Multi-component origin of Caledonian lamprophyres of northern England

R. Macdonald,[1] R. S. Thorpe,[2] J. W. Gaskarth,[3] and A. R. Grindrod[1]

[1]Department of Environmental Sciences, University of Lancaster, Lancaster LA1 4YQ, UK. [2]Department of Earth Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK. [3]Department of Geological Sciences, University of Aston, Gosta Green, Birmingham B4 7ET, UK.

ABSTRACT. Mafic lamprophyre dykes in northern England were emplaced soon after the final closure of the Iapetus Ocean at the end of the Caledonian orogeny. High $Mg/(Mg+Fe)$ ratios and Cr and Ni contents are consistent with equilibrium with mantle peridotite. Incompatible trace element abundances suggest that the mantle sources were metasomatized prior to the melting events. Three components are recognized in the lamprophyre chemistry: (i) a depleted mantle source, taken to be that overlying the subducting lithosphere; (ii) a H_2O-rich subduction zone component, related to the dehydration of the subducting oceanic crust; and (iii) a CO_2-rich phase thought to result from the degassing of the mantle after ocean closure. This multi-component origin may be applicable to other lamprophyres of calc–alkaline affinity.

KEYWORDS. lamprophyres, dykes, Iapetus Ocean, England.

THE final stages of the Caledonian orogeny in NW Europe resulted in the collision of the 'European' and 'North American' continental plates, together with a number of smaller massifs (Dewey, 1969, 1982; Watson, 1984). The plates had been separated by the Iapetus Ocean, final closure of which in late Silurian times was related to subduction towards the NW and SE. The Iapetus suture line crosses Britain northeastwards from the Solway Firth (fig. 1). There is apparently a contrast in basement age and type to the north and south of the presumed position of the suture. To the north, the basement dates from c.2900 Ma and was formed in a cratonic environment. Basement south of the suture is thought to have formed largely between 700 and 450 Ma by the formation and lateral accretion of island arcs unrelated to the northern margin (Thorpe et al., 1984).

There was an important change in tectonic regime, roughly coinciding with the closure of Iapetus, at about 420 Ma, when strike–slip motion occurred on NE–SW lines parallel to the Caledonian belt (Watson, 1984). The change was accompanied by the onset of late Caledonian magmatism. This was dominated by calc–alkaline, granitoid, plutonic activity, but the masses had abundant associations of minor intrusions, including lamprophyric, appinitic and felsic varieties, and there were important sequences of calc–alkaline lavas. Recent geochemical and isotopic studies (summarized in Sutherland, 1982, and by Watson, 1984) have been made of the late- and post-orogenic granites, the appinites, and the lavas. The current work is the first modern geochemical study of any part of the very extensive late-Caledonian dyke swarms and aims to provide information on the processes occurring in the Iapetus subduction zone just prior to, and following, ocean closure.

Geological summary

The lamprophyres occur as thin dykes, and more rarely sills, in close geographical association with a poorly exposed granitic batholith which has been interpreted (Bott, 1978) to underlie much of N. England (fig. 1). On the basis of palaeomagnetic data, Piper et al. (1978) suggested that the dykes of the Cross Fell inlier are of early Devonian age. A different view has been expressed by Arthurton and Wadge (1981) who recognize an end-Silurian cleavage in several dykes and infer that they were intruded towards the end of the Silurian. Possibly there was more than one period of dyke emplacement (see also Rock, 1984, table 7). The dykes analysed here have no tectonic fabric and some of them contain granite xenoliths. We regard them as
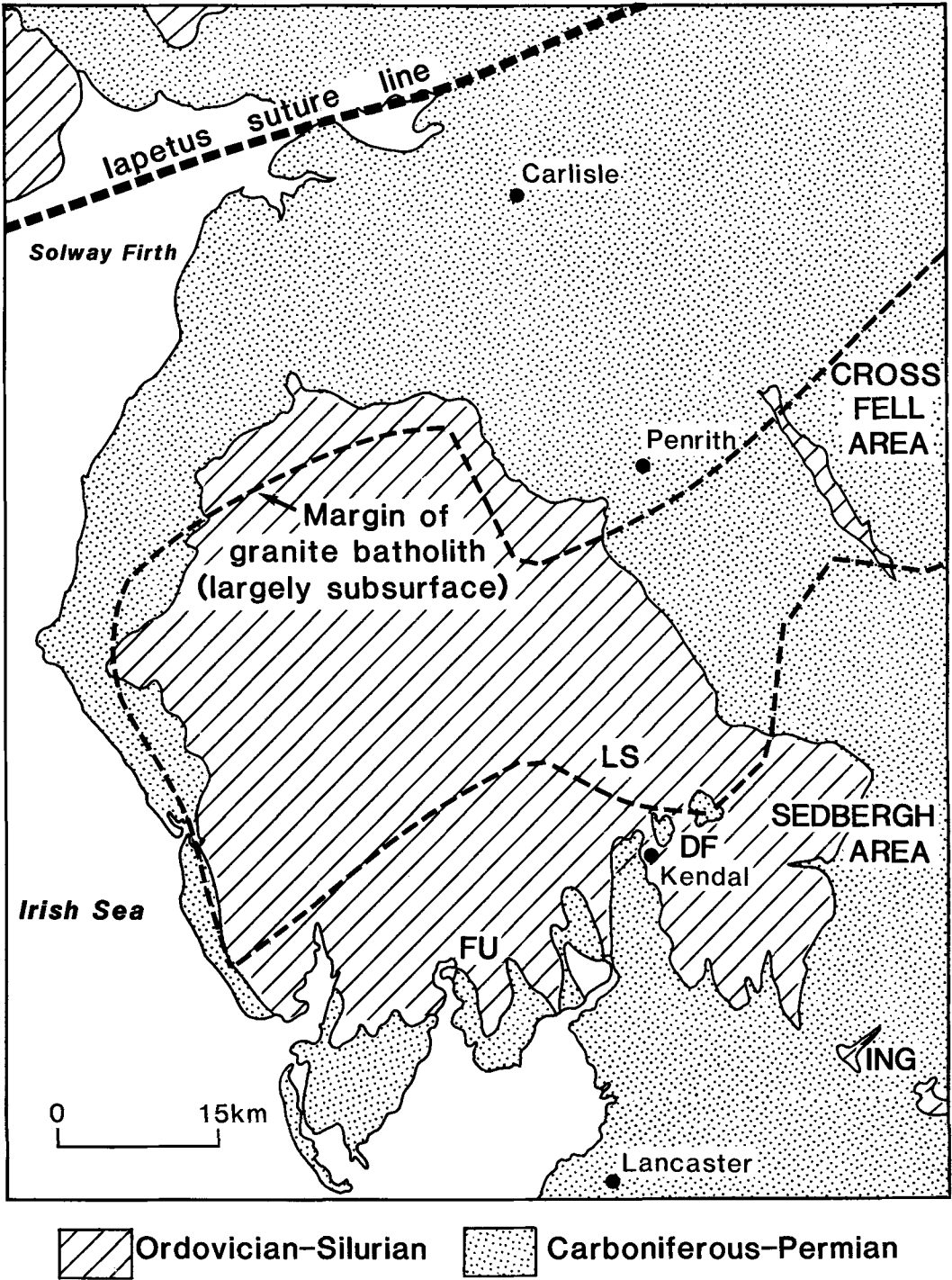
FIG. 1. Map of northern England showing locations of sampled areas. Abbreviations are as follows: LS, Long Sleddale; DF, Docker Fell; FU, Furness; ING, Ingleton. Position of Iapetus suture from Watson (1984).

being of early Devonian age (cf. Piper *et al.*, 1978). We assume, but cannot prove, that they belong to one intrusive episode. The lamprophyres are associated in the field with a suite of silicic minor intrusions which include quartz–feldspar porphyries, felsites, microgranites, and rocks of monzonitic type. Discussion is restricted here to the more mafic dykes, with MgO > 6%.

Petrography

Two types of mafic lamprophyre are readily distinguished in the field. A group of dark coloured, microphyric rocks of basaltic aspect are kersantites, both olivine-free and olivine-bearing types being represented. The second group, of strongly porphyritic rocks rich in biotite phenocrysts, is comprised of kersantites and minettes, although alteration of the groundmass feldspar may make the detailed classification difficult. The terms kersantites and mica lamprophyres are here applied to the two groups respectively, in order to stress the textural differences between them and to facilitate discussion of their chemical compositions.

The kersantites are from Backside Beck within the Lower Palaeozoic inliers *c.* 8 km northeast of Sedbergh (Ingham, 1966, plate 27) and Long Sleddale within Lower Palaeozoic rocks in the east of the Lake District (fig. 1). The samples from Backside Beck (BB6, BB8, BB12) comprise zoned clinopyroxene, phlogopite, and calciferous amphibole (all variably altered to chlorite, epidote, and zoisite), and Fe–Ti oxide together with pseudomorphs after olivine with the mineralogy of 'pilite' (Velde, 1968), in a matrix dominated by these phases and their alteration products. Some samples contain xenocrysts of quartz and plagioclase, showing complex reactions (now represented by alteration products) with the surrounding matrix. The samples from Long Sleddale (LS1–LS4) comprise phlogopite (partially and variably altered to chlorite and Fe–Ti oxide), plagioclase (partially and variably altered to sericite and epidote), green amphibole (partially or completely altered to chlorite) and Fe–Ti oxide. The amphibole in LS4 is Ti-rich (TiO$_2$ = 3.1–4.5%) and calciferous. Some samples contain circular ocelli (up to 2 mm in diameter) filled with carbonate $\pm$ quartz $\pm$ plagioclase feldspar, surrounded by matrix in which biotite and feldspar show tangential orientation.

The mica lamprophyres are from four areas of Lower Palaeozoic rocks: (i) the south and southeast Lake District; (ii) the Ingleton inlier; (iii) the inliers to the NE and SE of Sedbergh (Smith, 1930; Ingham, 1966); and (iv) the Cross Fell inlier (Arthurton and Wadge, 1981). The analysed samples are characterized by biotite phenocrysts which are generally zoned to more Fe-rich rims (partially altered to chlorite, serpentine, and sericite), and rarer feldspars set in a fine-grained matrix containing plagioclase (oligoclase-andesine) and alkali feldspar (partially to completely altered to epidote, sericite, carbonate, and silica), Fe–Ti oxide and apatite. Some rare chlorite and epidote masses may represent pseudomorphs after pyroxene and/or olivine. The matrix locally has irregular concentrations of the alteration products noted above and these may reflect late-magmatic segregations analogous to the ocelli described above, pseudomorphs of felsic and mafic minerals, or products of post-magmatic hydrothermal alteration. These minerals also occur within microscopic segregations and veins within some samples, indicating mobility of these phases within hydrothermal solutions during consolidation of the lamprophyre magma.

The micas in the mica lamprophyres from Birksfield Beck (BiD) and Ingleton (ING1) are titaniferous, between phlogopite and siderophyllite in composition, with Mg/Fe (atomic) = 3.3–11.9, TiO$_2$ = 3–4%, and Cr$_2$O$_3$ up to 1.7% in the centre of zoned crystals (ING1). The phlogopites in the analysed samples have chemical compositions corresponding to those given for lamprophyres by Rock (1984, figs. 1 and 2).

Some of the mica lamprophyres contain xenoliths of granitic material and/or siliceous sedimentary rock and derived xenocrysts of quartz and feldspar. The xenocrysts have a rim of chlorite and epidote pseudomorphing primary minerals formed by reactions between the xenocryst and melt. These include the dyke from south of Marsh Gate (MG1) which contains a xenolith of graphic granite, the highly xenolithic dykes in the R. Rawthey (RB1 and RB2; cf. Smith, 1930, pp. 336–7), and dykes in Birksfield Beck (BiD; Smith, 1930, p. 338), and Ecker Seck Beck (ES1, ES4, ES6). These xenoliths and xenocrysts show complex reaction relationships with the surrounding mica lamprophyre. Some of the xenoliths may be derived from representatives of the granite batholith which is interpreted to underlie the Lake District (fig. 1).

The mineralogical features of the kersantites and mica lamprophyres are consistent with derivation from magnesium- and alkali-rich mantle-derived parent magma by complex fractional crystallization processes, accompanied and followed by late- and post-magmatic modification by hydrothermal processes and interaction with crustal material. The effects of the last-named process were minimized by excluding xenolithic material wherever possible during sample preparation.

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Table I.   Major and trace element abundances in Caledonian mica lamprophyres of N. England

Locality	Cross Fell	Sedbergh area												Ingleton	Docker Fell	Furness	Mean	S.D.
Specimen No.	KN2	RB1	RB2	MV1	BB7	ES6	ES4	ES1	FG1	BiD	MG1	CR1	KNB1	ING1	DF1	FU1		
Nat.Grid Ref.†	689281	712978	711978	699989	694989	698957	699958	704960	706962	693949	695942	686917	622909	705742	557957	355825		
SiO_2	49.7	52.0	53.6	54.7	48.9	52.6	39.1	48.3	44.3	46.8	46.7	41.8	38.0	45.0	47.3	47.4	47.3	4.9
TiO_2	1.54	1.50	1.54	0.77	1.51	0.95	0.84	0.94	1.96	1.03	1.02	1.03	1.09	1.65	1.11	1.13	1.23	0.34
Al_2O_3	14.06	12.65	12.75	12.11	11.64	12.46	9.74	11.27	9.73	11.20	11.68	10.87	10.10	12.34	14.88	15.52	12.06	1.69
Fe_2O_3	8.40*	1.32	1.39	2.70	6.25*	4.93*	8.32*	6.43*	7.82*	2.74	1.01	7.57*	1.14	2.83	4.14	5.38*	7.29	1.37
FeO	–	5.03	4.97	4.32	–	–	–	–	–	4.92	4.82	–	4.94	5.67	5.45	–	–	–
MnO	0.28	0.19	0.15	0.13	0.22	0.20	0.23	0.17	0.25	0.29	0.19	0.15	0.67	0.19	0.15	0.12	0.22	0.13
MgO	7.61	7.04	6.86	9.45	7.52	7.14	7.64	7.89	8.38	9.55	9.38	7.11	7.41	8.88	9.79	6.29	8.00	1.10
CaO	5.70	7.65	6.03	5.21	6.74	6.58	12.79	7.39	9.12	7.20	10.17	11.80	15.96	8.61	4.39	7.55	8.31	3.06
Na_2O	2.53	1.85	2.03	1.32	0.81	0.93	1.03	1.26	n.d.	0.63	0.80	0.80	0.19	1.16	1.28	2.90	1.20	0.80
K_2O	2.31	2.98	4.60	2.48	6.73	2.73	3.38	4.65	6.09	5.12	3.94	5.85	5.81	5.10	5.59	6.06	4.59	1.44
P_2O_5	0.92	0.93	0.95	0.91	1.01	0.81	0.82	0.95	1.47	0.89	0.99	1.16	1.45	1.04	1.17	0.99	1.03	0.20
H_2O+	3.69	2.16	2.15	2.85	1.27	2.65	1.77	1.39	1.79	1.49	2.52	1.27	1.50	2.96	2.16	2.04	2.10	0.69
CO_2	3.49	5.42	3.67	3.47	7.04	7.73	12.83	8.75	8.40	7.30	7.64	10.21	12.21	4.55	2.10	4.99	6.86	3.17
Total	100.23	100.72	100.69	100.32	99.64	99.70	99.77[1]	99.39	99.31	99.16	100.46	99.62	100.47	99.98	99.51	100.37	100.19	–
(ppm)																		
Ba	1584	1070	1759	3879	2076	1744	8707	1953	1973	3446	2289	3218	6256	1545	1944	2832	2892	1994
Ce	166	185	176	207	203	300	268	215	226	237	245	190	236	182	420	440	243	81
Co	43	43	39	40	30	33	48	25	42	41	42	38	50	42	50	30	40	7
Cr	339	246	253	359	370	398	843	404	277	427	430	824	786	411	416	286	442	196
Nb	22	23	26	12	23	19	13	14	30	14	14	15	19	24	17	20	19	5
Ni	227	138	107	236	228	232	416	272	253	340	327	316	299	250	336	172	259	80
Rb	88	154	164	82	158	75	64	112	184	126	113	239	84	147	92	117	125	47
Sr	419	650	947	1575	712	281	2623	829	1143	738	501	1430	1703	484	457	1217	982	615
Th	30	47	48	28	35	45	22	27	23	29	35	24	24	50	45	46	35	10
V	187	218	219	126	191	129	141	140	188	144	155	145	147	213	152	145	165	32
Y	29	34	35	24	38	29	22	25	40	31	33	32	40	30	39	28	32	6
Zr	320	366	377	231	374	319	192	243	364	227	253	256	274	360	277	273	294	60

*total Fe as Fe_2O_3.   Totals include [1]BaO = 0.97%, SrO = 0.31%, [2]BaO = 0.42%, SrO = 0.86%, [3]BaO = 0.40%, SrO = 0.56%.

Analysis by XRF, using Philips PW 1400 spectrometer (University of Lancaster). Majors on fusion discs, traces on powders.
FeO by modified Wilson (1955) method; H_2O+ and CO_2 gravimetrically. n.d. = not detected.

† All grid refs. prefixed by SD-, except KN2(NY)

Table II.   Major and trace element abundances in Caledonian kersantites of N. England

Locality	Long Sleddale				Sedbergh area					Mean	S.D.
Specimen No.	LS1	LS2	LS3	LS4	BB6	BB8	BB10	BB11	BB12		
Nat.Grid Ref.†	488073	488073	488073	488073	697984	693989	696991	697985	698982		
SiO_2	53.1	49.7	49.0	50.1	42.1	40.1	36.9	42.1	42.9	45.1	5.5
TiO_2	1.44	1.62	1.72	1.57	0.93	0.95	0.99	0.94	1.08	1.25	0.33
Al_2O_3	14.68	15.20	15.58	15.82	11.19	10.67	11.38	10.92	10.86	12.92	2.30
Fe_2O_3	2.99	3.11	3.31	3.52	8.99*	9.24*	9.32*	9.05*	7.43*	8.62*	0.74
FeO	3.94	4.85	5.14	4.63	–	–	–	–	–	–	–
MnO	0.20	0.16	0.18	0.16	0.17	0.46	0.23	0.18	0.17	0.21	0.10
MgO	6.78	7.66	6.92	.12.50	12.50	10.76	11.08	11.70	7.63	9.09	2.37
CaO	6.15	6.51	7.57	8.63	8.87	9.08	12.63	10.31	11.71	9.05	2.20
Na_2O	2.67	2.28	2.39	2.40	1.22	0.57	0.97	1.01	2.19	1.74	0.79
K_2O	3.66	3.59	2.76	2.36	2.47	3.37	1.64	2.27	1.33	2.61	0.82
P_2O_5	0.74	0.67	0.57	0.54	0.80	0.99	0.83	0.78	1.27	0.80	0.22
H_2O+	2.68	2.50	2.97	1.66	2.27	3.45	4.83	3.38	2.88	2.96	0.89
CO_2	1.78	2.26	2.42	2.15	6.01	10.20	9.22	5.84	10.30	5.58	3.61
Total	100.81	100.11	100.53	100.30	98.80[2]	99.84	100.02	99.44[3]	99.75	99.93	–
(ppm)											
Ba	1568	1092	618	656	3791	4753	1837	3595	1809	2191	1491
Ce	237	170	137	121	257	298	251	250	300	225	66
Co	40	43	38	41	43	39	50	48	39	42	4
Cr	244	214	197	241	844	881	1090	861	557	570	355
Nb	14	18	21	18	14	16	14	12	23	17	4
Ni	129	141	127	138	461	346	563	471	240	291	173
Rb	85	76	55	41	45	58	31	40	51	54	17
Sr	1274	922	714	800	7275	939	1006	4732	1340	2111	2305
Th	25	17	12	11	24	26	25	24	41	23	9
V	242	213	194	196	163	158	176	160	172	186	28
Y	25	24	25	24	22	28	31	24	27	26	3
Zr	230	221	225	214	165	210	186	142	311	212	48

Footnotes as for Table I

Petrochemistry

Major element analyses are given in Tables I and II. The high H_2O and CO_2 values are believed to be partly primary, being characteristic of the rock type (Rock, 1984), and partly related to secondary alteration, as the petrographic evidence of chloritization and carbonatization indicates. To facilitate inter-sample comparisons, further discussion uses all analytical data recalculated to 100% volatile-free.

SiO_2 values in both groups are variable, certain of the mica lamprophyres containing distinctly high SiO_2 (> 55%) for high-MgO rocks. Al_2O_3 is also variable (11–17%) and FeO_t (total Fe as FeO) generally low in all rocks. Mg-numbers ($100 \times Mg/(Mg + Fe^{2+})$, calculated assuming $Fe^{3+}/Fe^{2+} = 0.15$ atomic), are high, ranging from 70–78 in the mica lamprophyres and from 62–70 in the kersantites. These are values expected of primary magmas in equilibrium with mantle peridotite (Frey et al., 1978). CaO values are variable; high CaO is associated with high CO_2 (r = 0.59) and is presumably secondary. Low values may be related to leaching on breakdown of groundmass plagioclase feldspars. The freshest rocks (e.g. ING 1, FU 1) have CaO $\simeq$ 8%, which is typical of calc-alkaline lamprophyres (Rock, 1984). Alkali contents are variable, though K_2O tends to be high, in the range

1.55–7.42% (recalculated). Some of the spread in K_2O/Na_2O ratios, 0.6–> 60 by weight, is probably related to alteration; nevertheless, even the freshest mica lamprophyres are thoroughly potassic ($K_2O/Na_2O > 2$), while the kersantites have, on average, slightly lower K_2O/Na_2O ratios. All samples have high P_2O_5 abundances, but TiO_2 is not similarly enriched. Indeed, in some rocks, $P_2O_5 > TiO_2$. Al_2O_3/TiO_2 ratios are low and comparable to those in MORB (Hickey and Frey, 1982, fig. 3).

The overall similarity of the mica lamprophyres and kersantites may be noted, though, at the same MgO values, the mica lamprophyres extend to higher abundances of SiO_2, K_2O (fig. 2), and P_2O_5 values, while Al_2O_3, FeO_t, and TiO_2 are about the same in both groups.

The absolute abundances of the trace elements are discussed below. Some important aspects of their distribution are: (i) At the same MgO contents, the mica lamprophyres have higher abundances of Rb, Th, LREE, Y, and Zr than the kersantites, though there is much overlap (cf. Tables I and II). Concentrations of Ba, Sr, Nb, Zn, Co, and Ni are about the same. The data confirm petrographic and major element evidence of a close compositional relationship. The resemblance between mica lamprophyres and K-rich basalts has been noted by, inter alios, Rock (1977, 1984), Bachinski and Scott (1979), Luhr and Carmichael (1981), Rogers et al. (1982), and Van Bergen et al. (1983), and the geochemical data for the English rocks are consistent with the idea that the lamprophyres are basalts enriched in alkalis, volatiles, and incompatible trace elements, with the mica lamprophyres being slightly more extreme than the kersantites in this respect. We note, however, that as well as greater enrichment in these components, the mica lamprophyres may also show different element ratios, e.g. higher Zr/Nb, Zr/Ti, Ba/Sr, and Rb/Sr. (ii) Positive correlations between MgO and Ni (r = 0.73; fig. 2) and Cr (0.51) are consistent with olivine + chromite fractionation from parental melts, or with differing degrees of partial melting of the source rocks. Ba (fig. 2), Nb, Rb, Sr, Th, Y, and Zr show insignificant (< 0.4) correlations with MgO. (iii) Apart from the geochemically coherent pairs Nb-Ta, Zr-Hf, and Th-U, element–element correlations are generally weak or absent. Only Zr-Nb (0.71) and K-Rb (0.54) have modest to strong correlation in the whole sample set.

The abundances of Sc and the first series transition elements in both groups are similar to those in magnesian basalts from other tectonic settings, such as the ocean floor and oceanic islands and continents (fig. 3, after Hickey and Frey, 1982). Rather low Cr and Ni values in some rocks may reflect chromite ± olivine fractionation, rather than
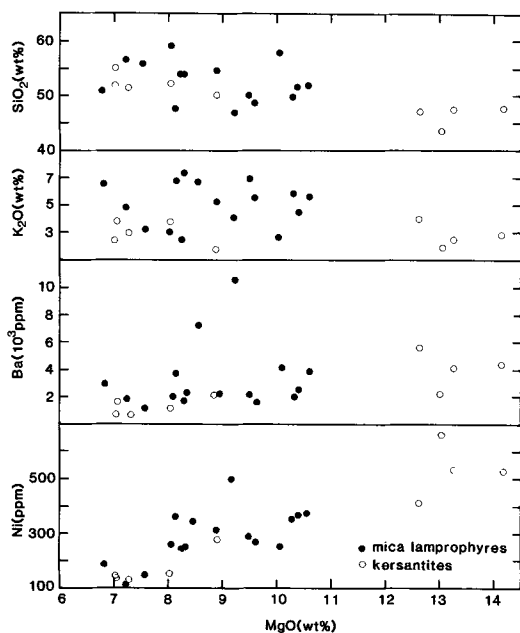

FIG. 2. MgO-element plots, using data recalculated 100% volatile free. Correlation coefficients are: MgO–SiO_2 0.28, MgO–K_2O 0.06, MgO–Ba 0.11, MgO–Ni 0.73.
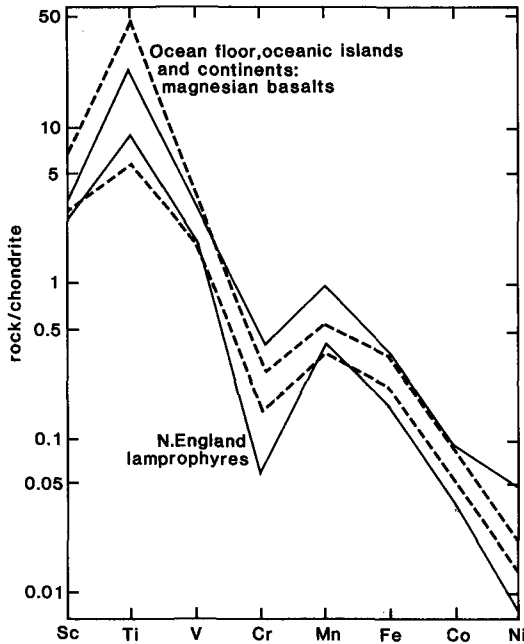
FIG. 3. Range of chondrite-normalized Sc and transition metal abundances in lamprophyres and magnesian basalts from various tectonic settings. Mica lamprophyres and kersantites grouped together for simplicity. Basalt data and normalizing values from Hickey and Frey (1982, fig. 4 and Table 2).

These *LREE*-enriched patterns are similar to those recorded for lamprophyric rocks by Kay and Gast (1973), Bachinski and Scott (1979), Luhr and Carmichael (1981), Rogers *et al.* (1982), and Rock (1984).

The large variation of *LREE* in relation to *HREE* has been observed in basaltic provinces and has been interpreted by Shimizu and Arculus (1975) and discussed by Macdonald *et al.* (1984). Assuming a mantle source with 2–3 times chondritic *REE* abundances (e.g. Kay and Gast, 1973; Sun and Hanson, 1975), the formation of kersantite and lamprophyre melts with *HREE* concentrations of 10–12 times chondritic values (cf. earlier) indicates formation by partial melting or fractional crystallization involving a mineral (such as garnet) or minerals with high *REE* partition coefficients. Shimizu and Arculus (1975) showed that the presence of garnet throughout during partial melting would generate magmas with constant *HREE* concentrations accompanied by varying degrees of *LREE* enrichment. The high degree of *LREE* enrichment (Ce_N = 139–540) suggests that, for formation by even a few per cent of partial melting of a mantle peridotite source, the source material is likely to have been *LREE*-enriched (cf. Venturelli *et al.*, 1984). The *REE* data are therefore consistent with formation of the kersantites and mica lamprophyres by varied degrees of partial melting of *LREE* enriched mantle

source characteristics, and high values of these elements may be related to higher degrees of melting of the source than is common in intra-plate settings. High MnO abundances in certain specimens may be a particular feature of the north English lamprophyres as a group (cf. Harker, 1892). Overall, however, the abundances and behaviour of this group of elements are comparable to those in the majority of magnesian basalts. In particular, ratios such as Ti/Sc and Ti/V are very similar to those found in MORB (Hickey and Frey, 1982).

Five representative samples of kersantite and mica lamprophyre have been analysed for the *REE* using the method described by Potts *et al.* (1981) (Table III and fig. 4). The analysed samples from both groups are all light *REE* (*LREE*) enriched with chondrite-normalized $Ce(Ce_N)$ = 139–540 and Yb_N = 10–12. Although Gd could not be determined in the analysed samples, the overall shapes of the *REE* patterns, and extrapolation from Sm to Tb suggest that the samples do not have significant Eu anomalies. The *REE* patterns are characterized by large variation of *LREE* in relation to the *HREE*, so that the Ce_N/Yb_N ratio ranges from 12.5–51.2 at nearly constant *HREE* concentrations.

Table III. Additional trace element data

Rock type	Mica lamprophyres			Kersantites	
Specimen no.	RB2	B1D	DF1	LS1	LS4
(ppm)					
Cs	2.88	11.1	6.54	2.21	1.05
Hf	12.4	6.00	6.38	6.41	5.39
Sc	22.5	22.1	20.2	26.3	24.0
Ta	1.36	0.62	0.84	0.82	1.10
Th	47.5	29.5	45.9	23.6	10.6
U	9.40	5.56	7.59	4.99	2.06
La	76	105	226	105	58
Ce	177	220	467	217	120
Nd	101	105	215	93	55
Sm	19.5	18.6	33.3	13.3	9.0
Eu	4.06	4.72	7.86	2.89	2.27
Tb	1.78	1.56	2.37	1.06	0.96
Tm	0.39	0.33	0.36	0.34	0.36
Yb	2.67	2.26	2.32	2.43	2.44
Lu	0.44	0.37	0.38	0.41	0.39

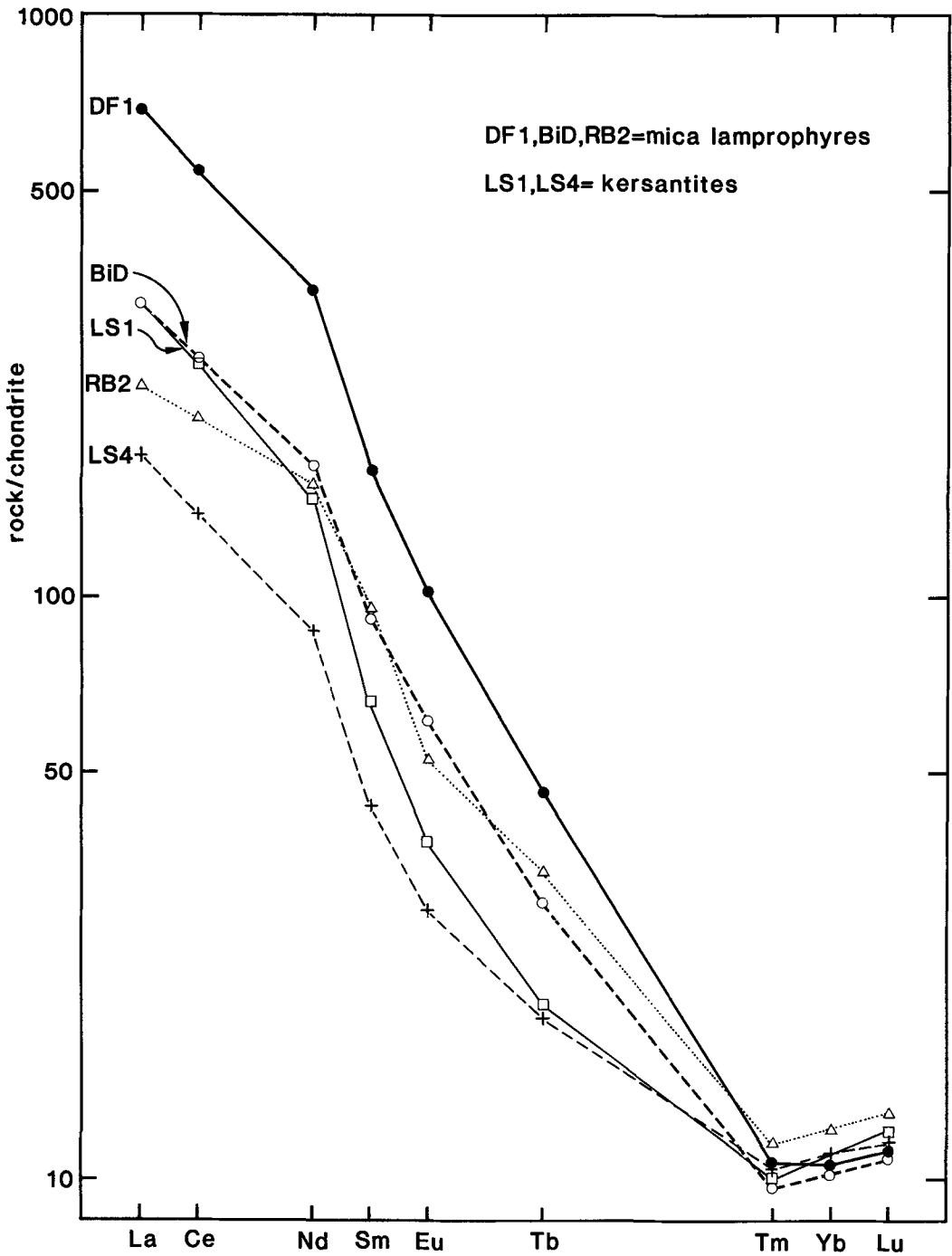Analyses by INAA, as described in Potts et al. (1981).

FIG. 4. Chondrite-normalized *REE* abundances in the two lamprophyre groups. Normalizing values from Nakamura (1974), except Tb and Tm, from Thompson (1982).
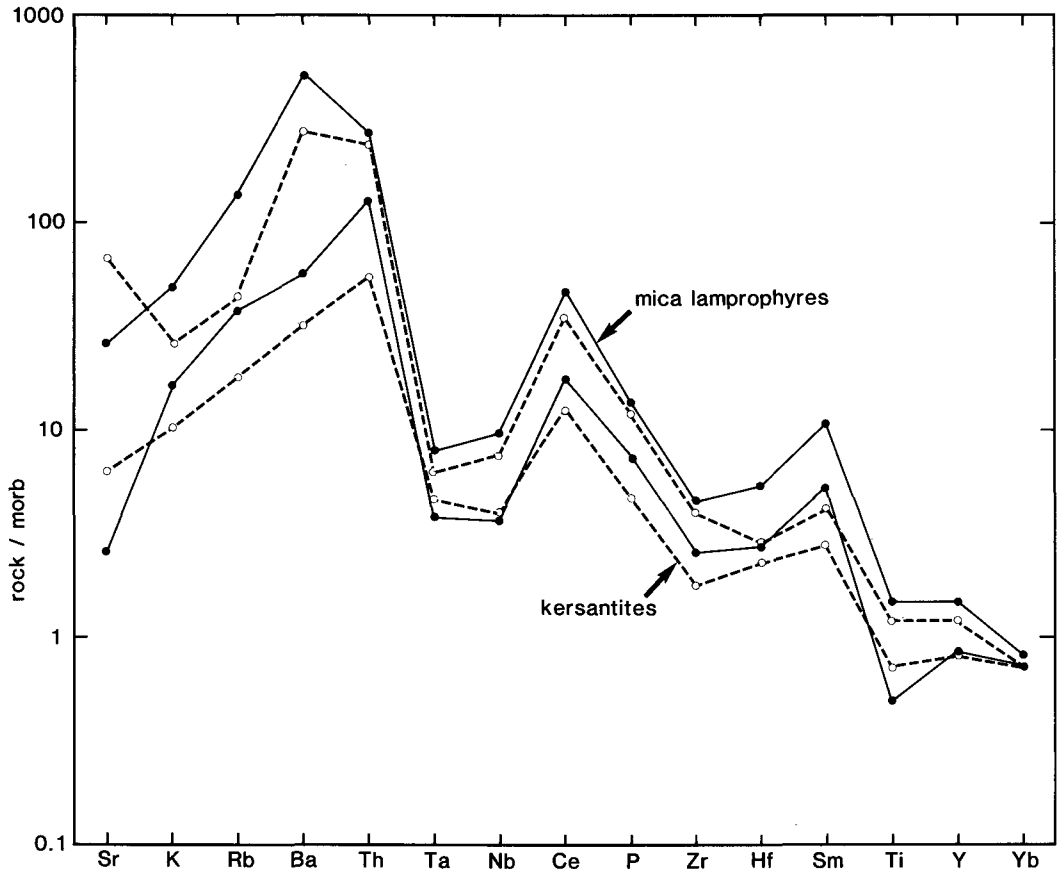
FIG. 5. Geochemical patterns for the two lamprophyre groups. MORB normalizing values and ordering of elements from Pearce (1982, 1983).

garnet-peridotite ($\pm$ subsequent fractional crystallization). The mantle source composition and magmatic processes involved are discussed below.

In fig. 5, the ranges of MORB-normalized abundances of the incompatible trace elements, plus selected more compatible elements, are plotted using the ordering of the elements and normalizing values of Pearce (1982, 1983), except that Y and Ti have been reversed in fig. 6. Key features include: (i) The mica lamprophyres and kersantites show comparable patterns, though, as noted above, the kersantites extend to lower levels for most elements. (ii) The alkalis, alkaline earths, *LREE*, P, and Th show variable but strong ($\times 10$–10^2) enrichment. Cs and U are not shown on the plot but are similarly enriched. (iii) The high field strength (HFS) elements Zr, Hf, Nb, and Ta show only modest enrichment ($\times 2$–9). (iv) Ti, Y, and the *HREE* occur at levels lower than, to just above, those in the standard MORB.

Discussion

The high Mg numbers and Ni and Cr contents in some of the lamprophyres are consistent with derivation of parent magmas by high degrees of partial melting of ultramafic mantle, followed by small but variable degrees of fractional crystallization, i.e. the rocks approach primary magmas in composition (Sato, 1977; Hickey and Frey, 1982). The abundances of such elements as Ti and the *HREE* indicate that the mantle sources were of 'depleted' type, similar to those from which MORB are generated. Paradoxically, the extreme enrichment in certain incompatible elements (e.g. Ba, Th, $\times 10^2$–10^3 chondritic) dictates that the mantle sources were strongly enriched in these elements relative to a chondritic mantle.

The MORB-normalized patterns (fig. 5) of the lamprophyres are most closely matched by certain 'alkaline' basalts of island arcs and continental
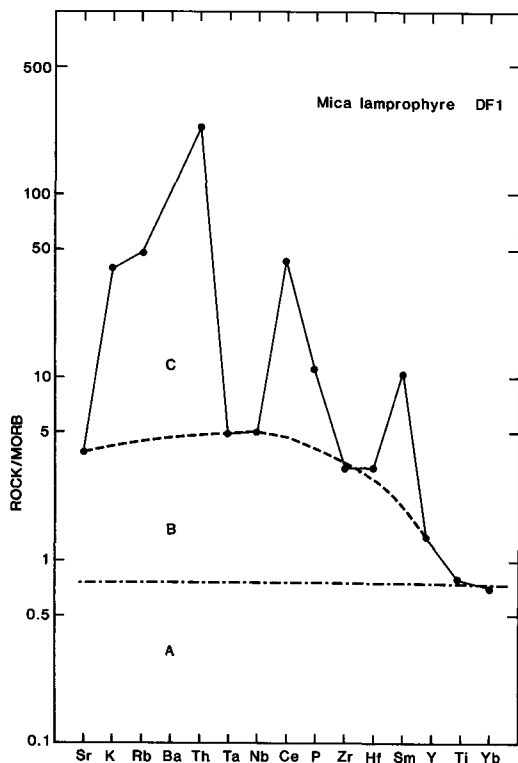
FIG. 6. MORB-normalized element plot for mica lamprophyre DF1, to show the three components, A–C, inferred to have contributed to the rock chemistry, following the procedure of Pearce (1983). The order of Yb and Ti has been reversed, for convenience, compared to fig. 5.

margins (Pearce, 1982, 1983). Recent studies (reviewed by Pearce, 1982) are making it clear that the compositional characteristics of such rocks are derived either from two magma sources or from a two-stage origin. Pearce (1983) has devised an empirical method for evaluating the nature and proportions of the various geochemical components in such rocks, based on the patterns shown by basalts from known tectonic settings. The technique is applied to the lamprophyres in fig. 6, using sample DF1 as an example. Three components may be distinguished.

Source of the components. A line drawn through the least enriched elements (Ti, Yb) is taken to represent a component (A) from a mantle source (or sources) with trace element characteristics similar to those of MORB sources. Depletion of these elements relative to MORB suggests that either less fractional crystallization or more partial melting of the source(s) took place in the generation of the lamprophyres.

There is no convincing evidence for the presence of basement older than Cadomian and Caledonian, or of ancient continental lithosphere, underlying northern England during closure of Iapetus (Brown and Locke, 1979; Hampton and Taylor, 1983; Thorpe *et al.*, 1984). The Lake District volcanism has been interpreted as being of intra-oceanic island arc type, with SE subduction on the southern side of Iapetus (Thorpe *et al.*, 1984). It is therefore probable that oceanic mantle overlay the subducting plate and we identify that as the source of component *A*.

Component *C*, lying above a line drawn through Nb, Ta, and Y and close to Zr and Hf represents the subduction zone component. The elements which have contributed substantially to it, Sr, K, Rb, Ba, Th, *LREE*, and P, are those which generally do so (Pearce, 1983). Many authors (Best, 1975; Hawkesworth *et al.*, 1977; Hickey and Frey, 1982; Pearce, 1982, 1983) suggest that this component results from enrichment of the mantle sources by aqueous fluids driven from subducted oceanic crust, the enriched elements being those which tend to be mobilized by aqueous fluids. In the context of the north English lamprophyres, the dehydrating subducting oceanic crust was that of the Iapetus Ocean.

An integral part of this interpretation is that much of the Zr, Hf, Nb, and Ta in the lamprophyres was derived from a third component (*B*). These elements cannot have been derived entirely from component A, because MORB-type basalts are characteristically depleted in them. It is also unlikely that they belong to component *C*, in that subduction zone basalts are also normally depleted in them, relative to the alkalis and *LREE* (Pearce, 1982, 1983). The source of component B can be inferred from the CO_2-rich nature of the magmatism. Carbonatites provide the most direct geological evidence of the ability of CO_2-rich fluids to transport large amounts of Zr, Hf, Nb, and Ta, as well as *LREE* and P, and metasomatism of sub-continental lithosphere by $CO_2 \pm H_2O$-bearing fluids is now commonly accepted (Bailey *et al.*, 1980; Hawkesworth and Norry, 1983). We suggest that the change in plate configuration, and accompanying tensional relaxation tectonics, effected by the closure of Iapetus permitted degassing from sublithospheric sources and that the newly formed suture acted as a channel for the ascending volatiles (Bailey, 1980).

The model envisages, therefore, the metasomatism of supra-Iapetus oceanic lithosphere by fluids from two different sources, the dehydration of Iapetus oceanic crust and a CO_2-rich phase from deeper in the mantle. The relative timing of the two metasomatic events cannot be determined

precisely. That involving CO_2 must have post-dated closure, but the aqueous metasomatism could have resulted from active subduction or from post-closure reactions related to increases in geothermal gradient. Watson (1984) has drawn attention to the likely mantle metasomatism which just pre-dated final closure, while Leeder (1982) has applied Crook's (1980) model of ultrametamorphism of stationary oceanic lithosphere beneath fore-arc terrains to post-subduction magmatism in the British Caledonides.

It can be inferred (Thompson, 1984) from the relatively SiO_2-rich nature of many of the mica lamprophyres that melting proceeded under conditions where the volatile phase had low $CO_2/(CO_2 + H_2O)$ ratio and this is consistent with the trace element evidence that it is the 'subduction-related' elements which show the greatest enrichments in the lamprophyres. Compositional variation within the suite as a whole can finally be seen to result from several possible variables: heterogeneity within the pre-metasomatized oceanic lithosphere; variations in the $CO_2/CO_2 + H_2O$ ratios of the volatile phase, which affected not only the major element composition of the magmas, but also the degree of enrichment of, and ratios between, the incompatible elements; and polybaric crystal fractionation processes, which, to judge from the near-primary magmatic nature of the rocks, cannot have been of major importance. We cannot assess, without isotopic data, the possible contribution from interactions with crustal rocks mentioned in the petrography section. The elements in which the magmas are likely to have been enriched by crustal contamination, e.g. K, Rb, and Ba, are largely those contributed also by the subduction zone component (C) and we suggest that the effects of crustal interactions would be swamped by that component.

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