Thermal aspects of the origin of Hebridean Tertiary acid magmas. II. Experimental melting behaviour of the granites at 1 kbar P_{H_2O}

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ABSTRACT. Experimental melting equilibria at 1 kbar P_{H_2O} are reported for three early Tertiary granites from Skye and one from Rhum, together with a quartz monzonite from Ardnamurchan. The Hebridean Province leucogranites show cotectic melting behaviour, whilst associated 'primitive' (mostly adamellitic) acid plutons have silicate liquidi $\sim 925\,°C$ and plagioclase liquidi $\sim 875\,°C$. At such high temperatures the more-fusible crustal rock types of the region would be almost completely molten. If the Tertiary 'primitive' acid magmas were simple crustal melts, they would inherit the incompatible element ratios of their sialic progenitors. This is demonstrably not so. Minor element ratios in these plutons are consistent with extensive fractional crystallization during the evolution of their magmas. But it is, in most individual instances, extremely difficult to specify, either by thermal or geochemical arguments, whether (1) fractional crystallization followed sialic contamination of basic magmas or (2) mixing occurred between fractionation residua and sialic melts. Both the minor element ratios and cotectic melting behaviour of the Hebridean Province leucogranites are consistent with the view that they are products of extreme fractional crystallization of (sial contaminated) more-basic magmas. Nevertheless, it is clear—when the sequence and timing of emplacement of acid magmas within individual intrusive centres is considered—that very complex polycyclic combinations of fusion, fractionation, and re-fusion were involved in the evolution of these granites.

The solidi of the samples studied experimentally, together with published data, show a progressive rise in temperature as the compositions of the rocks diverge from the minimum melting composition in $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 at 1 kbar$_{H_2O}$. This relationship is important when considering the likely nature of sialic contamination of basic to intermediate continental magmatic suites fed through reservoir systems which are swarms of dykes and, or, sills. Because salic low-solidus crustal rock types also show near-cotectic melting behaviour,

the composition of the contaminant may be strongly biased towards these (usually minor) crustal units, rather than the 'bulk' or average crustal composition.

THE main objective of this study is to use data from melting experiments to place thermal constraints upon the various current hypotheses concerning the genesis of the acid magmas in the Hebridean Tertiary Igneous Province. Part I (Thompson, 1981) was concerned with the melting behaviour of representative samples of the major fusible crustal rock types in that area. This part reports the melting behaviour at 1 kbar P_{H_2O} of five samples of acid plutons, from Skye, Rhum, and Ardnamurchan. These were chosen to span the range of compositions occurring in the Province (fig. 3). Their petrographic nomenclature is problematical because the published names of all the major acid plutons in the Province include references to textural or compositional attributes, such as Granophyre, Felsite, Granite, or Epigranite. Ignoring their textures, the compositional limits of the Hebridean Tertiary Province acid plutons are as follows.

The leucogranites are plagioclase-free alkali feldspar granites (Streckeisen, 1973), consisting of quartz and alkali feldspar, together with negligible amounts of mafic minerals. The term leucogranite is preferred to alkali feldspar granite for these plutons because it avoids ambiguity about their peralkalinity; some of them are peralkaline whilst others are not (Thompson, 1982a). Most of the other acid plutons are granites in the nomenclature of Streckeisen (1973) but show a substantial range of ratios of plagioclase to alkali feldspar. In the

more mafic samples, plagioclase exceeds one-third of the total feldspar (e.g. Thompson, 1969) and the rocks would be called adamellites by most UK petrologists.

Each of the samples used in the melting experiments is typical of its pluton. Their petrographic descriptions are in the appendix and their chemical analyses are given in Table I. The compositions of most Hebridean Tertiary acid major plutons lie within the range limited by samples SK 127 (leuco-granite), SK 69 (potassic 'adamellitic' granite), and 450 (sodic 'adamellitic' granite). Two rare but

TABLE I. Chemical analyses and C.I.P.W. norms of samples used in melting experiments

Sample	SK 69	SK 127	SK 884	450	MS 76
SiO_2	69.79	77.12	72.58	70.34	59.75
Al_2O_3	13.68	11.11	12.73	12.89	16.61
Fe_2O_3	0.71	1.72	2.04	2.97	3.27
FeO	3.17	0.71	1.69	2.41	3.24
MnO	0.04	0.02	0.10	0.11	0.38
MgO	0.56	0.06	0.65	0.68	2.15
CaO	1.60	0.11	1.45	1.98	4.10
Na_2O	4.00	3.55	2.94	4.26	4.22
K_2O	4.67	4.90	3.34	3.00	3.41
H_2O^+	0.48	0.17	1.26	0.18	0.81
H_2O^-	0.11	0.17	*	0.08	*
CO_2	0.25	n.f.	0.23	n.f.	0.29
TiO_2	0.52	0.15	0.72	0.85	1.22
P_2O_5	0.25	Tr	0.11	0.19	0.21
	99.83	99.79	99.84	99.94	99.66

C.I.P.W. norms

Q	23.8	37.5	39.33	29.29	10.81
Or	27.6	29.0	19.76	17.70	20.15
ab	33.8	29.9	24.86	36.03	35.72
an	4.7	-	5.09	7.21	16.30
C	0.3	-	2.41	-	-
ac	-	0.1	-	-	-
di	-	0.4	-	1.23	0.75
hy	5.9	-	2.03	1.88	6.93
mt	1.0	1.9	2.96	4.31	4.75
hm	-	0.4	-	-	-
il	1.0	0.3	1.37	1.61	2.32
ap	0.6	Tr	0.25	0.40	0.47
cc	0.6	-	0.52	-	0.66

SK 69 Glamaig Granite, Western Redhills, Skye (Thompson, 1969 Table 3).

SK 127 Southern Porphyritic Granite, Western Redhills, Skye (Thompson, 1969, Table 3).

SK 884 Coire Uaigneich Granite, centre of pluton at foot of Coire Uaigneich (NG541216). Analysed by Geochemical Laboratories, Manchester University.

450 Granophyre, Long Loch, Rhum (Dunham, 1968). Analysed by P.J. Watkins, Imperial College.

MS 76 Quartz monzonite, Centre 3, Ardnamurchan. (NM472684). Analysed by Geochemical Laboratories, Manchester University.

* Powders dried at 110°C before analysis.

TABLE II. Selected results of melting experiments on Hebridean Tertiary acid rocks at 1kb$_{H_2O}$

Temp. (°C)	Time (days)	Products	Remarks
SK 69 Glamaig Granite, Skye			
902	17	Bi, Cpx, Ox, Gl	>95% Gl + vapour phase Bi.
852	17	Pl, Bi, Cpx, Ox, Gl	Trace of Pl.
815	26	Pl, Bi, Cpx, Ox, Gl	+ vapour phase Bi.
780	21	Am, KF, Pl, Bi, Ox, Gl	+ vapour phase Bi.
752	32	Am, KF, Pl, Ox, Gl	
742	27	Qz, Am, KF, Pl, Ox, Gl	"
720	19	Qz, Am, KF, Pl, Ox	Solidus ∿ 730°C.
SK 127 Southern Porphyritic Granite, Skye			
850	7	Ox, Gl	
755	27	Ox, Gl	+ quench Acmite.
750	21	Qz, Ox, Gl	Trace of Qz; silicate liquidus 752°C.
735	32	KF, Qz, Ox, Gl	
717	30	KF, Qz, Ox, Gl	
710	35	KF, Qz, Ox	Solidus 715°C.
SK 884 Coire Uaigneich Granite, Skye			
923	22	Opx, Ox, Gl	> 95% Gl.
858	21	Pl, Qz, Opx, Ox, Gl	Ox = Mt + Ilm.
804	21	Am, KF, Pl, Qz, Opx, Ox, Gl	
741	27	Cpx, Am, KF, Pl, Qz, Opx, Ox, Gl	Trace of Opx. Gl??
732	18	Cpx, Am, KF, Pl, Qz, Opx, Ox	Solidus = 735°C. Trace of Opx.
450 Granite, Long Loch, Rhum			
993	5	Ox, Gl	>90% Gl + quench Am.
937	21	Ox, Gl	+ quench Am.
890	5	Cpx, Ox, Gl	Silicate liquidus ∿920°C
852	17	Pl, Cpx, Ox, Gl	
785	24	Am, Pl, Cpx, Ox, Gl	Trace of Am.
766	22	Bi, Qz, Am, Pl, Cpx, Ox, Gl	Trace of Bi.
741	27	KF, Bi, Qz, Am, Pl, Cpx, Ox	Solidus ∿750°C
MS 76 Monzonite, Centre 3, Ardnamurchan			
1019	9	Pl, Cpx, Am, Ox, Gl	∿90% Gl, Trace of Pl. + quench Am & vapour phase Bi.
993	5	Bi, Pl, Cpx, Am, Ox, Gl	+ vapour phase Bi.
766	22	Bi, Pl, Cpx, Am, Ox, Gl	+ vapour phase Bi.
741	27	KF, Qz, Bi, Pl, Cpx, Am, Ox	Solidus ∿750°C.

Abbreviations: KF = alkali feldspar, Qz = quartz, Pl = Plagioclase, Bi = Biotite, Am = Amphibole, Cpx = Ca-rich clinopyroxene, Opx = Orthopyroxene, Ox = Fe - Ti oxides, Gl = Glass.

important variants are represented by sample SK 884, from the unusual normative-quartz-rich Coire Uaigneich pluton of Skye (Dickin and Exley, 1981), and by MS 76, the quartz monzonite of Centre 3, Ardnamurchan. Although this small group of samples adequately represents the entire Hebridean Tertiary Province for the specific purposes of this paper, it should be emphasized that a much more detailed experimental study of many more samples would be needed to elucidate fully the crystallization of the acid magmas in any one of the intrusive complexes.

The experimental methods used in this work were described in Part I, together with a discussion of the identification of stable and quench phases. The results of the experiments are listed in Table II. They shed light on several topics, as follows.

Comparison of liquidi of samples and melting behaviour of country rocks. The liquidus of leucogranite SK 127 is 752 °C at 1 kbar$_{H_2O}$. This is only 37 °C above both the solidus of this rock and the minimum melting temperature (715 °C) in the synthetic system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 at 1 kbar$_{H_2O}$ (Tuttle and Bowen, 1958). SK 127 could therefore, on thermal grounds, be either a product of extreme fractional crystallization or a cotectic partial melt of any igneous, metamorphic or sedimentary country rock type which begins to fuse at the 'granite' minimum. There are no other thermal restraints on its genesis. Nevertheless, chemical data can be used to throw considerable light on the evolution of the Southern Porphyritic Granite magma (Thompson, 1982a), as is discussed further below.

At the other thermal extreme, monzonite MS 76 has a liquidus in excess of 1020 °C at 1 kbar$_{H_2O}$. It is very unlikely that such a refractory rock type could have arisen through fusion of sial at shallow crustal levels. Walsh and Henderson (1977) have pointed out, nevertheless, that the slope of the chondrite-normalized *REE* pattern of this intermediate composition is considerably steeper than that of its basic and acid associates in Centre 3. It is therefore implausible that it evolved by simple fractional crystallization; a combination of this process with contamination by *LREE*-enriched sial is more likely (Thompson, 1982a).

Although the melting behaviours of samples SK 69, SK 884, and 450 differ in detail (Table II), they are broadly similar. Their plagioclase liquidi are at 860–880 °C and their silicate liquidi are at 910–930 °C. Comparison of the experimental melting sequences with the mineral parageneses of the rocks will be used below to argue that these three plutons all crystallized at water vapour pressures less than 1 kbar. Nevertheless, the liquidi of these samples may be compared with the state of fusion

of various Hebridean pre-Tertiary crustal rock types at the same temperature and P_{H_2O}, because they all involve the same solid phases (compare Table II and Thompson, 1981, Table III) and would therefore show similar *relative* melting relationships at other lower water vapour pressures (Wyllie et al., 1976).

At 910–930 °C and 1 kbar$_{H_2O}$ Lewisian mesocratic gneiss and Torridonian arkose and shale (and similar clastic sediments) would be more than 80% liquid, whilst Lewisian leucogneiss would be entirely molten (Thompson, 1981). Even at 860–880 °C all these rock types would contain glass fractions exceeding 60% (up to 90% in Lewisian leucogneiss). Apart from small amounts of biotite in the leucogneiss and shale, the residual solid phases in these four types of country rock at 860–880 °C are combinations of orthopyroxene and plagioclase (gneisses), quartz (arkose), or cordierite (shale). The thermal data therefore provide a simple test for the unmodified crustal fusion hypotheses originally put forward by Brown (1963) for Hebridean Tertiary acid plutons in general, by Wager et al. (1953) for the Coire Uaigneich Granite (SK 884), by Dunham (1968) for Rhum felsites and granophyres (e.g. 450), and by Thompson (1969) for the Glamaig Granite (SK 69). If country rock partial fusion is the only process that contributed significantly to the genesis of these granites, then the thermal restraints require that the latter should have similar (or slightly higher) incompatible element abundances (except for Sr) and *identical incompatible element ratios* to their postulated crustal source rocks. This is definitely not the case for either the Glamaig, Coire Uaigneich and Rhum granites or other 'chemically primitive' (mostly adamellitic) acid plutons of the Hebridean Tertiary Province.

Fig. 1 illustrates this point by means of normalized plots of 19 incompatible elements in Tertiary granites from Skye (Glamaig; Coire Uaigneich), Rhum (Western), and Mull (Derrynaculen, Centre 1) and in Lewisian granulite- and amphibolite-facies acid gneisses and Torridonian arkose. Table III lists new trace element data, mostly used in fig. 1. The elements are normalized to chondrites, except for K, Rb, and P, which are normalized to 'primitive mantle' values (Sun, 1980; Thompson, 1982a). The patterns in fig. 1 summarize several previous discussions, each based on smaller ranges of elements, of the differences in incompatible element abundances and ratios between Hebridean Tertiary granites and the country rocks of the region (Thorpe et al., 1977; Meighan, 1979; Walsh et al., 1979; Dickin and Exley, 1981). These data will be discussed further below.
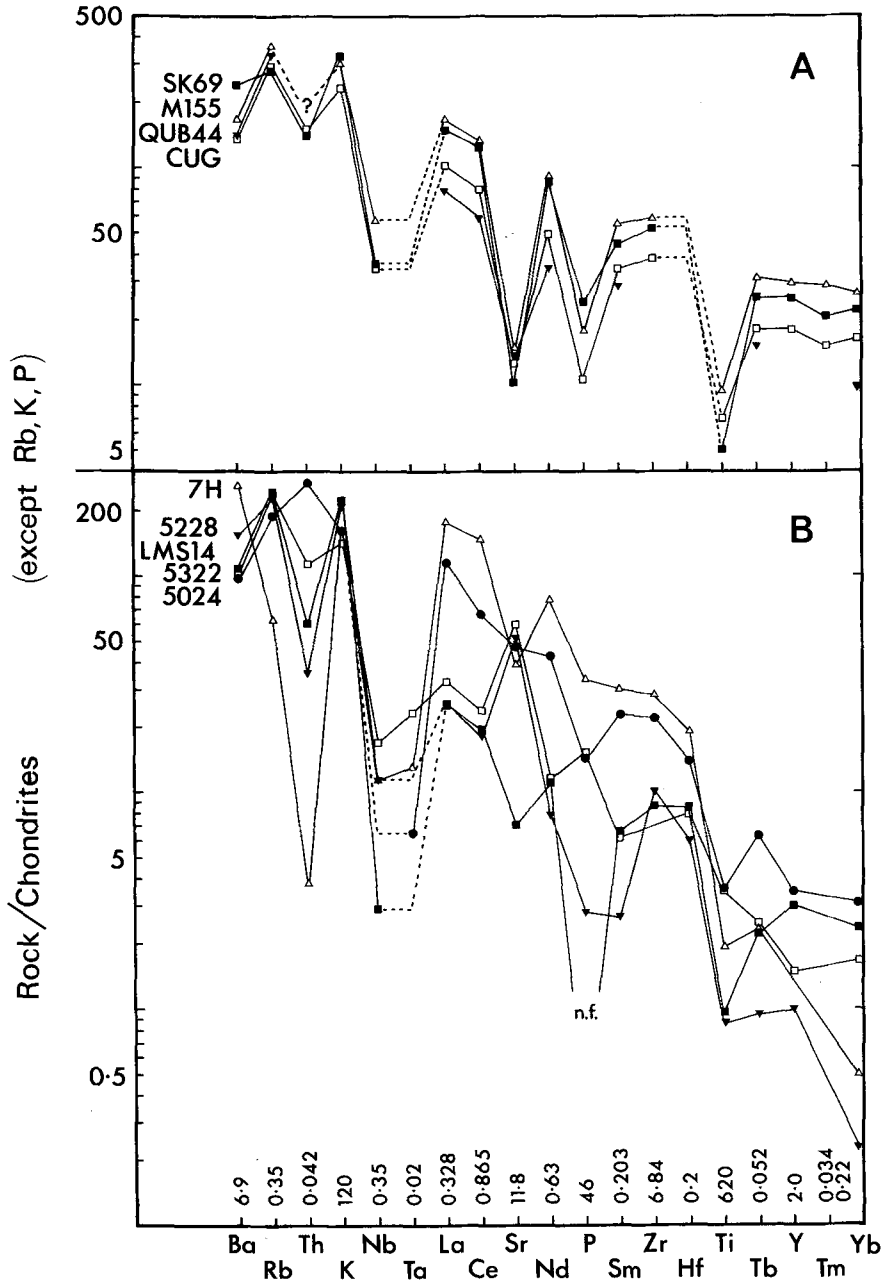
Solidi of acid and intermediate silica-saturated

FIG. 1. Selected trace elements in (A) 'primitive' (mostly adamellitic—see text) acid plutons from the Tertiary Hebridean Province and (B) representative Lewisian acid gneisses and a Torridonian arkose. Element abundances are normalized to chondrites, except for Rb, K, and P (see text). The normalization factors (Thompson, 1982a) are given on the diagram. Key to samples: SK 69, Glamaig Granite, Western Redhills, Skye; M 155, Derrynaculen Granite, Centre 1, Mull; QUB 44, Western Granite, Rhum; CUG, Coire Uaigneich Granite, Skye; 7H, granulite-facies Lewisian; 5228, 5322, and 5024, amphibolite-facies Lewisian; LMS 14, Torridonian arkose. Sources of data (other than in this paper) are Weaver and Tarney (1980, 1981), Thompson (1981, 1982a and references cited therein), and Thompson et al. (1982).

rocks at 1 kbar$_{H_2O}$. It is apparent from Table II that the solidi of the samples used in this study vary considerably. Only the leucogranite SK 127, which has more than 90% (ab + or + q) in its CIPW norm, begins to melt at the same temperature (715 °C) as the minimum in the synthetic system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 at 1 kbar$_{H_2O}$. Fig. 2 is a plot of CaO versus solidus temperature at 1 kbar$_{H_2O}$ for a range of igneous rocks from leucogranite to tonalite, together with arkose and shale. It is clear that there is a broad positive correlation between these parameters, with the solidus of tonalite at a temperature 50–80 °C above that of such rock types as granite or arkose at the same P_{H_2O}. The scatter in the correlation between solidus and CaO is to be expected because, although this component has a strong effect in raising the melting temperature of salic compositions (James and Hamilton, 1969), the latter are also sensitive to other parameters, such as Mg/Fe and Na/K.

The relationship shown in fig. 2 is an important constraint on the way in which, in some cases, basic magma may interact with continental crust. 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 and Mathews, 1981). Nevertheless, in other instances a large simple magma chamber may not occur beneath an eruptive zone and the 'magma reservoir' may be no more than the aggregate volume of innumerable dykes and sills beneath the area. The magmatic plumbing beneath zones of regional tension, with fissure-erupted lavas, may be of the latter type
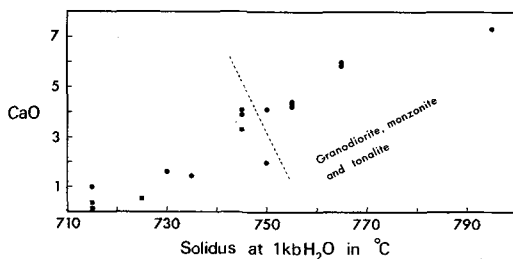

FIG. 2. CaO *vs.* solidus in water-saturated experiments at 1 kbar P_{H_2O} for acid and intermediate igneous rocks (●) and clastic sediments (■). The dashed line separates data for granodiorites, monzonites, and tonalites from those for acid igneous rocks and sediments. Sources of data (other than this paper) are Piwinskii (1968), Piwinskii and Wyllie (1968) and Thompson (1981).

(Weertman, 1971). Possible examples are the Snake River Plain and Rio Grande Rift, western USA; the Deccan, India; and the Hebridean Tertiary Province (Thompson, 1982a). Patchett (1980) has proposed a mechanism whereby basic dykes or sills in a zone of repeated magma injection within continental crust could become strongly contaminated by sialic partial melts. In his model Patchett assumed that all major sialic rock types would begin to melt at the same temperature as the minimum in the synthetic system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 at the same P_{H_2O}. It is clear from fig. 2 that this is not so; granodiorites, monzonites, and tonalites would begin to melt at considerably higher temperatures than granites, pegmatites, arkoses, and shales. Indeed, some of the latter have such small melting intervals that they would become largely or entirely molten at temperatures below the solidi of intermediate rocks. It is therefore to be expected that the sialic contaminants of basic magmas in a system operating according to Patchett's model, that is within continental crust including clastic sediments (or metasediments) and igneous rocks ranging from granites to tonalites (or their volcanic equivalents), will be strongly biased towards the compositions of the most easily fusible rock types. Thompson *et al.* (1982) have reported chemical evidence suggesting that this is so in the early basic magmas forming the lava fields of the Hebridean Tertiary Province.

Limits on P_{H_2O} *during crystallization of Hebridean Tertiary acid plutons.* Comparison of the petrography of the samples (appendix) with their melting behaviour at 1 kbar$_{H_2O}$ (Table II) shows that these plutons all crystallized at lower values of water vapour pressure. Plagioclase is not on the silicate liquidi of samples SK 69, SK 884, and 450 at 1 kbar$_{H_2O}$ but forms the major phenocryst phase in all three rocks. It is well established from all relevant hydrous melting experiments (e.g. Wyllie *et al.*, 1976) that addition of water depresses the temperature of disappearance of plagioclase relative to other silicates such as pyroxenes. The Glamaig, Coire Uaigneich, and Rhum granites must therefore have begun their crystallization at values of P_{H_2O} below 1 kbar. The same reasoning applies to the monzonite (MS 76) if, as seems likely from the available experiments, its plagioclase liquidus falls below its silicate liquidus at 1 kbar$_{H_2O}$. Brown (1963) argued from the occurrence of quartz paramorphs after tridymite in the Coire Uaigneich Granite that P_{H_2O} was only about 275 bars when this pluton began to crystallize.

Consideration of the melting behaviour of sample SK 127 also leads to the conclusion that the natural magmas were drier than the experimental conditions. Both quartz and alkali feldspar

form abundant phenocrysts in the Southern Porphyritic Granite. The cotectic melting behaviour of this pluton means that, whatever the genesis of the magma, it is inconceivable that it was not in equilibrium with more than one salic phase. Thompson (1982a) has shown that alkali feldspar fractionated from the Southern Porphyritic Granite magma immediately before its final emplacement (see below). Nevertheless, in the 1 $kbar_{H_2O}$ melting experiments quartz was the only silicate liquidus phase. The quartz primary phase field expands, relative to that of alkali feldspar, with rising P_{H_2O} in the synthetic system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 (Tuttle and Bowen, 1958). It may therefore be deduced that the Southern Porphyritic Granite magma began to crystallize at less than 1 kbar water vapour pressure. Further experimental refinement of P_{H_2O} in this magma would be complicated by three factors.

1. Petrographic and chemical evidence indicate that at least the outer parts of this pluton interacted with a through-flowing fluid phase throughout most of its crystallization history, and that this fluid caused subtle local changes in the abundances and ratio of Na and K in the granite (Thompson, 1965, and unpublished work).

2. Interstitial fluorite in many samples of the Southern Porphyritic Granite testifies to a significant partial pressure of fluorine in the volatile component of the magma. Fluorite is a common accessory mineral in acid plutons throughout the Hebridean Tertiary Province.

3. Detailed crystallization experiments would need to follow the same T-f_{O_2} path as the magma.

In addition to the liquidus and near-liquidus phase relationships discussed so far, the experiments summarized in Table II shed some light on the lower-temperature stages of crystallization of these Hebridean Tertiary plutons. The various assemblages of amphiboles and pyroxenes found in the sub-solidus run products correspond well with the minerals in the different samples (see appendix). One of the main discrepancies between the rocks and the sub-liquidus experiments concerns biotite in SK 69. In the experiments this is a near-liquidus phase which disappears again at a temperature about 40 °C above the solidus. In the rock (Thompson, 1969) it is clear that biotite appeared relatively late in the paragenesis and was stable at the solidus. Another mineral pair which, in contrast, show the same relationship in both experiments and rock in SK 69 are clinopyroxene and amphibole. The former occurs in near-liquidus run products (Table II) and then reacts to amphibole before crystallization has proceeded very far. In quickly cooled samples from the margins of Glamaig Granite, clinopyroxene cores are pre-served to varying extents within rims of amphibole. In samples, such as SK 69, from the centre of the pluton, this reaction has clearly gone to completion. The combined phase relationships of plagioclase, clinopyroxene, amphibole, and biotite in SK 69 rock and experiments suggest that the interior of this pluton may have begun to crystallize at a water vapour pressure less than 1 kbar but subsequently developed P_{H_2O} somewhat above 1 kbar, as it approached its solidus. Subsequently, a network of ramifying channels, filled with hydrothermal fluids, developed throughout the almost solid mass (Thompson, 1969).

Evolution of Hebridean Tertiary granites

The conclusion reached above that the Hebridean Tertiary 'primitive' granites cannot be products of simple crustal fusion is consistent with published geochemical studies which model them as mixtures of mantle-derived magmas and sialic melts or selective contaminants (Moorbath and Welke, 1969; Thorpe et al., 1977; Carter et al., 1978; Meighan, 1979; Walsh et al., 1979; Dickin, 1981; Thompson, 1982a; Walsh and Clarke, 1982). Nevertheless, several interesting problems remain, such as: did sialic contamination occur before, during, or after fractional crystallization of the mantle-derived magma component; was the contaminant a silicate melt or some other fluid (Thompson et al., 1982); what are the identities of the crustal rock types providing the sialic fractions (Brown, 1963; Bell, 1976)?

In fig. 3 the normative quartzofeldspathic components of the acid rocks used in the experimental studies are compared with liquidus equilibria at 1 $kbar_{H_2O}$ in the synthetic systems $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 and $NAlSi_3O_8$–$KAlSi_3O_8$–$CaAl_2Si_2O_8$ (Tuttle and Bowen, 1958; James and Hamilton, 1969). Also plotted is the field occupied by the compositions of the major acid plutons of the British Tertiary Volcanic Province (Thompson, 1982b) abbreviated to BTVP. Allowing for analytical imprecision and values of $P_{H_2O} < 1$ kbar in the magmas (see above), it is clear that the compositions of the low melting temperature BTVP acid plutons are controlled by cotectic liquidus phase equilibria in Ab-Or-An-Qz (fig. 3). With the exception of the Coire Uaigneich Granite, the distribution of BTVP acid rock analyses as a whole in fig. 3 is consistent with an origin of their magmas by fractional crystallization of more-basic liquids (Carmichael et al., 1974). This conclusion differs from that previously reached by Brown (1963), who noted that the compositions of most of the BTVP granites lie to the right of the thermal valley in the Ab-Or-Qz projection (op. cit. fig. 2) and therefore

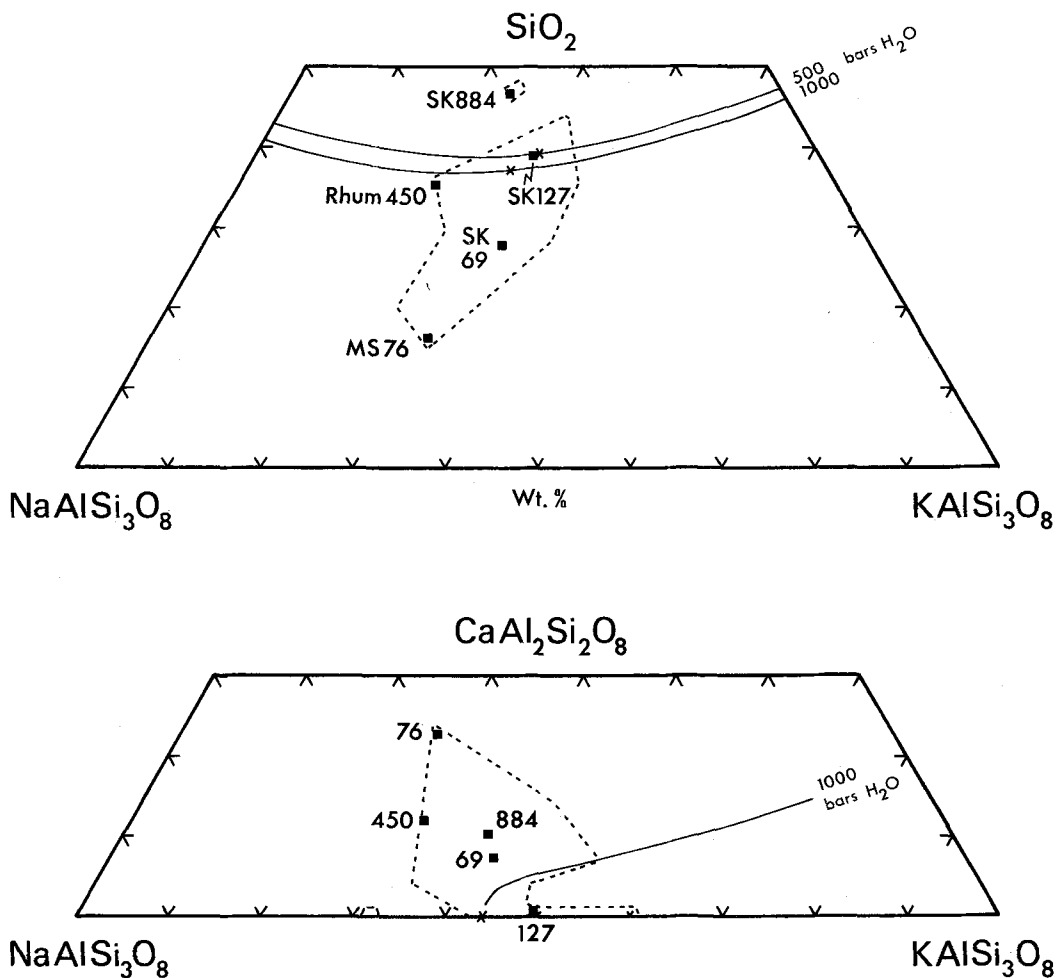FIG. 3. Normative salic components of the samples used in the experiments compared with liquidus phase relations at 1 $kbar_{H_2O}$ in the synthetic systems $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2 and $NaAlSi_3O_8$–$KAlSi_3O_8$–$CaAl_2Si_2O_8$ (Tuttle and Bowen, 1958; James and Hamilton, 1969). The quartz–feldspar field boundary at 500 bars P_{H_2O} in Ab–Or–Qz is also drawn. Temperature minima in both synthetic systems are marked by crosses. The dashed line encloses the field of British Tertiary Volcanic Province acid plutons (Thompson, 1982b).

considered that they could not be derived by fractional crystallization of more -basic liquids. The subsequent work of James and Hamilton (1969) has resolved this problem; almost all the more-potassic BTVP granites lie on the two feldspar surface in Ab-Or-An-Qz or above it in the phase volume of primary plagioclase (fig. 3).

Many of the an-poor BTVP granites are per-alkaline. When analyses of these are plotted in Ab-Or-Qz (fig. 3), they appear to be more potassic than would seem to be consistent with their evolution by fractional crystallization of a more-basic parent. Thompson and MacKenzie (1967) have

shown that this problem is in artefact of the CIPW normative recalculation procedure for peralkaline compositions; these should strictly not be plotted in Ab-Or-Q. Another complication occurs in parts of the Southern Porphyritic Granite (Skye), where it is clear, from petrographic and chemical evidence, that Na has been lost, relative to K, in an escaping vapour phase during solidification of the pluton (Thompson, 1965, and unpublished data).

If the phase chemistry of Hebridean Tertiary granites (except Coire Uaigneich) suggests that fractional crystallization was a dominant process during their evolution, is the geochemical evidence
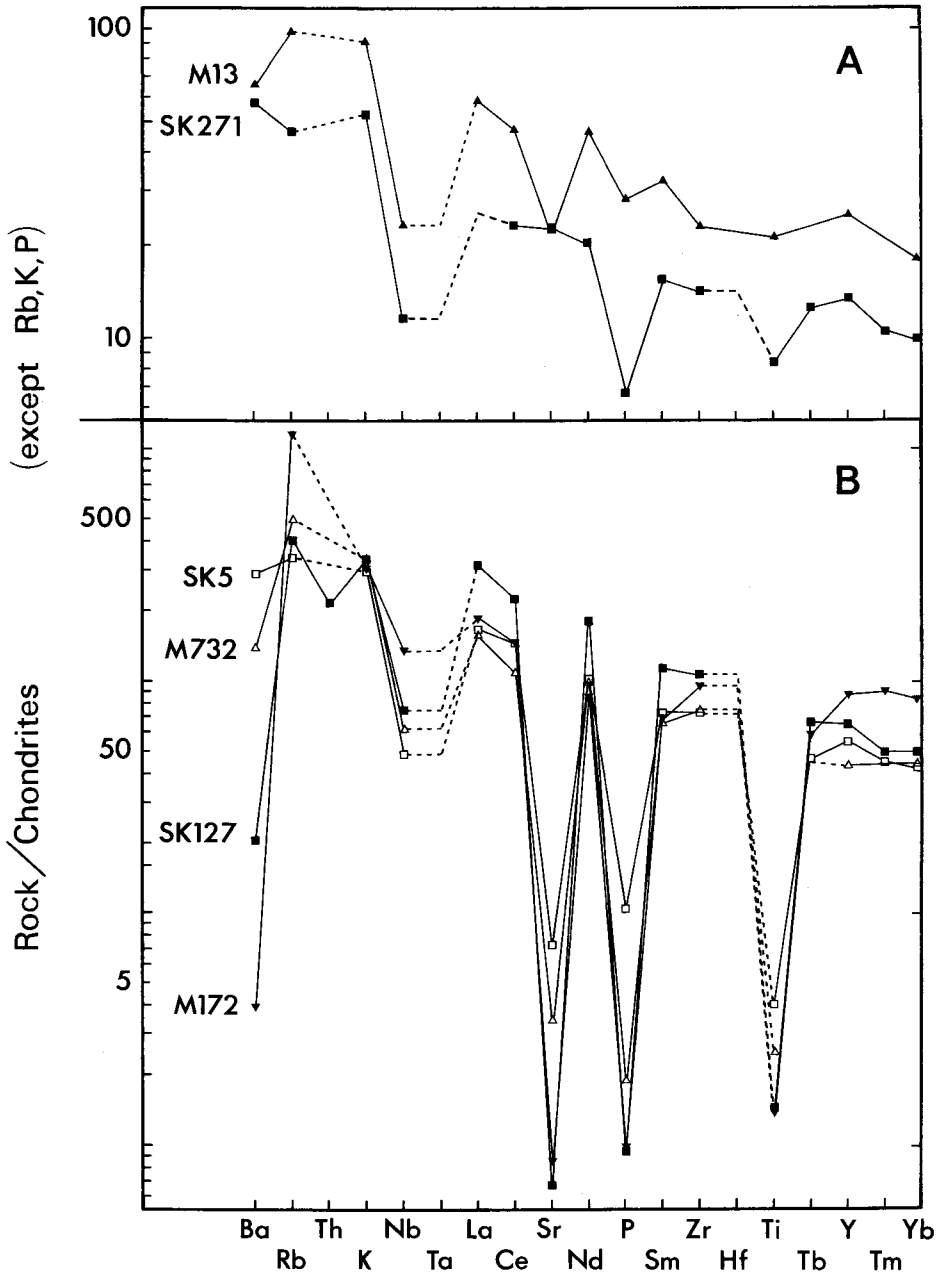
FIG. 4. Selected trace elements in (A) basic rocks closely associated with the Tertiary granites of Skye and Mull and (B) Tertiary leucogranites from Skye and Mull. See fig. 1 for details of construction of the diagram. Key to samples: M 13, Quartz gabbro, Glen More Ring Dyke, Centre 2, Mull; SK 271, Marsco Summit Gabbro, and SK 5 Marsco Granite, Western Redhills, Skye; M 732, Loch Airdeglas Granite, Centre 2, Mull; SK 127, Southern Porphyritic Granite, Western Redhills, Skye; M 172, Toll Doire Granite, Centre 3, Mull. Sources of data (other than in this paper) are Thompson (1969, 1982a), Thorpe et al. (1977), Walsh et al. (1979), and Walsh and Clarke (1982). The values of Tb and Tm in SK 271 are interpolated from the data in Table III.

consistent with this hypothesis and does it show when the sialic fractions entered the magmatic systems? Walsh et al. (1979) and Walsh and Clarke (1982) have demonstrated very clearly that the acid plutons of Centre 2, Mull, are related by fractional crystallization to intermediate and basic magmas which also form plutons in that complex. Both their elemental and isotopic data show that the basic magmas were contaminated with sial *before* they began to fractionate and that no further significant addition of crustal melt took place during the process. The Ardnamurchan cone sheets (Holland and Brown, 1972) appear to have evolved in a similar way (Thompson, 1982a). The normalized incompatible element pattern for a basic sample (M 13) from Centre 2, Mull (Walsh and Clarke, 1982), is shown in fig. 4, together with data for sample SK 271 (Table III) from the Marsco Summit Gabbro, Skye, which was emplaced very shortly before the Glamaig Granite (Thompson, 1969). Both patterns may be modelled by adding approximately 10% each of granulite-facies and amphibolite-facies Lewisian leucogneiss to Preshal Mhor-type basalt (from Skye or Mull) with MORB-like radiogenic isotope and incompatible element abundances and ratios (Thompson, 1982a, fig. 14).

A contrasting genetic scheme is provided by the hypothesis of Dickin and Exley (1981) that the Coire Uaigneich Granite, Skye, originated by mixing of approximately two-thirds of high-fraction partial melt from Torridonian arkose and one-third of the *residual* magmas from protracted fractional

crystallization of the Cuillin basic to ultrabasic intrusion. There is no doubt that the mixing took place shortly before the final emplacement of the magma because the granite is elementally and isotopically very heterogeneous and also full of unresorbed detrital zircons inherited from the Torridonian source. Dickin and Exley (1981) conclude that the arkose which yielded the sialic melt fraction was chemically like the Torridonian xenoliths within the granite, rather than the sediments surrounding its present outcrop. Torridonian arkose LMS 14 (Table III), used in melting experiments in the first part of this paper (Thompson, 1981), is chemically similar to the xenoliths. Unpublished studies (J. L. Brown, pers. comm., 1981) have shown that the magma of the Cuillin Intrusion was probably of Preshal Mhor type; the published incompatible element ratios of one of its filter-pressed, late-stage, magmatic residua (Dickin and Exley, 1981, sample CC 4) are compatible with this hypothesis.

A remarkable chemical feature of the Coire Uaigneich Granite is apparent in fig. 1. The normalized incompatible element pattern of this pluton is indistinguishable from those of other Skye, Rhum, and Mull 'primitive' acid rocks, thought to contain sialic fractions from *Lewisian* sources (e.g. Carter et al., 1978; Walsh et al., 1979; Dickin, 1981) and to have evolved by fractional crystallization of more-basic magmas, as discussed above. The explanation for this similarity between granites of dissimilar origins lies in the demonstration by Moorbath et al. (1967) that the sources of the Torridonian arkoses were high structural levels of the Lewisian complex. The only diagnostic incompatible element difference between the arkoses and Lewisian gneisses at present erosion levels is uranium, which is enriched in the sediments. This element is not plotted on fig. 1, but causes the Pb isotope ratios of Torridonian arkoses to differ greatly from Lewisian gneisses (Dickin and Exley, 1981).

If the source of the sialic contribution to the Coire Uaigneich Granite had been acid Lewisian gneiss, rather than Torridonian arkose, the bulk composition of the mixture of crustal melt (Thompson, 1981, fig. 1) and Cuillin intrusion fractionation residua would have fallen within the main group of BTVP granites on fig. 3. Only the inherited zircons would distinguish such a mixture from the product of sial-contaminated *basic* magma, *subsequently* fractionated. It is therefore apparent that, except in a few favourable cases, great care is needed when formulating detailed hypotheses as to the origins of individual 'primitive' acid magmas in the Hebridean Tertiary Province. The clear demonstration by Dickin and Exley (1981) that

TABLE III. Trace elements in Skye Tertiary granites and associated mafic rocks, Lewisian gneiss and Torridonian sediments

	SK884	SK271	SK69	SK127	SK167	SK5	JE6	LMS12A	LMS14
Ba	930	390	1670	145	2235	2020	1770	678	729
Be	1.7	0.8	2.0	4.0	1.6	3.0	1.1	6.4	0.5
Nb	12	4	13	26	11	17	-	20	1
Rb	102	16	96	143	53	121	-	265	84
Sr	146	266	121	8	240	87	410	44	83
Y	36	27	50	132	72	109	12	63	6
Zr	262	97	355	737	357	503	115	280	59

All values in ppm.

Key to samples: SK884, Coire Uaigneich Granite; SK271, Marsco Summit Gabbro; SK69, Glamaig Granite; SK127 Southern Porphyritic Granite; SK167, Ferrodiorite; SK5, Marsco Granite; JE6, Lewisian leucogneiss; LMS12A, Torridonian shale; LMS14, Torridonian arkose. Samples SK884 to SK5 are listed in chronological order of emplacement within the Skye intrusive complexes (see text). For localities and other details of samples see appendix and (Thompson, 1969, 1981a).

Nb, Rb, Sr, Y and Zr determined by XRF at Imperial College by M. A. Morrison. Ba and Be determined by ICP at King's College and Imperial College by M. Thompson, J. N. Walsh and P. J. Watkins. Other ICP data are: LMS12A; Li = 43, B = 643. SK271; Cr = 87, Ni = 51, Ce = 19.6, Pr = 2.6, Nd = 12.7, Sm = 3.1, Eu = 1.19, Gd = 3.5, Dy = 4.1, Ho = 0.82, Er = 2.36, Yb = 2.20, Lu = 0.32 (all in ppm).

even the presence of inherited zircons does not necessarily mean that an acid magma is a simple sialic melt may have implications for hypotheses about the origins of British Caledonian granites (Pidgeon and Aftalion, 1978).

Turning to the more 'evolved' Hebridean Tertiary granites with near-cotectic melting behavior, such as SK 127 (Table I), it appears probable from their normalized incompatible element patterns (fig. 4) that they evolved by fractional crystallization from 'primitive' acid magmas (fig. 1). Note that one of the patterns on fig. 4 is the Loch Airdeglais Granite (M 732) which is the acid terminus of the complete basic-to-acid, fractionation-related suite of plutons from Centre 2, Mull, described by Walsh and Clarke (1982). It is apparent from figs. 1 and 4 that, in general, the troughs at Nb, Sr, P, and Ti in the leucogranite patterns are deeper than in the 'primitive' granite patterns. This is consistent with separation of plagioclase, apatite and Fe-Ti oxide during the evolution of the former from the latter. Similarly, Thompson (1982a) has argued that only the fractionation of alkali feldspar can explain why the abundance of Ba in the Southern Porphyritic Granite, Skye (e.g. Table III, SK 127), is much lower than in Lewisian acid gneisses and Torridonian sediments (Table III), the Glamaig Granite (fig. 1)—which precedes Southern Porphyritic in the Skye Western Redhills (WRH) Complex (Thompson, 1969; Bell, 1976)—or several batches of basic magma associated with the WRH granites (Table III and unpublished data). It is clear from fig. 4 that similar reasoning may be applied to parts of the Toll Doire Granite (M 172) of Centre 3, Mull (Walsh et al., 1979).

Sample SK 5 (Table III, fig. 4) is from the Marsco Granite, Skye, and gives an indication of the extreme complexity of genetic processes in the Hebridean Tertiary acid magma suites. This pluton was emplaced very soon after the Southern Porphyritic Granite (SK 127) in the Skye Western Redhills complex (Bell, 1976). The Marscoite Suite, which intervenes between them, has a chilled but plastic contact against Southern Porphyritic Granite and grades without any sharp contact into Marsco Granite (Wager et al., 1965; Thompson, 1969). Nevertheless, the normalized incompatible element pattern of SK 5 is systematically different from that of SK 127 (fig. 4), showing that these two magmas evolved within entirely separate chemical systems (see also Dickin, 1981). Evidence for complex polycyclic genetic models, which might explain this type of problem associated with the compositions and emplacement sequences of the Hebridean Tertiary Province acid magmas, has been discussed elsewhere (Thompson, 1980, 1982a).

REFERENCES

Ahern, J. L., Turcotte, D. L., and Oxburgh, E. R. (1981) J. Geol. **89**, 421–32.

Bell, J. D. (1976) Proc. Geol. Assoc. **87**, 247–71.

Brown, G. M. (1963) Mineral. Mag. **33**, 533–62.

Carmichael, I. S. E., Turner, F. J., and Verhoogen, J. (1974) Igneous Petrology. St. Louis: McGraw-Hill Book Co.

Carter, S. R., Evensen, N. M., Hamilton, P. J., and O'Nions, R. K. (1978) Science, **202**, 743–7.

Dickin, A. P. (1981) J. Petrol. **22**, 155–89.

——and Exley, R. A. (1981) Contrib. Mineral. Petrol. **76**, 98–108.

Dunham, A. C. (1968) Q. J. Geol. Soc. Lond. **123**, 327–52.

Holland, J. G., and Brown, G. M. (1972) Contrib. Mineral. Petrol. **37**, 139–60.

James, R. S., and Hamilton, D. L. (1969) Ibid. **21**, 111–41.

Meighan, I. G. (1979) Bull. Geol. Surv. G.B. 10–22.

Moorbath, S., Stewart, A. D., Lawson, D. E., and Williams, G. E. (1967) Scott. J. Geol. **3**, 389–412.

——and Welke, H. (1969) Earth Planet Sci. Lett. **5**, 217–30.

O'Hara, M. J., and Mathews, R. E. (1981) J. Geol. Soc. Lond. **138**, 237–77.

Patchett, P. J. (1980) Nature, Lond. **283**, 559–61.

Pidgeon, R. T., and Aftalion, M. (1978) Geol. J. Spec. Issue, **10**, 183–220.

Piwinskii, A. J. (1968) J. Geol. **76**, 548–70.

——and Wyllie, P. J. (1968) Ibid. **76**, 205–34.

Streckeisen, A. L. (1973) Neues Jahrb. Mineral. Monat. 149–64.

Sun, S-S. (1980) Phil. Trans. R. Soc. Lond. **A297**, 409–45.

Thompson, R. N. (1965) D.Phil. thesis. University of Oxford.

——(1969) Q. J. Geol. Soc. Lond. **124**, 349–85.

——(1980) Geol. Rundsch. **69**, 245–62.

——(1981) Mineral. Mag. **44**, 161–70.

——(1982a) Scott. J. Geol. **18**, 49–107.

——(1982b) In Sutherland, D. S. (ed.), Igneous Rocks of the British Isles, John Wiley and Sons Ltd., 461–77.

——Dickin, A. P., Gibson, I. L., and Morrison, M. A. (1982) Contrib. Mineral. Petrol. **79**, 159–68.

——and MacKenzie, W. S. (1967) Am. J. Sci. **265**, 714–34.

Thorpe, R. S., Potts, P. J., and Sarre, M. B. (1977) Earth Planet Sci. Lett. **36**, 111–20.

Tuttle, O. F., and Bowen, N. L. (1958) Mem. Geol. Soc. Am. **74**, 1–153.

Wager, L. R., Vincent, E. A., Brown, G. M., and Bell, J. D. (1965) Phil. Trans. R. Soc. Lond. **A257**, 273–307.

——Weedon, D. S., and Vincent, E. A. (1953) Mineral. Mag. **30**, 263–76.

Walsh, J. N., Beckinsale, R. D., Skelhorn, R. R., and Thorpe, R. S. (1979) Ibid. **71**, 99–116.
——and Clarke, E. (1982) *Mineral. Mag.* **45**, 247–55.
——and Henderson, P. (1977) *Contrib. Mineral. Petrol.* **60**, 31–8.
Weaver, B. L., and Tarney, J. (1980) *Earth Planet Sci. Lett.* **51**, 279–96.
————(1981) Ibid. **55**, 171–80.
Weertman, J. (1971) *J. Geophys. Res.* **76**, 1171–83.
Wyllie, P. J., Huang, W-L, Stern, C. R., and Maaløe, S. (1976) *Canad. J. Earth Sci.* **13**, 1007–19.

APPENDIX

Rocks used in melting experiments

SK 69. Glamaig Granite, Glen Sligachan, Skye. For locality, description and modal analysis see Thompson (1969). Equigranular texture. Early subhedral plagioclase (An_{28}) surrounded and corroded by anhedral perthitic alkali feldspar, the latter intergrown with anhedral quartz. The mafic minerals are unaltered dark-green amphibole, partially chloritized biotite and Fe–Ti oxide. The main accessories are apatite, zircon, and allanite. Small fine-grained mafic inclusions in the sample (Thompson, 1980) were removed before crushing.

SK 127. Southern Porphyritic Granite, Marsco, Skye. For locality and description see Thompson (1969). Abundant euhedral phenocrysts of quartz and perthitic alkali feldspar, in subequal amounts, set in a micrographic-textured groundmass of these minerals, together with sparse Fe–Ti oxides.

SK 884. Coire Uaigneich Granite, Coire Uaigneich, Skye. For locality see Table I. Sparse subhedral phenocrysts of plagioclase (An_{50}) and quartz. Groundmass mostly of fine-grained, partly granular, partly micrographic quartz, perthitic alkali feldspar and plagioclase. Apart from small relict areas of dark-green amphibole, the ferromagnesian minerals are entirely replaced by chlorite, epidote, and sphene; crystal shapes suggest former pyroxene, amphibole, and biotite. Accessory Fe–Ti oxide, apatite, and zircon. See Wager *et al.* (1953) and Dickin and Exley (1981) for further details.

450. Granite, Long Loch, Rhum. See Dunham (1968) for petrographic details.

MS 76. Monzonite, Centre 3, Ardnamurchan. For locality see Table I. Equigranular texture. Predominantly subhedral oligoclase, zoned outwards to anorthoclase and intergrown with anhedral alkali feldspar and interstitial quartz. Mafic minerals mostly augite and Fe–Ti oxide. Minor interstitial amphibole and biotite, together with sparse large biotite poikilocrysts. Accessory apatite and zircon.