

Thermal aspects of the origin of Hebridean Tertiary acid magmas. I. An experimental study of partial fusion of Lewisian gneisses and Torridonian sediments

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ABSTRACT. Thermal aspects of the conflicting hypotheses that the acid magmas of the British Tertiary Igneous Province were generated by either fractional crystallization of basic magmas or partial fusion of country rocks around basic intrusions are investigated by combining petrological and experimental data. Sparse large xenoliths (up to 12 m² outcrops) of Lewisian gneiss occur in the ferrodiorite member of the Marscoite Suite in the Western Redhills Eocene intrusive complex of Skye. Most of the blocks are of granodioritic-tonalitic gneiss which is very similar to the grey gneisses of the northern and southern regions of the mainland Lewisian. One is a two-pyroxene basic granulite, closely resembling in petrography and composition the granulite-facies basic gneisses of the central region of the Scottish mainland Lewisian. During Tertiary thermal metamorphism the xenoliths recrystallized patchily to pyroxene hornfels and up to 50% of melting occurred in any parts of blocks that were rich in alkali feldspar and quartz. Microprobe analyses of intergrown Ca-rich and Ca-poor pyroxenes in a hornfelsed ultramafic mica pyroxenite lens within a leucogneiss block give a calculated temperature of 950°C for the Tertiary metamorphism. Melting experiments at 1 kb P_{H_2O} were carried out on leucocratic and mesocratic Lewisian gneisses (from the xenoliths), Torridonian arkose and shale. Extensive melting of the leucogneiss and arkose, to peraluminous liquids, occurs within a few degrees above their solidus (715°C). The silicate liquidus of the leucogneiss is at 930°C. Microprobe analyses of the glass products of melting experiments (mostly of leucogneiss) show that liquid composition trends during progressive melting are consistent with theoretical equilibria in the synthetic system Ab-Or-An-Qz-H₂O. Partial fusion in the Skye Lewisian gneiss xenoliths took place at a water vapour pressure of a few hundred bars, probably under water-undersaturated conditions.

DISCUSSION as to whether the Early Tertiary acid magmas of the Hebridean igneous province were produced by fractional crystallization of basic magmas, partial fusion of sialic crust around large mafic intrusions, or some combination of these processes, has proceeded for many years. Apart from the constraints provided by field and geo-

physical studies of the region, most contributions to the debate have involved the interpretation of various types of geochemical data (e.g. Moorbath and Bell, 1965; Thompson, 1969; Moorbath and Welke, 1969; Thorpe *et al.*, 1977; Carter *et al.*, 1978; Meighan, 1979; Walsh *et al.*, 1979; Moorbath and Thompson, 1980).

Brown (1963) studied the melting behaviour at 1 kb water-vapour pressure of several Tertiary granites from Skye and Rhum, together with a sample each of Lewisian basic gneiss and Torridonian arkose. As Brown emphasized, at the time he made his experiments the alloys used in the manufacture of cold-seal apparatus were inadequate to sustain the required pressures and temperatures for long enough to allow the attainment of equilibrium. Brown therefore based most of his discussion of the thermal constraints upon possible origins of the acid magmas on an analogy with relationships in the synthetic system NaAlSi₃O₈-KAlSi₃O₈-SiO₂-H₂O (Tuttle and Bowen, 1958). Subsequent experimental studies of both acid igneous rocks and appropriate synthetic systems (e.g. James and Hamilton, 1969; Luth, 1976; Wyllie *et al.*, 1976) have shown that natural compositions may only be compared realistically with the system Ab-Or-Qz-H₂O, if they are virtually free of other components, notably Ca. Such rocks occur in the British Tertiary Igneous Province but are rare.

The experiments reported here were made using apparatus suitable to allow run times of sufficient length to reach equilibrium. The main objective of the study was to test the hypothesis that the Hebridean Tertiary acid magmas originated by partial fusion of sialic crust, by comparing the melting temperatures of examples of the country rocks of the region with the liquidus of representative acid rocks. The report is in two parts, considering the country rocks and the plutons, respectively. The partial melting behaviour of Lewisian gneiss—as deduced from petrological study of xenolithic

blocks within Skye Tertiary intermediate magmas, and reproduced experimentally—is treated in the most detail in the present account. This is because the Lewisian complex is the most frequently postulated source of a crustal component in the Hebridean Tertiary acid magmas (e.g. Brown, 1963; Walsh *et al.*, 1979; Moorbath and Thompson, 1980).

Choice of samples for melting experiments

The principal types of country rocks surrounding the Hebridean Tertiary igneous centres are: Mesozoic and Torridonian sediments, Dalradian and Moine metasediments, and Lewisian gneiss. Although the sediments and metasediments must, of course, be treated individually in any geochemical study, they may be grouped together for the purposes of the types of thermal investigation reported here. Thus quartzites, limestones, and their metamorphosed equivalents may be excluded from any assessment of the possible sources of acid magmas. The sediments and metasediments with relevant compositions range from quartzofeldspathic psammites to pelites, all with substantial amounts of normative alkali feldspar and quartz. Accordingly, a Torridonian arkose and shale were chosen as representing this composition range (Table I, LMS12A and LMS14) for melting experiments. These samples have previously been used for Sr-isotope studies by Moorbath *et al.* (1967), who give their locality and petrographic descriptions.

Lewisian. Lewisian gneisses occur within the immediate vicinity of Hebridean Tertiary igneous intrusive complexes only in Skye and Rhum. The Rhum Lewisian comprises leucocratic and mesocratic quartzofeldspathic gneisses. Their petrography and thermal metamorphism by Tertiary magmas have been described by Tilley (1944). The Lewisian within the region of the Skye Tertiary intrusive complex occurs only as a small outcrop in the area in the Eastern Redhills (Stewart, 1965) and as xenoliths within the ferrodiorite member of the Marscoite Suite of the Western Redhills (Wager *et al.*, 1965; Bell, 1976; Thompson, 1969). The xenoliths are angular and up to at least 5 m in largest dimensions.

Most of the blocks are of leucocratic to mesocratic, coarsely banded gneiss. The main constituent minerals are plagioclase (An₂₉) and quartz, together with variable amounts of orthoclase microperthite in the paler bands (Table II). In a few of the available thin sections from the interior parts of the blocks the ferromagnesian mineral in the darker bands of the gneiss is a pale green clinopyroxene, in < 1.5 mm anhedral which

resemble texturally the pyroxene in granulite-facies Lewisian gneisses. Minor amounts of sphene and opaque oxide are intergrown with the pyroxene. As in Rhum (Tilley, 1944, Figs. 3 and 4), the original mafic minerals in most thin sections of the Skye blocks are recrystallized to fine-grained aggregates of biotite, plagioclase, and Fe-Ti oxide (\pm orthopyroxene or green amphibole). As also in Rhum (Dunham, 1967, Plate 27), the leucogneisses have undergone partial melting varying in amount from about 50% in block interiors to near-total, with breakdown of gneissose banding, within 15 to 30 cm of block margins. The melted areas have recrystallized to acid igneous-textured rocks, resembling many Skye granites (Thompson, 1969) except that their plagioclase 'phenocrysts' are deformed residual Lewisian gneiss feldspars.

One of the leucogneiss blocks encloses a sharply bounded 1 × 0.2 m lens of mica pyroxenite, which is foliated parallel to the over-all fabric of the block. The predominant phase is an oriented poikiloblastic intergrowth (< 6 × 2 mm anhedral) of diopside (Wo₄₅En₅₀Fs₅) and bronzite (Wo₁En₈₀Fs₁₉) with β of the clinopyroxene parallel to α of the orthopyroxene. The associated minerals are phlogopite, andesine (An₄₈) and almost wholly serpentinized olivine (Tables I and II).

One block exposed for 1.5 m² of outcrop is entirely basic two-pyroxene, labradorite granulite (Table II), with the original texture well preserved in three quarters of the block and recrystallized in the remainder to poikiloblastic plagioclase-two pyroxene-amphibole hornfels.

Chemical analyses of representative samples of the Skye xenolithic gneisses show that the predominating leucocratic/mesocratic type (Table II, JE6 and JE7) is very similar in composition to the Rhum gneisses (Dunham, 1967), 25–30 km SW of the Marsco area, and to the biotite-plagioclase-microcline-quartz grey gneisses of Rona, 29–36 km NNW of Marsco, studied by Holland and Lambert (1972). These authors stated (p. 346) that: 'The biotite-gneisses of Rona most closely resemble the Laxford assemblage of the type area.' The chemical similarity of the Harker's Gully xenoliths to amphibolite-facies grey gneisses of the mainland and Rona is confirmed by the values of Rb (63 ppm), Sr (413 ppm) and ⁸⁷Sr/⁸⁶Sr (0.7340) reported by Moorbath and Bell (1965) for a leucogneiss sample from the centre of one of the First Terrace (Table II) stream-bed outcrops (compare with Sheraton *et al.*, 1973, Table 4, and Lyon *et al.*, 1973).

The two-pyroxene granulite xenolith at the head of Allt Coire nam Bruadaran (Table II, SK587) resembles the mafic pyroxene gneisses of the central region of the mainland Lewisian complex.

TABLE I. Electron probe microanalyses of minerals in a mica pyroxenite lens within a Lewisian leucogneiss xenolith in ferrodiorite

	1	2	3	4
SiO ₂	53.49	55.44	41.64	57.07
Al ₂ O ₃	0.89	0.64	14.07	28.07
Cr ₂ O ₃	0.32	0.17	0.71	n.f.
Fe ₂ O ₃ *	1.89	0.63	-	-
FeO*	3.11	12.53	6.40	0.06
MnO	0.42	0.74	0.05	0.03
MgO	17.02	29.10	23.14	0.02
CaO	22.72	0.96	0.02	9.40
Na ₂ O	0.24	0.04	0.49	5.69
K ₂ O	n.f.	n.f.	8.91	0.20
TiO ₂	0.04	0.03	0.58	0.02
	100.14	100.22	96.00	100.55

Cation proportions

Basis	0=6	0=6	0=22	0=8
Si	1.957	1.975	5.881	2.544
Al	0.041	0.029	2.341	1.473
Cr	0.009	0.004	0.079	0.000
Fe ³⁺	0.052	0.017	-	-
Fe ²⁺	0.095	0.373	0.754	0.004
Mn	0.012	0.021	0.004	0.000
Mg	0.927	1.545	4.870	0.000
Ca	0.891	0.036	0.000	0.448
Na	0.008	0.000	0.132	0.491
K	0.000	0.000	1.604	0.011
Ti	0.000	0.000	0.058	0.000
Σ	4.000	4.000	15.722	4.968

NaFeSi ₂ O ₆	0.81	-
CaFeAlSiO ₆	4.45	1.72
CaAl ₂ SiO ₆	0.30	0.81
Ca ₂ Si ₂ O ₆	42.71	0.56
Mg ₂ Si ₂ O ₆	46.91	78.07
Fe ₂ Si ₂ O ₆	4.81	18.85

1. Ca-rich member of two-pyroxene intergrowth (see text).
2. Ca-poor member of two-pyroxene intergrowth (see text).
3. Pale brown mica.
4. Plagioclase.

* Fe₂O₃ calculated by assuming stoichiometry in the pyroxenes. All Fe recorded as FeO in the other phases.

A bulk analysis of the rock (SK665) containing these minerals is given in Table II.

JE6 Leucocratic gneiss xenolith in ferrodiorite, First Terrace, Harker's Gully, Marsco, western Redhills, Skye (NG 502260).

JE7 Mesocratic gneiss. Same locality as JE6.

TABLE II. Chemical and modal analyses and C.I.P.W. norms of Lewisian gneisses and Torridonian sediments

Sample	JE6	JE7	SK587	SK665	LMS14	LMS12A
SiO ₂	71.41	67.21	50.88	53.18	85.04	51.43
Al ₂ O ₃	15.75	16.98	13.94	6.62	7.53	20.29
Fe ₂ O ₃	0.43	0.67	3.66	0.93	0.53	9.39
FeO	0.70	1.70	6.38	6.60	0.48	1.54
MnO	0.45	0.35	0.24	0.27	0.02	0.04
MgO	0.60	1.71	6.38	18.95	0.37	4.14
CaO	2.09	3.57	14.01	9.64	0.35	0.53
Na ₂ O	4.63	4.86	3.26	1.16	1.37	0.96
K ₂ O	3.42	1.80	0.30	1.23	3.20	6.16
H ₂ O*	0.39	0.71	0.59	1.16	0.71	4.75
CO ₂	0.08	0.07	n.f.	n.f.	n.f.	n.f.
TiO ₂	0.10	0.36	0.61	0.13	0.10	1.05
P ₂ O ₅	0.07	0.12	0.14	0.05	n.f.	0.16
	100.12	100.11	100.39	99.92	99.70	100.14

C.I.P.W. norms

Q	25.70	21.19	-	-	63.39	15.05
or	20.21	10.64	1.78	7.29	18.93	36.41
ab	39.18	41.12	25.86	9.81	11.59	8.13
an	9.41	16.48	22.51	9.21	1.72	1.72
ne	-	-	0.94	-	-	-
c	0.99	1.00	-	-	1.18	11.41
di	-	-	38.07	30.42	-	-
hy	3.09	6.89	-	30.12	1.24	10.31
ol	-	-	4.04	10.19	-	-
mt	0.62	0.97	5.30	1.34	0.76	2.06
ht	-	-	-	-	-	7.97
il	0.19	0.68	1.15	0.24	0.20	1.99
ap	0.15	0.26	0.31	0.09	-	0.34
cc	0.18	0.16	-	-	-	-

Modes (volume percent) 3000 points

Quartz	32.8	16.5	††	-
Alkali feldspar	19.6	3.3	-	-
Plagioclase	46.4	65.6	X	12.7
Biotite	1.1	5.7	X	9.5
Pyroxene*	Tr?	8.4	X	73.7
Olivine†	-	-	-	4.1
Amphibole	Tr	Tr	X	-
Opagues	Tr	0.3	X	Tr
Apatite	Tr	0.2	X	-

SK587 Mafic gneiss xenolith in ferrodiorite, Allt Coire nam Bruadaran, Western Redhills, Skye (NG 519245).

SK665 Mica pyroxenite lens within leucogneiss xenolith in ferrodiorite, foot of Harker's Gully, Marsco, Western Redhills, Skye (NG 502262).

LMS14 Torridonian arkose, Applecross (Moorbath *et al.*, 1967).

LMS12A Torridonian shale. Same locality as LMS14.

Analyses by Geochemical Laboratories, Manchester University, using gravimetric and colourimetric methods.

All powders dried at 110°C before analysis.

* Modal pyroxene includes Ca-rich and Ca-poor phases; intergrown in SK665 (see text).

† Modal olivine in SK665 almost all pseudomorphed by "iddingsite".

†† SK587 is strongly banded, precluding modal analysis. X = phase present.

Comparison with the data of Sheraton *et al.* (1973, Fig. 5) shows that the composition of SK587 falls within the SiO_2 and K_2O range of these granulite-facies gneisses, at the low-potash end of the K_2O range at $\sim 51\%$ SiO_2 . In contrast, the SiO_2 and K_2O contents of SK587 are far outside the range of these oxides in Lewisian amphibolite-facies grey gneisses. Rona metadolerites have similar SiO_2 contents to SK587 but differ substantially in their values of CaO , Na_2O , K_2O , and TiO_2 (Holland and Lambert, 1972).

In so far as it is possible to reach a certain conclusion from interpretation of the petrographic textures of complex polymetamorphic rocks, it appears that (*before* the Tertiary events) the Skye and Rhum leuco- and mesocratic Lewisian gneisses were at a higher grade of regional metamorphism than the grey gneisses outcropping on Raasay and Rona. Perhaps these rocks are samples of deep levels within the Lewisian complex, carried up in the Tertiary basic magmas of Skye and revealed by regional up-doming on Rhum. The two-pyroxene basic granulite may have been brought up from even deeper within the crust (Hamilton *et al.*, 1979).

The poikiloblastic two-pyroxene intergrowth in the mica pyroxenite lens within the gneiss xenolith at the foot of Harker's Gully is interpreted as the product of Tertiary thermal metamorphism of a Lewisian mica-amphibolite (\pm pyroxene) pod. The crystallization temperature of the two-pyroxene porphyroblasts has been calculated to be 950°C from the compositions of the co-existing Ca-rich and Ca-poor pyroxenes (Table I), using equation (5) of Wells (1977). The pressure at which the Tertiary thermal metamorphism occurred cannot be specified from the mineral assemblage in the ultramafic gneiss. Nevertheless, it is evident from Table I that the pyroxenes are Al-poor and contain negligible (if any) Al^{VI} , in contrast with the pyroxenes in Lewisian pyroxene granulites (e.g. Wood, 1975). The crystallization of such Al-poor pyroxenes in equilibrium with plagioclase and olivine implies a maximum pressure of no more than a few kilobars.

The igneous microgranular/micrographic textures seen in the quartzo-feldspathic parts of the Skye gneiss blocks are interpreted as indicating that these xenoliths were melted locally. The acicular habit of the apatite crystals in the igneous-textured areas contrasts with the equigranular anhedral apatite elsewhere in the gneisses and gives further support to the partial-fusion hypothesis (Wyllie *et al.*, 1962). The petrographic study shows that the composition of the partial melt varied within each gneiss xenolith. In the central parts of blocks, the liquid was a minimum-melting-

temperature cotectic composition, crystallizing to a leucogranite. The melt within a few centimetres of the margins of blocks was adamellitic, as a result of almost complete fusion of the gneiss.

Melting experiments

The samples used in the melting experiments were Lewisian leucocratic (JE6) and mesocratic (JE7) gneisses, Torridonian arkose (LMS14) and shale (LMS12A). Finely ground powders of these rocks were sealed, together with excess water, in gold capsules which were held at 1 kb pressure in cold-seal rod bombs of M22 alloy (Williams, 1968) for periods of up to 5 weeks. Details of the experimental method have been published elsewhere (Thompson and MacKenzie, 1967). The pressure of 1 $\text{kb}_{\text{H}_2\text{O}}$ was chosen for all the experiments because a large proportion of other published experimental studies of relevant equilibria have been conducted at this water vapour pressure, facilitating comparisons of the results. As the main concern of this study is with the *relative* melting temperatures of Hebridean Tertiary acid plutons and their country rocks, it is not necessary (or implied) that the choice of 1 kb pressure and water-saturated conditions should represent the conditions during the genesis of the Tertiary magmas.

In all the experiments reported here (Table III) the equilibrium temperature was approached from below. Attempts to approach equilibrium temperatures from above produced inconsistent results, due to delayed and unreproducible nucleation of various phases—especially plagioclase. Although the phase relations reported here are unreversed, the run times were sufficiently long to allow reasonable certainty that equilibrium had been attained (Piwinski, 1967). The oxygen fugacity was not controlled during the experiments. Nevertheless, the use of gold capsules for long run times in M22 pressure vessels probably allowed the Ni-rich alloy of the bomb to control f_{O_2} in the charges to values close to those generated by the $\text{Ni} \rightleftharpoons \text{NiO}$ reaction.

Results. Selected results of melting experiments are listed in Table III. Except in near-solidus runs, the crystalline products were euhedral and free from remnants of residual phases. During quenching from temperatures near or above the liquidus, some experiments precipitated clinopyroxene in radiating aggregates of comparatively large crystals. Another occasional complication in the near-liquidus experiments was the growth of biotite as large flakes in equilibrium with the aqueous vapour phase at the interface between the surface of the charge and the enclosing capsule.

It is apparent from Table III that the melting behaviour of the leucogneiss (JE6) was investigated in greater detail than the other samples. This rock type is the one which has most frequently been invoked as the source of a major rheomorphic fraction in the Tertiary acid magmas (e.g. Brown, 1963; Moorbath and Bell, 1965; Carter *et al.*, 1978; Walsh *et al.*, 1979). The solidi of both JE6 and the mesocratic gneiss, JE7, at 1 kb water vapour pressure are at 715 °C. This temperature is within 5 °C of that determined by Tuttle and Bowen (1958) for the thermal minimum in $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 - H_2O at 1 kb and by Piwinski (1968) for the solidus of a Sierra Nevada granite (No. 104) at 1 kb $P_{\text{H}_2\text{O}}$. With rising temperature the degree of fusion of JE6 increases rapidly until, at 750 °C, it is more than half molten (Thompson and Dunham, 1969). At about 780 °C all the alkali feldspar in JE6 is consumed. With further increase in temperature, the refractory residuum melts progressively more slowly until the silicate liquidus is reached at 930 °C. In contrast, the small amount of alkali feldspar in JE7, the mesocratic gneiss, is consumed within a few degrees above its solidus. Only a small amount of liquid appears in this sample at temperatures as high as 735 °C, and several percent of plagioclase and orthopyroxene remain in the glass produced in the run at 952 °C.

The solidus of arkose LMS14 is below 717 °C (Table III) but is unlikely to be less than 715 °C (by comparison with leucogneiss JE6 and unpublished data on a Skye Tertiary leucogranite). Alkali feldspar persists in the residuum of LMS14 to about 735 °C, at which stage the arkose is approximately half melted. At higher temperatures the incorporation of the remaining quartz, orthopyroxene, and magnetite into the melt proceeds slowly.

The shale LMS12A has a distinctly higher solidus temperature at 1 kb water vapour pressure than the other three compositions included in this study (Table III). This is due to the high normative or/ab ratio of LMS12A and is in accord with published analyses of the initiation of partial melting in synthetic Ab-Or-An-Qz-H₂O systems (Tuttle and Bowen, 1958; Weill and Kudo, 1968). LMS12A contains a moderate amount of liquid at 740 °C. Its solidus is therefore probably only a few degrees above 717 °C. At higher temperatures the residual phases of the shale are very refractory and the rock is only about 70% melted at 893 °C.

Compositions of liquids produced during partial fusion. Attempts were made to obtain electron probe microanalyses of the glass products of partial melting experiments on samples JE6, LMS12A and LMS14. The analyses were most successful in the case of leucogneiss JE6. The analyses were made

using the automated MAC microprobe at the Geophysical Laboratory, Carnegie Institution of Washington. Details of the method have been published elsewhere (Thompson, 1974). For these analyses the specimen current was 0.004 μA and the beam diameter was varied between 10 and 20 μm , depending on the sizes of the glass pools.

The glasses are colourless (JE6 and LMS14) or pale greenish brown (LMS12A). Their compositions and CIPW norms are given in Table IV. The amounts by which the totals of the analyses fall short of 100% give an estimate of the H₂O contents of the glasses. All the glasses are peraluminous, reflecting the peraluminous compositions of both Lewisian gneiss samples and the Torridonian sediments (Table II). It is apparent that the FeO, MgO, CaO and TiO₂ contents of the liquids produced by progressive fusion of gneiss JE6 all increase systematically with rising temperature.

In fig. 1 the quartzo-feldspathic components of the analysed glasses are compared with experimental equilibria at 1 kb H₂O in the synthetic systems $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - SiO_2 and $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - $\text{CaAl}_2\text{Si}_2\text{O}_8$ (Tuttle and Bowen, 1958; James and Hamilton, 1969). When projected into Ab-Or-Qz, the JE6 glasses define a fish-hook-shaped trend which, at first sight, appears to contradict the known phase equilibria of this system (Tuttle and Bowen, 1958). Although the bulk composition of JE6 falls within the feldspar primary phase field in Ab-Or-Qz, the liquids produced during partial fusion of this gneiss up to 780 °C fall in the quartz primary phase field and trend away from the rock composition. Between 780 °C and 930 °C (the liquidus), the trend of glass compositions makes a 180 deg. turn and crosses first the quartz-feldspar field boundary and then the thermal valley in the feldspar primary phase field. The explanation of this trend is clear from the Ab-Or-An projection. Between the solidus (715 °C) and approximately 780 °C, the partial melts of JE6 are in equilibrium with quartz, alkali feldspar, and plagioclase (Table III). These liquids therefore lie along the intersection of the quartz-feldspar field boundary and the two-feldspar surface in Ab-Or-An-Qz. This line projects close to the trace of the two-feldspar surface in Ab-Or-An (fig. 1).

With loss of alkali feldspar from the solid residuum of JE6, the liquids formed during higher degrees of partial fusion of this gneiss leave the two-feldspar surface and lie on the quartz-plagioclase field boundary in Ab-Or-An-Qz. As the temperature rises from about 780 °C to 820 °C, the liquids are in equilibrium with residual plagioclase and quartz and trend towards the Ab-Qz join in the Ab-Or-Qz projection (fig. 1). Finally,

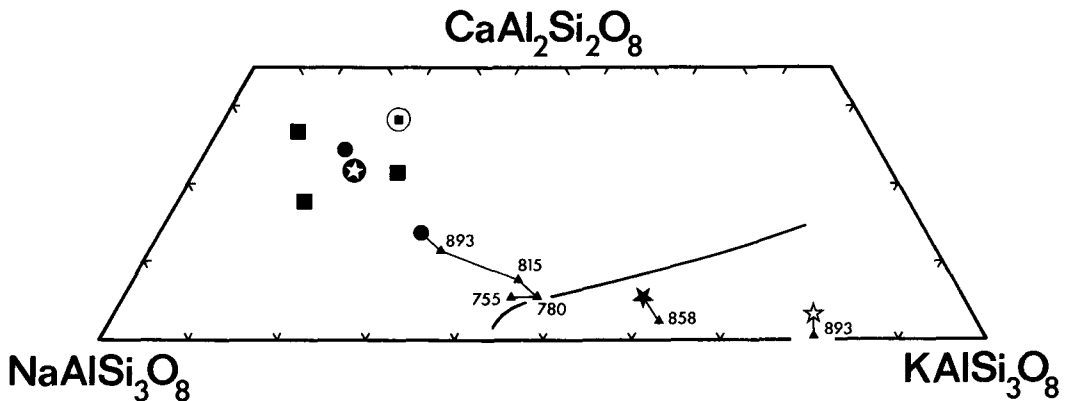
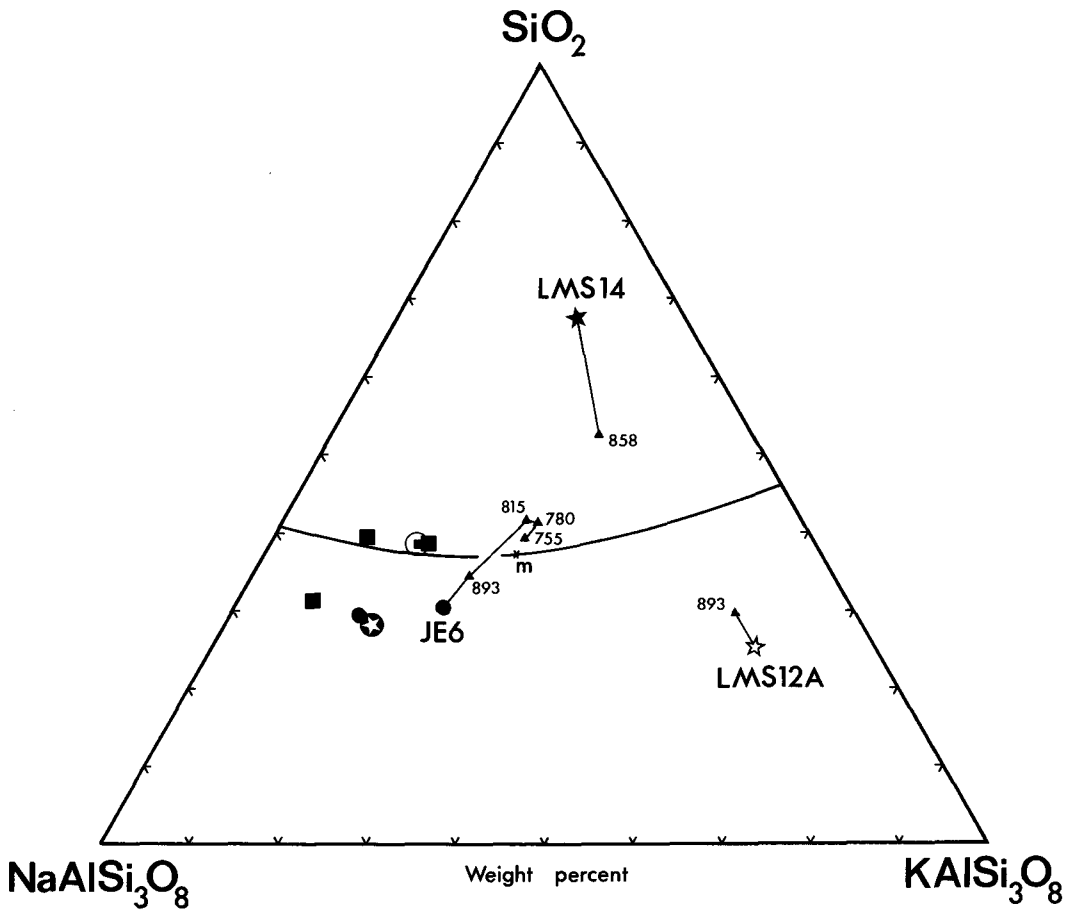


FIG. 1. Normative salic components of Lewisian gneisses, Torridonian sediments, and the glasses formed during their experimental partial fusion at 1 kb water-vapour pressure, compared with liquidus phase relations at 1 kb_{H₂O} in the synthetic systems NaAlSi₃O₈-KAlSi₃O₈-SiO₂ and NaAlSi₃O₈-KAlSi₃O₈-CaAl₂Si₂O₈ (Tuttle and Bowen, 1958; James and Hamilton, 1969). The temperature minimum on the quartz-feldspar field boundary in Ab-Or-Qz is marked *m*. Key to symbols: filled circles = Lewisian gneiss xenoliths in Eocene ferrodiorite, Skye; filled squares = Lewisian gneisses, Rhum (Dunham, 1967); circled square = average amphibolite-facies Lewisian grey gneiss, Rona (Holland and Lambert, 1972); circled star = average amphibolite-facies Lewisian grey gneiss, Rhiconich (Sheraton *et al.*, 1973); filled star = Torridonian arkose; open star = Torridonian shale; filled triangles = glass products of partial melting experiments (at temperature given by each point).

TABLE III. Selected results of melting experiments on Lewisian gneisses and Torridonian sediments at 1 kb, H_2O

Temp. (°C)	Time (days)	Products	Remarks
JB6 Leucocratic gneiss from Xenolith, SSW			
952	16	Ox, G1	Trace of Ox
937	24	Ox, G1	Silicate liquids 950°C
922	22	Pl, Ox, G1	
902	17	Pl, Opx, Pl, Ox, G1	Trace of Pl, Opx, Ox
893	24	Pl, Opx, Pl, Ox, G1	~90% G1
850	7	Pl, Opx, Pl, Ox, G1	85% G1 (Thompson and Durham, 1969)
845	26	Qz, Am, Pl, Opx, Pl, Ox, G1	~75% G1
804	30	Qz, Am, Pl, Opx, Pl, Ox, G1	
780	24	KF, Qz, Am, Pl, Opx, Pl, Ox, G1	~70% G1; trace of KF
750	24	KF, Qz, Am, Pl, Opx, Pl, Ox, G1	60% G1 (Thompson and Durham, 1969)
735	32	KF, Qz, Am, Pl, Opx, Pl, Ox, G1	
725	36	KF, Qz, Am, Pl, Opx, Pl, Ox, G1	
710	35	Kf, Qz, Am, Pl, Opx, Pl, Ox	Solidus 745°C
JB7 Mesocratic gneiss from xenolith, SSW			
952	16	Opx, Pl, G1	> 90% G1; + quench Cpx
890	5	Opx, Pl, G1	
850	7	Ox, Opx, Pl, G1	Trace of Ox
800	24	Pl, Ox, Opx, Pl, G1	~30% G1
755	27	Am, Qz, Pl, Ox, Opx, Pl, G1	
735	32	Am, Qz, Pl, Ox, Opx, Pl, G1	
725	36	Am, Qz, Pl, Ox, Opx, Pl, G1	Trace of G1
710	35	KF, Am, Qz, Pl, Ox, Opx, Pl	Solidus 745°C
LMS14 Torridonian arkose, Applecross			
858	24	Ox, Opx, Qz, G1	~75% G1
800	15	Ox, Opx, Qz, G1	~70% G1; Ox = Mt
760	30	Ox, Opx, Qz, G1	~60% G1
740	35	Ox, Opx, Qz, G1	~50% G1
717	30	KF, Pl, Ox, Opx, Qz, G1	~30% G1; solidus probably ~745°C

TABLE III (cont.)

LMS12A Torridonian shale, Applecross	
893	24 Bi, Cord, Ox, G1 ~70% G1; + vapour phase Bi
800	45 KF, Opx, Bi, Cord, Ox, G1
760	30 KF, Opx, Bi, Cord, Ox, G1
740	35 Qz, KF, Opx, Bi, Cord, Ox, G1
717	30 Qz, KF, Opx, Bi, Cord, Ox Solidus ~725°C

Abbreviations: KF = alkali feldspar, Qz = quartz, Pl = plagioclase, Bi = biotite, Am = amphibole, Cpx = Ca-rich clinopyroxene, Opx = orthopyroxene, Cord = cordierite, Ox = Fe-Ti oxides, G1 = glass.

TABLE IV. Electron probe microanalyses of interstitial glasses formed in partial melting experiments on Lewisian leucogneiss and Torridonian sediments

Sample	JB6	JB6	JB6	JB6	LMS14	LMS12A
Temp. (°C)	755	780	845	893	858	893
SiO ₂	72.30	72.07	74.57	70.42	74.61	66.28
Al ₂ O ₃	11.89	12.13	11.86	13.63	10.25	15.40
FeO*	0.74	0.77	0.79	0.83	1.03	1.31
MnO	n.f.	n.f.	n.f.	n.f.	0.31	0.17
MgO	0.12	0.20	0.25	0.38	0.44	0.49
CaO	0.60	0.59	0.87	1.41	0.20	0.51
Na ₂ O	3.37	3.06	3.24	4.12	1.77	1.37
K ₂ O	4.17	4.25	4.10	3.48	4.39	8.21
TiO ₂	n.f.	0.04	0.06	0.14	0.01	0.49
P ₂ O ₅	n.f.	n.f.	0.01	n.f.	n.f.	0.34
G.I.P.W. norms	93.19	93.11	95.69	94.41	92.98	94.57
Q	34.65	35.83	36.90	28.96	45.33	25.15
or	24.64	25.12	24.22	20.57	25.94	48.52
ab	28.52	25.89	27.43	34.86	15.00	11.59
an	2.98	2.93	4.23	7.00	1.00	0.31
c	0.74	1.42	0.54	0.52	2.21	4.15
hy	1.66	1.85	2.68	2.24	3.47	3.13
ll	-	0.08	0.12	0.27	0.02	0.93
sp	-	-	0.03	-	-	0.79

All the experiments were conducted at a water-vapour pressure of 1 kb.

* All Fe recorded as FeO.

JB6 Lewisian leucogneiss.

LMS14 Torridonian arkose.

LMS12A Torridonian shale.

See text for analytical methods.

Each analysis is the mean of 3 or 6 spots except for

JB6/815°C, where only 2

satisfactory analyses were

obtained.

all the quartz is consumed at about 820 °C and, with rising temperature, the liquids enter the plagioclase primary phase field in Ab-Or-An-Qz (fig. 1). Thus, it is clear that the compositions of partial melts of JE6 vary with rising temperature in a way which is consistent with theoretical equilibria in the synthetic system Ab-Or-An-Qz at 1 kb water vapour pressure, despite the corundum-normative nature of the liquids and the occurrence of small amounts of amphibole and biotite within the melting interval of the gneiss.

The limited microprobe data on the compositions of glasses produced by partial fusion of the two Torridonian sediments (Table IV) may be combined with the information on the sequences of residual phases as a function of temperature (Table III) to give a generalized outline of the sequences of liquid compositions produced during progressive melting of these samples at 1 kb_{H₂O}. In terms of their major components, the products of the early stages of partial fusion of the arkose (LMS14) appear to be very similar to those of leucogneiss JE6. The solidus of both compositions is apparently the same (715 °C) and the liquids produced during small degrees of melting of LMS14 are in equilibrium with residual quartz, alkali feldspar, and plagioclase. In contrast to JE6, however, the first feldspar to be consumed during progressive fusion of arkose LMS14 is plagioclase—within a few degrees of the solidus. Liquids resulting from further melting will lie near to the quartz-alkali feldspar field boundary in Ab-Or-Qz, between the minimum melting temperature and the Or-Qz join. In the Ab-Or-An projection they will fall in the alkali feldspar primary phase field (fig. 1). At approximately 735 °C all feldspar in the solid residuum of LMS14 is consumed and the liquids leave the quartz-alkali feldspar field boundary to enter the primary phase field of quartz. The analysed glass from a run at 858 °C (Table IV) is an example of this stage of fusion of the arkose.

The bulk composition of Torridonian shale LMS12A is too far removed from that of the thermal minimum in Ab-Or-An-Qz for this sample to begin melting at 715 °C at 1 kb water vapour pressure. When fusion commences at 725 °C, the first liquid must lie (in projection) approximately on the quartz-alkali feldspar field boundary in Ab-Or-An-Qz. It should be emphasized that this approximation is considerable in the case of LMS12A because the liquids are strongly peraluminous and both biotite and cordierite are abundant residual phases. Although the analysed glass from the 893 °C run (Table IV) has been plotted on fig. 1, it should strictly not be projected into Ab-Or-An-Qz, as it is not in equilibrium with any of the solid phases of this system.

Discussion

Partial fusion of sedimentary and metamorphic country rocks occurs adjacent to basic intrusions or in xenoliths included within them at several places in the Hebridean igneous province. The rheomorphic liquids are only preserved as fresh quenched glasses in those cases where the partial fusion took place on a very small scale, adjacent to or within a dyke, sill or plug (e.g. Wyllie, 1961). In one such instance, Butler (1961) has shown that the fusion was not an isochemical process but involved local metasomatic re-distribution of Na₂O and K₂O.

Evidence for partial fusion of country rocks on a larger scale is found locally adjacent to the major basic/ultrabasic plutons of the province. Examples of this are the Torridonian sediments at the margin of the Cuillin Intrusion at Camasunary, Skye, and the Lewisian gneiss in contact with the Rhum pluton (Dunham, 1967). In these cases—as with the Lewisian xenoliths described above—the evidence for fusion is textural, because the postulated liquids have subsequently crystallized. So far as the author is aware, even in these larger-scale examples there is no evidence that any partial fusion occurred at distances of more than about 50 m from the basic mass.

In a discussion of the origin of the Rhum granites, Dunham (1970) calculated the thermal effects within a carapace of Lewisian leucocratic gneiss of an 'open-system' basic magma chamber (Brown, 1956) with the dimensions of the present Rhum layered intrusion. He estimated that a volume of acid magma between 14 and 25 km³ could be generated by complete fusion of upper-crust leucogneiss in such a system; this would be enough to give rise to the exposed volume of acid igneous rocks on Rhum. Dunham assumed that the basic magma was essentially anhydrous but that the fusion of the country rock took place under water-saturated conditions.

The mineralogical and experimental data obtained for the Skye Lewisian blocks in the present study may be combined to give an estimate of P_{H_2O} during partial fusion. The petrographic study indicates that about 50% of liquid developed throughout the leucocratic gneiss blocks. Even within the outermost few centimetres of the xenoliths, where melting was almost total, a small amount of residual plagioclase remained. If P_{H_2O} in the leucogneiss blocks had been as high as 1 kb, the experiments show that they would have been above their liquidus at 950 °C, the temperature of two-pyroxene equilibration in the ultramafic lens within one of them. Considering the other extreme condition, if the leucogneiss blocks had been

anhydrous at 950°C, they would have been approximately at their solidi at 1 atmosphere and slightly sub-solidus at higher pressures. Although it may therefore be deduced that the value of P_{H_2O} was a few hundred bars during the partial fusion of the gneiss blocks, it is not possible to be more precise (or to specify whether $P_{H_2O} = P_{total}$) without an accurate estimate of the load pressure.

Brown (1963) concluded that the unconformity between Torridonian sediments and Lewisian gneiss lies between 1 and 3 km below the present sea level in central Skye. It was shown above that the petrography and chemical compositions of the Lewisian blocks in the Skye ferrodiorite suggest the possibility that these samples may have been incorporated into the Tertiary magmas at a greater depth in the Lewisian complex than is exposed nearby immediately beneath the Torridonian on northern Raasay and Rona. It is therefore possible that the partial fusion of the blocks—if this occurred before they were incorporated into the magma—took place under conditions of $P_{H_2O} < P_{total}$. Fusion of blocks within the magma would also have occurred at $P_{H_2O} < P_{total}$, because the only sources of water in such a system would be the hydrous minerals in the gneiss and dissolved water in the ferrodiorite liquid. The latter precipitated olivine and pyroxenes, with amphibole only appearing as a late-stage interstitial phase.

If the study reported here of small-scale partial melting of Lewisian blocks brought up in Skye Tertiary magmas gives any indication of the conditions under which large-scale fusion of the Lewisian gneisses took place at depth around the Tertiary central complexes (if this process indeed occurred), then it appears that these systems were water-undersaturated. The initiation of fusion in such a system occurs at a higher temperature than in an equivalent water-saturated system and is controlled by the dehydration temperatures of the hydrous minerals, biotite and amphibole (Brown and Fyfe, 1972). The maximum extent of fusion depends upon both P_{H_2O} and temperature and cannot therefore be specified by the type of thermal analysis used by Dunham (1970). Nevertheless, it is clear that water undersaturation may have been a major factor in restricting the amount of crustal fusion around the Hebridean intrusive complexes.

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