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## *Melting relations of Tertiary granitic rocks in Skye and Rhum*

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*Summary.* The results of reconnaissance melting experiments on Tertiary granophyres and Torridonian arkose at 1000 kg/cm<sup>2</sup> water-vapour pressure show that the melting behaviour of these rocks can be viewed in relation to the synthetic system NaAlSi<sub>3</sub>O<sub>8</sub>-KAlSi<sub>3</sub>O<sub>8</sub>-SiO<sub>2</sub>-H<sub>2</sub>O. By analogy with this system, *P-T* curves are constructed for Skye granophyres and, viewed in relation to the stability of tridymite, the depth and temperature of emplacement are estimated. Further estimates of the likely depth of magma generation, and the behaviour of the country rocks at that level, lead to the conclusion that most of the Tertiary granitic rocks were produced through partial melting of Lewisian basement rocks, the heat being provided by the basic magmas available during this volcanic episode. Subsidiary amounts of granitic magma were similarly derived from higher levels, within the Torridonian arkose group, and evidence is provided for the depth and temperature at which these, together with tridymite-bearing metamorphosed arkose in Rhum, were produced.

THE igneous rocks of the British Tertiary Volcanic Districts fall broadly into two categories, basic and acid. The basic rocks occur as extensive basalt flows, large layered intrusions, and hypabyssal intrusions. The acid rocks rarely form lava flows, but are usually in the form of fairly large intrusions such as ring-dykes, or as the central member of multiple basic-acid minor intrusions. Although the basic and acid rocks are closely related in space and time there is no convincing evidence for a more intimate genetic relationship such as would be found in differentiated bodies where the basic grade into the acid rocks: in fact the basic and acid rocks usually intrude each other. Thus, while the derivation of the basic and ultrabasic rocks from a basaltic magma can be clearly demonstrated, the role of an acid magma, and its source and properties, are difficult to demonstrate. Few petrologists working in this region would now advocate an origin for most of this large bulk of acid

rocks by a simple process of crystal fractionation of a basic magma, just as few could contemplate their formation by metasomatism *in situ* of the country rocks. Most of the evidence points to their intrusive nature, and much evidence demonstrates the previous existence of granitic liquids in the region (e.g. pitchstones, rhyolite flows, and glassy chilled margins).

A high-level source of heat, during the Tertiary Volcanic episode, could have been provided by the large amount of available basaltic magma, particularly during its crystallization to form the masses of gabbroic rock exposed in each centre (which may only be a part of more extensive deeper masses, as shown by geophysical evidence). A source of acid material could well be some of the rocks that formed the walls of these large basic fractionation chambers, i.e. the Pre-Cambrian acid gneisses and arkoses. Although workers in this region have thought of this as a likely source, attempts to demonstrate chemical affinities, including trace element contents, have not yet been successful (Professor Wager, personal communication). No attempt had as yet been made to estimate the depth and temperature at which the acid intrusive rocks are likely to have been generated, and later crystallized, and to relate this to the distribution of the country rocks and their melting behaviour at these depths and temperatures. A beginning was made by Black (1954), who estimated the depth at which the metasomatized infilling of a Tertiary vent had formed in Rhum (see p. 555) and by Wyllie (1961) who estimated that a picritic sill in Soay had melted the greater part of a Torridonian arkose inclusion at a maximum depth of about 1.7 km. More pertinent to the problem of the larger granitic intrusions of the region was the demonstration by Wager *et al.* (1953) that the Coire Uaigneich granophyre in Skye, approximating in composition to local Torridonian arkose, had been intruded as a liquid to form a ring-dyke 100 yds wide. The level of intrusion was not then considered, and the estimated temperatures were based on experimental data available only for the synthetic *dry* system Ab-Or-Qz (Schaerer, 1950).

The present paper considers certain features of the Coire Uaigneich granophyre, other acid rocks of Skye and neighbouring regions, and Torridonian arkose, in the light of some of the more recent experimental work by Tuttle and Bowen (e.g. 1958) and others. Estimates are made of the likely temperatures and depths at which the acid intrusive rocks were generated and later emplaced, while the effects of heating under similar conditions on the country rocks are considered. The experimental work of Tuttle and Bowen on the system  $\text{NaAlSi}_3\text{O}_8$ - $\text{KAlSi}_3\text{O}_8$ - $\text{SiO}_2$ - $\text{H}_2\text{O}$  has clarified the problem of high-level intrusive granites beyond all

measure and has pointed a way towards more detailed analysis of the environmental conditions necessary for the formation of specific bodies of granitic rock. However, Reynolds (1956) has remained sceptical and observed that the melting temperatures given for 'ternary' minimum compositions in the isobaric sections of the system  $\text{Ab-Or-Qz-H}_2\text{O}$  are, in fact, only the temperatures at which crystallization *begins* from a glass of that composition. Since then, Tuttle and Bowen (1958, p. 82) have reversed the experimental procedure by heating a mixture of 'ternary' minimum composition and shown that melting begins at about the temperature at which crystallization began in the other type of experiment. In other words the melting temperature interval, for 'ternary' minimum compositions, is probably negligible. Furthermore, two natural granites were subjected to heating experiments at various pressures of water vapour and shown to follow closely the behaviour of similar compositions in the synthetic system. (See also reference to other melting experiments on p. 542.)

In order to apply to the present problem the precise results obtained for the synthetic system, heating experiments were carried out on specimens of Skye granophyres, a Rhum granophyre, Torridonian arkose, and a Lewisian basic gneiss, at  $1000 \text{ kg/cm}^2$  pressure of water vapour. This work was of a reconnaissance nature in that the  $50^\circ \text{C}$  intervals of temperature and the short duration of separate runs precluded a precise estimate of temperatures of beginning and near-completion of melting. Despite this, the results confirmed that the specimens behaved as would be expected from their normative compositions in relation to the system  $\text{Ab-Or-Qz-H}_2\text{O}$ , and showed that no serious error would arise from considering their melting behaviour by close reference to that well-studied system.

*The rocks and their relationship to the system  $\text{Ab-Or-Qz-H}_2\text{O}$*

The Tertiary granitic rocks of Skye are confined to the central intrusive complex (Harker, 1904). The general age relationships show that after a long period of basalt surface eruption the Cuillin basic intrusion was emplaced, followed by the formation of the Western Redhills granitic complex and then the Eastern Redhills granitic complex. Most of the rocks considered in this account belong to the Western Redhills complex (see Wager *et al.*, 1948; Bell, 1959; Wager *et al.*, in MS.). The Coire Uaigneach granophyre is unique in that it was intruded after the Cuillin basic mass but is cut by the cone-sheet complex that preceded the Western and Eastern Redhills intrusions.

Previous work has shown that the Western Redhills complex consists essentially of a group of granophyre ring-dykes arranged concentrically around a common focus. Although the bulk of the rocks are granitic in composition, within which granitoid, granophyric, and felsitic textures provide the basis for a broad subdivision, varying mineralogical characters have made it possible to recognize separate intrusions within each of which the rock is relatively homogeneous. These distinctions are based chiefly on the character of the feldspars and of the subordinate ferromagnesian minerals (hornblende, fayalite, hedenbergite, riebeckite, etc.). The present account is not concerned with these minor, though critical, differences, but with the contents of normative quartz, albite, and orthoclase in each analysed rock type.

High-level granitic rocks occur in most of the other Tertiary Volcanic Centres of Western Scotland such as Rhum and Mull, and in Slieve Gullion in Ireland. Similar types of granophyre and felsite occur there, and closely associated with them in space and time are gabbroic intrusions. However, the acid rocks are clearly separate intrusions. The analyses considered here, as in the case of the Skye rocks, have all been published elsewhere but have not previously been examined in relation to the system Ab-Or-Qz (with or without water).

The normative contents of Ab, Or, and Qz are given in table I (the older, less reliable data are not included). In all cases the total Ab + Or + Qz exceeds 80 % of the rock's normative constituents and in most cases lies between 85 and 90 %. Re-calculation in terms of the coordinates of an Ab-Or-Qz ternary diagram means, therefore, neglect of only minor amounts of the other constituents. In any case, reference to the three-component phase diagrams involving Ab-SiO<sub>2</sub> or Or-SiO<sub>2</sub> and either anorthite, fayalite, or diopside (Schairer, 1957, figs. 31-35) shows that the addition of small amounts of these components has little effect on the position of the critical SiO<sub>2</sub>-alkali-feldspar boundary. Only the addition of anorthite to the Or-SiO<sub>2</sub> system (*op. cit.*, fig. 32) produces a marked change, but this is an unlikely association and is not relevant to the acid igneous rock system.

The data listed in table I are plotted on fig. 1, together with the position of the low-temperature trough (at the feldspar-quartz field boundary) and the temperature minima within these troughs, at various pressures of water vapour. Apart from three specimens falling well within the quartz field, the rest are clustered in a well-defined area close to the region of minimum melting temperatures in this system. Tuttle and Bowen (*op. cit.*, fig. 57) noted this feature for eight Skye granitic rocks,

TABLE I. Normative compositions (Qz-Or-Ab) of selected analysed rocks from the British Tertiary Volcanic Province (plotted in figs. 1 and 2)

Serial number (fig. 1)	Specimen name	Normative % (wt.)			Total (Qz + Or + Ab)
		Qz	Or	Ab	
1	Chilled Coire Uaigneich granophyre, Skye ... ..	39.87	20.30	23.57	83.74
2	Glamaig granite (G1) ... ..	20.72	29.03	36.10	85.85
3	Beinn Dearg Mhor granophyre (G2) ... ..	27.10	25.80	36.15	89.05
4	Marsco porphyritic granophyre (G3) ... ..	36.18	30.58	25.15	91.91
5	Porphyritic felsite (PF) ... ..	35.34	29.03	30.60	94.97
6	Marsco granite (G4) ... ..	25.48	24.75	35.84	86.07
7	Maol na Gainmich granite (CG)	29.70	30.60	31.50	91.80
8	Meall Dearg granophyre ... ..	23.40	25.19	35.49	84.08
9	Harker's (1904) analysed granophyre... ..	27.01	28.91	30.49	86.41
10	Glas Beinn Mhor granite (GBM)	31.80	24.47	30.39	86.66
11	Beinn an Dubhaich granite ... ..	32.94	29.47	28.30	90.71
12	Papadil granophyre ... ..	26.94	19.46	34.58	80.98
13	Orval granophyre ... ..	31.62	20.02	33.01	84.65
14	Porphyritic felsite ... ..	30.24	18.35	36.15	84.74
15	Loch Ba felsite ... ..	31.44	31.14	27.77	90.35
16	Glen More granophyre ... ..	21.42	26.69	35.11	83.22
17	Porphyritic felsite, Slieve Gullion ... ..	32.40	29.47	30.39	92.26
18	Porphyritic granophyre, Forkhill ... ..	26.28	32.80	30.92	90.00
19	Tardree rhyolite ... ..	44.21	24.65	19.45	88.31
20	Average Skye Torridonian (3 analyses) ... ..	42.90	20.02	20.96	83.88

Nos. 2-9, Western Redhills Complex, Skye (earlier nomenclature in parentheses). Nos. 10-11, Eastern Redhills Complex, Skye. Nos. 12-14, Isle of Rhum. Nos. 15-16, Isle of Mull. Nos. 17-19, Northern Ireland.

and because they fell in the region occupied by the maximum number of the world's analysed granites, called them 'normal'. The same could, therefore, be said of most of the specimens from different parts of this Tertiary Province, as plotted in fig. 1. This would indicate that they crystallized from a liquid close to the 'ternary' minimum composition and had suffered little change since then, apart from slight polymorphic changes in the feldspars (cf. Tuttle and Keith, 1954).

Studied in detail, however, the distribution of plotted points in fig. 1 raises certain problems. In plotting compositions of granites from contrasted environments it is possible to explain the spread by relating it to the various positions of the 'ternary' minimum at different water-vapour pressures—i.e. to greatly varying depths of formation and

water contents of the granite magmas. In this Province, however, it is likely that all these rocks, of broadly similar structure, texture, and mineralogy, began and completed crystallization at similar crustal levels and with similar contents of dissolved water. Thus the plotted points should first be viewed in relation to a single isobaric section. The

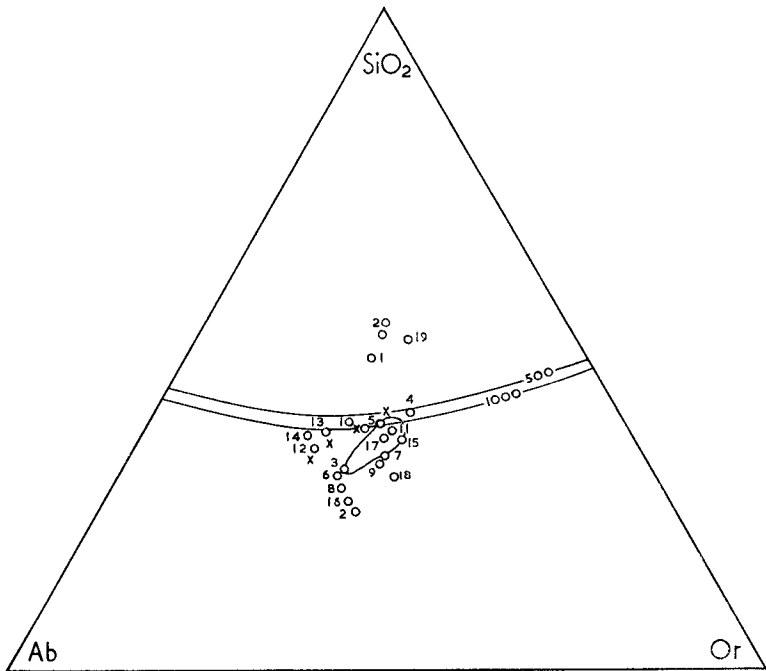


FIG. 1. Plot of the normative albite-orthoclase-quartz ratios (wt. %) of the specimens listed in table I. The quartz-feldspar boundaries at 500 and 1000 kg/cm<sup>2</sup> water-vapour pressure, the isobaric temperature minima for these pressures and for 2000 and 3000 kg/cm<sup>2</sup> (crosses), and the region occupied by 'normal' granites (oval) are taken from Tuttle and Bowen, 1958, figs. 22, 23, and 38.

appropriate section, i.e. pressure of water vapour, could be selected with reference to the concentration of points near a particular minimum, but from fig. 1 it is seen that there is no obvious single choice. However, the pressures close to or above 2000 kg/cm<sup>2</sup> are not only unlikely in this region of high-level volcanicity, but their minima lie well away from the region of maximum concentration of points, while the low-temperature trough for 500 kg/cm<sup>2</sup> lies at the edge of the region. Thus the isobaric section at 1000 kg/cm<sup>2</sup> would appear the more relevant to a consideration

of this suite of rocks. Another criterion for making this selection would be connected with the inferred order of crystallization of certain rocks, where compositions lie close to the boundary-trough region at low to moderate pressures. The shift in the position of the boundary, shown in fig. 1, means that rocks such as nos. 4 and 5 would crystallize quartz on the liquidus at moderate ( $1000 \text{ kg/cm}^2$ ) pressures of water vapour, but feldspar on the liquidus at lower pressures. These rocks are distinguished from the others by the presence of quartz phenocrysts, the quartz in the other rocks having formed alongside feldspar after a period in which feldspar crystallized alone. The  $500 \text{ kg/cm}^2$  isobaric section shows all the points on the feldspar side of the boundary, and the  $2000 \text{ kg/cm}^2$  section shows a very large proportion on the quartz side of the boundary. Only the  $1000 \text{ kg/cm}^2$  section divides the plotted points so that nos. 4 and 5 fall on the opposite side of the boundary from the others. (It should be noted that nos. 1, 19, and 20 are not relevant to this discussion.)

The isobaric section for  $1000 \text{ kg/cm}^2$  in the system  $\text{Ab-Or-SiO}_2\text{-H}_2\text{O}$  is, therefore, selected as the most suitable for comparison with the compositions of these granitic rocks. They are plotted in fig. 2 in relation to some isobaric fractionation curves,<sup>1</sup> for this water-vapour pressure, projected on to the anhydrous base of the tetrahedron (from Tuttle and Bowen, *op. cit.*, fig. 30). The scatter of the plotted points is significant, as opposed to the significance of the overall concentration, and invites the following comments:

Only three specimens fall clearly on the quartz side of the quartz-feldspar boundary. Only one specimen falls clearly on the albite side of the feldspar 'thermal valley' (*Pm*). The three specimens from Rhum (nos. 12-14) are separated from the others, and plot close to the 'thermal valley'; the majority (including all those from the Western and Eastern Redhills complexes of Skye) fall well within the field in which liquids would begin by crystallizing a potassium-rich feldspar (later to be made more sodic in the absence of fractionation). Most of the scattered points would fall on different fractionation curves, such that variation within the Province cannot be related to the fractional crystallization, or fractional melting, of a single type of magma or rock. Apart from two types (nos. 1 and 19), the acid rocks of this Province cannot be derived

<sup>1</sup> For examining homogeneous granites of this type, the isobaric equilibrium curves would be more appropriate than the fractionation curves. However, in the way in which the diagram is used here the difference is not significant, while the fractionation curves are needed to illustrate a later argument.

by fractional melting of Torridonian arkose (e.g. no. 20) or of any other highly siliceous sediment, for liquids thus obtained could only lie either in the boundary trough or on the silica-rich side of it; a few more of the plotted points would lie on the silica-rich side of boundary troughs

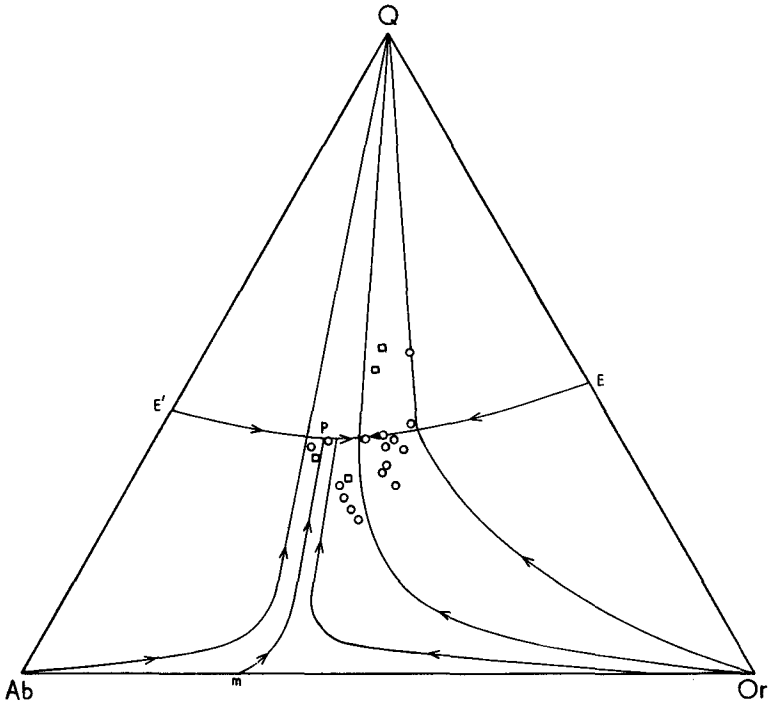


FIG. 2. The specimens shown in fig. 1 (and listed in table I), plotted in relation to the isobaric section for  $1000 \text{ kg/cm}^2$  water-vapour pressure in the system Ab-Or- $\text{SiO}_2\text{-H}_2\text{O}$ , projected on to the anhydrous base of the tetrahedron (from Tuttle and Bowen, 1958, fig. 30). Certain isobaric fractionation curves are reproduced, together with the quartz-feldspar boundary ( $E\text{-}E'$ ) and the feldspar 'thermal valley' ( $Pm$ ). The specimens designated by squares are those investigated experimentally (table III).

appertaining to high pressures of water vapour but at these depths (6 km or more) there would be no Torridonian arkose. Fractional melting of pelitic rocks such as shales would be unlikely to produce liquids lying in this part of the system (cf. Wyllie and Tuttle, 1961, fig. 3B). Fractional crystallization or melting of basalts or andesites could not produce liquids lying in the potash-feldspar field but only



those in the low-temperature trough (from the Ab-Qz side to the minimum), the feldspar 'thermal valley', or the soda-feldspar field (i.e. nos. 12, 13, and 14); this can be demonstrated by adding a triangle, with An at the apex, to the base of fig. 2, from which it would be seen that liquid fractions of basic magmas approach *m* from the An-Ab side (cf. Wyllie and Tuttle, 1961, fig. 3B); an example of such a liquid, if An is taken into account, could be that which produced the granophyre in Honolulu (Kuno *et al.*, 1957).

These facts impose restrictions on the composition of a likely source material for the bulk of the acid rocks from this Province, and are discussed in this context later (pp. 556 ff.). Further restrictions are imposed by a consideration of the likely temperatures and depths at which these liquids would be generated and complete crystallization. The plotted points do not fall on, or close to, a single isotherm for the section of the system shown in fig. 2, but on isotherms varying from about 720° C (the 'ternary' minimum) to 810° C (apart from the pair well within the silica field). These are temperatures of *complete* melting and, together with the character of the earlier crystallized phases, are relevant to the problems of the source of the liquids. It is also necessary, however, to consider the conditions under which these magmas were emplaced and completed crystallization. For this purpose, *P-T* curves have been constructed for representative specimens plotted in figs. 1 and 2 and are considered in detail in the following sections, in relation to the *P-T* curve for the 'ternary' minimum. The values used, which were obtained by superimposing the plotted normative compositions on to the various isobaric sections of the system NaAlSi<sub>3</sub>O<sub>8</sub>-KAlSi<sub>3</sub>O<sub>8</sub>-SiO<sub>2</sub>-H<sub>2</sub>O (Tuttle and Bowen, *op. cit.*, figs 22-24) and on the diagram for the dry system (Schairer, 1950, fig. 1), are given in table II.

Before these values are considered in detail a brief account is given of melting experiments carried out, on five rocks, to ascertain whether any significant error would result from interpreting the genesis of the granitic rocks of this Province by analogy with the synthetic systems.

#### *Melting experiments at 1000 kg/cm<sup>2</sup> pressure of water vapour*

The fact that granites usually contain more than 80 %, and often close to 90 %, of normative Ab+Or+Qz, and can contain up to 6 % of dissolved water at high pressures (Burnham and Jahns, 1958), means that they differ only slightly from the compositions used in experimental work on the system Ab-Or-Qz-H<sub>2</sub>O. The effect of other constituents, if in small amounts, is slight (p. 536).

In the experimental work on the synthetic system, Tuttle and Bowen (*op. cit.*) located with great precision the composition and temperature value for the minimum, at which liquidus and solidus meet at one point. Bulk compositions falling close to this 'ternary' minimum would, therefore, melt or crystallize completely through a very narrow temperature interval. Most natural granites are believed to be relatively close in composition to the 'ternary' minimum composition, and despite their slightly variable melting or cooling intervals would be expected to begin

TABLE II. Approximate temperatures for complete melting of certain specimens, obtained from plotting normative compositions in relation to the isotherms in two isobaric sections of the system  $\text{NaAlSi}_3\text{O}_8\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O}$  (Tuttle and Bowen, 1958) and the dry system (Schairer, 1950)

Specimen no. (see table I)	Probable melting temperature ( $^{\circ}\text{C}$ )		
	Dry	500 kg/cm <sup>2</sup>	
		H <sub>2</sub> O	H <sub>2</sub> O
1	1200	890	840
2	c. 1020	860	810
3	c. 1020	820	790
4	1100	775	740
12	c. 1000	810	785
20	1250	960	900
'Ternary' minimum	960	770	720

melting or complete crystallization close to the minimum in the synthetic system. (It should be noted that, except for a limited range of compositions, liquids of 'ternary' minimum composition are only produced on cooling other liquids if the early feldspars are prevented from reaction by crystal removal or zoning, or on melting a rock if that rock contained zoned feldspars.) Confirmation of this behaviour is given by Tuttle and Bowen's experiments on the Quincy and Westerly granites (*op. cit.*, table 12), and on other granitic rocks by Jahns and Burnham (1958). The series of experimental studies by Winkler and von Platen (e.g. 1961) and some by Kranck and Oja (1960) show that rocks of variable composition would, by a process of anatexis, produce granitic melts close in composition to the 'ternary' minimum provided they contain normative alkali feldspar and quartz. Despite these studies, the existing data on the melting relations of granites are scarce, and encompass less than half-a-dozen natural granites.

For this reason it was felt necessary to make a reconnaissance study of the melting relations of some granitic rocks and the prevalent country rocks of the British Tertiary Volcanic Province.

The specimens examined included the Coire Uaigneich and the Beinn Dearg Mhor granophyres from Skye, and the Papadil granophyre from Rhum (nos. 1, 3, and 12, table I). The reason for the choice of the three granophyres can be seen from figs. 1 and 2, in that they fall in the three separate regions defined by the feldspar-quartz and feldspar troughs at

TABLE III. Results of melting experiments at 1000 kg/cm<sup>2</sup> water-vapour pressure

Starting material*	Temperature (° C)	Product†
Coire Uaigneich granophyre (1)	700	No glass
	750	Trace glass
	800	40 % glass
	850	65 % glass; 20 % quartz
	900	95 % glass; 2 % quartz
Beinn Dearg Mhor granophyre (3)	700	No glass
	750	Trace glass
	800	45 % glass
	850	75 % glass; 10 % feldspar
	900	97 % glass; 1 % feldspar
Papadil granophyre (12)	700	No glass
	750	Trace glass
	800	40 % glass
	850	70 % glass; 20 % feldspar
	900	90 % glass; 5 % feldspar
Torridonian arkose (20)	700	No glass
	750	Trace glass
	800	40 % glass
	850	55 % glass; 30 % quartz
	900	80 % glass; 15 % quartz
Lewisian basic gneiss (horn- blende-andesine-quartz)	700 to 900	No glass

\* Numbers refer to those in figs. 1 and 2 and tables I and II.

† Residual material below 850° C omitted. Above this temperature, only the amount of glass and of residual quartz and feldspar (alkali or plagioclase) are listed. Other constituents of these higher temperature quenches include iron oxides (common) and ferro-magnesian silicates (rare, except in the Beinn Dearg Mhor hedenbergite granophyre).

1000 kg/cm<sup>2</sup> pressure of water vapour. Two contrasted types of country rock were also examined, Torridonian arkose (no. 20, table 1) and Lewisian gneiss (hornblende-andesine-quartz rock) from Rhum, not only to illustrate the way in which a source for the granitic liquids could be selectively eliminated but also, in the second specimen, to see whether incipient melting of andesine (even in the presence of quartz) was likely under these conditions (cf. reference to Black's hypothesis, p. 555). The results are given in table III.

The powders, taken from the supply used for chemical analysis in the case of the granophyres, were ground to  $< 400$  mesh and the charges placed in gold envelopes. These were heated, in the presence of excess water under pressure, in Tuttle cold-seal bombs ('test-tube' variety) placed vertically in the furnaces with the closed end down. The experiments were conducted using five of the furnaces in the School of Chemistry, University of Leeds (under the guidance of Prof. P. J. Wyllie), for which the recorded temperature readings of the chromel-alumel thermocouples attached to each bomb were believed accurate to  $\pm 5^\circ \text{C}$ .

The selected temperature intervals ( $50^\circ \text{C}$ ) are an indication of the preliminary, reconnaissance nature of the experiments; time limitations precluded the completion of runs at closer temperature intervals. The charges may have lost a trace of material from the envelopes but, according to Tuttle and Bowen (*op. cit.*, pp. 90-91), this becomes serious only for charges held at high pressures for several days. Loss of small amounts of silica (said to be the most likely loss) from specimens outside the 'ternary' minimum region would, in any case, have no effect on the temperature of beginning, but only on the temperature of completion of melting. The duration of each run was limited to 3 days (1 day for the runs at  $900^\circ \text{C}$ ), in order to avoid undue strain on the stellite bombs. This was believed long enough to achieve melting results but would not justify more than a cursory examination of the character of the residual crystalline phases.

The results were rewarding in that not only was the temperature of beginning of melting established but also, in some cases, a temperature of almost complete melting. Thus, at  $700^\circ \text{C}$  no melting took place. At  $750^\circ \text{C}$  all four specimens (disregarding the Lewisian specimen in this discussion) showed the development of a small amount of liquid (i.e. glass). At  $800^\circ \text{C}$  the glass content had increased to about 40 %, and at  $850^\circ \text{C}$  to about 70 %. At  $900^\circ \text{C}$  the Beinn Dearg Mhor granophyre was completely glass, apart from magnetite granules (due to oxidation) and less than 1 % residual feldspar crystals; the Coire Uaigneich granophyre melt contained about 2 % residual quartz, the Torridonian arkose melt about 15 % residual quartz, and the Papadil granophyre melt about 5 % residual feldspar. Thus, in a general way, these rocks behaved according to what would be predicted from their compositions as plotted on figs. 1 and 2. The two siliceous specimens contained quartz on the liquidus (with more for the arkose than for the granophyre), and the Papadil granophyre contained feldspar on the liquidus. The difference in behaviour of the two granophyres lying in the feldspar field, and on

similar isotherms, is probably due to the fact that the Papadil granophyre contains 7 % normative anorthite, compared with only 2 % in the Beinn Dearg Mhor granophyre.

The temperature of beginning of melting, therefore, lies between 700° and 750° C for these four specimens (the 'ternary' minimum is 720° C for the synthetic system at this water-vapour pressure). On the other hand, as will be seen from table II, column 4, complete melting should take place at temperatures lower than those observed, if direct analogy is drawn with the synthetic system. With longer runs, complete melting would probably have been achieved at lower temperatures, although liquidus temperatures are sensitive to the effect of other constituents, particularly anorthite, in the more complex natural systems. Hence the values quoted in table III, suggestive of near-complete melting, are only of a semi-quantitative nature.

Despite the reservations mentioned above it has been possible to demonstrate that the four significant rocks will begin melting between 700 and 750° C at 1000 kg/cm<sup>2</sup> water-vapour pressure, and will be almost liquid at 100° or so above this temperature. Also, the pattern of melting of each specimen is similar to what is predictable from their compositions as plotted in fig. 2. Hence it is practicable to relate the melting behaviour of the granophyres to the behaviour of similar compositions in the well-studied synthetic system Ab-Or-Qz-H<sub>2</sub>O, with some degree of confidence.

#### *The Coire Uaigneich granophyre*

Wager *et al.* (1953) showed that this granophyre body, 100 yds wide, had been intruded as a liquid to give a chilled margin, against Tertiary basalts, consisting essentially of 94 % glass (since devitrified) and 2 % tridymite crystals (since inverted to quartz). The centre of the dyke had crystallized as a granophyre of almost identical composition in which tridymite had continued to grow, in areas comprising about 50 % of the rock, and was followed by feldspar and quartz. They also showed that the granophyre had a highly siliceous composition, close to that of Skye Torridonian arkose, and contained a few shadowy inclusions of arkose. They plotted its composition in relation to the dry system Ab-Or-Qz and commented on the higher temperatures at which crystallization would begin from such a liquid than from liquids corresponding to the other Skye granophyres (which plotted in the rather broad low-temperature trough of the dry system). At that time it was not feasible

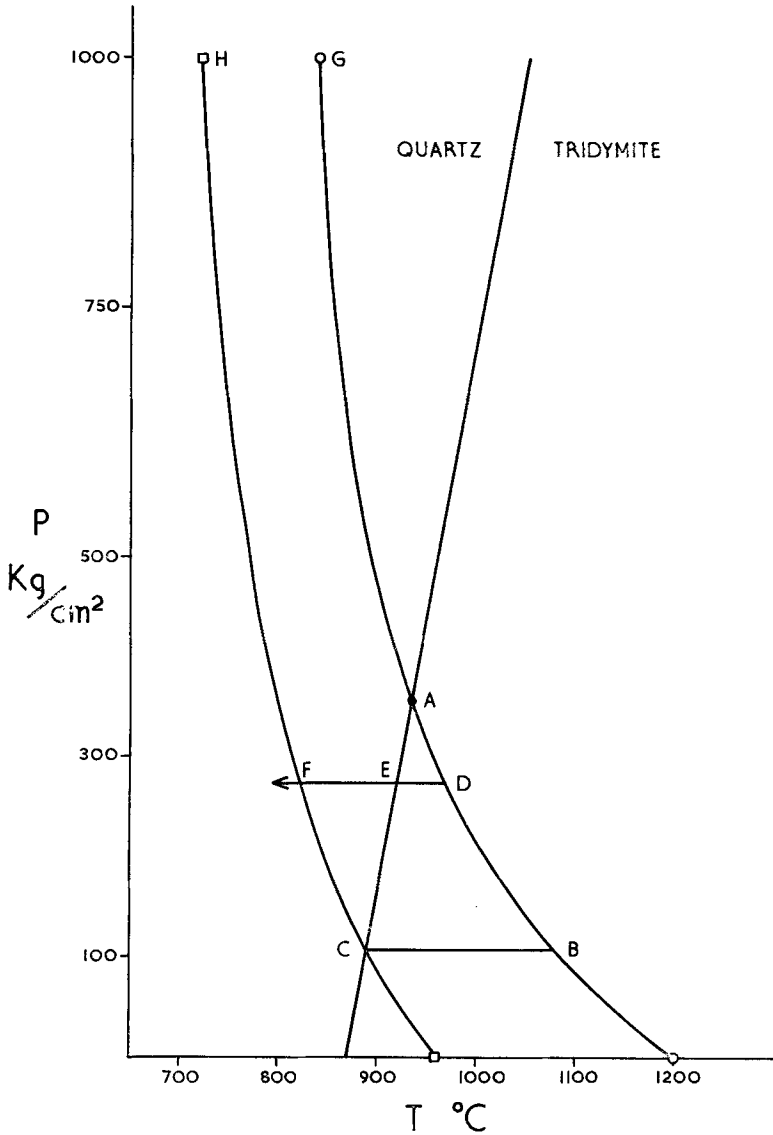


FIG. 3.  $P$ - $T$  curve for the liquidus of the Coire Uaigneich granophyre, Skye ( $GB$ , circles) and for the 'ternary' minimum composition (i.e. solidus) in the system  $Ab$ - $Or$ - $Qz$ - $H_2O$  ( $HC$ , squares), plotted from data in table II. Quartz-tridymite inversion curve from Tuttle and England (1955).

to attempt, from experimental evidence, an estimate of the temperatures and depth at which this liquid had been emplaced. The fact, however, that in the Brito-Icelandic Tertiary Province tridymite is generally confined to siliceous lavas (e.g. the Tardree rhyolite and the Icelandic liparites) or to arkoses thermally metamorphosed under a thin cover (e.g. the Rhum Torridonian) suggests that this mineral may be a useful geological barometer.

The dry melting temperature of this granophyre would be unusually high (1200° C, see table II), and for it to move far without much crystallization would require superheat in excess of this liquidus temperature, i.e. higher than the melting temperatures of basalts. This, and the presence of about 1 % water in the rock analysis, implies that the liquid was hydrous and may well have been saturated with water (cf. Tuttle and Bowen, *op. cit.*, fig. 27). From the data given in table II (no. 1), a  $P$ - $T$  curve for the liquid has been drawn (fig. 3), together with the experimentally determined  $P$ - $T$  curves for the 'ternary' minimum (Tuttle and Bowen, *op. cit.*, figs. 26 and 43, and table 12) and for the inversion quartz  $\rightleftharpoons$  tridymite in the presence of water vapour (Tuttle and England, 1955; Tuttle and Bowen, 1958, fig. 13).

From fig. 3 (point  $A$ ) it is seen that tridymite could not have formed initially from this liquid at water-vapour pressures of more than 360 kg/cm<sup>2</sup> and at temperatures less than 935° C. The liquid could not have been superheated above the liquidus temperature when intruded, because the chilled rock contains 2 % tridymite prisms orientated parallel to the intrusion walls. This gives a maximum figure for pressure of water vapour and a corresponding minimum for temperature. In the coarser-grained granophyre, away from the chill, quartz has crystallized in appreciable quantity, so that the join  $BC$  gives a minimum figure for pressure of water vapour (105 kg/cm<sup>2</sup>) and a corresponding likely maximum temperature for the magma (1080° C). A refinement of this range is obtained by using the evidence that in the central granophyre tridymite continued to form, apart from the phenocrysts, the tridymite-feldspar areas comprising about 40 % of the rock. A precise estimate of the temperature range over which the tridymite formed would be impracticable, but from the melting experiments at 1000 kg/cm<sup>2</sup> (p. 543) it was observed that in the melting interval for this rock (cf.  $GH$  but more probably the 150° C of  $DF$ , in fig. 3) about 65 % liquid formed with the first 100° C rise, and the rest in the next 50° C. Hence it is most likely that the tridymite completed its crystallization during the first 50° C fall within the cooling temperature interval, i.e.  $DE$  in fig. 3. The line  $DEF$

thus represents a close approximation to the cooling trend (in an isochemical plane) of the Coire Uaigneich granophyre.

It is suggested that the liquid *D* was *intruded* at a temperature of about 970° C and a water-vapour pressure of 275 kg/cm<sup>2</sup>, with 2 % tridymite crystals in suspension. The margins chilled directly to temperatures below *F* (820° C), while the central part of the intrusion continued to crystallize tridymite from *D* to *E*, and quartz from *E* to *F*, together with feldspar. Crystallization could be completed at temperatures slightly lower than *F*, at the intersection of an upward-curving line from *D* with the 'ternary' minimum curve, if the water-vapour pressure could increase with crystallization, through the load pressure being in excess of that necessary for water-saturation of the initial liquid. Completion of crystallization at temperatures higher than *F* is not likely, even though crystal-liquid equilibrium may have been maintained on cooling, because the crystallization path of this liquid (no. 1, figs. 1 and 2) would remain in the field of the silica phase almost until it reached the 'ternary' minimum.

It is unlikely that the Coire Uaigneich liquid was *generated* at a depth much greater than that represented by *A*, otherwise quartz, rather than tridymite, would have crystallized first, with decrease in either temperature or water-vapour pressure, unless the liquid was greatly superheated.

The Coire Uaigneich granophyre was intruded amongst Tertiary basalts, so the cover must have consisted almost entirely of basalt flows—the latest surface deposit to precede the granophyre intrusion. This means that, assuming a basalt density of 3.0, the thickness of cover was about 1 km (actually 920 m). The analysed granophyre lies at about 500 m above sea-level so that, although a very thin layer of basalt may have been eroded in the short interval that preceded this (early) granophyre intrusion, a figure of 1.5 km for maximum post-Tertiary terrestrial erosion of basalt in Skye would be a fair estimate.

#### *The Beinn Dearg Mhor and similar granophyres*

The fayalite-hedenbergite granophyre forming the 2000 ft mountain of Beinn Dearg Mhor was previously called G2 by Wager *et al.* (1948), the analysed specimen (H-932) being the one used in the melting experiments. It is part of the Western Redhills complex of Skye, and occurs in the form of a ring-dyke with an average width of one mile. In contrast to the Coire Uaigneich granophyre, this and the other granitic rocks of Skye do not contain inverted tridymite. On the other hand, they are found intruded at the same general level as the Coire Uaigneich granophyre,



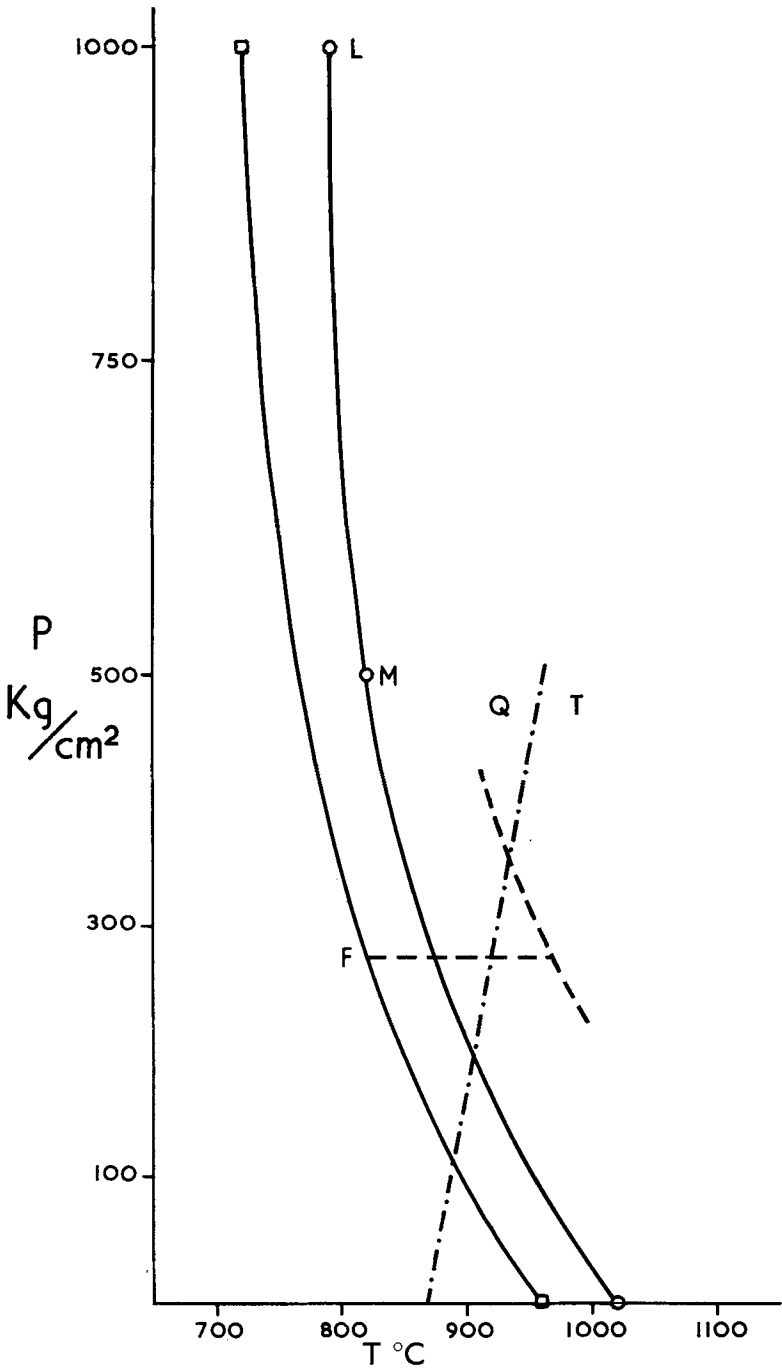


FIG. 4.  $P$ - $T$  curve for the liquidus of the Beinn Dearg Mhor granophyre, Skye (circles), derived from the data in table II. The solidus (squares) and the Coire Uaigneich granophyre data (dashed lines) are reproduced from fig. 3.

and their crystallization history can be examined in a similar way by reference to the  $P$ - $T$  curve shown in fig. 4, where the Beinn Dearg Mhor granophyre is taken as an example. Most of the other rocks plotted in figs. 1 and 2 approximate in composition to this granophyre (no. 3) but two extreme examples (nos. 2 and 4) will be considered later in this section in order to illustrate the possible minor degrees of variation in the crystallization behaviour of this suite of rocks.

For the present purposes it is assumed that the analysed Beinn Dearg Mhor granophyre completed crystallization at the same level (as it is, topographically), and under the same depth of cover, as the Coire Uaigneich granophyre. The two episodes of intrusion were separated only by cone-sheet injection, which would allow little time for surface erosion and, in any case, reference to fig. 4 shows that the absence of tridymite from the Beinn Dearg Mhor granophyre defines a minimum pressure of water vapour (200 kg/cm<sup>2</sup>). In view of the lower silica content, the  $P$ - $T$  curve for the Beinn Dearg Mhor granophyre lies closer to the 'ternary' minimum curve than does that for the Coire Uaigneich granophyre. The point  $F$  would represent final crystallization of the granophyre at this level, as it did in fig. 3. Whereas the Coire Uaigneich granophyre cannot have been generated far below its intrusion level (see p. 548), no comparable evidence exists for the level of generation of the large body of less-siliceous granophyres. However, as stated on p. 539, it is quite likely that they began crystallizing at pressures of water vapour in excess of 500 kg/cm<sup>2</sup>, and probably close to 1000 kg/cm<sup>2</sup>, if their mineralogy and textures are to be explained.

In contemplating the upward movement of magma of this sort, one is faced with the problem of whether the temperatures decreased, remained constant, or increased. It is usual to speak of magmas cooling (and therefore crystallizing) as they move upwards, but even the relatively anhydrous basalts, unless they were superheated, show evidence of having moved a long way to the surface without much fall in temperature, and consequent crystallization, on the way. In the case of hydrous magmas, reference to fig. 4 shows that one such as the Beinn Dearg Mhor granophyre could crystallize completely between  $M$  and  $F$ , i.e. with a decrease of water-vapour pressure but at constant temperature. Furthermore, as pointed out by Tuttle and Bowen (*op. cit.*), the latent heat released on crystallization could actually raise the temperature of such a mass, and heat, apart from the small amount needed for the energy of polymorphic mineral inversions, would have to be lost to the walls if the temperature is not to rise. Hence the upward movement of these

crystallizing granitic liquids, in an environment in which the wall-rocks were probably at a high temperature (as indicated by the occasional high-level generation of rocks such as the Coire Uaigneich granophyre), may well have taken place without loss of heat, and even with a slight rise in temperature. The generation of Beinn Dearg Mhor liquid at *L* (fig. 4), for example, would not be difficult to envisage, for this is a very thick intrusion and crystallization from *L* to *F* would require a temperature rise of only 30° C.

It is proposed, therefore, that the Beinn Dearg Mhor granophyre liquid was generated at temperatures and pressures of water vapour corresponding to points between *L* and *M* and that crystallization of feldspar, followed by quartz, took place as the liquid moved to higher levels, i.e. towards *F*. Such crystallization could raise the temperature of the liquid slightly, while the water-vapour pressure decreased (these granophyres are characteristically drusy, proving the presence of a separate vapour at some stage). By the time the crystal mush reached its present level of final consolidation, i.e. *F*, there would be present only a small amount of liquid (see table III) corresponding closely (but not exactly, in composition and temperature, if the feldspars have remained in equilibrium with the liquid; see fig. 2) to the 'ternary' minimum. The scarcity of interstitial liquid would account for the absence of much evidence for 'chilling' (which can only be observed in a liquid) and intrusive veins at the contacts of these granophyres. Had liquids of this composition been generated at pressures lower than, say, *M*, then they would have been emplaced at temperatures probably to the right of *F* (but within the quartz stability field), and with a fairly high liquid:crystal ratio.

The processes outlined above could apply to the other rocks, plotted in figs. 1 and 2, that have similar melting temperatures and intrusion levels. From the representative types listed in table II it can be seen that, apart from the Coire Uaigneich granophyre (no. 1), rocks such as no. 2 would have higher, and those such as no. 4 lower, melting temperatures than the average represented by nos. 3 and 12 (the differences are less marked at the non-applicable dry-melting temperatures). The behaviour of the higher-melting-temperature granophyres would be little different from that outlined above except that more liquid could have been present on emplacement, attended by more tendency for chilling and for veining of the country rocks.

The lower-melting-temperature rocks, however, pose a special problem. Their normative compositions, and hence their melting temperatures,

lie close to those of the 'ternary' minimum at moderate pressures of water vapour. This means that if generated in the presence of water vapour under pressure, and at temperatures not far in excess of liquidus temperatures, they would have had little opportunity for movement to regions of lower containing pressures before crystallization was completed. One such rock is the Marsco porphyritic granophyre, once called G3 (no. 4, figs. 1 and 2), which, because of the presence of quartz as phenocrysts, is believed to have begun crystallizing at moderate, rather than low, pressures of water vapour, i.e. at about 1000 kg/cm<sup>2</sup> (see p. 539). The  $P$ - $T$  curve is not plotted on fig. 4, but from the data given in Table II (no. 4) it can be seen that it would lie at temperatures only slightly higher than those for the 'ternary' minimum curve. There is little doubt, from this evidence, that after the generation of this liquid at depths comparable with those at which the Beinn Dearg Mhor granophyre was generated, upward movement and the reduction of water-vapour pressure would be accompanied by crystallization attended, of necessity, by a slight rise in temperature (cf. p. 550), for otherwise its  $P$ - $T$  curve would soon intersect that of the 'ternary' minimum. Nevertheless, the balance between crystallization and the released latent heat of fusion must have been a very delicate one, and this granophyre might have completed crystallization at a deeper level, being emplaced in a hot solid state.

#### *Metamorphism of Torridonian arkose*

The  $P$ - $T$  curves shown in fig. 4, including both Coire Uaigneich and Beinn Dearg Mhor granophyres, are appropriate for considering pressure and temperature relationships but cannot be studied together in order to gain a picture of the origin of these two contrasted granophyres. The reason is that compositional differences are not shown on the diagram, whereas figs. 1 and 2 show that the two rocks plot on opposite sides of a low-temperature trough. Thus a more realistic but complicated  $P$ - $T$  diagram would show the curves for the two granophyres lying on opposite sides of the 'ternary' minimum curve, with temperatures rising in both directions. Such a diagram would clearly illustrate the impossibility of deriving the two granophyres from a common source, becoming increasingly obvious at moderate to low pressures of water vapour. For this reason (discussed on pp. 540 and 557), the bulk of the acid rocks of this Province cannot owe their origin to total or even partial fusion of a siliceous sediment unless accompanied by extensive metasomatic replacement of silica by the feldspar components.

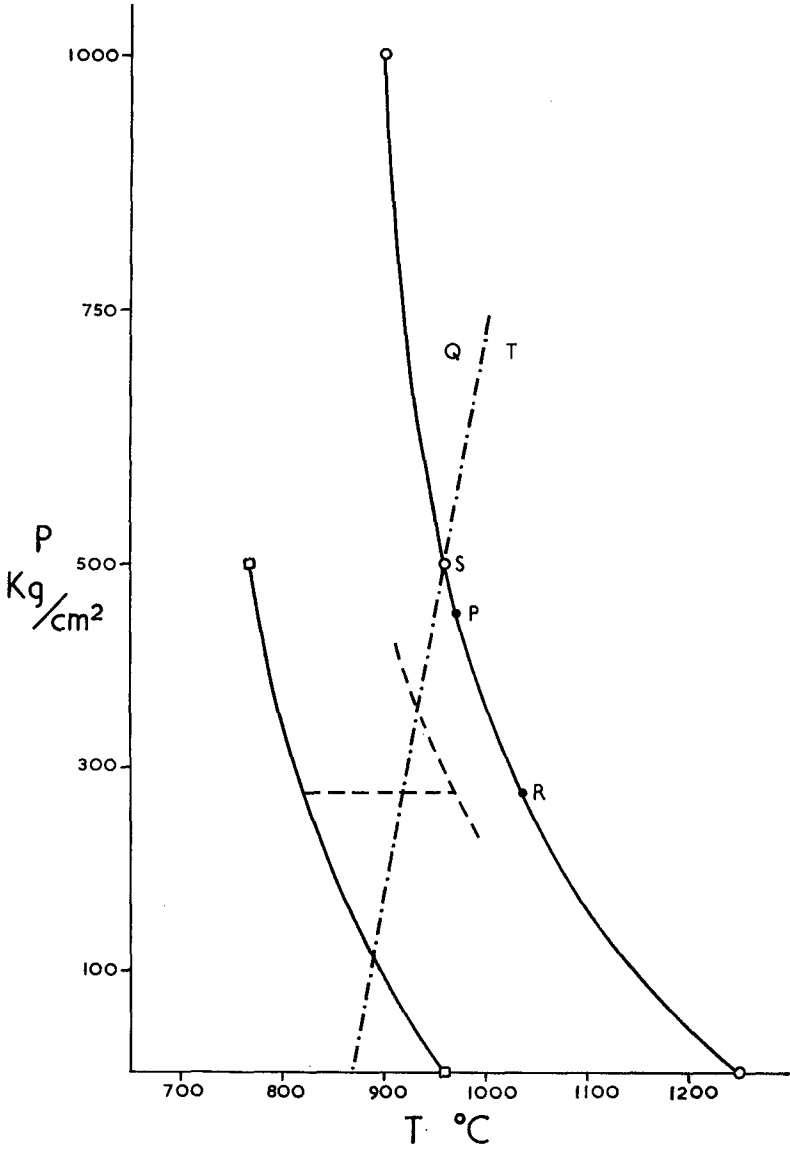


FIG. 5.  $P$ - $T$  curve for the liquidus of the average Skye Torridonian arkose (circles) derived from the data in table II. The solidus (squares) and the Coire Uaigneich granophyre data (dashed lines) are reproduced from fig. 3.

However, the Coire Uaigneich granophyre does afford evidence that liquids having the composition of Skye Torridonian arkose have been generated in small amounts in this region. The Torridonian rocks of Western Scotland are variable in composition, the xenolith studied by Wyllie (1961) being an extreme variety, low in potassium content (Butler, 1961, has suggested that the xenolith has suffered some Na-metasomatism). Such a rock could not be the source of the Coire Uaigneich granophyre, which could only be derived by the melting of a rock having a normative composition lying on a line joining its composition with the  $\text{SiO}_2$  corner of the system (fig. 2). Such a rock composition is that of no. 20 in fig. 2, representing the average of three Torridonian arkoses from Skye (Kennedy, 1951). The Torridonian rock used in the melting experiments (p. 543) would approximate to this composition, being a member of the Rudha na Roinne Grits of Rhum, which have been correlated with the Beinn na Seamraig Grits of Skye (Black and Welsh, 1961), from which two of the analysed specimens were taken.

The  $P$ - $T$  curve for the average analysed Torridonian is plotted on fig. 5, in relation to the curve for the Coire Uaigneich granophyre. At the temperatures estimated for the intrusion of this granophyre ( $970^\circ\text{C}$ ) the arkose would melt completely at a water-vapour pressure of  $450\text{ kg/cm}^2$  (point  $P$ ), corresponding to a further thickness of Torridonian material of only 700 m directly below the level of intrusion of the Coire Uaigneich granophyre, i.e. below the approximate junction between Tertiary basalts and Torridonian sediments in this region of Skye, west of the Camasunary fault. The Torridonian in this region is probably Beinn na Seamraig Grits (see p. 558), c. 900 m in thickness (Clough, in Peach *et al.*, 1907, p. 357), so this would be a likely source for the granophyre liquid. Total melting at higher levels within the Torridonian could take place at temperatures between  $P$  and  $R$ , i.e. at less than  $1035^\circ\text{C}$ . (which was the temperature estimated by Wyllie, 1961, for maximum fusion of Torridonian arkose by a fairly small picrite sill). As the Coire Uaigneich granophyre has, in fact, slightly lower melting temperatures than this particular arkose (table II), and contains shadowy inclusions of arkose, it could be produced by partial rather than total melting, at depths and temperatures slightly lower than those cited above.

In Rhum, the partial fusion of Torridonian arkose at the north-eastern margins of the Tertiary intrusive complex has produced tridymite, since inverted (Harker, 1932, p. 68). This arkose belongs to the Rudha na Roinne Grits (Black and Welsh, 1961, fig. 1) and thus could

have melting temperatures close to those shown in fig. 5. The point *S* marks the maximum water-vapour pressure ( $500 \text{ kg/cm}^2$ ) and corresponding minimum temperature ( $960^\circ \text{ C}$ ) at which tridymite could have formed, but this applies to total melting; the partial fusion observed in the rocks would take place at lower temperatures and pressures. From the melting experiments conducted on similar arkose collected away from the partially fused zone (table III) it was shown that, although only about 55 % of fusion took place over the first  $100^\circ \text{ C}$  of the melting interval, a lot of liquid was produced by the next  $50^\circ \text{ C}$  temperature rise. Thus, although the total melting interval of temperature is wider at lower pressures of water vapour (fig. 5), the production of such a metamorphosed arkose, with over 50 % of the rock remaining unfused and yet tridymite (probably preceded by the new quartz of the 'granophyric' intergrowths) forming in the rest, would happen at much lower pressures than represented by point *S*. A water-vapour pressure of about  $200\text{--}300 \text{ kg/cm}^2$  would fulfil most of these requirements, the amount of observed fusion taking place at about  $950^\circ \text{ C}$ . These pressures would correspond to a cover of about  $700\text{--}1000 \text{ m}$  of basalt.

Black (1953) made an estimate of the depth at which a Tertiary vent developed in this region of eastern Rhum, but used the theoretical data of Mosesman and Pitzer for the inversion relations of quartz and tridymite, since shown to be in error (Tuttle and Bowen, *op. cit.*). The application of the new experimental data to Black's observations on the partial fusion of andesine in the vent rocks, and the formation of tridymite in the neighbouring country rocks, would imply that the two processes could take place together only at pressures of water vapour in excess of  $1000 \text{ kg/cm}^2$ , i.e. at depths of over  $4 \text{ km}$ , rather than the  $1 \text{ km}$  proposed. It seems that Black's evidence should be reconsidered in relation to the effects of other rock constituents on lowering the temperature of incipient melting of andesine, and to the possibility that the vent material may have formed at a deeper level than the tridymite-bearing arkose into which it is emplaced. With reference to the latter possibility, it is significant that in present melting experiments Torridonian arkose from this part of Rhum was almost completely melted at  $900^\circ \text{ C}$ , whereas at the same temperatures and pressure of water vapour a hornblende-andesine-quartz rock did not show signs of even incipient melting (table III). By coincidence, the use by Black of Mosesman and Pitzer's data, giving higher temperatures for the quartz  $\rightleftharpoons$  tridymite inversion in the presence of water vapour under pressure, together with the acceptance of high temperatures for the incipient fusion of andesine, gives

results similar to those obtained here for the pressure and depth at which tridymite would form in metamorphosed arkose, but naturally much higher temperatures (over  $1100^{\circ}\text{C}$ ). At such temperatures and pressures of water vapour, the slightly fused Torridonian arkose mentioned by Black would have been completely fused (fig. 5). Black (*op. cit.*, p. 523) also states that because the ultrabasic layered rocks now lie at a higher level than the enclosing belt of metamorphosed rocks they were emplaced under an even thinner cover, while in misinterpreting Wager's reference (1953) to the Rhum intrusion he envisages the exposed layered rocks as formed in place, i.e. very close to the surface. In the writer's opinion (Brown, 1956) the layered ultrabasic rocks were finally emplaced essentially as a solid mass removed from a deeper magma chamber, stoping of the roof rocks being therefore unlikely. Rather, the cover would be domed, and partly uplifted along the ring-fracture, in which case it would be the same order of thickness as estimated above for the marginal Torridonian rocks, i.e. about 1 km. Uplift of the ultrabasic mass was aided by a narrow marginal ring of lubricating gabbro which, rather than the large ultrabasic mass, would be the agent chiefly responsible for the thermal metamorphic effects in the arkose, estimated at about  $950^{\circ}\text{C}$ .

#### *The source of granitic liquids in Skye and adjacent areas*

It has been shown that liquids of the composition of the Coire Uaigneich granophyre could be generated at a level where, in Skye, Torridonian arkose is present. In addition, plentiful evidence exists in this Province for the incipient fusion of such material, even at fairly high levels and at moderate temperatures. However, granitic rocks of a composition similar to the Coire Uaigneich granophyre are rare, and it is somewhat surprising that more rocks are not present having compositions lying between that of the Coire Uaigneich granophyre (or Torridonian arkose) and the quartz-feldspar boundary trough (as shown in fig. 2), i.e. produced by *partial* fusion of these siliceous sediments. If the other granitic rocks are produced by a similar process of fusion of country rocks then their source must lie beneath the Torridonian.

As mentioned on p. 539, the bulk of the granitic rocks from the British Tertiary Volcanic Province plot on the feldspar side of the quartz-feldspar boundary in the system  $\text{Ab-Or-Qz-H}_2\text{O}$  at moderate to low pressures of water vapour. Furthermore, the majority plot on the orthoclase side of the feldspar thermal valley while, finally, the plotted



points show such a scatter that no correlation with specific isobaric fractionation curves within the system is possible (fig. 2). Hence, in searching for a source for most of these granitic liquids, it is possible to eliminate certain processes:

The partial or total melting of siliceous sediments. This would produce liquids in the low-temperature trough at the quartz-feldspar boundary, or in the silica-rich part of the field.

The partial or total melting of standard shales. This would produce liquids of the above-mentioned type (cf. Wyllie and Tuttle, 1961, fig. 3B).

The fractional crystallization or melting of basalts or andesites. This would produce liquids either in the Ab-Qz region of the low-temperature trough or on the albite side of the feldspar 'thermal valley' (cf. Wyllie and Tuttle, 1961, fig. 3B).

The fractional crystallization or melting of a single type of magma or rock. This would produce a suite of liquids having compositions falling on isobaric fractionation curves of the type shown in fig. 2, whereas these rocks are widely scattered in relation to such curves.

From this evidence it would seem that the only likely source for this variety of granitic rocks, all formed at about the same time and in a similar environment, is by the partial melting of rocks of a specific overall composition, but far from homogeneous in detail. They would have to contain a large amount of total normative alkali feldspar + quartz (in view of the large bulk of these granitic derivatives), but with feldspar well in excess of quartz, the feldspar being relatively rich in potassium compared with sodium. An unlikely alternative to this hypothesis would be that each liquid was produced by total melting of a rock of its own composition, for this process would almost certainly be preceded by fractional melting so that groups of rocks lying along isobaric fractionation curves would be common. It seems more likely that partial melting took place at slightly different levels, in rocks of slightly different composition, and that the increase in volume produced by melting resulted in fracturing of the overlying rocks and migration of the liquids to higher levels. Despite the variability in generation temperatures of these liquids, in relation to single isobaric sections of the system Ab-Or-Qz-H<sub>2</sub>O, this may not be as significant as the variation in the observed normative compositions. Thus the load pressure and temperature may have been broadly uniform at the general level of generation of these liquids, but there may have been slight variations in the amount of dissolved water, below the maximum permissible at those depths and

temperatures. For example, at a specific load pressure of, say, 1000 kg/cm<sup>2</sup>, a liquid saturated in dissolved water and of 'ternary' minimum composition would be produced at 720° C. To produce a liquid of this composition but undersaturated in water, from the heating of a relatively 'dry' rock, would require higher temperatures, say 770° C. A nearby rock layer under the same pressure but rich in hydrous minerals (e.g. amphibole) would, at 770° C, possibly produce a water-saturated liquid, which would be far removed from the 'ternary' minimum composition at this pressure of water vapour and would correspond to liquids lying on the 770° C, rather than the 720° C, isotherm. Thus at a pressure of 1000 kg/cm<sup>2</sup> and a temperature of 770° C a suite of liquids could be produced, varying in bulk, anhydrous composition and water content, the range of such liquids being increased at greater depths.

In central Skye, the distribution of the Pre-Tertiary rocks is complicated by the thrusting and folding in the region of the Eastern Redhills granitic complex, and by the Camasunary fault in the region of the Western Redhills complex. The source of granitic rocks of both complexes would, however, from depth consideration appear to be either the Torridonian sediments or the Lewisian complex, which away from the thrust region (i.e. underneath the bulk of these granites in a zone from Soay to Scalpay) would underlie the Torridonian. In view of the scarcity of siliceous granites of the Coire Uaigneich granophyre type, it has been shown that the Torridonian grits, arkoses, and shales are not the source of most of these granites, while the similar and, if anything, more siliceous composition of the Moine granulites (cf. Kennedy, 1951) would preclude them on similar grounds in centres east of the Moine thrust plane, such as Mull and Ardnamurchan. The depth of the Lewisian complex in the Skavaig-Sligachan region of Skye is difficult to estimate, because there the Torridonian rocks have not been correlated with the succession in south-eastern Skye. However, from Clough's description of the Torridonian of Soay (1904) they would appear to be closest in character to the Beinn na Seamraig Grits of Skye (Clough, in Peach *et al.*, 1907, p. 356) and the Rudha na Roinne Grits of Rhum (Black and Welsh, 1961, p. 268). The lower unit on Soay, containing shale bands with ripple-marked surfaces, may correspond in part to the Loch na Dal beds of south-eastern Skye. This correlation can only be tentative, and is complicated by the absence of a definable line of strike between the Torridonian of Soay and that on Scalpay (which seems to be of the Applecross division, overlain by Trias; see Bailey, 1954, p. 108). However, if the Soay correlation can be accepted, then the Lewisian

would lie at less than 1 km below the exposed Torridonian (dipping  $15^\circ$  W.) in the Loch Skavaig region; if, on the other hand, the Soay sediments belong to the Applecross Group, and the full sequence of south-eastern Skye is present here, then the depth of Lewisian may be up to 3 km. Whatever the exact depth, it is believed likely that bodies of fractionating Tertiary basic magma lay within the Lewisian complex, for blocks of coarse Lewisian-type gneiss have been found in the ferro-diorite-marscoite intrusions in the Western Redhills complex of Skye, and in great abundance within the uplifted layered ultrabasic complex and the granophyres of Rhum (e.g. Black and Welsh, 1961, fig. 1). From various lines of evidence it has been suggested, earlier in this account, that the bulk of these granitic liquids were generated close to a pressure of  $1000 \text{ kg/cm}^2$  of water vapour, i.e. corresponding to a cover of 1 km of basalt (the level of emplacement) plus rather more than 3 km of the less-dense sediments and gneiss. On environmental grounds, therefore, the banded Lewisian complex seems the most likely source of the granitic liquids in regions such as Skye. On chemical grounds, however, it is not easy to prove this parental relationship. For the reasons stated on pp. 539 and 557, it is unlikely that the source rock was homogeneous in composition, and although this agrees well with the heterogeneous nature of the Lewisian it precludes direct comparison of compositions. The overall composition of the parent rock should, however, as pointed out on p. 557, fall within certain limits such that the liquids produced by partial melting fall within the potash-feldspar field of fig. 2. The ideal composition would, in terms of the end-components of that diagram, be around  $\text{Qz}_{20}\text{Ab}_{40}\text{Or}_{40}$ , corresponding to oxide percentages of  $\text{SiO}_2 = 73$ ,  $\text{Al}_2\text{O}_3 = 15$ ,  $\text{Na}_2\text{O} = 5$ , and  $\text{K}_2\text{O} = 7$ , i.e. a 'sodaclase granite' such as the Stone Mountain Granite, Georgia (Washington, 1917). No such compositions are to be found in published analyses of the Lewisian complex acid rocks, the commoner types being too rich in  $\text{SiO}_2$ ,  $\text{CaO}$ , or  $\text{Na}_2\text{O}$ , although some gneisses of the Laxfordian complex are relatively rich in microcline.

For these reasons, the precise source of the Tertiary granitic liquids must remain, at present, in some doubt. Various lines of evidence have been presented that point to a source at a depth appropriate to the existence of Lewisian rocks of some sort, whereas other locally available rocks have been eliminated in considering a likely source. It may be that an ancillary process, such as K-metasomatism, operated during the melting of the Lewisian rocks, but in view of the lack of evidence for K-metasomatism at the margins of basic intrusions (e.g. Butler, 1961)

it seems at the moment unlikely that this process would accompany the melting of basement rocks by the Tertiary basic magmas in this Province.

### *Conclusions*

The observed field relations, textures, mineral associations, and chemical compositions of certain granitic rocks from the British Tertiary Volcanic Province can be considered in relation to experimental data on the synthetic system  $\text{NaAlSi}_3\text{O}_8$ - $\text{KAlSi}_3\text{O}_8$ - $\text{SiO}_2$ - $\text{H}_2\text{O}$  and to melting experiments carried out on some of these rocks in the presence of water vapour under pressure. The Coire Uaigneich granophyre of Skye, containing inverted tridymite, was probably emplaced at a temperature of about  $970^\circ\text{C}$  and under a cover of about 1 km of basalt, while the fusion of Torridonian arkose, to produce this granophyre, could take place at less than 700 m below the level of granophyre intrusion. Post-Tertiary terrestrial erosion of basalt can be estimated, and is of the order of 1.5 km in the low valleys of central Skye.

The bulk of the Tertiary granitic rocks of this province are unlikely to have been derived by the fractional crystallization of one type of magma, or the fractional melting of one type of rock. Source rocks that can be eliminated, for most of the granitic liquids, include siliceous sediments and standard-type shales, while basalt magma would not produce such liquids through crystal fractionation. It is likely that they originated through the partial melting, in the presence of water vapour under pressure, of the varieties of rocks belonging to the Lewisian-gneiss basement complex.

In the Western Redhills complex of Skye, the Beinn Dearg Mhor granophyre was probably generated under a cover of 3-4 km, and was emplaced at about 1 km below the surface. The greater part of the mass would be crystalline at the time of emplacement, which would account for the absence of chilled contacts and of veining of adjacent rocks. The final consolidation at fairly high temperatures and yet under low pressures of water vapour, in the presence of little interstitial liquid, would prohibit extensive exsolution in the perthitic feldspars. The Marsco porphyritic granophyre of Skye, approximating more closely to a 'ternary' minimum composition, may have been emplaced in a hot solid state.

High-level granitic rocks approximating to a 'ternary' minimum composition are expected to be rare, while magmas of this composition would find difficulty in reaching the surface. Rhyolite lavas (as opposed to what may be the more common ignimbrites) are more likely to have

normative compositions falling in the higher temperature part of the granite system, such as the Tardree rhyolite of this Province. The presence formerly of such liquids at the surface (i.e. 'dry'), and of the Coire Uaigneich granophyre liquid at only 1 km below the surface, indicate the ease with which the other granitic rocks of this Province, having much lower melting temperatures, particularly in the presence of water vapour under pressure, could have been generated as liquids.

The metamorphism of a Torridonian arkose in Rhum, to produce tridymite crystals, is shown to have taken place at about 1 km depth, which would be equivalent to the depth of cover under which the uplifted ultrabasic layered complex was emplaced.

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