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Crustal contamination and the granite problem in the British Tertiary Volcanic Province

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Isotopic studies on the British Tertiary Volcanic Province have shown that the granites contain both mantle-derived and crustal components, while basic rocks display pronounced crustal contamination. In order to study contamination mechanisms in greater detail, isotopic and chemical variations in Skye plateau lavas and Cuillins Complex intrusive units were examined as a function of time. In both cases degrees of crustal contamination generally fall with time, which, it is argued, reflects the progressive melting and 'sweating out' of Lewisian acid gneissic sheets from the more refractory intermediate basement during repeated intrusion and contamination of sheet-like magma reservoirs. Long lived developing magma chambers do not fit the data well. Skye granites had basic precursors that suffered similar types of contamination in the lower crust, but tended to form longer lived developing magma chambers in the upper crust. Nevertheless, Skye granites display similar crustal Pb contents to associated basic intrusions, and are argued not to be the products of crustal anatexis, but the differentiates of Preshal Mhor basic magmas contaminated by *ca.* 10% with large degree partial melts of Lewisian acid gneisses.

Introduction

Magmatism in the British Tertiary Volcanic Province (B.T.V.P.) was triggered by high tensional stress in the lithosphere of NW Britain, associated with the opening of the N Atlantic. In the resulting régime of extensional tectonics, sheet-like intrusions were particularly favoured (Vann 1978; Weertman 1971). Although the estimated volume of granitic intrusions in the British Tertiary is very small (*ca.* 500 km^3: Richey 1961; Gass & Thorpe 1976), the volume of basic intrusions is comparatively large, totalling an estimated 50000 km^3 in the province as a whole (McQuillin & Tuson 1963; McQuillin *et al.* 1975; Riddihough & Max 1976; Chalmers & Western 1979). The emplacement of large magma volumes into a small crustal section and a tendency to form sheet intrusions with large surface area together yield ideal conditions for strong magma-crust interaction in the B.T.V.P.

The intrusive centres of the B.T.V.P. were emplaced into continental crust of variable age and composition (figure 1). The simplest crustal structure is found in the Skye centre, which lies to the west of the Moine thrust, where a *ca.* 2700 Ma-old Lewisian foreland is either exposed at the surface or overlain by only a relatively thin sedimentary cover. Geophysical measurements in NW Scotland (Hall & Al-Haddad 1976; Hall 1978) show that Lewisian granulite-facies gneiss has markedly higher P-wave velocities than amphibolite-facies gneiss. On the basis of the L.I.S.P.B. profile (Bamford *et al.* 1977) we argue that the basement under the Isle of Skye consists of granulite-facies lower crust and amphibolite-facies upper crust. The original

Lewisian supracrustals have all been removed by erosion. The simplicity of its crustal structure makes the Skye centre an ideal subject for a study of crustal contamination of B.T.V.P. magmas. Further south, crustal structure becomes more complex, and the results of magma crust interaction more difficult to interpret.

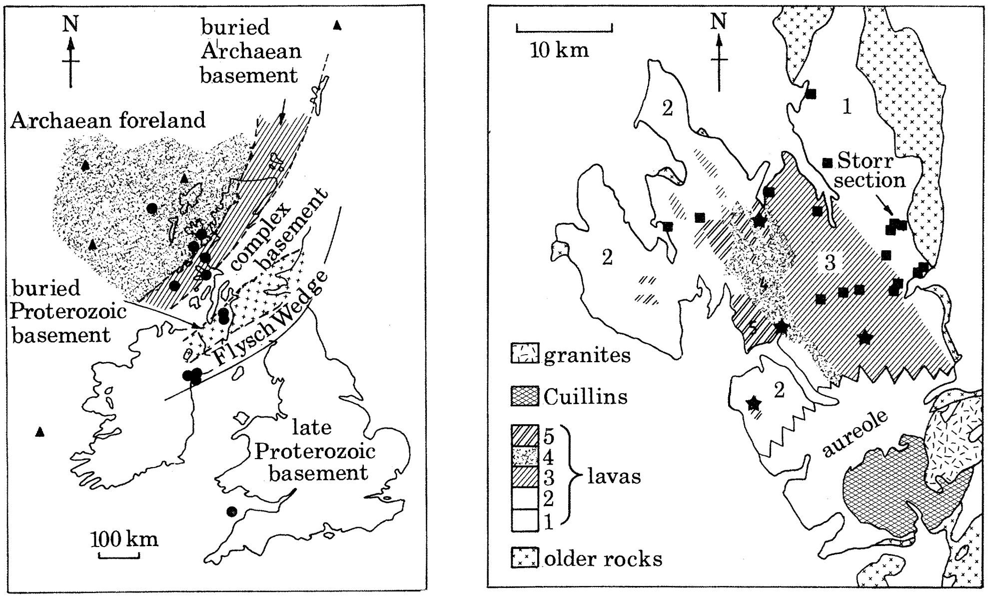


FIGURE 1. (*a*) Map of the British Isles showing exposed (●) and geophysically determined (▲) intrusive centres in the British Tertiary province emplaced into crustal blocks of different ages. (*b*) Map of the Isle of Skye showing intrusive complexes and lava groups. ★: Low-Fe intermediate lava localities; ■: other lava localities.

HYDROTHERMAL ALTERATION

The British Tertiary province was one of the first to receive detailed petrographic attention (see, for example, Harker 1904) but earned an early reputation for severe alteration (see, for example, Bailey *et al.* 1924; Daly 1933; Tilley & Muir 1962) which dissuaded detailed geochemical study until the 1970s. This reputation was compounded by the discovery of massive oxygen isotope exchange between rocks and meteoric-hydrothermal fluids in the central complexes of Skye, Mull and Ardnamurchan, with the suggestion that trace element abundances and hence Pb and Sr isotope ratios could also have been upset by hydrothermal metamorphism (Taylor & Forester 1971). All subsequent geochemical work has had to consider these problems (see, for example, Ridley 1973) but work on the lavas by Thompson *et al.* (1972), Hawkesworth & Morrison (1978), and Moorbath & Thompson (1980), and on the granites by Pankhurst *et al.* (1978) and Dickin *et al.* (1980) has shown that the effects of hydrothermal alteration can be avoided if samples are carefully collected. We can therefore continue with confidence to draw petrogenetic conclusions on the basis of elemental and isotopic data in the B.T.V.P.

THE GRANITE PROBLEM

Hypotheses for the origin of B.T.V.P. granites have tended to polarize between crustal melting and basaltic differentiation models. The discovery of the Glen More ring dyke in Mull (Bailey *et al.* 1924), apparently showing *in situ* differentiation from olivine-bearing quartz gabbro to granophyre, influenced opinion towards the 'basaltic-differentiation' model for a quarter of a century. Wager (1956) raised the crustal melting alternative, and this was most popular in the 1960s (see, for example, Brown & Rushton 1960; Brown 1963; Wager *et al.* 1965; Moorbath & Bell 1965; Bell 1966; Thompson 1969). More recently, the basaltic differentiation model has been emphasized (see, for example, Beckinsale *et al.* 1974; Thorpe *et al.* 1977; Thorpe 1978; Meighan 1979). This work has been reviewed by Bell (1976), Gass & Thorpe (1976) and Thompson (1982*a*).

The most crucial realization of recent years has been that *both* basaltic differentiation *and* crustal melting played a role in the genesis of most B.T.V.P. granites. This model was first proposed in detail by Moorbath & Welke (1969), who showed that the Pb isotope compositions of both acid *and* basic Tertiary igneous rocks from Skye lay on a Pb/Pb mixing line between 60 Ma-old mantle and *ca.* 3 Ga-old Lewisian crust. Moorbath & Welke were able to calculate the percentages of Pb in each rock of crustal and mantle origin, and found a range of 22–65% crustal Pb in the basic-to-intermediate lavas and 35–77% crustal Pb in the granites. The comparison between acid and basic rocks was crucial. By demonstrating the presence of a large crustal Pb component in basic rocks which were 'indubitably derived from upper mantle source regions' they showed that granites with a similar range of crustal Pb contents could be derived from basic magma by 'progressive contamination with substantial proportions of unradiogenic Pb and radiogenic Sr during differentiation...', noting that 'on a large scale' complete melting of small pockets of country rock 'still amounts to partial fusion'.

Mantle heterogeneity

One model that has arisen since Moorbath & Welke's study is the 'mantle isochron' interpretation of isotopic data from continental regions (Brooks *et al.* 1976), in which correlations between initial $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ in continental basic-to-intermediate rocks are interpreted as dating mantle differentiation events. Since then, many of the distinctive isotopic and chemical characteristics of continental magmas have been attributed to the 'special' properties of continental lithosphere. Therefore, just as post-crystallization alteration must be considered before petrogenetic interpretation begins, so the effect of mantle heterogeneity on isotope systematics must be examined before the data are used to study magma–crust interaction.

Carter *et al.* (1978) showed that Rb/Sr and Sm/Nd pseudo-isochron diagrams for Hebridean rocks yield sharply contradictory apparent ages (or 'erupted isochrons'). They argued that these pseudo-isochrons were generated by crustal contamination, and did not date mantle differentiation events in the continental lithosphere. Moorbath & Thompson (1980) presented a larger set of Sr isotope data on basic-to-intermediate B.T.V.P. rocks, and showed that for lavas which were primary, or had fractionated olivine alone, there was no recognizable correlation between initial $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$. Where such correlations *have* been observed the sample suite has usually included rocks which have fractionated plagioclase (see, for example, Pankhurst 1977; Beckinsale *et al.* 1978; Dickin *et al.* 1981). Moorbath & Thompson did however observe a weak correlation between initial $^{87}Sr/^{86}Sr$ and Sr content in the Skye lavas, which they ascribed to a process of crustal contamination acting on magmas with variable Sr contents *after* differentiation. This provided evidence against the view that isotopic heterogeneity was principally inherited from the mantle source. Additional evidence was obtained by Thirlwall & Jones (1983), who found a good correlation between ϵ_{Nd} and molar

FeO/(FeO + MgO) in the more primitive Skye lavas. They argued that since 'very few basalts have F/M appropriate for magmas in equilibrium with mantle olivine, the F/M variation must be produced by fractional crystallization in or near the crust', and hence that the ϵ_{Nd} against F/M correlation must also have been produced in the crust, by contamination. It is therefore concluded that the small degree of isotopic heterogeneity that may have been inherited from the mantle by the Tertiary magmas was far exceeded by the overwhelming influence of the continental crust.

Crustal contamination

Before quantitative conclusions can be drawn about the relative contributions of crustal and mantle-derived material to B.T.V.P. granites, it is necessary to consider mechanisms of crustal contamination of basic magmas.

Dickin (1981) was able to resolve the relative fractions of Pb from mantle-derived magmas, Lewisian granulite-facies gneiss, and Lewisian amphibolite-facies gneiss in Skye Tertiary igneous rocks, on the basis of compositions in the $^{208}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ diagram, and compared these fractions in the lavas and granites. However, this led to the question of whether these fractions represented the bulk rock, or whether Pb and other isotope ratios could be *selectively* modified by crustal contamination. Dickin (1981) argued that the fusible upper crust had contributed a melt fraction to the Skye Redhills granites, but that basic magma precursors to both the Skye lavas *and* granites had been contaminated in the refractory lower crust by a large-ion-lithophile-enriched fluid phase released by the breakdown of minor amounts of hydrous and sulphide minerals. This model was based on the observation of Patchett (1980) that hydrous mineral breakdown curves in the crust were at comparable temperatures with the H_2O-saturated tonalite solidus.

Thompson (1983) has since shown that the intermediate gneisses which form the bulk of the granulite-facies terrain of NW Scotland do indeed have high solidus temperatures (greater than 750 °C), but 2700 Ma acid minor intrusions within the granulite-facies terrain have much lower melting temperatures, and their melting interval may be so narrow that the *liquidus* is almost reached before the intermediate gneiss solidus. Thompson *et al.* (1982) proposed that partial melting of these minor intrusions (e.g. '7H', Weaver & Tarney 1980, 1981) and their addition in the proportions of 10% melt to 90% Tertiary basic magma, could explain the incompatible element ('spidergram') patterns of lavas whose initial $^{87}Sr/^{86}Sr$ ratios are indicative of crustal contamination.

Thirlwall & Jones (1983) have challenged this interpretation on the basis of the pattern defined by Skye lavas on the ϵ_{Nd} against Sm/Nd diagram. Skye Main Lava Series (S.M.L.S.) basalts vary strongly in ϵ_{Nd} (from +9 to −10), but only decrease slightly in $^{147}Sm/^{144}Nd$ ratios over this range. Extrapolating this array to an intersection on the Lewisian crustal isochron indicated a contaminant with an average ϵ_{Nd} value of −15 and $^{147}Sm/^{144}Nd$ around 0.15, 'a typical value from intermediate Lewisian gneisses' (Thirlwall & Jones 1983). This is far more radiogenic than that of 7H ($\epsilon_{Nd} = -42$, calculated from $^{147}Sm/^{144}Nd$ of 0.075; Weaver & Tarney 1980).

The contamination model of Thirlwall & Jones (1983) for S.M.L.S. lavas requires the uncontaminated precursors of analysed S.M.L.S. basalts to have had Nd contents of 4.7–26 μg/g (Thompson *et al.* 1980), overlapping the range of Nd contents in the later Preshal Mhor Basalt

(P.M.B.) lavas (5.4–6.5 μg/g), but a restricted range of ^{147}Sm/^{144}Nd ratios near 0.150, much less than the range for P.M.B. lavas (0.225–0.245; Thompson *et al.* 1980). This raises a severe problem when Sm contents are considered, since Thirlwall & Jones's model requires the precursors of S.M.L.S. lavas to have had as little as 1.2 μg/g Sm, while P.M.B. lavas, themselves depleted in the refractory incompatible elements Hf, Zr, Ta and Nb relative to the S.M.L.S., average 2.7 μg/g Sm (Thompson *et al.* 1980), and even the most incompatible-element-depleted m.o.r.b. glass of Cohen *et al.* (1980) has 1.8 μg/g Sm.

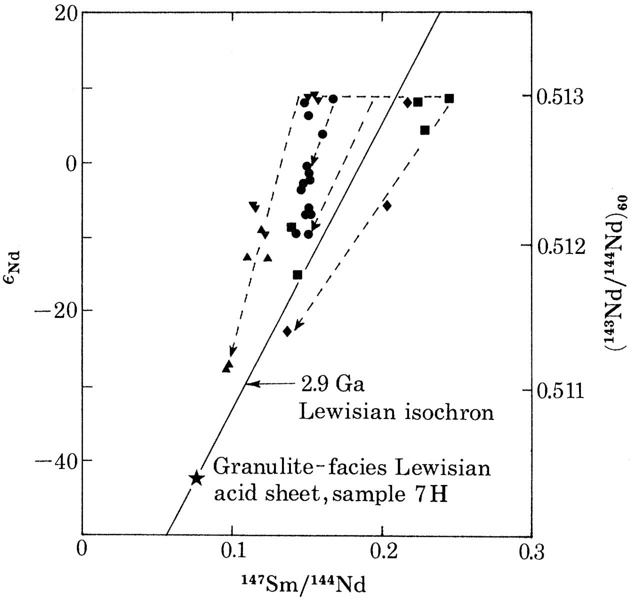


FIGURE 2. Plot of ϵ_{Nd} against ^{147}Sm/^{144}Nd based on Thirlwall & Jones (1983). ●: S.M.L.S. basalts; ▼: S.M.L.S. hawaiites to benmorites; ▲: S.M.L.S. low-Fe intermediates; ■: P.M.B.; ◆: P.M.B., Cuillins.

An alternative interpretation of the Nd isotope data (figure 2) is to assume that S.M.L.S. magmas, with a range of ^{147}Sm/^{144}Nd ratios from 0.15 to 0.20, and P.M.B. magmas, with ^{147}Sm/^{144}Nd up to 0.25, were all contaminated with crustal Nd of approximate composition $\epsilon_{Nd} = -40$. This model has the advantage that it is able to explain the compositions of differentiated high-Fe S.M.L.S. lavas (e.g. SK 914), low-Fe intermediate S.M.L.S. lavas (e.g. SK 942), and Cuillins P.M.B. type units (e.g. LR 31, $\epsilon_{Nd} = -22.6$), as well as the composition of S.M.L.S. basalts. For this model to form the 'secondary array' of S.M.L.S. basalt compositions observed by Thirlwall & Jones (1983), a regular and predictable contamination mechanism is required, in which the precursors with highest ^{147}Sm/^{144}Nd ratios (i.e. the most primitive magmas with lowest r.e.e.–profile slope) became the most contaminated, while the more (r.e.e.) fractionated magmas suffered less contamination. Just such a process is demonstrated by the good correlation of F/(F + M) against ϵ_{Nd} in these lavas (Thirlwall & Jones 1983, figure 5). This model requires S.M.L.S. basalt precursors to have had 10–22 μg/g Nd, and hence *ca.* 3.3–6.4 μg/g Sm, significantly greater than the more primitive P.M.B. lavas, and consistent with their abundances of other incompatible elements.

We therefore argue that Nd isotope data supports the model of Thompson *et al.* (1982) for contamination of Skye magmas by acid minor intrusions such as '7H', rather than intermediate gneisses which make up the bulk of Lewisian crust. In the remainder of this paper we shall explore an additional line of evidence in distinguishing between contamination models for basic magmas, and subsequently draw quantitative conclusions about the size of crustal contribution to the Redhills granites.

Dimensions of space and time in contamination

Thompson (1983) noted that 'if a basic magma reservoir within sialic crust is comparatively large and approximates in shape to a sphere or cylinder, and if the magma within it is convecting and undergoing fractional crystallization, then the magma will have the thermal ability to melt and assimilate its wall rocks with little regard for their composition (Ahern *et al.* 1981) – especially if the magma chamber is a long-lived and open system type (O'Hara & Matthews 1981).' In these circumstances we would expect contamination to be due to partial melting of the relatively refractory intermediate gneisses which make up the bulk of the Lewisian complex (Thirlwall & Jones 1983).

However if the magma reservoir in the crust is 'no more than the aggregate volume of innumerable dykes and sills' then only limited amounts of heat will be available to melt the wall rocks of each minor intrusion (Patchett 1980). In this situation we would expect crustal contaminants to be 'strongly biased towards the compositions of the most easily fusible rock types' (Thompson 1983), as modelled by Thompson *et al.* (1982).

O'Hara (1973, 1975, 1977, 1980*a*) and O'Hara & Matthews (1981) have argued the importance of 'advancing, periodically replenished, periodically tapped, continuously fractionated' long lived magma chambers in controlling the composition of erupted products, and have attempted to determine the likely behaviour of such systems. In a discussion on B.T.V.P. magmatism (Morrison *et al.* 1980), O'Hara (1980*b*) predicted that 'successive flows from the same magma chamber' under his model, would show 'evidence of a positive correlation between silica saturation level and strontium isotope ratio.'

In contrast, Patchett (1980) argued that the most favourable situation for contamination of basic sheet intrusions was where small magma pulses followed each other at intervals through the same zone of crust, so that 'new batches of magma will intrude through the heated, mechanically weakened crust adjacent to earlier largely solidified conduits and assimilate any partial melts or hot fluids that are present.' If these melts were derived from fusible leucogneiss sheets scattered through the Lewisian basement, then successive basic magma pulses would progressively sweat out the low-melting phases from a large zone of crust, leaving a refractory residuum of intermediate gneisses.

The two different models of magma chambers described above therefore make predictions about the expected variation of crustal contamination of erupted products with time. The advancing, continuously fractionated magma reservoir should yield products showing progressive increases in differentiation and contamination with time, while the intrusive plexus magma reservoir should yield products showing relatively constant degrees of differentiation, and erratic but progressively *decreasing* degrees of contamination with time. These predictions can now be tested against the natural system by examining the variation of isotope ratios and elemental contents of erupted products with time. Hence we may attempt to deduce the geometry of reservoirs involved in the Skye magmatic plumbing system, and thus the mechanisms of crustal contamination occurring in these reservoirs.

Storr lava section

From published isotopic data (Dickin 1981), the relative fractions of Pb from the mantle, lower crustal granulite-facies Lewisian, and upper crustal amphibolite-facies Lewisian gneiss in Skye lavas are plotted as a stratigraphic section (figure 3), in an attempt to identify variations

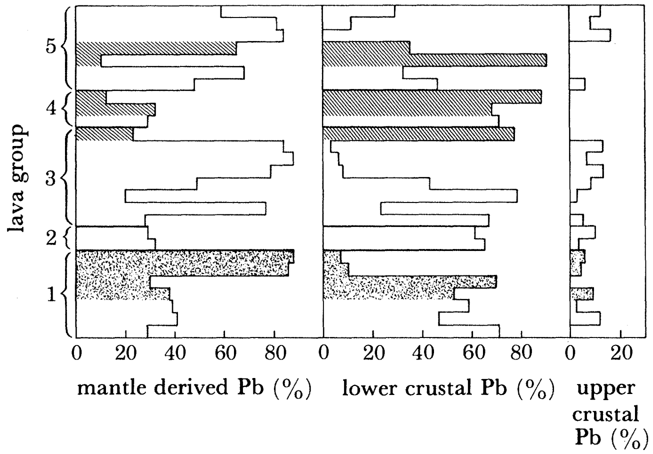


Figure 3. Profiles of the percentage contribution of total Pb from three sources in Skye lavas, against estimated stratigraphic succession in the lava pile. Stipple denotes Storr section lavas; cross hatch: low-Fe intermediate lavas. Lava groups 1–5 are as in figure 1.

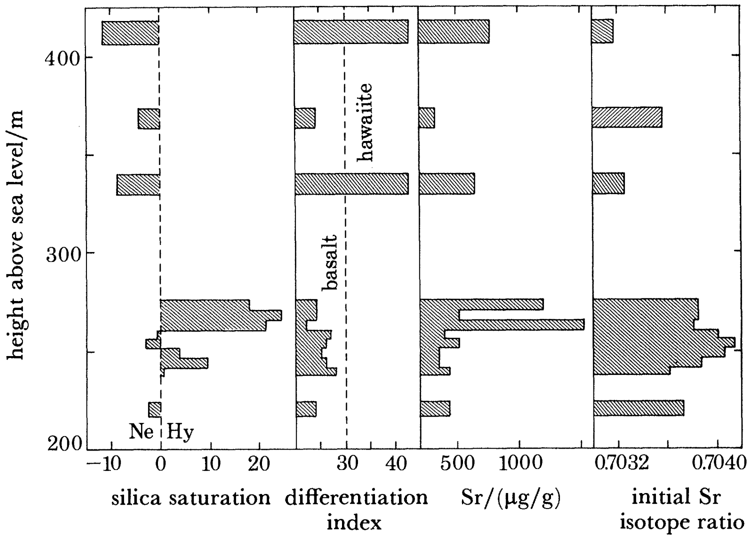


Figure 4. Profiles of C.I.P.W. normative silica saturation (Thompson *et al.* 1972), Thornton–Tuttle differentiation index, Sr content, and initial Sr isotope ratio, against height above sea level for Storr section lavas. Gaps are areas of no exposure or severe alteration.

of contamination with time through the whole thickness of the lava pile. The observed variations are unfortunately too erratic to interpret, partly due to the paucity of isotopic data through such a large section, and partly due to the complex structure of the lava pile, in which flows from different vents, each erupting intermittently, give rise to a series of interdigitating flows of widely varying character (Anderson & Dunham 1966). The latter feature is illustrated by the

Table 1. Storr section data

flow no.	1	2	3	4	5	6	7	8	9	10	11	12
sample	SK921	SK922	SK923	SK924	SK925	SK926	SK927	SK928	SK929	SK931	SK932	SK934
height/m	226	241	245	250	255	259	264	268	274	335	369	412
SiO_2	45.05	45.88	46.14	45.68	45.19	46.34	45.39	46.73	46.83	46.86	44.89	47.94
TiO_2	2.15	1.99	1.83	1.95	2.03	1.90	1.90	1.60	1.44	3.34	2.05	2.23
Al_2O_3	14.01	13.80	14.77	14.02	13.51	14.55	14.48	14.59	14.90	15.68	16.04	17.07
Fe_2O_3†	13.94	13.10	12.76	13.20	13.32	13.65	12.75	12.00	11.67	15.19	14.76	14.28
MnO	0.20	0.17	0.18	0.19	0.16	0.22	0.19	0.17	0.16	0.20	0.21	0.20
MgO	11.47	9.58	9.85	11.52	12.27	9.78	10.55	10.16	9.86	4.31	9.97	4.57
CaO	9.04	8.73	8.81	8.52	8.30	9.11	8.81	9.06	9.63	6.66	9.29	6.56
Na_2O	2.70	2.96	2.72	2.66	2.89	2.84	2.29	2.53	2.92	4.75	2.81	4.91
K_2O	0.35	0.53	0.53	0.47	0.37	0.57	0.48	0.38	0.44	0.77	0.22	0.77
P_2O_5	0.23	0.23	0.20	0.22	0.22	0.25	0.21	0.16	0.17	0.47	0.20	0.37
F/(F+M)‡	0.525	0.556	0.541	0.511	0.497	0.560	0.524	0.519	0.519	0.761	0.574	0.741
Si sat.§	2.6ne	0.8hy	9.8hy	3.9hy	2.7ne	0.5ne	21.5hy	24.5hy	17.9hy	8.7ne	4.5ne	11.5ne
T.T.D.I.‖	24	28	26	25	26	27	22	24	24	43	24	43
Ba	145	190	287	183	170	210	287	157	235	147	50	200
Be	1.2	1.4	1.3	1.4	1.1	1.3	1.2	1.1	1.0	1.8	1.0	2.1
Cr	428	—	316	498	576	464	496	544	321	nf	67	17
Hf	3.40	3.52	3.73	3.68	3.27	4.82	3.28	2.48	2.78	6.67	3.74	8.15
Nb	8	7	—	5	9	—	—	6	9	15	6	20
Ni	378	—	252	342	317	286	283	300	195	nf	176	14
Rb	1	10	7	6	4.4	7	5	3.8	5.4	13	3	18
Sr	443	453	346	348	532	386	1528	501	1196	645	332	783
Ta	0.43	0.28	0.36	0.40	0.42	0.60	0.36	0.20	0.29	0.86	0.31	1.03
Th	0.87	0.82	0.92	0.87	0.81	1.15	0.73	0.36	0.53	1.15	0.55	1.37
Y	19	21	—	20	21	—	—	23	20	40	26	45
Zr	134	142	—	138	125	—	—	123	100	253	133	311
La	—	10.0	10.9	13.6	—	13.0	10.5	7.0	9.5	—	—	22.5
Ce	25.9	25.0	25.5	30.4	27.0	41.1	25.7	18.0	22.7	42.0	20.7	52.3
Nd	19.6	16.6	18.7	20.2	19.1	27.4	17.8	12.9	18.6	33.0	17.0	41.4
Sm	7.7	4.7	5.0	5.1	—	7.1	4.7	3.4	4.3	8.2	—	10.4
Eu	1.71	1.66	1.80	1.85	1.65	2.57	1.71	1.21	1.47	3.14	1.85	3.55
Gd	5.5	4.5	5.1	5.7	5.4	6.6	4.6	3.3	3.3	8.9	6.5	8.4
Tb	0.72	0.71	0.75	0.73	0.70	1.02	0.65	0.52	0.63	1.30	0.86	1.44
Tm	0.19	—	—	—	0.26	—	—	—	0.27	0.50	0.28	0.64
Yb	1.39	1.59	1.67	1.47	1.53	2.28	1.42	1.20	1.51	3.04	2.24	2.88
Lu	0.30	0.23	0.27	0.27	0.30	0.26	0.26	0.18	—	0.44	0.36	—
$(^{87}Sr/^{86}Sr)_{60}$	0.70373	0.70360	0.70387	0.70405	0.70414	0.70401	0.70381	0.70385	0.70385	0.70325	0.70356	0.70318

(†, Total Fe as Fe_2O_3. ‡, $Fe_2O_3/(Fe_2O_3+MgO)$. §, Silica saturation = C.I.P.W. ne/hy (Thompson *et al.* 1972). ‖, Thornton–Tuttle Differentiation Index. n.f.: not found —: not determined.

distribution of low-Fe intermediate lavas (Thompson *et al.* 1972), which have a distinctive, well characterized chemistry suggestive of a close genetic relation, yet were erupted in three different structural groups in the upper part of the lava pile (figure 3). To avoid these problems it is necessary to look in detail at a shorter stratigraphic section in a relatively isolated part of the lava pile.

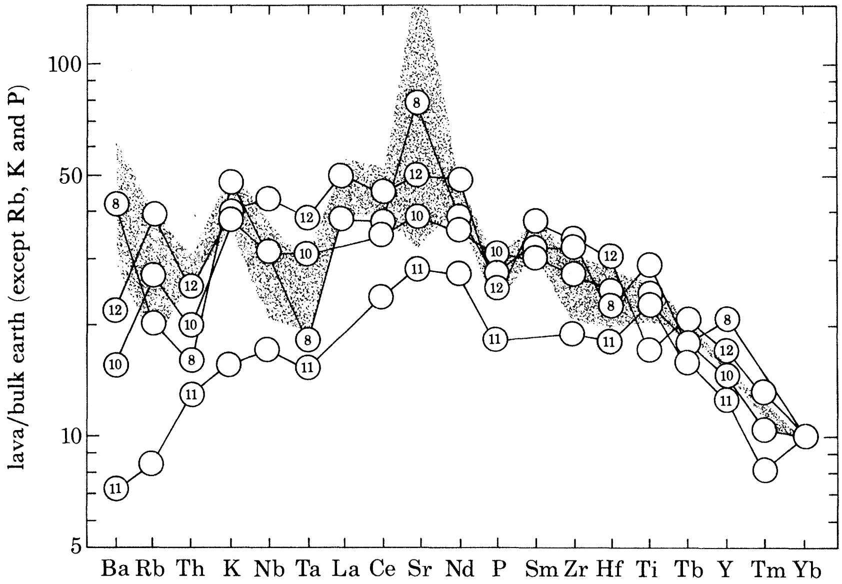


FIGURE 5. Chondrite-normalized, except for Rb, K and P, incompatible element 'spidergram' diagram (Thompson 1982*b*) for Storr section lavas. Shaded envelope indicates compositions of flows 2–7 (table 1). Upper flows numbered.

The Storr section forms a simpler eruptive sequence in the lower part of the lava pile (Thompson 1974) which Anderson & Dunham (1966) attributed to a single vent in Trotternish (figure 1). This section was discussed briefly by Morrison *et al.* (1980), and will be examined in detail here using data from table 1.

In figure 4, silica saturation, differentiation index, Sr content and initial Sr isotope ratio are plotted as histograms against altitude for the analysed lavas. Gaps in the sequence are due to poor exposure or local conditions of severe alteration. If these lavas were vented from a magma chamber similar to O'Hara's model, undergoing simultaneous differentiation and contamination, then we should expect to see progressive increases in differentiation index, silica saturation and initial Sr isotope ratio up the sequence. Differentiation index increases generally upwards, but within the detailed basalt sequence this is reversed. A general correlation between silica saturation and $^{87}Sr/^{86}Sr$ is observed but both generally *decrease* up the sequence.

Contamination processes can also be recognized by variation of incompatible element ratios with a 'spidergram' plot (Sun 1980; Thompson 1982*b*). Figure 5 shows such a plot, doubly normalized for Yb = 10 to correct for olivine fractionation (Thompson *et al.* 1983). The lava flow numbers 2–7 from the Storr section have a restricted range of compositions (except for Sr) which define the shaded envelope in figure 5. The upper flows (including hawaiites) have similar heavy rare earth contents, but significantly lower concentrations of light rare earths, Ba and Th. Thompson *et al.* (1982) showed that these elements were strongly enriched during contamination with Lewisian gneiss. Therefore the degree of crustal contamination decreases upwards in the Storr section. This is confirmed by Pb isotope evidence (figure 3), which shows an increasing mantle Pb component and decreasing lower crustal component with height in the Storr lavas (shown stippled). Upper crustal Pb contamination was low throughout.

Petrographic evidence and low pressure melting experiments (Thompson *et al.* 1972) show that basalts and hawaiites in the Storr section crystallized minor olivine, and sometimes plagioclase, in upper crustal high-level magma chambers. However, since Pb isotope data (figure 3) show very little evidence of contamination at this stage, magma residence times in these chambers was probably short relative to that in lower crustal reservoirs where most contamination of the magmas occurred. Similar short-lived high-level chambers and longer-lived deeper chambers have been inferred for the Hawaiian magmatic system on the basis of geophysical evidence (see, for example, Ryan *et al.* 1981). Hence the eruptive order in the Storr section probably approximates to the order of tapping of lower crustal magma reservoirs, and it is concluded that the degree of contamination suffered by Storr section magmas in the lower crust decreased with time. This is consistent with the existence of a plexus of minor intrusions suffering contamination by Patchett's model (1980) and the gradual sweating out the low melting fractions from a crustal section to leave a relatively refractory residuum, but is not consistent with the presence of evolving long-lived magma chambers of the type predicted by O'Hara (1980*b*).

Because the Storr data require extrapolation through the (unseen) upper crustal reservoirs to the deeper chambers, the complexities of this plumbing system mean that modelling of granite genesis in the light of the evolution of the lavas (as attempted by Dickin (1981)) will be difficult, and possibly misleading. A better alternative may be to look at basic rocks in the central complexes themselves (e.g. Walsh *et al.* 1979). The Skye intrusive complex is ideal for such an investigation because it shows the greatest development of both basic and acid plutonic rocks in the B.T.V.P.

Structure of the Cuillins centre

The four multicomponent intrusive centres on Skye, formed by progressive movement of the focus of activity, are the Cuillins basic complex and the Strath na Creitheach, Western Redhills and Eastern Redhills granite complexes. Although the Cuillins form the only large basic complex exposed, gravity evidence demonstrates the presence of basic rock under the granite centres (Bott & Tuson 1973), and minor basic to intermediate bodies are associated with the granites, suggesting that a complex similar to the Cuillins underlies each of the granite centres. Therefore, a geochemical study of the Cuillins may help in understanding the genetic history of the granite magmas. We report here new major element, trace element, and Sr, Pb and Nd isotope data on a suite of 35 whole rock samples in a complete transverse across the Cuillins Complex (figure 6) as an attempt to study contamination in the magma reservoirs themselves.

The Cuillins Complex is a basically funnel-shaped structure, whose outer intrusive contacts dip inwards at an average of *ca.* 30°. Although Bott & Tuson (1973) modelled their gravity data as a solid truncated cone of basic rock reaching from the surface into the lower crust, this is not an exclusive solution, and it is more realistic to view the Cuillins Complex as a discrete body, overlying a larger mass of basic rock at depth, whose form is as yet unknown.

On the west side of the Cuillins, the outer gabbros cut plateau lavas at the surface, but on the eastern side the contact is against lavas, Mesozoic sediments and Torridonian sandstone, which have been brought up by the Camasunary fault. Bott & Tuson's gravity data suggests a thickness of *ca.* 1 km for the Torridonian strata in central Skye, so that these units probably form the wall rocks of the funnel-shaped body at depth, though it may penetrate into Lewisian gneisses at the base. Plateau lavas must have formed the roof of the complex, since fallen basaltic blocks are widely scattered throughout the layered units. These fallen blocks form compelling evidence that the layered sequence youngs upwards and inwards.

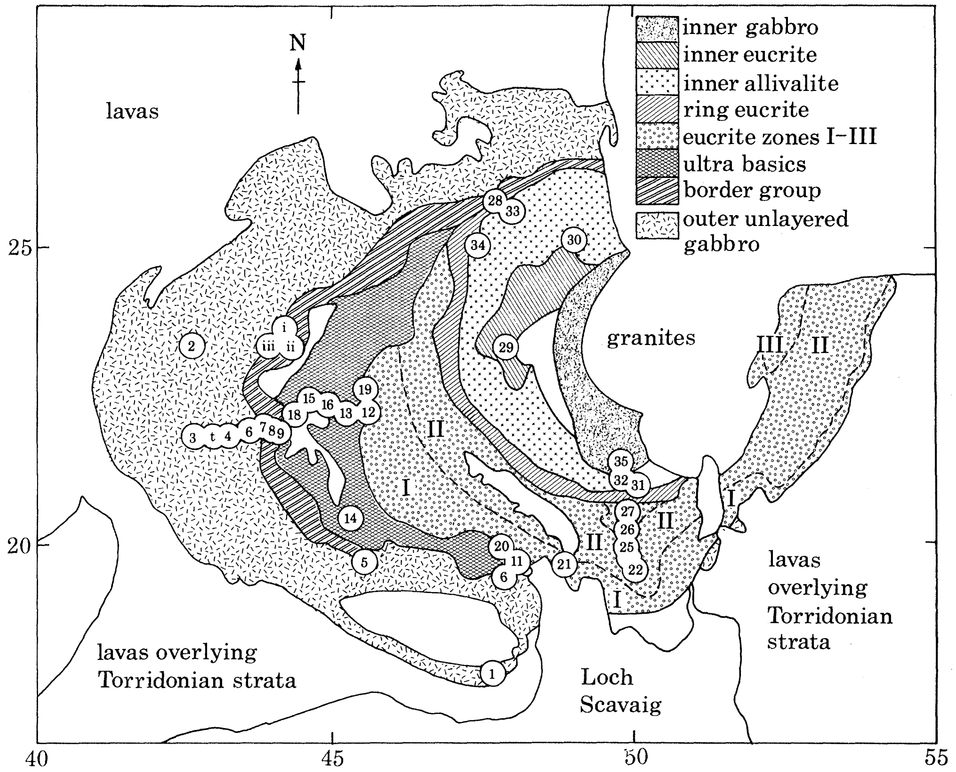


Figure 6. Map of the Cuillins Complex that shows localities for analysed samples.

Following earlier work on the Skaergaard intrusion (Wager & Deer 1939), Wager & Brown (1968) interpreted the Cuillins as the product of crystal settling in a single magma chamber, on the basis of optically determined cryptic layering in plagioclase and olivine. This necessitated a complex structural model in which each major unit was tectonically isolated. In contrast, Bailey (1945) interpreted the Cuillins as a multiple intrusion. Hutchison & Bevan (1977) have presented strong evidence for multiple intrusion in the ultramafic unit of the W Cuillins. They observed cryptic variation in (unit I) peridotite and allivalite E of the Border Group, overlain in turn by a pegmatitic zone, and an upper border group with reversed cryptic variation, before the influx of the new magma forming (unit II) allivalite.

MAJOR ELEMENT CHEMISTRY

New major element data for the suite of Cuillins samples (summarized in table 2) are shown as histograms in figure 7. There is clearly no systematic increase in iron oxide, or decrease in magnesium oxide throughout the intrusion, such as is seen in Skaergaard (Wager & Brown 1968). Instead there are a *series* of major element trends, which correspond to the lithologically mapped units and confirm the fact that the Cuillins Complex is a multiple intrusion.

TABLE 2. MAJOR ELEMENT DATA

	outer unlayered gabbro (av.)	border group (av.)	peridotite (12)	allivalite (17)	layered eucrite (av. ex 19)	ring eucrite (28)	inner eucrite (29)	inner allivalite (av.)	inner gabbro (35)
SiO_2	49.18	47.65	39.29	46.78	49.27	47.79	46.46	46.05	47.61
TiO_2	0.92	0.31	0.06	0.26	0.40	0.34	1.84	0.22	1.02
Al_2O_3	18.42	21.27	2.26	23.61	15.85	16.03	13.36	21.22	15.60
Fe_2O_3†	10.06	6.73	11.26	6.30	8.68	7.26	16.54	6.63	10.35
MnO	0.17	0.11	0.15	0.10	0.17	0.13	0.28	0.12	0.20
MgO	6.08	7.16	44.47	8.57	8.70	10.52	5.96	9.55	7.88
CaO	11.23	14.53	1.00	13.75	14.88	15.42	10.44	14.34	14.03
Na_2O	2.51	1.57	0.00	1.34	1.63	1.02	2.74	1.11	1.80
K_2O	0.47	0.10	0.02	0.09	0.11	0.11	0.15	0.05	0.16
P_2O_5	0.13	0.02	0.01	0.02	0.03	0.01	0.17	0.02	0.06
H_2O	0.11	0.07	0.07	0.11	0.06	0.11	0.03	0.06	0.08
H_2O^+	0.71	0.64	2.30	0.37	0.57	0.85	2.10	0.87	1.07
total	99.99	100.16	100.89	101.30	100.35	99.59	100.07	100.24	99.86

† Total Fe as Fe_2O_3.

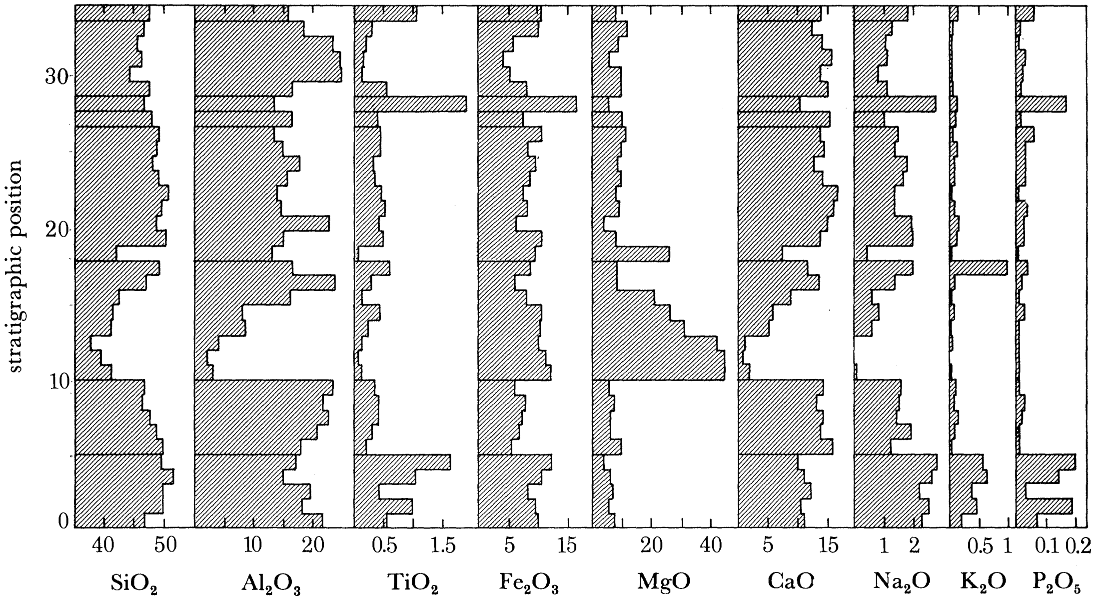


FIGURE 7. Profiles of major element oxide weight percentages against stratigraphic position in the Cuillins Complex.

In the upper half of the section most oxides are relatively constant except in the Inner Eucrite (sample 29). The ultrabasic unit (samples 11–18) shows strong evidence of fractionation, with dramatic increases in Al_2O_3 and Na_2O, and decreases in MgO and CaO. As might be expected, the Border Group (samples 6–10) is much more homogeneous, as are the Outer Unlayered Gabbros (O.U.G., samples 1–5). However, between these two units there is a dramatic change in composition. The Border Group and upper half of the complex generally have CaO $> 12\%$, $Na_2O < 2\%$, $K_2O < 0.2\%$ and $P_2O_5 < 0.05\%$. These compositions are typical of the Preshal Mhor magma type (Esson *et al.* 1975). In contrast, the O.U.G. have CaO $< 12\%$ and Na_2O, K_2O and P_2O_5 contents averaging 2.5, 0.47 and 0.13% respectively which are within the range of Skye Main Lava Series (S.M.L.S.) compositions. An early minor intrusion (LH15A) is likewise of S.M.L.S. type, but the later Cuillins minor intrusions, and gabbroic minor intrusions within the Redhills centres, are of Preshal Mhor type (M.A.M. unpublished data; B. Bell, personal communication).

ISOTOPE CHEMISTRY

Basic rocks from the Cuillins have a large range of initial $^{87}Sr/^{86}Sr$ compositions (0.7032–0.7132, table 3), which also encompass the composition of minor basic masses from the Redhills centres. These variations are attributed to processes of crustal contamination. A selection of samples from this suite (table 4) defines a strong linear array on a plot of initial $^{207}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ (not shown), whose slope corresponds to an apparent age of 2880 ± 130 Ma (2σ), after reduction of m.s.w.d. from 39 to 1 in order to encompass geological scatter. This age provides powerful evidence that the Tertiary basic intrusions of Skye are largely mixtures of mantle-derived magmas and Lewisian crustal material (Moorbath & Welke 1969).

Crustal sources are better discriminated on plots of $^{206}Pb/^{204}Pb$ against $^{208}Pb/^{204}Pb$ (figure 8) and $^{87}Sr/^{86}Sr$ (figure 9), using end-member compositions from Dickin & Jones (1983). In these diagrams, the Outer Unlayered Gabbros (samples 1–5), an early Cuillins minor intrusion (sample i), and the Marsco Summit gabbro (a), have compositions indicative of extensive contamination by granulite-facies *lower* crust. The composition of a granulite-facies Lewisian acid sheet, 7H (Weaver & Tarney 1980; Thompson *et al.* 1982), is shown for reference in figure 9, suggesting that this type of material may have been important in lower crustal contamination. However, the Pb isotope composition of 7H itself is unsuitable as a contaminant for the Skye lavas, so it is not used in modelling the relative contributions of Pb to the magmas from different sources.

In contrast to the O.U.G., most rocks from higher in the Cuillins suite, along with the Marsco plug (b) and Broadford gabbro (e) from the Redhills centres, principally contain mixtures of mantle-derived and amphibolite-facies Lewisian upper crustal Pb and Sr. In figure 8, this mixing line is straight, since ^{204}Pb forms the denominator on both axes. In figure 9, however, two component mixing yields a curve whose form reflects the relative Pb/Sr ratios in the end members involved in mixing. The reference curve in figure 9 corresponds to an amphibolite-facies Pb/Sr ratio of four times that in the mantle-derived component. The ferrodiorite in Harker's gulley (c) and the Beinn na Cro gabbro (d) have compositions in figure 8 between the two major groups.

In figure 8, the composition of Torridonian (upper Proterozoic) sedimentary strata is not well resolved from Tertiary mantle-derived magmas, but in figure 9 these end members are clearly distinguished, and samples which contain a significant component of Torridonian material stand out by having high $^{87}Sr/^{86}Sr$ ratios for any given Pb isotope ratio. Rocks of this type in the Cuillins occur at the top of the ultrabasic sequence (sample 18), the base of the layered eucrite series (sample 19) and in an intrusive tholeiite (t) from near these localities. These samples also have high U/Pb ratios, which were probably also inherited from the Torridonian, unlike the low U/Pb ratios of the other Cuillins rocks (Moorbath & Welke 1969), or the Redhills minor basic intrusions (table 4).

Other compositions in figure 9 are more ambiguous, and it is not clear whether a Torridonian component is involved in their genesis (e.g. the Marsco plug (b)). In order to clarify such problems, a small selection of samples was also analysed for $^{143}Nd/^{144}Nd$ (table 5). These data

Table 3. Sr isotope data

(For all analytical details see Appendix.)

position in sequence	sample number	grid reference	unit	$^{87}Sr/^{86}Sr$	Rb (μg/g)	Sr (μg/g)	$^{87}Rb/^{86}Sr$	$(^{87}Sr/^{86}Sr)_i$	2σ
outer unlayered gabbro									
1	LR 275	4771/1769		0.70491	3	387	0.02	0.70489	3
2	LR 15†	4296/2338		0.70690	6	500	0.03	0.70687	4
3	LR 31†	4310/2201		0.70699	6	389	0.04	0.70696	4
4	LR 34†	4344/2191		0.70728	9	356	0.07	0.70722	4
5	LR 223†	4669/1878		0.70515	11	344	0.09	0.70507	2
border group: eucrites/allivalites									
6	LR 252	4790/1956‡		0.70691	n.d.	n.d.	0.03	0.70688	3
7	LR 125†	4388/2172		0.70744	0	239	0.00	0.70744	4
8	LR 124†	4393/2169		0.70719	2	183	0.03	0.70716	4
9	LR 123†	4405/2171		0.70582	1	155	0.02	0.70580	4
10	LR 213	4417/2175		0.70613	1	178	0.02	0.70611	3
layered ultrabasic series: peridotites and allivalites									
11	LR 251	4808/1953	P	0.70485	n.d.	n.d.	0.00	0.70485	3
12	LR 240	4565/2204	P	0.70516	0	6	0.00	0.70516	3
13	LR 238	4531/2182	P	0.70478	1	9	0.32	0.70451	2
14	LR 107†	4520/2036	P	0.70422	1	39	0.07	0.70416	4
15	LR 234	4473/2197	P	0.70560	5	51	0.28	0.70536	3
16	LR 237	4519/2176	AI	0.70483	2	79	0.07	0.70477	3
17	LR 236	4499/2174	A?	0.70596	0	138	0.00	0.70594	3
18	LR 214	4432/2182	AII	0.71366	32	169	0.55	0.71319	3
layered eucrites									
19	LR 239	4559/2217	I	0.71034	0	59	0.00	0.71034	3
20	LR 253	4786/1974	I	0.70524	n.d.	n.d.	0.00	0.70524	3
21	LR 155	4877/1959	I/II	0.70450	5	166	0.09	0.70442	3
22	LR 84†	4992/1954	II	0.70450	0	113	0.00	0.70450	3
23	LR 85†	4977/1978	II	0.70486	0	105	0.00	0.70486	3
24	LR 86†	4999/2013	II	0.70439	0	125	0.00	0.70439	3
25	LR 87†	5001/2030	II	0.70380	2	119	0.05	0.70476	3
26	LR 88†	5010/2050	III	0.70428	n.d.	n.d.	0.02	0.70426	5
27	LR 89†	5016/2058	III	0.70386	0	109	0.00	0.70386	4
ring eucrite									
28	LR 58	4768/2542		0.70381	1	111	0.03	0.70378	3
inner eucrite									
29	LR 92†	4805/2355		0.70323	1	133	0.02	0.70321	2
inner allivalites									
30	LR 96†	4876/2505	III	0.70340	1	109	0.03	0.70337	4
31	LR 41†	5032/2071	IV	0.70362	0	150	0.00	0.70362	4
32	LR 42†	5029/2095	IV	0.70362	0	148	0.00	0.70362	5
33	LR 60†	4781/2534	V	0.70348	1	144	0.02	0.70346	4
34	LR 264	4736/2505	V	0.70365	n.d.	n.d.	0.02	0.70363	3
inner gabbro									
35	LR 43†	5011/2148		0.70376	1	167	0.02	0.70374	4
Cuillins intrusive tholeiites									
t	LR 33†	4321/2194		0.70643	9	219	0.12	0.70633	4
t	LR 126T†	4371/2182		0.71090	13	179	0.21	0.71072	2
Cuillins minor intrusions									
i	LH 15A†	409/258	early	0.70964	10	280	0.10	0.70956	3
ii	LH 137†	409/258	middle	0.70350	0	80	0.00	0.70350	4
iii	LH 152†	409/258	late	0.70441	0	122	0.00	0.70441	4
Redhills minor intrusions									
a	SK 271	Marsco summit gabbro		0.70676	16	264	0.18	0.70661	8
b	MS 300	Marsco plug		0.70552	11	350	0.09	0.70544	4
c	SK 167	Ferrodiorite		0.71120	53	237	0.65	0.71066	6
d	B 304	Beinn na Cro gabbro		0.70960	74	135	1.59	0.70836	11
e	B 1	Broadford gabbro		0.70449	19	171	0.32	0.70424	4

† Oxford analysis.
‡ N.B. new locality for exposure of border group rocks, confirmed by chemistry.
n.d.: not determined.

are shown on the ϵ_{Sr} against ϵ_{Nd} plot (figure 10), where products of simple mantle-derived magma–amphibolite-facies Lewisian mixing fall close to the slightly curved reference line. The Glas Bheinn Mhor-Dunan Epigranite (G.B.M.D.E.) from the Eastern Redhills, which Dickin (1981) suspected of containing a substantial Torridonian fraction, stands out clearly as doing so in figure 10, but the Marsco plug (b) does not appear to contain such a component. The atypical composition of this rock in figure 9 must be due to different Sr/Pb ratios in the mixing end members. A plot of Nd against Pb isotope compositions is omitted, since this does not resolve different source components well.

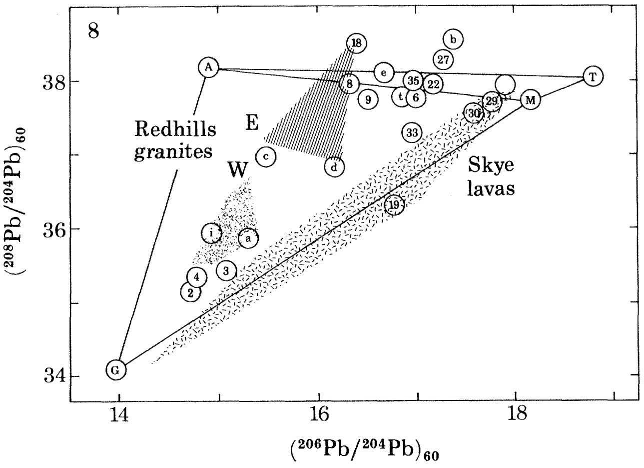
TABLE 4. Pb ISOTOPE DATA

position in sequence	sample number	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	U‡ (μg/g)	Pb‡ (μg/g)	age corrected $^{206}Pb/^{204}Pb$	age corrected $^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	% from source in: mantle	% from source in: lower crust	% from source in: upper crust
						Cuillins layered series						
2	LR 15	14.778	14.823	35.244	0.1	1	14.72	14.82	35.16	16	71	13
3	LR 31†	15.136	14.908	35.503	0.1	1	15.08	14.91	35.42	23	66	11
4	LR 34	14.828	14.823	35.415	0.1	1	14.77	14.82	35.33	16	67	17
6	LR 252	17.024	15.265	37.857	0.1	1	16.97	15.26	37.76	64	3	33
8	LR 124†	16.381	15.117	38.037	0.1	1	16.32	15.12	37.94	43	1	56
9	LR 123†	16.584	15.193	37.846	0.1	1	16.53	15.19	37.75	50	5	45
	BM 37	17.921	15.497	37.952	0.030	1	17.90	15.50	37.93	88	0	12
18	LR 214	16.555	15.171	38.764	0.350	1.41	16.41	15.16	38.50	—	—	—
19	LR 239	17.249	15.323	37.166	0.41	0.43	16.70	15.30	36.29	—	—	—
22	LR 84†	17.207	15.279	38.045	0.1	1	17.15	15.28	37.95	67	0	33
27	LR 89	17.332	15.300	38.353	0.1	1	17.27	15.30	38.26	63	0	37
29	LR 92†	17.835	15.471	37.779	0.1	1	17.78	15.47	37.68	88	2	10
30	LR 96	17.625	15.447	37.650	0.1	1	17.57	15.45	37.55	82	6	12
33	LR 60†	17.011	15.331	37.402	0.1	1	16.95	15.33	37.31	67	14	19
35	LR 43	17.035	15.280	38.043	0.1	1	16.98	15.28	37.95	62	0	38
						Cuillins minor intrusions						
	LR 126T†	16.994	15.208	37.961	0.1	2	16.88	15.20	37.77	—	—	—
	LH 15A	14.975	14.837	36.033	0.1	1	14.92	14.83	35.94	16	52	32
						Redhills basic intrusions						
a	SK 271	15.360	14.892	35.938	0.1	2.72	15.34	14.89	35.91	29	52	19
b	MS 300	17.403	15.280	38.582	0.092	2.33	17.38	15.28	38.54	61	0	39
c	SK 167	15.495	14.927	36.948	0.5	10	15.47	14.93	36.91	26	28	46
d	B 304	16.228	15.057	36.894	0.83	8.75	16.18	15.06	36.83	48	27	25
e	B 1	16.692	15.171	38.137	0.103	2.67	16.67	15.17	38.10	51	0	49
						Skye Lavas						
	SK 894	15.679	15.026	35.666	0.1	1.34	15.62	15.02	35.57	39	59	2
	SK 931	17.664	15.354	37.466	0.1	1	17.60	15.35	37.37	86	10	4
	SK 934	17.766	15.406	37.592	0.1	1	17.71	15.40	37.49	88	7	5

† Oxford analysis.
‡ Figures given to one significant figure are estimates based on Moorbath & Welke (1969).

CONTAMINATION OF CUILLINS MAGMAS

Structural evidence shows that the Cuillins Complex was principally emplaced into Torridonian strata, yet isotopic data show very little evidence of contamination by the Torridonian. Indeed, the O.U.G., which form the outer envelope of the intrusion, contain no observable Torridonian component, but rather show evidence of *lower* crustal Pb contamination. Therefore it is very unlikely that the Cuillins Complex melted its way progressively up through the crust as in the model of Ahern *et al.* (1981). Rocks in the Cuillins Complex which *do* show evidence of Torridonian contamination (samples 18, 19 and t, figure 9), are of similar age, and must represent pulses of magma which interacted with marginal Torridonian country rocks at one stage in the life of the complex before injection into its interior.



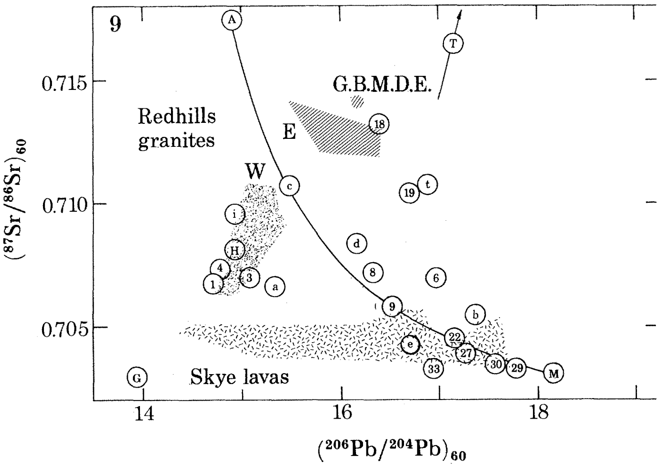


FIGURE 8. Plot of $^{208}Pb/^{204}Pb$ against $^{206}Pb/^{204}Pb$ at 60 Ma. Source compositions: G, average granulite-facies Lewisian gneiss; A, average amphibolite-facies Lewisian gneiss; T, Torridonan; M, Skye mantle-derived magmas; (Dickin & Jones 1983). Data point labels are from table 3. (E, W: eastern and western Redhills granite.)

FIGURE 9. Plot of $^{87}Sr/^{86}Sr$ against $^{206}Pb/^{204}Pb$ at 60 Ma, symbols as in figure 8. Curve is mixing line corresponding to a Pb/Sr ratio in mantle-derived magmas of a quarter of that in the amphibolite-facies Lewisian component. G.B.M.D.E.: Glas Bheinn Mhor-Dunan Epigranite; H: Lewisian acid sheet '7H' (Weaver & Tarney 1980; Thompson *et al.* 1982).

TABLE 5. Nd ISOTOPE DATA

position in sequence	sample number	Sm (μg/g)	Nd (μg/g)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	$(^{143}Nd/^{144}Nd)_i$	ϵ_{Nd} (60 Ma)
				Cuillins centre				
3	LR 31	1.620	7.18	0.1365	0.511458	±20	0.511404	−22.6
8	LR 124	0.918	2.723	0.2038	0.512345	±27	0.512265	− 5.8
29	LR 92	4.303	11.97	0.2173	0.513061	±21	0.512976	+ 8.1
				Strath na Creitheach centre				
M.D.E.	SC 5	15.20	70.33	0.1307	0.511681	±21	0.511630	−18.1
				Redhills centres				
b	MS 300	3.924	16.43	0.1443	0.511854	±16	0.511797	−14.9
L.A.E.	LA 3F	3.838	19.18	0.1210	0.511824	±44	0.511777	−15.3
d	B 304	9.898	42.78	0.1399	0.512178	±24	0.512123	− 8.5
	repeat	—	—	—	0.512171	±41	—	—
G.B.M.D.E.	GB 12	12.98	59.64	0.1316	0.512020	±18	0.511968	−11.5

The high structural level of the Cuillins Complex led to the early development of a convecting groundwater system (King 1977) which caused rapid freezing of each pulse of magma emplaced into the complex. This would have prevented large scale crustal melting and contamination of the basic magmas, making the Cuillins Complex itself little more than a subterranean crystallization repository analogous to the extrusive lava pile. In this case, crustal contamination of the Cuillins magmas must have occurred in deeper reservoirs below the influence of meteoric

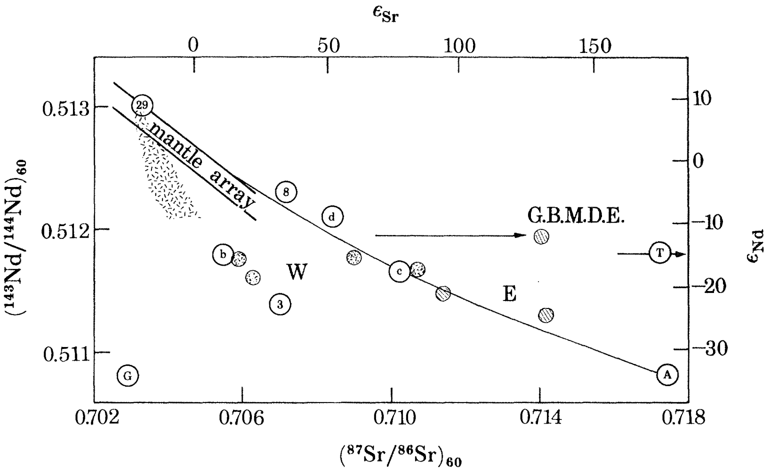


FIGURE 10. Plot of $^{143}Nd/^{144}Nd$ against $^{87}Sr/^{86}Sr$ at 60 Ma; ε values also shown. Symbols are as in figure 8.

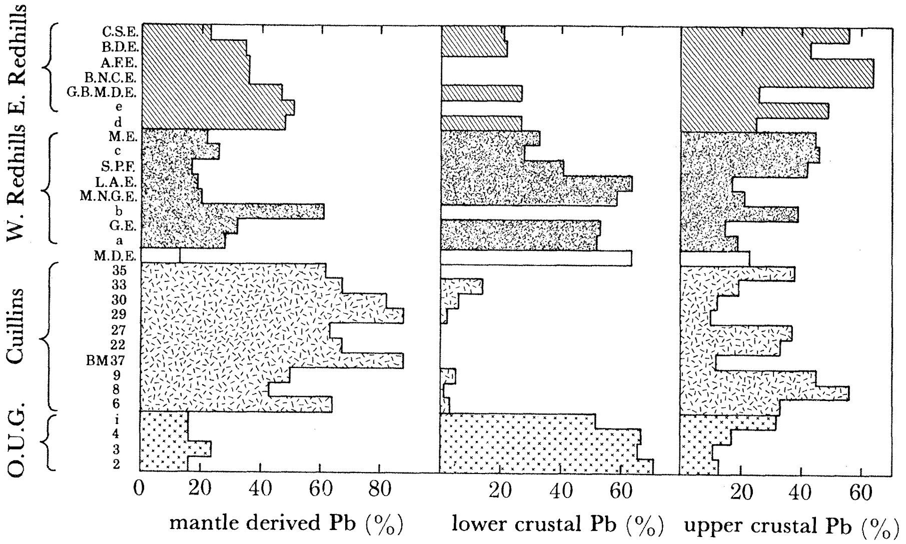


FIGURE 11. Profiles of percentage Pb contribution from three sources in Skye intrusive rocks. Crosses indicate Outer Unlayered Gabbro; scatter dash: Main Cuillins units; blank: Strath na Creitheach centre; stipple: W Redhills centre; cross hatch: E Redhills centre. Granite abbreviations: M.D.E., Meall Dearg Epigranite; G.E., Glamaig Epigranite; M.N.G.E., Maol na Gainmhich Epigranite; L.A.E., Loch Ainort Epigranite; S.P.F., Southern Porphyritic Felsite; M.E., Marsco Epigranite; G.B.M.D.E., Glas Bheinn Mhor-Dunan Epigranite; B.N.C.E., Beinn na Cro Epigranite; A.F.E., Allt Fearna Epigranite; B.D.E., Beinn an Dubhaich Epigranite; C.S.E., Creag Strollamus Epigranite.

hydrothermal convection systems. These reservoirs now form basic–ultrabasic intrusions, which are identified with the large positive gravity anomaly under central Skye.

Walsh *et al.* (1979) proposed that the positive gravity anomaly under Mull was produced by a solid cylinder of basic material on top of a whale-backed basic magma ridge, formed by updoming of the Moho. However, the detailed forms of the basic intrusion(s) cannot be deduced from gravity data alone, and we shall attempt instead to model these in Skye by considering isotopic data as a function of time.

In figure 11, relative fractions of mantle-derived, lower crustal and upper crustal Pb in the intrusive units are plotted in stratigraphical order. The lower half of this diagram, representing the Cuillins Complex, displays very marked variations in lower crustal Pb component. The O.U.G., resembling the S.M.L.S., contain a large lower crustal component which falls somewhat with time, while the Cuillins *sensu stricto*, resembling the P.M.B., have a minimal lower crustal component. Thompson (1982*b*) suggested that lower crustal contamination was reduced in the late-stage Preshal Mhor lavas because 'by this stage of the magmatism the lower and middle crust beneath central Skye had become so filled with innumerable basic dykes and sills that its high density allowed later basaltic magma batches to reach high crustal levels before they stagnated in low-density amphibolite-facies Lewisian.' This model can also explain the Cuillins data.

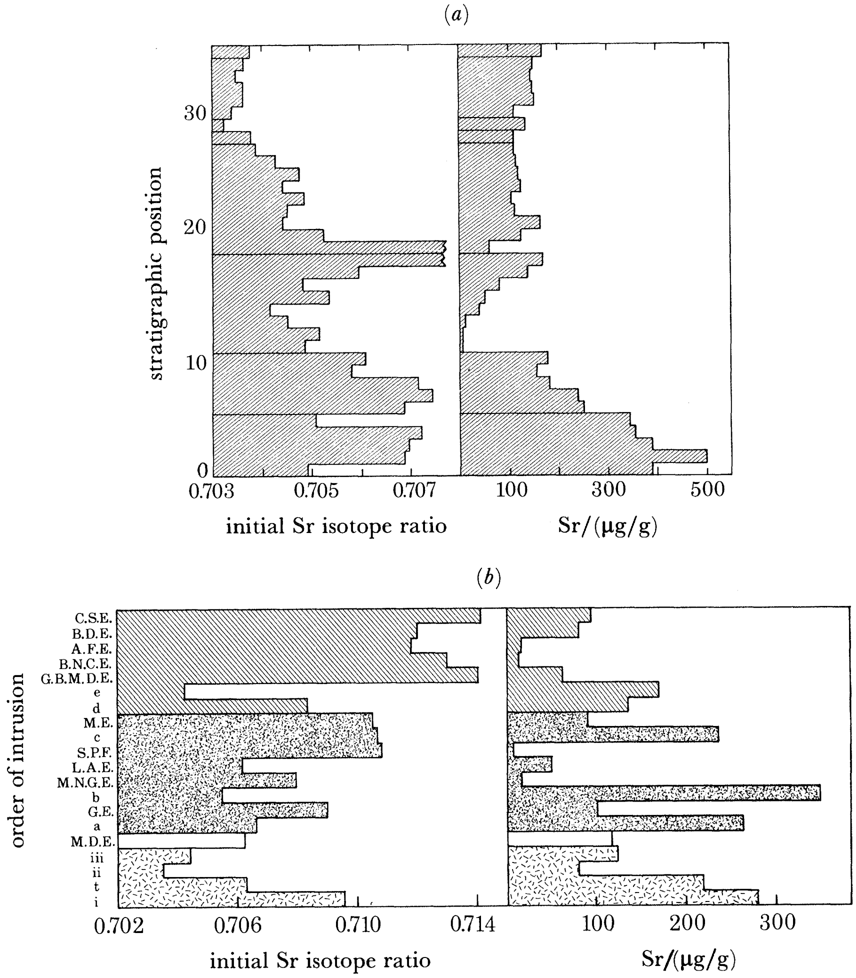


FIGURE 12. Profiles of initial Sr isotope ratio and Sr content: (*a*) against stratigraphic position in the Cuillins Complex; (*b*) against order of intrusion in the Skye igneous complex as a whole. Shading and abbreviations are as in figure 11.

In figure 12*a*, initial Sr isotope ratios for the Cuillins rocks are plotted against their stratigraphic position. The O.U.G. (samples 1–5), contaminated in the lower crust, have relatively high $^{87}Sr/^{86}Sr$ ratios which are consistent with a melt contribution from granulite-facies leucogneiss (figure 9). However, because significant lower crustal contamination of the main

Cuillins units can be ruled out (figure 11), $^{87}Sr/^{86}Sr$ ratios can be interpreted directly as a measure of the degree of upper crustal contamination with confidence. Ignoring samples that have suffered Torridonian contamination (18 and 19), $^{87}Sr/^{86}Sr$ falls progressively in the Border Group and lower ultramafic section, and again in the layered Eucrite series. The upper part of the ultramafic section (e.g. sample 17) may represent a magma pulse of similar intrusive age to the outer Border Group (Hutchinson & Bevan 1977) and must be treated with caution. Pb data for this section are sparser, and give a rather irregular picture, but the upper crustal Pb fraction generally falls, and the mantle derived Pb fraction generally rises from sample 8 to 30 (figure 11). Therefore, Sr and Pb isotope evidence for the major part of the Cuillins section indicates decreasing degrees of crustal contamination of the basic magmas with time. In contrast, major element compositions (figure 7) and Sr contents (figure 12*a*) in the main Cuillins section (samples 6–35) are remarkably constant, with the exception of *in situ* differentiation in the ultramafic unit.

It is concluded that neither elemental nor isotopic data for most of the Cuillins section is consistent with the existence of large, long-lived, periodically tapped and replenished magma chambers in the crust under the Cuillins intrusive centre. Isotopic data could represent the downward emptying of a large stratified magma chamber (as modelled by Blake (1981)) but such a model is ruled out by major element data, which do not show the required progressive decrease in degree of differentiation towards the top of the sequence. Instead the data in figures 11 and 12*a* (see also note added in proof) are consistent with a model in which magma reservoirs feeding the Cuillins consisted of numerous minor intrusions in the upper crust which progressively sweated out fusible components from a large section of more refractory basement. The erratic manner with which crustal contamination decreased with time (e.g. figure 11) is itself a consequence of this model, in which the distribution of successive intrusive sheets through the crustal section must have been at least partially a random 'Monte Carlo'-type process giving rise to erratic short-term variations in contamination. These short-term variations were probably smoothed out higher in the magmatic plumbing system by mixing between more-contaminated and less-contaminated batches of basic magma from different reservoirs.

Contamination of Redhills magmas

In the upper part of figure 11, relative mantle-derived, lower crustal and upper crustal Pb fractions are plotted for the Redhills intrusions in stratigraphic order. After the near disappearance of lower crustal Pb from the main Cuillins units, there is a dramatic return to large fractions of this component in the early Redhills granites. This lower crustal signature in the granites is so reminiscent of the S.M.L.S. magma types, and unlike P.M.B. lavas, that Dickin (1981) assumed the granites to be derived from S.M.L.S.-type precursors which had undergone further differentiation and contamination in the upper crust. However, since the Redhills minor intrusions are shown to be of P.M.B. type by their major element compositions, yet at least in the case of the Marsco Summit gabbro, contain a substantial component of lower crustal Pb (a, figures 8 and 9), it seems most probable that the granites are also derived from P.M.B. magmas which have undergone contamination in the lower crust.

Brown & Mussett (1976) identified two basic masses at depth in Skye on the basis of magnetic data; one under the Cuillins and one under the Redhills. It is therefore likely that the return to lower crustal interaction in the western Redhills resulted from a shift of magmatism to a new crustal segment, where sill injection into the lower crust and consequent melt extraction could begin again. Conduits in the old magmatic focus under the Cuillins probably became blocked by the sheer number of minor basic intrusions in the crust.

Pb data for the Redhills are more complex than the Cuillins, owing to the occurrence of both upper and lower crustal magma–crust interaction. The trends of lower and upper crustal contamination with time are to some extent reversed, so that while the lower crustal contribution falls with time, the upper crustal component rises. This pattern could represent intrusion of a series of sills at successively higher levels through a gradational 'Conrad discontinuity' between lower crustal granulite-facies gneiss and upper crustal amphibolite-facies gneiss. In this case the nature of contamination would be changing, but its overall magnitude should not change markedly. An alternative model is of progressively decreasing degrees of lower crustal contamination, resulting from gradual sweating out of fusible components from this segment of crust, followed by the development of two large, long-lived evolving magma chambers, under the western and eastern Redhills respectively. Comparing the lower with the upper crustal Pb components in figure 11, it is difficult to decide which model fits the data better. However, examination of the mantle-derived fractions points clearly to the latter, since the mantle-derived component decreases in two clear cycles, with a marked step between the two centres. Furthermore, this component is consistently larger in all of the E Redhills intrusions (except the Creag Strollamus Epigranite, C.S.E.) than in the last five W Redhills bodies, which is taken to indicate a real fall-off in lower crustal contamination with time, rather than merely an upward migration of sill emplacement through a gradational metamorphic boundary.

Sr isotope compositions of Cuillins minor intrusions and Redhills basic and granitic bodies are plotted in order of intrusion in figure 12*b*. The Cuillins minor intrusions reflect the trend of falling upper crustal contamination seen in the major units, but with an upturn at the top of the sequence. Allowing for the fact that the $^{87}Sr/^{86}Sr$ ratio of the G.B.M.D.E. has been raised by Torridonian contamination, Sr isotope ratios in the granites broadly define two cycles of increasing contamination with radiogenic upper crust. This evidence is consistent with that from Pb isotopes in pointing to long-lived developing magma chambers under both western and eastern Redhills.

Skye granite petrogenesis

It is concluded that the evolution of Redhills magmas in the crust must have been relatively complex compared with the S.M.L.S. and Cuillins, and involved lower crustal sheet injection, followed by the development of large classical-type magma chambers fitting O'Hara's criteria in the upper crust. However, there is no reason to believe that differentiation through to granite compositions occurred in these chambers. On the contrary, the very similar ranges of upper crustal Pb component in the granites (15–64%) and the Redhills basic intrusions (19–49%) suggests that late stage fractionation to acid residua may well have occurred *after* contamination (and limited differentiation) of P.M.B. basic magmas.

Walsh *et al.* (1979) and Walsh & Clarke (1982) have demonstrated that magmas resembling the contaminated basic and intermediate plutons of centre 2 in Mull probably evolved to granitic compositions by plagioclase fractionation (with pyroxene at the beginning and K-feldspar at the end), with little *further* contamination during differentiation. Thompson (1982*b*) showed similarly that an early adamellite (the Glamaig Epigranite) and a late peralkaline leucogranite (the Southern Porphyritic Epigranite) from the W Redhills had 'spidergram' profiles which could be linked mainly by fractionation of plagioclase, Fe–Ti oxide and apatite. This probably occurred in Cuillins-type magma chambers under the Redhills centres. These chambers were probably shallower than the reservoirs where upper crustal contamination occurred, but sufficiently deeper than the Cuillins Complex itself that they were not rapidly chilled by meteoric-hydrothermal convection systems.

Although Thompson (1983) was able to show on the basis of 'spidergram' diagrams and melting relations that the crustal contribution to the granites was subordinate to the mantle derived component, he was not able to model Redhills granite petrogenesis quantitatively because crystal fractionation had obscured the incompatible element signatures of the two components. However Thompson (1982*b*) did attempt to model the 'spidergram' profile of a Redhills *basic* intrusion, the Marsco Summit Gabbro, by addition of 10% granulite-facies leucogneiss (7H) and 10% amphibolite-facies gneiss (5024) to the P.M.B. Lava SK946. The new Pb isotope data presented here for the Marsco Summit Gabbro (a, figures 8 and 9) show, in fact, that this unit was principally contaminated by lower crustal granulite-facies gneiss. Using a new Th determination on the Marsco Summit Gabbro (below N.A.A. detection limit of 0.2 μg/g, S. J. Parry, personal communication), contamination of this body was remodelled using the crustal end members of Thompson *et al.* (1982). The best fit to the Th-inclusive 'spidergram' was obtained by mixing P.M.B. lava SK946, a granulite-facies leucogneiss (7H) and a granulite-facies quartz-feldspar intergrowth (S.Q.K.F.) in the ratios 83:14:3 respectively, yielding a total crustal component of 17%.

Thompson *et al.* (1982) obtained the best fit to 'spidergram' profiles of contaminated S.M.L.S. basalts by addition of *ca.* 20% of granulite-facies crustal component to an uncontaminated lava, SK940. However, they estimated that not more than 10% of a granitic crustal melt could be added to uncontaminated S.M.L.S. magmas without destroying correlations between silica saturation and Ti, P, Zr, Hf and middle r.e.e. which Thompson *et al.* (1980) observed in both contaminated and uncontaminated lavas and attributed to variations in basaltic melt fraction extracted from the mantle. Thompson *et al.* (1982) concluded that the 20% contamination result calculated using a bulk assimilation model could be achieved by only 10% contamination with a *ca.* 50% partial melt of the crustal rocks, leaving a plagioclase residuum poor in l.i.l. elements.

These arguments suggest that the 17% crustal fraction in the Marsco Summit Gabbro determined from 'spidergram' modelling may be an over-estimate by a factor of two, so that this unit actually suffered only 8% bulk crustal contamination. This compares with a 71% crustal Pb component, and indicates that crustal Pb in the Marsco Summit Gabbro was enriched by a factor of eight over the bulk crustal melt contribution. This enrichment factor may now be applied to the crustal Pb fractions in the Redhills epigranites to calculate quantitatively the bulk crustal contribution to the granites. Excluding the G.B.M.D.E., for which the results are disturbed by Torridonian contamination, all of the remaining Redhills granites yield crustal fractions in the narrow range of 8–11% bulk crustal contribution. These values must be regarded as minima for the younger granites of the E Redhills, where inverse correlations of initial ^{87}Sr/^{86}Sr and Sr content are indicative of some late-stage high level crustal contamination during differentiation through to acid residua. Nevertheless, the closeness of this result to the 10% crustal fraction determined for S.M.L.S. basalts is very striking, and suggests that as in Mull, Skye Redhills granites are little more than late-stage high-level differentiation products of crustally contaminated Preshal Mhor basic magmas.

We are very grateful to B. Bell for access to samples of Beinn na Cro gabbro and Broadford gabbro, and to S. J. Parry for permission to use unpublished data on the Marsco Summit gabbro. R. Goodwin, P. N. Taylor and J. Hutchinson are thanked for analytical assistance. J.L.B. acknowledges receipt of an N.E.R.C. research studentship during this work, and A.P.D. acknowledges financial assistance from the Department of Geology & Mineralogy and University College, Oxford. Isotopic research at Oxford and East Kilbride is supported by the N.E.R.C.

Appendix. Analytical details

Analytical methods for the Storr section data have been published previously (Thompson *et al.* 1982). Major element analyses and Rb–Sr contents on Cuillins samples were determined by X.R.F. spectrometry at Imperial College, with fused discs and pressed pellets respectively. Sr isotope ratios were determined at Oxford and East Kilbride by routine methods, and are all normalized to a value of 0.71025 for the N.B.S. 987 standard (0.70800 for Eimer and Amend). Pb was separated at Oxford by electrodeposition (Arden & Gale 1974) and at East Kilbride by two-stage HBr columns, and analysed in both cases on a VG Isomass 54E machine. Blanks (averaging 5 ng) were not corrected, but all data are corrected for mass fractionation of 0.1% per a.m.u. Within-run precision averaged 0.03% (2σ), but between-run reproducibility is estimated at 0.05% (1σ). U and Pb were determined by mass spectrometric isotope dilution at East Kilbride. Nd was separated by a routine HCl–acetic acid–methanol 3-column procedure at East Kilbride and analysed on a 54E machine. Data were normalized to $146/144 = 0.7219$ to correct for fractionation. Sm and Nd were determined by isotope dilution. Age corrections for the Cuillins samples are to 60 Ma, otherwise as in Dickin (1981). Current decay constants are used in calculations ($\lambda^{87}\mathrm{Rb} = 1.42\times10^{-11}$, $\lambda^{147}\mathrm{Sm} = 6.54\times10^{-12}$, $\lambda^{238}\mathrm{U} = 1.55125\times10^{-10}$, $\lambda^{235}\mathrm{U} = 9.8485\times10^{-10}$, $\lambda^{232}\mathrm{Th} = 4.9475\times10^{-11}\,\mathrm{a}^{-1}$).

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Discussion

R. Hutchison, *Mineralogy Department, British Museum* (*Natural History*), *Cromwell Road, London SW7 5BD, U.K.*). The Cuillin layered igneous complex is surrounded by remnants of the Skye lava plateau, which it post-dates. The lavas must have been over 3 km thick, so that a large volume of magma must have been transported through the crust underlying the complex. Volatiles must therefore have been 'sweated out' of the crust before the onset of basic and ultrabasic plutonism. Contamination of the complex was probably controlled more by its geometry, e.g. ring-dyke against funnel-shaped intrusions, and by the regional geology, e.g. the Camasunary Fault, rather than by crust-magma interaction at depth.

A. P. Dickin. Dr Hutchison's comment is based on the assumption that most of the extrusive magma in the Skye lava pile rose to the surface through a small zone of conduits in the crust, into which the Cuillins complex was later emplaced. However, the structure of the Skye lava pile (Anderson & Dunham 1966) shows that the centre of activity migrated considerably during the history of eruption, and none of the major lava groups appears to have its centre over the Cuillins Complex. Similarly, within the area of major plutonism there was a migration of activity with time, from the Cuillins centre, through the three granite centres. Within each magmatic centre, including the Cuillins Complex, there is evidence of strong lower crustal Pb contamination at first, although this generally falls with time. In contrast, there is little evidence for contamination in the uppermost crust. The Cuillins Complex was largely emplaced into Torridonian strata, yet very few of the major intrusive units suffered significant contamination with Torridonian Sr, Pb or Nd. In conclusion, we find a picture of intense magmatism through a series of small crustal segments, leading to melt extraction and crustal basification, before migration of the centre of activity to a fresh segment of crust.

M. J. O'Hara (*Department of Geology, U.C.W., Aberystwyth, U.K.*). Articulation of the jaw-cracking mouthful 'periodically Refilled, periodically Tapped, continuously Fractionated magma chambers' is evidently causing speakers both difficulty and embarrassment. I hope others will join me in referring to them simply as 'R.T.F.-magma chambers'.

Divested of preconceived notions, and any implicit, but unnecessary assumptions, the operation of R.T.F.-magma chambers is likely to lead to the geochemical results outlined by O'Hara & Matthews (1981). The geochemical consequences were set out as 25 (composite) conclusions, 15 arising from O'Hara (1977, 1978*a*, 1980*a*, *b*). Irvine (1979), Walker *et al.* (1979), Sparks *et al.* (1980) and Huppert & Sparks (1980), and 10 being new conclusions.

In composite conclusion 6, reference was made to a specific model of a magma chamber beneath central volcanoes at high and intermediate crustal levels, which is overwhelmingly supported by field and geophysical evidence of plutonic rock columns cross-cutting and apparently replacing pre-existing crustal rocks and eruptives. That particular option indeed leads to the prediction that contamination by crustal rocks is likely to increase during the life of that particular type of magma chamber, as noted by O'Hara (1978*b*).

However, there is nothing in the formulation of the equations describing R.T.F.-magma chamber operation (O'Hara & Matthews 1981) that specifies or constrains *anything* about the shape, attitude, position, size, number or individual duration of magma chambers in which magma mixing and fractionation occurs. This is not to deny that some shapes, attitudes, etc. will make certain consequences more likely than others.

Cox (1979) has suggested the possibility that crustal flotation leads to development of a picritic magma chamber (or megasill) located at the top of the mantle in flood basalt provinces. This logically leads to the conclusion that contamination of the liquid residing in that magma chamber will *decline* with time, because the magma chamber in this case expands by uplift of the roof. There is no renewal of the crustal rocks at the contact, which, therefore, become increasingly depleted in fusible constituents, as time passes. If magmas rising from such a sub-crustal widespread magma chamber subsequently establish a high level R.T.F. chamber as part of a central volcanic structure along the lines envisaged by O'Hara (1977), a second phase of contamination (which would *increase* with time) may be superimposed upon the effects imposed in the sub-crustal chamber. The authors of the present paper have conveyed in a cartoon their conception that there is a need to choose between two alternative somewhat restrictive models of the volcanic plumbing system underlying Skye in the Tertiary. I believe this might be misleading to their audience, and even to the authors themselves for two reasons:

(i) the models are but two extremes of a wide spectrum of possibilities which has several other extremes, at least one of which (discussed above), may offer a satisfactory model that fits the available information for the Skye province;

(ii) there is a risk that the entirely viable principle of R.T.F.-magma chamber operation, which may be applied to most of the possible models of the volcanic plumbing, might be rejected because it has become attached *in their minds* to one specific model of the volcanic plumbing which they reject as the major influence in the situation which they have investigated.

I hope that this is not the case. It appears to me (on a first brief acquaintance with the data) that R.T.F.-magma chambers of one shape or another may have played a significant role in the evolution of these rocks and that these authors' extensive data base affords them excellent opportunities to constrain or even to define some of the parameters of these processes in the case of the Skye province.

A. P. Dickin. In our study, we have not started with specific 'extreme' assumptions about the shape, size, or location of magma chambers in order to deduce whether these were of an 'advancing, periodically replenished, periodically tapped' type or not. On the contrary, we have used our extensive data base for Skye to examine the compositional variations of magmas with time in order to assess the importance of advancing, periodically replenished and tapped chambers in the Skye magmatic plumbing system. *From* these results we have then drawn conclusions about the form of magmatic reservoirs, and hence the mechanisms responsible for crustal contamination in Skye. This approach is facilitated in Skye by Pb isotope and other data which allow us to distinguish between upper and lower crustal contamination.

Our results for the Skye lavas and the Cuillins Complex (see also the note added in proof) showed that contamination decreased with time in both the lower *and* upper crust in a manner that is not consistent with the operation of the advancing, periodically replenished, periodically tapped, continuously fractionated magma chamber' described by O'Hara & Matthews (1981). However, while our results show that such chambers were not a major influence in the evolution of the Tertiary basic rocks, we would not rule out their existence in Skye entirely. Indeed, our results show that the Redhills granites had a complex evolution involving two cycles of increasing upper crustal contamination with time, probably corresponding to the development of advancing, periodically replenished and tapped magma chambers below the W and E Redhills granite centres.

O'Hara now suggests that the special case of a non-advancing, sill-like, magma chamber located at the top of the upper mantle could produce a *decrease* in the degree of lower crustal contamination with time, provided that renewed magma-crust interaction was prevented by a process of 'crustal flotation'. Even this extreme model cannot be reconciled with our data base. This can be illustrated by reference to the Skye Main Lava Series (S.M.L.S.), since stratigraphic variations in lava composition can be considered to represent the effect of successive tappings of the lower crustal reservoir(s).

Although the Storr section lavas show an overall decrease in the degree of lower crustal contamination with time, examination of detailed temporal and spatial variations of composition within the S.M.L.S. shows that magma batches with *different* pre-eruption histories, that had suffered *different* degrees of contamination, were available for eruption at the *same* time, while magma batches with *similar* pre-eruption histories, that had suffered *similar* degrees of contamination, were erupted from different vents at *different* times during the formation of the lava pile. Coupled with the evidence for a migration of the centre of igneous activity with time (Anderson & Dunham, 1966), this clearly implies that not only were several distinct lower crustal magma chambers available for tapping at any one time, but that such reservoirs were continuously being formed throughout the emplacement of the S.M.L.S.

The ability of S.M.L.S. magmas to systematically 'sweat out' the sparse but widespread leucocratic minor sheets within the Lewisian basement, while failing to assimilate the more refractory intermediate gneisses which form the bulk of the crust, suggests that the magma reservoirs involved had a high surface-area to volume ratio, and leads to the intrusive plexus model described by Thompson (1982). Similar conclusions were reached by Cox (1980) when he noted that 'injection at a variety of similar but not identical levels is a more plausible model' for the plumbing of flood basalt vulcanism, than a single reservoir at the seismic Moho.

References

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Note added in proof (18 *November* 1983). Since the meeting, further evaluation of the fieldwork has shown that the Inner Eucrite (LR92) is younger than the Inner Allivalite, and should be number 34, not 29, in the Cuillins section. This makes the data for the upper part of the Cuillins Complex consistent with our overall model.