

Petrology of ultramafic lamprophyres from the Beaver Lake area of Eastern Antarctica and their relation to the breakup of Gondwanaland

S. F. Foley¹, A. V. Andronikov², and S. Melzer³

¹Institut für Geologische Wissenschaften, Universität Greifswald, Greifswald, Germany

²Department of Geological Sciences, University of Michigan, Ann Arbor, Mi, U.S.A.

³Projektbereich 4.1, Geoforschungszentrum Potsdam, Potsdam, Germany

With 6 Figures

Received March 31, 2000;

revised version accepted September 3, 2001

Summary

Mesozoic melilite-bearing ultramafic lamprophyres are developed as sill, dyke and plug-like intrusive bodies in the East Antarctic Beaver Lake area. They consist of varying amounts of olivine, melilite, phlogopite, nepheline, titanomagnetite and perovskite as major phases, accompanied by minor amounts of apatite, carbonate, spinel, glass and, rarely, monticellite. The rocks are mineralogically and geochemically broadly similar to olivine melilitites, differing in higher CO₂ and modal phlogopite and carbonate contents. The ultramafic lamprophyres are MgO-rich (13.4–20.5 wt%) and SiO₂-poor (32.8–37.2 wt%), indicative of a near-primary nature. Major and trace element features are consistent with minor fractionation of olivine and Cr-spinel from melts originating at depths of 130–140 km.

Primary melts originated by melting of upper mantle peridotite which had been veined by phlogopite + carbonate + clinopyroxene-bearing assemblages less than 200 Ma before eruption. The presence of the veins and their time of formation is required to explain high incompatible trace element contents and growth of ⁸⁷Sr/⁸⁶Sr, leaving ¹⁴³Nd/¹⁴⁴Nd unaffected. The major element, compatible trace element, and most radiogenic isotope characteristics are derived from melting of the wall-rock peridotite. The depth of about 130 km is indicated by the presence of phlogopite rather than amphibole in the veins, by control of the REE pattern by residual garnet, by the high MgO content of the rocks, and by the expected intersection of the rift-flank geotherm with the solidus at this depth. The higher CO₂ contents than are characteristic for olivine melilitites favoured the crystallization of melilite at crustal pressures, and suppressed the crystallization of clinopyroxene. The Beaver Lake ultramafic lamprophyres are a distal effect of the

breakup of Gondwanaland, too distal to show a geochemical signature of the Kerguelen plume. Upward and outward movement of the asthenosphere-lithosphere boundary beneath the Lambert-Amery rift led first to the production of phlogopite- and carbonate-rich veins, and later to the generation of the ultramafic lamprophyres themselves.

Introduction

Ultramafic lamprophyres (UML) are rare, but widespread, hypabyssal rocks rich in K, Mg, Cr, Ni, Sr, Ba, REE, and volatiles, containing less Si and more Ca than most other silicate igneous rocks (*Rock, 1986*). Their mineralogy is characterized by phenocrysts of magnesian olivine, Ti-rich phlogopite, Ti-augite and rarely richteritic amphibole. The groundmass may be made up of feldspathoids, melilite, Ca–Fe–Mg carbonates (partly primary), Mg–Mn-ilmenite, perovskite, Ti–Cr-spinel, Ti-magnetite, monicellite, and glass. UML can also contain various deep-seated xenoliths.

UML may be subdivided, following *Rock (1986, 1991)*, into two common types defined by the predominance of either melilite or carbonate in the groundmass as alnöite (v. *Eckermann, 1966*) and aillikite (*Malpas et al., 1986*), respectively. Rarer types include polzenite (melilite and feldspathoids in the groundmass), ouachitite (feldspathoids and carbonates) and damkjernite (feldspathoids, carbonates and rare alkali feldspars).

The intrusive UML bodies of the Beaver Lake area in the northern Prince Charles Mountains (Fig. 1) are one of only three currently known occurrences of the UML in East Antarctica. The other two are Proterozoic damkjernite dykes in the Vestfold Hills area (*Delor and Rock, 1991; Mikhalsky et al., 1994*), and Paleozoic ouachitite dykes at Schirmacher Oasis (*Hoch, 1999*).

The Beaver Lake occurrences are related to the Lambert-Amery rift system, the largest continental rift system in Antarctica (*Kurinin and Grikurov, 1980*), and can be divided into two separate spatial groups (Fig. 1). The northern group is represented by a dyke and two-multiphase stocks, known as the Novoe and Konus bodies. In the Konus body a tuffaceous breccia of alkaline nepheline-rich picrite is later intruded by ultramafic lamprophyre. The Novoe body contains three phases of emplacement: autolithic kamafugite breccia, ultramafic lamprophyre, and nepheline-rich alkaline picrite. Following *Mitchell (1986)*, the dyke and the Novoe intrusion may represent different erosion levels of the root zone of a diatreme-like intrusive, whereby the dyke represents a diatreme-related dyke, and the Novoe body can be considered a “blow of a diatreme”. The dyke is 1–2 m thick and is located 500 m west of the Novoe body (Fig. 1; *Andronikov and Egorov, 1993*). All intrusives of the northern group were emplaced into metamorphic rocks of the Precambrian crystalline basement.

The southern group is represented by two sills \approx 12 m and 5 m thick which intrude Permian sediments and crop out on the southern shore of Radok Lake (Fig. 1). Only the lower sill Radok-1 is treated here; the other is highly serpentinized and has, therefore, not been investigated in detail. The Radok-1 sill dips between 5 and 10° to the southeast and can be traced for 950 m along outcrop. The timing of the emplacement is constrained by K–Ar determination on bulk rock of 110–117 Ma (*Ravich et al., 1978; Laiba et al., 1987*) and on mica separates (110 Ma; *Walker and Mond, 1971*).

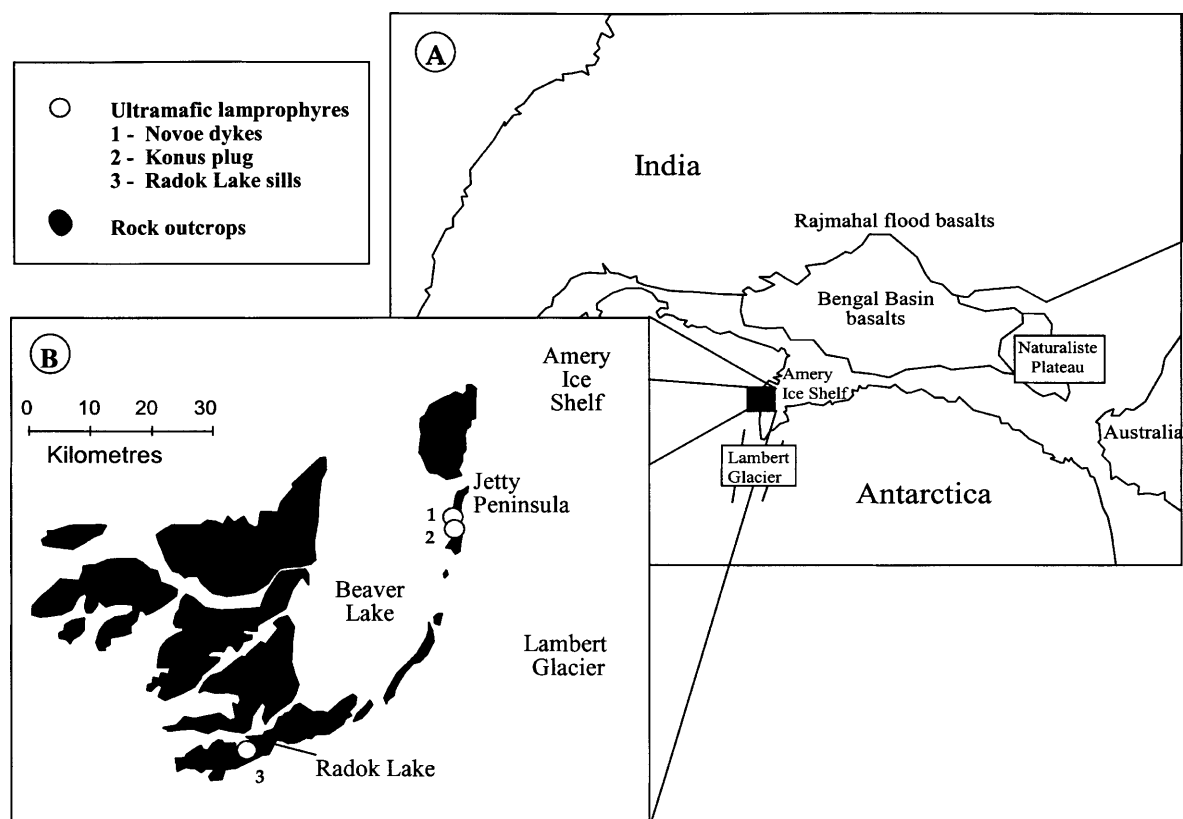


Fig. 1. Relation of the Beaver Lake locality to the pre-rift positions of Antarctica and India in Gondwanaland at 120 Ma. **A** Shows position of the Rajmahal flood basalts and Bengal Basin basalts related to the Kerguelen plume activity and the splitting apart of Antarctica (after *Kent*, 1991; pre-rift continental positions from *de Wit et al.*, 1988). **B** Shows the three ultramafic lamprophyre localities as numbered circles in a blow-up of the southwest corner of the Amery Ice Shelf – Lambert Glacier area. Rock outcrops are black; white areas are continental or glacier ice. See *Andronikov and Egorov* (1993) for intrusions of other rock types

The petrography and major oxide compositions of the Beaver Lake area UML have been investigated previously, but mostly in the Russian literature (*Egorov and Andronikov*, 1989; *Andronikov*, 1990; *Egorov*, 1994); the only information in the western literature are short descriptions in *Walker and Mond* (1971) and *McKelvey and Stephenson* (1990) and a summary in *Andronikov and Egorov* (1993). Here, we present the first thorough account in english and, using additional trace element data from *Andronikov and Foley* (2001), assess the petrogenesis of the rocks and their relation to the Lambert-Amery rift.

Petrography and mineral chemistry

The three facies of ultramafic lamprophyre are sampled from localities up to 40 km apart (Fig. 1) and vary quite extensively in modal abundances of the minerals present, but less so in terms of mineral chemistry. Mineral analyses were obtained

Table 1. *Modal mineral abundances in the Beaver Lake ultramafic lamprophyre facies*

Intrusion type	Ol	Ne	Mel	Phl	Ti-Mag	Prv	Ap	Carb	Cpx	Spl	Glass	Mtc
Dyke	10–15	7–10	30–40	7–10	7–10	3–5	< 1	5–10	–	2–3	3–5	–
Plug	7–10	10–15	20–30	15–20	7–10	7–10	< 1	3–5	+ **	+	10–15	–
Sill	5–7	20–25	15–20	30–40	10–15	10–15	2–3	3–5*	–	< 1	2–3	+

* Carbonate is mainly secondary calcite; ** clinopyroxene occurs only within leucocratic globules

at the GeoForschungsZentrum, Potsdam (Germany) using a Cameca SX-50 microprobe (beam current 15 nA, accelerating voltage 20 kV). Modal abundances of the various rock types are summarized in Table 1.

The dyke rocks are richer in olivine and melilite than the other lamprophyre facies (Table 1) and have a much more uniform grain size (0.1–0.3 mm). The matrix is made up by nepheline, phlogopite, perovskite, Cr-spinel, carbonates, titanomagnetite and glass with accessory apatite. The abundances of phlogopite and perovskite are lower than in the plug and sill facies. The plug facies rocks have a groundmass of similar grain size to the dyke rocks (0.1–0.2 mm), but with olivine phenocrysts up to 0.6 mm. Mineral abundances are intermediate between those of dyke and sill facies rocks (Table 1), except for the higher content of glass in the matrix. The plug rocks are unique in containing leucocratic globules 2–5 mm in diameter; these consist principally of phlogopite, nepheline and clinopyroxene as primary minerals, whereby clinopyroxene occurs only in these globules. The sill facies rocks of the Radok Lake locality are characteristically phlogopite-rich (up to 40%) and contain olivine phenocrysts and large nepheline grains. Its minerals have a larger average grain size of 0.4–0.6 mm, possibly due to a higher H₂O content, as indicated by the higher proportion of phlogopite.

Following the ultramafic lamprophyre classification of *Rock* (1986) the dyke rocks are alnöites, whereas both plug and sill rocks are best termed polzenites. The more recent IUGS recommendations would describe all these rocks as (olivine-) melilitolites (*Woolley et al.*, 1996).

Olivine

Two types of the phenocrysts can be distinguished in both dyke and sill rocks. The first generation is characterized by Mg# (100 Mg/[Mg + Fe]) of 85.3–88.4 in the dykes and 86.7–87.5 in the sills (Table 2) and forms mostly idiomorphic grains up to 0.7 mm long. These have low CaO (< 0.19 wt%) and high NiO (up to 0.31 wt%) contents in the dyke rocks, consistent with a high pressure origin. Some phenocrysts with corroded and partly phlogopitized borders (Fig. 2a) are compositionally identical to this first phenocryst group. The second type of phenocryst is normally smaller and characterized by lower amounts of NiO (down to 0.06 wt%) and higher MnO (up to 0.48 wt%), whereas Mg# (86.3–88.5) is similar to the first type.

Olivines in the plug are similar to the first phenocryst type in the dyke rocks in Mg# (87–89) and NiO (up to 0.32 wt%), but have higher CaO (0.19–0.44%). In the sill, CaO contents in olivines are intermediate (0.09–0.20%), and resorption of this

Table 2. Representative microprobe analyses of minerals from Beaver Lake UML

Rock type	dyke	dyke	dyke	plug	sill	sill	sill	Dyke	Dyke	Sill	Dyke	Plug	Sill	Sill
sample #	SD-10	SD-10	SD-7	KN-9	R-133/6	R-110	R-11	SD-7	SD-14	R-9	SD-7	KN-9	R-9	R-11
Mineral	Ol	Ol	Ol xct	Ol	Ol	Ol xct	Mtc	Mel	Mel	Mel	Ne	Ne	Ne	Ks
SiO ₂	40.3	41.0	40.7	40.4	40.6	41.3	35.5	43.1	42.6	43.2	41.7	42.3	40.7	41.7
TiO ₂	0.03			0.20	0.02		0.07	0.14	0.04	0.09	0.03	0.07	0.02	
Al ₂ O ₃	0.03	0.05	0.02	0.07	0.06			7.12	6.87	6.90	35.2	33.6	33.8	34.3
Cr ₂ O ₃	0.04	0.06	0.03	0.11			0.02	0.33	0.03	0.09	0.02		0.13	0.03
FeO	13.9	10.7	9.3	10.9	11.8	8.1	17.7	2.16	2.32	2.58	1.33	0.49	0.67	0.64
MnO	0.16	0.10	0.11	0.19	0.20	0.03	0.81	0.11	0.01					0.01
NiO	0.31	0.15	0.31	0.11	0.25	0.32		0.18	0.14	0.07		0.03	0.08	
MgO	45.3	47.6	47.9	45.6	46.4	50.4	14.6	9.5	8.2	9.4	0.10	0.08	0.49	0.14
CaO	0.13	0.15	0.09	0.41	0.17	0.02	31.5	33.7	34.8	34.5	0.19	0.32	15.7	5.9
Na ₂ O								3.12	3.24	2.92	12.6	16.4	8.5	17.5
K ₂ O								0.25	0.22	0.18	8.9	6.4	8.5	
Total	100.25	99.81	98.41	98.05	99.56	100.15	100.09	99.71	98.45	99.93	100.02	99.63	100.05	100.38
Mg#	85.3	88.8	90.2	88.2	87.5	91.8	59.5	88.7	86.3	86.7				
Cations														
No.	4	4	4	4	4	4	4	7	7	7	4	4	4	4
Oxygens														
Si	1.0049	1.0100	1.0104	1.0150	1.0089	1.0032	0.9984	1.9478	1.9585	1.9494	1.0101	1.0253	0.9962	1.0295
Ti	0.0006			0.0038	0.0004		0.0015	0.0048	0.0014	0.0031	0.0005	0.0013	0.0004	
Al	0.0009	0.0015	0.0006	0.0021	0.0018			0.3792	0.3722	0.3674	1.0053	0.9599	0.9733	1.0001
Cr	0.0008	0.0012	0.0006	0.0022			0.0004	0.0118	0.0011	0.0032	0.0004		0.0025	0.0006
Fe ²⁺	0.2894	0.2212	0.1923	0.2294	0.2455	0.1634	0.4166	0.0816	0.0892	0.0975	0.0270	0.0099	0.0123	0.0132
Mn	0.0034	0.0021	0.0023	0.0040	0.0042	0.0006	0.0193	0.0042	0.0004				0.0016	0.0002
Ni	0.0062	0.0030	0.0062	0.0022	0.0050	0.0062		0.0065	0.0052	0.0025		0.0006	0.0016	
Mg	1.6837	1.7457	1.7739	1.7094	1.7188	1.8229	0.6109	0.6414	0.5599	0.6358	0.0036	0.0029	0.0179	0.0052
Ca	0.0035	0.0040	0.0024	0.0110	0.0045	0.0005	0.9505	1.6308	1.7147	1.6704	0.0049	0.0083	0.7458	0.0048
Na							0.2734	0.2888	0.2558	0.5943	0.7724	0.7458	0.2812	0.2812
K							0.0144	0.0129	0.0104	0.2751	0.1978	0.2647	0.5520	0.5520

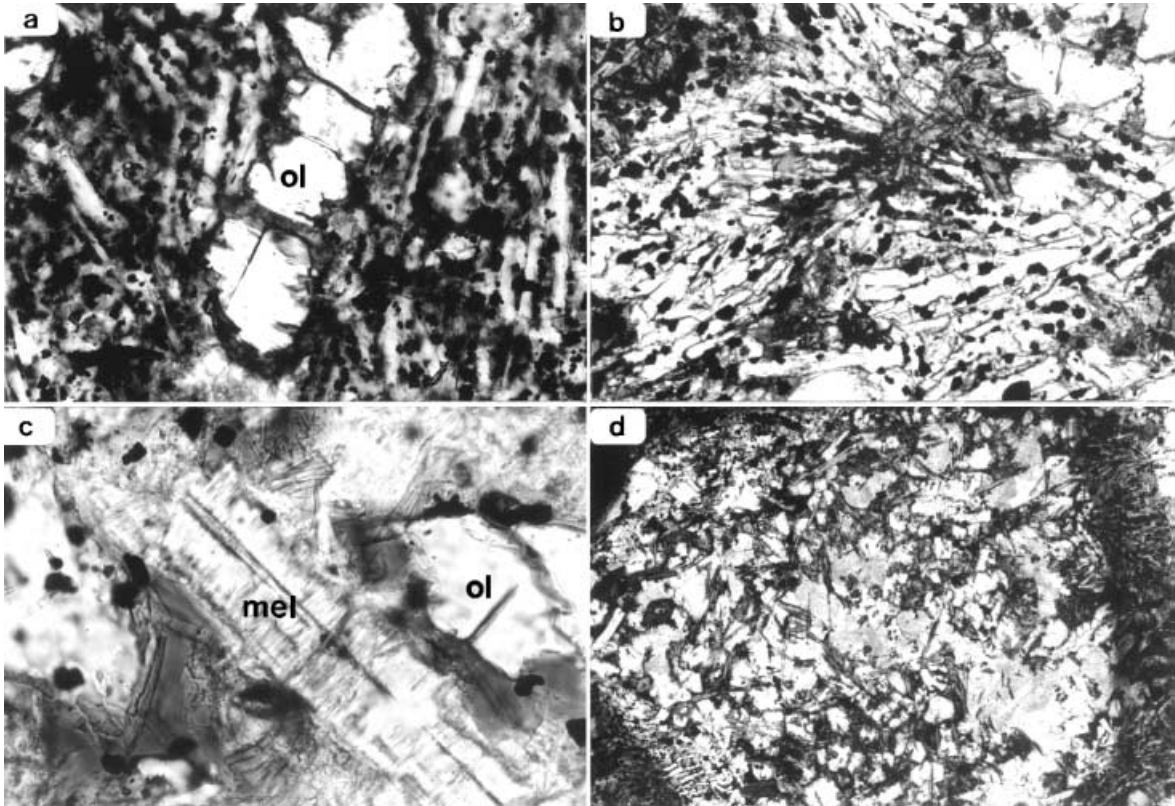


Fig. 2. Appearance of olivine (a) and melilite (b–c) in Beaver Lake ultramafic lamprophyres. a Shows resorbed olivine phenocrysts (sample SD-10) with phlogopite rims; b fresh melilite mats in plug sample KN-14; c breakdown “peg” structure in melilite from dyke sample N-22. Width of photos a–c = 1.5 mm. d Large scale photo (width 6 mm) of leucocratic globule consisting of phlogopite, clinopyroxene, nepheline, glass and natrolite. Carbonates and oxides are conspicuously rare in these globules, interpreted as immiscible silicate liquids

phenocryst population is common, as in the dyke. The second generation olivines in the sill rock are smaller (0.20–0.25 mm) and often included in large nepheline crystals. Mg# (85.8 to 88.8) and NiO (0.02–0.09 wt%) are similar to the later generation olivines in the dykes, whereas CaO is appreciably higher (1.09–1.38% CaO). The sill also contains accessory (< 1 vol%) monticellite as small (0.05–0.15 mm) equant crystals; these have Mg# of 55.9–59.5 with 31.4–31.5 wt% CaO. The presence of monticellite is typical of UML as a group (Rock, 1986, 1987), but this is the first report from Antarctic ultramafic lamprophyres. By analogy with melilitites from South Africa, the monticellite may result from reaction between olivine and melt to form monticellite and phlogopite (Brey, 1978), noting that the sills are the most phlogopite-rich of the UML rocks.

Olivine xenocrysts have been observed in all three lamprophyre facies and can make up to 10% of the rock volume where they are concentrated by flowage effects in lateral parts of the dyke. They are distinguished from all phenocrysts by markedly higher Mg# (89.7–92.1) and frequent signs of deformation.

Melilite

Melilite is the main mineral in the groundmass in the dyke rocks, forming fresh elongated crystals and displaying some flow orientation (Fig. 2b). The abundance of melilite in the other facies is lower, but petrographic features are similar. Grains often display “peg structures” and transverse joints (Fig. 2c; see *Yoder*, 1973), but can also be entirely fresh (Fig. 2b); completely altered grains are rare. The development of these breakdown structures tends to be more advanced in melilites with lower Na₂O contents. The material making up the peg structures is dominated by clinopyroxene, which may take up the Na released by melilite breakdown. It should be noted that similar “alteration” features occur commonly in igneous melilites, and indicate a complex igneous history rather than post-igneous alteration.

Compositionally, the melilites in all Beaver Lake ultramafic lamprophyres are dominated by åkermanite (Ca₂MgSi₂O₇; 62–68%) – sodamelilite (CaNaAlSi₂O₇; 23–32%) solid solutions (Table 2). Gehlenite contents are minor (Ca₂AlSiO₇; 2–9%), corresponding to Na₂O contents of 2.4–3.4 wt%, but this sets them apart from melilitites of East and South Africa to higher Al₂O₃ for a given Na₂O content (*Boctor and Yoder*, 1986; *Dawson et al.*, 1985).

Nepheline/kalsilite

Nepheline and phlogopite are the latest-crystallizing minerals in all three rock types. The abundance and composition of nephelines is consequently variable, and they occur as interstitial crystals of varying size. Larger ones may poikilitically include fresh melilite grains.

The main generation of nepheline in plug and sill rocks is characterized by 20–26% kalsilite end-member and low FeO contents (0.5–0.6 wt%; Table 2), whereas nephelines in the dyke rocks contain higher FeO contents (1.13–1.33 wt%) and have slightly higher kalsilite contents (30–32%). The composition of nephelines in the sills is generally uniform in the range given above, but in phlogopite-poor parts of the rock kalsilite with 66% kalsilite end-member occurs. It may be that previously existing kalsilite is transformed to nepheline with much lower kalsilite content by reaction, with phlogopite taking up the K₂O.

Phlogopite

Phlogopite is developed as a late interstitial phase, and may form flakes up to 1mm in size with well-pronounced pleochroism in the sill rocks. Accessory minerals such as apatite and oxides are included in phlogopite. The modal abundance of phlogopite is very variable in the sill rocks, ranging from patches with 80 vol% to small areas with only 10%.

Representative phlogopite compositions are listed in Table 3, showing that all are within the phlogopite field but with variable Mg# (72–85), and that TiO₂ contents vary widely from <2 to >9 wt%. Al₂O₃ contents range from 13–16.3 wt%. A larger set of analyses is plotted in Fig. 3, from which separate compositional trends are immediately apparent: the dyke and sill rocks define a trend with lower Si and Al

Table 3. Representative microprobe analyses of minerals from the Beaver Lake ultramafic lamprophyres

Rock type	Dyke	plug	sill	sill	sill	Plug	Plug	Dyke	Dyke	Dyke	Sill
Sample #	SD-14	KN-N1	R-9	R-11	R-11	KN-9	KN-9	SD-10	SD-10	SD-14	R-11
Mineral	Phl	Phl Matrix	Phl	Phl Core	Phl rim	Prv	Prv	CrSp xct	CrSp xct	CrSp core	TiMt rim
SiO ₂	38.2	35.7	38.8	36.3	38.9	0.35	0.82				
TiO ₂	4.18	6.82	4.05	3.12	2.74	57.8	56.9	1.46	1.46	1.37	16.9
Al ₂ O ₃	11.3	14.3	13.2	16.1	14.0	0.29	0.33	20.9	20.9	38.5	2.08
Cr ₂ O ₃		0.14	0.04	0.01		0.40	0.22	41.1	41.1	22.2	0.77
Fe ₂ O ₃								34.0	7.50	6.90	34.3
FeO	8.72	9.44	8.91	7.01	8.74	1.46	1.47	39.4	12.5	12.7	40.7
MnO	0.14	0.22	0.05	0.09	0.08	0.03	0.03	0.87	0.68	0.41	0.63
NiO	0.05		0.11		0.08	0.10	0.10	0.02	0.22	0.05	
MgO	20.4	15.6	19.8	20.2	20.9		0.01	4.11	14.9	16.8	3.48
CaO	0.08	0.06			0.04	39.7	38.9	0.13	0.19	0.05	0.08
Na ₂ O	0.30	0.26		0.32	0.35		0.88				
K ₂ O	8.50	8.84	11.2	9.20	9.73						
F	0.71	0.72	0.19	0.23	0.27						
Total	92.6	92.1	96.3	92.5	95.7	100.0	99.7	99.1	99.5	98.9	98.9
Mg#	80.7	74.7	79.8	83.7	81.0			15.7	68.0	70.2	13.2
Cations (basis = 22 oxygens)											
Si	5.747	5.436	5.643	5.402	5.637		Ti	0.467	0.034	0.029	0.469
Ti	0.473	0.782	0.443	0.349	0.299		Al	0.073	0.759	1.293	0.090
Al	1.997	2.570	2.256	2.815	2.389		Cr	0.056	1.000	0.500	0.022
Cr		0.017	0.005	0.001			Fe ³⁺	0.937	0.174	0.148	0.950
Fe ²⁺	1.097	1.203	1.085	0.872	1.060		Fe ²⁺	1.210	0.321	0.303	1.255
Mn	0.018	0.028	0.006	0.011	0.010		Mn	0.027	0.018	0.010	0.020
Ni	0.006		0.013		0.009		Ni	0.001	0.005	0.001	
Mg	4.573	3.546	4.292	4.468	4.510		Mg	0.225	0.683	0.713	0.191
Ca	0.013	0.010		0.092	0.006		Ca	0.005	0.006	0.002	0.003
Na	0.087	0.077		0.098	0.098						
K	1.631	1.719	2.080	1.746	1.801						

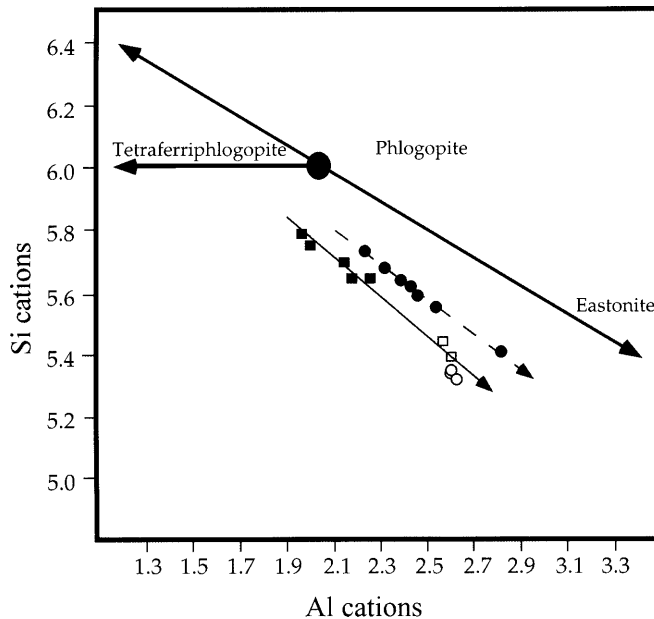


Fig. 3. Phlogopite compositions from sill (filled circles), plug (open squares) and dyke (filled squares) rocks and from leucocratic globules in the plug rocks (open circles). Distinct fractionation lines for sill and dyke/plug are apparent. Cations calculated on the basis of 22 oxygens per formula unit

than that defined by the sill phlogopites. Phlogopite is less abundant in the dykes, but has uniformly high Mg# (79.8–83.8), and also higher K_2O/Na_2O .

Reconnaissance analyses of fluorine show relatively low contents (0.13–0.27 wt%); BaO was measured only for one phlogopite grain from sill sample R-101 at 1.18 wt%. Second-generation phlogopite can also be observed rimming resorbed olivines (Fig. 2a), but no compositional data are available for these.

Oxide minerals

Oxide minerals include perovskite, Cr-spinel and titanomagnetite, which occur with differing relative modal abundances between the lamprophyre facies. Perovskite is most abundant in the sill samples, whereas it is subordinate to titanomagnetite in the dykes, in contrast to the observations of *Andronikov* (1990) and *Andronikov and Egorov* (1993). Perovskite compositions do not vary greatly between rock types, with FeO contents ranging between 1.1 and 1.7 wt%. For two perovskite grains from sill sample R-101, the content of BaO was 0.7–1.7 wt%.

Minerals of the Cr-spinel-titanomagnetite series occur as complex multiply zoned crystals, but with distinct zones observable in reflected light microscopy and a bimodal distribution in compositions (Fig. 4), so that we will refer to Cr-spinels and titanomagnetites as separate groups in the following. Cr-spinels are less abundant than titanomagnetite in all rocks, but most common in the dykes, and occur universally as cores with titanomagnetite rims, whereas titanomagnetites often occur as discrete crystals with no Cr-spinel cores. Large Cr-spinel phenocrysts occasionally occur, but always with a thin rim of titanomagnetite.

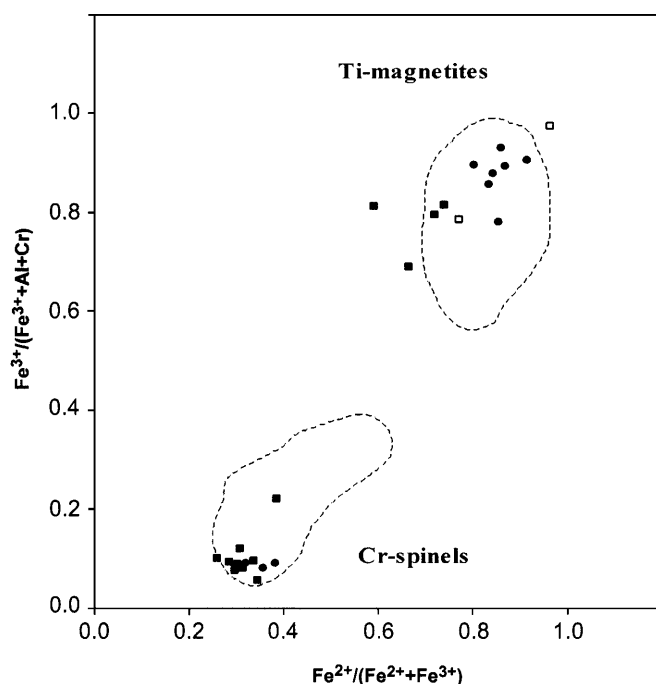


Fig. 4. Chemistry of Cr-spinel and titanomagnetite crystals from the Beaver Lake ultramafic lamprophyres compared to those from melilitites (data from Dawson et al., 1985). Symbols as Fig. 3

Cr-spinel compositions in the dyke rocks are generally fairly uniform with 1.4–1.8 wt% TiO₂, Cr# = 26–36. The rare Cr-spinel macrocrystals are slightly Cr-richer and Al-poorer (Cr# = 51–54). Cr-spinel cores in the sill rocks are Al-richer and Cr-poorer than the main population in the dykes (1.3–1.6 wt% TiO₂, Cr# = 28–30). Mg# of all Cr-spinels are in the range 75–60 (Fig. 4).

Titanomagnetites show appreciable differences between lamprophyre facies (Fig. 4). Titanomagnetites in the sill rocks have consistently lower Mg# and higher TiO₂ and Fe₂O₃ contents (3–15 wt% TiO₂, Mg# = 13–20) than those from the dyke rocks (12.8–16.9 wt% TiO₂, Mg# = 16–41).

The two major divisions Cr-spinel and titanomagnetite correspond well to those from South African and East African rift system melilitites, where they represent Cr-spinels included in olivines and titanomagnetites in the groundmass (Dawson et al., 1985; Fig. 4).

Other groundmass minerals and accessory phases

In addition to nepheline, phlogopite and oxide minerals in the groundmass, accessory phases, notably carbonates, apatite and glass are present. More rarely, titanite, amphibole and priderite have been found.

Carbonates are a mixture of primary and secondary phases, partly replacing glass. Carbonate is most common in the dyke rocks, where it occurs dominantly as elongated lenses and small veinlets up to 0.5 cm long. Cores of these areas are calcitic, whereas rims consist of well-formed dolomite crystals (0.6–3.2 wt% FeO; 15–20 wt% MgO; 30–37 wt% CaO).

Apatite is most common in the sill lamprophyre, forming up to 3% of the groundmass. It is characteristically enriched in fluorine (1.1–1.4 wt%), whereas

chlorine contents are very low (0.03–0.17%). Apatite mainly forms small grains, often included in phlogopite.

Interstitial glass occurs in all three ultramafic lamprophyre facies and varies widely in composition as a result of its residual character. Furthermore, it is often serpentinised and carbonatized. Several analyses of fresh glass show variation in SiO_2 from 58–65 wt% in the dykes, through ≈ 48 wt% in the plug to 40 wt% in the sills. The high SiO_2 glass in the dykes is also rich in Mg# (≈ 80 –85) and has relatively low Na_2O (1.5–2.3 wt%), K_2O (1.0–1.1 wt%) and Al_2O_3 (7.5–9.2 wt%). Mg# of the low SiO_2 glass in the sills is also high (≈ 67), whereas that in the plug has low Mg# (≈ 35) but much higher alkalis (7.7 wt% Na_2O ; 2.5 wt% K_2O).

Very rare amphibole characterized by low Ti and alkali contents (0.18–0.19 wt% TiO_2 ; 0.8–1.0 wt% Na_2O ; 0.3 wt% K_2O) occurs in the dykes. Rare aggregates and single crystals of priderite $((\text{K,Ba})(\text{Ti,Fe})_8\text{O}_{16})$ were observed in the sills. This mineral is characteristic for lamproites (Mitchell and Bergman, 1991), but occurs rarely in both alnöitic and aillikitic UML.

In one sill sample (R-11), a kalsilite-rich member of the nepheline-kalsilite series occurs (Table 2). This intermediate composition of $\text{Ks}_{66}\text{Ne}_{34}$ is considerably more Na-rich than most volcanic kalsilites (Edgar, 1989; Gallo et al., 1984), and is similar to exsolved crystals of Ks_{58} reported from the Nyiragongo volcano in the eastern Congo (Sahama, 1978).

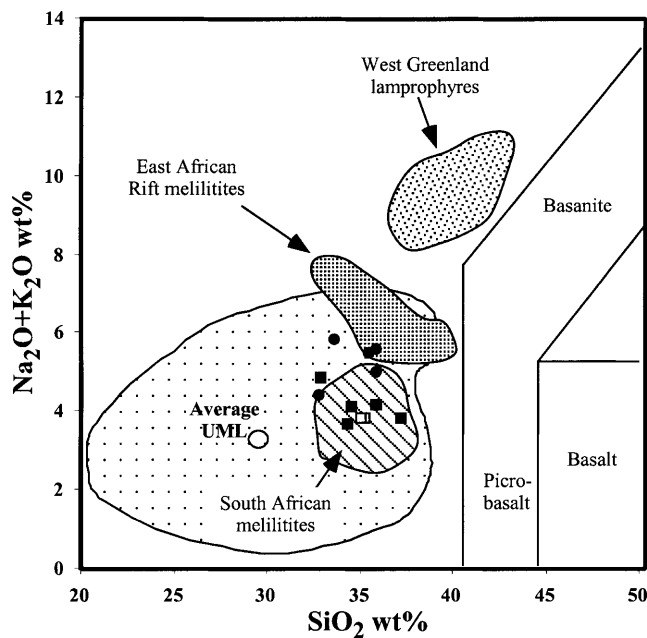


Fig. 5. Alkali and SiO_2 contents of bulk rock ultramafic lamprophyres from Beaver Lake (symbols as in Fig. 3). Range of ultramafic lamprophyres shown after Rock (1986) with average shown as an open circle. Fields for South African and East African melilitites from Dawson et al. (1985) and for West Greenland lamprophyres from Scott (1979). Other rock fields from IUGS nomenclature system

Table 4. *Chemical compositions of the Beaver Lake ultramafic lamprophyres*

Sample # Body type	SD-7 Dyke	SD-14 Dyke	R-34 Sill	R-133/10 Sill
SiO ₂	34.3	34.5	32.8	35.5
TiO ₂	2.56	2.47	2.20	2.30
Al ₂ O ₃	8.26	8.22	7.58	8.93
Cr ₂ O ₃	0.07	0.08	0.08	0.04
Fe ₂ O ₃	3.64	4.67	4.79	2.86
FeO	6.29	6.01	5.30	7.84
MnO	0.20	0.20	0.16	0.19
MgO	17.2	17.4	14.4	15.7
CaO	13.3	10.7	16.0	16.5
Na ₂ O	1.94	1.78	1.91	2.43
K ₂ O	1.74	2.32	2.52	3.04
P ₂ O ₅	0.93	0.93	0.73	0.84
LOI	9.18	10.4	11.8	3.57
CO ₂	2.90	4.00	6.18	1.67
Total	99.6	99.6	100.3	99.7
Mg#	82.0	83.7	82.8	78.1
Na ₂ O + K ₂ O	3.68	4.10	4.43	5.47
Trace elements (ppm)				
La	95	96	89	79
Ce	157	158	154	135
Pr	17.2	17.5	17.6	14.9
Nd	67	68	69	58
Sm	12.2	12.3	12.2	10.6
Eu	3.6	3.7	3.5	3.2
Gd	9.9	10.2	9.5	9.1
Tb	1.19	1.27	1.14	1.13
Dy	6.0	6.2	5.1	5.7
Ho	0.88	0.91	0.72	0.83
Er	2.4	2.4	1.8	2.1
Tm	0.34	0.35	0.24	0.30
Yb	1.8	1.9	1.2	1.5
Lu	0.25	0.28	0.16	0.23
Rb	81	81	125	148
Ba	2290	2590	1060	1790
Th	22	23	22	16
U	3.6	3.6	2.1	2.9
Nb	30	24	21	21
Ta	3.1	2.5	2.8	1.5
Pb	8.5	8.6	8.9	12.2
Sr	957	994	1120	968
Zr	60	74	39	67
Hf	1.2	1.3	0.81	1.4
Y	28	29	21	26
Sc	27	28	17	25
V	272	278	191	277
Cr	508	531	547	298
Ni	293	275	239	209

Leucocratic globules

A very typical feature of the ultramafic lamprophyres from the Konus plug intrusion is the presence of rounded (2–5 mm size) leucocratic globules. These consist of well-formed square small (~ 0.1 mm) nepheline crystals, small dark-greenish-brown phlogopite and long needles of brownish clinopyroxene in a matrix composed principally of yellowish glass, mostly altered to fans of acicular natrolite. The junctions between globules and rock groundmass are sharp and do not display visible signs of reaction; all minerals within the globules are nucleated within the globule and not at the margins (Fig. 2d).

Nepheline crystals are characterized by higher amounts of the kalsilite end-member ($K_{S_{30-31}}$) and higher FeO (1.1–1.7 wt%) than in the normal groundmass population. Phlogopite compositions lie at the most fractionated end of the trend defined by dyke and plug phlogopites (Fig. 4), but not far removed from those of the plug rock's groundmass. Clinopyroxene occurs only in these leucocratic globules. It can be classified as Al-poor Fe–Ti-augite with varying concentrations of Na_2O . Crystal rims show enrichment in TiO_2 (5.7–5.9 wt%) and Al_2O_3 (7.3–8.0 wt%) and depletion in Na_2O (0.9–1.0 wt%) relative to cores (2.7–3.8 wt% TiO_2 , 1.5–2.0 wt% Al_2O_3 , up to 2.8 wt% Na_2O). Mg# falls from 68–63 in cores to as low as 50 in rims. Glass appears to contain 45–47 wt% SiO_2 , about 30 wt% Al_2O_3 and high contents of K_2O (1–2 wt%) and especially Na_2O (10–12.5 wt%).

Whole-rock geochemistry

The ultramafic lamprophyre samples contain only small amounts of xenolithic material and are therefore suitable for whole-rock analysis. All samples were checked carefully macroscopically before analysis and so the data given are believed to represent pristine rock analyses. It cannot be excluded that they contain xenocrystic material (particularly olivine), but microscopic inspection suggests that this should not exceed about 2–3% in samples on a macroscopic scale. Major and trace element analyses as well as radiogenic isotopes are published by *Andronikov* and *Foley* (2001) for several samples. Table 4 lists additional analyses that have not been published previously. They were obtained by the same techniques (wet chemical for major elements in St.-Petersburg, and ICP-MS for trace elements in Göttingen) and using the same standards as described in *Andronikov* and *Foley* (2001).

Major element composition

Major oxide concentrations for the whole sample set fall well within the interval given for ultramafic lamprophyres by *Rock* (1986, 1991). In Fig. 5 they are compared to *Rock's* ultramafic lamprophyre field and also to several individual localities of ultramafic lamprophyres and melilitites, showing that they plot towards the high- SiO_2 end of the UML field but close to the compositions of melilitites from South Africa and from the East African Rift. It is noteworthy that these compositions consistently fit the characteristics summarized by *Woolley* et al. (1996) for melilitites in that they have $SiO_2 < 38$ wt%, $CaO > 13$ wt% and contain essential melilite and perovskite.

High and fairly uniform MgO (16.2–17.4 wt%) and high Mg# in the range 82–84.5 are typical of the dyke facies rocks. The plug has lower MgO (13.4–13.6 wt%) and Mg# (79), which is consistent with its apparent position later on fractionation trends based on mineral analyses (Fig. 3). These characteristics are typical for little-fractionated melts of mantle peridotite, whereas the high TiO₂, K₂O, P₂O₅ and CO₂ contents require the involvement of other minerals in the source region such as carbonates, apatite, phlogopite and Ti-oxide minerals. Fe₂O₃/FeO ratios are generally low, indicating that oxidation during emplacement was not strong, and may partly result from the removal of near-surface parts of the intrusions by erosion. CO₂ contents range from 1.5–6.2 wt% with an average of 3.06 wt%; this value is very similar to the average for alnöitic and polzenitic UML (3.1 wt%) and is much higher than in most non-lamprophyric melilitites (< 1 wt%; *Rock*, 1986). Previous analyses of the water content for some Beaver Lake ultramafic lamprophyre samples show the H₂O content to be ~0.40–0.60% (*Andronikov*, 1990), indicating a high CO₂/H₂O ratio. Exact values for this ratio corresponding to igneous conditions cannot be given due to the possibility of post-igneous modification, but the bulk of the CO₂ and H₂O must be of igneous origin because they are contained in primary igneous minerals.

Trace element concentrations

Trace element characteristics are considered in more detail in a companion paper by *Andronikov* and *Foley* (2001). REE display similar LREE-enriched patterns for rocks from all lamprophyre intrusions, with slightly steeper patterns for the Radok Lake sills than for the dykes and plug further north. This uniformity of incompatible trace element distributions indicates that fractionation of minerals rich in these elements must have been absent or very limited. Possible exceptions are the high field strength elements, which show troughs of variable sizes in the patterns, quantified by average (Zr + Hf)/(Zr + Hf)* values of 0.35 for the dykes, 0.48 for the sills, and 0.88 for the plug rocks, whereby (Zr + Hf)* is interpolated between Nd and Sm.

Compatible trace elements (Sc, V, Cr, Ni) are present in abundances typical for alnöitic and polzenitic UML, and are much higher than in most basaltic rocks. The dyke rocks are significantly richer in Ni and Cr with respect to the plug rock, whereas the sill has noticeably less Sc and V.

Discussion

Fractionation of the ultramafic lamprophyres and parental magma composition

The similarity of most major and trace element abundances as well as radiogenic isotopic compositions of the rocks (see below) indicates a similar source for all UML types at Beaver Lake. Small differences in geochemistry and mineral chemistry allow differences in fractionation history and the degree of partial melting to

be ascertained, but the rocks of this locality can be considered uniform in comparison to ultramafic lamprophyres as a whole (Fig. 5).

An origin of the parental magmas for the ultramafic lamprophyres in the peridotitic upper mantle is indicated by the general geochemical features of the whole-rocks (high Mg#, MgO contents, Ni and Cr contents), and the high contents of the compatible trace elements (Ni and Cr > 200 ppm) preclude extensive fractionation from the parental magma. Thus, fractionation cannot have been controlled by an extensive series of mafic phases, and is probably restricted to two phases at the most.

Only olivine and Cr-rich spinel can be demonstrated to control the fractionation of the ultramafic lamprophyre magma; these show zonation from early Cr-rich core compositions in the case of spinel, and early olivine compositions in the form of discrete crystals with higher Mg# and Ni contents, and lower CaO. The most primitive Cr-spinels have Mg# up to 74, Cr# ($100\text{Cr}/(\text{Cr} + \text{Al} + \text{Fe}^{3+})$) above 50, and low $\text{Fe}^{3+}/\text{Fe}^{2+}$. These and the low-CaO, high-Ni olivines are interpreted as remnants of the fractionating assemblage operating when the magmas were at deeper levels. Both of these early minerals are unlikely to be xenocrystic; xenocrystic olivine has been identified as an independent population (see above), and Cr-spinels would not be expected to be so widespread, abundant, and of uniform composition if they were xenocrystic. The later low-Ni, high-CaO olivines and titanomagnetites are characteristic of later crystallization together with phlogopite, nepheline and melilite at shallower crustal depths. The hiatus in crystallization is indicated by the compositional gap in spinel compositions (Fig. 4) and the occurrence of resorbed olivines.

Fractionation of phlogopite is often considered important in the development of UML rock compositions (Rock, 1986), but phlogopite is a late-crystallizing phase in the Beaver Lake rocks with its abundance showing a marked antipathetic relationship to nepheline. The petrographic and mineral chemical evidence for control of fractionation by only olivine and Cr-spinel is consistent with relationships between compatible and incompatible trace elements. In plots such as Cr vs. Sr and Cr vs. Ce (see Fig. 5 in Andronikov and Foley, 2001), trends deviating strongly from those expected from partial melting of peridotites indicate fractionation of mafic minerals rich in Cr. This figure shows that the dyke and plug rocks fall along a single line differing from that of the sills, in keeping with mineral chemical evidence that they are related (Fig. 3). Andronikov and Foley (2001) conclude that dyke and sill rocks can be explained by fractionation of ~3% olivine and < 1% spinel, and ~5% olivine and ~2% spinel, respectively, from melts derived by less than 5% partial melting, using the simple assumption that all Ni resides in olivine and all Cr in spinel. Thus, the compositions of the ultramafic lamprophyres are not far removed from their primary magma compositions: these were olivine melilititic melts enriched in incompatible trace elements and volatile components with high CO₂ contents.

Constraints on the mineralogy and geochemistry of the source region

The mineralogical characteristics of the Beaver Lake rocks, including essential phlogopite and primary carbonates, classifies the rocks as ultramafic lamprophyres

and sets them apart from melilitites according to *Rock* (1991), although chemically, they are equivalent to melilitites (*Woolley et al.*, 1996) apart from higher volatile contents. The origin of melilitite magmas is generally accepted to be due to partial melting of garnet peridotite in the presence of CO₂ and H₂O (*Brey and Green*, 1977; *Brey*, 1978), and so alnöitic ultramafic lamprophyre melts may be expected to have a similar origin, perhaps with an increased role for the volatile components. This genetic model would explain high MgO contents and Mg#, and can account for LREE-enriched trace element patterns with La 100–300 times chondrite as 0.5–1.5% melting of a primitive garnet lherzolite (*Frey et al.*, 1978).

However, steep troughs in the trace element patterns and isotopic results cannot be explained by fractionation of primary magmas produced in this way, and lead us to prefer an origin by melting of a mixed source assemblage consisting of phlogopite- and carbonate-bearing veins within peridotite. In this scenario, unusual trace element features and isotopic results can be attributed to the vein assemblage, whereas the major elements are derived from the surrounding peridotite. This mechanism allows for a much larger degree of melting of peridotite, which is in keeping with the high MgO and Mg# in excess of those normally attributed to primary melts of peridotite.

Although the sloping trace element patterns of the rocks broadly fit low-degree melting of a peridotite source, important deviations from the pattern are seen for Zr, Hf, Nb and Rb. These are too large to be explained by partial melting of lherzolite with or without carbonate, nor can they be explained by fractionation of Cr-spinel and olivine. Strong variation in Zr and Hf is not a characteristic of melilitic rocks elsewhere (*Dawson et al.*, 1985; *Boctor and Yoder*, 1986; *Rock*, 1986) and appears to be a local characteristic. Incorrect analyses due to incomplete dissolution of a mineral before ICP-MS analysis can also be discounted, because the pattern of Zr, Hf and Nb variation with no concomitant Ti variation could not be caused by any of the phases occurring in the ultramafic lamprophyres (Table 1). Furthermore, other ultramafic alkaline rocks dissolved at the same time with the same technique do not show these Zr–Hf–Nb features.

Troughs in trace element patterns at Nb, resulting in high La/Nb, have also been explained by crustal contamination and by partial melting of enriched continental lithosphere, possibly previously affected by subduction processes (*Varne*, 1985; *Rogers et al.*, 1987). Control of incompatible trace element abundances by contamination with continental crustal material is also unlikely: Ce/Pb ratios, chosen as sensitive to crustal contamination, range in the UML from 11 to 28, few are outside the range of 20–30 outlined by *Hofmann et al.* (1986) for oceanic basalts. Furthermore, Nd isotope ratios vary little in the Beaver Lake lamprophyres, but should be severely affected if crustal assimilation were important, because this area is dominated by early Precambrian crust with very low ¹⁴³Nd/¹⁴⁴Nd. Furthermore, no crustal xenoliths are observed in the intrusions, and the low SiO₂ contents of the rocks argue against significant contamination. On plots of Th/Zr vs. Nb/Zr, the Beaver Lake UML fall in the field characteristic for subduction-influenced source regions (*Beccaluva et al.*, 1991). This would be consistent with the suggestion of *Sheraton et al.* (1993) that collision between Indian and East Antarctic Shields occurred in Proterozoic times. However, the

deeper troughs for Zr and Hf rather than Nb are not characteristic for subduction-related processes (Foley and Wheller, 1990).

Alternatively, the combined trace element and isotopic evidence can be explained by the genesis of the ultramafic lamprophyre magmas by melting of a mixture of veins and peridotitic wall-rocks. This scenario has an advantage over melting of carbonate- and amphibole- or phlogopite-bearing peridotite in which minerals are homogeneously distributed, namely that veins can contain minerals which are not constrained to be in equilibrium with peridotite (Foley, 1992). We argue that the veins in the source region of the Beaver Lake lamprophyres consist of the assemblage carbonate, phlogopite, clinopyroxene and baddeleyite (not discounting the possibility of additional minerals), and that the impregnation of the peridotite with these veins occurred shortly before their re-melting and was related to the activity of the Lambert-Amery Rift (see next section).

Andronikov and Foley (2001) present Nd and Sr isotope data for all three intrusive types, and further data, including Pb isotopes, has been presented for the Radok Lake sill locality by Paul et al. (1997). The rocks show a narrow range of Nd isotopic ratios ($\epsilon\text{Nd} + 1.7$ to $+ 4.3$) and a much wider range of $^{87}\text{Sr}/^{86}\text{Sr}_t$ (0.70434 to 0.7086), leading to a horizontal array projecting to the right from an ocean island basalt (OIB)-like position on a $\epsilon\text{Nd}-\epsilon\text{Sr}$ plot. Pb isotopes are similar to those of EM2-enriched OIBs ($^{208}\text{Pb}/^{204}\text{Pb} = 39.0-39.3$, $^{207}\text{Pb}/^{204}\text{Pb} \approx 15.6$ and $^{206}\text{Pb}/^{204}\text{Pb} = 18.5-18.9$; Paul et al., 1997).

The phlogopite in the veins is enriched in Rb and so can lead to rapid growth of $^{87}\text{Sr}/^{86}\text{Sr}$ of the vein assemblage in a geologically short period of time, whereas none of the vein minerals can affect Nd isotopes appreciably in the same period. Using concentrations of 200 ppm Rb and 300 ppm Sr corresponding to analysed phlogopites in the Aillik UML (S.Foley, unpubl. data), an initial asthenospheric $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7036 would grow to 0.7050 in 50 Ma and only 160 Ma would be needed to create the range of $^{87}\text{Sr}/^{86}\text{Sr}$ measured for the Beaver Lake UML. This is within the time-frame of activity of large continental rifts such as the Lambert-Amery rift.

The carbonates impart the variable primary CO_2 content to the primary melt composition, but do not affect the radiogenic isotope systems significantly, because their low Rb contents cannot cause rapid growth of $^{87}\text{Sr}/^{86}\text{Sr}$. The stability of baddeleyite in the veins is promoted with respect to zircon in the presence of carbonates (Heaman and LeCheminant, 1993). Experiments on materials containing several wt% CO_2 (Meen et al., 1989) showed that baddeleyite can exist with a melt containing only 0.2 wt% ZrO_2 at temperatures relevant to melting of veins in the UML source.

Partial remelting of these cpx + phl + carbonate veins with phlogopite and baddeleyite remaining in the residue releases a carbonate-rich melt with high $^{87}\text{Sr}/^{86}\text{Sr}$ which then interacts with melts from the surrounding peridotite. The vein-derived melt dominates the trace element characteristics of the primary UML, and causes the troughs for Rb, Nb, Zr and Hf by their retention in residual phlogopite and baddeleyite. The higher D_{Rb} for phlogopite relative to D_{Sr} allows retention of Rb whilst transmitting the $^{87}\text{Sr}/^{86}\text{Sr}$ characteristics of the phlogopite to the melt. The vein melting model implies also that parental melts to the different intrusions are very local in extent. The differing trace element patterns for dyke and

plug rocks cannot be explained by fractional crystallization, but must be due to fractionation of independent, even if very similar melts.

Petrogenesis of the Beaver Lake ultramafic lamprophyres

The great majority of ultramafic lamprophyres are associated with continental rifts, either in lamprophyre-carbonatite dyke swarms, nephelinite-carbonatite volcanoes or intrusive carbonatite-bearing complexes (Rock, 1986). The Beaver Lake rocks are similar to those bordering the Labrador Sea (Hansen, 1980; Larsen, 1980; Collerson and Malpas, 1977; Foley, 1984, 1989) in being situated on the border of a large rift that cuts an Archean craton. This raises the possibility of deep melting events at the base of the cratonic lithosphere occurring in close geographical proximity to shallow production of oceanic crust.

The invocation of vein melting and the tectonic setting of a rift flank underlain by old continental lithosphere can be combined into the following petrogenetic model for the Beaver Lake ultramafic lamprophyres. The development of a rift beneath the Lambert Glacier was associated with the breakup of Gondwanaland, and resulted in protrusion of relatively hot asthenosphere to shallower levels beneath the rift, causing the lithosphere/asthenosphere boundary to dip steeply towards the west. The rift-associated heating at deeper levels caused the geotherm for a locality at the rift margin, such as Beaver Lake, to be deflected towards higher temperatures at high pressures (Fig. 6). Continued lateral evolution of the rift will result in grazing of the solidus at depths of 130 to 160 km. Although the relevant solidus with CO₂ and H₂O is well-studied up to 30 kbar, it is only cursorily known at higher pressures, but melting temperatures and melting regimes appear to be as shown in Fig. 6. On the basis of available experiments (Ryabchikov et al., 1993; Dalton and Presnall, 1998), initial melts between 40 and 50 kbar are carbonatitic to kimberlitic at degrees of melting up to 1%, with much lower Na₂O in the carbonatitic melts than at pressures between 20 and 30 kbar (Wallace and Green, 1988). The silicate content of higher-degree melts increases steadily and quickly compared to lower pressure melting, meaning that the distinction between carbonatite and silicate melts is less clear than at pressures below 30 kbar. Initial low-degree melts produced at this solidus migrate upwards and quickly encounter much colder rocks where they solidify rapidly in veins because of their small volume and consequent low heat content. Given the carbonatitic to kimberlitic nature of the melts, the veins will contain carbonates, clinopyroxene and phlogopite. The presence of phlogopite is required to cause the rapid ⁸⁷Sr/⁸⁶Sr growth and this is also consistent with the depths suggested: amphibole is unstable at pressures greater than 30 kbar in peridotitic or carbonatitic systems (Wallace and Green, 1991), and has $D_{Rb} < D_{Sr}$ and so cannot cause the rapid ⁸⁷Sr/⁸⁶Sr growth. Phlogopite replaces amphibole as the stable hydrous mafic phase at higher pressures.

Continued development of the rift results in upward and outward movement of the lithosphere/asthenosphere boundary with consequent re-melting of the recently veined lower lithosphere. The carbonate-rich veins partially melt at lower temperatures than the surrounding peridotite, and further heating causes mixing of melts from veins and from peridotite. The trace element patterns of the resulting mixed melts are dominated by the vein-derived melts, whereas the radiogenic

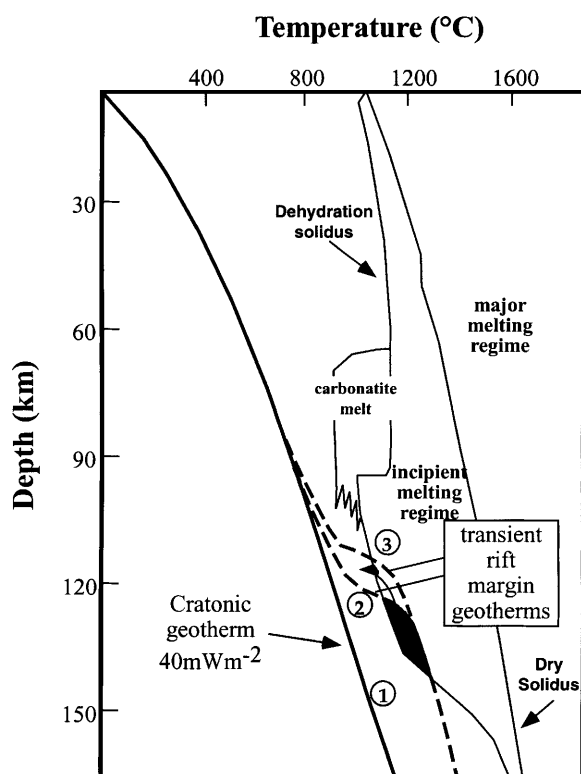


Fig. 6. Petrogenetic model for the Beaver Lake ultramafic lamprophyres. The position on the flank of the developing Lambert-Amery rift leads to a progression from cratonic geotherm typical for the Archean block of the Prince Charles Mountains (west and south of Beaver Lake) to rift-influenced geotherm (temporal progression shown as numbered circles 1-2-3). Solidi for pyrolitic mantle for dry, water-undersaturated (dehydration solidus) and CO₂-bearing conditions are taken from *Green and Falloon (1998)*. The shelf on the geotherm at 90–100 km is due to the upper stability limit of amphibole in peridotite; water may be contained in phlogopite at greater depths than this. The shift of the solidus to higher temperatures at depths greater than 130 km is due to the more reducing conditions in the deeper asthenosphere. Low-degree melts follow the path shown by the arrow, and solidify in the overlying lithosphere to form veins. In the time before they are re-melted (geotherm 3), radiogenic Sr has grown in phlogopite, but there is insufficient time for noticeable disturbance of Nd isotopes

isotope systems differ in behaviour; Sr isotopes are influenced by growth from Rb in phlogopite in the veins, whereas Nd isotopes are inherited from the peridotite with little influence from the vein assemblage.

This scenario is thus in agreement with models for an enriched lithosphere source for ultramafic lamprophyres, albeit very recent enrichment. This agrees with the conclusion of *Paul et al. (1997)* that the isotope characteristics are different from those of Kerguelen plume-related basalts (*Kent et al., 1997*) and so probably indicate a continental lithosphere source. Partial melting close to the migrating lithosphere-asthenosphere boundary may be promoted by a redox contrast between the reduced asthenosphere and the more oxidized lithosphere (*Foley, 1988*), restricting the

carbonate vein assemblages to the lithosphere. *Andronikov* and *Sheraton* (1996) noted a large variation in redox conditions for mantle xenoliths from beneath this area, with a strong tendency for more reducing values in xenoliths from deeper levels.

Similarities and differences to other ultramafic lamprophyres and related rocks

The mineralogical and chemical characteristics of the Beaver Lake ultramafic lamprophyres shows their genesis to be closely related to that of melilitites. The principal mineralogical differences are the occurrence of large amounts of phlogopite and the absence of melilite phenocrysts in the UML, whereas the chief chemical differences are the higher volatile contents, which lead to the importance of carbonate and phlogopite. In our petrogenetic model these differences are all attributable to the involvement of carbonate-rich veins in the production of melts; if they were not involved then the melts of purely peridotitic source rocks in the presence of CO₂ and H₂O (*Brey*, 1978) would crystallize to form olivine melilitites or nephelinites with little phlogopite. This origin for melilitites corresponds to the incipient melting regime of *Green* and *Falloon* (1998), who assigned them to low-degree melting of peridotite at 30–35 kbar pressure.

In his review of lamprophyres, *Rock* (1991) concluded that two types of primary melts were involved in the genesis of ultramafic lamprophyres; one melilititic, giving rise to the alnöitic UML, and the other more related to carbonatites, giving rise to the aillikites. The generally higher trace element and CO₂-contents in aillikites may be incorporated in the present model by invoking a greater proportion of carbonate veins in the mixed melt. Therefore, the much-publicised gradations from melilitites, through alnöites to aillikites (*Rock*, 1986,1991) may be due to progressively increasing role for carbonate-bearing veins. Further evidence for similarities in the evolution of the respective melts may be seen in the fractionation control by olivine and spinel in potassic lamprophyres of West Greenland (*Scott*, 1979), and similar disequilibrium olivine phenocrysts and Cr-spinels in the type aillikites (*Malpas* et al., 1986). Compositionally similar spinel grains occur as inclusions in olivine phenocrysts in melilitites of South Africa (Fig. 4).

Another major difference between melilitites and many of the Beaver Lake ultramafic lamprophyres is the rarity of clinopyroxene in the lamprophyres. Clinopyroxene occurs in the leucocratic globules, which are interpreted as immiscible liquids, but not in the groundmass outside the globules. Clinopyroxene is also found in melilite-free autoliths of apparently kamafugitic affinity in the first intrusive episode of the composite body at the plug locality (*Andronikov*, 1990). *Yoder* (1973) showed that melilite may be produced at the expense of clinopyroxene in the presence of carbonate according to the reaction:



Melilite of akermanitic composition is unstable with excess CO₂ at pressures higher than 3–5 kbar, indicating crystallization at crustal levels, thus explaining the lack of large phenocrysts. The above reaction may also explain the otherwise puzzling presence of clinopyroxene in only one of two conjugate liquids, which would

normally be expected to be saturated in the same phases (*Foley, 1984*): carbonate was preferentially partitioned into the rock groundmass, and not the immiscible droplets, so that clinopyroxene was suppressed there, but not in the carbonate-poorer immiscible liquid.

Conclusions

The Mesozoic ultramafic lamprophyres of the Beaver Lake area consist of three intrusive facies, a dykes, multiple plug-like intrusions, and sills. The rocks are broadly mineralogically and geochemically similar to olivine melilitites, differing in higher CO₂ and modal phlogopite and carbonate contents.

Primary ultramafic lamprophyre melts originate by melting at depths of about 130 km of a mixed source consisting of peridotite and veins dominated by clinopyroxene, carbonate and phlogopite. The major element, compatible trace element, and most radiogenic isotope characteristics are derived from the peridotite, whereas incompatible trace elements and high ⁸⁷Sr/⁸⁶Sr are inherited from the vein assemblage. Locally characteristic low Zr and Hf contents may be due to control by baddeleyite in the source. The rocks experienced fractionation of a few percent of Cr-spinel and olivine at high pressures before emplacement.

The higher CO₂ contents than are characteristic for olivine melilitites favoured the crystallization of melilite at crustal pressures, and suppressed the crystallization of clinopyroxene. The alnöitic ultramafic lamprophyres such as those at Beaver Lake may be intermediate between olivine melilitites and the carbonate-rich aillikitic ultramafic lamprophyres not only in terms of geochemistry and mineralogy, but also in the role of carbonate-rich veins in the melting process. The genesis of the Beaver Lake ultramafic lamprophyres is related to the breakup of Gondwanaland, but the rocks show no geochemical signature of the direct involvement of the Kerguelen plume, as is characteristic for basaltic rocks on other borders of the breakup area.

Acknowledgements

The authors are very grateful to *K.Simon* for his assistance with ICP-MS analyses, and to *O.Appelt* and *D.Rhede* for the assistance with the microprobe analyses. AVA is very grateful to *B. Beliatsky*, *A. Borisova*, *T. Churikova*, *M. Hoch* and *S. Mukasa* for fruitful discussions. This investigation was supported by the Alexander von Humboldt Foundation to AVA and by Deutsche Forschungsgemeinschaft grant Fo 181/3 to SFF. The constructive criticism of two *Mineralogy and Petrology* reviewers is greatly appreciated.

References

- Anders E, Grevesse N* (1989) Abundances of the elements: meteoritic and solar. *Geochim Cosmochim Acta* 53: 197–214
- Andronikov AV* (1990) Mesozoic alkaline ultramafic magmatism of Jetty Peninsula (Prince Charles Mountains, East Antarctica). Thesis, Leningrad State University, Leningrad, 228 pp (in Russian)
- Andronikov AV, Egorov LS* (1993) Mesozoic alkaline-ultramafic magmatism of Jetty Peninsula. In: *Findlay RH, Unrug R, Banks MR, Veivers JJ* (eds) *Gondwana Eight: assembly, evolution and dispersal*. Balkema, Rotterdam Brookfield, pp 547–557

- Andronikov AV, Sheraton JW* (1996) The redox state of lithospheric upper mantle beneath the East Antarctic shield. *Terra Antarctica* 3: 39–48
- Andronikov AV, Foley SF* (2001) Trace element and Nd–Sr isotopic composition of ultramafic lamprophyres from the East Antarctic Beaver Lake area. *Chem Geol* 175: 291–305
- Beccaluva L, Girolamo P, Serri G* (1991) Petrogenesis and tectonic setting of the Roman Volcanic Province, Italy. *Lithos* 26: 191–221
- Boctor NZ, Yoder HS* (1986) Petrology of some melilite-bearing rocks of Cape Province, Republic of South Africa: relationship to kimberlite. *Am J Sci* 286: 513–539
- Brey G* (1978) Origin of olivine melilitites – chemical and experimental constraints. *J Volcanol Geotherm Res* 3: 61–88
- Brey G, Green DH* (1977) Systematic study of liquidus phase relations in olivine melilite + H₂O + CO₂ at high pressures and petrogenesis of an olivine melilitite magma. *Contrib Mineral Petrol* 61: 141–162
- Collerson KD, Malpas J* (1977) Partial melts in upper mantle nodules from Labrador kimberlites. *Ext Abs 2nd Int Kimberlite Conf, Santa Fe*
- Dalton JA, Presnall DC* (1998) The continuum of primary carbonatitic-kimberlitic melt compositions in equilibrium with lherzolite: data from the system CaO–MgO–Al₂O₃–SiO₂–CO₂ at 6 GPa. *J Petrol* 39: 1953–1964
- Dawson JB, Smith JV, Jones AP* (1985) A comparative study of bulk rock and mineral chemistry of olivine melilitites and associated rocks from East and South Africa. *N Jb Miner Abh* 152: 143–175
- Delor CP, Rock NMS* (1991) Alkaline-ultramafic lamprophyre dykes from the Vestfold Hills, Princess Elizabeth Land (East Antarctica): primitive magmas of deep mantle origin. *Antarctic Sci* 3: 419–432
- De Wit M, Jeffrey M, Bergh H, Nicolayson LO* (1988) Geological map of sectors of Gondwana, reconstructed to their disposition at 150 Ma. University of Witwatersrand, scale 1:2.000.000
- Edgar AD* (1989) Mineral chemistry and petrogenesis of an ultrapotassic-ultramafic volcanic rock. *Contrib Mineral Petrol* 71: 171–175
- Egorov LS* (1994) Some petrological, geochemical and genetic peculiarities of hypabissal alkaline ultrabasic rocks by an example of polcenitic-alkaline picritic complex of Jetty Oasis (Eastern Antarctic Prince Charles Mountains). *Geochemistry* 1: 24–39 (in Russian)
- Egorov LS, Andronikov AV* (1989) New data on stock bodies of alkaline-ultrabasic rocks of Jetty Peninsula (McRobertson Land, East Antarctica) obtained during the 1986/1987 season. *Inf Bull SAE* 111: 5–13 (in Russian)
- Foley SF* (1984) Liquid immiscibility and melt segregation in alkaline lamprophyres from Labrador. *Lithos* 17: 127–137
- Foley SF* (1988) The genesis of continental basic alkaline magmas – an interpretation in terms of redox melting. *J Petrol Spec Lithosphere Issue*: 139–161
- Foley SF* (1989) Emplacement features of lamprophyre and carbonatitic lamprophyre dykes at Aillik Bay, Labrador. *Geol Mag* 126: 29–42
- Foley SF* (1992) Vein-plus-wall-rock melting mechanism in the lithosphere and the origin of potassic alkaline magmas. *Lithos* 28: 435–453
- Foley SF, Wheller GE* (1990) Parallels in the origin of the geochemical signatures of island arc volcanics and continental potassic igneous rocks: the role of residual titanates. *Chem Geol* 85: 1–18
- Frey FA, Green DH, Roy SD* (1978) Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilitites from south eastern Australia utilizing geochemical and experimental petrological data. *J Petrol* 19: 463–513

- Gallo F, Giametti F, Venturelli G, Vernia L (1984) The kamafugitic rocks of San Venanzo and Cupaello, central Italy. *N Jb Min Mh* 5: 198–210
- Green DH, Falloon TJ (1998) Pyrolite: a Ringwood concept and its current expression. In: Jackson I (ed) *The Earth's mantle: composition, structure and evolution*. Cambridge University Press, pp 311–378
- Hansen K (1980) Lamprophyres and carbonatitic lamprophyres related to rifting in the Labrador Sea. *Lithos* 13: 145–152
- Heaman LM, LeCheminant AN (1993) Paragenesis and U-Pb systematics of baddeleyite (ZrO₂). *Chem Geol* 110: 95–126
- Hoch M (1999) Geochemistry and petrology of ultramafic lamprophyres from Schirmacher Oasis, East Antarctica. *Mineral Petrol* 65: 51–67
- Hofmann AW, Jochum KP, Seufert M, White WM (1986) Nb and Pb in oceanic basalts: new constraints on mantle evolution. *Earth Planet Sci Lett* 79: 33–45
- Kent RW (1991) Lithospheric uplift in eastern Gondwana: evidence for a long-lived mantle plume system? *Geology* 19: 19–23
- Kent RW, Saunders AD, Kempton PD, Ghose NC (1997) Rajmahal basalts, eastern India: mantle sources and melt distribution at a volcanic rifted margin. In: Mahaoney JJ, Coffin MF (eds) *Large Igneous provinces: continental, oceanic and planetary flood volcanism*. Am Geophys Union Geophys Monogr 100: 145–182
- Kurinin RG, Grikurov GE (1980) Structure of the Lambert Glacier rift zone. *Tr Sov Antarct Exped* 70: 75–86 (in Russian)
- Laiba AA, Andronikov AV, Egorov LS, Fedorov LV (1987) Stock and dyke bodies of alkaline ultrabasic composition in Jetty Peninsula (Prince Charles Mountains, East Antarctica). In: Ivanov VL, Grikurov GE (eds) *Geological–geophysical investigations in Antarctica*. PGO “Sevmorgeologia”, Leningrad, pp 35–47 (in Russian)
- Larsen LM (1980) Lamprophyric and kimberlitic dykes associated with the Sarfartoq carbonatite complex, SW Greenland. *Rapp Grondlands geol Unders* 100/79: 65–69
- Malpas J, Foley SF, King AF (1986) Alkaline mafic and ultramafic lamprophyres from the Allik Bay area, Labrador. *Can J Earth Sci* 23: 1902–1918
- McKelvey BC, Stephenson NCN (1990) A geological reconnaissance of the Radok Lake area, Amery Oasis, Prince Charles Mountains. *Antarctic Sci* 2: 53–66
- Meen JK, Ayers JC, Fregeau EJ (1989) A model of mantle metasomatism by carbonated alkaline melts: trace element and isotopic compositions of mantle source regions of carbonatite and other continental igneous rocks. In: Bell K (ed) *Carbonatites*. Unwin-Hyman, London, pp 465–499
- Mikhalsky EV, Beliatsky BV, Andronikov AV, Gratchiov AF (1994) Dykes of Proterozoic lamprophyre of the Vestfold Hills, East Antarctica. *Petrology* 2: 587–600 (in Russian)
- Mitchell RH (1986) *Kimberlites: mineralogy, geochemistry and petrology*. Plenum Press, New York, 442 pp
- Mitchell RH, Bergman SC (1991) *Petrology of lamproites*. Plenum Press, New York, 447 pp
- Paul DK, Kent RW, Kempton PD (1997) Age composition and mantle sources of Cretaceous mafic alkaline igneous rocks in Eastern India and Eastern Antarctica: evidence for melting on the fringes of the Kerguelen plume. *EOS* 78, 46: 728
- Ravich MG, Solov'ev DS, Fedorov LV (1984) *Geological structure of McRobertson Land, East Antarctica*. Amerind Publishing, New Delhi, 230 pp
- Rock NMS (1986) The nature and origin of ultramafic lamprophyres: alnöites and allied rocks. *J Petrol* 27: 155–196
- Rock NMS (1987) The nature and origin of lamprophyres: an overview. In: Fitton JG, Upton BGJ (eds) *Alkaline igneous rocks*. Geol Soc Spec Pub 30: 191–226
- Rock NMS (1991) *Lamprophyres*. Blackie and Son Ltd, Glasgow, 285 pp

- Rogers NW, Hawkesworth CJ, Matthey DP, Harmon RS* (1987) Sediment subduction and the source of potassium in orogenic leucitites. *Geology* 15: 451–453
- Ryabchikov ID, Brey GP, Bulatov VK* (1993) Carbonate melts coexisting with mantle peridotites at 50 kbar. *Petrology* 1: 159–163
- Sahama T* (1978) The Nyiragongo Main Cone. *Mus Roy Afr Centrale Sci Géol* 81: 88 pp
- Scott BH* (1979) Petrogenesis of kimberlites and associated potassic lamprophyres from central West Greenland. In: *Boyd FR, Meyer HOA* (eds) *Kimberlites, diatremes and diamonds: their geology, petrology and geochemistry*. American Geophysical Union, Washington, pp 190–205
- Sheraton JW, Tingey RL, Black LP, Oliver RL* (1993) Geology of the Bunger Hills area, Antarctica: implications for Gondwana correlations. *Antarctic Sci* 5: 85–102
- Sun SS, McDonough WF* (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition of the earth and mantle evolution. In: *Saunders AD, Norry MJ* (eds) *Magmatism in ocean basins*. *Geol Soc Spec Pub* 41: 313–345
- Varne R* (1985) Ancient subcontinental mantle: a source for K-rich orogenic volcanics. *Geology* 13: 405–408
- von Eckermann H* (1966) Progress of research on the Alnö carbonatite. In: *Tuttle OF, Gittins J* (eds) *Carbonatites*. J Wiley, New York, pp 3–31
- Walker KR, Mond A* (1971) Mica lamprophyre (alnöite) from Radok Lake, Prince Charles Mountains, Antarctica. *Austral BMR Geol Geophys Rec* 108: 6 pp
- Wallace ME, Green DH* (1988) An experimental determination of primary carbonatite magma composition. *Nature* 335: 343–346
- Wallace ME, Green DH* (1991) The effect of bulk rock composition on the stability of amphibole in the upper mantle: implications for solidus positions and mantle metasomatism. *Mineral Petrol* 44: 1–19
- Woolley AR, Bergman SC, Edgar AD, LeBas MJ, Mitchell RH, Rock NMS, Scott Smith BH* (1996) Classification of lamprophyres, lamproites, kimberlites, and the kalsilitic, melilitic and leucitic rocks. *Can Mineral* 34: 175–186
- Yoder HS* (1973) Melilite stability and paragenesis. *Forsch Mineral* 50: 140–173

Authors' addresses: *S. F. Foley*, Institut für Geologische Wissenschaften, Universität Greifswald, FL Jahnstrasse 17a, D-17487 Greifswald, Federal Republic of Germany, e-mail: sfoley@uni-greifswald.de; *A. V. Andronikov*, Department of Geological Sciences, University of Michigan, Ann Arbor, Mi 48109-1063, USA; *S. Melzer*, Projektbereich 4.1, Geoforschungszentrum Potsdam, Postfach 600751, D-14407 Potsdam, Federal Republic of Germany