Oligocene lamproite containing an Al-poor, Ti-rich biotite, Middle Park, northwest Colorado, USA

R. N. THOMPSON

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

D. VELDE

Départment de Petrologie, Université P. et M. Curie (U.R.A. 736 du CNRS), 4, Place Jussieu, 75252 Paris, France

P. T. LEAT

British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK

M. A. MORRISON

School of Earth Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

J. G. MITCHELL

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

A. P. DICKIN

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

AND

S. A. GIBSON

Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

Abstract

A small 33 ± 0.8 Ma lamproite pluton is exposed in the midst of a $23-26$ Ma basalt–rhyolite province in Middle Park, NW Colorado. It contains abundant phlogopite phenocrysts in a fine-grained groundmass of analcime pseudomorphs after leucite, biotite, potassic richterite, apatite, ilmenite and accessory diopside. The phlogopite phenocryst cores contain ~4 wt.% TiO_2, 1% Cr_2O_3 and 0.2% BaO. The smallest groundmass biotites have normal pleochroism but compositions unlike any previously reported, with ~2% Al_2O_3, ~8% TiO_2 and F <1.5%. Apart from those elements affected by leucite alteration, both the elemental and isotopic composition of this lamproite are close to those of the Leucite Hills, Wyoming. Its Nd-isotopic model age ($T_{DM} = 1.6$ Ga) is outside the Leucite Hills range but within that of other Tertiary strongly potassic magmatism in the region underlain by the Wyoming craton. Evidence from both teleseismic tomography and the mantle xenoliths within other western USA mafic ultrapotassic igneous suites shows that the total lithospheric thickness beneath NW Colorado was probably ~150–200 km at 33 Ma, when the Middle Park lamproite was emplaced. This is an important constraint on tectonomagmatic models for the Cenozoic evolution of this northernmost part of the Rio Grande rift system.

KEYWORDS: Oligocene lamproite, Al-poor Ti-rich biotite, richterite, lithospheric mantle.

Introduction

DESPITE their extreme rarity, lamproites have been the focus of considerable attention in recent years. The main reason for this interest has inevitably been the economic one, generated by the discovery that some lamproites contain diamonds. In addition, this rock-group is interesting to mineralogists because of the unusual species and zoning trends of its component minerals, and to geochemists because its elemental and isotopic composition gives an insight into the composition and evolution of the subcontinental lithospheric mantle.

The Middle Park lamproite was sampled by us as a 'lamprophyre' during a regional geochemical survey of igneous rocks associated with the Rio Grande rift system, including its northern extension into NW Colorado (Tweto, 1979a; Eaton, 1986). Because Tertiary minettes are relatively common in NW Colorado (e.g. Leat *et al.*, 1988; Thompson *et al.*, 1989), we have described this sample as 'minette' in previous papers (e.g. Leat *et al.*, 1991), on the basis of its chemical analysis alone. Subsequent detailed electron microprobe study has shown the true nature of this rock and has also explained why its K$_2$O content is not particularly high; a disconcerting attribute for a would-be lamproite! This paper reports mineralogical and geochemical data for the new lamproite, focusing on hitherto unrecorded biotite variants in its groundmass mica. The discussion then looks more broadly at what this lamproite occurrence can tell us about mantle evolution below NW Colorado and the constraints that it places on the tectonomagmatic history of this region during the Tertiary.

Nomenclature

The classification and nomenclature of mafic potassic igneous rocks has recently been facilitated by publication of the recommendations of the appropriate IUGS working group (Woolley *et al.*, 1996). The proposed diagnostic criteria are the presence of Al-poor titanian phlogopite and Fe-rich leucite or forsteritic olivine as phenocrysts, together with one or more of titanian potassic richterite, Al-Na-poor diopside, leucite, wadeite and priderite in the groundmass. The mineralogy of the Middle Park rock (see below) leaves no doubt that it is a lamproite but its bulk chemical composition is less diagnostic. This is because the abundant primary leucite has been pervasively altered to analcime. Mitchell and Bergman (1991) point out that this is a common feature of older lamproites. We shall argue below that this process has substantially affected the abundances of K$_2$O and Na$_2$O in the Middle Park example, thus preventing the use for classification

purposes of all chemical plots that involve these elements, as also shown for Spanish examples by Venturelli *et al.* (1991), Ferriz *et al.* (1994), and Salvioli-Mariani and Venturelli (1996).

Geological setting

The Middle Park lamproite crops out about 5 km east of Lake Granby, NW Colorado. Its few tens of square metres of exposure has insufficient relief to permit determination of whether the pluton is a dyke, sill or plug. The locality is marked as 'lamprophyre' on USGS map GQ-1156 (Izett,1974) at 40° 11' 20" N and 105° 57' 19" W. Figure 1 shows the location, in relation to other major features of NW Colorado geology. Middle Park is one of a chain of intermontane basins along the axis of the Southern Rocky Mountains. Izett (1975) summarized the development of Middle Park thus:
1. Laramide (Late-Cretaceous) orogenesis caused differential uplift and thrust-related deformation of the Pre-Cambrian gneissose granite-amphibolite basement, and Cretaceous marine sediments, around the site of the future basin.
2. Andesitic volcanism accompanied Palaeocene arkosic early-basin infill.
3. During the Eocene, late-Laramide folding and faulting was followed by uplift and erosion.
4. Basaltic and basalt-related volcanism began at ~30 Ma in the Rabbit Ears Range and Never Summer Mountains (between Cameron Pass and Specimen Mountain, Fig. 1).
5. Sediment deposition was accompanied by basaltic volcanism between about 26 and 11 Ma, when further minor faulting and uplift occurred.

Age

The Middle Park lamproite is characterized by abundant phlogopite phenocrysts, up to 5 mm in length. Fragments of these were separated by hand picking for K-Ar dating. The purity of the separate is confirmed by noting that its K$_2$O content falls between the core and rim values for the phenocrysts determined by electron-probe microanalysis (Table 2). Table 1 shows that the lamproite phlogopite gives a well-constrained age of 33 ± 0.8 Ma (2σ). This pre-dates by 7 m.y. the oldest published dates for the lavas and plutons of the Trail Mountain Volcanics (Izett, 1974), which crop out around the Middle Park lamproite (Fig. 1). An age of 33 Ma is essentially the same as, or perhaps genuinely slightly older than, the published dates for the extensive Lower-Tertiary volcanics that crop out within ~30 km to the N and NW of the lamproite (Izett and Barclay, 1973; Izett, 1975). Unfortunately the latter dates lack precision details.
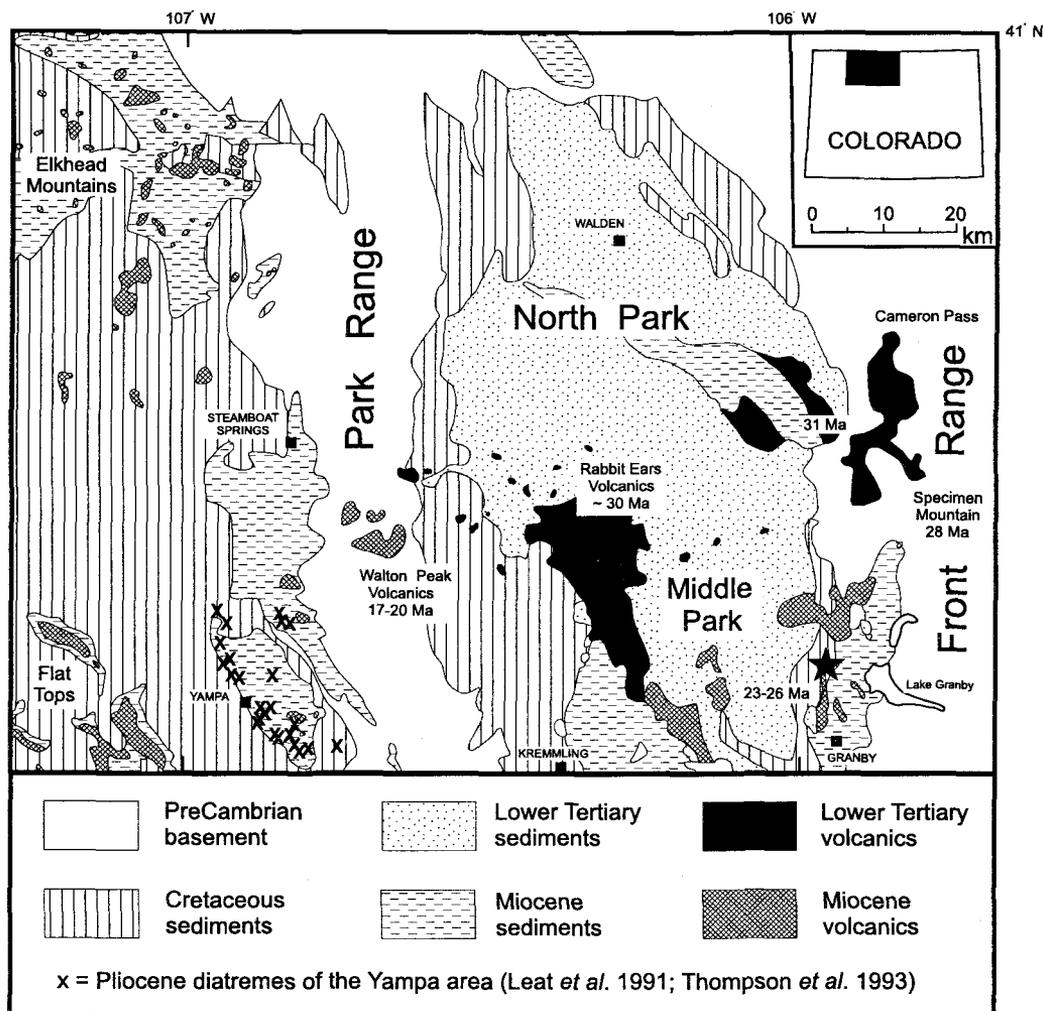
FIG. 1. Simplified geological map of North and Middle Parks and adjacent region, NW Colorado. All faults have been omitted. Filled star marks Middle Park lamproite locality. Sources of data are: Tweto (1979*b*), Izett and Barclay (1973), Izett (1974) and Snyder (1980).

Petrography

In hand specimen the lamproite comprises abundant flow-aligned mica phenocrysts in a medium-grey, fine-grained groundmass. Scattered irregularly shaped vesicles, up to 1 cm in size, range from empty to infilled with zeolites and chalcedony. In thin section the mica phenocrysts (<5 mm) have pale-brown, moderately birefringent cores and dark, reddish-brown rims that are intergrown with the groundmass. The boundary between the pale cores and the dark rims is sharp, irregular and often curvilinear. The shapes of scattered limonitic pseudomorphs suggest that olivine may have been a minor phenocryst phase but none remains unaltered. Elongate <0.5 mm apatite euhedra are the only definite microphenocrysts. Mica and apatite are prominent constituents of the groundmass but by far the dominant mineral appears to be altered leucite (see below), in equant subhedral <0.1 mm grains. Most of the space between these is occupied by <1 mm poikilocrysts of amphibole that is weakly

TABLE 1. Potassium-argon age of hand-picked phlogopite phenocrysts in the Middle Park lamproite

Sample	K_2O (wt. %)	Radiogenic ^{40}Ar (mm^3g^{-1})	Atmospheric contamination (%)	Age* (Ma $\pm$ 1σ)
6LT56	9.91 $\pm$ 0.05	$(1.071 \pm 0.011)10^{-2}$ $(1.048 \pm 0.010)10^{-2}$	16.0 15.3	33.2 $\pm$ 0.4 32.5 $\pm$ 0.4

Details of analytical procedures given in Wilkinson *et al.* (1986)
K_2O is mean of five analyses
* Decay constants of Steiger and Jäger (1977)

pleochroic in shades of yellow and brownish pink. Opaques showing the same size range as the leucite and two crystal shapes, equant and elongate, are prominent accessory phases. Finally there are scattered, tiny (0.1 by 0.02 mm), interstitial crystals of very-pale-green clinopyroxene. The Middle Park lamproite petrographically resembles overall a lamproite from Middle Table Mountain, Leucite Hills, Wyoming, figured by Mitchell and Bergman (1991, fig. 2.22).

Mineralogy

Phlogopite and biotite

Typical phlogopite phenocrysts are 1.5 x 0.3mm in size, with dark borders <0.02 mm thick. Groundmass phlogopites are small (0.05mm) and invariably reddish-brown in colour. None of the micas shows any indication of reverse pleochroism, an observation that would indicate that the tetraferriphlogopite molecule, if at all present, accounts for less than 10% of the phlogopite composition (Wendlandt, 1977). This point is discussed in detail below.

The phenocrysts (Table 2, analyses 1–3) are phlogopite, with only 12 mole percent of the annite component in solid solution, together with 4 wt.% TiO_2, 1% Cr_2O_3 and 0.2% BaO. Fluorine is high, around 2%. In rare occurrences the cores are complex, containing an oval centre with a slightly darker brown colour. Differences between the various phenocrysts, their reddish-brown edges and the groundmass crystals are as follows:

Cores have cation totals close to 16 (15.7) atoms for a formula calculated on 22 oxygens. Al is close to 2 and (Si+Al) close to 8, even though the stoichiometric number of atoms is seldom achieved. Cr is invariably present, Mg is close to 5 and Fe slightly less than 1. Ti is below 0.5 p.f.u.. The brown crystal centres contain more Al, Fe, Ti, and less F than the common phlogopites (Table 2, analysis 4). In one phlogopite crystal an aggregate of transparent blue

spinel crystals was found, similar to those described in various lamproites, including the Leucite Hills wyomingites (Wagner and Velde, 1987). The rims mark an abrupt change in composition, with an increase in Fe, Ba, Ti (up to 8% TiO_2). The rims are lower in Cr, Al and F and the total number of cations is lower. Figure 2 reproduces profiles of major-element variations across a small zoned crystal.

Some groundmass crystal compositions correspond well with the composition of the outside zone of the phenocrysts. Small crystals (0.05 mm) in the groundmass show a more extreme composition that has not as yet been reported (Table 2, analyses 9–14). These micas are biotites, with a combination of very low Al (~2% Al_2O_3), high Ti (up to 9% TiO_2) and low F (<1.5%). They are Ti-rich (close to 1 atom per formula unit) as the edges of the phenocrysts, but with Al around 0.4 p.f.u.. They are Si-rich, with Si between 6.1 and 6.2 p.f.u., but (Si+Al) remains around 7 atoms p.f.u. Their Mg contents are lower (2 and 3 p.f.u.) and Fe contents higher (2.5 and 4 p.f.u.) than all the other micas in the lamproite. Their F content is lower than found in the other mica crystals, and varies inversely with Fe content. Nevertheless, the pleochroism is normal and never as strong as previously described ferri-annite-rich micas (Mokhtari *et al.*, 1985); it is thus impossible to propose the presence of tetrahedral Fe^{3+} beyond 0.1 atom p.f.u. These groundmass micas therefore are not tetraferriphlogopites which, besides their different optical properties, never contain significant amounts of TiO_2 (Farmer and Boettcher, 1981). They are much richer in TiO_2 than previously reported ferri-annite solid solutions (Mokhtari *et al.*, 1985).

Possible substitution schemes. Classical papers on biotite compositions (e.g. Dymek, 1983) do not consider micas with tetrahedral sites that are not filled by Si and Al and most reported compositions do, in fact, contain octahedral Al. The crystallography of Ti-rich micas is poorly known. A few authors (e.g. Bol *et al.*, 1989) accept the possibility of

TABLE 2. Phlogopite and biotite analyses from the Middle Park lamproite

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	39.04	39.55	39.63	36.09	39.54	40.89	39.24	38.83	38.31	38.43	40.53	38.15	38.97	38.85
Al_2O_3	12.68	12.85	12.34	15.92	9.25	8.16	9.59	10.70	2.48	2.39	3.30	1.97	2.59	2.85
Cr_2O_3	0.52	0.79	1.04	0.07	0.02	bd	bd	0.03	0.04	0.02	bd	0.06	bd	bd
FeO	5.27	5.78	5.13	14.04	11.46	11.78	11.23	8.99	26.37	24.82	20.46	25.61	22.56	23.55
MgO	22.23	21.23	21.91	14.65	17.10	16.13	16.88	19.88	9.89	10.87	11.35	10.45	12.37	10.96
Na_2O	0.20	0.15	0.18	0.19	0.42	0.79	0.40	0.15	0.52	0.67	0.65	0.59	0.61	0.59
K_2O	10.28	10.21	10.08	10.21	9.74	9.90	9.75	10.00	8.85	9.40	8.63	8.82	8.91	8.85
BaO	0.53	0.36	0.18	0.19	0.72	0.67	0.72	0.33	0.73	0.98	1.14	1.01	1.01	1.44
MnO	0.06	0.09	bd	bd	0.18	0.15	bd	bd	0.24	0.19	0.16	bd	0.16	0.03
NiO	0.17	0.21	0.20	0.02	0.06	0.03	0.01	0.09	0.03	bd	0.10	0.10	0.12	0.06
TiO_2	4.01	4.62	4.19	3.94	8.24	7.81	8.06	5.54	8.20	8.05	8.34	7.80	7.69	8.75
F	2.02	1.71	2.52	1.26	3.11	3.33	3.39	4.55	0.75	1.28	1.29	1.42	1.21	1.83
Total	97.01	97.55	97.40	96.58	99.84	99.64	99.27	99.09	96.41	97.10	95.95	95.98	96.20	97.76
$O = F$	0.85	0.72	1.06	0.53	1.31	1.40	1.43	1.92	0.32	0.54	0.54	0.60	0.51	0.77
Total	96.16	96.83	96.34	96.05	98.53	98.24	97.84	97.17	96.09	96.56	95.41	95.38	95.69	96.99
Cations on the basis of 22 O														
Si	5.66	5.68	5.72	5.33	5.80	6.02	5.79	5.74	6.16	6.16	6.36	6.21	6.20	6.16
Al	2.17	2.18	2.10	2.77	1.60	1.42	1.67	1.86	0.47	0.45	0.61	0.38	0.49	0.53
Cr	0.06	0.09	0.12	0.01	0.00			0.00	0.01	0.00		0.01		
Fe	0.64	0.69	0.62	1.73	1.41	1.45	1.39	1.11	3.55	3.33	2.68	3.48	3.00	3.12
Mg	4.80	4.54	4.71	3.23	3.74	3.54	3.71	4.38	2.37	2.59	2.65	2.53	2.93	2.59
Na	0.06	0.04	0.05	0.06	0.12	0.23	0.11	0.04	0.16	0.21	0.20	0.19	0.19	0.18
K	1.90	1.87	1.86	1.93	1.82	1.86	1.84	1.89	1.81	1.92	1.73	1.83	1.81	1.79
Ba	0.03	0.02	0.01	0.01	0.04	0.04	0.04	0.02	0.05	0.06	0.07	0.06	0.06	0.09
Mn	0.01	0.01			0.02	0.02			0.03	0.03	0.02		0.02	0.00
Ni	0.02	0.02	0.02	0.00	0.01	0.00	0.00	0.01	0.00		0.01	0.01	0.02	0.01
Ti	0.44	0.50	0.46	0.60	0.91	0.87	0.90	0.62	0.99	0.97	0.98	0.96	0.92	1.04
F	0.92	0.78	1.15	0.59	1.44	1.55	1.58	2.13	0.38	0.65	0.64	0.73	0.61	0.92
Total	15.77	15.65	15.67	15.67	15.46	15.45	15.45	15.67	15.60	15.71	15.32	15.66	15.64	15.52

1–3 Phlogopite phenocryst cores
4 Brown Al-rich centre of phlogopite phenocryst
5–8 Phlogopite phenocryst rims and groundmass crystals
9–14 Al-poor biotite groundmass crystals
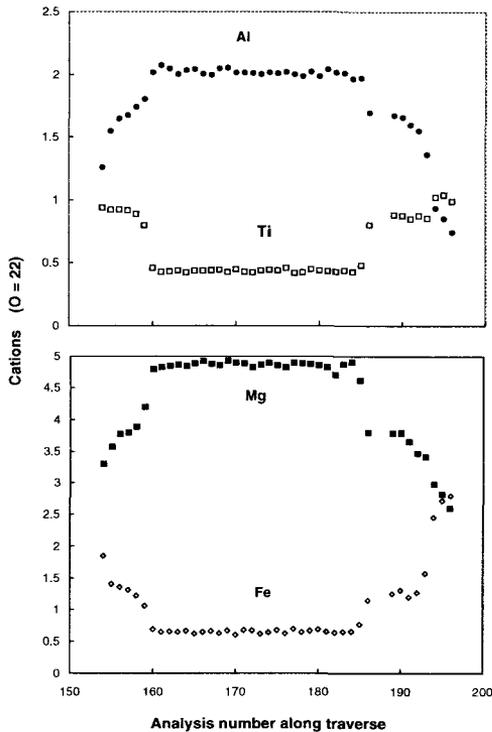
FIG. 2. Profiles across a zoned mica crystal, with phlogopite centre and biotite rim, for the elements Al, Ti, Fe and Mg. The crystal is 0.3 mm wide.

tetrahedral Ti, but without any firm evidence to justify the assumption. Farmer and Boettcher (1981) on the other hand proposed the replacement of Si and Al in tetrahedral sites by Ti and even alluded to the possible sequence of tetrahedral site preference: Si > Al > Ti > Fe^{3+}. It is, however, extremely difficult to solve the mechanisms by bulk chemical composition determinations alone and unambiguously assign the established variations to one or another solid solution scheme.

Compositional profiles in zoned mica crystals indicate the following (Fig. 2): Mg and Fe are inversely correlated, as in the normal phlogopite-annite series of compositions. Ti and Al are inversely correlated but the decrease in Al is more marked than the increase in Ti content. The Si content exceeds 6 cations p.f.u. in Ti-rich biotites but the increase in Si does not compensate for the decrease of aluminium. Figure 3 represents the variation of (Si+Al), tetrahedral cations, as a function of the variation of (Fe+Mg+Ti), reputed octahedral cations. The diagram indicates two trends: one for the brown

phlogopite phenocryst cores, (Si+Al)>8, and the phlogopite phenocrysts; the second for the reddish-brown micas, crystal rims and groundmass. A significant proportion of the biotites contain more than 6 'octahedral' cations. Our problem is then to try to determine which, among those three elements, may fill the tetrahedral site. Ti does not show a strong correlation with either Fe (positive) or Mg (negative). Nevertheless, the observation that Mg diminishes with Al is difficult to reconcile with the possible replacement of Al by Mg and suggests that another atom, either Fe or Ti, is involved. Ti remains roughly constant in the low-Al micas and it is only between Fe and Al that an inverse correlation is apparent. Such absence or presence of visible correlations are nevertheless weak arguments to establish one or the other of the possible substitution schemes. Taking into account the fact that less than half a vacant site is created by the entry of one Ti atom into the structure, and assuming that all sites in the tetrahedral layer are occupied, only two schemes need be considered among the variety of possible substitutions:

No vacancy substitution (Ti in tetrahedral site)

$$[Si_6(Mg,Fe^{2+})Ti^{4+}] \quad (Mg,Fe)_6K_2 \quad\quad (1)$$
Cations: 16 = (8+6+2)
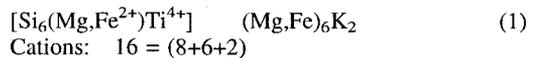
0.5 vacancy substitution (Fe in tetrahedral site, Ti in octahedral site)

$$[Si_6Fe_2^{2+}] \quad (Mg,Fe)_4\square_{0.5} \; Ti_{1.5}^{4+}K_2 \quad\quad (2)$$
Cations: 15.5 = (8+5.5+2)
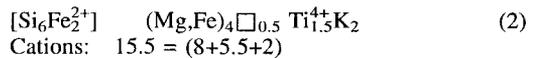
The fact that the biotites with the highest Ti content are not those that show the lowest sum of cations would tend to validate a combination of the two hypothetical schemes 1 and 2 proposed above, concomitant with a replacement of octahedral Mg with Fe. It should be noted that the existence of tetrahedrally co-ordinated Ti^{4+} has been demonstrated in potassic richterite (Della Ventura *et al.*, 1991), but never shown to exist in biotites.

Analcime

The <0.1mm equant crystals that comprise the majority of the groundmass show morphologies consistent with dodecahedral habits and appear, at first sight, to be leucite. They are cloudy in plane-polarized light and almost isotropic between crossed nicols, with faint patchy birefringence. Analcime is notoriously unstable under an electron beam and reliable results by electron microprobe analysis proved extremely difficult to obtain. They imply the presence of potassium-rich analcime (SiO_2 = 52%; Al_2O_3 = 18.5%; Na_2O = 9.2%; K_2O = 1.7%). Their chemical homogeneity has been verified by
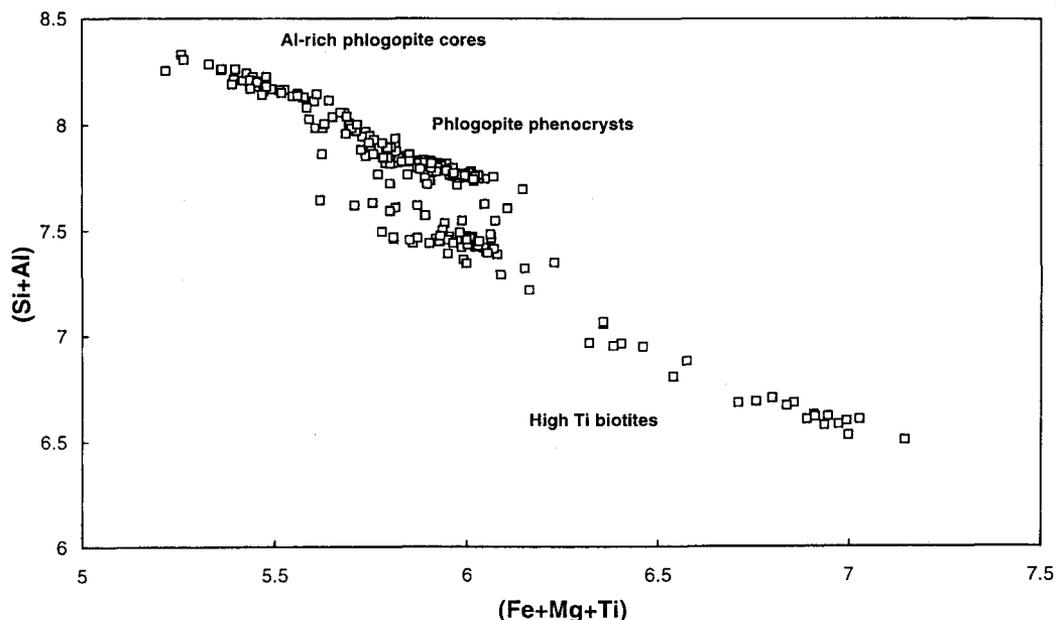
FIG. 3. Variation of tetrahedral cations (Si+Al) as a function of octahedral cations (Fe+Mg+Ti) for all analysed micas. Brown phlogopite centres have complete tetrahedral occupancy (Si+Al = 8). Phlogopites have lower (Si+Al). Rims and groundmass crystals have (Si+Al)<7.5 and lower; for a number of analyses the sum of 'octahedral' cations is >6.

SEM. Mitchell and Bergman (1991) summarised studies of leucite alteration in mafic ultrapotassic rocks and pointed out that, in lamproites, the product is usually analcime but that other phases can also occur. The composition of this phase in 6LT56 differs from that reported by Mitchell et al. (1987) for Smoky Butte analcime, in that it contains more potassium (up to 2% K_2O) and lower silicon than the latter. Hence we interpret it as pseudomorphed leucite. The unusual potassium content of the analyses is similar to that reported for analcime derived from nepheline in alkaline igneous rocks (Wilkinson and Hensel, 1994), but unlike the nearly stoichiometric analcimes found in the groundmass of the same eruptive rocks. They correspond to the L-type analcime of Luhr and Kyser (1989).

Richterite

Richterite crystals are elongated (0.5 × 0.2 mm) and poikilitic. Their composition varies little, with a slight increase in Ti (from 0.4 to 0.6 atom p.f.u.), parallel to an increase in Fe (from 1 to 1.6 atoms p.f.u.). Potassium remains below 0.9 atom and Sr is close to 0.05 atom p.f.u (Table 3, analyses 1–2).

Such characteristics bring this richterite close to that of the Cancarix and Smoky Butte lamproites, in terms of its high K content and close to the Jumilla lamproite, in terms of its high Fe and Ti contents (Wagner and Velde, 1986).

Ilmenite

Ilmenite crystals are small (0.05 mm) and euhedral. Their composition shows little variation, with MgO ~2–3% and MnO ~1%. The computation of the structural formula on the basis of two cations and 3 oxygens does not lead to the appearance of any Fe^{3+} (Table 3, analysis 3).

Diopside

The small crystals have been analysed but the zoning visible at high power could not be detailed because of the minute size of the prisms, so that specific compositions could not be ascribed to the different sectors. Although always low, in keeping with the peralkaline character of the rock, the Al_2O_3 content of the diopside varies between 0.1 and 0.5% (Table 3, analyses 4–5).

TABLE 3. Representative analyses of Middle Park lamproite minerals

	1	2	3	4	5
SiO_2	52.28	49.62	bd	52.74	51.75
Al_2O_3	0.53	0.62	0.01	0.16	0.32
FeO	7.99	13.04	41.96	6.34	6.71
MgO	17.24	13.37	3.03	14.93	14.53
CaO	6.41	4.88	bd	22.74	23.03
SrO	0.59	0.53	bd	bd	bd
Na_2O	4.06	4.61	bd	0.45	0.46
K_2O	4.54	4.47	bd	bd	bd
MnO	0.19	0.26	0.97	0.18	0.21
TiO_2	3.38	4.92	54.12	1.41	1.95
Cr_2O_3	0.03	bd	0.01	0.03	0.02
NiO	0.02	bd	0.05	bd	bd
ZrO_2	0.21	0.50	0.09	bd	bd
F	2.76	1.48	bd	bd	bd
O=F	1.16	0.62			
Total	99.07	97.68	100.24	98.98	98.98
Si	7.65	7.35		1.97	1.94
Al	0.09	0.11		0.01	0.01
Fe^{3+}				0.00	0.03
Fe^{2+}	0.98	1.62	0.87	0.20	0.18
Mg	3.76	2.95	0.11	0.83	0.81
Mn	0.02	0.03	0.02	0.01	0.01
Ca	1.01	0.78		0.91	0.93
Sr	0.05	0.05			
Na	1.15	1.32		0.03	0.03
K	0.85	0.84			
Ti	0.37	0.55	1.00	0.04	0.06
Cr	0.00			0.00	
Ni	0.00				
Zr			0.00		
F	1.28	0.69			

1 and 2, Richterite
3, Ilmenite
4 and 5, Clinopyroxene

Apatite

Apatites are abundant in the rock, as evidenced by the high P_2O_5 content reported in the bulk composition. Crystals are euhedral, and they appear in a range of sizes. Their composition does not seem to vary in any systematic fashion from centre to edge of the crystals, nor is there any compositional difference between small and large crystals. Their major character is their high F content (~4%), high SrO (1.2%), significant barium (0.5% BaO) and high *LREE* ($La_2O_3 = 0.23$ and $Ce_2O_3 = 0.39\%$). All these features are comparable to what is known of apatites from lamproites in general, and from Smoky Butte in particular (Wagner, 1987).

Geochemistry

In Table 4 the chemical composition of the Middle Park lamproite (6LT56) is compared with published and new data for lamproites from the 1–3 Ma (Mitchell and Bergman, 1991) Leucite Hills volcanic field, ~300 km to the NW. Considering major elements first, it is clear that 6LT56 shares some of the characteristic features of the Leucite Hills samples, such as SiO_2 ~50%, as well as very low Al_2O_3 (9.45%) and CaO (5.84%) for a magmatic rock with MgO >6%. Note the contrasting relatively high Al_2O_3 and CaO in representative minettes (Table 4, 89SB232 and 7993) and the relatively low SiO_2 and high CaO in representative kamafugites (Table 4,

4342 and 92SOB100). The forgoing points are summarized on Fig. 4; two plots that have been used in previous attempts to classify lamproites and allied rock types.

Although sample 6LT56 is peralkaline [mole $(K_2O + Na_2O)/Al_2O_3 = 1.14$] it is neither perpotassic nor ultrapotassic. Nevertheless, published descriptions of lamproites with mineralogy like 6LT56 have much higher K_2O and lower Na_2O. Presumably the alteration of the leucite has changed the abundances of these two oxides (cf. Venturelli *et al.*, 1991; Ferriz *et al.*, 1994; Salvioli-Mariani and Venturelli, 1996),
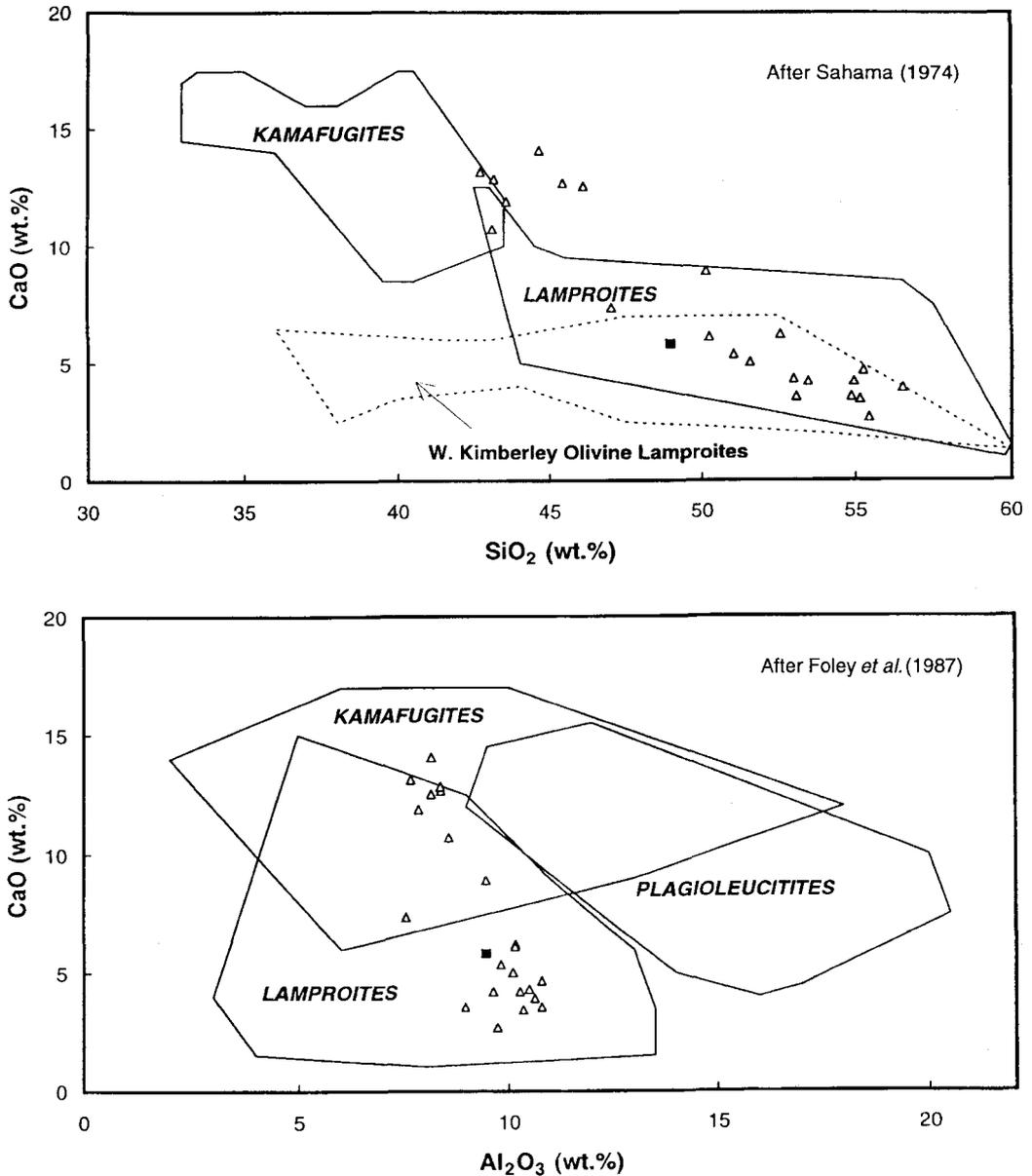
FIG. 4. Middle Park lamproite (filled square) plotted on two diagrams used to classify mafic ultrapotassic igneous rocks. Data for Leucite Hills lamproites (open triangles) – from Carmichael (1967), Kuehner *et al.* (1981), Thompson *et al.* (1984) and Table 4 – are also shown for comparison.

TABLE 4. Chemical composition of Middle Park lamproite and other mafic potassic magmatic rocks

Sample	6LT56	MAD1	MAD2	5LT269	5LT271	5LT287	5LT288	5LT289	5LT291	89SB232	7993	4342	92SOB100
Locality	Middle Park Leucite Hills Wyoming	Leucite Hills Wyoming	Leucite Hills Wyoming	Leucite Hills Wyoming Pilot Butte	Leucite Hills Wyoming Cabin Butte	Leucite Hills Wyoming Boars Tusk	Leucite Hills Wyoming North Table	Leucite Hills Wyoming Middle Table	Leucite Hills Wyoming South Table	Two Buttes, Colorado	Sedberg, Cumbria	Bufumbira, Uganda	Alto Paranaiba
Wt.%													
SiO_2	48.94	44.65	45.43	46.10	55.24	52.54	56.50	50.14	54.94	50.25	50.72	43.15	45.45
TiO_2	4.69	2.25	2.30	2.56	2.62	2.47	2.63	2.65	2.36	1.29	1.05	3.71	5.60
Al_2O_3	9.45	8.16	8.38	8.15	10.80	10.16	10.63	9.47	9.63	12.55	11.30	12.24	8.02
Fe_2O_3	9.83	6.38	6.44	6.67	3.89	5.04	4.04	5.87	4.70	9.15	7.50	13.08	14.50
MnO	0.14	0.12	0.12	0.13	0.05	0.07	0.05	0.10	0.06	0.15	0.16	0.20	0.18
MgO	8.81	12.30	12.61	11.99	6.77	7.72	6.82	9.93	9.87	9.40	11.92	8.54	8.40
CaO	5.84	14.06	12.67	12.54	4.68	6.23	3.94	8.92	4.21	9.51	9.76	11.83	11.44
Na_2O	3.65	0.93	1.01	0.89	1.44	1.63	1.20	0.83	1.26	2.00	0.87	2.03	1.32
K_2O	4.38	7.18	7.90	7.79	12.08	10.30	12.10	9.20	10.89	5.02	5.71	3.40	2.30
P_2O_5	2.69	3.04	1.88	1.50	1.72	1.91	1.72	1.57	1.58	0.40	1.23	0.62	0.66
Total	98.42	99.07	98.74	98.32	99.29	98.07	99.63	98.68	99.50	99.72	100.22	98.80	97.87
LOI	3.19			4.12	1.62	1.55	1.15	2.93	1.16	5.07			1.87
ppm													
Ba	1891	5844	7404	9223	5961	8567	5882	9496	3717	2162	4120	1119	38611
Cr	463	488	523	536	352	568	379	503	527	426	563	369	37
Hf	27.1	40.8	39.3							4.6	8.18	10.4	18.31
Nb	174	131	128	151	61	78	51	111	49	12.6	11.2	108	315
Ni	296	173	184	177	234	225	275	193	412	104	405	74	115
Rb	117	201	228	256	312	286	288	294	264	120	186	127	418
Sc	24.5									30			30
Sr	1797	3663	5433	4500	2978	2489	1939	4671	2153	645	2063	1005	1978
Ta	8.1	6.52	8.92							0.75	0.9	9.12	18.36
Th	17.8	37.8	49.8							9.24	39.6	11.3	35.19
U	6.4	8.43	11.1							2.38	6.99	2.25	7.16
V	155			61	82	144	105	136	102	217			686
Y	42	27	26	26	15	15	14	18	18	26	32	29	36
Zn	276	98	103	108	79	88	80	119	96	150	72	97	97
Zr	1140	1587	1734	1631	1640	1615	1650	1697	1559	180	379	306	860

TABLE 4 (contd.)

Sample	6LT56	MAD1	MAD2	5LT269	5LT271	5LT287	5LT288	5LT289	5LT291	89SB232	7993	4342	92SOB100
Locality	Middle Park	Leucite Hills Wyoming	Leucite Hills Wyoming	Leucite Hills Wyoming Pilot Butte	Leucite Hills Wyoming Cabin Butte	Leucite Hills Wyoming Boars Tusk	Leucite Hills Wyoming North Table	Leucite Hills Wyoming Middle Table	Leucite Hills Wyoming South Table	Two Buttes, Colorado	Sedberg, Cumbria	Bufumbira, Uganda	Alto Paranaiba
La	247.7	347	338							50	120	81	270
Ce	540.4	605	630							113	235	164	494
Pr	58.6	69.0	69.9								25.1	14.9	
Nd	209.3	258	265							54.0	112	64	220
Sm	27.6	30.3	30.6							9.8	19.05	10.7	33.18
Eu	6.28	6.78	6.82							2.77	5.42	2.97	7.82
Gd	24.7	16.05	16.00							7.5	13.4	8.1	23.31
Tb	1.98	2.00	2.01								1.74	1.18	2.68
Dy	8.23	6.48	6.69								6.24	5.51	
Ho	1.28	1.15	1.10								1.05	1.01	
Er	3.00												
Tm	0.41												
Yb	2.29	1.33	1.28							1.95	1.97	2.11	3.81
Lu	0.32	0.19	0.20							0.30	0.29	0.34	0.38
$^{87}Sr/^{86}Sr_m$	0.706062									0.707627			0.706503
$(^{143}Nd/^{144}Nd)_m$	0.511658									0.512392			0.512303
$^{87}Sr/^{86}Sr_i$	0.705974									0.707375			0.705767
$(^{143}Nd/^{144}Nd)_i$	0.511641									0.512368			0.512252
ϵ_{Nd}	−18.63									−4.44			−5.43

Major elements calculated on a volatile-free basis; total iron reported as Fe_2O_3. Of the trace elements in 6LT56: Ba, Cr, Nb, Ni, Rb, Sr, V, Y, Zn and Zr were analysed by XRF (University of Birmingham); others by ICPMS (University of Durham); further ICPMS data are Cs 6.34, Cu 39.0, Pb 16.0 ppm. Nd and Sm were also determined by isotope dilution (McMaster University); Nd 191.9, Sm 25.3 ppm. Nd isotopes normalized to $^{146}Nd/^{144}Nd = 0.7219$; see Leat et al. (1990) for details of analytical techniques and errors. Initial Sr and Nd isotopic ratios for the Middle Park lamproite are calculated to 33 Ma.

6LT56, Middle Park lamproite; MAD1, MAD2, 7993 and 4342 (Thompson et al., 1984); 89SB232 (Gibson et al., 1993); 92SOB100 (Gibson et al., 1995a); 5LT269, 271, 287, 288, 289 and 291, new analyses.

by exchange with circulating groundwater. Therefore it seems prudent to be cautious about treating the abundances of SiO_2 and Al_2O_3, and the trace elements Ba and Rb, as magmatic values.

Figure 5 is a normalized plot comparing a range of incompatible-element abundances in 6LT56 with those in a typical Leucite Hills lamproite. If K, Ba, Rb and Sr are excluded from consideration, the two rock-types have similar incompatible-element abundances and ratios. The Leucite Hills sample (MAD1), has a somewhat steeper rare-earth-element pattern slope than 6LT56. The other elements that show appreciable differences – Th, Zr, Hf and Ti – are all prone to significant abundance variations from locality to locality in lamproites and minettes (e.g. Thompson *et al.*, 1989; Mitchell and Bergman, 1991; Gibson *et al.*, 1992, 1993). Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ of 6LT56 are also very similar to the range of these isotopic ratios in the Leucite Hills lamproites (Mitchell and Bergman, 1991, table 7.20). On a plot of these ratios, the point for Middle Park ($\varepsilon_{Nd} = -18.6$) falls between the fields for Leucite Hills phlogopite lamproites and Smoky Butte lamproites.

Discussion

Reports of new lamproite occurrences tend to focus on their exotic mineralogy and chemical compositions. A somewhat different emphasis is appropriate in discussion of the Middle Park lamproite, as it occurs in a region with a long and varied tectonomagmatic history and it is quite closely associated in space and time with basaltic (*s.l.*) magmatism. Because this very small pluton is represented by only a single sample, we can extract no information about its mantle source from internal geochemical trends. Nevertheless, we can borrow from the consensus of geochemical research on mafic ultrapotassic rock-types in recent years (e.g. Eggler *et al.*, 1988; Mitchell and Bergman, 1991; Foley, 1992; Carlson and Irving, 1994; Gibson *et al.*, 1995a, b; Pearson *et al.*, 1995; Carlson *et al.*, 1996) and assert that the mantle source of this lamproite was almost certainly entirely within the
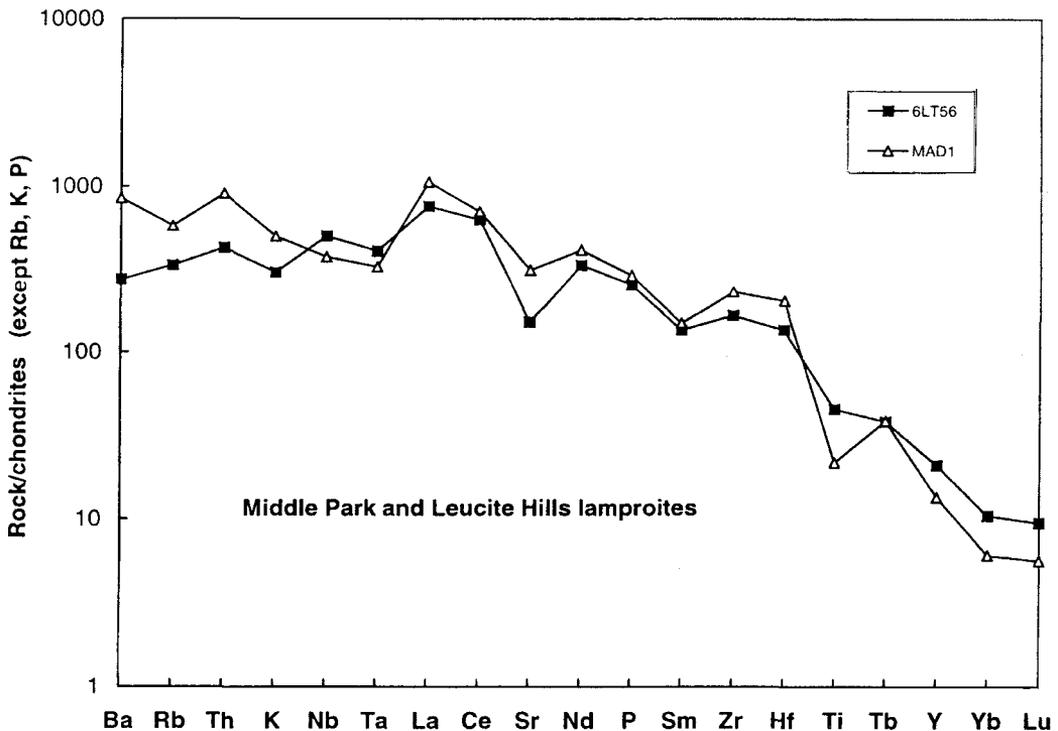
FIG. 5. Normalized abundances for a range of elements in Middle Park lamproite (6LT56) and a Leucite Hills madupitic lamproite (MAD1) analysed by Thompson *et al.* (1984). The normalizing factors are average chondrites, except for K, Rb and P, which are bulk-Earth values (Thompson *et al.*, 1984).

long-term stable mechanical boundary layer of the subcontinental lithospheric mantle.

Current research on the osmium-isotope systematics of these rock-types has clarified the geochemical picture further (Carlson and Irving, 1994; Pearson *et al.*, 1995). It appears probable that the lithospheric source of lamproites and closely allied magmas was strongly depleted in its basaltic fraction during continent formation, subsequently invaded by one or more episodes of very-small-melt-fraction magmatism from the underlying convecting mantle, as previously suggested by Frey and Green (1974) and McKenzie (1989). This metasomatized lithosphere was later 'reactivated' slightly, so that – in the case of some magma batches with extreme compositions – essentially only the veins melted (Carlson *et al.*, 1996). Possible causes for such reactivation of long-stable lithospheric mantle are: (1) Extension, causing decompression; (2) Heating from below by a mantle plume; (3) Thickening and subsequent delamination of part of the overthickened lithosphere, in an orogenic cycle (McKenzie, 1989; von Blanckenburg and Davies, 1995). Lamproitic and allied mafic ultrapotassic magmatism tends to occur either at the onset of such events or – when they have progressed to mostly basaltic (*s.l.*) volcanism – around their geographic fringes (Thompson *et al.*, 1989; Gibson *et al.*, 1992, 1993).

Mantle source of the Middle Park lamproite

The Sr and Nd initial isotopic ratios of the Middle Park lamproite are within the range of those characteristic of the Cenozoic mafic ultrapotassic magmatism that occurs throughout the parts of Wyoming and Montana underlain by the Wyoming craton (Eggler *et al.*, 1988), and also adjacent to the NW margin of this craton in the Great Falls tectonic zone, which was active during the mid-Proterozoic (Carlson and Irving, 1994). The Middle Park lamproite outcrops about 130 km south of the Cheyenne Belt (Houston *et al.*, 1989, Fig. 2), a major structural boundary in southern Wyoming that marks the boundary, at the surface, between the Archaean Wyoming craton and the Proterozoic rocks that form the crustal basement throughout NW Colorado (Fig. 1). The Proterozoic region is dominated by ~1.8 Ga arc volcanic rocks and associated calcalkaline plutons; emplacement of the youngest major plutons was completed by ~1.4 Ga (Houston *et al.*, 1989). These dates bracket the Nd-isotope model age of the Middle Park lamproite (T_{DM} = 1.6 Ga) and it therefore seems reasonable to suppose that the precursor event that established the lithospheric mantle source of the Middle Park lamproite took place during final stabilization of the continent in this region.

Tectonomagmatic context of the Middle Park lamproite

Figure 1 has been drawn to emphasise how closely the Middle Park lamproite is associated with other magmatism. Its locality is surrounded by a Miocene 23–26 Ma basalt-latite-rhyolite suite of lavas and related hypabyssal plutons (Izett, 1974). Extensive Oligocene basalt-andesite lavas and pyroclastic rocks crop out ~30 km west of the lamproite (Rabbit Ears Volcanics) and ~30 km north of it, between Specimen Mountain and Cameron Pass (Izett, 1975). These volcanic rocks are presumably remnants of quite an extensive field because there are dated rhyolitic ignimbrites within the successions of both main outcrops. The age of these – 28 to 31 Ma (Izett and Barclay, 1973; Izett, 1975), if their unpublished precisions are reasonable – is scarcely younger than the lamproite, which may therefore be viewed as either a precursor or an outlying member (or both) of this basalt-dominated volcanism. Finally, the Windy Gap Member of the Late-Cretaceous succession ~10 km west of Granby (Fig. 1) contains laharic debris with andesitic clasts up to 40 cm in diameter (our unpublished analyses). Although these clasts may have travelled as much as several tens of kilometres from their source volcanoes, the latter cannot be far from the lamproite. Late-Miocene and Pliocene magmatism does not appear to be present in North and Middle Parks but it is widespread just to the west, in the Elkhead Mountains (8.7–11.6 Ma) and Yampa (5.3–5.9 Ma) volcanic fields (Fig. 1). Minettes occur in small numbers in both fields. They are accompanied by potassic basalts (shoshonites *s.l.*) in the Elkhead Mountains, whilst the varied Yampa magmatism ranges to basanites that resemble typical ocean-island basalts, in terms of both elemental and isotopic ratios (Leat *et al.*, 1991; our unpublished analyses).

It is clear from this summary that the Laramide (Late Cretaceous)-to-Present magmatic history of NW Colorado is extremely similar to the Cenozoic volcanic sequence throughout much of the southwestern USA; NW Colorado has undergone rather limited extension but is otherwise 'normal' (e.g. Izett, 1975; Tweto, 1979a; Gans *et al.*, 1989; Fitton *et al.*, 1991; Gibson *et al.*, 1992; Davis and Hawkesworth, 1995). Throughout the south-west, basalt-to-andesite magmatism of broadly calcalkaline or shoshonitic affinities was succeeded by basalts and basanites resembling those of oceanic islands. It is inappropriate here to add to the countless general discussions of southwestern USA Cenozoic tectono-magmatic evolution (e.g. Lipman, 1980; Gans *et al.*, 1989; Best and Christiansen, 1991; Harry and Leeman, 1995; Hawkesworth *et al.*, 1995) but the Middle Park lamproite throws a fascinating new

ingredient into such debates because it was emplaced in the midst of an otherwise utterly 'typical' example of this tectonomagmatic sequence. There is near-unanimity that the tectonomagmatic history of the southwestern USA has involved lithospheric thinning but a detailed understanding of the extent and rates of this process throughout the Cenozoic is elusive because, although the geochemistry of the mafic magmas provides the best clues, these tend to be vague and ambiguous. Nevertheless, in NW Colorado we have two clearcut end-members to the hypothetical lithospheric thinning story: (1) Devonian diamondiferous kimberlites in the Front Range contain xenoliths originating from lithospheric mantle ~200 km thick (Eggler *et al.*, 1988); (2) Pliocene OIB-like basanites at Yampa (Fig. 1) have rare-earth element abundances and ratios closely similar to basanites along the axis of the Rio Grande rift, in the Espanola Basin, New Mexico (Gibson *et al.*, 1992). The latter erupted through lithosphere measured by teleseismic tomography to be ~70 km thick (Davis *et al.*, 1993).

We can use two approaches to estimate the lithospheric thickness beneath Middle Park at 33 Ma, when the lamproite was emplaced. Firstly, teleseismic tomographic studies of the part of the Wyoming craton that gave rise to the similar Leucite Hills lamproites at 1−3 Ma show a lithosphere between 150 and 200 km thick (Humphreys and Dueker, 1994, Fig. 10k). Secondly, mafic ultrapotassic magmas (minettes rather than lamproites) bearing lithospheric mantle xenoliths were erupted during the Eocene in the NW sector of the Wyoming craton and the Miocene on the Colorado Plateau (Alibert *et al.*, 1986; Hearn, 1989). In both cases the highest equilibration pressures calculated from the mineral assemblages of the xenoliths are ~150 km or more (McKenzie, 1989; Carlson and Irvine, 1994). If the lithospheric thickness beneath Middle Park was still ~150 km or more at 33 Ma, it is remarkable that extensive basaltic magmatism broke out in that region so shortly afterwards. Clearly there is future progress to be made in understanding the Cenozoic tectonomagmatic evolution of the southwestern USA, by focusing on small but significant details, such as the Middle Park lamproite.

References

Alibert, C., Michard, A. and Albarede. F. (1986) Isotope and trace element geochemistry of the Colorado Plateau volcanics. *Geochim. Cosmochim. Acta*, **50**, 2735−76.

Best, M.G. and Christiansen, E.H. (1991) Limited extension during peak Tertiary volcanism, Great Basin of Nevada and Utah. *J. Geophys. Res.*, **96**, 13509−28.

Bol, L.C.G.M., Bos, A., Sauter, P.C.C. and Jansen, J.B.H. (1989) Barium-titanium-rich phlogopites in marbles from Rogaland, southwest Norway. *Amer. Mineral.*, **74**, 439−47.

Carlson, R.W. and Irving, A.J. (1994) Depletion and enrichment history of subcontinental lithospheric mantle: an Os, Sr, Nd and Pb isotopic study of ultramafic xenoliths from the northwestern Wyoming Craton. *Earth Planet. Sci. Lett.*, **126**, 457−72.

Carlson, R.W., Esperança, S. and Svisero, D.P. (1996) Chemical and Os isotopic study of Cretaceous potassic rocks from southern Brazil. *Contrib. Mineral. Petrol.*, submitted.

Carmichael, I.S.E. (1967) The mineralogy and petrology of volcanic rocks from the Leucite Hills, Wyoming. *Contrib. Mineral. Petrol.*, **15**, 24−66.

Davis, J.M. and Hawkesworth, C.J. (1995) Geochemical and tectonic transitions in the evolution of the Mogollon-Datil Volcanic Field, New Mexico, U.S.A. *Chem. Geol.*, **119**, 31−53.

Davis, P.M., Slack, P., Dalheim, H.A., Green, W.V., Meyer, R.P., Achauer, U., Glahn, A. and Granet, M. (1993) Teleseismic tomography of continental rift zones. In *Seismic Tomography: Theory and Practice* (H.M. Iyer and K. Hirahara, eds.), Chapman and Hall, 397−439.

Della Ventura, G., Robert, J.L. and Bény, J.M. (1991) Tetrahedrally coordinated Ti^{4+} in synthetic Ti-rich potassic richterite: evidence from XRD, FTIR and Raman studies. *Amer. Mineral.*, **76**, 1134−40.

Dymek, R.F. (1983) Titanium, aluminium and interlayer cation substitutions in biotite from high-grade gneisses, West Greenland. *Amer. Mineral.*, **68**, 880−99.

Eaton, G.P. (1986) A tectonic redefinition of the Southern Rocky Mountains. *Tectonophysics*, **132**, 163−93.

Eggler, D.H., Meen, J.K., Welt, F., Dudas, F.O., Furlong, K.P., McCallum, M.E. and Carlson, R.W. (1988) Tectonomagmatism of the Wyoming Province. *Colo. Sch. Mines Quart.*, **83**, 25−40.

Farmer, G.L. and Boettcher, A.L. (1981) Petrologic and

crystal-chemical significance of some deep-seated phlogopites. *Amer. Mineral.*, **66**, 1154−63.

Ferriz, F.J., Fernandez Soler, J.M. and Camara, F. (1994) Presencia de afloramientos de lamproitas en las proximidades de Moratalla y Cehegin (Murcia). *Bol. Soc. Espan. Mineral.* **17**, 231−9.

Fitton, J.G., James, D. and Leeman, W.P. (1991) Basic magmatism associated with late Cenozoic extension in the western United States; compositional variations in space and time. *J. Geophys. Res.*, **96**, 13693−711.

Foley, S.F. (1992) Vein-plus-wall-rock melting mechanisms in the lithosphere and the origin of potassic alkaline magmas. *Lithos*, **28**, 435−53.

Foley, S.F., Venturelli, G., Green, D.H. and Toscani, L. (1987) The ultrapotassic rocks: characteristics, classification and constraints for petrogenetic models. *Earth-Sci. Rev.*, **24**, 81−134.

Frey, F.A. and Green, D.H.. (1974) The mineralogy, geochemistry and origin of lherzolite inclusions in Victorian basanites. *Geochim. Cosmochim. Acta*, **38**, 1023−59.

Gans, P.B., Mahood, G.A. and Schermer, E. (1989) Synextensional magmatism in the Basin and Range Province; a case study from the eastern Great Basin. *Geol. Soc. Amer. Spec. Paper*, **233**, 1−53.

Gibson, S.A., Thompson, R.N., Leat, P.T., Dickin, A.P., Morrison, M.A., Hendry, G.L. and Mitchell, J.G. (1992) Asthenosphere-derived magmatism in the Rio Grande rift, western USA: implications for continental break-up. In *Magmatism and the Causes of Continental Break-up* (B.C. Storey, T. Alabaster and R.J. Pankhurst eds.), Geol. Soc. London Spec. Publ., **68**, 61−89.

Gibson, S.A., Thompson, R.N., Leat, P.T., Morrison, M.A., Hendry, G.L., Dickin, A.P. and Mitchell, J.G. (1993) Ultrapotassic magmas along the flanks of the Oligo-Miocene Rio Grande rift, USA: monitors of the zone of lithospheric mantle extension and thinning beneath a continental rift. *J. Petrol.*, **34**, 187−228.

Gibson, S.A., Thompson, R.N., Leonardos, O.H., Dickin, A.P. and Mitchell, J.G. (1995a) The Late Cretaceous impact of the Trindade mantle plume: evidence from large-volume, mafic, potassic magmatism in SE Brazil. *J. Petrol.*, **36**, 189−229.

Gibson, S.A., Thompson, R.N., Dickin, A.P. and Leonardos, O.H. (1995b) High-Ti and low-Ti mafic potassic magmas: key to plume-lithosphere interactions and continental flood-basalt genesis. *Earth Planet. Sci. Lett.*, **136**, 149−65.

Harry, D.L. and Leeman, W.P. (1995) Partial melting of melt-metasomatized subcontinental mantle and the magma source potential of the lower lithosphere. *J. Geophys. Res.*, **100**, 10255−69.

Hawkesworth, C., Turner, S., Gallagher, K., Hunter, A., Bradshaw, T, and Rogers, N. (1995) Calc-alkaline magmatism, lithospheric thinning and extension in the Basin and Range. *J. Geophys. Res.*, **100**, 10271−86.

Hearn, B.C., Jr., (1989) Alkaline ultramafic magmas in north-central Montana, USA: genetic connections of alnöite, kimberlite and carbonatite. In *Kimberlites and Related Rocks, 1* (A.L. Jaques, J. Ferguson and D.H. Green, eds.), Geol. Soc. Austr. Spec. Publ., **14**, 109−19.

Houston, R.S., Duebendorfer, E.M., Karlstrom, K.E. and Premo, W.R. (1989) A review of the geology and structure of the Cheyenne belt and Proterozoic rocks of southern Wyoming. *Geol. Soc. Amer. Spec. Pap.*, **235**, 1−12.

Humphreys, E.D. and Dueker, K.G. (1994) Western U.S. upper mantle structure. *J. Geophys. Res.*, **99**, 9615−34.

Izett, G.A. (1974) Geologic map of the Trail Mountain quadrangle, Grand County, Colorado. *U. S. Geol. Surv. Map*, GQ-1156.

Izett, G.A. (1975) Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas. *Mem. Geol. Soc. Amer.*, **144**, 179−209.

Izett, G.A. and Barclay, C.S.V. (1973) Geologic map of the Kremmling quadrangle, Grand County, Colorado. *U. S. Geol. Surv. Map*, GQ-1115.

Kuehner, S.M., Edgar, A.D. and Arima, M. (1981) Petrogenesis of the ultrapotassic rocks from the Leucite Hills, Wyoming. *Amer. Mineral.*, **66**, 663−77.

Leat, P.T., Thompson, R.N., Morrison, M.A., Hendry, G.L. and Dickin, A.P. (1988) Silicic magmas derived by fractional crystallization from Miocene minette, Elkhead Mountains, Colorado. *Mineral. Mag.* **52**, 577−85.

Leat, P.T., Thompson, R.N., Morrison, M.A., Hendry, G.L. and Dickin, A.P. (1990) Geochemistry of mafic lavas in the early Rio Grande rift, Yarmony Mountain, Colorado, U.S.A. *Chem. Geol.*, **81**, 23−43.

Leat, P.T., Thompson, R.N., Morrison, M.A., Hendry, G.L. and Dickin, A.P. (1991) Alkaline hybrid mafic magmas of the Yampa area, NW Colorado, and their relationship to the Yellowstone mantle plume and lithospheric mantle domains. *Contrib. Mineral. Petrol.*, **107**, 310−27.

Lipman, P.W. (1980) Cenozoic volcanism in the western United States: implications for continental tectonics. In *Continental Tectonics*, U.S. Nat. Acad. Sci., 161−74.

Luhr, J.F. and Kyser, T.K. (1989) Primary igneous analcime: the Colima minettes. *Amer. Mineral.*, **74**, 216−223.

McKenzie, D.P. (1989) Some remarks on the movement of small melt fractions in the mantle. *Earth Planet. Sci. Lett.*, **95**, 53−72.

Mitchell, R.H. and Bergman, S.C. (1991) *Petrology of*

Lamproites. Plenum Press, 1–447.

Mitchell, R.H., Platt, R.G. and Downey, M. (1987) Petrology of lamproites from Smoky Butte, Montana. *J. Petrol.,* **28,** 645–77.

Mokhtari, A, Wagner, C. and Velde, D (1985) Presence of late crystallizing ferriannite-rich annite in basic eruptive rocks from Morocco. *Neues Jahrb. Mineral. Mh.,* 513–20.

Pearson, D.G., Rogers, N.W., Irving, A.J., Smith, C.B. and Hawkesworth, C.J. (1995) Source regions of kimberlites and lamproites: constraints from Re-Os isotopes. *Sixth Kimb. Conf., Novosibirsk, Russia, extended abs.,* 430–2.

Sahama, T.G. (1974) Potassium-rich alkaline rocks. In *The Alkaline Rocks* (H. Sorensen, ed.), John Wiley, 96–109.

Salvioli-Mariani, E. and Venturelli, G. (1996) Temperature of crystallization and evolution of the Jumilla and Cancarix lamproites (SE Spain), as suggested by melt and solid inclusions in minerals. *Europ. J. Mineral.,* **8,** 1027–39.

Snyder, G.L. (1980) Geologic map of the northernmost Gore Range and southernmost Northern Park Range, Grand, Jackson and Routt Counties, Colorado. *U. S. Geol. Surv. Map,* **I-1114.**

Steiger, R.H. and Jäger, E. (1977) Convention on the use of decay constraints in geo- and cosmochronology. *Earth Planet. Sci. Lett.,* **86,** 359–62.

Thompson, R.N., Morrison, M.A., Hendry, G.L. and Parry, S.J. (1984). An assessment of the relative roles of crust and mantle in magma genesis: an elemental approach. *Phil. Trans. Roy. Soc. Lond.,* **A310,** 549–90.

Thompson, R.N., Leat, P.T., Dickin, A.P., Morrison, M.A., Hendry, G.L. and Gibson, S.A. (1989) Strongly potassic mafic magmas from lithospheric mantle sources during continental extension and heating: evidence from Miocene minettes of northwest Colorado, U.S.A. *Earth Planet. Sci. Lett.,* **98,** 139–53.

Thompson, R.N., Gibson, S.A., Leat, P.T., Mitchell, J.G., Morrison, M.A., Hendry, G.L. and Dickin, A.P. (1993) Early Miocene continental extension-related basaltic magmatism at Walton Peak, northwest

Colorado: further evidence on continental basalt genesis. *J. Geol. Soc. Lond.,* **150,** 277–92.

Tweto, O. (1979*a*) The Rio Grande rift system in Colorado. In *Rio Grande Rift: Tectonics and Magmatism* (R.E. Riecker, ed.), Amer. Geophys. Union, 33–56.

Tweto, O. (1979*b*) Geologic map of Colorado. Scale 1:500,000. *U. S. Geol. Surv. Map.*

Venturelli, G., Capedri, S., Barbieri, M, Toscani, L, Salvioli-Mariani, E. and Zerbi, M. (1991). The Jumilla lamproite revisited: a petrological oddity. *Europ. J. Mineral.,* **3,** 123–45.

von Blanckenburg, F. and Davies, J.H. (1995) Slab breakoff: a model for syncollisional magmatism and tectonics in the Alps. *Tectonics,* **14,** 120–31.

Wagner,C. (1987) *Contributions a l'étude minéralogique et géochimique des roches hyperalcalines potassiques. Lamproites et roches voisines.* Unpublished Thèse de Doctorate d'État, Université P. et M. Curie, 87-23, 273 pp.

Wagner, C. and Velde, D. (1986) The mineralogy of K-richterite-bearing lamproites. *Amer. Mineral.,* **71,** 17–37.

Wagner,C. and Velde, D (1987) Aluminous spinels in lamproites: occurrence and probable significance. *Amer. Mineral.,* 72, 689–96

Wendlandt, R.F. (1977) Barium-phlogopite from Haystack Butte, Highwood Mountains, Montana. *Ann. Rept. Carnegie Inst. Wash. Ybk.,* **76,** 534–9.

Wilkinson, J.F.G. and Hensel, H.D. (1994) Nephelines and analcimes in some alkaline igneous rocks. *Contrib. Mineral. Petrol.,* 118, 79–91.

Wilkinson, P., Mitchell, J.G., Cattermole, P.J. and Downie, C. (1986) Volcanic chronology of the Meru-Kilimanjaro region, northern Tanzania. *J. Geol. Soc. Lond.,* **143,** 601–5

Woolley, A.R., Bergman, S.C., Edgar, A.D., Le Bas, M.J., Mitchell, R.H., Rock, N.M.S. and Scott Smith, B.H. (1996) Classification of lamprophyres, lamproites, kimberlites, and the kalsilitic, melilitic and leucitic rocks. *Canad. Mineral.,* **34,** 175–86.