The role of fractional crystallization in the formation of granitic and intermediate rocks of the Beinn Chaisgidle Centre, Mull, Scotland

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ABSTRACT. Major and trace element data are presented for the basic, intermediate, and acid rocks of the Beinn Chaisgidle Centre of the Tertiary igneous complex on the Isle of Mull. The variation in the bulk chemical composition, the iron enrichment trend in the clino-pyroxenes, the systematic decrease in concentrations of the transition metal cations, and the increase in the incompatible elements suggest that the magma from which these rocks formed underwent crystal fractionation. The rocks show a coherence of rare earth element patterns for all the rocks in the sequence, and there is a progressive increase in negative Eu anomaly with increasing silica content.

THE igneous rocks of Mull include an extensive sequence of basaltic lavas, which have been intruded by the Central Intrusive Complex. The rocks of the intrusive complex have been ascribed to three succeeding centres, or foci, of igneous activity and the rocks from the second centre (the Beinn Chaisgidle centre) form the subject of this paper.

A comprehensive account of the Tertiary igneous geology of Mull, including a full account of the Beinn Chaisgidle rocks, was given in the 'Mull Memoir' (Bailey et al., 1924). This classic account described the detailed relationships between the igneous rocks of Mull, and introduced the concept of magma series. Implicit to the Mull Memoir's account of the granitic rocks was the idea that the granites were the end product of an evolutionary process from basic magma. It was widely accepted that granitic rocks originated from a basaltic parent magma until Wager and co-workers suggested an origin for the Skye granites by partial melting of older crustal material. Conscious of the problems of deriving what appeared to be a large volume of granitic material by fractionation from basic magma, and the apparent absence of intermediate rocks, Wager and his colleagues proposed that the granites crystallized from magmas largely formed by fusion of sialic material. These ideas

were developed in several publications on the origin of the Tertiary granites, including Wager (1956), Brown (1963), Bell (1966), Dunham (1967), Le Bas (1967), and Thompson (1969). Support for the partial fusion hypothesis was provided by studies of the Sr isotope compositions of the Skye granites (Moorbath and Bell, 1965), and it is probably the preferred model at the present day. However it has also been recently argued that the granitic rocks are largely derived by fractional crystallization of more basic magma (Thorpe et al., 1977 and Meighan, 1979). Furthermore, Carter et al. (1978) argued from Sr and Nd isotopic data that the basic rocks may have been contaminated with Lewisian Sr and Nd, thus complicating interpretation of the isotopic data.

A detailed study of the Mull granitic rocks (Walsh et al., 1979) demonstrated that there are two groups of granitic rocks in Mull. The early granites (the granites associated with Centre 1, Loch Uisg, Derrynaculen, Glas Bheinn, etc.) are distinct from the granites in Centres 2 (Beinn Chaisgidle) and 3 (Loch Ba). It was shown on the basis of major, trace element, REE and Sr isotope data that, whereas the early 'primitive' Centre 1 granites had formed predominantly by partial melting of older siliceous material, the Centre 2 and 3 granites had formed predominantly by fractional crystallization from basaltic parent magmas. It was, however, suggested that neither of these processes had occurred under 'closed system' conditions.

To demonstrate that granitic rocks have formed by fractional crystallization from basaltic parent, it is desirable to show that there exists a continuum of chemical compositions from basic, *through intermediate*, to acid rock; and that the chemical variations found in such a series of rocks are characteristic of a fractionation sequence. The study of the Mull granites (Walsh et al., 1979) referred to the presence of basic and intermediate rocks in the

Beinn Chaisgidle Centre, and the purpose of this paper is to document the variations in the major, trace, and *REE* for these rocks, and to assess the extent to which they provide evidence of a fractionation sequence.

A detailed account of the petrography and field relationships of the rocks of the Beinn Chaisgidle Centre is given in the Mull Memoir (Bailey *et al.*, 1924). An excellent section through the rocks of the centre is exposed in the gorge of the Allt Molach, running almost due west from the A869 road (NGR 630314). This section runs across the strike of the rocks and enables a representative collection of fresh rocks from the centre to be collected. The samples used in this study were taken from the Allt Molach section, and the numbers of the intrusions follow those used in the Mull Memoir account. In addition, samples were col-

lected from the Loch Airdeglais granophyre, lying to the south of the A869 (NGR 627288), which is known to be part of the Beinn Chaisgidle sequence of intrusions (Walsh *et al.*, 1979). Table I gives the sample locations and brief petrographic notes on the intrusions; full details of the petrography are given in the Mull Memoir (Ch. 29).

Nomenclature for the rocks is somewhat problematical. The Mull Memoir refers to intrusions 1, 3, 5, 7, 9, 10, and 13 as 'quartz gabbro' (or quartz-dolerite) and 2, 4, 6, 8, 11, and 12 as 'granophyre'. The term quartz gabbro (or dolerite) would be acceptable for intrusions 1, 7, 9, 10, and 13 (although intrusion 1, the Glen More ring dyke, is a variable mass and is more acidic in composition in some parts). However, as Table II shows, intrusions 3 and 5 are of intermediate (dioritic) composition. In addition the term 'granophyre' (used in the

TABLE I. *Ring intrusions from the Beinn Chaisgidle Centre*

Rock names given follow Mull Memoir (Bailey *et al.*, 1924), but see text for discussion. Sample locations for intrusions 1, 2, and the Loch Airdeglais granophyre shown on OS Sheet 49, samples from intrusions 3–13 inclusive are from the gorge of the Allt Molach, Mull Memoir fig. 52. Detailed petrography of the rocks is given by Bailey *et al.*, 1924 (Ch. 29).

INTRUSION 1. Quartz-gabbro (Glen More Ring Dyke). M13 (641325), M16 (641326). Gabbros with plagioclase (40–50%) and subordinate alkali felspar and quartz, clinopyroxene (25%), Fe–Ti oxides (10–15%), and some chlorite.

INTRUSION 2. Porphyritic felsite (Ishriff Ring Dyke). M721 (635319), M720 (631316). Porphyritic acid rocks containing some plagioclase and small amounts of pyroxene and Fe–Ti oxides.

INTRUSION 3. 'Quartz-gabbro.' M311, M322. Rocks contain plagioclase and significant amounts of alkali felspar and quartz, clinopyroxene (10%) altering to chlorite and some Fe–Ti oxides.

INTRUSION 4. Pyroxene granophyre. M713. Acid rock with altered felspar, small amounts of clinopyroxene, epidote, and chlorite, with 1–3% Fe–Ti oxides.

INTRUSION 5. M523, M524. Rocks similar to Intrusion 3.

INTRUSION 6. Pyroxene-felsite. M718. Contains 1% clinopyroxene and small amounts of Fe–Ti oxides, epidote, and chlorite.

INTRUSION 7. Quartz-gabbro. ME722. Fresh gabbroic rock, with more mineralogical variations between samples than other intrusions. ME722 contains more augite than other intrusion 7 samples, small amounts of olivine, and only very small amounts of Fe–Ti oxides.

INTRUSION 8. Porphyritic granophyre. M717. Coarser grained, porphyritic granophyre with abundant quartz.

INTRUSION 9. Quartz-gabbro. M913, M91, M923. (Specimens all similar.) Coarse grained gabbro with 40–50% plagioclase, small amounts of alkali felspar and quartz, clinopyroxene (25%), chlorite (10%), and Fe–Ti oxides (10–15%).

INTRUSION 10. Quartz-dolerite. M010B. Dolerite with clinopyroxenes showing alteration to chlorite.

INTRUSION 11. Pyroxene granophyre. M715. Quartz, alkali felspar with some plagioclase. Fe–Ti oxides (2–4%) and clinopyroxene (1–2%) often altered to chlorite.

INTRUSION 12. M714. A more porphyritic acid rock than intrusion 11 granophyre.

INTRUSION 13. Quartz-dolerite. M013A. Coarser grained than M010B, but finer grained than the 'gabbros' from the Centre.

LOCH AIRDEGLAIS GRANOPHYRE. M731 (627288), M732 (628286). Quartz + alkali felspar acid rock.

(Sample locations for acid rocks also given in Walsh *et al.*, 1979.)

Survey mapping as a field term) is not really appropriate for many of the acid rocks. The chemical compositions presented in Table II demonstrate that these so-called 'granophyres' include rocks with < 65% SiO_2 (intrusion 2) and even 'granite' would not really be appropriate. Attempting to apply the classification used by Streckheisen (1976) for the 'quartz–feldspar group' would term the Beinn Chaisgidle acid rocks as rhyodacites and rhyolites. However, the Mull Memoir rock names are well established and therefore to avoid adding to the confusion by adopting new terminology, the general terms 'basic' (intrusions 1, 7, 9, 10, and 13), 'intermediate' (intrusions 3 and 5), and 'acidic' (intrusions 2, 4, 6, 8, 11, and 12) have been used in this account.

The age relationships between the Beinn Chaisgidle intrusions, which are discussed by Bailey et al., 1924 (Ch. 29), are not known with any certainty. Intrusion 1 is not the first intrusion formed, and indeed was probably intruded late in the Beinn Chaisgidle sequence. The available data on the time relationships of the intrusions is also discussed by Skelhorn et al. (1969). Specific time relationships can be established: for example, intrusion 4 has a chilled contact against intrusion 5, but in many cases evidence of relative ages is lacking, and an overall time sequence cannot be established.

Chemical analyses. Although the Beinn Chaisgidle rocks can be divided into the three general

groups, there are some variations between the intrusions in each group in their bulk chemical compositions, given in Table II. Intrusion 7 appears to be more 'basic' in composition than the other basic masses, but it is rather less homogeneous than the other intrusions, with local concentrations of mineral phases; the analysis given in Table II (ME 722) is somewhat more basic than other rocks from this intrusion. There are substantial differences in the compositions of the 'acidic' intrusions; the Ishriff ring intrusion (intrusion 2) is clearly 'subacidic', for example, whereas the Loch Airdeglais intrusion, and to a lesser extent intrusion 8, are the only truly acid granites. There is also some variation in composition within the intrusions, and intrusion 1 (the 'Glen More Ring Dyke') has an acid facies in parts of its outcrop (analyses given in Table II are examples of the more 'typical' basic facies). The variation shown in the Glen More Ring Dyke was cited in the Survey account as an example of 'gravitational differentiation' (Bailey et al., 1924, Ch. 30).

Considered together, the compositions given in Table II for the Beinn Chaisgidle rocks indicate that there is a considerable range of rock compositions, with SiO_2 contents, for example, varying form 47 to 73%, and there are comparatively few gaps in this range.

The petrographic notes in Table I, together with the detailed petrography in the Mull Memoir,

TABLE II Representative major and trace element analyses for the Beinn Chaisgidle Centre, Isle of Mull

wt. %	Intrusion 1		Intrusion 2		Intrusion 3		Int.4	Intrusion 5		Int.6	Int.7	Int.8	Intrusion 9			Int.10	Int.11	Int.12	Int.13	Loch Airdeglais	
	M13	M16	M721	M720	M311	M322	M713	M523	M524	M718	ME722	M717	M913	M91	M923	MO108	M715	M714	MO13A	M731	M732
SiO_2	49.65	51.96	64.85	66.43	56.09	58.07	68.42	56.53	61.88	68.10	46.89	70.31	50.72	51.41	51.64	51.29	67.58	69.08	50.33	72.80	73.01
Al_2O_3	13.03	13.35	13.57	13.58	13.46	13.64	13.75	13.87	14.47	13.70	16.37	13.16	16.39	15.82	14.71	13.03	13.79	14.02	12.96	12.93	12.94
Fe_2O_3	7.28	4.02	1.15	2.85	4.47	4.68	2.67	3.92	4.25	2.85	1.63	2.38	2.94	3.98	2.82	4.24	2.95	3.08	4.84	2.08	2.10
FeO	8.29	9.16	5.01	4.02	7.22	6.32	2.28	7.30	4.75	2.97	7.19	2.29	6.83	6.96	9.16	9.89	2.67	1.55	9.37	1.19	0.86
MgO	4.51	3.99	0.51	0.23	2.19	1.62	0.25	1.72	0.88	0.34	10.17	0.10	5.25	4.82	4.69	3.71	0.62	0.27	4.50	0.06	0.05
CaO	8.42	7.93	2.71	2.31	5.02	4.34	1.44	4.55	3.40	1.88	11.53	1.33	10.95	10.04	9.25	6.79	2.11	1.20	7.49	0.92	0.83
Na_2O	3.20	3.47	4.40	4.80	4.61	4.52	4.71	4.25	4.63	4.60	1.54	4.63	2.81	2.94	3.01	3.95	4.48	4.84	3.35	4.15	4.18
K_2O	1.30	1.05	3.63	4.11	2.75	3.00	4.45	3.09	3.28	4.33	0.32	4.52	0.63	0.62	1.01	1.48	4.08	4.70	1.34	4.72	4.91
H_2O+	1.25	1.73	1.54	0.56	0.97	1.03	0.20	1.61	0.58	0.23	2.99	0.03	1.39	1.24	1.21	2.33	1.21	0.21	2.23	0.29	0.21
H_2O-	0.31	0.42	-	-	0.24	0.11	0.80	0.40	0.16	-	0.39	0.31	0.44	0.22	0.29	0.24	0.03	0.34	0.59	-	-
TiO_2	2.15	1.89	0.76	0.64	1.93	1.52	0.55	1.73	1.06	0.67	0.43	0.46	1.05	1.50	1.49	2.18	0.71	0.54	2.23	0.30	0.26
P_2O_5	0.29	0.36	0.16	0.11	0.70	0.63	0.09	0.59	0.34	0.14	0.02	0.06	0.16	0.15	0.20	0.40	0.19	0.09	0.46	0.00	0.02
MnO	0.23	0.22	0.17	0.22	0.26	0.24	0.15	0.26	0.21	0.17	0.16	0.14	0.18	0.19	0.21	0.30	0.18	0.16	0.24	0.09	0.08
TOTAL	99.91	99.55	99.82	99.86	99.91	99.72	99.76	99.82	99.89	99.98	99.63	99.72	99.74	99.89	99.69	99.83	99.60	100.08	99.84	99.53	99.45
Trace elements (ppm)																					
Ba	446	504	1109	1319	1002	1029	1170	1009	1052	1112	84	1006	202	263	329	573	944	1292	540	931	968
Co	47	40	7	6	21	17	5	17	13	7	45	6	34	37	37	35	6	5	37	5	5
Cr	14	17	0	0	5	4	0	8	20	9	264	6	82	73	25	5	9	8	40	12	12
Cu	84	104	7	4	6	6	4	6	5	7	23	6	96	103	94	5	6	4	21	7	8
Li	17	15	24	19	17	16	8	26	14	11	27	13	22	25	22	23	9	5	32	7	12
Nb	8	8	19	21	17	14	24	16	20	23	0	28	4	7	4	8	23	25	10	23	22
Ni	36	28	3	4	11	10	2	12	10	4	136	3	53	46	40	17	3	3	25	2	2
Rb	34	26	104	121	67	80	130	88	82	127	6	156	14	23	22	36	130	126	33	170	175
Sc	44	36	12	13	22	20	8	20	14	10	33	6	39	39	41	36	12	8	34	7	5
Sr	265	281	162	141	272	241	80	230	208	106	190	58	241	249	238	196	114	73	300	52	41
V	470	312		6	62	44	4	39	16	8	132	4	226	283	293	302	13	4	291	3	3
Y	49	60	79	92	85	90	86	81	91	91	10	103	37	45	50	60	87	73	51	97	89
Zn	116	111	87	133	137	131	103	142	128	117	76	148	91	105	109	111	104	66	120	85	80
Zr	159	224	417	427	318	353	506	319	428	517	18	627	108	143	160	159	466	535	177	534	517

indicate that the Beinn Chaisgidle rocks are reason-
ably free from post-magmatic alteration. The
amount of phenocryst phases found in the rocks
is not large, although certainly not entirely absent.
The rocks do not show any significant igneous
layering, but some of the intrusions are not
mineralogically homogeneous. The granites are
known to have exchanged oxygen by interaction
with meteoric water; the rocks have $\delta^{18}O$ values
ranging from -1.1 to -4.0, and these values fall
within the range for other Mull granites (Walsh et
al., 1979). It has been demonstrated for the Mull
Loch Uisg Granophyre (Pankhurst et al., 1978)
and for the Mull granites as a whole, including the
Beinn Chaisgidle granites (Walsh et al., 1979) that
interaction with meteoric water has not substan-
tially altered the major, trace element, or Sr isotopic
compositions. It would be reasonable to extend
this conclusion to the basic and intermediate rocks
of Beinn Chaisgidle. On balance, therefore, it is
hoped that the analyses given in Table II are
reasonably indicative of magmatic compositions.
However, the analyses are from plutonic igneous
rocks and some caution should be exercised in too
literal an interpretation of the compositions,
especially the major elements. It would probably
not be justified to treat them as direct equivalents
of non-porphyritic fine-grained extrusive rocks,
and detailed geochemical modelling of the data has
not been attempted.

The variation in bulk composition for the Beinn
Chaisgidle rocks can be seen in fig. 1a and b, the
AFM ($Na_2O + K_2O - FeO_{total} - MgO$) and Na_2O-
K_2O-CaO plots. Despite some reservations in the
interpretation of the analyses it is possible to
suggest that the plots demonstrate the existence of
systematic relationships between the intrusions.
The AFM plot shows the rock compositions closely
following the typical 'tholeiitic' iron enrichment
trend which has been documented elsewhere
(Wager and Brown, 1968; Smith and Kapp, 1963;
Carmichael, 1964). The degree of enrichment is
however less than the extreme iron enrichment
trend found in the Skaergaard (Wager and Brown,
1968). The more basic rocks usually found in a
tholeiitic fractionation sequence are not well repre-
sented in the Beinn Chaisgidle rocks. However, the
later stages of fractionation are well covered, and
the AFM plot would appear to indicate that the
Beinn Chaisgidle rocks represent a sequence of
compositions that provide as good an example of
an evolved tholeiitic fractionation sequence as
any other so far documented. Further evidence
of the fractionation and close genetic relation-
ship between the rocks is demonstrated by the
linear plot shown on the Na_2O-K_2O-CaO plot
(fig. 1b).

Fig. 2 shows selected trace element concentra-
tions plotted against a 'differential index' ($\frac{1}{2} SiO +$
$K_2O-CaO-MgO$). The selection of an index of
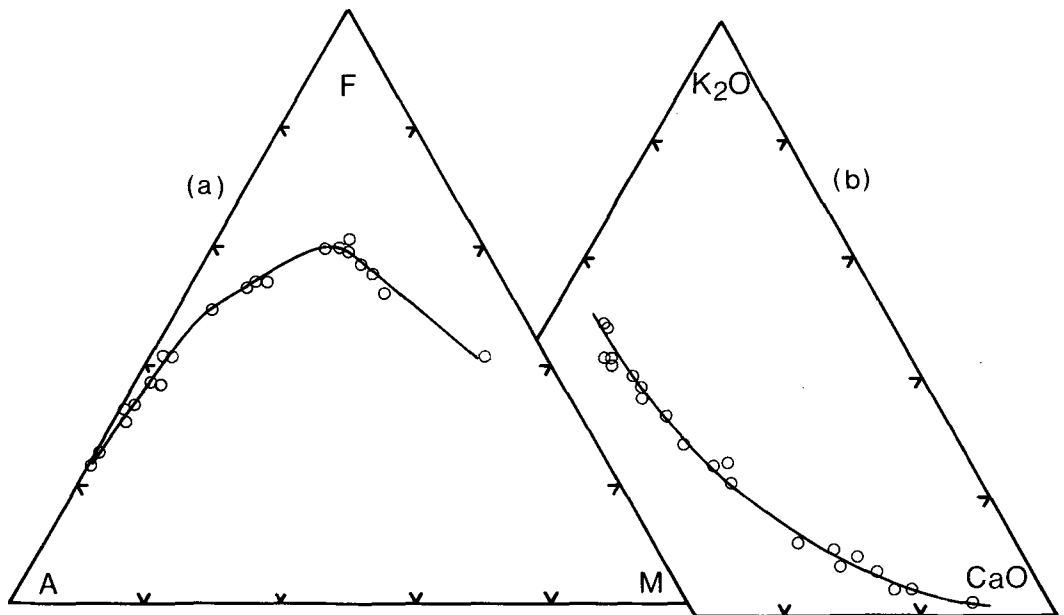
FIG. 1 (a). AFM ($Na_2O + K_2O - FeO_{TOTAL} - MgO$) diagram. (b). Na_2O-K_2O-CaO diagram for the Beinn Chaisgidle
rocks.

differentiation presents considerable difficulties, and many variables have been used in the literature (see discussion by Wilcox in Yoder, 1979). The most straightforward, and easily understood, index that is commonly used is SiO_2 content. This works well for intermediate and acid rocks, but is not suitable for basic rocks. Differentiation or fractionation trends for basic rocks may be well shown by plotting selected trace elements against MgO content, or the $Fe_2O_3/(Fe_2O_3 + MgO)$ ratio, but these often do not show significant variations for more acidic rocks. The index ($\frac{1}{3}$ $SiO_2 + K_2O-CaO-MgO$) was used here as it clearly distinguishes between the different rocks of the Beinn Chaisgidle suite. It is not entirely satisfactory because it cannot be readily related to mineralogical trends in the rocks. However, it is well established in the literature (e.g. Carmichael, 1964) and the values obtained faithfully reflect the sequence in the Na_2O-K_2O-CaO and AFM diagram trend line, and this latter trend is generally recognized as a good index of fractionation for tholeiitic rocks.

The extent of the role of fractional crystallization in the formation of the rocks of the Beinn Chaisgidle centre can be judged from the plots of selected metal cations from the first transition series against the index shown in fig. 2. This plot shows also the magnitude of the octahedral site preference energies (OSPE) for the most likely valency states of these cations. The influence of octahedral site preference energy on the relative rates of removal of the transition metals from a fractionating basic magma is well documented (Curtis, 1963; Burns and Fyfe, 1966; Burns, 1970; Henderson and Dale, 1968). More recent work, notably Jensen (1973) and Henderson (1979), has emphasized that the small differences in ionic radii between the transition metal cations should not however be ignored. Furthermore Whittaker (1978) and Henderson (1979) refer to the inadequacy of using octahedral site preference energy alone to establish predicted orders of uptake into crystallizing phases from a silicate melt. These workers point out that the possible existence of fivefold co-ordination sites within the silicate liquid melt must also be considered. In spite of these reservations the overall sequence of rates of removal for elements such as Cr, Ni, Co, and Sc is well established, and the Skaergaard data, for example, are recognized as demonstrating the value of octahedral site preference energies in predicting transition element behaviour.

The trends shown by the transition metal concentrations in the calculated liquid compositions for the Skaergaard intrusion are well known, and need only be summarized briefly here. Wager and Brown (1968) documented the trace element varia-

tions in the Skaergaard intrusion and showed that the initial magma contained about 170 ppm Cr, and that this decreased to less than 10 ppm when some 85 % of the intrusion had crystallized. Ni fell from 180 ppm in the original magma to less than 10 ppm with some 95% crystallized and Co fell from 55 ppm to less than 5 ppm with some 98 % of the intrusion crystallized. Vanadium appears to have built up in the original Skaergaard magma from 190 ppm to 300–400 ppm, and then with magnetite becoming a major cumulus mineral the concentration fell rapidly. Similar trends, which are taken as a general characteristic of fractionating tholeiitic magma, have been noted in other examples, e.g. Thingmuli in Iceland (summarized by Carmichael et al., 1974).

Fig. 2 demonstrates very comparable trends for the transition metal contents of the Beinn Chaisgidle rocks when plotted against the differentiation index. Cr^{3+}, with a high OSPE, falls even more rapidly than Ni^{2+}. Co, with a relatively small OSPE, shows a more modest rate of decrease, and Sc (with an octahedral site preference energy of zero in its trivalent state) behaves in a very similar way to Co, but shows a very slightly slower rate of fall. As shown by the Skaergaard (and Thingmuli rocks, see Carmichael et al., 1974, p. 72) there is an increase, and then rapid decrease in the vanadium contents for the Beinn Chaisgidle rocks.

The incompatible elements Zr and Nb show a regular and systematic increase when plotted against differentiation index for the Beinn Chaisgidle rocks (fig. 2). Other trace element concentrations increase with increasing differentiation index, Ba, La, Ce, and Y for example, although in the final stages of the fractionation sequence they do not continue to increase. Rb increases throughout the sequence, and Sr is high in the rocks with low differentiation index, but then falls with increasing differentiation index values. P_2O_5 increases and then decreases, having notably high values in the intermediate rocks. The variation in the transition metals and other elements for the Beinn Chaisgidle rocks is clearly defined and is consistent with the rocks being related through fractional crystallization. Moreover the distribution of the transition metals (and other elements) excludes the possibility that mixing of basic and acid magma formed the intermediate rocks.

Clinopyroxenes. One other characteristic of fractionated tholeiitic sequences is an increasing iron concentration in the pyroxenes (Muir, 1951; Brown, 1957; Brown and Vincent, 1963; Atkins, 1969; Carmichael, 1960; Konda, 1970). Clinopyroxene is found in most rocks of the Beinn Chaisgidle centre, although the amounts in the acid
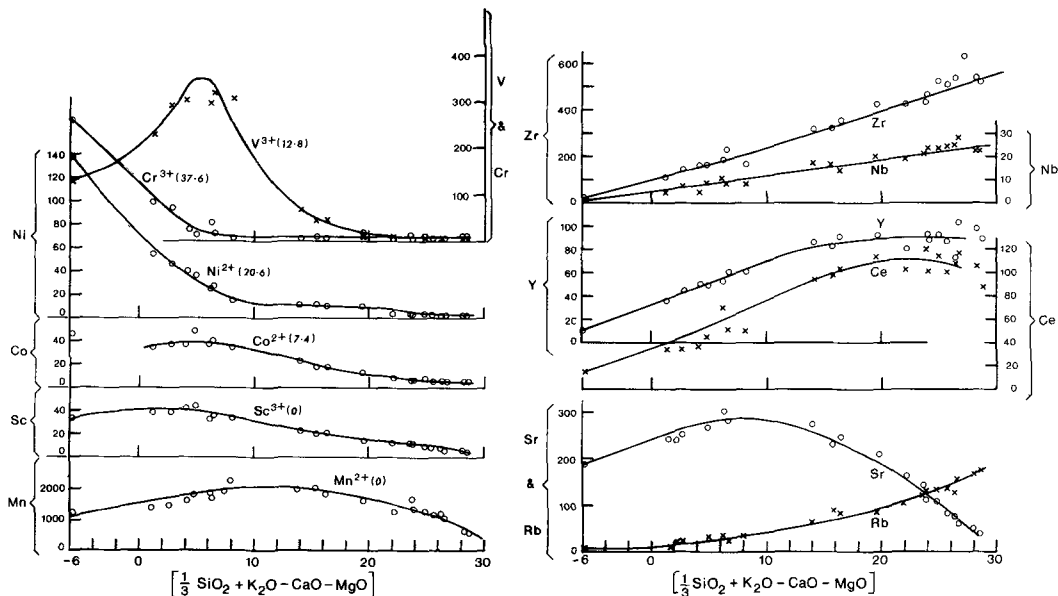
FIG. 2. Selected trace elements (as ppm) plotted against differentiation index. The OSPE (octahedral site preference energies) for the transition metals are given in K cal/mole for the most likely valency state. The rate of decrease from basic, through intermediate to acid rocks correlates with the magnitude of the OSPE for Cr, Ni, Co, and Sc. The trends closely follow those for other tholeiitic fractionation trends (e.g. Skaergaard); similarly the rise and fall in V, corresponding to magnetite precipitation. The incompatible elements, notably Zr and Nb, increase systematically with differentiation index, and Y and Ce show almost identical trends.

rocks are often very small. Fig. 3 shows the variation in bulk composition for the pyroxenes from the Beinn Chaisgidle rocks plotted in the pyroxene quadrilateral Di–Hd–En–Fs. The systematic iron enrichment shown by the basic, intermediate, and acidic rocks for Beinn Chaisgidle parallels that shown by the Skaergaard and Bushveld intrusions.

Rare earth elements. REE contents for twenty of the rocks from the Beinn Chaisgidle centre are given in Table III. The determinations were made using inductively coupled plasma spectrometry,
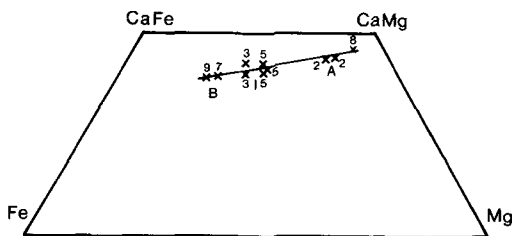
FIG. 3. The iron enrichment trend for the clinopyroxenes from the Beinn Chaisgidle basic (B), intermediate (I), and acid (A) rocks, plotted in the system $CaMgSi_2O_6$–$CaFeSi_2O_6$–$Mg_2Si_2O_6$–$Fe_2Si_2O_6$. The small numbers beside the data points refer to the intrusion number from which the rock came.

following the method of Walsh *et al.* (1981), which enables all the rare earths to be determined, excluding Tb and Tm, with analytical precision of 1–2 %. Fig. 4 shows the chondrite-normalized abundances of a representative range of these *REE* contents plotted on the conventional diagram. As almost all the *REE* have been determined the smooth patterns obtained may be taken as indicating a reasonable degree of analytical consistency. There is a systematic increase in absolute abundance of the *REE* from basic to intermediate to acid rocks, although intermediate and acid rocks show some overlap. More significantly there is a substantial uniformity in *RE* patterns (excluding Eu anomalies) between the different rock types, with no real change in light to heavy rare earth ratio. There is significant light *REE* enrichment in all the Beinn Chaisgidle rocks. However, from the range of *REE* measured it can be seen that the patterns tend to have a characteristic shape, with relatively little change in the chondrite-normalized abundances from Dy through to Lu.

The patterns obtained are consistent with (although not in themselves proof of) an origin by progressive fractionation from a basic magma for the Beinn Chaisgidle rocks. If the acid rocks of this centre were to have formed by melting from crustal

TABLE III. Rare earth element concentrations (in ppm) for the Beinn Chaisgidle Centre rocks

Sample	Intrusion 1		Intrusion 2		Intrusion 3		Int. 4	Intrusion 5		Int.6	Int.8	Intrusion 9			Int.10	Int.11	Int.12	Int.13	Loch Airdeglais	
	M13	M16	M721	M720	M311	M322	M713	M523	M524	M718	M717	M913	M91	M923	M010B	M715	M714	M013A	M731	M732
La	19.0	28.2	50.4	53.4	42.3	41.9	56.2	41.6	48.8	54.2	53.3	14.5	16.7	18.1	25.1	43.9	57.0	24.2	50.7	51.8
Ce	40.8	57.4	106.2	110.5	92.3	89.6	116.3	86.1	103.9	115.2	113.8	27.0	30.5	35.4	52.2	97.8	118.4	55.3	103.4	96.0
Pr	5.7	7.6	13.1	13.8	12.1	12.3	14.5	11.5	13.3	14.4	14.6	3.6	4.1	4.6	7.0	13.0	14.8	7.5	13.5	14.0
Nd	28.7	37.8	61.9	65.3	59.7	60.5	68.4	58.3	65.9	67.4	66.6	19.1	22.4	23.6	34.6	59.2	66.5	39.3	61.1	63.2
Sm	6.4	8.7	12.4	13.2	12.8	12.2	13.5	11.7	13.2	13.7	14.4	4.3	4.8	5.7	8.2	12.7	12.8	8.5	12.8	13.4
Eu	1.92	2.65	2.88	3.40	3.57	3.31	2.68	3.38	3.47	2.92	2.63	1.45	1.55	1.81	2.64	2.78	2.59	2.62	1.85	1.83
Gd	7.1	9.9	12.6	13.6	13.4	12.5	13.6	12.5	13.7	14.1	14.7	6.1	7.05	7.3	9.2	12.6	12.3	8.9	12.9	13.6
Dy	7.26	9.54	12.43	13.53	12.96	12.84	14.41	12.15	14.01	14.87	16.37	5.45	6.07	6.93	8.84	13.17	12.81	8.67	14.34	15.23
Ho	1.57	2.15	2.71	2.99	2.82	2.81	3.22	2.64	3.10	3.31	3.66	1.29	1.46	1.65	1.94	2.91	2.79	1.85	3.20	3.41
Er	4.35	5.7	7.2	8.7	7.4	8.1	9.3	7.9	9.3	10.1	11.4	4.0	4.5	4.8	5.45	8.5	8.3	5.2	10.1	10.5
Yb	4.00	5.50	7.16	8.23	7.27	7.29	9.44	6.64	8.57	9.56	10.59	3.08	3.40	3.96	4.78	7.82	7.56	4.40	9.41	9.79
Lu	0.62	0.91	1.13	1.31	1.13	1.14	1.49	1.04	1.35	1.50	1.63	0.54	0.59	0.66	0.78	1.20	1.15	0.68	1.46	1.51
Eu/Eu*	0.86	0.86	0.69	0.77	0.82	0.82	0.60	0.85	0.78	0.64	0.55	0.88	0.82	0.87	0.90	0.66	0.63	0.92	0.44	0.42

material, it would require that the source material happened to have a similar rare earth pattern to the basic magma.

Fig. 5 shows the plot of Eu/Eu* against SiO_2 content for the Beinn Chaisgidle rocks. The systematic relationship between these variables shown by these rocks is what would be predicted for a series of rocks formed by a fractionation sequence. The decrease in Eu/Eu* (Eu* derived by extrapolation between Sm and Gd) probably correlates with progressive removal of plagioclase (and alkali feldspar) from the magma. This was possibly enhanced

by changes in the oxidation state within the magma reservoir.

Conclusions. The published Sr isotopic data on these rocks shows the $^{87}Sr/^{86}Sr$ initial ratio (at 58.2 Ma) for the basic rocks is 0.70608, for the intermediate rocks initial ratios of 0.70596, 0.70597, and 0.70605 were obtained, and in the acidic rocks the initial ratios ranged from 0.70663–0.70868 (Walsh et al., 1979). There is therefore only a small increase in initial ratios in passing from basic through intermediate to acidic rocks and the Beinn Chaisgidle granites include the lowest ratios for any Mull
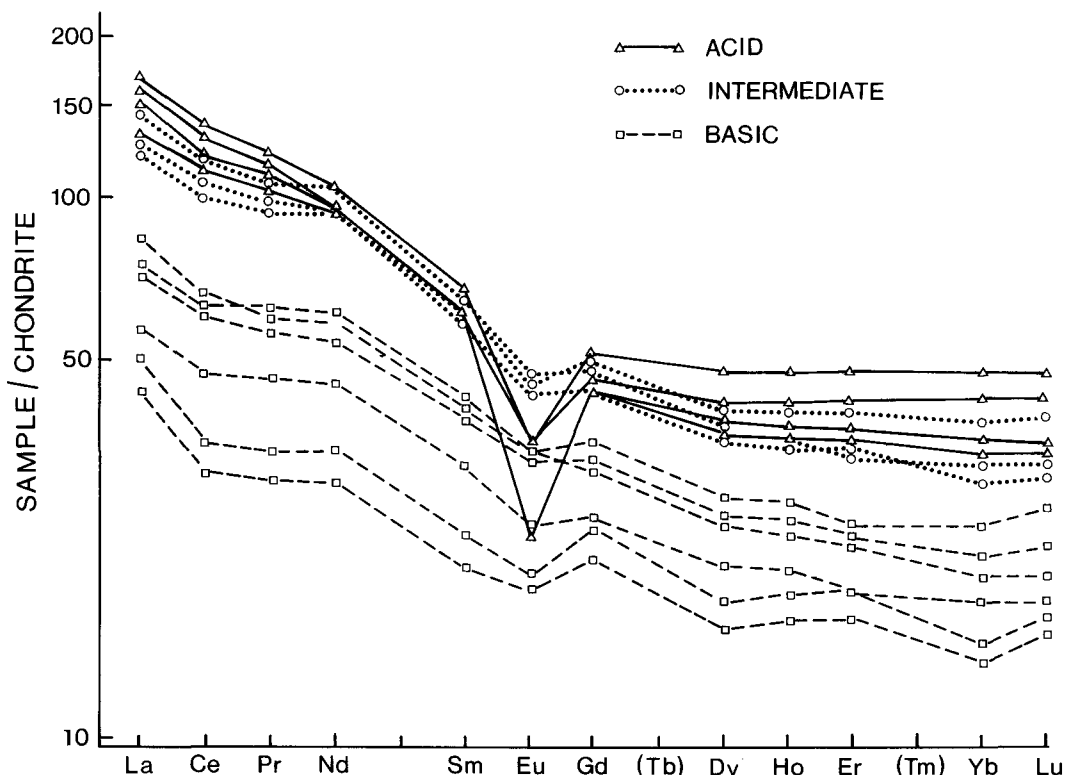
FIG. 4. Chondrite-normalized (Nakamura, 1974) *REE* patterns for the Centre rocks.
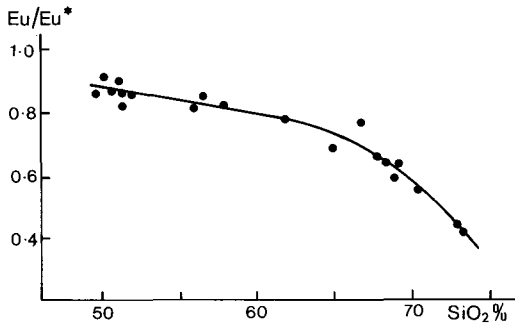
FIG. 5. Plot to demonstrate the increase in negative Eu anomaly with increased silica content.

granites, and indeed the lowest yet published for the Scottish Tertiary Province. It was suggested by Walsh *et al.* (1979) that the Beinn Chaisgidle granites had formed by crystal fractionation from basaltic parent magma and that the small increase in $^{87}Sr/^{86}Sr$ initial ratio was the result of fractionation under open system conditions with relatively small amounts of crustal material contributing to the source magma.

The chemical trends demonstrated in this paper for the basic, intermediate, and acidic rocks of Beinn Chaisgidle provide effective confirmatory evidence of this fractionation. The variations in bulk chemical composition, in the transition metals, in the incompatible elements, and in pyroxene chemistry all demonstrate that, in this particular example, granitic and intermediate magmas have formed by fractional crystallization from a basaltic parent magma.

The alternative hypothesis to crystal fractionation would be to suggest that the sequence of rock compositions found was the result of the mixing of acid magma (formed by melting of crustal material) with basic magma. In this instance such a hypothesis would be difficult to sustain. Magmatic mixing would not explain the different behaviour of the different transition metal cations, nor would it explain why elements such as Mn or P are higher in the intermediate rocks than either basic or acid members. It would be particularly difficult to account for the *REE* patterns by mixing of a crustal melt magma with a basaltic magma. The Sr isotope data would also put serious limitations on any source material for melting. However, it should be emphasized that we do not suggest that crystal fractionation is always the origin of acid magmas in the Tertiary Province, or even the most usual origin, only that it has occurred in this one instance.

It is not the intention of this paper to speculate on the nature of the magma chamber that formed

these intrusions. However, it is worth noting that these ring intrusions are intimately associated, and it is probable that they were formed from a single parent magma, over a relatively short period of time. There is no evidence of *in situ* fractional crystallization, although some small-scale mixing of magma may have occurred, and this could account for some of the variations in composition noted *within* intrusions. Furthermore the rock analyses given in Table II may not be fully representative of the overall magma composition of their intrusions (i.e. ME 722 is probably more 'basic' in composition than the magma composition of intrusion 7). Nevertheless the gross variations in chemistry described in this paper must be the result of crystal fractionation on a large scale, prior to intrusion. One plausible hypothesis for this would be that the magma chamber from which these rocks formed was itself zoned. The intimate association of these rocks, with no clearly defined time relationships for the basic, intermediate, and acid rocks, might therefore represent the tapping off from different levels of a zoned magma reservoir.

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