A granophyre from Coire Uaigneich, Isle of Skye, containing quartz paramorphs after tridymite.

(With Plate XIII.)

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THE narrow belt of granophyre lying to the west of Blaven in the Isle of Skye showed so admirably the effects of chilling that a series of specimens was collected by one of us (L.R.W.) and found to contain, in the chilled marginal rock, phenocrysts of tridymite, now inverted to quartz. In the Thulean Tertiary igneous province former tridymite is known from certain acid lavas, for example, the Tardree rhyolite (von Lasaulx, 1877) and certain Icelandic liparites (Hawkes, 1916), and from metamorphosed arkoses adjacent to basic igneous intrusions (Harker, 1908, 1932), but it has not previously been noted in the intrusive acid rocks. In addition to phenocrysts of tridymite inverted to quartz, there is present in the groundmass of the unchilled granophyre a second generation of inverted tridymite crystals, surrounded by a final stage of quartz and felspar which has crystallized with normal microgranitic textures. Some of the textural features resemble those of the normal Skye granophyres, while others resemble certain metamorphosed arkoses.

Field occurrences.

The material studied was all collected in the neighbourhood of the col between Blaven and the basalt hills of An Stac and An da Bheinn (fig. 1). Here the granophyre is about 100 yards wide and is intruded into basalts, the parallel, steep-sided margins of the intrusion dipping at 80° to the ESE. (fig. 1, inset). The contacts with the basalt on both sides are sharp, and marked chilling of the granophyre has occurred to give a dark, flinty rock. The strongly chilled rock extends for about a foot into the granophyre and then gradually, over a distance of about six feet, gives place to a normal-looking, rather fine-grained granophyre.

Small platy phenocrysts may be seen in the chilled rock, which have some degree of parallelism with the boundary wall of country-rock. In

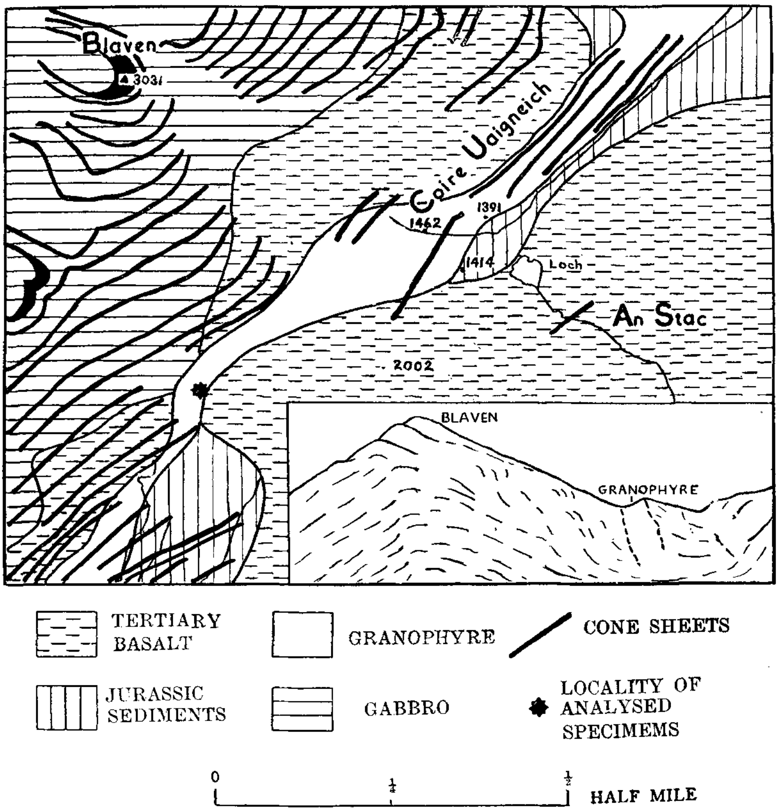

FIG. 1. Outline map of the Coire Uaigneich area, based on the maps of the Geological Survey. Inset: appearance of the area from the SW.

the central part of the granophyre the phenocrysts cannot be detected in the field and the rock appears uniform.

The granophyre examined forms part of a narrow intrusion mapped

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FIG. 2, B and B′. Main unchilled granophyre, showing development of criss-crossing tridymite crystals and the parallel relationship of some of them to the original tridymite phenocrysts. Areas of quartz and felspar with micrographitic texture are also shown. In B′, note that the same quartz unit may partly replace both the phenocrystic and the attached groundmass tridymite. B, ordinary light; B′, crossed Nicols.

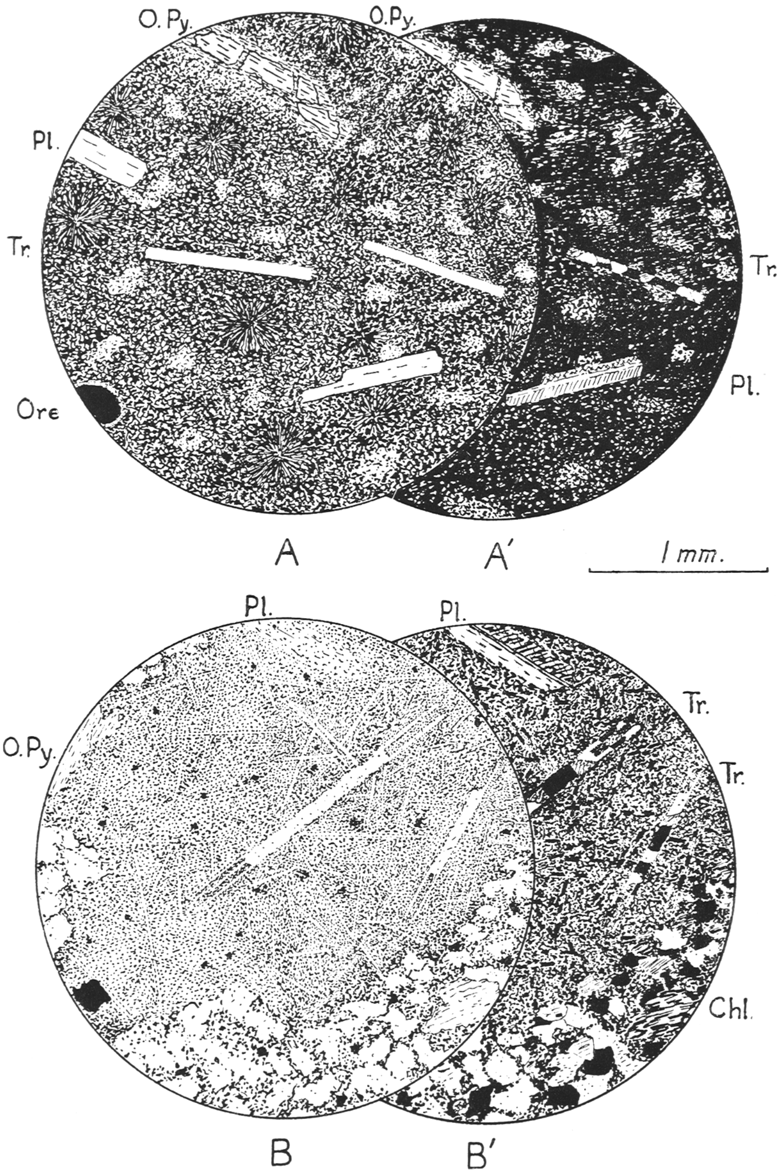

FIG. 2, A and A′. Chilled margin, showing phenocrysts of plagioclase (Pl), orthopyroxene (OPy), tridymite (Tr), and ore in a cryptocrystalline groundmass. Note the several quartz units now composing the tridymite crystal. A, ordinary light; A′, crossed Nicols. [FIG. 2, B and B′. *For description see opposite.*]

by Harker as extending for 3 miles to the NNE. and varying from 100 yards to a third of a mile in width (fig. 1). A rapid traverse along it suggests that the whole of this granophyre is essentially one mass; also it seems probable from petrographic similarities that the small area of granophyre to the west of Camasunary belongs to the same intrusion (unpublished thesis by J. M. Carr). To the east of Blaven the intrusion dips away from the Cuillins, the presumed centre from which it came, and it therefore appears to have a ring-dike form. Harker's map shows the granophyre to be cut by cone sheets and we have confirmed this. Richey (1932, p. 75) pointed out that this distinguishes it from the main granites and granophyres of Skye and suggests an earlier age.

The chilled margin.

The flinty chilled margin of the granophyre, in thin section, shows phenocrysts of felspar, tridymite now inverted to quartz, orthopyroxene, and iron-ore, set in a dense, dark-coloured cryptocrystalline groundmass (text-fig. 2, A and pl. XIII, fig. A). The orientation of the tabular felspars and inverted tridymites roughly parallel with the wall-rock is taken as indicating viscous flow.

The felspar phenocrysts (2·7 % by volume) are fairly thick, tabular crystals usually showing combined Carlsbad-albite twinning, the albite twin units often being very thin lamellae. Most crystals also show slight, continuous normal zoning. In all sections of the chilled granophyre studied, the felspar phenocrysts are fresh and gave the following data: $2V_\gamma = 75°$; maximum extinction angle in the zone $\perp$ (010) is α' : (010) 30°. This represents andesine-labradorite (approximately $An_{50} \pm 3$ %), and for felspars of this general composition, the optical data we have obtained does not make it possible, at present, to distinguish between high- and low-temperature types.

The former tridymite phenocrysts usually appear in thin section as narrow rectangular areas averaging 0·5 mm. in length, but broader sections and even rather irregular hexagonal sections are occasionally seen, depending presumably on their orientation relative to the section. The phenocrysts must be plate-like in form with a thickness approximately one-tenth or less of the diameter. In all cases the tridymite has inverted to quartz, the original tridymite crystal now being represented by many individual quartz units (text-fig. 2, A′). In the average elongate section, the long sides are definite, whereas the ends are not so clearly bounded, implying that the (001) faces of the original tridymite crystals were better developed than the faces at right angles to them.

Ray (1947), reporting on quartz paramorphs after tridymite from a quartz-latite-porphyry in Colorado, states that the *c*-axis of the quartz had a preferred orientation of $61° \pm 5°$ to the *c*-axis of the original tridymite plate. Ray investigated cases where each tridymite crystal had inverted to one quartz unit, but some degree of similar orientation is found in the Skye rocks where many individual quartz units replace a single tridymite crystal. By orientating sections of the chilled marginal phase of the Skye granophyre on the universal stage to give sections parallel with the *c*-axis of the original tridymite plate, it has been possible to plot stereographically the *c*-axes of the quartz units as angular distances from the *c*-axis of the original tridymite. The following results were obtained:

Angular distance from *c*-axis of original tridymite crystal ...	0–10°	10–30°	30–50°	50–70°	70–90°
Number of *c*-axes of quartz units	0	3	10	22	11

This would seem to indicate that, as Ray found in the case of single crystal paramorphs of quartz after tridymite, there is a limited degree of preferred orientation at approximately 60° to the original *c*-axis of the tridymite phenocrysts in the Skye example.

The orthopyroxene, modal amount 0·6 %, occurs as idiomorphic crystals with $2V_\alpha$ 51°, n_γ 1·716. These optics indicate a composition of 58 % $MgSiO_3$ according to Hess (1952) and, adopting Poldervaart's nomenclature (1947), it is named hypersthene. There is a varying amount of alteration to a bastite-like material.

Iron-ore, modal amount 0·7 %, occurs as rather rounded crystals up to 0·3 mm. across which are frequently rimmed by biotite.

The groundmass is cryptocrystalline with several minute crystals occurring in the thickness of the slice (pl. XIII, fig. A). Presumably it is composed largely of quartz and felspar, made dark with small magnetite crystals. Occasionally there are slightly coarser areas in which chlorite may be identified.

Traced inwards from the margin the rock quickly becomes less flinty and lighter in colour (pl. XIII, fig. B). Within a foot of the margin, the plagioclase begins to alter along cracks and the hypersthene becomes completely altered to bastite. For some feet, however, the groundmass remains essentially cryptocrystalline, a texture contrasting markedly with that found in the unchilled granophyre, next to be described.

THE MAIN GRANOPHYRE.

The main granophyre, as we shall term the unchilled material, shows, where we have studied it in the region of the col, areas having two generations of tridymite crystals, side by side with other areas having the typical micrograniticstructure of the normal Tertiary acid rocks of Skye. The phenocrysts so well seen in the chilled rock are still present in the main granophyre, although greatly altered. The tridymite phenocrysts have the same form and are similarly inverted to quartz; the scattered andesine phenocrysts are present but replaced by a cloudy acid felspar, the refractive index of which is less than Canada balsam; the hypersthene crystals are present but completely converted to bastite. The rest of the rock has crystallized with two different textures (text-fig. 2, B and pl. XIII, fig. C); two-thirds consists of patches in which criss-crossing thin lamellae of inverted tridymite crystals are dominant; the remaining third, which is, in general, interstitial to the criss-crossing tridymite patches, consists of quartz and felspar with a rough micrographic texture.

The criss-cross crystals of the groundmass could not have been identified with certainty as former tridymite if tridymite phenocrysts had not originally been present, as it is their relation to the phenocrysts which proves their origin. Thus the inverted tridymite phenocrysts often have thin outgrowths of the same dimensions and general form as the criss-cross pseudomorphs of the groundmass (text-fig. 2, B). These extensions, which may be confidently interpreted as former tridymite crystals, are now quartz, sometimes in optical continuity with quartz units replacing the tridymite phenocrysts. This detail of texture makes it clear that the acicular-looking crystals of the groundmass were originally a second generation of small tridymite plates which crystallized from part of the magma surrounding the phenocrysts and which later inverted to quartz.

All the felspars of the groundmass have a lower general refractive index than quartz, and must be a potash-soda-felspar, presumably a cryptoperthite. There may be some small difference in composition of the felspars of the groundmass, as that part which is enclosed in the criss-cross tridymite areas is less cloudy with inclusions than that in the microgranite areas, but no precise optical data have been obtained.

METAMORPHOSED TORRIDONIAN ARKOSES HAVING RELATED TEXTURES.

Harker has described and figured the results of the metamorphism of Torridonian arkoses in the Isle of Rhum (1908, pp. 61–67). In a later description of this rock (1932, p. 68) he ascribed the elongated quartz crystals to inversion from tridymite. Other examples have been described by M. K. Wells (1951, p. 720) and we have ourselves examined several cases from the metamorphosed Torridonian arkose adjacent to the basic complex of Rhum. A fairly typical example from within 10 feet of the contact with the eucrite in Allt Mor-n-h-Uamha, east of Allival in Rhum, is figured here (pl. XIII, fig. D). In hand-specimens the rock is beginning to have the appearance of a miarolitic granophyre; under the microscope areas of fritted quartz representing some of the original detrital grains can be seen, together with patches having a criss-cross arrangement of quartz after tridymite closely resembling that of the Coire Uaigneich granophyre. There are also areas showing a micropegmatitic intergrowth of quartz and acid felspar comparable with those found in the final stages of crystallization of the Coire Uaigneich granophyre. These similarities in texture suggest that the metamorphism, at its maximum, must have resulted in liquefaction of a considerable part of the arkose, otherwise the structures would be unlikely to resemble so closely those found in the granophyre produced by crystallization from a liquid.

Chemical composition.

Chemical analyses of the chilled marginal facies, and of the main granophyre from the central part of the intrusion, are given in table I, analyses 1 and 2. Their close similarity is at once apparent, and there can be little doubt that the two rocks originated from a common magma, an inference also drawn from the similarity of the phenocrysts.

The presence of andesine-labradorite and hypersthene in the chilled marginal rock might perhaps have been taken as some indication that the granitic magma involved would prove to be richer in basic oxides than usual, and in fact it is richer in MgO and CaO, although poorer in Na_2O and K_2O than the other Skye granites analysed. These differences, surprisingly, are not accompanied by low silica, the percentage of which, on the contrary, is high. If the normative plagioclase composition of the granophyre (Ab_{75}–Ab_{78}) is referred to the thermal equilibrium diagram for the plagioclases, it is seen that the appropriate plagioclase to crystallize first from a liquid of this composition, ignoring the effects of other constituents, would be An_{65}—so that the presence of phenocrysts at least as basic as the andesine-labradorite of the chilled marginal rock is to be anticipated. It is interesting that the early crystallizing pyroxene should be a hypersthene. Clinopyroxenes of diopside-heden-

TABLE I. Chemical analyses of the granophyre of Coire Uaigneich, Blaven, Skye, with some comparisons.

	1.	2.	A.	B.	C.	D.	E.
SiO_2	74·47	74·22	75·80	74·88	76·41	71·68	70·34
Al_2O_3	11·32	11·07	12·45	12·73	11·71	12·55	13·18
Fe_2O_3	2·06	1·75	1·47	0·53	1·68	2·29	2·65
FeO	2·22	2·43	0·44	1·33	0·77	2·40	2·24
MgO	0·78	0·74	0·08	0·25	0·17	0·24	0·40
CaO	1·69	1·56	1·00	1·12	0·42	0·92	1·24
Na_2O	2·79	2·95	2·30	3·33	3·62	4·28	3·61
K_2O	3·44	3·42	4·17	4·99	4·92	4·37	4·90
H_2O^+	0·47	0·90	1·30	0·79	0·50	0·64	0·76
H_2O^-	0·04	0·04	0·80	0·16	0·12	0·25	0·46
TiO_2	0·67	0·77	trace	0·18	0·14	0·38	0·46
P_2O_5	0·06	0·09	trace	0·05	0·04	0·03	0·10
MnO	0·06	0·06	0·017	0·02	0·002	0·05	0·19
others	—	—	—	—	—	—	Cl 0·02
Total	100·07	100·00	99·83	100·36	100·50	100·08	100·55
Norm (C.I.P.W.):							
qu	39·87	39·11	44·21	32·94	35·34	27·10	27·01
or	20·30	20·20	24·65	29·47	29·03	25·80	28·91
ab	23·57	24·96	19·45	28·30	30·60	36·15	30·49
an	7·98	6·79	4·95	5·00	1·11	2·06	5·22
cor	0·06	—	2·33	—	—	—	—
di	—	0·32	—	0·71	0·54	2·18	0·24
hy	3·30	3·42	0·20	1·82	0·17	1·44	2·40
mt	2·99	2·56	1·41	0·70	2·09	3·32	3·85
ht	—	—	0·50	—	0·24	—	—
ilm	1·28	1·47	—	0·46	0·26	0·71	0·87
ap	0·13	0·20	—	—	0·10	0·07	0·24

Mode (volume %) of H291 (analysis 1). Phenocrysts: felspar 2·7, pyroxene 0·6, ore 0·7, tridymite 1·7, total phenocrysts 5·7 %. Groundmass: 94·3 %.

1. Chilled marginal granophyre (H291), Coire Uaigneich, Blaven, Skye. Analyst: E. A. Vincent (new analysis).
2. Granophyre near centre of intrusion (H289), Coire Uaigneich, Skye. Analyst: E. A. Vincent (new analysis).

A. Rhyolite, New quarry, Tardree Mountain, Co. Antrim. Analyst: W. H. Herdsman. (Holmes, 1936.)

B. Biotite-hornblende-granite, Kilchrist, Skye. (Beinn an Dubhaich mass). Analyst: Geochemical Laboratories. (Tilley, 1949.)

C. Porphyritic felsite (H868), Harker's Gully, Marsco, Skye. Analyst: E. A. Vincent (new analysis).

D. Pyroxene-granophyre, G[2] (H932), SE. face of Beinn Dearg Mhor, Skye. Analyst: E. A. Vincent (new analysis).

E. Hornblende-granophyre, Druim Eadar da Choire, Skye. Analyst: W. Pollard. (Skye Memoir, 1904.)

bergite type are usual in the Skye pyroxene-granites and granophyres, and orthopyroxene does not appear to have been noted elsewhere.

In table I are also listed analyses of certain other Skye granites, and of the Tardree rhyolite, Co. Antrim, for purposes of comparison. Harker, in the Skye memoir (1904, p. 153), observed that the British Tertiary granites fell into a more acid and a less acid group. Examples of the former are afforded by the granites of St. Kilda, the Mourne Mountains, and northern Arran, and in Skye by the Beinn an Dubhaich mass. A recent analysis of the last granite is given as analysis B in the table, while analysis C is of another silica-rich granitic rock from Skye—the porphyritic felsite of Harker's gully on Marsco. While these two analyses are roughly comparable with those of the Coire Uaigneich granophyre in silica percentage, they are poorer in iron and magnesium and significantly richer in the alkali metals. Analyses D and E represent more normal types of Skye granophyre, and belong to the less acid group of Harker. In these rocks, iron and magnesium contents are comparable with those of the Coire Uaigneich granophyre, while the higher potassium and sodium contents, on the other hand, resemble those of the Beinn an Dubhaich granite and the porphyritic felsite of Marsco. Other, as yet unpublished, analyses of Skye granites show these same general characteristics. Thus, as far as is shown by data at present available, the formerly tridymite-bearing granophyre of Coire Uaigneich has a bulk chemical composition significantly different from that of other Skye granites and granophyres.

It has some similarities with the rhyolite of Tardree Mountain, Co. Antrim, also a tridymite-bearing rock, although here the tridymite occurs in fissures and cavities and not as phenocrysts or in the groundmass (von Lasaulx, 1877). The Tardree occurrence is thus different from the lavas carrying tridymite described from the West Indies by MacGregor (1938) and from the San Juan region in Colorado by Larsen (1936).

Some of the differences in chemical composition of the Skye granophyres are significantly displayed when the normative (weight %) contents of quartz, orthoclase, and albite are plotted on a triangular diagram (fig. 3). The thermal relationships between these three components in dry melt are known from Schairer's (1950) work on the system SiO_2–$KAlSiO_4$–$NaAlSiO_4$. In the phase diagram for this system there occurs a low-temperature 'trough', within the stability field of the alkali-felspars. Barth (1951) has plotted normative proportions of quartz, orthoclase, and albite for various granitic and rhyolitic rocks on this diagram, and has shown that the majority fall in or near the low-temperature trough. The Skye granite analyses also fall in or near this trough, except for the Coire Uaigneich granophyre, which, with the Tardree rhyolite, falls outside the trough towards the SiO_2 corner of the

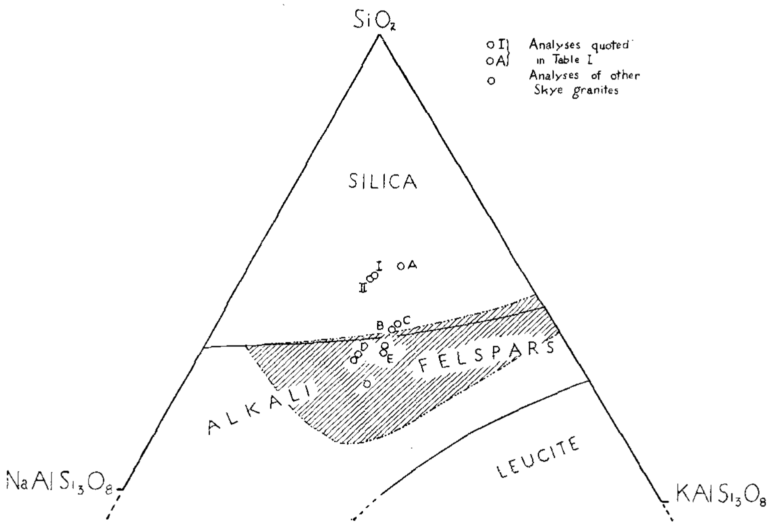

FIG. 3. Portion of the phase diagram SiO_2–$KAlSiO_4$–$NaAlSiO_4$ (after Schairer, 1950). The area below the 1050° C. isotherm ('low-temperature trough') is shaded.

triangle. Although having a slightly higher silica content than the Coire Uaigneich granophyre the analyses of the Beinn an Dubhaich granite and porphyritic felsite of Marsco (table I, B and C) fall nearer the trough, because their alkali content is relatively high and much SiO_2 is used in building the normative felspars, leaving less as excess quartz.

From the work of Fenner (1913) and others it is clear that tridymite forms as a metastable phase below its minimum temperature of existence as a stable mineral. Thus no absolute temperatures may be inferred from the presence of tridymite when considering the cooling history of this Skye granophyre. Whether tridymite crystallized or not is likely to be a complex function of temperature, composition, and the amount of fluxes present. In the SiO_2–$KAlSi_3O_8$–$NaAlSi_3O_8$ portion of Schairer's dry-melt phase diagram the appropriate form of silica in the region of the plotted points for the Coire Uaigneich granophyre is tridymite and the temperature of the beginning of crystallization lies between 1200°

and 1300° C. It is not suggested that there is any close correspondence between these temperatures and the actual temperature of crystallization of the Coire Uaigneich granitic magma, but it is likely that magma of this composition would crystallize at higher temperatures than normal granite and it is of interest that in the particular case here considered tridymite crystallized as the early phenocrystic material.

Conclusions.

From the textures described it is clear that tridymite, andesine-labradorite, hypersthene, and iron-ore crystals were just beginning to precipitate from the Coire Uaigneich granite magma when it was emplaced. Close to the cold country-rock, the magma with its enclosed crystals was apparently chilled rapidly, probably through several hundred degrees, giving, as a temporary stage, a glass. Thereafter, cooling of the marginal material would be slower, the glass being devitrified at some stage, say at a temperature of 200–300° C., to give the cryptocrystalline groundmass now found (pl. XIII, fig. A). A little farther from the margin (pl. XIII, fig. B), chilling caused by the cold country-rock would be less marked, but still the temperature of the liquid seems to have been carried rapidly down below that required for the formation of tridymite before appreciable crystallization took place. Still farther in from the margin a stage is reached where chilling was less rapid and minute crystals of tridymite had time to form in continuation of the phenocrysts, although the majority of the liquid solidified below the tridymite range. The main part of the granophyre, away from the effects of rapid chilling, would cool more uniformly, and here the textures are typically as shown in pl. XIII, fig. C. While about two-thirds of the liquid crystallized, tridymite was precipitated especially around the original tridymite phenocrysts, giving the criss-crossing tridymite areas. In the later stages, while the remaining third of the liquid crystallized, quartz, not tridymite, was precipitated, together with felspar and chlorite, giving the areas of microgranitic texture. These may reasonably be considered to have resulted from crystallization of a wetter residual liquid at relatively low temperatures. At some stage, apparently prior to the final quartz-felspar crystallization, the tridymite inverted to quartz. It was probably at this stage also that the plagioclase phenocrysts and perhaps also early groundmass felspars were made over to more acid felspars, and hypersthene was replaced by bastite.

The higher-temperature criss-cross tridymite texture is found in the later differentiates of the Skaergaard intrusion, east Greenland. Acicular quartz was described from high ferrogabbros and figured from the andesine-andesite (Wager and Deer, 1939, p. 116 and pl. 19, fig. 1). It was stated at the time that the significance of this texture was not understood. Re-examination now makes it clear that the acicular quartz must have inverted from tridymite, and no doubt other examples will be found in the mesostases of quartz-bearing intermediate rocks.

Evidence for the ultimate origin of the Coire Uaigneich granite magma is not provided by the observations here recorded—only the existence of a granite liquid carrying 5 % of crystals when intruded into its present position can be inferred, the chilled contacts clearly precluding any hypothesis of the generation of the magma in situ. Fusion of Torridonian sandstone adjacent to the basic rocks of Rhum seems to have produced a liquid capable of crystallizing with a mineralogical composition and texture similar in significant ways to this granitic magma. It should also be remarked that shadowy relics of an arkose have been found in the main part of the Coire Uaigneich granophyre, although not as yet in the marginal chilled material. Rocks such as the Coire Uaigneich granophyre, having a composition falling outside the usual eutectic compositions of granites, are not likely to be late residues from a crystal fractionation process, and perhaps in this granophyre we are studying a magma formed by refusion of an original, quartz-rich material which has not suffered appreciable subsequent fractional crystallization. A study of trace elements in the Skye granophyres, Torridonian arkose, and acid Lewisian gneiss, which is in progress, may perhaps provide useful evidence on the problem of the ultimate origin of some of the acid magmas of the British Tertiary igneous province.

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EXPLANATION OF PLATE XIII.

Photomicrographs of former tridymite-bearing granophyre from Coire Uaigneich, Skye, and of arkose with tridymite from Rhum.

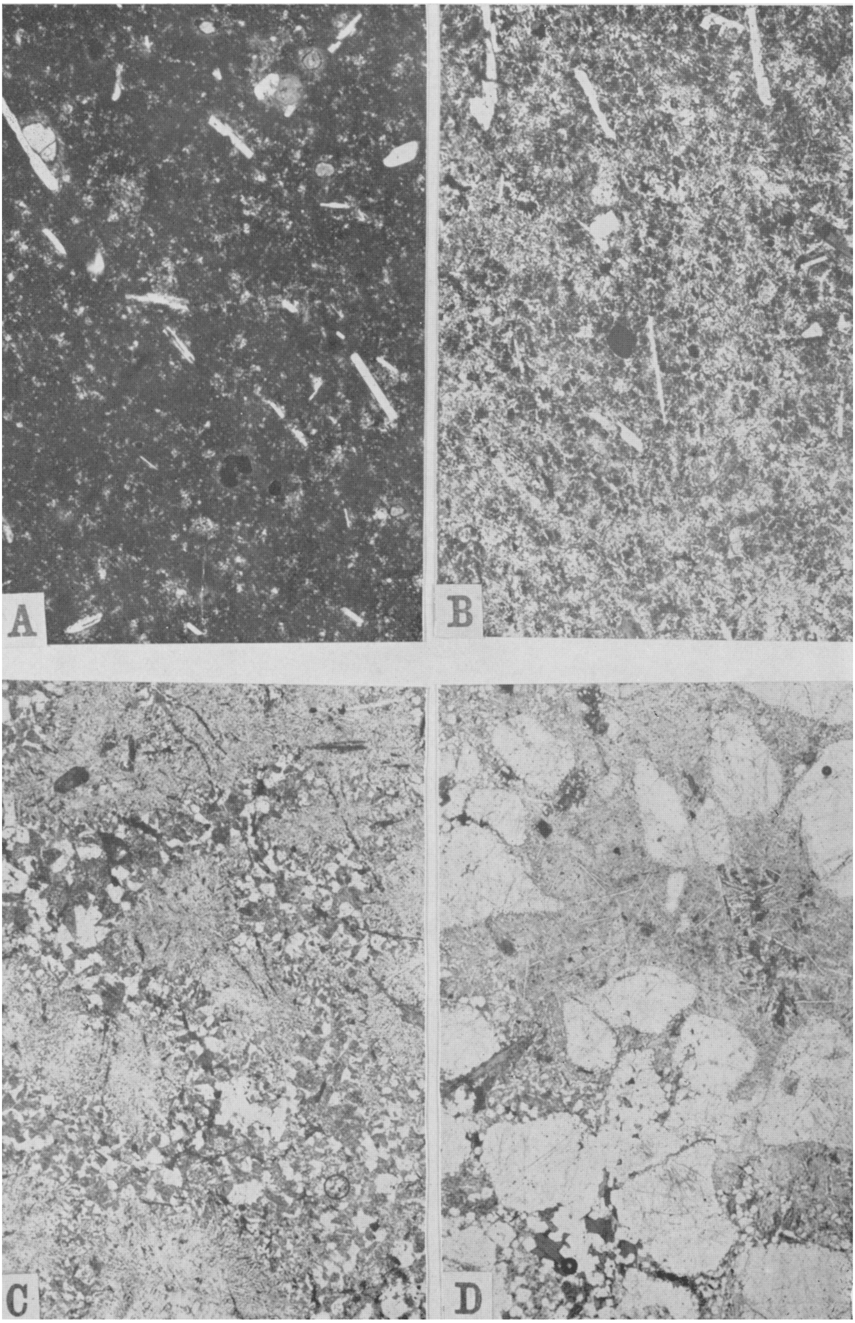
FIG. A. Chilled marginal granophyre with phenocrysts of replaced tridymite, plagioclase, hypersthene, and ore in a cryptocrystalline groundmass. (H 4180.)

FIG. B. Granophyre, about 2 feet from the margin; the groundmass is slightly more crystalline, but the phenocrysts, except the tridymite, are still unaltered. (H 290.)

FIG. C. Main unchilled granophyre, showing areas composed partly of criss-crossing, inverted, tridymite crystals, surrounded by areas of normal granophyric quartz and felspar. (H 289.)

FIG. D. Metamorphosed Torridonian arkose, Allt Mor-n-h-Uamha, Rhum, showing corroded, original quartz grains surrounded by areas with tridymite crystals and others of quartz and felspar with microgranitic texture. (H 3144.)

All photographs in ordinary light. Magnification $\times 17$.



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