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SPECIAL

The Great Glen Fault: a major vertical lithospheric boundary

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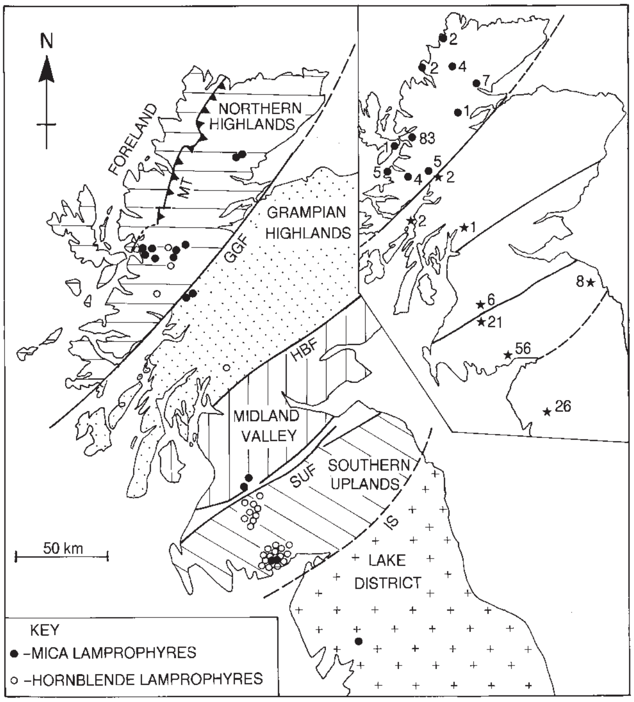
Two lamprophyre suites are used to constrain sub-continental lithospheric mantle domains in Late Caledonian Northern Britain (at 400 Ma). A Northern Highlands and a Southern domain are resolved. The first has low (εNd (− 6.4 to − 12.8); the latter has higher (+ 3.9 to − 3.4). The boundary between them is coincident with the surface expression of the Great Glen Fault. The two mantle domains tightly bracket the fault. The lamprophyre magmas were generated at depths of at least 100 km. At the end of the Caledonian Orogeny the Great Glen Fault was a major vertical discontinuity that transected the sub-continental lithospheric mantle.

Keywords: Caledonian Orogeny, Great Glen Fault, lithosphere, mantle, lamprophyres.

This paper presents new Nd isotopic data for two groups of mafic lamprophyres, mica-phyric (minettes and kersantites) and hornblende-phyric (spessartites and vogesites). These occur across the whole of the Caledonian orogenic belt in Northern Britain including all the major tectonic blocks (viz. the Lake District, the Southern Uplands, the Midland Valley, the Grampian Highlands and the Northern Highlands), and the stable Foreland region (Fig. 1). In some areas mica-phyric varieties may be more common than the hornblende-phyric and vice-versa, but both types are found in all areas. Canning *et al.* (1996), studying minettes only, inferred that the Great Glen Fault represented a major compositional boundary at depth within the Caledonian continental lithospheric mantle. BIRPS seismic profiling has indicated that the Great Glen Fault and its continuation, the Walls Boundary Fault, could be a vertical boundary in both crust and mantle (Klemperer & Peddy 1992). One Moho-parallel reflector recognized beneath the Malin Sea, appears to be cut by the Great Glen Fault at a depth of approximately 50 km (Snyder & Flack 1990). Steeply inclined or vertical structures are difficult to recognize by seismic reflection, but our data provide a unique opportunity to infer the geometry and extent of the Great Glen Fault zone at depths below that which the seismic data can image.



KEY
● -MICA LAMPROPHYRES
○ -HORNBLENDE LAMPROPHYRES

Fig. 1. Maps of Northern Britain showing Caledonian tectonic blocks and boundaries discussed in the text with 25 km post-Caledonian dextral displacement on the Great Glen Fault removed (Rogers *et al.* 1989). Main map shows samples for which Nd isotope data is available, inset shows regional distribution and numbers of lamprophyre samples from each area: stars, Southern group; circles, Northern Highland group. GGF, Great Glen Fault; HBF, Highland Boundary Fault; SUF, Southern Uplands Fault; IS, Iapetus Suture. Additional data from Canning *et al.* (1996), Dempster & Bluck (1991), Macdonald *et al.* (1985), Shand *et al.* (1994) and Thompson *et al.* (1984).

It is now widely accepted that volatile-rich, mafic, potassic magmas, that crystallize to produce lamprophyres, represent either small degree melts of metasomatized sub-continental lithospheric mantle, or, melts of discrete metasomatic veins within it (e.g. Gibson *et al.* 1993; Mitchell 1995). Most of the lamprophyres discussed here, reviewed by Canning *et al.* (1996) and Canning (1997), have compositions close to primary melts, and mineralogical and chemical constraints show that they were virtually unaffected by fractionation and/or contamination processes. They therefore carry an effectively unadulterated geochemical and isotopic signature of their mantle source regions. All dykes in this study are essentially undeformed and are the products of a pulse of post-orogenic magmatism dated at 400 Ma ± 10 (Rock *et al.* 1988, and references therein). This allows contemporaneous sampling of the continental lithospheric mantle across the assembled Caledonian orogenic belt and all its major tectonic boundaries, including the postulated Iapetus suture (Fig. 1).

Petrography and geochemistry of the Caledonian lamprophyres. The petrological characteristics of the Caledonian lamprophyres have been described by Rock *et al.* (1988); Henney (1991) and Canning (1997), and only features relevant to this study are included here. Chemically and mineralogically the lamprophyres are identical to worldwide members of these suites. The mica-lamprophyres are all porphyritic with phenocrysts of olivine, clinopyroxene and biotite-phlogopite, set in a felsic groundmass of K-feldspar (minettes) and plagioclase (kersantites). The hornblende lamprophyres (vogesites and spessartites) are also porphyritic but with hornblende,

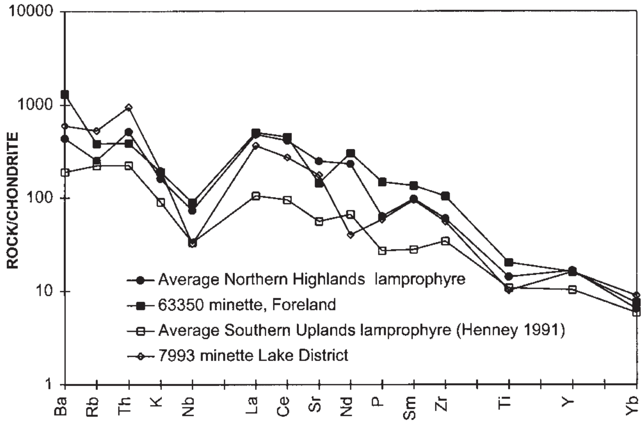


Fig. 2. Chondrite-normalized (Thompson *et al.* 1984) spidergrams for average lamprophyres and individual minette dykes from both from the Northern Highlands and Southern groups.

clinopyroxene and olivine as principal phases. Comparison of mineral chemical data for the phenocrysts with experimental results indicate crystallization at depths of up to 60 kms (Esperança & Holloway 1987). Textures, such as skeletal phenocrysts and spherulitic groundmass feldspars, indicate fast emplacement and cooling of the magmas. Thus what limited fractionation occurred, was mainly at mantle depths from where the magmas rose rapidly to crustal levels.

The lamprophyres in this study have high MgO (5–15 wt%) and high Mg# (>65) typical of near primary mantle melts. They display characteristic compositions, including high K and Na, low Ti and Nb, elevated light rare earth element (LREE) concentrations and high abundances of the large ion lithophiles (LILE), particularly Ba and Sr, typical of potassic and calc-alkaline lamprophyres (Fig. 2). All have high initial $^{87}Sr/^{86}Sr$ and low initial $^{143}Nd/^{144}Nd$ ratios consistent with a lithospheric origin (Canning 1997). There is considerable variation between individual lamprophyres in the inter-element ratios of both the LILE and the HFSE, which indicates varying mineral phases or their proportions in the source regions and thus argues for a genesis by discrete melting of metasomatic veins within the lithospheric mantle (Foley 1992).

Isotopic and chemical variations across the Caledonian belt. Canning *et al.* (1996) showed the minettes of Northern Britain could be divided into a Northern Highlands group and a Southern group, on the basis of both LILE abundances and Sr–Nd isotopes. Our more extensive database shows that this division holds true for all the mica- and the hornblende-phyric varieties. Lamprophyres from north of the Great Glen Fault, the Northern Highlands group, have LREE enriched compositions with high abundances of LILE, notably Ba, Sr and P. Samples from south of the fault are less LREE or LIL element enriched, although the absolute abundances of these elements in the two groups overlap marginally. The Nd isotopic data dramatically demonstrate the separation of the two groups (Table 1). All the Caledonian lamprophyres are LREE enriched and have low $^{147}Sm/^{144}Nd$ ratios. εNd values, calculated at 400 Ma, show considerable variation throughout the province, from $+3.9$ to -12.8. Nevertheless the Southern group have Nd concentrations from 19 to 151 ppm, $^{147}Sm/^{144}Nd$ ranging between 0.0837 and 0.1350 and εNd of $+3.9$ to -3.4. The Northern Highlands group, in contrast, have Nd concentrations of 88 to 163 ppm, $^{147}Sm/^{144}Nd$ of 0.070 to 0.0847 and εNd between -6.4 and -12.8. In each domain these two petrographically distinct lamprophyre types (mica- and hornblende-phyric) are isotopically more similar to each other than to their mineralogical equivalents in the other area. T_{DM} model ages for the two domains are also distinct. Values for the Southern group range from 1100 to 570 Ma; those for the Northern Highlands group are 1520–1150 Ma. The Southern domain extends across all of the Caledonian tectonic architecture to the south of the Great Glen Fault as far as the Lake District. The Northern group is restricted to the Northern Highlands and the Foreland region (see Fig. 3). No isotopic changes or compositional jumps are seen across any other major faults, even the Iapetus suture zone.

Discussion. The variation in εNd demonstrates the existence of two major lithospheric mantle domains below Northern Britain, the boundary between which appears coplanar with the Great Glen Fault. The mineral and bulk rock composition of the different lamprophyre varieties from throughout the orogen are very similar (Canning 1997 and our unpublished data), suggesting that all the lamprophyres were generated under similar conditions and at similar depths. The trace element and isotopic contrasts between the Northern Highland and Southern domains do however require two separate sources, with differing histories and time-integrated LREE enrichments. These differences cannot be modelled by varying the amounts of melting involved in lamprophyre genesis (and thereby fractionating Sm/Nd) as the rare samples in the two groups that have nearly identical REE abundances still have totally distinct εNd (samples PFT02b, DO 94/21; Table 1). The isotopic characteristics of the Northern Highlands dykes require a series of metasomatic events affected the lithospheric mantle to the north of the Great Glen Fault but not that to the south.

The nature and depth of the Great Glen Fault. The Great Glen Fault was a major intracontinental strike-slip fault at the end of the Caledonian Orogeny, separating the Northern Highlands and Grampian Highlands blocks. Detailed structural mapping indicates it was unlikely that Caledonian movements overprinted an earlier structure and instead the fault was probably initiated at a late orogenic stage during oblique continental convergence (Stewart *et al.* 1997). Rogers & Dunning (1991) concluded that major transcurrent motion on the fault was restricted to 429–425 Ma, and had effectively ceased by Old Red Sandstone times. Production of the post-Caledonian, (*c.* 400 Ma) lamprophyres was probably triggered by heating associated with post-orogenic extension and collapse (Canning *et al.* 1996; compare Turner *et al.* 1996). Extensional basin deposits of Devonian Old Red Sandstone age cut by the lamprophyres have been found locally throughout the orogen.

Several dyke samples were collected from outcrops close to the Great Glen Fault zone (measured orthogonally). Two Southern group minettes were collected from Kerrera and the adjacent mainland, under 10 km from the fault. Two other minette dykes from Onich, Argyll with REE and εNd characteristics of the southern suite (BAM1 and LL3, Table 1) came from outcrops approximately 1 km south of the surface expression of the Great Glen Fault (Fig. 1). These minettes show that the southern domain extends to the limit of the Great Glen Fault zone. We have coverage in the Northern Highlands domain to within 12 km of the fault. At the surface the fault is marked by a 1–3 km wide series of mylonites, cataclasites and fractured Moine and Dalradian country rock (Stewart *et al.*

Table 1. *Representative Nd isotopic data for lamprophyres from the major Caledonian tectonic blocks of Northern Britain*

Type	No.	$^{143}Nd/^{144}Nd$	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd_{400}$	εNd
Northern Highlands							
Vogesite	GA 94/20	0.511876	126.3	16.52	0.0791	0.511669	− 8.9
Minette	UG 94/7	0.511850	150.5	20.48	0.0823	0.511634	− 9.5
Minette	DO 93/1	0.511838	152.3	20.12	0.0799	0.511629	− 9.7
Minette	DO 94/14	0.512005	163.3	21.62	0.0801	0.511795	− 6.4
Minette	LM 94/2	0.512002	131.2	17.90	0.0825	0.511786	− 6.6
Vogesite	UG 93/8	0.511926	160.5	20.80	0.0784	0.511721	− 7.9
Kersantite	DO 94/5	0.511732	121.3	14.05	0.0701	0.511548	− 11.2
Minette	DO 94/21	0.511859	140.7	19.69	0.0847	0.511637	− 9.5
Minette	GA 94/12	0.511683	87.8	12.00	0.0827	0.511466	− 12.8
Grampian Highlands							
Minette	BAM 1	0.512302	77.3	10.46	0.0819	0.512088	− 0.7
Minette	LL3	0.512349	95.3	14.30	0.0908	0.512111	− 0.2
Midland Valley							
Minette	mv207	0.512356	74.1	11.23	0.0917	0.512119	− 0.2
Minette	mv187	0.512526	54.8	9.05	0.0998	0.512268	2.7
Southern Uplands							
Minette	BP22	0.512312	55.5	8.35	0.0909	0.512074	− 1.0
Minette	PFT03	0.512259	103.3	14.31	0.0837	0.512040	− 1.7
Hnnbd lamp	1367	0.512492	30.2	6.36	0.1275	0.512158	0.6
Hnnbd lamp	BP21	0.512338	56.7	10.07	0.1075	0.512057	− 1.3
Hnnbd lamp	1381	0.512403	31.0	5.53	0.1078	0.512121	− 0.1
Hnnbd lamp	1314	0.512449	19.6	4.09	0.0126	0.512119	− 0.1
Hnnbd lamp	1380	0.512661	28.2	6.24	0.1337	0.512311	3.7
Hnnbd lamp	1360	0.512409	35.8	6.61	0.1042	0.512091	− 0.7
Hnnbd lamp	1305	0.512369	62.1	10.24	0.0997	0.512108	− 0.3
Hnnbd lamp	BP19	0.512330	56.1	8.90	0.0959	0.512079	− 0.9
Hnnbd lamp	1366	0.512405	28.6	5.96	0.1260	0.512075	− 1.0
Hnnbd lamp	PFT02b	0.512310	147.5	20.66	0.0847	0.512088	− 0.7
Hnnbd lamp	1365	0.512409	35.8	6.16	0.1042	0.512136	0.2
Hnnbd lamp	1296	0.512521	24.8	4.97	0.1212	0.512204	1.5
Hnnbd lamp	BP11	0.512330	151.2	22.59	0.0900	0.512090	− 0.6
Hnnbd lamp	BSM01	0.512390	78.0	13.08	0.1010	0.512130	0.0
Hnnbd lamp	LD117	0.512679	21.9	4.90	0.1350	0.512330	3.9
Hnnbd lamp	LD114	0.512417	22.6	4.47	0.1195	0.512108	− 0.5
Hnnbd lamp	LD131	0.512463	29.4	5.22	0.1073	0.512185	1.1
Hnnbd lamp	LD118	0.512550	23.3	4.73	0.1225	0.512233	2.0
Hnnbd lamp	LD107	0.512459	21.2	4.27	0.1218	0.512144	0.3
Hnnbd lamp	LD116	0.512449	28.7	5.16	0.1218	0.512048	− 1.6
Hnnbd lamp	LD119	0.512329	18.9	3.86	0.1087	0.512165	0.7
Lake District							
Minette	7993	0.512221	112.0	19.05	0.1029	0.511951	− 3.4

εNd values calculated at 400 Ma. Hnbd lamp, hornblende lamprophyre. Nd isotope determinations for the Northern Highlands, Grampian Highlands and Lake District samples were carried out using a MAT261 mass spectrometer at the Open University, Milton Keynes. During the period of analysis the following results were produced from the international standard J&M: 0.511778 ± 0.000012. Nd isotopic analysis for the Midland Valley and Southern Uplands samples were performed using a VG 354 mass spectrometer at the BGS Isotope Unit, Grays Inn, London (La Jolla—0.511833 ± 0.000019). REE analyses (including Nd and Sm) on all the samples were carried out by ICPAES at Royal Holloway College, University of London, procedures given in Henney (1991) and Canning (1997).

1997). Our ability to fix the sharp boundary clearly indicates that the fault zone remains narrow and vertical at the depth of lamprophyre generation and that the fault cannot be listric. Therefore the lithospheric mantle boundary is located to within less than 13 km of the surface expression of the Great Glen Fault. Any imbrication or splaying of the fault that could have caused physical mixing of the magma source regions must be restricted to a zone much less than the 13 km of sample spacing.

The depth to which the fault extends can also be constrained. In the more mafic lamprophyre varieties, the mica and clinopyroxene phenocrysts were only in magmatic equilibrium at pressures of *c.* 20 kbar and temperatures of 1000–1200°C (Canning *et al.* 1996; Esperança & Holloway 1987). This equates to depths of around 60 km in the lithosphere where the magmas underwent limited fractionation during uprise from their source regions. Magmas with such steep REE patterns as these lamprophyres are almost invariably considered to have garnet as a residual phase in their source regions. McKenzie & O'Nions (1991) using REE inversion modelling on minettes with REE contents typical of the Southern group showed that garnet was not unequivocally required if an amphibole-bearing peridotite source is invoked

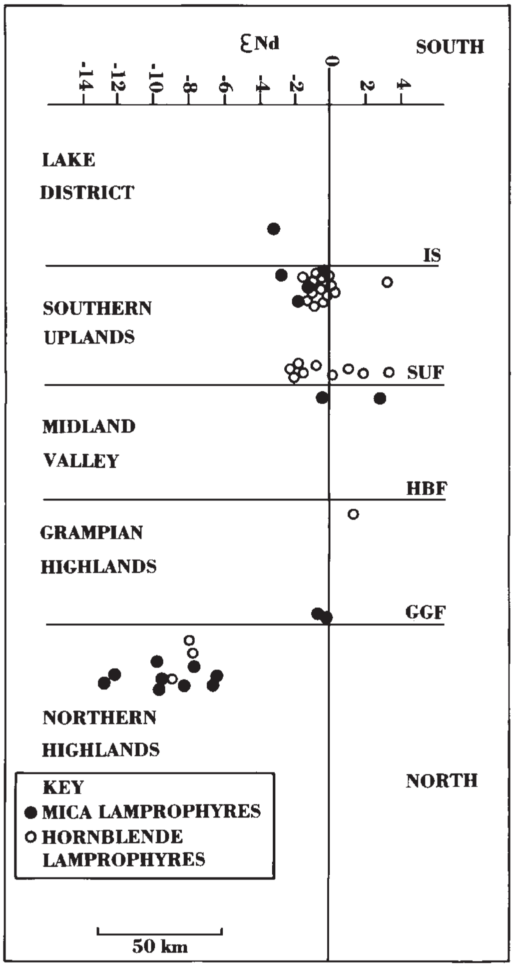


Fig. 3. εNd versus geographical distribution diagram for data from Table 1. Additional data from Dempster & Bluck (1991) and Canning *et al.* (1996).

instead. All of the lamprophyres show relative K depletion on spidergrams, many also have Rb depletion (Fig. 2), features which can be attributed to K-amphibole (richterite) and/or phlogopite as residual phases (e.g. Foley 1992; Mitchell 1995; Gibson *et al.* 1995). Whichever mineralogical combination is favoured for the source region this still requires magma generation at depths of 100 km or more (Tatsumi 1989; Sudo & Tatsumi 1990) and hence the Great Glen Fault clearly transected the Caledonian lithospheric mantle.

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