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# The diagnostic geochemistry, relative abundance, and spatial distribution of high-calcium, low-alkali olivine tholeiite dykes in the Lower Tertiary regional swarm of the Isle of Skye, NW Scotland

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SUMMARY. Dykes from four sections across the axis of the Skye regional swarm have been analysed for major elements, Nb, Rb, Sr, Y, Zr, and rare-earth elements. 70 % of the dykes are characterized by relatively high CaO (11–12 %), and low abundance of elements such as $TiO_2$ ($\sim$1 %), $K_2O$ (0·05–0·20 %), Zr (30–60 ppm), with a light-rare-earth depleted chondrite normalized pattern. The remainder of the swarm comprises dykes equivalent in composition to the Skye Main Lava Series and dykes belonging to a further magma type distinguished by a flat chondrite normalized rare-earth pattern. The high-calcium, low-alkali tholeiite dykes are confined to a narrow persistent zone forming the major axis of dilation of the swarm; other basaltic dykes are axially less persistent and have a wider lateral distribution. The more evolved dykes tend to be restricted to central Skye.

THE occurrence of Lower Tertiary Ca-rich, alkali-poor olivine tholeiite lavas on the Isle of Skye was first noted by Thompson *et al.* (1972). These lavas, which are distinct in their major-element chemistry from the other basaltic flows present on the island, occur in the Osdale group at the top of the lava pile remnant. It was suggested that the low-alkali tholeiites represent the products of substantial partial melting in the upper mantle at the culmination of the thermal event that produced the Skye Main Lava Series. It was also suggested that a considerable volume of this magma type may have been erupted to form the missing upper part of the lava pile. The purpose of this work was to examine the chemistry of the Skye basaltic dyke swarm and to compare it with that of the lavas. Implicit was the assumption that the dykes were feeders for the majority of the lavas and that the Skye dyke swarm preserves a more complete record of the types extruded than the lavas after erosion.

The subdivision of rock and magma types in the Hebridean Tertiary igneous province needs to be done with care in order to avoid ambiguity. *All* the basaltic dykes to be discussed in this paper fall into the broad chemical groups *olivine tholeiite* and *alkali basalt*; in many nomenclature schemes they would be called transitional basalts. We intend to show in this paper that the basalts of the Skye lava pile and dyke swarm may be divided into three *magma types*, each of which shows internal chemical variation but cannot be related to the others by low-pressure crystal–liquid processes. Individual basaltic rock compositions can be uniquely allocated to one or other of the magma types on the basis of the major and trace element geochemistry. We are dissuaded from using chemically based names (such as low-alkali tholeiites) for these groups because current studies of other Hebridean centres (e.g. Lamacraft, 1976; M. A. Morrison, personal communication) are defining several comparable magma types which *may or may not* be chemically identical to those on Skye. We therefore propose to use

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names for the magma types that are *specific to Skye*. The Skye Main Lava Series remains as defined by Thompson *et al.* (1972), except for one flow (SK971, see below) and is considered to be a magma type in the sense described above. We propose the term 'Preshal Mhor magma type' for the distinctive low-alkali tholeiites of Skye. A third magma type will be discussed below.

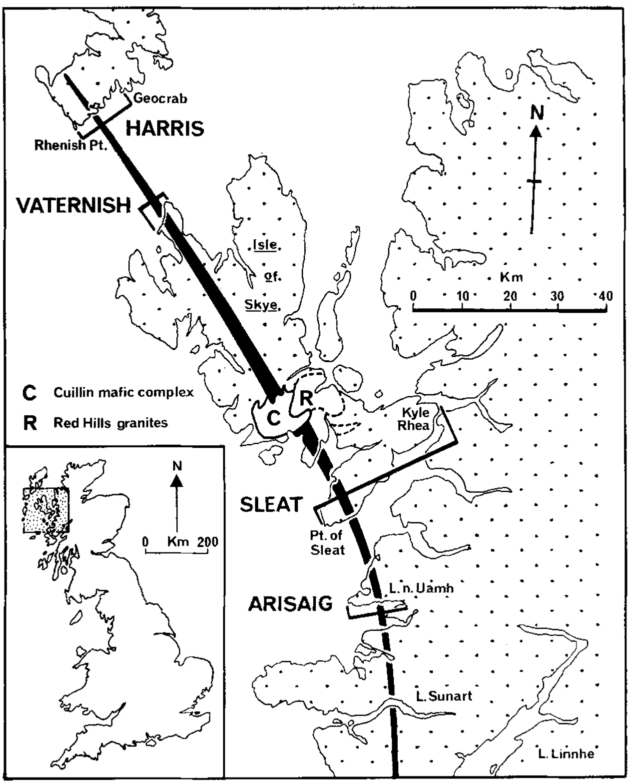



FIG. 1. Map showing the position of the major axis of dilation of the Skye regional swarm and of the four transverse coast sections where the dykes were sampled (adapted from Wilson *et al.*, 1974).

*Sampling of the swarm.* The Skye regional swarm is about 120 km long and is centred on the Cuillin plutonic complex. The trend of the swarm is NW–SE. It outcrops in Harris, throughout Skye and Arisaig, and extends across Loch Sunart, terminating at Loch Linnhe. For the purpose of this study the dykes were sampled along four transverse sections each crossing the swarm: along the SE coast of Harris, from Rhenish Point to Geocrab; on the Vaternish peninsula (Skye), from Ardmore Point to Vaternish Point; along the SE coast of the Sleat of Skye, from the Point of Sleat to Kyle Rhea; and along the north coast of Loch nan Uamh, near Arisaig.

The total number of dykes encountered along the four traverses was 608. In order to reduce the chemical study to manageable proportions a sampling scheme was adopted (Table I), which was maintained regardless of such features as width, phenocryst content, and degree of hydrothermal alteration of individual dykes. The Vaternish and Sleat sections were sampled from comprehensive sets of drill cores taken by the University of Liverpool for a paleomagnetic survey, whereas the Harris and Arisaig sections were sampled conventionally by one of the authors (D. P. M.). A few dykes of Permo-Triassic age are found both in Skye and on the mainland and every effort was made to distinguish these and omit them from the sampling scheme. Table I gives relevant sampling and field data for each of the sections.

The great majority of dykes sampled are porphyritic and only very rarely are the phenocrysts evenly distributed across the intrusion. Usually marginal aphyric zones and a central porphyritic core are developed. Where possible the dykes were sampled close to the chilled margin, as this is frequently the freshest part of the intrusion. However, the obvious sampling problems

TABLE I. *Sampling data*

| | Scheme | Nt | Ns | W | D | L |
|---|---|---|---|---|---|---|
| Harris | (all) | 41 | 41 | 13 | 1.2 | 75 |
| Vaternish | (1 in 2) | 87* | 36 | 6 | 3(?)* | 50 |
| Sleat | (1 in 4) | 382† | 92 | 34 | – | 25 |
| Arisaig | (1 in 3) | 98 | 33 | 12 | 4.2 | 45 |
| Total | | 608 | 202 | | | |

Nt: Total number of dykes exposed
Ns: Number of dykes sampled
W: Width of section normal to swarm (km)
D: Average percent crustal dilation along section W
L: Approximate distance of section from the Cuillin mafic plutonic centre (km)

* From Wilson *et al.*, 1974
† Personal communication, R. L. Wilson, University of Liverpool.

*Erratum:* Note D, *for* along section W *read* across section

make it essential that observed concentrations of elements be treated with caution, as it is difficult to assess to what degree the samples taken approach the original proportions of 'liquid+crystals' in the magma (see below).

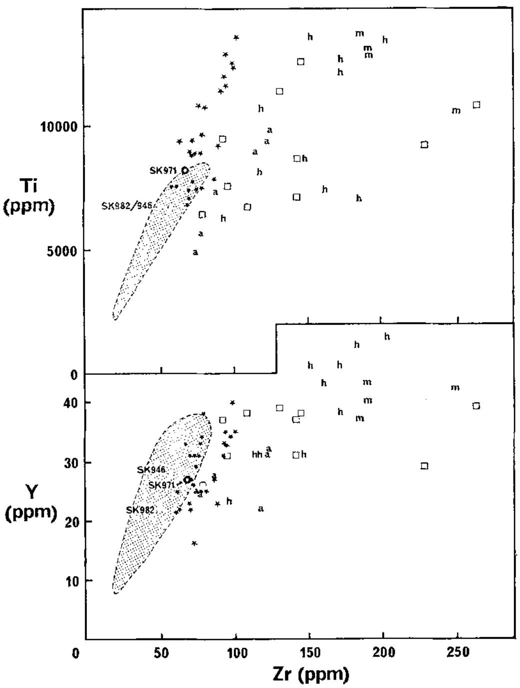
The dykes from Harris, Sleat, and Arisaig are all exposed where they are intruded into basement rocks (Lewisian, Torridonian, and Moinian). The Vaternish dykes, however, are sampled where they are intruded into the lower part of the lava pile (the Ramascaig Group).

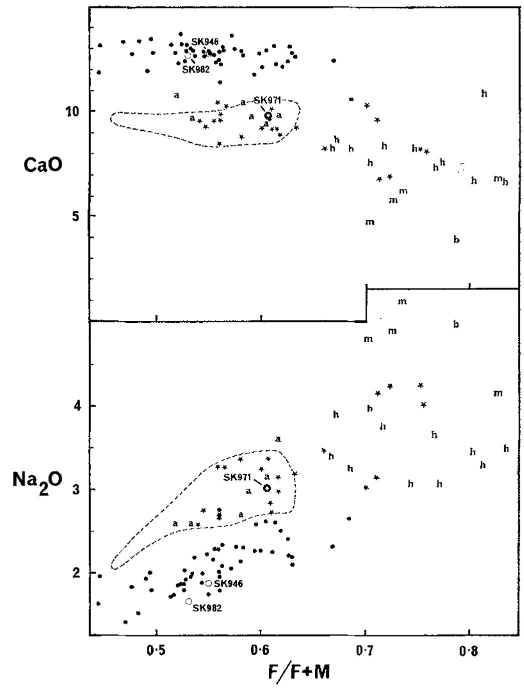
*Analytical procedure.* The analytical methods used to determine major, trace, and rare-earth elements are identical to those described in Wood *et al.* (1976, p. 242). The analytical precision for the trace elements was monitored by analysing some of the USGS standards in parallel and is considered to be better than $\pm 1$ ppm for Nb, $\pm 3$ ppm for Y, $\pm 8$ ppm for Sr, and $\pm 5$ ppm for Zr at concentrations of 10, 30, 210, and 110 ppm, respectively.

## *Geochemistry of the dykes*

Initially 202 dykes from all four sections were analysed for $TiO_2$, CaO, $K_2O$, and the trace elements Nb, Rb, Sr, Y, and Zr. The elements analysed in this initial survey were chosen to include ones such as Ti, Nb, Y, and Zr, which are considered to be relatively stable during hydrothermal alteration (Hart, 1971; Pearce and Cann, 1973; Wood *et al.*, 1976). CaO was also included at this stage because the Preshal Mhor type lavas described by Thompson *et al.* (1972) and Esson *et al.* (1975) have much higher contents of CaO (12–13 %) than the Skye Main Lava Series (less than 11 %). Subsequently 92 of those dykes were re-analysed for all the major elements. A complete list of the analytical data for all 202 dykes and specimen localities is available on request to D. P. M.

*The Preshal Mhor magma type.* Figs. 2 and 3 show that large numbers of dykes are similar in composition to the few known Preshal Mhor type lavas (Esson *et al.*, 1975), and we propose, on the basis of the available data, that they should be allocated to the same magma type. The Preshal Mhor lavas were distinguished initially by their relatively high CaO contents (11–12 %) and the low total alkali concentrations. As can be seen from figs. 2 and 3, these features are characteristic of the magma type as a whole. However, our new data suggest that the rocks also have characteristic trace-element ratios and a light-rare-earth depleted chondrite normalized pattern (see below). Taken together, these features allow the ready identification of the members of this magma type (Table IIa and IIb). The CIPW norms of the dykes mostly contain *hy+ol*, but small amounts of *ne* occur in some samples when $Fe_2O_3$ is fixed at 1·50 %, as suggested by Thompson *et al.* (1972). Using the actual values of $Fe_2O_3$ found in the dykes and lavas ($\approx$ 3 %) would eliminate any *ne* in their norms. The Preshal Mhor magma type is therefore appreciably less Si undersaturated than that of the Skye Main Lava Series.




FIGS. 2 and 3: FIG. 2 (left). Plots of Ti and Y versus Zr for 193 dykes. The Preshal Mhor type dykes (i.e. high-calcium, low-alkali tholeiite) fall within the stippled area (137 points) with Ti/Zr and Y/Zr approximately equal to 120 and 0·5, respectively. Low-alkali tholeiite lavas SK946 and SK982 plot in the same region. Open squares and letter symbols are Skye Main Lava Series type dykes. The dykes analysed for major elements in this group have been classified by means of normative feldspar and Thornton–Tuttle index (Thompson *et al.*, 1972, p. 222) into alkali-basalts, hawaiites, and mugearites which are plotted as 'a', 'h', and 'm', respectively. These dykes display a range of Ti/Zr and Y/Zr ratios but remain distinct from the Preshal Mhor type dykes. The points plotted as stars are dykes belonging to a third magma type (the Fairy Bridge magma type, see text), which have trace element ratios more akin to the Preshal Mhor magma type than to the Skye Main Lava Series magma type. FIG. 3 (right). Plots of CaO and $Na_2O$ versus F/(F+M) (($FeO+Fe_2O_3$)/($FeO+Fe_2O_3+MgO$)) for 92 dykes. Closed circles—Preshal Mhor type dykes; other symbols as in fig. 2. The dashed line indicates the limits of variation displayed by the Skye Main Lava Series basalts. The Fairy Bridge type dykes are similar in major element chemistry to the Skye Main Lava Series dykes, whereas the Preshal Mhor type dykes form a trend distinct from the other magma types.

It is apparent from figs. 2 and 3 that the Preshal Mhor magma type shows a range in chemistry. We investigated initially whether this is due simply to the redistribution of phenocrysts within the dykes at the present level of exposure.

To test the hypothesis that olivine in some dykes may be accumulative we have calculated the theoretical liquidus olivine that should be in equilibrium with a representative range of rocks with varying olivine phenocryst contents (2000 point modal analyses). For these calculations we have used $Fe_2O_3$ = 1·5 % and $K_D$ = 0·33 ($K_D = X^{ol}_{FeO} . X^{liq}_{MgO} / X^{liq}_{FeO} . X^{ol}_{MgO}$) (Cawthorn *et al.*, 1973). Table III compares calculated values with microprobe analyses of olivine

TABLE IIA. *Representative analyses, CIPW norms, and modes of 15 Preshal Mhor type dykes and lavas*

| | 1 S028 | 2 S020 | 3 H191 | 4 I057 | 5 H070B[a] | 6 A021 | 7 S012 | 8 I033 | 9 I041 | 10 S008 | 11 I013 | 12 H205 | 13 H105 | 14 SK946 | 15 SK982 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Major elements (wt. %)* | | | | | | | | | | | | | | | |
| $SiO_2$ | 44.93 | 45.53 | 45.98 | 46.78 | 47.24 | 46.62 | 46.40 | 46.33 | 46.25 | 46.97 | 47.85 | 47.55 | 48.38 | 47.09 | 46.84 |
| $TiO_2$ | 0.37 | 0.54 | 0.64 | 0.79 | 0.84 | 0.93 | 1.02 | 1.07 | 1.13 | 1.24 | 1.29 | 1.31 | 1.38 | 1.12 | 1.11 |
| $Al_2O_3$ | 20.72 | 19.66 | 19.53 | 17.83 | 15.37 | 15.80 | 14.78 | 14.81 | 14.62 | 13.87 | 14.04 | 13.97 | 13.40 | 14.92 | 15.53 |
| $Fe_2O_3$ | 1.50 | 1.50 | 1.50 | 1.50 | 3.25 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 3.82 | 3.17 |
| FeO | 5.33 | 6.37 | 6.57 | 7.23 | 6.95 | 8.76 | 9.02 | 9.64 | 10.22 | 10.87 | 10.73 | 10.68 | 11.90 | 7.30 | 7.66 |
| MnO | 0.10 | 0.13 | 0.14 | 0.14 | 0.18 | 0.17 | 0.18 | 0.18 | 0.18 | 0.21 | 0.21 | 0.23 | 0.22 | 0.20 | 0.23 |
| MgO | 8.52 | 8.45 | 7.66 | 8.99 | 10.21 | 9.07 | 8.25 | 8.03 | 6.98 | 7.42 | 6.07 | 7.19 | 6.21 | 9.05 | 9.72 |
| CaO | 13.08 | 13.31 | 13.01 | 13.42 | 12.75 | 12.88 | 12.25 | 12.63 | 13.07 | 12.37 | 12.41 | 12.71 | 10.51 | 12.67 | 12.63 |
| $Na_2O$ | 1.96 | 1.78 | 1.71 | 2.00 | 1.79 | 1.99 | 2.00 | 2.27 | 2.20 | 2.38 | 2.30 | 2.27 | 2.64 | 1.87 | 1.78 |
| $K_2O$ | 0.21 | 0.14 | 0.11 | 0.12 | 0.09 | 0.11 | 0.13 | 0.14 | 0.15 | 0.13 | 0.08 | 0.36 | 0.45 | 0.10 | 0.04 |
| $P_2O_5$ | 0.07 | 0.08 | 0.05 | 0.11 | 0.05 | 0.11 | 0.11 | 0.07 | 0.07 | 0.14 | 0.09 | 0.08 | 0.11 | 0.11 | 0.09 |
| $H_2O^+$ | 3.10 | 2.43 | 1.21 | 0.71 | 1.01 | 2.01 | 3.55 | 2.84 | 2.41 | 1.84 | 2.92 | 1.09 | 2.91 | 1.41 | 1.25 |
| Sum | 99.89 | 99.90 | 100.98 | 99.62 | 99.73 | 99.89 | 99.17 | 100.51 | 98.78 | 98.94 | 99.57 | 98.66 | 99.61 | 99.77[b] | 100.25 |
| F/F + M[c] | 0.44 | 0.48 | 0.51 | 0.49 | 0.50 | 0.53 | 0.56 | 0.58 | 0.61 | 0.63 | 0.66 | 0.63 | 0.68 | 0.55 | 0.53 |
| *Trace elements (ppm)* | | | | | | | | | | | | | | | |
| Nb | 2 | 4 | 4 | 6 | 4 | 4 | 6 | 4 | 4 | 9 | 8 | 6 | 6 | – | 4 |
| Rb | 2 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 8 | 2 | 0 |
| Sr | 166 | 167 | 117 | 106 | 95 | 109 | 104 | 99 | 107 | 118 | 123 | 106 | 126 | 133 | 95 |
| Y | 8 | 15 | 16 | 20 | 21 | 26 | 24 | 26 | 27 | 31 | 37 | 30 | 37 | 28 | 22 |
| Zr | 20 | 30 | 27 | 44 | 37 | 39 | 43 | 52 | 47 | 63 | 68 | 69 | 83 | 58 | 50 |
| Ti/Zr | 111 | 108 | 142 | 108 | 136 | 142 | 142 | 123 | 144 | 117 | 117 | 114 | 100 | 116 | 133 |
| Y/Zr | 0.40 | 0.50 | 0.59 | 0.45 | 0.56 | 0.66 | 0.55 | 0.50 | 0.57 | 0.49 | 0.56 | 0.43 | 0.44 | 0.48 | 0.56 |
| *C.I.P.W. weight norms (using standard state* $Fe_2O_3$*)* | | | | | | | | | | | | | | | |
| Or | 1.24 | 0.65 | 0.83 | 0.71 | 0.53 | 0.65 | 0.77 | 0.83 | 0.89 | 0.77 | 2.12 | 0.47 | 2.66 | 0.59 | 0.24 |
| Ab | 13.45 | 12.19 | 14.47 | 16.71 | 15.15 | 16.84 | 16.92 | 18.80 | 18.58 | 20.14 | 19.46 | 19.21 | 22.34 | 15.82 | 15.06 |
| An | 47.12 | 45.19 | 45.20 | 39.32 | 33.64 | 33.85 | 30.97 | 29.81 | 29.57 | 26.78 | 26.92 | 27.69 | 23.38 | 32.02 | 34.81 |
| Ne | 1.70 | – | – | 0.11 | – | – | – | 0.22 | 0.02 | – | – | – | – | – | – |
| Di Wo | 7.23 | 8.38 | 7.94 | 11,08 | 12.23 | 12.24 | 12.15 | 13.52 | 14.53 | 14.06 | 14.22 | 14.55 | 11.71 | 12.34 | 11.38 |
| Di En | 4.84 | 5.44 | 4.90 | 6.97 | 7.55 | 7.24 | 6.92 | 7.44 | 7.39 | 7.14 | 6.67 | 7.37 | 5.26 | 7.65 | 6.95 |
| Di Fs | 1.85 | 2.37 | 2.58 | 3.42 | 3.97 | 4.40 | 4.70 | 5.59 | 6.80 | 6.59 | 7.38 | 6.84 | 6.38 | 4.56 | 4.87 |
| Hy En | – | 1.65 | 4.35 | – | 4.34 | 1.56 | 4.71 | – | – | 1.45 | 3.45 | 3.22 | 5.60 | 5.07 | 4.17 |
| Hy Fs | – | 0.72 | 2.29 | – | 2.28 | 0.95 | 3.21 | – | – | 1.34 | 3.82 | 2.99 | 6.79 | 3.02 | 2.44 |
| Ol Fo | 11.48 | 10.51 | 6.89 | 10.80 | 9.49 | 9.56 | 6.25 | 8.80 | 7.07 | 6.93 | 3.50 | 5.13 | 3.22 | 6.88 | 9.17 |
| Ol Fa | 4.84 | 5.05 | 3.99 | 5.85 | 5.49 | 6.40 | 4.67 | 7.29 | 7.10 | 7.06 | 4.27 | 5.25 | 4.30 | 4.52 | 5.92 |
| Il | 0.70 | 1.01 | 1.22 | 1.50 | 1.60 | 1.76 | 1.94 | 2.03 | 2.15 | 2.36 | 2.45 | 2.49 | 2.62 | 2.13 | 2.11 |
| Mt | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 | 2.18 |
| Ap | 0.16 | 0.19 | 0.12 | 0.26 | 0.12 | 0.26 | 0.26 | 0.16 | 0.16 | 0.32 | 0.21 | 0.19 | 0.26 | 0.22 | 0.20 |
| $H_2O$ | 3.10 | 2.43 | 1.21 | 0.71 | 1.01 | 2.01 | 3.55 | 2.84 | 2.41 | 1.84 | 2.92 | 1.09 | 2.91 | 1.41 | 1.25 |
| *Phenocryst modes (volume %)* | | | | | | | | | | | | | | | |
| Olivine | 5.5 | 4.9 | – | 1.0 | 6.6 | 0.6 | 7.9 | 0.7 | 1.5 | – | tr. | – | – | – | – |
| Plag. | 39.6 | 34.3 | – | 11.1 | 1.3 | 2.7 | 1.2 | 7.2 | 4.4 | – | 3.5 | – | – | – | – |
| Groundms | 54.9 | 60.8 | – | 87.9 | 92.1 | 96.7 | 90.7 | 92.1 | 94.1 | – | 96.5 | – | – | – | – |

1–13 Dykes from Harris (Code 'S'), Vaternish (Code 'I'), Sleat (Code 'H') and Arisaig (Code 'A'), (arranged in order of increasing $TiO_2$ content).
14 SK946 Massive centre of lava flow from Abhainn Choishleadar, near Edinbane (from Table 1, Esson *et al.*, 1975).
15 SK982 Lower chilled margin of columnar mass forming north cliff of Preshal More, near Talisker (Ibid).
a Analysed wet chemically by H. Lloyd.
b Total contains 0.10% $CO_2$ (norm contains 0.23% calcite).
c F/F+M is ($FeO + Fe_2O_3$)/($FeO + Fe_2O_3 + MgO$) using standard $Fe_2O_3$ (1.5%).
All powders dried at 100°C before analysis.
Rb, Sr, Y and Zr for SK946 from Table II, Esson *et al.*, 1975.

phenocryst cores. Olivine accumulation would be detected by the calculated liquidus olivine being more magnesian than the phenocryst core, whereas it is clearly apparent that this is not so.

Plagioclase phenocrysts display a much wider modal range (0–40 %, mean 13 %). The case for plagioclase redistribution is considered in fig. 4. Vectors on this diagram represent the subtraction of the modal proportion of the observed phenocryst phases in some of the most porphyritic rocks. Clearly even this extreme phenocryst redistribution cannot account for the range of compositions within the Preshal Mhor magma type, which is therefore *not* the result of phenocryst sorting during dyke injection. However, fig. 4 also makes it apparent that

**TABLE IIB.** *Major and trace element data for 34 Preshal Mhor type dykes*

| | S001 | S002 | S003 | S015 | S017 | S021 | S024 | S006 | S027 | S038 | S039 | I009 | I019 | I031 | A027 | A036 | A045 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Major elements (wt. %)* | | | | | | | | | | | | | | | | | |
| $SiO_2$ | 47.03 | 46.60 | 45.91 | 45.84 | 48.04 | 44.28 | 46.70 | 47.24 | 46.61 | 47.77 | 46.71 | 45.34 | 47.35 | 45.45 | 47.27 | 47.36 | 47.25 |
| $TiO_2$ | 0.85 | 1.23 | 0.97 | 0.88 | 0.70 | 0.53 | 0.76 | 0.81 | 1.08 | 1.16 | 0.87 | 0.82 | 1.14 | 0.93 | 0.88 | 1.10 | 0.88 |
| $Al_2O_3$ | 14.47 | 15.19 | 16.12 | 15.97 | 16.35 | 19.05 | 17.77 | 17.78 | 14.84 | 14.80 | 16.37 | 17.01 | 14.74 | 15.84 | 18.08 | 17.62 | 16.51 |
| $Fe_2O_3$ | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | | | | | | | | |
| FeO | 8.29 | 10.09 | 8.80 | 8.49 | 7.55 | 6.28 | 7.73 | 8.12 | 10.05 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| MnO | 0.16 | 0.19 | 0.17 | 0.15 | 0.15 | 0.12 | 0.15 | 0.15 | 0.19 | 10.19 | 8.80 | 7.95 | 9.81 | 9.47 | 8.40 | 9.48 | 8.83 |
| MgO | 8.94 | 7.85 | 8.13 | 8.14 | 8.34 | 8.87 | 10.13 | 8.59 | 6.74 | 0.18 | 0.16 | 0.15 | 0.18 | 0.17 | 0.16 | 0.16 | 0.18 |
| CaO | 13.14 | 11.74 | 12.46 | 12.84 | 12.22 | 13.26 | 12.70 | 13.13 | 12.65 | 7.87 | 9.38 | 9.78 | 8.18 | 9.10 | 8.18 | 8.76 | 9.28 |
| $Na_2O$ | 1.82 | 2.58 | 1.95 | 1.78 | 1.84 | 1.44 | 1.85 | 1.94 | 2.08 | 12.73 | 12.73 | 11.91 | 12.81 | 12.79 | 12.79 | 10.31 | 12.83 |
| $K_2O$ | 0.15 | 0.21 | 0.18 | 0.10 | 0.24 | 0.11 | 0.09 | 0.14 | 0.18 | 2.25 | 1.88 | 1.92 | 2.12 | 1.71 | 2.21 | 2.72 | 2.09 |
| $P_2O_5$ | 0.12 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.10 | 0.10 | 0.12 | 0.14 | 0.10 | 0.12 | 0.18 | 0.13 | 0.13 | 0.20 | 0.07 |
| | | | | | | | | | | 0.13 | 0.11 | 0.06 | 0.13 | 0.09 | 0.08 | 0.14 | 0.08 |
| *Trace elements (ppm)* | | | | | | | | | | | | | | | | | |
| Zr | 48 | 64 | 43 | 41 | 36 | 23 | 38 | 38 | 50 | 47 | 40 | 39 | 49 | 45 | 42 | 61 | 48 |
| Y | 18 | 25 | 22 | 23 | 19 | 12 | 19 | 19 | 29 | 28 | 18 | 19 | 25 | 19 | 20 | 25 | 21 |
| Rb | 3 | 4 | 3 | 1 | 5 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |
| Nb | 4 | 6 | 6 | 6 | 2 | 4 | 4 | 5 | 6 | 6 | 6 | 4 | 6 | 6 | 4 | 6 | 3 |
| Sr | 122 | 136 | 142 | 116 | 113 | 113 | 103 | 114 | 118 | 99 | 118 | 114 | 126 | 101 | 119 | 276 | 97 |

| | H037B | H042 | H110 | H173 | H195 | H208B | H220 | H236 | H261A | H263 | H281 | A001 | A009 | A024 | A048 | A051 | A093 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Major elements (wt. %)* | | | | | | | | | | | | | | | | | |
| $SiO_2$ | 46.98 | 47.82 | 46.37 | 46.22 | 46.82 | 47.43 | 47.87 | 47.52 | 47.54 | 47.62 | 47.57 | 49.92 | 46.71 | 45.93 | 47.55 | 49.41 | 47.39 |
| $TiO_2$ | 0.71 | 1.02 | 0.95 | 0.78 | 0.99 | 0.96 | 1.31 | 1.29 | 1.31 | 1.13 | 1.21 | 0.89 | 0.83 | 0.73 | 1.04 | 1.17 | 0.96 |
| $Al_2O_3$ | 15.46 | 15.64 | 15.78 | 19.33 | 15.84 | 17.70 | 14.40 | 15.99 | 14.60 | 14.27 | 14.06 | 16.69 | 16.75 | 16.94 | 16.21 | 14.37 | 16.83 |
| $Fe_2O_3$ | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| FeO | 7.61 | 9.24 | 8.75 | 6.60 | 7.08 | 7.53 | 10.06 | 8.31 | 10.05 | 10.29 | 9.97 | 8.38 | 8.05 | 7.66 | 9.48 | 10.16 | 8.70 |
| MnO | 0.16 | 0.19 | 0.18 | 0.14 | 0.20 | 0.17 | 0.21 | 0.20 | 0.21 | 0.22 | 0.22 | 0.16 | 0.16 | 0.15 | 0.18 | 0.19 | 0.16 |
| MgO | 11.83 | 7.97 | 8.60 | 7.41 | 8.76 | 6.73 | 7.41 | 7.69 | 7.26 | 7.52 | 7.54 | 7.95 | 8.39 | 8.58 | 8.78 | 7.17 | 8.82 |
| CaO | 11.77 | 12.93 | 12.81 | 13.62 | 12.61 | 13.59 | 12.06 | 11.35 | 12.21 | 13.04 | 12.92 | 12.63 | 12.69 | 12.73 | 12.30 | 12.01 | 12.67 |
| $Na_2O$ | 1.62 | 2.09 | 1.85 | 1.86 | 1.97 | 2.03 | 2.60 | 2.75 | 2.60 | 2.23 | 2.25 | 2.16 | 1.96 | 1.72 | 2.29 | 2.50 | 2.17 |
| $K_2O$ | 0.11 | 0.09 | 0.09 | 0.08 | 0.08 | 0.10 | 0.21 | 0.28 | 0.16 | 0.08 | 0.09 | 0.28 | 0.10 | 0.10 | 0.12 | 0.32 | 0.16 |
| $P_2O_5$ | 0.05 | 0.09 | 0.06 | 0.05 | 0.08 | 0.07 | 0.10 | 0.14 | 0.11 | 0.08 | 0.08 | 0.11 | 0.08 | 0.07 | 0.09 | 0.10 | 0.13 |
| *Trace elements (ppm)* | | | | | | | | | | | | | | | | | |
| Zr | 32 | 48 | 46 | 32 | 51 | 45 | 60 | 79 | 66 | 56 | 55 | 43 | 39 | 38 | 50 | 64 | 39 |
| Y | 13 | 28 | 23 | 21 | 25 | 24 | 28 | 20 | 26 | 28 | 30 | 28 | 22 | 19 | 23 | 32 | 18 |
| Rb | 1 | 0 | 1 | 0 | 1 | 0 | 4 | 4 | 3 | 3 | 0 | 6 | 1 | 0 | 1 | 6 | 1 |
| Nb | 4 | – | 4 | 4 | 6 | 3 | 4 | 4 | 4 | 4 | 6 | 6 | 3 | 5 | 4 | 7 | 6 |
| Sr | 99 | 100 | 111 | 129 | 103 | 120 | 147 | 289 | 144 | 99 | 130 | 110 | 109 | 108 | 128 | 117 | 132 |

***Erratum:*** **The last 8 columns should be closed up (line 4 should not be blank)**

the observed variation within this magma type might well result from the fractionation, below the level of emplacement, of *both* of the observed phenocryst phases in approximately their modal proportions. It can also be deduced from the data presented in figs. 2, 3, and 4 that the Preshal Mhor magmas *cannot* be related to other basaltic compositions observed in the dyke swarm by the fractionation of plagioclase+olivine (see also below).

TABLE III. *Calculated liquidus olivine compositions compared with observed phenocryst core compositions. Major elements wt. %, trace elements p.p.m.*

| Dyke | % of Ol phenocrysts | F/(F+M) | Calculated liquidus olivine | Observed phenocryst core |
|---|---|---|---|---|
| S001 | 1.6 | 0.52 | 85.3 Fo | 85.8 Fo |
| S015 | 2.6 | 0.60 | 83.8 | 86.1 |
| S020 | 4.9 | 0.48 | 87.7 | 87.8 |
| S006 | 5.7 | 0.53 | 85.1 | 84.7–87.2 |
| S021 | 6.2 | 0.47 | 88.4 | 87.5 |
| S012 | 7.9 | 0.56 | 83.1 | 83.3 |
| S024 | 9.1 | 0.48 | 87.6 | 87.1 |

TABLE IV. *Compositional variation within the Skye Main Lava Series*

| | Hy-normative basalts | Alkali basalts | Hawaiite | Mugearites, benmoreites |
|---|---|---|---|---|
| $TiO_2$ | 1.4–1.7% | 2.2–2.5 | 2.2–3.8 | 0.8–2.8 |
| CaO | 9.3–10.3 | 8.5–9.2 | 6.5–7.5 | 2.8–6.2 |
| $K_2O$ | 0.3–0.9 | 0.2–0.5 | 0.5–1.3 | 1.2–3.8 |
| Nb, ppm | 6–7 | 6–10 | 7–30 | 60* |
| Rb | 3–14 | 6–10 | 7–25 | 70* |
| Sr | 360–420 | 420–580 | 680–810 | 180* |
| Yt | 22–27 | 27–31 | 26–52 | 60* |
| Zr | 97–110 | 70–160 | 190–310 | 400* |

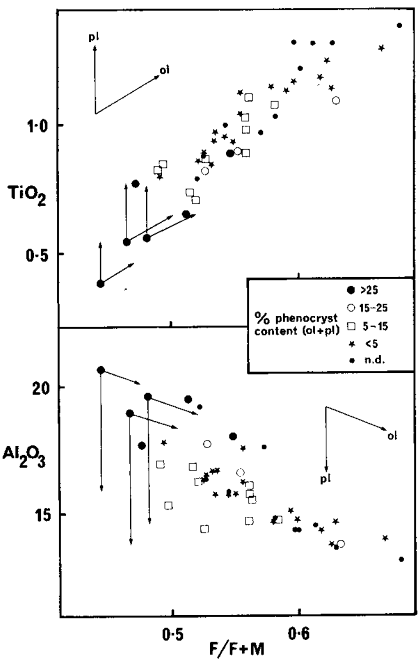
Major element data from Thompson *et al.*, 1972
* For benmoreite only

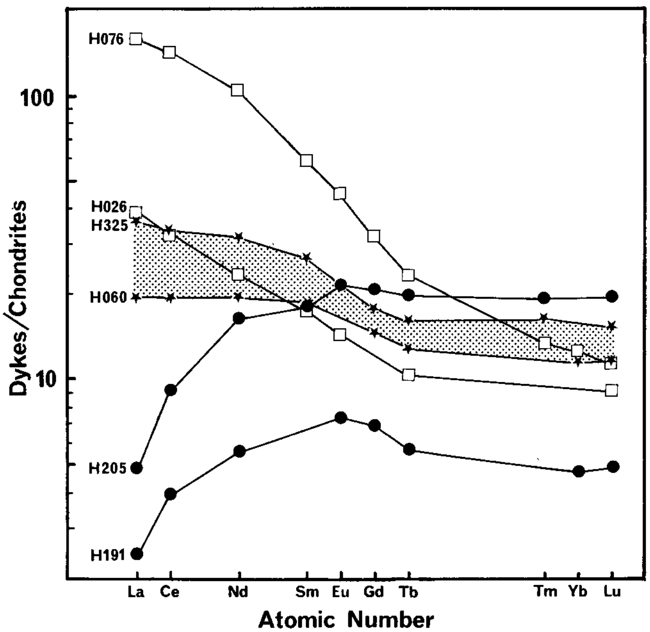
*Other magma types.* The remainder of the dykes (some 30 % of the swarm) have been compared compositionally with the Skye Main Lava Series. Table IV lists, for certain analysed elements, the observed ranges within the lavas studied previously by Thompson *et al.* (1972). Data are presented for the *hy*-normative basalts, the alkali basalts (*ne*-normative), the hawaiites, and the more evolved mugearites and benmoreites. These values have been used to identify the remaining dykes. Compositions comparable to the mugearite and benmoreite lavas are rare. Most of these remaining dykes are *hy*-normative basalts with a few hawaiites; there are very few dykes belonging to the *ne*-normative group, in sharp contrast to the approximately equal proportions of *hy* and *ne*-normative basalt types within the Skye Main Lava Series. We are forced to conclude that the *ne*-normative alkali basalt lavas were fed from fissures or vents situated more centrally within Skye than the sections we have sampled.

A group of 29 dykes (mainly from the Vaternish and Sleat sections) have characteristics that exclude them from *both* the Preshal Mhor and the Skye Main Lava Series magma types. They have Ti/Zr ratios comparable to Preshal Mhor type magma (fig. 3a) and thus clearly different from Skye Main Lava Series, and yet the basalts are not of a high-CaO, low-total-alkali type.

In thin section these dykes can be distinguished from the Preshal Mhor type dykes by the appearance of a distinctly brown or lilac-brown groundmass pyroxene containing numerous titanomagnetite inclusions. Preshal Mhor-type dykes contain a pale green ophitic pyroxene with interstitial titanomagnetite.

A search of the available analyses of Skye Lavas has found only one of a comparable composition to these dykes (SK971, Thompson *et al.*, 1972). This flow is in the Ramascaig group near Fairy Bridge (NG277505) (analysis 7, Table V). We are confident that this lava and 29 dykes represent a distinct magma type for which we propose the name 'Fairy Bridge', and representative analyses of this magma type are shown in Table V.




FIGS. 4 and 5: FIG. 4 (left). Variation of $TiO_2$ and $Al_2O_3$ with F/(F+M) for Preshal Mhor type dykes only. Subtraction vectors are drawn for several of the most porphyritic samples to show the maximum effect of the removal of olivine or plagioclase phenocrysts. Independent evidence (see text and Table III) suggests that olivine removal alone cannot be responsible for the internal variation shown by the group and even extreme removal (or addition) of plagioclase can only account for some of the scatter about the trend, not the trend itself. FIG. 5 (right). Rare-earth patterns of samples chosen to represent the limits of variation of each magma type (symbols as in fig. 2). The Fairy Bridge magma type dykes have patterns that fall within the shaded area and cannot be produced from Preshal Mhor type parents as a result of crystal/liquid processes involving olivine and plagioclase.

It is now possible to return to the problem of the inter-relationship of the different magma types. Variation within the Preshal Mhor magma type appears to be the result of the fractionation, at comparatively low pressure, of olivine and plagioclase in approximately their observed phenocryst proportions. This fractionation has no effect on the Ti/Zr ratio of the magma, which remains constant at about 120 (fig. 3a), as neither of these elements enter the precipitating phases in significant quantities. On this basis only the Fairy Bridge basalts could conceivably be considered as possible low-pressure derivatives of the Preshal Mhor magmas. However, in order for this to be so, the shapes of chondrite normalized rare-earth element patterns for the two magma types would have to be the same, which they are not (see below).

TABLE V. *Representative analyses of Fairy Bridge type dykes and a lava*

| | 1 I061 | 2 H060 | 3 I043 | 4 H002 | 5 H325 | 6 A012 | 7 SK971 |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 45.80 | 47.48 | 46.06 | 46.46 | 47.79 | 45.73 | 46.94 |
| $TiO_2$ | 1.04 | 1.20 | 1.44 | 1.77 | 1.87 | 2.00 | 1.37 |
| $Al_2O_3$ | 16.43 | 15.96 | 16.30 | 16.44 | 13.86 | 16.59 | 17.15 |
| $Fe_2O_3$ | 1.50 | 1.50 | 1.50 | 2.00 | 1.50 | 2.00 | 2.11 |
| FeO | 8.42 | 10.29 | 10.50 | 11.12 | 12.11 | 11.69 | 9.83 |
| MnO | 0.14 | 0.19 | 0.16 | 0.18 | 0.23 | 0.16 | 0.19 |
| MgO | 7.95 | 7.67 | 7.56 | 6.80 | 5.56 | 5.26 | 7.69 |
| CaO | 9.51 | 9.64 | 9.07 | 8.12 | 9.67 | 6.99 | 9.73 |
| $Na_2O$ | 2.72 | 3.38 | 3.11 | 3.45 | 3.11 | 4.23 | 3.01 |
| $K_2O$ | 0.36 | 0.45 | 0.61 | 0.57 | 0.65 | 0.68 | 0.43 |
| $H_2O$ | 4.64 | 1.85 | 2.52 | 1.58 | 2.45 | 3.50 | 1.55 |
| $P_2O_5$ | 0.16 | 0.12 | 0.12 | 0.25 | 0.23 | 0.32 | 0.18 |
| Sum | 98.71 | 99.46 | 98.85 | 98.74* | 99.03 | 99.15 | 100.24 |
| F/(F+M) | 0.55 | 0.60 | 0.61 | 0.66 | 0.71 | 0.72 | 0.61 |

*Trace elements*, p.p.m.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Nb | 7 | 4 | 6 | 6 | 7 | 6 | 6 |
| Rb | 0 | 4 | 9 | 6 | 8 | 11 | 0 |
| Sr | 287 | 476 | 570 | 511 | 267 | 551 | 420 |
| Yt | 27 | 27 | 31 | 25 | 33 | 35 | 27 |
| Zr | 69 | 70 | 74 | 81 | 94 | 95 | 68 |
| Ti/Zr | 090 | 103 | 117 | 131 | 119 | 126 | 121 |
| Yt/Zr | 0.39 | 0.38 | 0.42 | 0.30 | 0.35 | 0.37 | 0.39 |

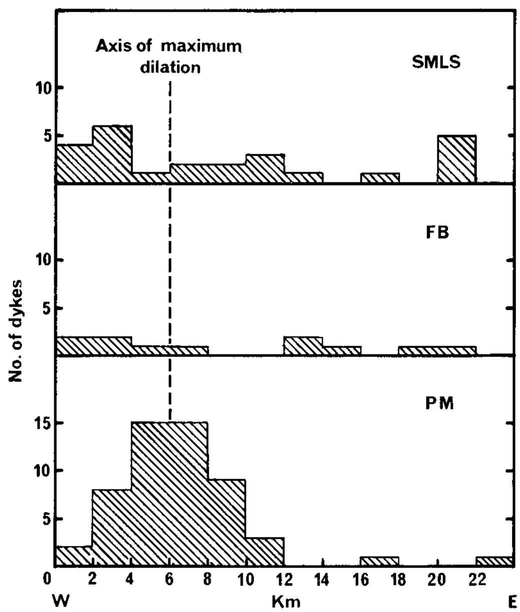
* Including 0.06% $CO_2$

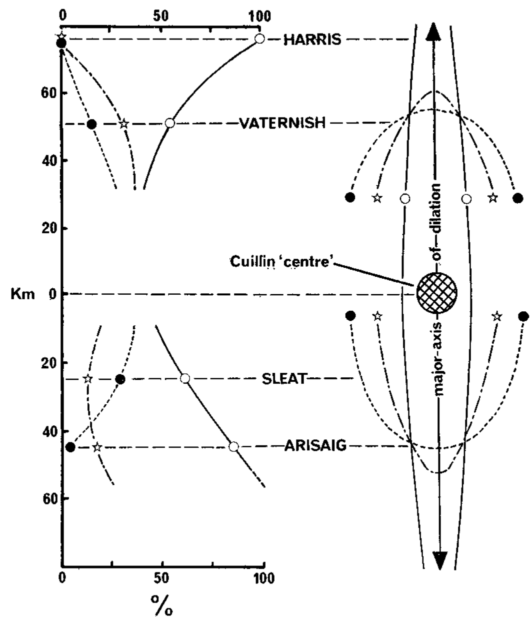
1 to 6: Fairy Bridge type dykes, arranged in order of increasing F/(F+M); section code as in Table II.

7: SK 971. Basalt from Ramascaig Group. Roadside on A850, 0.9 km S of Fairy Bridge (NG277505); (Table 1, Thompson *et al.*, 1972)

*Rare-earth geochemistry.* The rare-earth elements were determined on 43 dykes from the Sleat section. The complete data are available on request to D. P. M. Limiting examples of each magma type are shown in fig. 5.

All the dykes belonging to the Preshal Mhor magma type have a light-rare-earth depleted chondrite-normalized pattern. In contrast, the basalts belonging to the Fairy Bridge magma type have a flat or slightly light-rare-earth enriched chondrite normalized pattern, which is quite distinct (shaded area, fig. 5). The partitioning of the rare-earth elements into olivine and




FIGS. 6 and 7: FIG. 6 (left). Histograms showing the distribution of dykes belonging to each magma type across the Sleat section (SMLS—Skye Main Lava Series; FB—Fairy Bridge magma type; PM—Preshal Mhor magma type). Preshal Mhor type dykes are confined close to the axis of maximum dilation whereas dykes belonging to other magma types have a wider lateral distribution. FIG. 7 (right). The relative abundance of the three magma types at each section (open circles—Preshal Mhor type; stars—Fairy Bridge type; closed circles—Skye Main Lava Series type). We interpret this distributional pattern as being a result of the Preshal Mhor magma type being injected within a longer and thinner zone than the other magma types. The more evolved Skye Main Lava Series dykes (hawaiites etc.) tend to be restricted to central Skye.

plagioclase is so slight that the fractionation of these phases in the amount observed as phenocrysts will have little or no effect on the shape of the patterns. As noted above, the patterns on fig. 5 demonstrate why the Fairy Bridge magma type *cannot* be the product of fractionation of the *observed* phenocrysts from the Preshal Mhor type.

The Skye Main Lava Series dykes show varying degrees of light-rare-earth enrichment, with La/Sm increasing from 1·2 for the *hy*-normative basalts to 3·0 for the mugearites and benmoreites. These patterns are quite distinct from those of the other two magma types.

*Spatial geochemistry.* Fig. 6 is a histogram showing the occurrence of Preshal Mhor type dykes along the 30 km Sleat of Skye section. It can be seen that these dykes are strongly concentrated in the centre of the section, where crustal dilation also reaches a maximum (Speight, 1972). Data from the other sections (Table VI) show that this narrow Preshal Mhor type swarm component is persistent, extending as far as to Harris in the north and Arisaig in the south. In contrast, dykes of other compositions, particularly the hawaiites and mugearites, are much

TABLE VI. *Distribution of dyke types within the swarm*

| | %PM | %FB | SMLS %a | SMLS %h | SMLS %m+b |
|---|---|---|---|---|---|
| Harris | 100 | – | – | – | – |
| Vaternish | 56 | 30 | 8 | 6 | – |
| Sleat | 60 | 13 | 18 | 6 | 3 |
| Arisaig | 81 | 16 | 3 | – | – |

PM: Preshal Mhor type dykes
FB: Fairy Bridge type dykes
SMLS: Skye Main Lava Series type dykes:
a: basalts
h: hawaiites
m+b: mugearites and benmoreites

TABLE VII. *Comparative analyses of basalts from the Scottish–Irish Tertiary igneous province, Iceland, and the Mid-Atlantic Ridge*

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $SiO_2$ | 46.72 | 47.54 | 48.14 | 46.62 | 49.09 | 49.21 |
| $TiO_2$ | 0.64 | 0.87 | 1.32 | 0.96 | 1.47 | 1.39 |
| $Al_2O_3$ | 14.48 | 15.66 | 14.66 | 16.05 | 15.35 | 15.81 |
| $Fe_2O_3$ | 3.82 | 3.38 | 4.74 | 11.11* | 12.22* | 2.21 |
| FeO | 8.70 | 6.85 | 7.85 | – | – | 7.19 |
| MnO | 0.22 | 0.19 | 0.20 | 0.17 | 0.17 | 0.15 |
| MgO | 8.44 | 8.31 | 6.86 | 8.15 | 7.27 | 8.53 |
| CaO | 11.93 | 13.04 | 11.48 | 12.66 | 12.41 | 11.14 |
| $Na_2O$ | 2.35 | 1.89 | 2.49 | 2.05 | 2.29 | 2.71 |
| $K_2O$ | 0.08 | 0.13 | 0.38 | 0.10 | 0.23 | 0.26 |
| $P_2O_5$ | 0.10 | 0.07 | 0.13 | 0.09 | – | 0.15 |
| Total | 97.48 | 99.93 | 98.25 | 97.96 | 100.50 | 98.75 |

| † | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Nb | 5 | 7 | 4 | – |
| Sr | 129 | 213 | 125 | 149 |
| Rb | 2 | 8 | 2 | 1 |
| Yt | 26 | 35 | 23 | 21 |
| Zr | 42 | 82 | 47 | 102 |

* Total iron expressed as $Fe_2O_3$
† Trace elements in p.p.m.

1: Olivine tholeiite, Antrim (anal. 8, Patterson, 1955)
2: Average of 16 low-alkali tholeiites, Mull (Lamacraft, 1976)
3: Average of 7 olivine tholeiites, Mull (*ibid.*)
4: Average of 38 low-alkali tholeiites (Preshal Mhor magma type), Skye
5: Average of 36 basalts from the northern part of the eastern volcanic zone, Iceland (Sigvaldason, 1974)
6: Average of 33 basalts from depths greater than 100 m from the Mid-Atlantic Ridge (Table 4, Melson *et al.*, 1968)

more restricted in their occurrence and are found only in central Skye. As a result the proportion of Preshal Mhor type dykes *increases* away from the Skye plutonic centre along the *axis* of the swarm (fig. 7).

The bulk of the Preshal Mhor type dykes have clearly been injected within a relatively narrow zone that defines the axis of maximum crustal extension for the swarm as a whole.

## *Conclusions*

Three main conclusions have been drawn from this study:

Dykes of the Preshal Mhor magma type make up over 70 % of the total swarm. Lavas of this type are now rare in Skye, but clearly the production of this magma type must have been substantial. Unless the Preshal Mhor type dykes failed to reach the surface to form flows, lavas of this type must have been abundant in the missing upper part of the pile, which may have been as much as 1500 m thick (P. M. King, personal communication), although only 700 m is preserved at present (Anderson and Dunham, 1966).

A second result of this study is the recognition of three compositionally distinct basaltic magma types, which are all well represented in the Skye regional dyke swarm. These comprise a group chemically equivalent to the extruded Skye Main Lava Series, the Preshal Mhor magma type, and the hitherto unrecognized Fairy Bridge magma type. We have attempted to show that when a wide variety of elemental abundances and ratios are considered together then these magma types may be defined unambiguously. It is not clear at this stage what the exact genetic relation is *between* the three magma types; however, they *cannot* be related by the accumulation or fractionation of the observed phenocryst phases.

The three magma types appear to be systematically distributed forming a *compound* dyke swarm, but to what degree a mantle-controlled distributional pattern has been modified by the stress field operating in the upper part of the crust is not evident. The injection of the Preshal Mhor type dykes, as a result of a higher degree of partial melting, would probably be associated with the emplacement of the central intrusive complex. This is supported by the fact that Preshal Mhor type dykes have been found to cut the Skye granite complex (Mattey, unpublished data) and that results from the theoretical analyses of stress trajectories (I. R. Vann, personal communication) indicate that the majority of dykes were injected in association with such a central intrusive complex.

Similar high-calcium low-alkali olivine tholeiite dykes (Preshal Mhor magma type in Skye) are found elsewhere in the Scottish–Irish Tertiary igneous province; in Antrim (Patterson, 1955), Arran (J. V. S. Turner, personal communication), Carlingford (T. Halsall, personal communication), and Mull (Lamacraft, 1976). Comparative analyses from some of these areas are given in Table VII, along with similar rocks from Iceland and the Mid-Atlantic Ridge. It has already been noted that there is a strong resemblance between the Skye high-calcium, low-alkali olivine tholeiites and mid-oceanic ridge basalt types (Esson *et al.*, 1975). The light-rare-earth depleted rare-earth element patterns (fig. 5) and low abundances of the large-ion lithophile elements in the Preshal Mhor-magma type further emphasize this similarity. The occurrence of high-calcium, low-alkali tholeiites at several of the other Tertiary igneous centres suggests that the style of magmatic events beneath Skye may be of a more general nature. Furthermore, the strong resemblance between Thulean high-calcium, low-alkali tholeiites and basalts that are erupted at constructive plate margins also suggests that there were genuine, but abortive, attempts to produce oceanic crust within the Scottish-Irish Tertiary igneous province.

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