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Lateral Chemical Heterogeneity in the Palaeocene Upper Mantle Beneath the Scottish Hebrides [and Discussion]

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Lateral chemical heterogeneity in the Palaeocene upper mantle beneath the Scottish Hebrides

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The early major products of Tertiary volcanicity in both Skye and Mull are transitional basic lavas, similar in their major-element chemistry to world-wide alkali basalt series. In contrast, their contents of incompatible trace elements bear more resemblance to those of olivine tholeiites. The Mull basalts have similar ranges of silica saturation, Mg/(Mg+Fe), Y and Yb, but lower overall abundance ranges of strongly incompatible elements than the Skye basalts. The variation of incompatible elements in the Mull and Skye lavas is consistent with a model of a mantle source from which a small amount of melt (no more than 1%?) had been extracted, with the pre-Tertiary upper-mantle fusion beneath Mull slightly greater than beneath Skye. Chemical and tectonic considerations suggest that this mantle was neither residual from the formation of the Archaean Lewisian complex, nor emplaced as a result of tension associated with the Cainozoic rifting of the North Atlantic. Data on major and trace elements for a mafic alkalic dyke of the Permian swarms that pass through western Scotland show that these have the requisite geochemical characteristics to have caused this depletion. Such dykes are more abundant in the region of Mull than Skye.

INTRODUCTION

Igneous activity within the British Tertiary Igneous Province produced a diversity of basic magma types and lasted for a period of several million years (Macintyre *et al.* 1975). Accordingly, careful sample selection is needed if the basic magmas are to monitor the composition and variability of their mantle source regions. In this paper we concentrate on the early major transitional-basalt suites of Skye and Mull; i.e. the Skye Main Lava Series (S.M.L.S.) and the Mull Plateau Group (M.P.G.) (Bailey *et al.* 1924; Thompson *et al.* 1972). We have excluded from this study the few tholeiitic lavas that occur only near the base of both the Skye and Mull lava piles (Bailey *et al.* 1924; Anderson & Dunham 1966). The long-recognized differences between the predominating transitional basalts and these rare tholeiites have been confirmed by recent studies, showing that the latter may have been substantially affected by crustal contamination (Morrison 1978; Beckinsale *et al.* 1978; Moorbath & Thompson 1979). In addition, we report data on major and trace elements for a crinanite sample (MS 209) from the Dippin Head sill, which was the earliest emplacement of basic magma in southern Arran (Halsall 1978). Details of our analytical procedures have been given elsewhere (Wood *et al.* 1976).

Current opinion seems to favour the hypothesis that the onset of igneous activity was contemporaneous throughout the province at about 59 Ma, with most of the lavas being extruded during a period of 1–2 Ma (Macintyre *et al.* 1975; Brown & Mussett 1976). These basalts therefore represent the products of approximately synchronous magma generation within the Palaeocene upper mantle beneath the Scottish Hebrides.

PROCESSES THAT CAN OBSCURE THE EFFECTS OF MANTLE INHOMOGENEITY

Hydrothermal alteration

The effects of this process on individual Mull lavas have been investigated by Morrison (1977, 1978) and Humphris *et al.* (1978). These studies reveal that, with the exception of Sr which shows limited mobility, the compositions of all the lavas affected by *zeolite-facies* alteration appear to be pyrogenic. Nevertheless, they have all been subjected to post-eruptive oxidation, to degrees varying even within individual lava flows. Consequently, the CIPW norms and iron/magnesium ratios $[F/(F+\dot{M}) = (FeO+Fe_2O_3)/(FeO+Fe_2O_3+MgO)]$ of these lavas were calculated by using the scheme adopted by Thompson *et al.* (1972), in which constant values of Fe_2O_3 are employed. In contrast, the local *greenschist-facies* alteration, which has affected two of the Mull lavas discussed here, caused considerable chemical changes. Nevertheless, Ti, P, Nb, Ta, Zr, Hf, Y and the rare-earth elements appear to have been immobile. Accordingly, the discussion of these two metabasalts is confined to variations in the ratios of these elements.

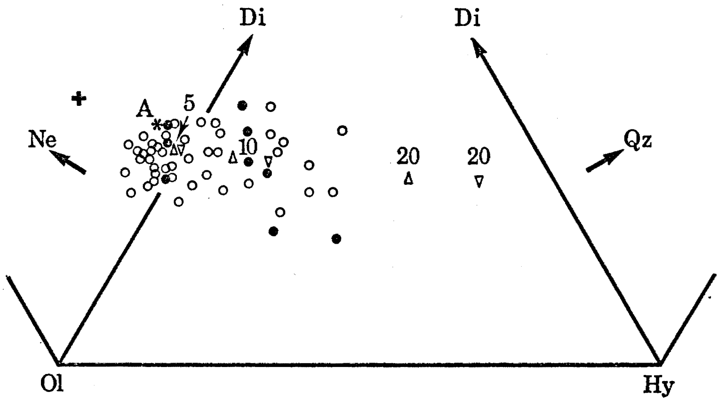

FIGURE 1. CIPW normative Di–Hy–Ol–Ne/Qz in S.M.L.S. and M.P.G. basalts. Key to symbols: ○, S.M.L.S. basalts; ●, M.P.G. basalts; +, Arran crinanite MS 209; A, Skye alkali basalt used in contamination calculations; ▽, basalt A plus cotectic-melting Skye granite; △, basalt A plus average Lewisian gneiss from Rona (Holland & Lambert 1972). The figures refer to the percentage of contaminant added.

Crustal contamination

Most of the Skye and Mull lavas exhibit a range of Pb, Sr and Nd isotope ratios intermediate between those of mantle-derived magmas in ocean basins and the Lewisian gneisses which form the sialic basement to these complexes. Estimates of the degree of contamination vary, depending on the isotope species used, from 6 to 65% for Pb and from 5 to 50% for Sr and Nd (Moorbath & Welke 1969; Carter *et al.* 1978; Moorbath & Thompson 1979). We have calculated the effects of adding various amounts of plausible sialic contaminants to one of the most strongly alkalic basalts recorded on Skye (Tilley & Muir 1962). Two models have been considered: (1) bulk dissolution of Lewisian crust, by using the mean Lewisian gneiss composition from the nearest outcrop to Skye, on the island of Rona (Holland & Lambert 1972); (2) upper-crust anatectic melt, by using a Skye granite (Southern Porphyritic Granite) showing cotectic melting at upper-crustal pressures (R. N. Thompson, unpublished). The range of compositions generated by these calculations are indicated on figure 1. It is apparent from this diagram that no more than 15% of either of these materials can be incorporated by simple mixing with the basalts, to account for the range of Si saturation that they display. Examination of table 1 shows that the addition of 15% of these materials to the S.M.L.S. *ne*-normative basalts would generate magmas with considerably different contents of minor and trace elements from those observed in the S.M.L.S. *hy*-normative basalts. Further, Moorbath & Thompson (1979) found no correlation between either SiO_2 content or Si saturation and initial $^{87}Sr/^{86}Sr$ ratios in the Skye basalts. The range of isotopic compositions shown by these lavas would thus appear to be the result of poorly understood selective contamination, discussed in more detail by Moorbath & Thompson (1979).

Table 1. Comparison of variations in minor elements in S.M.L.S. basalts with sialic bulk-contamination models

	Na_2O	K_2O	TiO_2	P_2O_5	Rb	Sr	Zr	Y
ne-normative less-magnesian basalt average	3.22	0.30	2.43	0.26	2.7	533	184	28
hy-normative less-magnesian basalt average	2.75	0.44	1.53	0.20	3.8	540	121	26
ne-normative basalt average plus 15% av. Rona gneiss	3.32	0.57	2.12	0.22	13	523	180	25
ne-normative basalt average plus 15% cotectic granite	3.27	0.99	2.09	0.22	24	454	267	44

Variable degrees of initial partial melting at any one site

Thompson *et al.* (1979) have shown that the degree of partial melting may have varied by up to a factor of two during the genesis of the S.M.L.S. basalts. This process can produce changes in the ratios of elements such as La/Yb. Nevertheless, it will be shown below that the variable relative abundances of the most strongly incompatible elements in the Hebridean basalts cannot be explained solely in terms of a Palaeocene variable partial melting model but appear to reflect heterogeneity in their mantle source regions.

Fractional crystallization

To eliminate the effects of this process upon the primary compositions of the Hebridean basalts, only those elements that were excluded from the precipitating phases (olivine and chrome spinel in the magnesian basalts; olivine and plagioclase in the less-magnesian basalts) are discussed here.

Differences between the Tertiary Hebridean lavas and other alkali basalt suites

The early Plateau lavas of the British Tertiary Province have traditionally been regarded as one of the world's most typical examples of an alkali olivine basalt suite (Kennedy 1933; Tilley 1950; Wager 1956; Coombs & Wilkinson 1969; Carmichael *et al.* 1974). The S.M.L.S. and M.P.G. contain both *ne*- and *hy*-normative varieties and are best described as transitional basalts. It can be seen from figure 1 that these two groups show similar ranges of Si saturation, as is necessitated by their similar major-element compositions (table 2). The S.M.L.S. and M.P.G. lavas superimpose on diagrams with the elements Ti, P, Zr, Nb and Y but, when published classification schemes with these elements are applied to them, they appear to be typical

TABLE 2. CHEMICAL ANALYSES OF PALAEOCENE BASALTIC ROCKS AND A PERMIAN DYKE

	S.M.L.S. averages		Mull Plateau Group basalts							hawaiites			Permian lamprophyre MS 144
	Mg-basalt	less-Mg basalt	LA13-5	LA20	M 51-5	M 1	LA7-11	M 19†	M 30†	Skye 907	Mull M 7	Arran MS 209	
						Major elements (percentages by mass)							
SiO_2	45.97	45.99	45.99	45.54	45.11	45.76	46.21	45.88	43.95	46.69	46.94	43.97	44.04
TiO_2	1.73	1.88	1.55	1.60	2.04	1.81	1.84	1.32	1.80	2.76	3.07	2.03	3.49
Al_2O_3	14.23	15.62	13.75	14.31	15.24	16.49	16.91	13.27	15.32	16.05	16.53	15.71	13.27
Fe_2O_3	12.84	12.65	2.80	1.40	2.70	3.21	6.40	3.44	2.80	2.00	4.08	13.14	3.32
FeO			8.64	10.27	9.21	9.25	6.84	7.45	9.65	11.81	10.18		8.72
MnO	0.18	0.20	0.19	0.18	0.18	0.18	0.18	0.17	0.19	0.19	0.19	0.17	0.16
MgO	11.63	8.38	11.95	11.50	8.49	8.31	6.71	10.49	7.57	5.61	5.42	5.70	7.68
CaO	9.25	9.49	9.90	10.55	11.39	10.17	8.91	9.67	8.15	6.28	7.51	7.51	9.43
Na_2O	2.62	2.85	2.14	2.60	2.28	2.94	2.82	1.89	3.73	5.07	4.18	5.14	1.48
K_2O	0.42	0.46	0.26	0.24	0.17	0.20	0.25	0.53	0.25	0.70	0.27	0.36	2.49
H_2O^+	1.03	2.50	2.88	2.36	3.00	2.58	2.64	5.92	4.31	—	1.38	5.11	3.91
P_2O_5	0.19	0.22	0.14	0.14	0.16	0.14	0.14	0.15	0.16	0.45	0.30	0.26	0.94
CO_2	0.05	—	0.12	0.11	0.10	0.05	0.21	0.30	0.69	0.00	0.05	0.76	1.32
Total	100.14	100.02	100.31	100.80	100.07	101.09	100.06	100.38	98.57	97.61	100.10	99.86	100.25
						trace elements (micrograms per gram)							
Zr	115	128	97	94	119	97	111	104	109	279	230	175	362
Y	20	26	23	25	25	27	26	21	22	45	35	31	30
Rb	4.5	6	2	n.d.	n.d.	1	2	12	1	6	3	6	49
Nb	7.5	6	4	3	4	3	5	7	3	26	8	4	67
Sr	528	468	255	292	293	276	329	274	297	724	560	416	1293
Ta	0.35	0.28	0.19	—	0.21	0.29	0.26	0.22	0.28	0.98	0.51	0.46	5.22
Hf	2.99	3.81	2.72	3.22	3.27	3.23	3.13	2.77	3.07	7.82	6.07	4.39	9.30
Th	0.66	0.56	0.41	—	0.28	—	0.32	0.99	0.34	1.34	0.61	0.64	8.22
La	8.31	8.78	5.41	—	4.88	—	4.80	7.86	4.75	—	8.23	—	—
Ce	22.99	25.24	15.31	15.06	16.76	15.09	15.07	20.20	15.91	50.35	30.57	21.57	150.51
Nd	18.10	20.15	13.97	14.89	14.76	—	14.69	14.14	14.05	38.94	29.69	12.59	81.32
Sm	3.91	5.38	3.78	4.69	4.84	—	4.50	4.05	4.29	—	8.44	—	16.12
Eu	1.53	1.87	1.45	1.60	1.67	1.69	1.68	1.40	1.60	3.64	2.82	2.24	4.53
Gd	4.41	5.67	4.60	5.06	5.37	5.42	5.19	3.88	4.83	10.65	8.53	—	9.61
Tb	0.67	0.83	0.73	0.82	0.81	0.86	0.82	0.63	0.78	1.64	1.15	0.77	1.55
Tm	0.24	0.33	0.27	0.33	0.31	0.39	0.35	0.28	0.34	0.55	0.38	0.38	0.41
Yb	1.55	2.20	1.99	1.99	2.06	2.85	2.19	1.69	2.00	3.41	2.37	2.21	2.54
Lu	0.27	0.35	0.36	0.33	0.35	—	0.34	0.28	0.32	0.57	0.39	—	0.30

n.d., Element below detection limit; —, element not sought.
† Affected by greenschist-facies hydrothermal alteration (see text).

olivine tholeiites (Morrison 1978). Consideration of the Arran crinanite (table 2, MS 209) shows that this is not merely an exercise in semantics. This sample has the major-element composition of a typical nepheline-hawaiite and trace-element abundances similar to the Skye and Mull lavas. This discrepancy between the major-element and trace-element chemistry of Hebridean alkali basalts was also noted by Durant (1978) in his study of the Islay and Jura dyke swarms.

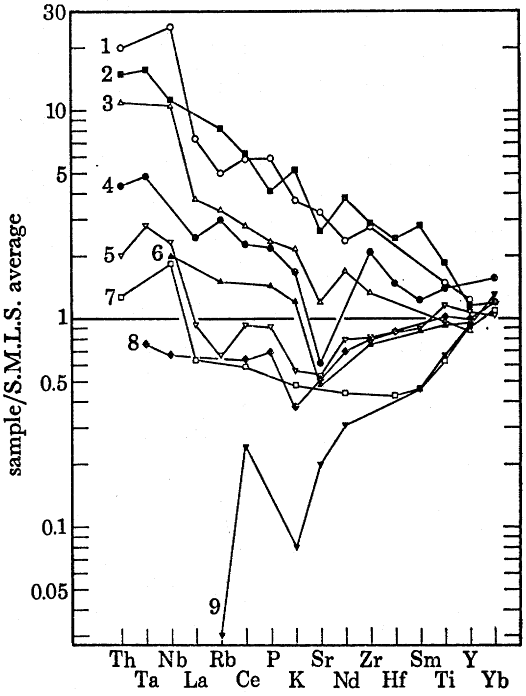

FIGURE 2. Comparison of abundances of incompatible elements in S.M.L.S. basalt and other lavas. The S.M.L.S. average (MgO = 8.41 %) to which the other lavas are normalized is the mean of the less-magnesian basalts (Thompson *et al.* 1979). MgO concentrations in the other samples range from 8.12 to 8.99 %, except for MS 144 (7.68 %). Key: 1, nephelinite (4168), New South Wales (Kesson 1973); 2, camptonite (MS 144), Dornie, Loch Duich (see text); 3, alkali olivine basalt (27417), New South Wales (Kesson 1973); 4, olivine tholeiite (72-3B), Snake River Plain (Leeman & Vitaliano 1976); 5, olivine tholeiite (V 11), eastern Iceland (Wood 1978); 6, olivine tholeiite (AJ 32), Anjouan, Comores (Flower 1973); 7, tholeiitic basalt glass (523-1 GL), FAMOUS area, Mid-Atlantic Ridge (Langmuir *et al.* 1977); 8, average of M.P.G. basalts with mean MgO (8.33 %) close to the S.M.L.S. average (this paper); 9, tholeiitic basalt glass (319-21/27-30 cm), D.S.D.P. Leg 34, Nazca Plate, eastern Pacific (Hart 1976). In addition, the following alkali olivine basalts plot along essentially the same line as no. 3 in the diagram: 0030436 (MgO = 8.79 %), Dunedin, New Zealand (Price & Chappell 1975); M 33 (MgO = 8.42 %), Madeira (Hughes & Brown 1972). A Kilauean olivine tholeiite K 10037, with MgO = 8.37 % (Gunn 1971), plots close to the S.M.L.S. average.

The magnitude of the depletion of incompatible elements in the Tertiary Hebridean basalts, relative to other alkali basalts, can be seen from inspection of figure 2. The contents of rare earths and other incompatible elements of representative world-wide samples, taken from the literature, are normalized on this diagram to their abundance in the average composition of S.M.L.S. less-magnesian basalts. Since MgO content is related linearly to the liquidus temperatures of basalts (Thompson 1973), constant values of this oxide were used as a criterion to select the other samples, so that only lavas at approximately comparable stages of fractional crystallization are plotted on figure 2. The trace elements are plotted from left to right along the abscissa in an empirical order of increasing abundance difference, relative both to the

S.M.L.S. and to each other. A logarithmic scale is employed on the ordinate to accommodate both typical mid-ocean ridge basalts and ultra-alkalic lavas on the same diagram.

The elements K, Rb and Sr show no regular behaviour, as noted by Kay & Gast (1973), Bougault *et al.* (1979) and others. In contrast, the other parts of the patterns on figure 2 are remarkably consistent. These diverse magmas appear to be buffered to approximately constant values of Y and Yb, while showing systematically increasing variability in the abundances of the progressively more incompatible elements, i.e. those with progressively lower bulk distribution coefficients between major upper-mantle minerals and basalt melt (Bougault *et al.* 1979). The patterns of many other samples superimpose on those plotted in figure 2 and are described in the legend.

The basalts with the incompatible-element abundances most similar to the S.M.L.S. on figure 2 (see also legend) are the *olivine tholeiites* from Kilauea, Anjouan (Comores), E Iceland and the FAMOUS area. In contrast, all the *alkali basalts* show progressive enrichment with increasing incompatibility in their trace-element abundances, relative to the Skye lavas. The abundances of Ta, La, P and Zr in the alkali olivine basalt from New South Wales, for example, are greater than those in the average S.M.L.S. basalt by factors of 10, 4, 2 and 1.5, respectively.

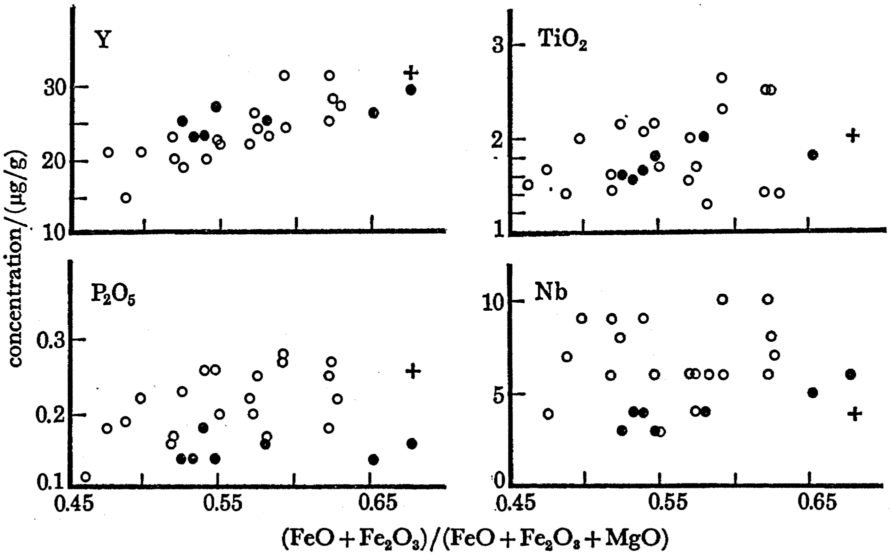

FIGURE 3. Nb, P_2O_5, TiO_2 and Y plotted against F/(F+M) for Palaeocene Hebridean basic rocks. Symbols as in figure 1.

LATERAL HETEROGENEITY IN THE PALAEOCENE UPPER MANTLE BENEATH THE SCOTTISH HEBRIDES

The pattern for the Mull basalts (a mean of samples with similar MgO to the S.M.L.S. average) lies close to that of the E Iceland lavas on figure 2 and appears to show substantial depletions of the more incompatible elements, relative to the Skye basalts. Thompson (1974) and Thompson *et al.* (1979) have published evidence that the Skye magnesian basalts were produced by variable degrees of partial melting of a spinel lherzolite at about 60 km depth, with the initial melt fraction varying by a factor of approximately 2 (in the range less than 10%) to generate the *ne*- and *hy*-normative magmas, respectively. Ti, P, Zr, Hf, Eu, Gd and Tb correlate negatively with Si saturation in the S.M.L.S. basalts, agreeing with the dilution trends that would be predicted from a partial melting model. The less incompatible elements Y and Yb show smaller concentration ranges, owing to their partial retention in upper-mantle clinopyroxene. The nearly identical Si saturation ranges in the S.M.L.S. and M.P.G. suggest that they were produced by similar degrees of partial melting.

In figure 3 selected trace elements are plotted against F/(F+M), which is the best index of fractional crystallization in these particular rocks (Thompson *et al.* 1979). This diagram takes no account of the effects of variable degrees of partial fusion on the elemental abundances. At similar values of F/(F+M), the M.P.G. show the following differences, relative to the S.M.L.S.: markedly lower abundances of the more incompatible elements such as Nb and P; slightly lower Ti abundances; similar abundances of less incompatible elements such as Y. These relations between the two groups are precisely those that would be predicted from the differences between their mean values shown on figure 2. Nevertheless, the Skye and Mull basalts do not occupy separate fields on figure 3 but overlap, with this overlap being greatest for the less incompatible elements and least for the more incompatible elements.

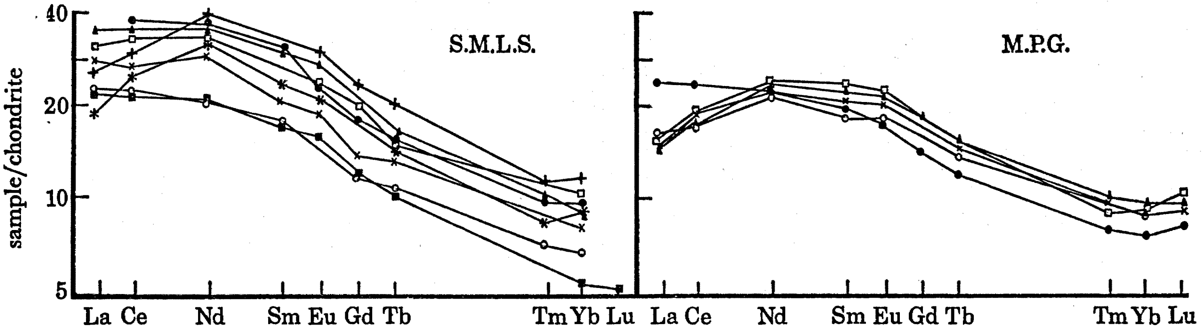

FIGURE 4. Chondrite-normalized rare-earth patterns for representative S.M.L.S. and M.P.G. basalts.

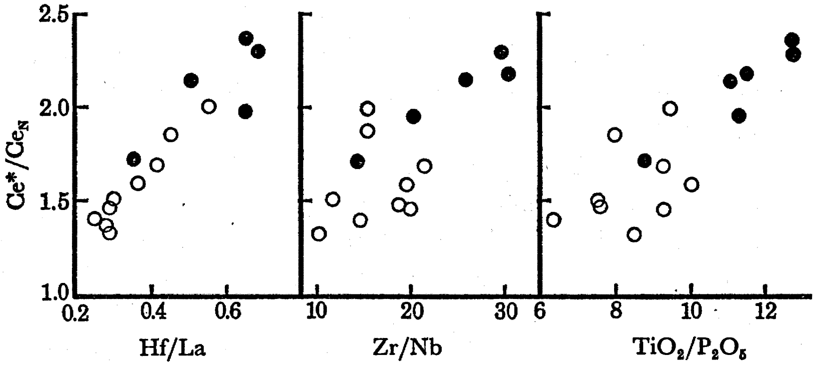

FIGURE 5. Ce^*/Ce_N plotted against Hf/La, Zr/Nb and TiO_2/P_2O_5 for S.M.L.S. and M.P.G. basalts. Symbols as in figure 1.

The chondrite-normalized rare-earth patterns for individual Skye and Mull basalts are shown in figure 4*a* and *b*, respectively. All the r.e.e. patterns are sigmoidal, to varying extents. Both the S.M.L.S. and the M.P.G. contain basalts with both relatively straight and strongly curved patterns. Most of the Skye basalts have the former type of pattern, while all but one of the M.P.G. have the latter type.

The approximately constant slopes on figure 4 of the middle r.e.e. for both basalt groups allow a straight-line projection to be made through the data to a point, designated Ce*, which is the value of Ce_N that would be expected if the patterns showed no downwards curvature at their light r.e.e. ends. Ce^*/Ce_N is therefore an index of the depletion in the l.r.e.e. relative to the m.r.e.e. We have calculated values of this ratio for all the patterns where Sm, Gd and Tb fit well to a straight line. Eu was not used because several of these basalts have small positive Eu anomalies. Figure 5 shows a plot of Ce^*/Ce_N against the ratios of other less incompatible to more incompatible elements. These parameters show moderately good positive correlations indicating that the incompatible elements were behaving coherently in all these magmas.

MS 209, the Arran crinanite, cannot be compared directly with the other basalts on figure 2 because of its lower MgO content. Reference to table 2 shows that, relative to Skye and Mull hawaiites of similar $F/(F+M)$, it is depleted in all the incompatible elements discussed here and hence *strongly* depleted in these elements, relative to other world-wide nepheline hawaiites.

To summarize, we interpret the data as demonstrating heterogeneity in the Palaeocene upper mantle beneath the Scottish Hebrides on two different scales: first, local variability beneath both Skye and Mull, on the scale of the mantle volumes involved in the production of individual magma batches; secondly, lateral heterogeneity on a larger scale between these igneous centres. The differences in abundances of incompatible elements between the S.M.L.S. and M.P.G. are of the same type as those encountered between other members of the world-wide spectrum of basic rocks (figure 2). Hence, although it is not possible to prove that this variability was not caused by some obscure metasomatic event, the fluid phase involved would have possessed relative abundances of incompatible elements typical of basic melts. This suggests that the upper mantle beneath the Hebrides achieved its pre-Palaeocene depletion in incompatible elements by the extraction of a magma or magmas.

PRE-TERTIARY HISTORY OF THE UPPER MANTLE BENEATH WESTERN SCOTLAND

The most plausible ways in which the volume of upper mantle that gave rise to the Palaeocene basaltic magmatism in western Scotland could have gained its distinctive abundances of incompatible elements are as follows:

1. Asthenosphere with the requisite geochemical characteristics, which was previously decoupled from the sub-Scotland lithosphere, may have penetrated diapirically upwards in the Palaeocene, in response to tension associated with the opening of the North Atlantic. This model seems intuitively reasonable but leads to the somewhat defeatist conclusion that depletion in incompatible elements of this mantle volume occurred by an unspecified process at some unknown place and time. Further, the increasing extent of this depletion with increasing distance from the initial rift position, noted above, is the opposite relation to that which would be predicted from published reconstructions of Cainozoic tectonomagmatic events in the North Atlantic (see, for example, Brooks 1973).

2. Mantle accreted onto the sub-Moho lithosphere during the formation of the Archaean Lewisian complex may have been thermally reactivated during the Palaeocene. The trace-element composition of this mantle would accordingly be residual from unspecified magmatic and/or metasomatic processes that took place up to 3000 Ma ago (Beckinsale *et al.* 1978). Carter *et al.* (1978) and Moorbath & Thompson (1979) have shown that the Hebridean basalts

show none of the Nd- or Sr-isotope characteristics that would be necessitated by this model. The concept of an inert Archaean lithosphere persisting beneath western Scotland until the Palaeocene ignores the complex and active Caledonian and post-Caledonian tectonomagmatic history of this region, discussed below.

3. The volume of upper mantle that produced the Palaeocene magmas may have become coupled to the sub-Scotland lithosphere during the Archaean–Cainozoic time interval, and acquired its trace-element characteristics through extraction of a melt rich in the incompatible elements. The products of the following episodes of post-Lewisian, pre-Tertiary magmatism are preserved in the geological record of western Scotland: Moine (Ross of Mull), Dalradian (SW Highlands), Arenig (Arran and Southern Uplands), Devonian (widespread, including Ross and Loch Don in Mull) and Carboniferous (predominantly in the Midland Valley rift but with dykes extending throughout the SW Highlands). Finally, Permian basaltic and lamprophyric dykes are associated with the numerous lavas and plugs of this age in SW Scotland, extending to within 30 km east of Arran. Petrographically similar dykes are quite abundant on the mainland and islands around Mull, while occurring more sparsely on and around Skye (Richey 1939, figure 5; Speight & Mitchell 1979).

If we consider the sites of Tertiary igneous activity in western Scotland in relation to the preceding Caledonian orogeny, Skye and Rhum fall just on the foreland of the Caledonian mobile belt, while Ardnamurchan, Mull and Arran are just within it. Mull and Arran have areas of greenschist-facies Dalradian schists. Greenschist-facies and amphibolite-facies Moines outcrop on Ardnamurchan and highly metamorphosed Moines occur in western Mull. The suture line of the Caledonian Iapetus Ocean may be the Highland Boundary Fault (Lambert & Mackerrow 1976). This is straddled by the Arran igneous centre, setting a Caledonian maximum age-limit to the sub-Arran upper mantle. Yet the Arran crinanite (MS 209) has abundances of incompatible elements similar to the S.M.L.S. and M.P.G. If the suture runs beneath the Solway Firth (Phillips *et al.* 1976), this is approximately 130 km southeast of Arran and 300 km from Skye. Even in this case, the sites of subsequent western Scotland Tertiary igneous activity were near to the Caledonian lithospheric plate margin, when seen on the structural scale of present-day plate boundaries.

Subduction is commonly postulated to have occurred along a northwestward inclined zone during the closure of the Iapetus Ocean (see, for example, Dewey 1971; Lambert & Mackerrow 1976; Phillips *et al.* 1976). Unless it was unusually steep, the slab must have passed beneath at least part of western Scotland. Toksöz & Bird (1977) have given detailed numerical modelling of how a subducting slab of oceanic lithosphere induces convection in the asthenospheric upper mantle within the upper-mantle wedge above the subduction zone. This convecting asthenospheric upper mantle may in turn erode and replace overlying lithospheric upper mantle, so that a back-arc basin forms. In other cases, such as the Cainozoic western U.S.A. (Scholz *et al.* 1971; Thompson 1977), a combination of flow-induced tension and conductive heating of the stretched lithosphere leads to a magmatically active, ensialic, extensional province.

The Upper Palaeozoic rift valley and alkaline volcanism of the Midland Valley of Scotland is a clear demonstration of post-Caledonian lithospheric extension. This tectonomagmatic episode died out in the Permian and was followed by quiescence during the Mesozoic. It is therefore logical to investigate the chemistry of the Permian magmatism, the last before the Palaeocene in western Scotland.

THE EILEAN DONAN CASTLE LAMPROPHYRE DYKE

The Permian dyke swarms of the Highlands and Inner Hebrides show two main trends (Richey 1939). A swarm striking NW–SE runs through the area surrounding the Tertiary outcrops of Mull and Ardnamurchan. Speight & Mitchell (1979) have shown that this swarm is so dense on southern Morvern and Lismore Island that the crustal extension associated with it amounts to 3%. A much more sparse swarm trends ENE–WSW through the Northern Highlands, Skye and Arisaig. Radiometric dates of members of this suite, summarized by Speight & Mitchell (1979), range from 288 to 235 Ma, confirming their Permian age. As very little is known about the trace-element chemistry of these dykes, a representative member of the swarm which passes through Skye was analysed for 31 elements.

This dyke 1 m wide cuts Lewisian gneiss on the roadside cliff of the A 871 at Dornie opposite Eilean Donan Castle, beside Loch Duich, about 8 km east of Skye (Grid ref. NG 884257). In thin section it closely resembles the camptonites of Lismore and Morvern (Bailey *et al.* 1924) and those south of Loch Monar (Ramsay 1955). The major-element composition of this dyke (table 1, MS 144) is very similar to those of the Loch Monar dykes (Ramsay 1955, table 1). The abundances of the rare earths and other incompatible elements in MS 144 are similar to those of world-wide nephelinites (Kay & Gast 1973).

PERMIAN–TERTIARY BASIC MAGMATISM IN WESTERN SCOTLAND

Although the sparse published data are insufficient to demonstrate that the Eilean Donan Castle dyke is representative of the whole Permian swarm, D. P. Mattey (1978, personal communication) has found similar abundances of incompatible elements in camptonite-suite dykes from the Arisaig coast and the Sleat Peninsular, Skye. It is apparent from figure 2 that this dyke is enriched in the incompatible elements in approximately the same order as the S.M.L.S. and M.P.G. basalts are depleted, relative to world-wide alkali olivine basalts.

The abundances of Nb, Ta and Th in the Eilean Donan Castle dyke support the hypothesis that the Permian and Palaeocene basic magmas of western Scotland belong to the same geochemical cycle. It may be seen from figure 2 that these elements are depleted in the S.M.L.S. by a factor of about 2–3 relative to the other incompatible elements. This results in an apparent enrichment in these elements relative to La, Rb and Ce, in the patterns of many non-Scottish rocks plotted on this diagram. Bougault *et al.* (1979) have shown that La/Ta varies little from 9 in basalts produced during the last few millions of years along the entire segment of the Mid-Atlantic Ridge from Iceland to 36°N. This ratio ranges from 14 to 43 in the S.M.L.S. averaging 31. The Eilean Donan Castle dyke shows the same relative impoverishment in Nb, Ta and Th as the S.M.L.S. basalts. Compared with other world-wide occurrences of strongly alkalic rocks with similar MgO and l.r.e.e. contents, this dyke has only about one-half its anticipated content of Nb, Ta and Th (Kay & Gast 1973; Kesson 1973). The bulk distribution coefficients of the Nb–Ta–Th and La–Rb–Ce element groups between likely major upper-mantle minerals and basaltic melt are very low (Bougault *et al.* 1979). It is therefore difficult to see how a twofold *difference* in the relative abundances of these element groups could result from any cause other than the pre-existing chemical composition of the upper mantle beneath western Scotland. We conclude that this upper-mantle relative depletion in Nb, Ta and Th was a pre-Permian feature of the western Scotland magmatic province. This distinguishes it from the upper mantle which has fed the Iceland–Azores section of the Mid-Atlantic Ridge and supports the hypothesis that the tectonic events associated with the opening of the North Atlantic were not responsible for the emplacement of depleted mantle below the Scottish Hebrides.

Kay & Gast (1973) modelled the production of r.e.e. patterns very like that of MS 144 by approximately 1% fusion of a garnet–lherzolite mantle with approximately four times chondrite abundances and chondritic relative abundances of the r.e.e., with garnet and clinopyroxene entering the melt in subequal proportions. The residual model mantle after extraction of this melt was strongly depleted in the more incompatible elements. The contrasting Zr/Nb, Hf/Ta and similar incompatible element ratios in the Permian and Palaeocene basic rocks suggest that the latter are the products of a second increment of melting from the same mantle volume that produced the former. Langmuir *et al.* (1977, fig. 6) showed that the first and second melt fractions extracted from a mantle with approximately chondritic relative abundances of the r.e.e. would have r.e.e. patterns with remarkably similar shapes to those of MS 144 and the S.M.L.S. and M.P.G. lavas, respectively. The trouble with such a model, as Langmuir *et al.* (1977) stress, is that pure incremental fusion cannot produce the observed *absolute abundances* of these elements in the Palaeocene lavas, because most of the incompatible elements would be concentrated in the first melt to be removed. Inefficient extraction of the Permian magmas, so that sufficient quantities of the incompatible elements remained to contribute to the Tertiary fusion episode, seems a reasonable postulate. It is hard enough to envisage how approximately 1% of liquid could be extracted from the mantle, let alone how it could *all* be extracted. Hence, the process we envisage is similar in principle to the dynamic melting model of Langmuir *et al.* (1977) but with two important differences:

(1) Melting was not continuous; there were only two main fusion episodes at approximately 240 and 60 Ma, respectively.

(2) During the first melting episode the ratio of extracted to retained melt was high and the residual material was therefore strongly depleted in the more incompatible elements. Slight variations in this ratio could thus give rise to the local heterogeneity indicated by the variable relative abundances of the incompatible elements in the S.M.L.S. and M.P.G. basalts.

Finally, this model also provides a satisfactory explanation of the lateral heterogeneity in the Palaeocene upper mantle, since dykes belonging to the Permian basalt–lamprophyre suite are more abundant in the region of Mull than Skye.

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Discussion

M. J. O'Hara (*Department of Geology, The University College of Wales, Aberystwyth, U.K.*). The authors have rejected the possible role of contamination in the generation of the geochemistry of the Skye Main Lava Series (S.M.L.S.). This they did largely on the grounds that the amounts of contamination required to explain the variations in major elements, specifically silica saturation, were not the same as those required to explain the variations in the Sr isotope ratios, nor did the two amounts appear to correlate in any way.

Contamination of major elements in a fractionating magma chamber proceeds differently from that of minor elements. The liquid composition is constrained to be on the cotectics defined by the precipitating phases (olivine, pyroxene, plagioclase). Perturbing the system by adding crustal material will increase the precipitation of plagioclase and orthopyroxene (possibly occult in augite). The extent of change in the *liquid* composition as measured by its silica saturation level in the CIPW norm may be small: the major element contamination is concealed in the hidden cumulates. Contamination of other elements that are less compatible with the precipitating phases (e.g. strontium) is more conspicuous in the liquid fraction and may build up to high levels while the major element contamination is retarded by the phase equilibria constraints. Variations in the cotectic liquid composition are most easily brought about by variations in the composition or amount of the primary magma feed put into the magma chamber.

There are two implications of the authors' data, if contamination did indeed play an important role in the genesis of the S.M.L.S.:

(*a*) the magma chambers in which high level fractionation occurred were small relative to the size of the cyclic inputs (e.g. they were only a few tens of times larger than the individual lava flows);

(*b*) the primary magma supplied to these chambers became more primitive with time.

Both propositions seem reasonable in this case. If this is the correct explanation I should expect to see some evidence of a positive correlation between silica saturation level and strontium isotope ratio *in successive flows from the same magma chamber*. Each time the magma chamber was 'flushed' and had to begin its evolution again, and in each different chamber, a different correlation between silica saturation level and strontium isotope ratio might result. The shotgun blast effect, which the authors have demonstrated for this correlation, may result from superposition of data from many cycles and different centres. Are the data sufficient to provide a reasonable test of this possibility?

M. Ann Morrison *et al.* Professor O'Hara's first sentence shows a misunderstanding of our position, for which our presentation must be blamed. We are convinced that interaction with continental crust was an important factor in the geochemical evolution of the S.M.L.S. and other British Tertiary Province magmas. Our continuing problem, which we share with other workers in the region, is to assess the relative importance of contamination and to deduce the mechanism by which it occurred. The processes that Professor O'Hara postulates to take place in high-level, open-system magma chambers are attractive as possible causes of the chemical diversity in the S.M.L.S. basalts. Nevertheless, various features of these lavas do not fit such a model. For instance:

(1) Although basic members of the S.M.L.S. show 4-phase cotectic points on their experimentally determined anhydrous liquidi (Thompson 1974), these occur only between about 10 kbar (less magnesian basalts) and 17 kbar (magnesian basalts). The higher pressure is approximately the same as that at which the geotherm intersects the anhydrous peridotite solidus beneath regions of current ensialic basaltic volcanism, such as the western U.S.A.

(2) Some of the Hebridean Tertiary magnesian basalts have both Sr and Nd isotopic ratios the same as those of basalts from ocean basins (Carter *et al.* 1978). There is therefore no *isotopic* evidence to support a hypothesis that these particular magma batches were contaminated by continental crust.

(3) The compositional pattern of consecutive flows in the *upper* part of the exposed lava pile remnant suggests that large, long-lived magma chambers were not a feature of the magmatic plumbing beneath northern Skye (Thompson *et al.* 1972, p. 247).

In the *lower* part of the lava succession in NW Skye there is a large-scale eruptive sequence: basalt–hawaiite–time gap–basalt–hawaiite (Thompson 1974, fig. 2) which, at first sight, seems to be in excellent accord with Professor O'Hara's model. Moorbath & Thompson (1979) have determined initial $^{87}Sr/^{86}Sr$ in five samples (three basalts overlain by two hawaiites) from a stratigraphic section through the lower half of this sequence (the Beinn Edra Group). The results, in upward order of flows, are: sample 925, $(^{87}Sr/^{86}Sr)_i = 0.70414$; 928, 0.70385; 929, 0.70380; 931, 0.70325; 934, 0.70318. The progressive fall in $(^{87}Sr/^{86}Sr)_i$ with time is the opposite from the trend that would be predicted by using Professor O'Hara's model. There is also no correlation between $(^{87}Sr/^{86}Sr)_i$ and silica saturation in these five lavas.

Moorbath & Thompson (1979) find that the only parameter in the S.M.L.S. that correlates reasonably well with $(^{87}Sr/^{86}Sr)_i$ in members of the basalt–benmoreite suite is total Sr content. As both experimental (Thompson 1974) and geochemical (Thompson *et al.* 1979) models show that these magmas evolved to their pre-eruptive compositions in the ^{87}Sr-poor deep crust or uppermost mantle, Moorbath & Thompson (1979) deduce that the $(^{87}Sr/^{86}Sr)_i$ range found in these lavas results largely from rapid isotopic equilibration between magmas of the S.M.L.S. basalt–benmoreite suite and ^{87}Sr-rich upper crust, during the uprise of the liquids from their site of differentiation to the surface.

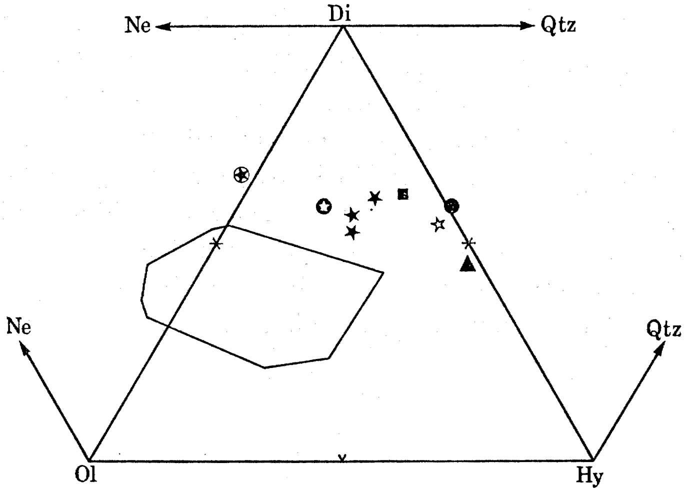
R. J. PANKHURST (*British Antarctic Survey, c/o I.G.S.,* 64/78 *Gray's Inn Road, London, U.K.*).Two recent publications have claimed that the low levels of lithophile elements in some Tertiary volcanics from the Hebrides was due to derivation from a depleted source region and this is verified by unpublished rare earth element data. Did the authors still wish to ascribe low-K contents to residual phlogopite in the mantle?

The authors appear to have ignored published evidence for vertical heterogeneity in the Tertiary Hebridean mantle (Beckinsale, Pankhurst, Skelhorn & Walsh 1978 *Contr. Miner. Petr.* **66**, 415–427). By using major element, trace element and Sr-isotope geochemistry on the same suite of samples it was shown that the relatively more alkaline volcanics of Mull were derived by variable degrees of partial melting of 'depleted' garnet peridotite and have low initial $^{87}Sr/^{86}Sr$ ratios which plot to the left of the Geochron. A second group of hypersthene-normative basalts, evolving to trachytes, have relatively undepleted trace element abundances and initial $^{87}Sr/^{86}Sr$ ratios close to 0.7055, although even in this group the basalts plot to the left of the Geochron. This was thought to indicate a more enriched, high-level mantle source. A few chemically distinct basalts showed intermediate trace element and isotope characteristics, but no evidence for crustal contamination was found. If the two sources formed by chemical fractionation of originally homogeneous parent material, the isotope systematics suggested that this must have occurred much earlier than the Permian volcanicity referred to in the present paper.

The group I and group II Mull volcanics appear to match the two major components of the Skye Main Lava Series in terms of major element chemistry. Could any such systematic division of the latter be made, e.g. on the basis of Sr/Ba or Ce/Yb ratios, and if not, could the authors offer any suggestions to explain the different chemical behaviour of volcanics from the two areas?

M. ANN MORRISON *et al.* We thank Dr Pankhurst for the summary of his recent paper. This deals exclusively with postulated *vertical* Palaeocene mantle inhomogeneity beneath Mull, based on chemical comparison of the lowest and second-lowest flows at two localities in SW Mull (Beckinsale *et al.* 1978, group II) and 14 flows higher in the lava pile in various parts of Mull and Morvern (Beckinsale *et al.* 1978, groups I and III). As emphasized in our paper, we base our assessment of *lateral* Palaeocene upper-mantle variation between Mull and Skye upon chemical comparison of the first *major* basic lava groups in each area, the Skye Main Lava Series and Mull Plateau Group.

Dr Pankhurst reiterates the claim of Beckinsale *et al.* (1978) that their group I and II basalts are the chemical equivalents on Mull of the *ne*- and *hy*-normative sub-divisions, respectively, of the S.M.L.S. basalts. This is incorrect. Both groups I and III of the classification of Mull basalts proposed by Beckinsale *et al.* fall within the overall major-element range of the S.M.L.S. basalts. Nevertheless, there are subtle trace-element differences between the S.M.L.S. and M.P.G. basalts, as detailed in our present paper. The basalt and basaltic-hawaiites in group II of Beckinsale *et al.* are *substantially* different in both petrography and chemical composition from any basic members of the S.M.L.S. This point is illustrated in figure 6.



percentage by mass

FIGURE 6. Normative diopside–hypersthene–olivine–nepheline/quartz in basic lavas and pyroclastics from Mull and Skye. All the norms were calculated with Fe_2O_3 set at 1.5%. M.P.G. and S.M.L.S. basalts fall within the outlined field. Key to symbols: filled stars, Mull Group II lavas of Beckinsale *et al.* (1978); open star, Macculloch's Tree flow, Mull (Morrison, unpublished); circled filled star, Fingal's Cave flow, Staffa (Tilley & Muir 1962); circled open star, Fingal's Cave flow (Morrison, unpublished); filled circle, glass separated from basal tuff, NW Skye (Anderson & Dunham 1966); filled square, basal pillow lava, NW Skye (Anderson & Dunham 1966); filled triangle, basal pillow lava (SK 965), NW Skye (Thompson *et al.* 1979).

Bailey *et al.* (1924) emphasized the petrological differences between the Ardtun and Macculloch's Tree lavas of SW Mull (group II of Beckinsale *et al.*) and the bulk of the M.P.G. basalts. As Beckinsale *et al.* give no systematic petrographic account of the samples that they have studied, we consider it important to stress to those unfamiliar with this area that augite is a major phenocryst phase in the Macculloch's Tree and lower Ardtun flows, as might be expected from their compositions (figure 6). In contrast, other authors throughout the last half century (e.g. Bailey *et al.* 1924; Anderson & Dunham 1966; Thompson *et al.* 1972) have emphasized the petrographic and experimental evidence that augite is not a near-liquidus phenocryst phase in the S.M.L.S. or M.P.G. basalts.

Hyaloclastites (some of them augite-phyric) and pillow lavas at the base of the volcanic pile in NW Skye have major-element compositions (figure 6) that closely resemble those of the Macculloch's Tree and Ardtun flows, as clearly shown by Anderson & Dunham (1966).

Taking them as a whole, the three most notable features of these distinctive local basal eruptives in Mull and Skye appear to be (1) their volumetric insignificance among the products of extrusive magmatism at these centres, (2) their eruption only at the outset of the volcanic activity and (3) their normative *di*-rich compositions, relative to the S.M.L.S. and M.P.G. basalts. It is apparent from figure 6 that these *di*-rich rocks have a wide range of silica saturation, which explains the disagreement between Bailey *et al.* (1924) and Tilley & Muir (1962) as to how they should be classified. The most Si-saturated compositions plot in the same part of figure 6 as published analyses of the Mull Non-Porphyritic Central magma type.

The petrography and major-element compositions of these basal volcanics suggest that they approach *low-pressure* olivine–plagioclase–augite–liquid cotectic equilibria in the natural basalt system. In contrast, the compositions of the S.M.L.S. and M.P.G. basalts are related to high-pressure (not less than 10 kbar) olivine–two pyroxene–liquid and olivine–plagioclase–aluminous augite–liquid cotectics (Thompson 1974). The ranges of most minor elements in the basal volcanics are largely, but not completely, co-extensive with those in the S.M.L.S. and M.P.G. basalts. Nevertheless, the abundances of K, Rb and Ba, and the $^{87}Sr/^{86}Sr$ ratios, distinguish the two magma types; all are higher in most samples of these *di*-rich volcanics than in the S.M.L.S./M.P.G. basalts (Morrison 1978, and unpublished; Beckinsale *et al.* 1978; Moorbath & Thompson 1979; Thompson *et al.* 1979). We suspect that it may not be a coincidence that batches of basic magma that had stagnated during their uprise within the K, Rb and Ba-rich, high-$^{87}Sr/^{86}Sr$ environment of the amphibolite-facies Lewisian gneisses (or Moine schists or Torridonian sediments), forming the upper crust beneath Mull and Skye, have higher values of all these parameters than subsequent magmas that had erupted after rapid uprise from the base of the crust.