The role of tholeiitic magmatism in the English Lake District: evidence from dykes in Eskdale

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Abstract

Mafic dykes occur in close association with, and both cut and are cut by, the Eskdale granite in the south-western Lake District. The dykes range compositionally from magnesian basalt to andesite and are divided into two groups: (1) high-Fe–Ti rocks of tholeiitic affinity forming most of the dykes and (2) a lower-Fe–Ti group, comparable in composition to the lavas of the Borrowdale Volcanic Group. The dykes extend the range of tholeiitic magmatism in the Lakes into late Ordovician, and possibly Silurian times, and indicate that published plate tectonic models partly based on the distribution of magma types are perhaps over-simplified. The Eskdale dykes form one end of a spectrum of Lake District compositions from tholeiitic to calc–alkaline. All the magma types may have shared a common mantle source, their final composition reflecting residence times in the crust or LIL-enriched mantle.

KEYWORDS: Tholeiitic magmatism, English Lake District, Eskdale.

Introduction

IGNEOUS rocks of tholeiitic affinity within the Lower Palaeozoic inlier of the English Lake District include the Eycott group and the Carrock Fell Complex, possibly of similar age (Fitton and Hughes, 1970; Hunter, 1980). The later Borrowdale Volcanic Group and the various granitoid intrusions are increasingly highly evolved calc-alkaline rocks (Fitton *et al.*, 1982; O'Brien *et al.*, 1985). A sequence of the principal magmatic events is summarized in Fig. 1. This change in magmatic character with time has been central to reconstructions of Caledonian plate tectonics by Fitton and Hughes (1970) and Fitton *et al.* (1982), who consider that magmatism was related to a southerly dipping subduction zone during the closure of the Iapetus Ocean.

Modern petrological studies of Lake District igneous rocks have been restricted to the lavas and major intrusions. The widespread and compositionally variable dykes and sills have been relatively neglected (Firman, 1978). Yet, as has been shown elsewhere in the Caledonides (Rock *et al.*, 1986; Barnes *et al.*, 1986; Macdonald *et al.*, 1985, 1986), the minor intrusions may contain petrological information not available in the lavas or major intrusions. In this communication we present geochemical data on dykes from the south-western Lake District, supporting the thesis that tholeiitic magmatism continued through the late Ordovician and possibly into Silurian times.

Geological setting

Detailed geological mapping by members of the British Geological Survey in the south-western

Mineralogical Magazine, September 1988, Vol. 52, pp. 459–72

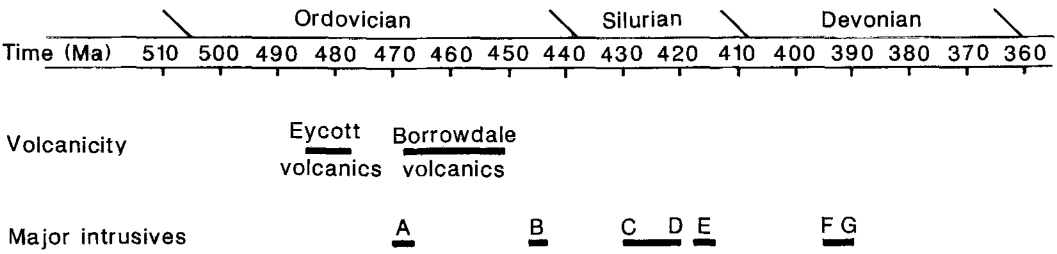

FIG. 1. Time scale of the major Caledonian igneous events in the Lake District, simplified and modified from O'Brien *et al.* (1985, Fig. 2). A, Carrock Fell; B, Threlkeld microgranite; C, Eskdale granite; D, Ennerdale granophyre; E. Carrock Fell granophyre and ferrogabbro; F, Shap granite; G, Skiddaw granite. The range of the Borrowdale Volcanic Group has been extended to 450 Ma, taking account of the presence of Caradocian acritarchs at Holehouse Gill, Ulpha.

Lake District from Wasdale to Eskdale and the Duddon valley has defined the presence of a predominantly ESE-WNW swarm of mafic dykes (Table 1). Most of these are intruded into the Birker Fell Formation, a sequence approximately 3000 m thick, of aphyric basalt and highly porphyritic andesitic to dacitic lava flows with interbedded tuffs forming the basal part of the Borrowdale Volcanic Group (BVG). The dykes also penetrate acid tuffs of the overlying Airy's Bridge Formation on Illgill Head (NY 16 04) above Wastwater and in the Scafell area (NY 21 05).

The dykes are concentrated in the area close to the margin of the Eskdale granite between Wasdale and Eskdale (Fig. 2), but scattered examples are also to be found up to 2 km from the granite contact south of Devoke water (SD 15 96). Sparse examples were emplaced in the granite, for example south of Boot in Eskdale (Fig. 2) and near Brantrake Moss (SD 157 981). They have not been found in the southern part of the area from Whitfell (SD 15 92) and Buckbarrow (SD 14 91) to the Duddon valley. North of Wastwater and Scafell, numerous ophitic dolerites were recorded during the primary geological survey and by Walker (1904), Dwerryhouse (1909) and Oliver (1961). Abundant mafic dykes similar to those in Eskdale have been mapped recently on Middle Fell (NY 15 06), NW of Wastwater (M. G. Petterson, pers. comm.).

Although the Eskdale dykes trend predominantly ESE-WNW, locally a conjugate ENE-WSW orientation has been noted. In some cases alignment is along minor faults that are truncated by later, Caledonian trending faults which affect the granites.

The dykes are subvertical, from 0.5-6.0 m wide and commonly have sharp, chilled contacts against the country rock. In parts of the sequence dominated by aphyric basalt lavas, the dykes can be hard to recognize, except on freshly broken surfaces where the coarser, doleritic texture is distinctive.

The age of emplacement of the dykes (Table 1) can be inferred only from available geological data. Two lines of evidence suggest that many of the dykes predate the intrusion of the Eskdale granite (429 Ma; Rundle, 1979). Firstly, several dykes are truncated by the granite (e.g. at locality A in Fig. 2). Secondly, many dykes outcrop within the extensive secondary amphibole and biotite zones of the contact metamorphic aureole to the granite (Fig. 2) and these contain a similar secondary mineral assemblage to that found in country rocks of similar composition. A few dykes (e.g. sample 1) cut the granite and are clearly later than 429 Ma. Unmetamorphosed dykes cutting the BVG (samples 2, 3, and 29; Fig. 2) are considered to be post-granite, although it is possible that the igneous mineralogy was preserved in some cases as a result of their location outside the biotite-amphibole zone of the aureole. The upper age limit is constrained locally by reference to the weak NE-ENE-trending cleavage affecting the BVG in this area. The volcanic rocks and the dykes within the aureole are generally uncleaved, but the ENE-trending dykes on the NE flanks of Harter Fell (Fig. 2) and some of those in the area NW of Wastwater are weakly cleaved and were thus emplaced in pre-Emsian times (late lower Devonian; Soper *et al.*, 1987). The field evidence, along with the geochemical data presented below, suggests, therefore, a possible age range for the dyke suite from late Ordovician to early Devonian.

Petrography

The Eskdale dykes range from fine- to medium-grained dolerites displaying a well-developed subophitic texture, to hornfelsic hornblende-plagioclase rocks (Table 1).

The dyke cutting the Eskdale granite (sample 1) and those outcropping relatively distally to the granite contact (2, 3, 29) preserve an igneous

Table 1. Selected field and petrographical features of Eskdale dykes

Dyke number	[1]Grid reference	Field name	[2]Texture	[2]Pyroxene	[2]Substantially metamorphosed?	[3]Age
1	1777 0080	Basalt	Ophitic	Yes	No	Post
2	2317 0206	Dolerite	Ophitic	Yes	No	?Post
3	2314 0212	Basalt	Ophitic	Yes	No	?Post
4	2313 0202	Dolerite	Ophitic	Yes?	Yes	Pre
5	2221 0162	Basalt	Trachytic	Yes	Part	Pre
6	2197 0142	Dolerite	Ophitic	No	Yes	Pre
7	2121 0082	Dolerite	Ophitic	No	Part	Pre
8	2121 0050	Dolerite	Ophitic	Yes	Part	Pre
9	2105 0062	Dolerite	Ophitic	Yes	Part	Pre
10	2261 0332	Basalt	Decussate	No	Part	Pre
11	2272 0395	Dolerite	Ophitic	Yes	Part	Pre
12	2215 0397	Dolerite	Ophitic	Yes?	Yes	Pre
13	2215 0385	Dolerite	Ophitic	Yes	Part	Pre
14	2234 0384	Dolerite	Ophitic	Yes	Part	Pre
15	2034 0255	Dolerite	Ophitic	No	Part	Pre
16	2038 0267	Basalt	Ophitic	No	Yes	Pre
17	2032 0237	Basalt	Ophitic	No	Part	Pre
18	1994 0309	Dolerite	Ophitic	No	Part	Pre
19	1953 0417	Hornfels	Hornfelsic	No	Yes	Pre
20	1945 0404	Basalt	Ophitic	No	Yes	Pre
21	1946 0395	Basalt	Ophitic	Yes?	Part	Pre
22	1941 0372	Dolerite	Ophitic	No	Part	Pre
23	1990 0299	Basalt	Ophitic	No	Part	Pre
24	1979 0233	Basalt	Ophitic	No	Yes	Pre
25	1974 0359	Dolerite	Ophitic	No	Yes	Pre
26	1970 0385	Dolerite	Ophitic	No	Part	Pre
27	2134 0461	Basalt	?	No	Yes	Pre
28	2138 0462	Basalt	Basaltic	No	Yes	Pre
29	2120 0494	Dolerite	Ophitic	Yes	No	?Post
30	1704 0433	Dolerite	Ophitic	Yes	Part	Pre

1: All sample sites occur within the 100km square NY

2: Presence of pyroxene and/or ophitic texture refers to degree of preservation of igneous characteristics; "substantially metamorphosed" column is an arbitrary guide to the degree of development of metamorphic minerals.

3: Relative to the Eskdale Granite.

mineralogy and granular to subophitic texture. The most obvious indicator of igneous mineralogy is the presence of fresh, colourless to pale brown clinopyroxene. These (Table 2) are generally augite or titanaugite, with a salite component, those in dyke 1 being more Ti-rich and having lower Mg/Fe ratios than those in the other dykes. Plagioclase compositions vary from An_{38} to An_{67}, though crystals are variably sericitized. Chlorite pseudomorphs in the post-granite dyke (1) are possibly after olivine. Blocky to ragged and skeletal Fe–Ti oxides sometimes altered to sphene are common in the dykes.

Most of the dykes cutting the BVG clearly show the effects of contact metamorphism, with the growth, in particular, of green calcic amphibole replacing clinopyroxene. Judging from dykes where only partial amphibolitization has taken place (e.g. 8, 9 and 30), replacement by actinolite or actinolitic hornblende took place around grain boundaries or epitaxially. Subsequent recrystallization to hornblende or pargasitic hornblende results in a finer grained aggregate of prismatic and sheaf-like crystals, sometimes with intergrown chlorite. There is a general trend from low Al to higher Al contents with increasing grade of contact metamorphism, though considerable variation (disequilibrium) can occur within one thin section.

Within a few metres of the granite contact, the subophitic texture is destroyed and a distinctly

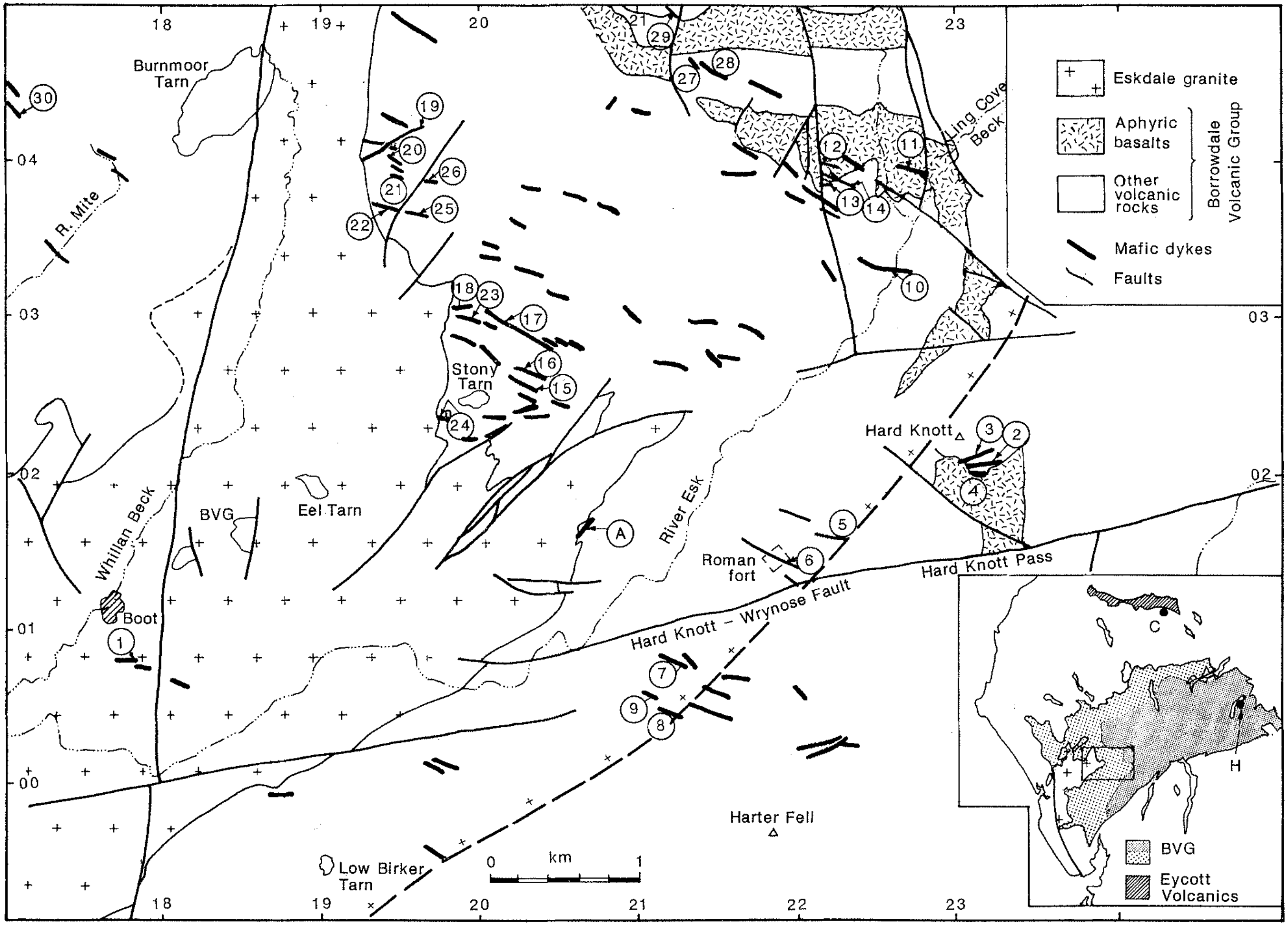

FIG. 2. Locality map, showing distribution of mafic dykes. Analysed specimens, circled numbers. In inset, C = Carrock Fell Complex; H = Haweswater Dolerite; BVG = Borrowdale Volcanic Group. The heavy dashed line with crosses is the approximate limit of the biotite-amphibole zone of contact metamorphism.

Table 2. Representative analyses of clinopyroxenes and amphiboles

	Clinopyroxenes			Amphiboles		
Specimen No.	1	2	30	24	25	30
SiO_2	46.46	50.11	47.89	45.17	52.28	40.81
TiO_2	3.52	1.14	2.35	1.48	0.53	0.81
Al_2O_3	5.02	4.08	4.26	9.44	2.85	12.67
Cr_2O_3	0.12	0.29	0.01	-	-	-
FeO*	11.30	7.93	9.48	15.67	13.73	21.28
MnO	0.28	0.20	0.25	0.37	0.43	0.37
MgO	11.82	14.11	13.24	11.88	14.70	6.38
CaO	20.43	21.26	21.02	10.80	11.73	11.91
Na_2O	0.55	0.39	0.49	1.87	0.30	1.57
K_2O	-	-	-	0.22	0.18	0.33
Total	99.50	99.51	98.99	96.90	96.73	96.13
Atomic proportions						
Si	1.776	1.873	1.822	6.750	7.652	6.370
Ti	0.101	0.032	0.067	0.166	0.058	0.095
Al	0.226	0.180	0.191	1.662	0.492	2.330
Cr	0.004	0.009	0.000	-	-	-
Fe	0.361	0.248	0.302	1.958	1.681	2.778
Mn	0.009	0.006	0.008	0.047	0.053	0.049
Mg	0.673	0.786	0.751	2.646	3.207	1.484
Ca	0.837	0.852	0.857	1.729	1.840	1.992
Na	0.041	0.028	0.036	0.542	0.085	0.475
K	-	-	-	0.042	0.034	0.066
O	6.000	6.000	6.000	23.000	23.000	23.000

FeO* is total Fe as FeO.

Amphibole names (IMA, 1978): 24 - magnesiohornblende; 25 - actinolite; 30 - ferroan pargasitic hornblende.

hornfelsic hornblende-plagioclase rock formed. In these dykes minor amounts of green-brown biotite are present, usually finely intergrown with amphibole (dykes 17, 19, 22 and 23). Biotite plus amphibole is the dominant paragenesis in the basaltic and andesitic lavas of the aureole to the Eskdale granite. Plagioclase compositions in metamorphosed specimens vary from secondary albite in partly amphibolitized dolerites, up to An_{68}. Commonly it is difficult to distinguish metamorphic plagioclase compositions from relict igneous where textural recrystallization of the plagioclase laths has not taken place. Hornfelsic plagioclase associated with hornblende has a composition An_{44}. Late-stage chlorite, epidote and rare calcite occur in patches and veinlets and probably represent low-grade alteration that has affected much of the BVG. One of the most evolved rocks (28) contains common groundmass quartz and sparse epidotized plagioclase phenocrysts. The fine-grained granular to sub-ophitic pyroxene is replaced by chlorite, epidote and amphibole.

Chemically, four of the dykes (see below and Table 3) form a distinct group. Two of these (4 and 25) are texturally similar to the amphibolitized dykes described above and have a sub-ophitic texture. Dykes 19 and 27 are porphyritic, the former containing abundant glomeroporphyritic aggregates and phenocrysts of clinopyroxene, now replaced by amphibole, and microphenocrysts of plagioclase. Dyke 27 contains abundant phenocrysts and microphenocrysts of sericitized plagioclase grading into a fine-grained matrix; there are also rare corroded(?) xenocrysts of quartz.

Analytical methods

Thirty specimens were analysed by XRF at the University of Lancaster, using a Philips 1400 spectrometer. Fused beads were made for major element determinations. Trace elements were determined on powders. Four samples were analysed for *REE* by ICPS at Royal Holloway and Bedford New College, courtesy of Dr J. N. Walsh. Representative analyses, chosen to show the range in compositions, are given in Table 3.

Table 3. Representative analyses of Eskdale dykes

	Group (1)					Group (2)			
Specimen No.	10	2	8	30	28	4	25	27	5
SiO_2	50.3	46.2	46.1	45.8	56.4	48.0	53.3	61.0	49.4
TiO_2	0.80	1.07	2.96	3.26	2.14	1.10	1.12	0.79	3.01
Al_2O_3	14.65	17.07	14.56	13.93	15.28	17.28	16.30	16.26	16.28
Fe_2O_3*	9.71	9.87	14.59	15.50	9.37	10.59	8.23	6.25	10.81
MnO	0.29	0.33	0.34	0.47	0.22	0.44	0.23	0.22	0.22
MgO	9.63	9.29	7.53	6.62	3.30	8.43	6.65	3.47	6.69
CaO	10.29	10.73	9.37	8.76	5.88	6.72	8.22	4.73	4.78
Na_2O	1.60	1.57	1.97	2.27	3.60	2.28	2.37	2.06	2.24
K_2O	0.58	0.36	0.51	0.63	0.87	1.53	1.48	2.72	1.02
P_2O_5	0.16	0.06	0.33	0.42	0.32	0.06	0.14	0.16	0.56
H_2O+	1.73	3.14	2.61	1.99	2.04	3.37	1.49	1.86	3.85
Total	99.74	99.69	100.87	99.65	99.42	99.80	99.53	99.52	98.86
Ba	180	202	126	162	189	305	140	690	186
Co	49	72	58	38	32	60	53	41	52
Cr	700	228	108	51	19	469	163	147	60
Cu	8	116	35	37	36	13	50	29	17
Nb	8	3	10	15	17	2	8	13	24
Ni	43	84	36	11	13	122	59	44	44
Rb	18	11	21	25	24	53	49	102	52
Sr	267	144	224	197	212	223	372	266	200
Th	4	1	3	4	10	2	6	13	8
V	190	171	353	264	258	180	203	130	295
Y	21	24	44	47	47	22	26	34	57
Zr	89	44	194	226	285	47	118	177	315
La	-	2.75	-	17.19	-	2.44	13.09	-	-
Ce	-	7.74	-	43.75	-	7.17	28.36	-	-
Nd	-	6.72	-	29.91	-	6.18	14.94	-	-
Sm	-	2.53	-	7.92	-	2.37	3.85	-	-
Eu	-	0.78	-	2.42	-	0.66	1.08	-	-
Gd	-	3.76	-	9.34	-	3.58	4.69	-	-
Dy	-	3.38	-	8.08	-	3.33	4.07	-	-
Ho	-	0.71	-	1.61	-	0.69	0.83	-	-
Er	-	2.05	-	4.69	-	2.00	2.50	-	-
Yb	-	2.05	-	4.64	-	2.06	2.48	-	-
Lu	-	0.36	-	0.76	-	0.35	0.43	-	-

Fe_2O_3* is total Fe as Fe_2O_3

Geochemistry: general features

All analysed specimens show varying degrees of alteration, from those largely retaining original igneous mineralogy to those in which the original minerals have been completely replaced during metamorphism and/or deuteric alteration. Under such conditions, mobility of certain elements may be suspected. Such mobility may be assessed by plotting data against a reputedly stable trace element, e.g. Zr. Fig. 3 plots Zr against Nb, another stable trace element, and Na and Rb, potentially mobile elements. The graphs indicate that during alteration Nb was stable, Na showed a limited mobility which was insufficient to destroy a positive Na–Zr correlation, and Rb was secondarily mobilized. Similar evaluation for all the data suggests that Ca, K, Ba, Ce and Sr showed some mobility, while all other elements were essentially stable. In the following discussion, we use mainly data for the stable elements, and assume that we are referring to magmatic abundances.

Most (27) of the analysed specimens are mafic, with MgO > 6%, while two rocks (27 and 28) have andesitic compositions. Sample 5 is chemically distinctive (see below).

The dykes can be divided, on the basis of Fe–Ti relationships, into two groups, though the distinction is rather arbitrary in magnesian compositions. Fe and Ti are particularly useful because they also

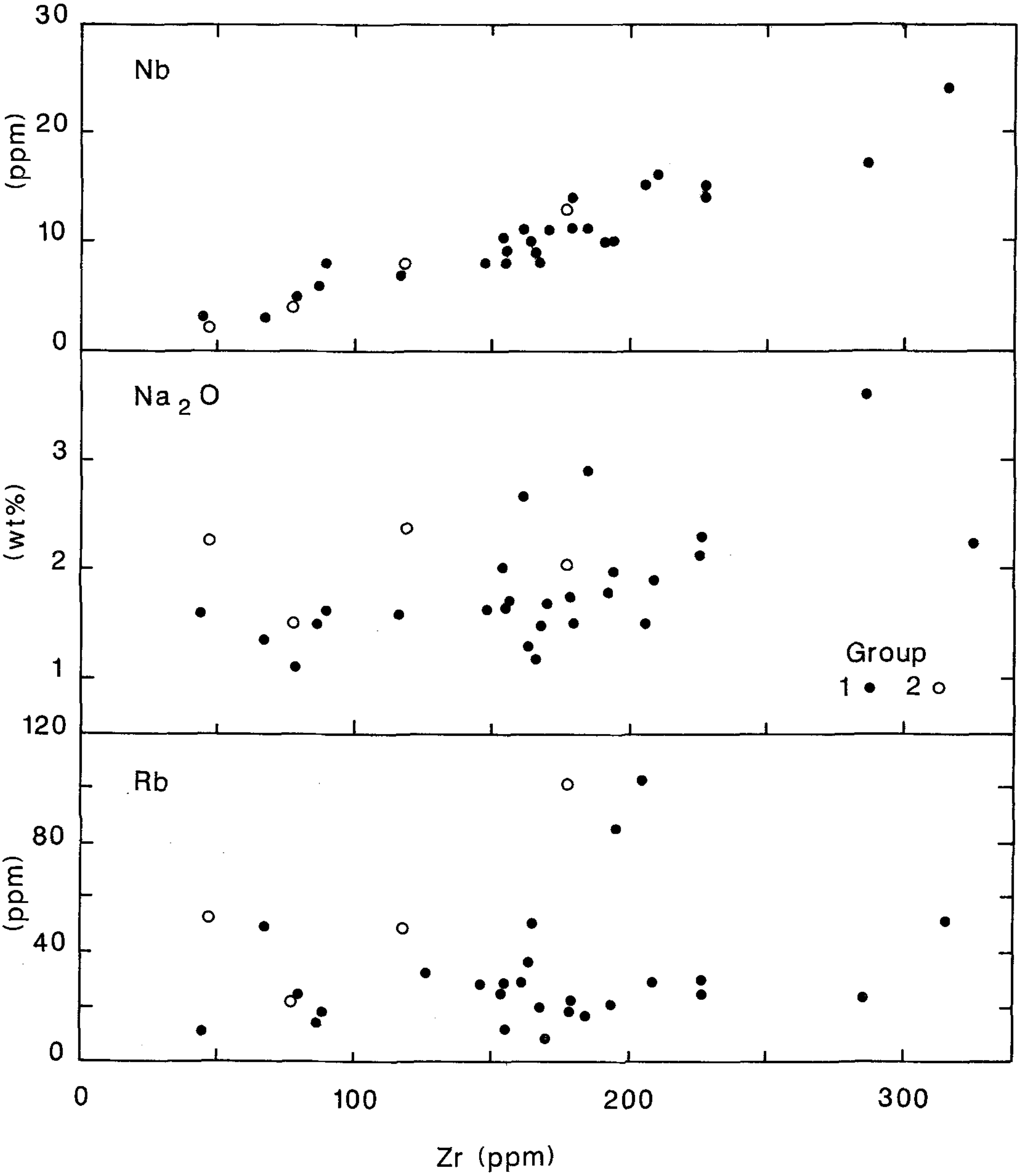

FIG. 3. Zr plots, to assess the degree of mobility of Nb, Na_2O and Rb during metamorphism and deuteric alteration of the Eskdale dykes.

provide important evidence of the magmatic affinities of the dykes.

A high-Fe-Ti set, *Group 1*, comprises 24 mafic rocks and one andesite. With increasing fractionation (using MgO as a differentiation index; Fig. 4), the group shows increases in TiO_2, $Fe_2O_3^*$, P_2O_5, Nb, V and Y to around 6% MgO. If dyke 28 at 3.3% MgO is typical of the suite, the abundances of these elements possibly decrease towards andesitic compositions, such that the compositional trends are peaked. Sr data are scattered, but probably have a similar trend, while Na_2O, Th and Zr increase

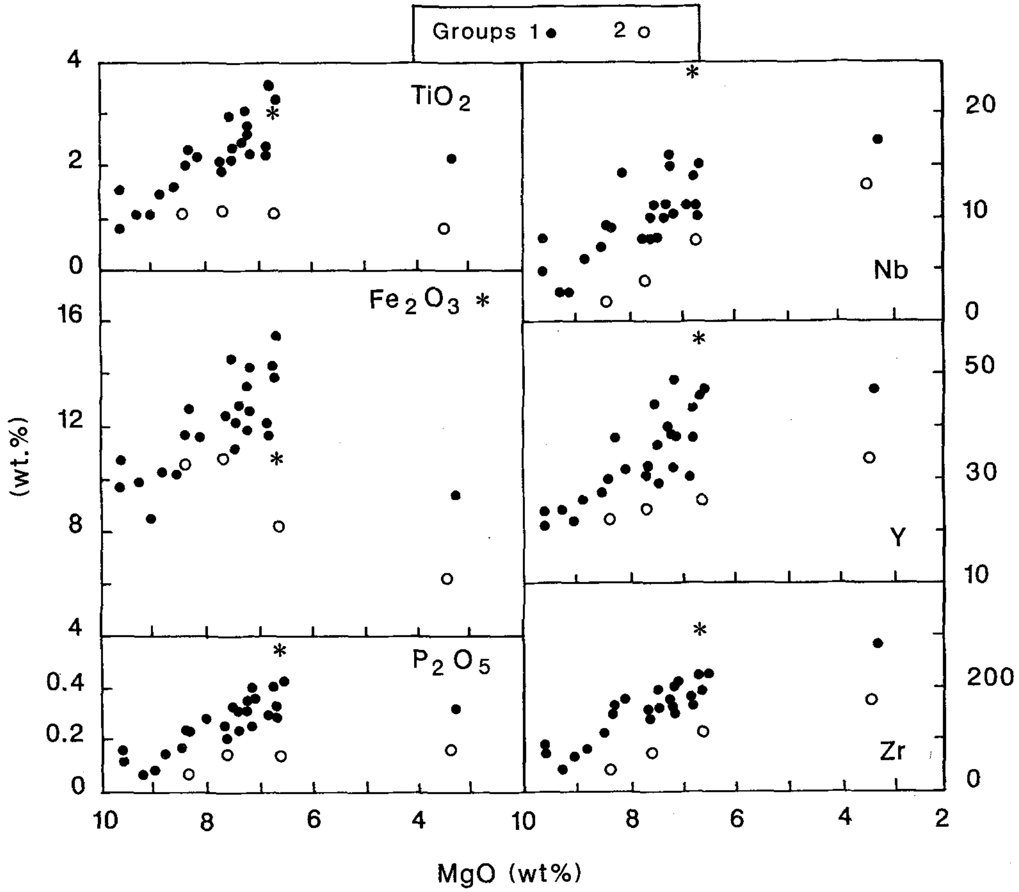

FIG. 4. MgO plots, to show differing fractionation trends and/or element abundances, in the dykes of Groups 1 and 2. *, compositionally anomalous specimen 5 (see text).

monotonically with decreasing MgO. Cr and Ni decline with increasing differentiation. Al_2O_3 shows a scattered, overall decrease, and SiO_2, initially about constant, increases only in intermediate compositions. These differentiation trends are typical of tholeiitic liquids worldwide (Graham, 1976; Wright and Peck, 1978; Macdonald *et al.*, 1981; Rock *et al.*, 1985), consistent with petrographic evidence from unmetamorphosed dykes of an oversaturated affinity.

There are no magmatic compositional differences between dykes which have been metamorphosed by the granite and those retaining primary igneous mineralogy, or between dykes truncated by the granite and the dyke (1) which cuts it; tholeiitic magmatism clearly straddled the emplacement of this major calc-alkaline intrusion.

The low-Fe-Ti type, *Group 2*, comprises only three analysed mafic dykes (4, 19, 25) and one andesite (27). While the most magnesian specimen (4) is barely distinguishable from the Group 1 dykes on these plots (Fig. 4), the group as a whole shows certain differences to Group 1. At given MgO content, the rocks have lower $Fe_2O_3^*$, TiO_2, P_2O_5, Nb, Y and Zr, and higher K_2O, Cr and Ni (and possibly SiO_2). With decreasing MgO contents, $Fe_2O_3^*$ and TiO_2 decrease, Al_2O_3 is about constant, and SiO_2 shows continuous increase. Nb and Y do not show the peak at intermediate compositions inferred for Group 1 (Fig. 4). These fractionation trends are more consistent with a calc-alkaline than tholeiitic affinity.

These points are reinforced by the *REE* data. Chondrite-normalized patterns for rocks from both groups are shown in Fig. 5. The higher-magnesian specimens, 2 and 4, show similar patterns: flat with

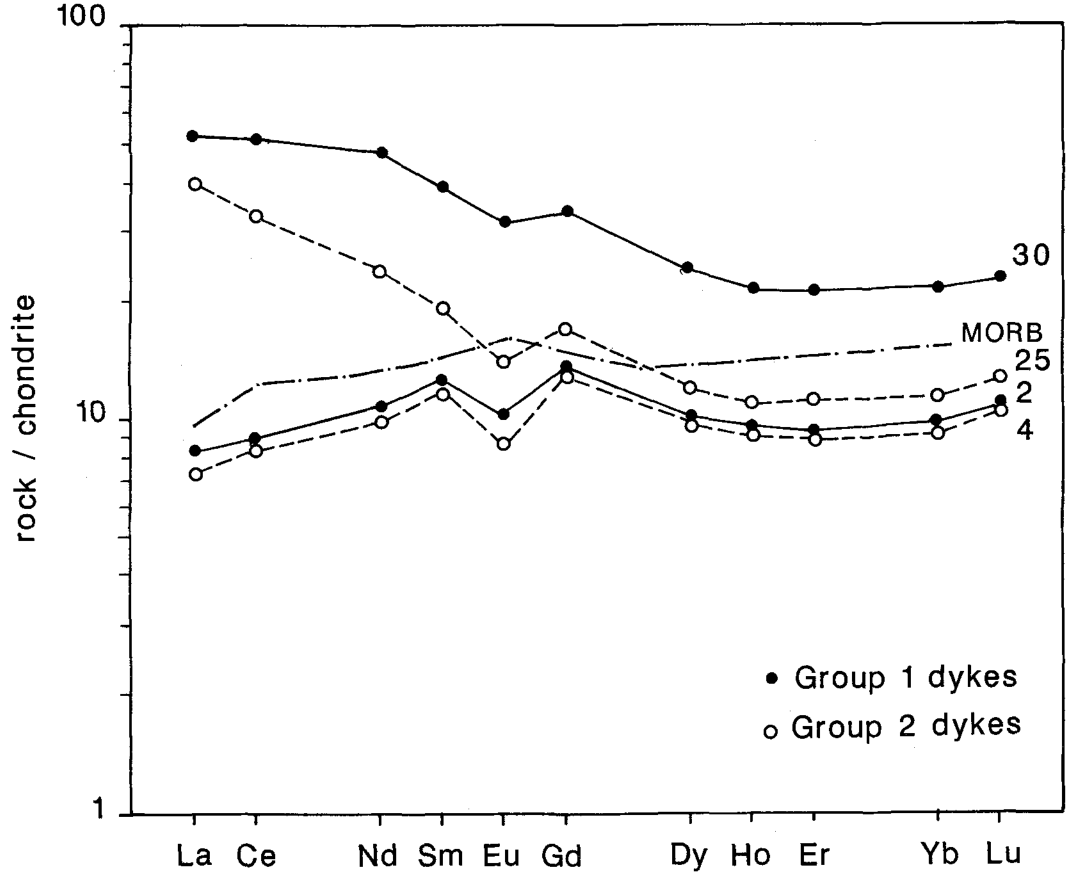

FIG. 5. Chondrite-normalized *REE* patterns for four mafic dykes. Normalizing factors from Thompson (1982).

LREE/*HREE* ratios < 1, and small Eu anomalies, the latter consistent with fractionation of plagioclase. The similarity of the patterns suggests a common mantle source, or parental magma for the two groups, perhaps comparable in *REE* characteristics to the mantle source of MORB (Fig. 5).

Although the more evolved member of Group 1 (30) has higher *REE* abundances than the Group 2 rock of comparable MgO content (25), it has a lower *LREE*/*HREE* ratio, e.g. La_N/Yb_N in 30 and 25 are 2.5 and 3.5 respectively. Relative *LREE* enrichment was stronger in the Group 2 rocks, consistent again with calc-alkaline, as opposed to tholeiitic, affinity.

Specimen 5 is distinctive in having, at given MgO content, low $Fe_2O_3^*$ and CaO contents, and slightly high Nb, Y and Zr contents (Fig. 4). It seems to represent a magmatic variant rare in the dyke swarm; we do not include it in further discussion.

Comparative suites

Tholeiitic magma was emplaced in Llanvirn times in the north-eastern Lake District to form the Eycott Volcanics and the Carrock Fell Complex (Fitton and Hughes, 1970; Hunter, 1980; Fitton *et al.*, 1982). The Eycott rocks differ chemically from the younger (Llanvirn-Caradoc), calc-alkaline BVG in being richer in Fe, Ti and V and in having consistently lower La/Y ratios (Fitton *et al.*, 1982). They are regarded as transitional between island arc tholeiites and calc-alkaline volcanic rocks. The chemical relationships between these volcanic groups and the Eskdale dykes are summarized in Fig. 6. The BVG shows, with increasing fractionation, the decreasing $Fe_2O_3^*$ and TiO_2 contents typical of increasingly fractionated calc-alkaline magmas. The Eycott rocks show muted increase in TiO_2 and variable degree of Fe enrichment, consistent with a character transitional to tholeiitic.

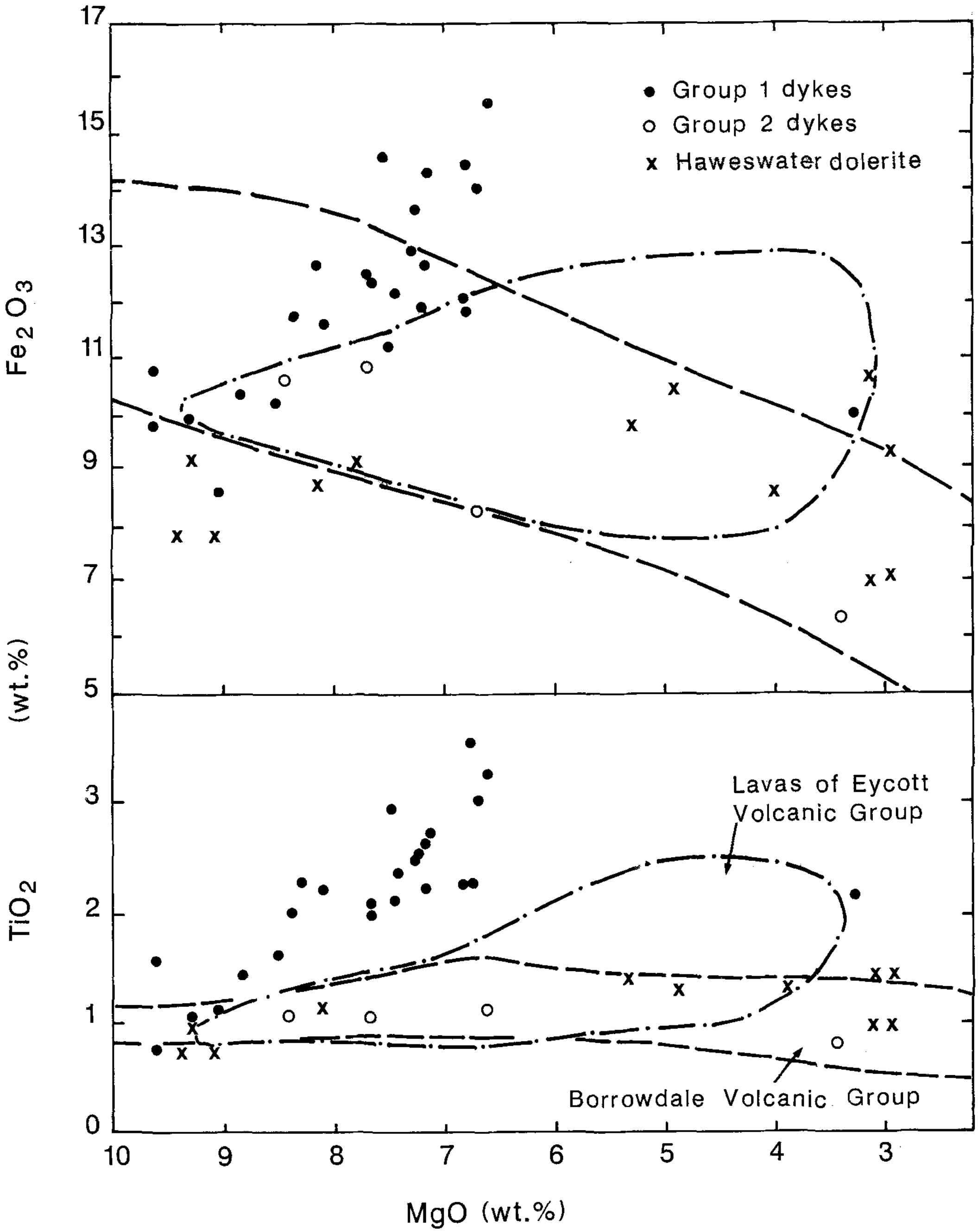

FIG. 6. MgO plots, to show the relationships between the Groups 1 and 2 dykes, the dolerites of the Haweswater complex, the Eycott volcanics and the Borrowdale volcanics (BVG). Eycott data—Fitton (1971); BVG—Fitton (1971) and D. Millward (unpubl.); Haweswater—Nutt (1979). Dyke 5 not shown.

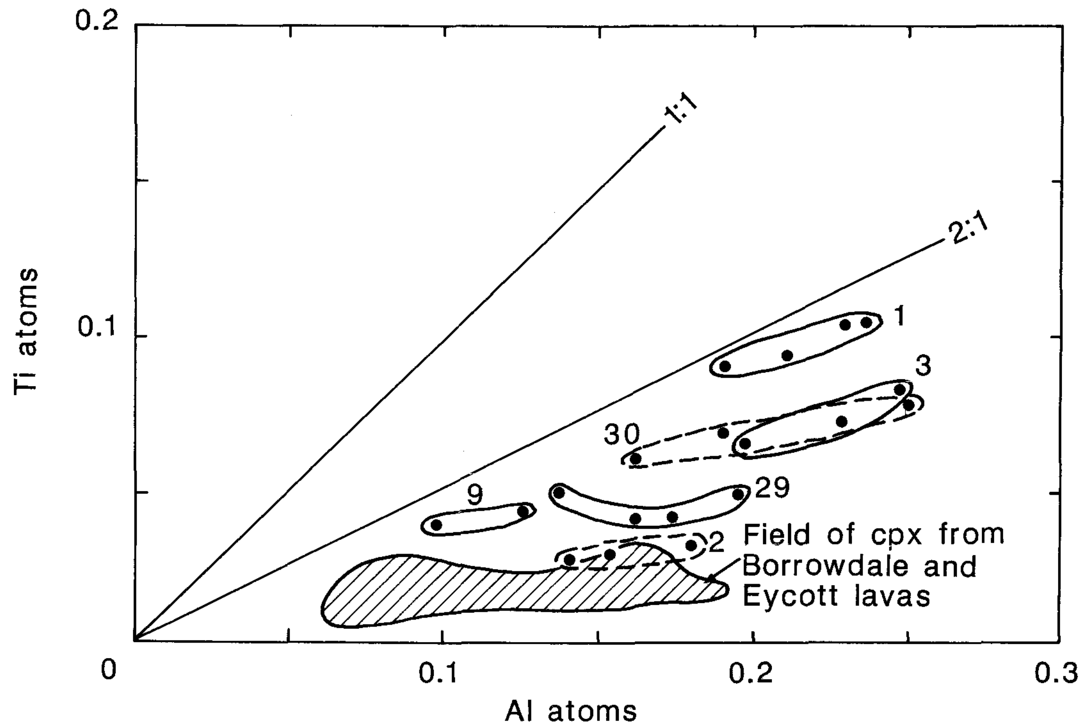

FIG. 7. Ti–Al (atomic) plot for pyroxenes from Eskdale dykes. Note that dyke 1 has the highest Ti contents and Ti/Al ratios, and that all the dykes are generally more Ti-rich than pyroxenes from the Borrowdale and Eycott lavas. Lava field from Fitton *et al.* (1982).

The strong Fe and Ti enrichment in the Group 1 dykes indicates a more thoroughly tholeiitic character. The Group 2 dykes have apparently a more calc-alkaline affinity. The more Ti-rich nature of the Group 1 dykes relative to the BVG and Eycott lavas is reflected in the compositions of clinopyroxene (Fig. 7).

The interrelationships between the groups are also shown on a TiO_2-Zr plot (Fig. 8). There is an excellent positive correlation between Ti and Zr in the mafic Group 1 dykes, as would be predicted from their tholeiitic affinity (Fig. 4), while the rocks of the BVG display a negative correlation, consequent on a TiO_2 depletion with increasing fractionation characteristic of calc-alkaline suites. The Eycott lavas and Group 2 dykes are transitional between the two. It should be stressed that a distinction between tholeiitic and calc-alkaline affinity cannot always be made on the basis of single specimens, as the large overlaps on Figs. 6 and 8 display. It is the compositional trend of the suite which may be diagnostic.

There is further evidence of post-BVG tholeiitic magmatism in the Lakes. The largest dolerite intrusion within the BVG crops out along the shores of Haweswater (NY4915) in the eastern Lake District (Hancox, 1934; Nutt, 1979). The dolerite and related gabbro, andesite and microdiorite cut the BVG rocks and are locally cleaved (Green, 1917), indicating a range of possible ages similar to the Eskdale dykes. Nutt (1979) concludes that this basic 'complex' represented a former magma chamber to the BVG extrusive rocks in the area. However, chemical data (Nutt, 1979, Table 2) show an initial muted increase of Fe and Ti, followed by a decrease, on MgO plots (Fig. 6), somewhat transitional between the Eycott Volcanic Group and the BVG. This correlation is confirmed by Ti–Zr relationships (Fig. 8). We feel that the Haweswater Dolerite is a post-BVG, pre-cleavage, transitional tholeiitic-calc-alkaline body.

Among other British Caledonide rocks, the Rhobell Fawr volcanic rocks of central Wales have transitional tholeiitic to calc-alkaline affinities (Kokelaar, 1979). There are also close similarities between Eskdale dykes and the meta-basaltic rocks of the Dalradian of SW Scotland (Fig. 8). Despite being part of a different magmatic province, this

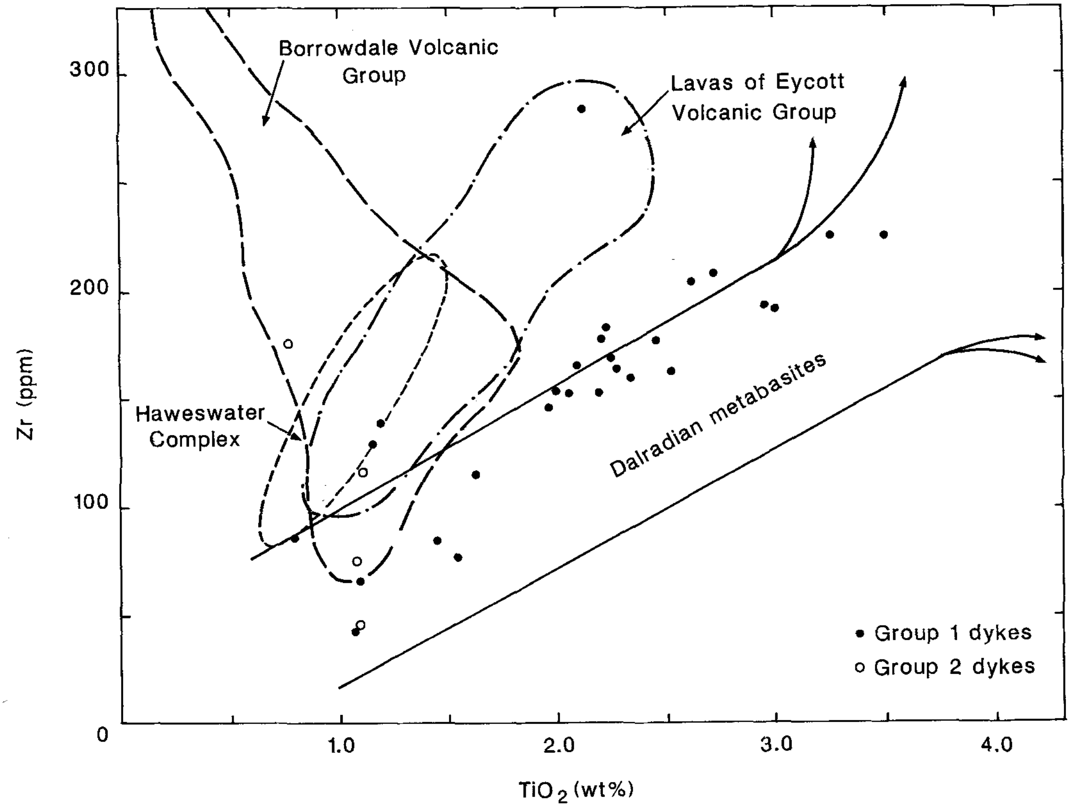

FIG. 8. Zr–TiO_2 plot to show the relationship between the Groups 1 and 2 dykes, the BVG and Eycott lavas, the Haweswater dolerites, and the Dalradian metabasites of the SW Scottish Highlands. Data sources for BVG, Haweswater and Eycott rocks, as in Fig. 6. Dalradian field from Graham (1976). Note the dissimilar trends of the Groups (1) and (2) dykes. One anomalously Zr-rich analysis omitted from the Haweswater field.

is a valid comparison because of tectonic considerations. The unquestionably tholeiitic Dalradian rocks have been interpreted (Graham, 1976; Graham and Bradbury, 1981; Plant *et al.*, 1984) as having been erupted in a rift-like oceanic basin marginal to Iapetus and related to its presumed opening. More recently Fettes *et al.* (1986) and Graham (1986) have suggested that the basin was a trans-Caledonide, pull-apart structure of late Pre-Cambrian age, occurring adjacent to a dominantly transcurrent continental margin.

Along similar lines, Hunter (1980) and O'Brien *et al.* (1985) have suggested that the Carrock Fell complex (Fig. 1) was emplaced in a back-arc extensional environment during the earliest stages of evolution of the southern margin of Iapetus. The Eskdale dykes *ipso facto* also indicate periods of crustal extension, and there is a clear link between Caledonian tholeiitic magmatism and extensional tectonics.

Significance of the dykes

We have suggested that the mafic lavas and intrusions of the Lake District form a complete spectrum of compositions from tholeiitic to calc-alkaline (Fig. 8), and that the magnesian rocks of both kinds, as exemplified by the Eskdale Groups 1 and 2 dykes, are compositionally very similar (Figs. 4, 5, 6 and 8). There are, however, slight differences, which may have genetic significance; these are shown on a chondrite-normalized diagram in Fig. 9. The main differences are that the Group 2 rocks have higher LIL/HFS ratios and a slightly deeper trough at Nb. The lower Nb abundances may be related to generation in a more hydrous environment, stabilizing such minerals as ilmenite or rutile. There is no general agreement as to whether the LIL-enrichment is a result of source enrichment by a silicate melt, e.g. from oceanic sediments, or by hydrous fluids

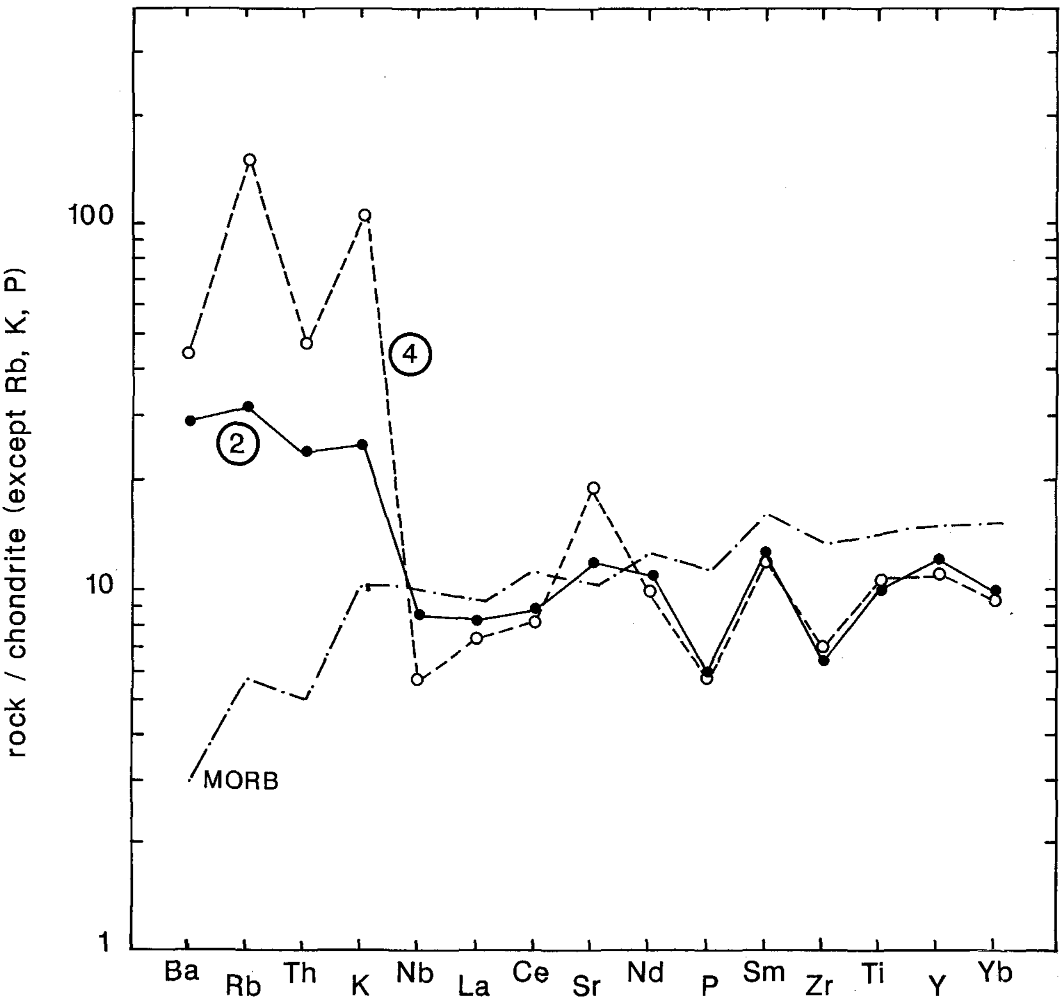

FIG. 9. Chondrite-normalized element abundance patterns for a Group 1 (2) and Group 2 (4) dykes. Normalizing factors from Thompson *et al.* (1984).

released by dehydration of the subducting slab (Saunders and Tarney, 1984; Thompson *et al.*, 1984). Without isotopic data for the Lake District rocks, these alternatives cannot be explored further.

The following considerations may be applicable to Lake District magmatism. Tholeiitic and calc-alkaline magmas shared a common (lithospheric?) mantle source. During periods of extension, e.g. during emplacement of the Eskdale dykes, tholeiitic melts reached the surface after some, but relatively minor, interaction with the overlying lithosphere (crystal fractionation excepted), as indicated by elevated LIL/HFS ratios compared to MORB (Fig. 9). In the more normal, compressional tectonic phases, magmas resided in the lithosphere sufficiently long to acquire a more distinctly LIL-enriched, subduction-related character. The nature of the mafic magmatism in the Lake District may have been a direct result of tectonic style.

Whatever their ultimate origin, tholeiitic magmas in the Lakes were not restricted to the early Ordovician. Plate tectonic models which envisage a magmatic trend from tholeiitic through calc-alkaline both with time and with distance from the Iapetus suture (Fitton *et al.*, 1982) must now be seen as too simplified.

Acknowledgements

We thank Dr R. H. Hunter and an anonymous referee for detailed reviews of the manuscript. The contributions of

DM and BBS are published with the permission of the Director, British Geological Survey (NERC).

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[*Manuscript received 19 October 1987; revised 25 November 1987*]