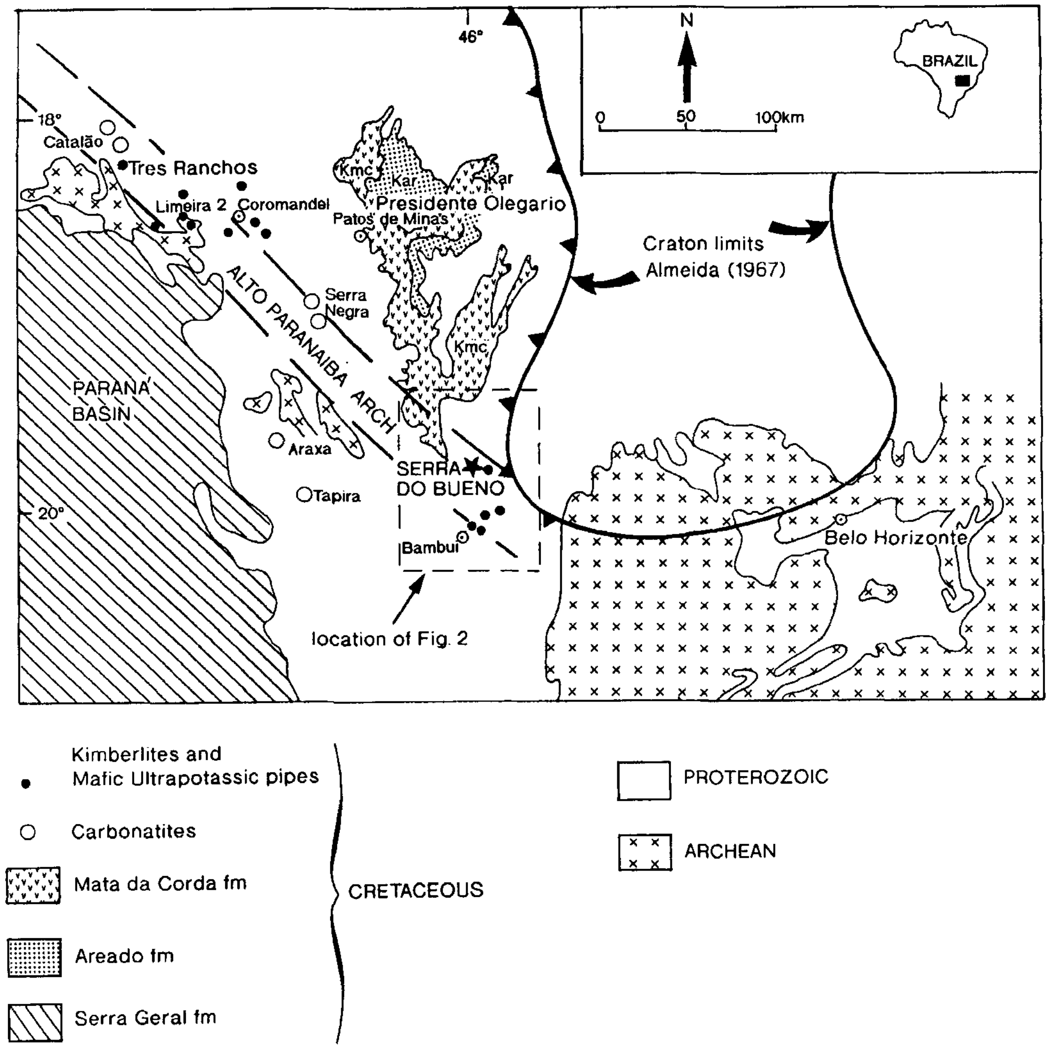


FIG. 1. Structural setting of the Alto Paranaíba Igneous Province (modified from Schobbenhaus *et al.*, 1984) and the location of Serra do Bueno diatreme. Other localities that are referred to in the text are also shown.

limestone and slate (from the surrounding Bambuí Group), feldspathic gneiss and dunite are also present within the intrusion. The feldspathic gneiss xenoliths have irregular, wavy margins and appear to have been partially melted by the surrounding magma. These gneiss xenoliths bear no resemblance to the Proterozoic rocks of the region and are probably derived from the underlying Archaean craton.

This region contains numerous alluvial diamond prospects (Barbosa *et al.*, 1970) and, although diamonds have not been directly recovered from any of the pipes, diamond indicator minerals have been identified from

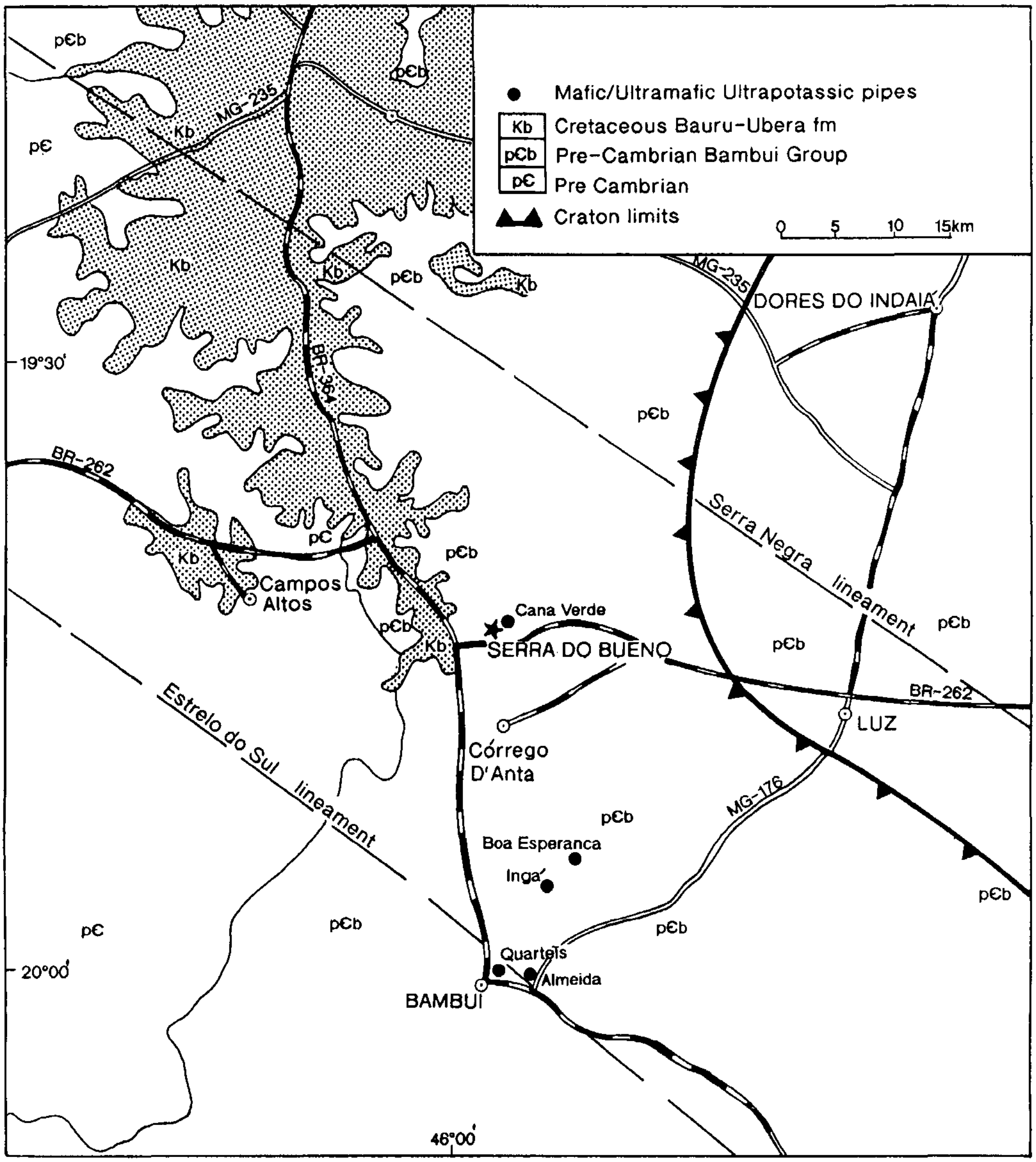


FIG. 2. Detailed map of the Bambuí region illustrating the location of the Serra do Bueno diatreme and its relationship to other ultramafic potassic pipes (modified from Barbosa, 1991).

both Boa Esperanca and Cana Verde (Ramsay and Tompkins, 1991; Fig. 2). Pyroclastic deposits consisting of lapilli and breccias have also been reported from the Cana Verde locality, less than 4 km, ENE of Serra do Bueno. This poorly exposed pipe has previously attracted economic geologists and others because of its location, near the headwaters of a small stream that contains alluvial diamonds. The Cana Verde outcrop is considerably weathered but it is possible to identify megacrysts of garnet (chrome-pyrope), diopside and chrome-diopside, rutile and titano-magnetite. Ramsay and Tompkins (in press) have analysed samples of tuff breccia from the Cana Verde pipe and have suggested that they have a similar bulk composition to those of the West Kimberley lamproites. However, due to the weathered nature of these tuffs, it is difficult to define them accurately. Given their very similar ultramafic compositions and close proximity, it is possible that the Cana Verde pipe and the Serra do Bueno diatreme are genetically related (Fig. 3).

The Serra do Bueno diatreme lies to the south of the present day outcrop of the tuffs and lavas of the Mata da Corda Formation that comprises much of the magmatism in the APIP (Fig. 1). Despite the tuffs and lavas outcropping over a large area they are poorly exposed, due to the intense tropical weathering. One of the freshest exposures of the latter is at Presidente Olegário in the northern portion of the province. Here lava flows and tuffs are cut by numerous thin dykes and are associated with a weathered intrusive facies. The volcanic succession consists of: (1) pyroclastic horizons with block-sized ejecta of volcanic and unexposed plutonic facies, and xenoliths of dunite and pyroxenites; and (2) amygdaloidal ultramafic potassic lavas (Leonardos *et al.*, 1991). Strongly weathered remnant vent regions of the Mata da Corda volcanics are also present at Japecanga (Tompkins, 1991) and in the area of Lagoa Formosa and Carmo do Paranaíba (Moraes *et al.*, 1986; Seer *et al.*, 1989). Some localities within these regions yield abundant unweathered material, suitable for detailed chemical studies (Gibson *et al.*, in press). The petrogenetic relationship between the lavas of the Mata da Corda Formation and the Serra do Bueno diatreme is considered below.

Interpretation of field characteristics

The present-day outcrop at Serra do Bueno appears to represent the deeply eroded remnants of the root zone of a vent. The structure seems to have developed in at least two stages: (1) an initial stage of explosive activity associated with the eruption of tuffs in the crater facies, subsequently followed by (2) the more quiescent intrusion of ultramafic potassic magma, which may have erupted at the surface to form lavas that have since been eroded. The two distinctive facies present at Serra do Bueno are similar to those that have been reported from kimberlites and lamproite pipes. However, one of the important differences between the feeder systems of these two magma types is the absence of a central intrusion in kimberlite diatremes (Mitchell and Bergman, 1991). In terms of its structure, the Serra do Bueno diatreme closely resembles the Ellendale lamproite pipes in Western Australia (Smith and Lorenz,

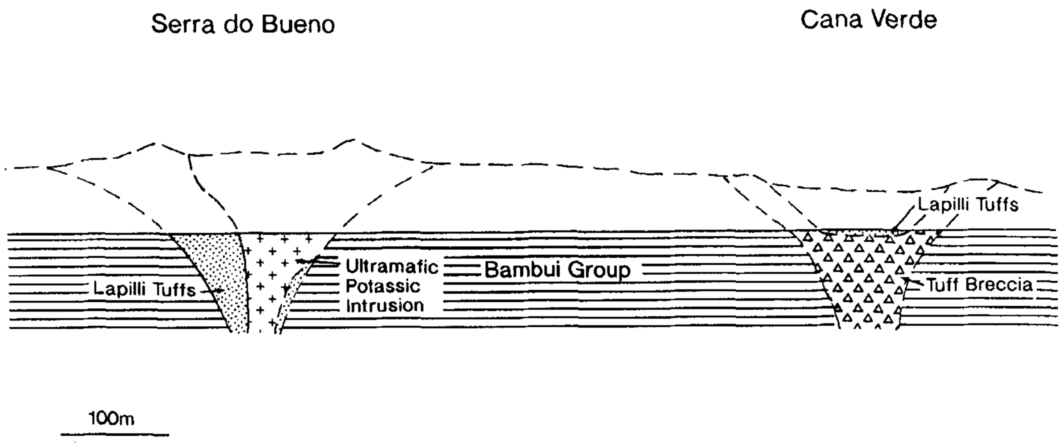


FIG. 3. Schematic diagram showing the structure of the Serra do Bueno diatreme, as we have inferred from the present-day outcrop (see text), and also its close spatial relationship to the Cana Verde pipe.

TABLE 1. Whole-rock K/Ar dates of the Serra do Bueno Intrusion

Sample No.	K_2O (wt.%)	Rad ^{40}Ar mm^3 gm^{-1}	Atmospheric contamination (%)	Age Ma $\pm 1\sigma$
92SOB5	2.01 + 0.01	$(2.45 \pm 0.03)10^{-3}$	27.7	37.4 ± 0.5
		$(2.44 \pm 0.03)10^{-3}$	25.3	37.2 ± 0.5

K/Ar ages were determined at the University of Newcastle. Decay constants are from Steiger and Jäger (1977).

1989). It is interesting to note that, unlike some basaltic volcanoes, the pyroclastic deposits form well-stratified units in both the lamproite vents and the Serra do Bueno diatreme.

It has been proposed that the contrast in morphology between kimberlite and lamproite pipes relates to the difference in volatile content of the two magma types. Mitchell and Bergman (1991) suggested that the high content of H_2O in lamproites, which becomes insoluble at low pressures, causes the explosive vent activity to occur only at shallow depths (0.5–1 km). A sudden reduction (by effervescence) in volatile content of the magma is thought to cause the change from pyroclastic to magmatic activity. Kimberlites are relatively rich in CO_2, which is insoluble in silicate melts at higher pressures than H_2O, and is therefore thought to exsolve at greater depths (1–2 km). The parental magma of the Serra do Bueno intrusion has a similar composition to the East African kamafugite family of rocks (see below). Very little information is available on the structure of the feeders of kamafugitic rocks but experimental studies have shown that the melts were generated in an environment with high CO_2/H_2O ratios (Edgar, 1987). If the magma associated with the Serra do Bueno diatreme is analogous to the East African kamafugites and was rich in CO_2, then the model proposed by Mitchell and Bergman (1991) to explain the different structure of kimberlite and lamproite vents may have been oversimplified. The Serra do Bueno diatreme demonstrates that CO_2-rich magmas are capable of forming vents at shallow depths, in addition to the deep root zones that have previously been associated with kimberlite pipes. We conclude

TABLE 2. Laser argon analyses for the Serra do Bueno intrusion (see text for discussion)

Sample	Analysis	^{40}Ar	^{39}Ar	^{36}Ar	% Atm	$^{39}Ar/^{40}Ar$	$^{36}Ar/^{40}Ar$
aao55	Ol	82.235	1.507	0.182	62.91	0.01833	0.00221
aao68	Ol	740.309	88.629	0.988	38.02	0.11972	0.00133
aao57	Ol	251.340	31.825	0.33	37.42	0.12662	0.00131
aao70	Ol	1096.383	157.879	1.259	32.73	0.14400	0.00115
aa074	Gndmass	743.630	97.257	0.911	34.90	0.13079	0.00122
aa064	Gndmass	1102.97	147.098	1.218	31.47	0.13337	0.00110
aao59	Gndmass	878.007	117.902	0.971	31.53	0.13428	0.00111
aa072	Gndmass	231.168	31.324	0.296	36.55	0.13550	0.00128
aao66	Gndmass	905.350	122.898	1.185	37.31	0.13575	0.00131
aap65	Gndmass	1579.591	216.643	2.007	36.22	0.13715	0.00127
aap6l	Gndmass	1290.583	178.283	1.588	35.06	0.13814	0.00123
aap63	Gndmass	615.979	85.378	0.712	32.96	0.13861	0.00116
aao62	Gndmass	937.059	133.597	1.001	30.43	0.14257	0.00107
aap59	Gndmass	989.395	143.373	1.164	33.53	0.14491	0.00118
aao53	Gndmass	364.897	53.591	0.354	27.61	0.14687	0.00097
aap57	Gndmass	1226.730	185.090	1.319	30.65	0.15088	0.00108

J = 0.01085

Laser argon determinations were made at the Open University using the method described by Hawkesworth *et al.* (1992).

from this that the contrast in morphology between kimberlite and lamproite pipes may be more complex than just their different volatile contents.

Age

Recent K/Ar ages of rocks from the APIP consistently fall between 70 and 90 Ma (Ulbrich and Gomes, 1981; Gibson *et al.*, in press), with most of these ages having been determined on rocks from the north-east and central parts of the province. The only previous available date for the Serra do Bueno dyke was an unpublished K/Ar age of 45 Ma by Hasui, reported by Ulbrich and Gomes (1981). As this is considerably younger than any other previously published ages for the APIP, we have dated a sample from this intrusion by K/Ar whole-rock techniques (Wilkinson *et al.*, 1986). This yielded an age of 37 ± 0.5 Ma (Table 1). Given the similar whole-rock composition of the Serra do Bueno dyke to other intrusions and lavas in the APIP (see below) we decided to also date the same sample by laser $^{40}Ar/^{39}Ar$ techniques. Although the rock contains phlogopite the crystals are very small and it was not possible to obtain laser analyses of them. Instead we have determined isochrons for Serra do Bueno using analyses from both the groundmass and olivine phenocrysts (Table 2). An isochron for both sets of analyses gives an age of 67 ± 16 Ma (Fig. 4*a*). The large error bar associated with this age is partly caused by an anomalous olivine analysis. If only the analyses from the groundmass are considered and the isochron is tied to atmospheric Ar (air), then an age of 90 ± 4 Ma is obtained (Fig. 4*b*). This latter age is consistent with K/Ar ages (84 Ma) that we have determined on mica separates from the Mata da Corda lavas

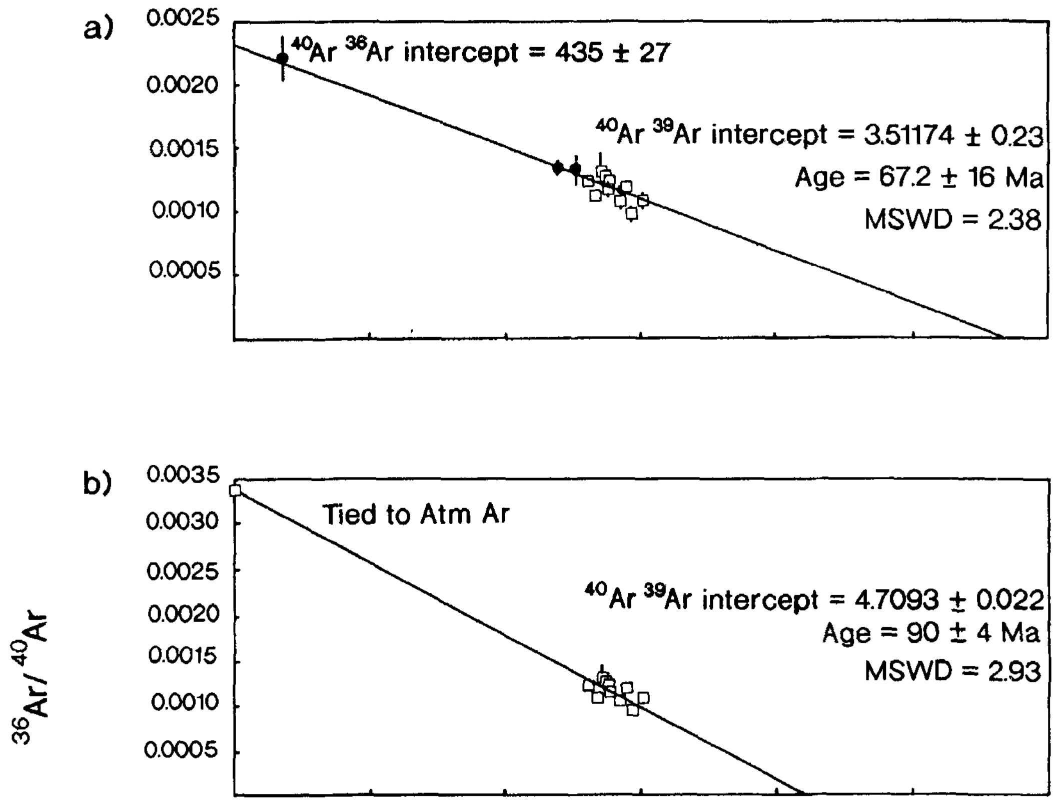


FIG. 4. $^{40}Ar/^{39}Ar$ correlation diagrams for the Serra do Bueno intrusion: (*a*) shows an isochron through analyses of both olivine phenocrysts (closed circles) and the groundmass (open squares); (*b*) shows an isochron through groundmass analyses.

TABLE 3. Representative mineral analyses

	Olivine SBOL1	SBOL2	SBOL3	Clinopyroxene SBCP1	SBCP2	Phlogopite SBPH1	Ilmenite SBIL1	SBIL2	Perovskite SBP1
SiO_2	40.5	39.9	40.4	52.7	53.1	41.0	0.46	0.22	0.08
TiO_2	-	-	-	1.49	1.27	6.10	22.0	16.6	54.9
Al_2O_3	-	-	-	0.64	0.60	8.02	0.44	0.42	0.16
Cr_2O_3	-	-	-	-	-	-	0.90	4.58	0.17
Fe_2O_3	-	-	-	0.84	2.59	-	56.9	64.8	-
MgO	46.9	45.7	46.1	15.2	14.8	17.8	2.80	4.59	0.04
CaO	0.18	0.11	0.16	23.9	23.8	-	0.25	0.13	38.4
MnO	0.13	0.12	0.15	0.10	0.16	0.09	0.98	0.96	-
FeO	11.2	13.0	12.0	3.92	3.10	9.63	14.5	8.21	1.67
Na_2O	-	-	-	0.56	0.98	0.78	-	-	-
NiO	0.39	0.21	0.32	-	-	0.03	0.04	0.11	-
K_2O	-	-	-	-	-	9.11	-	-	-
BaO	-	-	-	-	-	2.51	-	-	-
F	-	-	-	-	-	2.31	-	-	-
Cl	-	-	-	-	-	0.01	-	-	-
H_2O	-	-	-	-	-	2.82	-	-	-
Total	99.3	99.0	99.1	99.4	100.4	100.2	99.3	100.6	95.4*

Mineral analyses were undertaken at the University of Brasilia using a Cameca SX-50 microprobe.

and other intrusions in the north of the APIP (Gibson *et al.*, in press). The slightly older $^{40}Ar/^{39}Ar$ age for the Serra do Bueno intrusion may be due to slight recoil effects arising during the generation of ^{39}Ar from ^{39}K during neutron irradiation. These may lead to a loss of ^{39}Ar from the microlites and crystallites that comprise the devitrified groundmass. If the proportion of ^{39}Ar lost via this mechanism exceeds the cumulative total loss of ^{40}Ar, then an over-estimate of the geological age may arise. The similarity in age of the Serra do Bueno intrusion, in the south of the APIP, with other intrusions and lavas in the north suggests that there were no spatial and temporal shifts in volcanic activity, i.e. magmatism was contemporaneous throughout the whole of this large alkaline province.

Petrology and mineral chemistry of the Serra do Bueno intrusion

The Serra do Bueno dyke comprises olivine phenocrysts and microcrysts of olivine, diopside, phlogopite, spinel, perovskite, ilmenite, leucite and zeolites set in a fine grained groundmass that contains devitrified glass. Representative mineral analyses are shown in Table 3.

Large (2 cm) euhedral to subhedral phenocrysts of olivine form approximately 25% of the rock. A few of these olivines have slightly corroded margins and some are partially mantled by laths of phlogopite. The olivine is highly magnesian ($Fo_{86}-Fo_{88}$) and shows no evidence of strong chemical zonation. It has high NiO (0.2–0.4 wt.%) and low CaO contents (<0.2 wt.%).

Small prismatic crystals (<0.5 mm) of clinopyroxene form approximately 40% of the matrix. The clinopyroxene crystals are diopsides ($Ca_{50}Mg_{44}Fe_6$) and show limited chemical zonation. They are relatively poor in TiO_2 (1–2 wt.%), Al_2O_3 (<0.7 wt.%) and Na_2O (<1 wt.%).The phlogopite is present in a low modal amount. It forms crystals that are typically <0.5 mm long and are often associated with the patches of devitrified glass. The phlogopite has a high content of TiO_2 (6 wt.%) and BaO (2.5 wt.%), low contents of Al_2O_3 (8 wt.%). Spinel, ilmenite and perovskite are present as small groundmass grains and representative analyses are shown in Table 3. Leucite and zeolites also occur in small amounts. Some of this leucite appears to be pseudomorphed by analcite. The groundmass contains up to 20% glass which is devitrified and has a green colouration.

Comparison with other ultramafic potassic rocks. The mineral compositions of the olivines, phlogopites and diopsides from Serra do Bueno are similar to those from other localities in the north of the APIP. For example, the olivine and diopside have similar compositions to those in the lavas at Presidente Olegário (Leonardos *et al.*, 1991) and the intrusions at Pântano (Meyer *et al.*, 1991), Limeira 2 and Indaiá 2 (Meyer and Svisero, 1991). In relation to other worldwide potassic rocks, the diopsides from the APIP are more enriched in Al than those of typical lamproites, e.g. Smoky Butte, West Kimberley, but are less enriched than those of the Ugandan kamafugites (Fig. 5). The Serra do Bueno and Presidente Olegário phlogopites are slightly more enriched in TiO_2 and depleted in Al_2O_3 than the phlogopite macrocrysts from the intrusions at Pântano, Limeira and Três Ranchos (Danni *et al.*, 1991; Fig. 6). The former appear to be similar in composition to madupitic lamproites from West Kimberley, Prairie Creek and Leucite Hills (Mitchell and Bergman, 1991; Fig.6).

Whole-rock chemistry

Major elements and chemical classifcation. The ultramafic dyke is the least weathered facies of the Serra do Bueno diatreme and has been analysed in order to determine the nature of the parental magma (Table 4). The intrusion is silica-undersaturated (SiO_2 = 40–41 wt.%) and rich in TiO_2 (4.3 wt.%). It is potassic, with a K_2O/Na_2O ratio of 1.5–1.8, and ultramafic (MgO = 15–16 wt.%). The rock has a high CaO (12–13 wt.%) and low Al_2O_3 content (6–7 wt.%).

The major-element chemistry of the Serra do Bueno intrusion is very similar to the lavas of the Mata da Corda Formation. They are all characterized by low SiO_2 and Al_2O_3 and high CaO contents relative to other potassic rocks. Using the classification scheme of Sahama (1974; Fig. 7*a*) and Foley *et al.* (1987), both the Serra do Bueno intrusion and the lavas plot in the same field as the kamafugite family of rocks from East Africa. The published analyses of the latter suggest that they generally have lower MgO contents (Fig. 7*b*). The similarity of the whole-rock chemistry of the Serra do Bueno intrusion to kamafugites contrasts with the lamproitic affinity of the

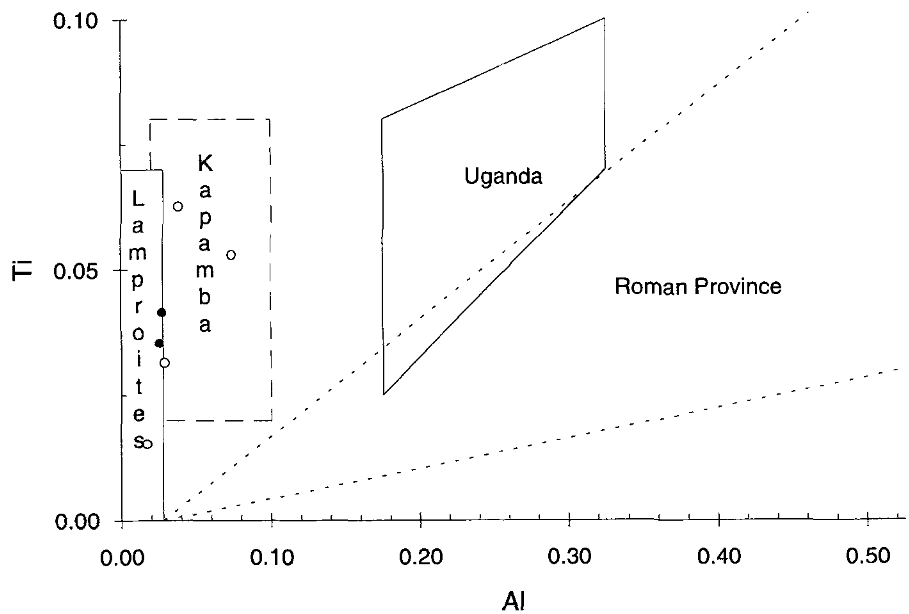


FIG. 5. Variation of atomic Ti and Al (on the basis of 6 oxygens) in clinopyroxene from the Serra do Bueno intrusion (closed circles) and the Mata da Corda lavas (open circles). The fields of clinopyroxene in worldwide lamproites, East African kamafugites, Kapamba and Roman Province lavas are shown for comparison. Data sources are as follows: Cundari and Ferguson (1982), Scott-Smith *et al.* (1989), Leonardos *et al.* (1991), Mitchell and Bergman (1991).

phlogopite microcrysts. However, the latter probably reflects the local post-emplacement crystallization environment of the intrusion and the whole-rock composition may be more indicative of the nature of the parental magma.

Trace elements and radiogenic isotopes. The Serra do Bueno intrusion has high concentrations of compatible trace elements, such as Cr (770–910 ppm), Ni (450–490 ppm) and Sc (25–30 pppm). Incompatible elements are also present in high abundances, e.g. Ba = 1750–2050, Nb = 135–150, Zr = 500–630. Fig. 8 shows the normalized concentrations of a range of incompatible elements from the intrusion. The rock essentially exhibits a smooth pattern between Ba and Lu, except for Rb and K where troughs occur. Although $(La/Nb)_n$ values are < 1 there is no marked trough at Nb. The Serra do Bueno intrusion shows a strong enrichment in light rare earth elements (*LREE*) relative to heavy rare earth

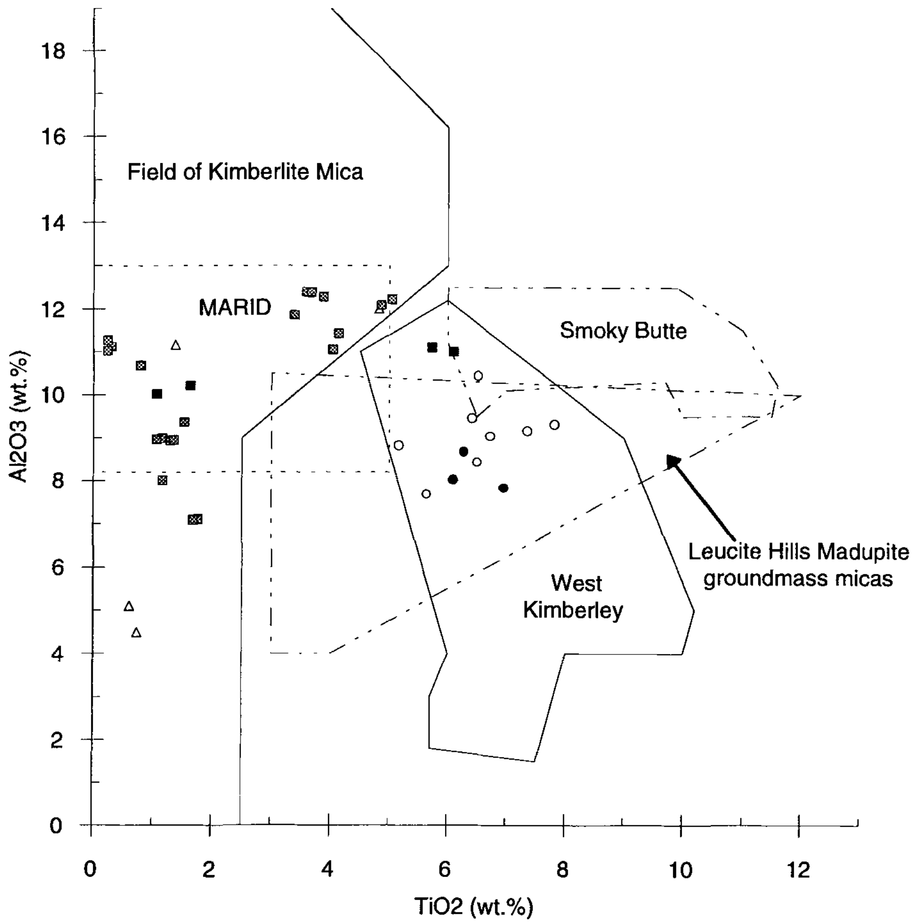
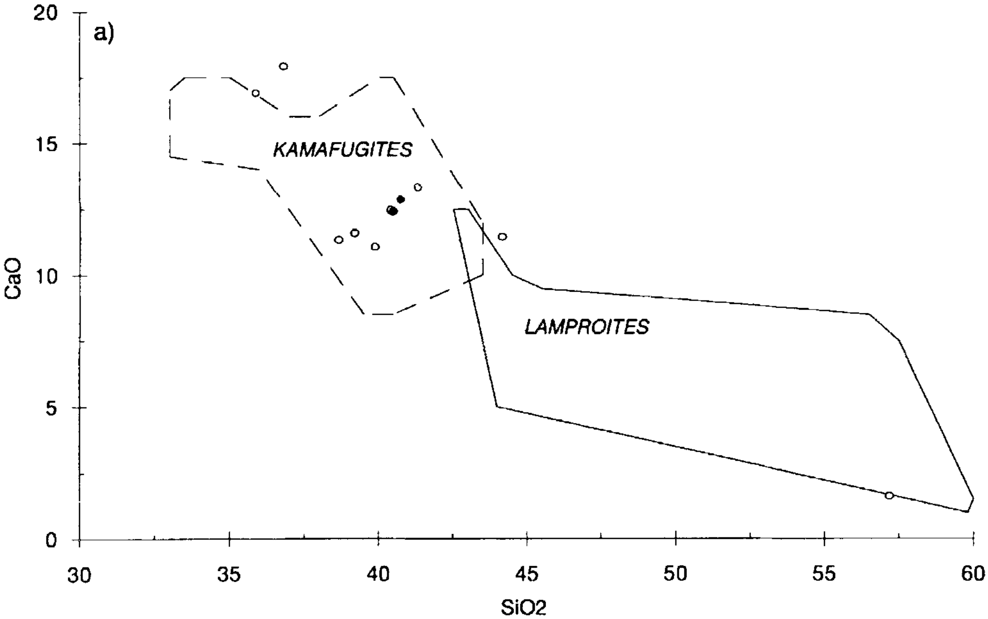


FIG. 6. Variation of TiO_2 and Al_2O_3 in phlogopite crystals from the Serra do Bueno intrusion (closed circles) and other Cretaceous alkaline rocks in the Alto Paranaíba Igneous Province (APIP). The fields of phlogopite in kimberlites, selected lamproites and the MARID (mica-amphibole-rutile-ilmenite-diopside) xenolith suite are shown for comparison (Dawson and Smith, 1977; Smith *et al.*, 1978; Jaques *et al.*, 1986; Scott-Smith *et al.*, 1989; Mitchell and Bergman, 1991). Symbols for the APIP are as follows: shaded squares, Três Ranchos (Danni *et al.*, 1991): open circles, Presidente Olegário, (Leonardos *et al.*, 1991); open triangles, Pântano (Meyer *et al.*, 1991); closed squares Limeira and Indaiá (Meyer and Svisero, 1991).



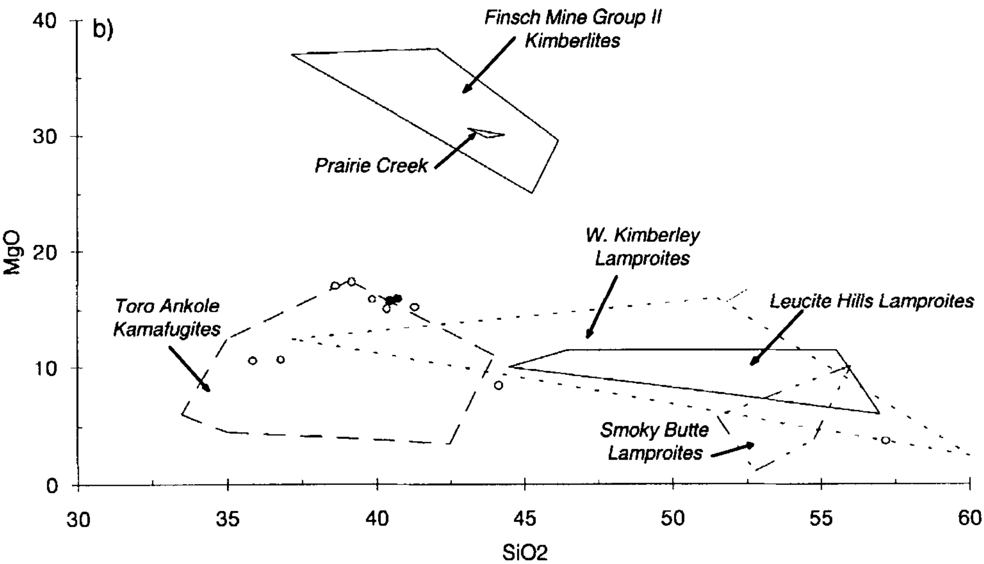


FIG. 7. (*a*) Classification of the Serra do Bueno intrusion (closed circles) and the Mata da Corda lavas (open circles) after Sahama (1974). (*b*) Comparison of SiO_2 and MgO contents of the Serra do Bueno intrusion and Mata da Corda lavas (samples loss on ignitions < 5 wt.%) with worldwide potassic rocks. Data sources are Fraser (1988), Table 4 and our unpublished data.

elements (*HREE*), for example La/Yb = ~85, and a moderate enrichment in *LREE/MREE* (middle rare earth elements); La/Sm = 8. These enrichments of *LREE* and *MREE* relative to *HREE* concentrations are similar to other ultramafic ultrapotassic rocks in the APIP (e.g. La/Sm = 8–11 and La/Yb = 70–180).

In Table 4 and Fig. 8 we have compared the contents of incompatible trace elements in the dyke with representative lavas and intrusions from the north and central regions of the APIP that have similar concentrations of MgO (16 wt.%). This table and diagram show that the -intrusions and lavas have remarkably similar concentrations of incompatible trace elements. Whilst slight differences occur in the concentrations of elements, such as Sr, P and Ti (that enter minerals which crystallise at high temperatures from these unusual magmas, e.g. apatite and perovskite), the incompatible trace element pattern of the Serra do Bueno intrusion is almost identical to the Presidente Olegário lava.

We have also determined initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of 0.705176 and 0.512312, respectively, for the Serra do Bueno intrusion. These ratios are comparable to those of other

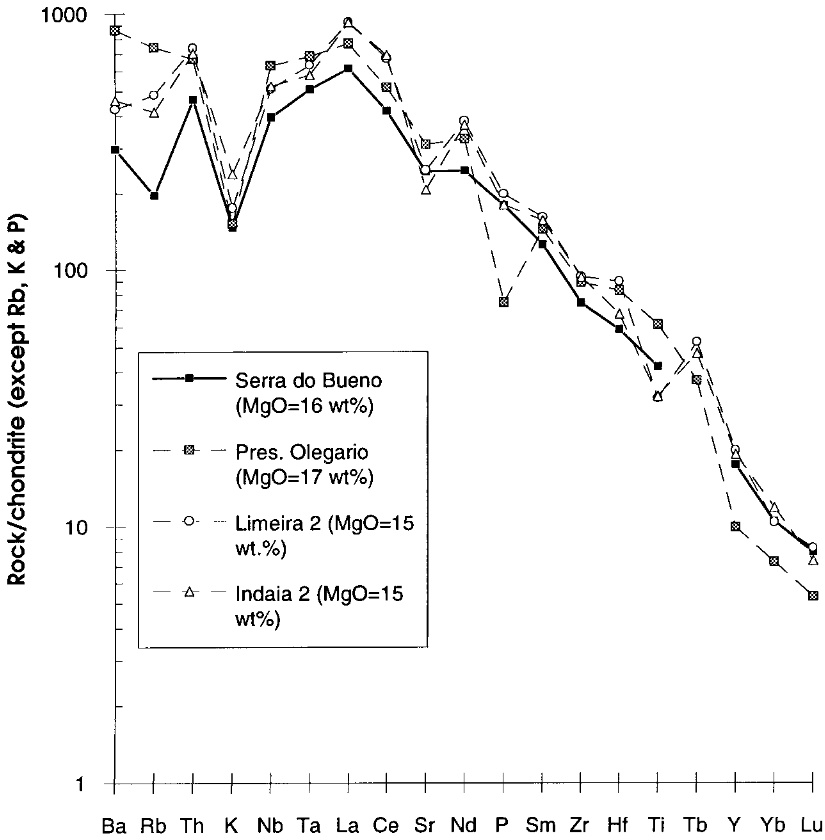


FIG. 8. Normalised abundances of a range of trace elements in the the Serra do Bueno intrusion. Other Cretaceous ultramafic ultrapotassic rocks from the Alto Paranaíba Igneous Province are shown for comparison. The normalisation factors are chondritic, except for Rb, K and P which are bulk-Earth values (Thompson *et al.*, 1984).

TABLE 4. Representative analyses of whole-rock compositions of selected intrusive and extrusive rocks from the Alto Paranaíba Igneous Province

Sample	Serra do Bueno (Intrusion) *92SOB4*	Serra do Bueno (Intrusion) *92SOB5*	Presidente Olegário (Lava) *92SOB9*	Limeira 2 (Intrusion) *90SB28*	Indaiá 2 (Intrusion) *91SB2O*
wt.%					
SiO_2	40.49	40.75	39.20	42.60	41.42
TiO_2	4.39	4.33	6.33	3.27	3.31
Al_2O_3	6.58	6.25	5.25	6.96	7.04
$Fe_2O_3{}^+$	13.71	13.53	14.71	10.69	10.64
MnO	0.20	0.19	0.20	0.19	0.19
MgO	15.69	15.91	17.35	15.07	15.35
CaO	12.39	12.84	11.56	14.61	13.34
Na_2O	1.45	1.39	0.68	1.12	1.90
K_2O	2.60	2.11	2.19	2.52	3.43
P_2O_5	1.39	1.37	0.57	1.52	1.38
Total	98.89	98.68	98.03	98.56	98.01
LOI	3.88	3.43	3.96	4.24	3.85
ppm					
Ba	1764	2052	5977	2937	3184
Cr	905	773	630	923	970
Hf	11.26	11.69	16.54	17.94	13.43
Ga	12.5	15.8	16.1	11.7	12.7
Nb	146	138	220	179	183
Ni	450	490	556	393	375
Rh	112	69	260	169	145
Sc	25.79	30.32	32.32	31.32	28.57
Sr	2030	2866	3659	2900	2433
Ta	9.51	10.16	13.67	12.67	11.58
Th	16.64	19.44	28.15	30.90	29.53
U	3.12	3.49	5.43	6.46	5.61
V	282	260	311	135	143
Y	32	34.9	19.9	39.5	38.2
Zn	118	117	102	93	90
Zr	626	507	608	640	638
La	173	201	251	303	303
Ce	306	362	446	583	599
Nd	130	154	205	240	232
Sm	21.7	25.4	29.0	32.6	31.6
Eu	5.3	6.1	7.0	8.8	8.3
Gd	16	22	19	22	24
Th	2.08	–	1.92	2.71	2.45
Ho	0.92	1.02	1.29	–	1.16
Tm	-	0.40	0.40	0.32	0.40
Yb	2.12	2.31	1.60	2.29	2.62
Lu	0.26	0.27	0.18	0.28	0.25
$(^{87}Sr/^{86}Sr)_m$		0.705259	0.705258	0.705739	0.705712
$(^{143}Nd/^{144}Nd)_m$		0.512367	0.512352	0.512301	0.512261
$(^{87}Sr/^{86}Sr)_{85}$	–	0.705175	0.705010	0.705536	0.705504
$(^{143}Nd/^{144}Nd)_{85}$	–	0.512312	0.512305	0.512256	0.512215

Elemental determinations were made by XRF, except Hf, Ta, Th, U and *REE* which were analysed by INAA at the University of Durham. Major elements are calculated on a volatile-free basis. $^+$Total Fe reported as Fe_2O_3. Sr and Nd isotope ratios were measured at McMaster University; 2σ errors: $^{87}Sr/^{86}Sr$ 0.000015, $^{143}Nd/^{144}Nd$ 0.000010. Nd isotopes normalised to $^{146}Nd/^{144}Nd$ = 0.7219.

intrusive and extrusive rocks in the APIP, whose initial Sr and Nd isotopic ratios range from 0.7046–0.7060 and 0.51238–0.51214 respectively.

The comparable whole-rock compositions and radiogenic isotopic ratios of mafic rocks in the APIP suggest that these Late Cretaceous alkaline igneous rocks were all derived from a similar source. When the geochemistry of this igneous province is considered as a whole (Bizzi *et al.*, 1991; Gibson *et al.*, in press), it seems probable that the source of the magmas was mostly within the sub-continental lithospheric mantle. On a conventional Sr- and Nd-isotope diagram these rocks predominantly plot in the enriched quadrant, in between the Group I and Group II South African kimberlites (Fig. 9). Relative to many other potassic mafic and ultramafic rocks (e.g. West Kimberley, Finsch Mine), they are only slightly enriched in ^{87}Sr. This, together with low $(La/Nb)_n$ ratios, suggests that enrichment of the lithospheric source-mantle in strongly incompatible elements and *LREE*s was more likely to have been caused by the percolation of K-rich small-volume melts from the underlying asthenosphere, rather than by subduction processes. The latter would have produced high Rb/Sr ratios and large $(La/Nb)_n$ ratios. The moderate $^{143}Nd/^{144}Nd$ isotope ratios suggest that the lithospheric mantle beneath Alto Paranaíba may have been metasomatised relatively recently, in comparison with the sources of other world-wide potassic magmas, such as Smoky Butte and the Leucite Hills (Gibson *et al.*, in press).

Conclusions

The similarities in mineralogy and whole-rock chemistry between the Serra do Bueno intrusion and the Mata da Corda lavas (e.g. Presidente Olegário) suggest that they are genetically related. This eroded vent may well have been one of many feeders that were associated with the eruption of the Mata da Corda tuffs and lavas. However, due to the effects of intense tropical weathering and variations in the exposure level, few of these are preserved. The Serra do Bueno diatreme therefore offers a rare opportunity to examine the feeder systems, and hence increase our understanding of the genesis of this voluminous ultramafic potassic volcanic province.

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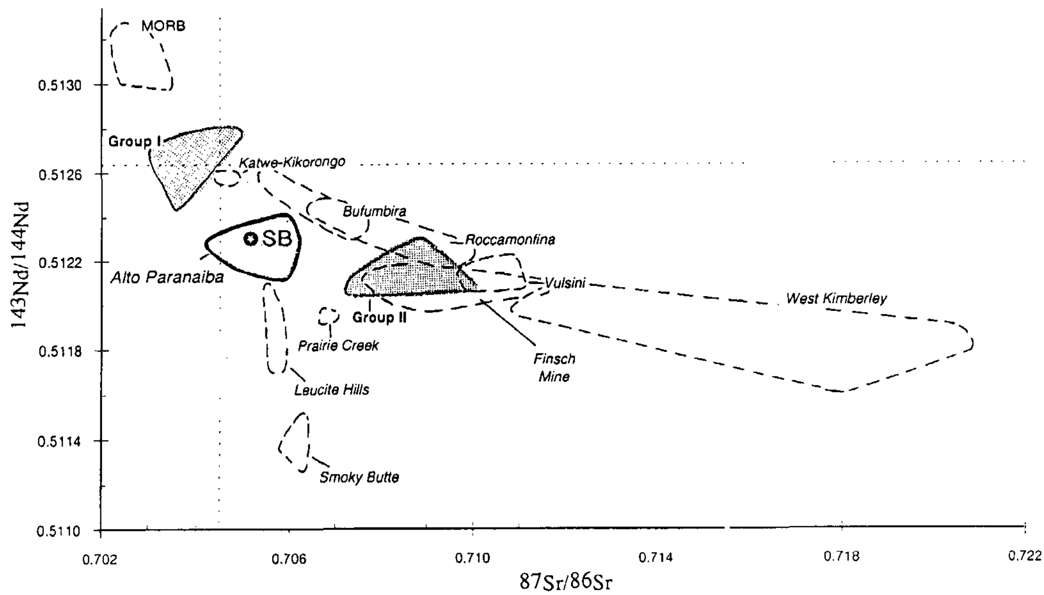

FIG. 9. Initial $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ for the Serra do Bueno intrusion. The fields of the Alto Paranaíba Igneous Province (Gibson *et al.*, in prep.) and other world-wide ultrapotassic rocks are shown for comparison. Data sources are as follows: Hawkesworth and Vollmer (1979), Smith (1983), Vollmer *et al.* (1984), Rogers *et al.* (1985), Fraser (1987), Ito *et al*, (1987), Davies and Lloyd (1989).

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