THE MINERALOGICAL MAGAZINE

AND

JOURNAL OF

THE MINERALOGICAL SOCIETY

No. 127.	December, 1929.	Vol. XXII.

On a partially fused quartz-felspar-rock and on glomero-granular texture.

(With Plate VII.)

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[Read June 11, 1929.]

THE PARTIALLY FUSED GRANITE.

THE specimen to be described was found in 1925 by Miss H. K. Cargill and Miss J. A. Ledeboer on a scree slope beneath a gully in the basaltic capping of the Slaufrudal granite-granophyre stock at Kvosafoss, SE. Iceland.[1] Unfortunately the rock was not discovered in situ, but it must belong to the upper part of the stock or a dike apophysis of it. An examination of the rock was begun by Miss Ledeboer, but she was unable to continue the work; I am indebted to her for the photographs of pl. VII, figs. 1 and 2.

The specimen is dark grey with evenly scattered, irregularly shaped blebs of light-coloured felspar (pl. VII, fig. 1). In thin section larger crystals of quartz and felspar are seen in a microcrystalline groundmass of the same minerals: zircon, magnetite, and chlorite pseudomorphs are estimated to comprise one per cent. The felspar is mainly perthite with rare acid oligoclase; the average diameter of the felspars (1 to 2 mm.) is slightly greater than that of the quartzes. The felspars occur in aggregates of intergrown anhedral crystals, as

[1] H. K. Cargill, L. Hawkes, and J. A. Ledeboer, Quart. Journ. Geol. Soc. London, 1928, vol. 84, pp. 505–539.

do the quartzes. The aggregates are composed either of felspars or of quartz, in no case are felspar and quartz phenocrysts in growth contact, although very rarely the two touch in a manner which suggests that displacement has taken place. These aggregates have smoothly curved sinuous outlines, and there is commonly a close parallelism of the borders of neighbouring quartz and felspar areas, which are separated by ramifying lanes of groundmass averaging ½ mm. in width. The structure is illustrated in fig. 1 and the photomicrographs of plate VII. Corrosion of both quartz and felspar is shown, being especially marked in the felspar. Where the aggregates are close together the corrosion outlines are smoothly curving, but where more groundmass intervenes the felspar exhibits fretted borders (pl. VII, fig. 4).

The groundmass shows a tendency to spherulitic structure and graphic intergrowths may be detected in it. Its larger quartz grains are 0·12 mm. across; they may adjoin the quartz phenocrysts, in which case they are in optical continuity with them. There is a tendency for the quartz and felspar to segregate at the borders of their respective phenocrysts, but the quartz may be concentrated in the middle of the lanes (pl. VII, fig. 4). Opaque material is scattered through the groundmass as fine dots and acicular forms (average length 0·02 mm.) and commonly marks the borders of the felspar areas (pl. VII, figs. 3 and 4).

The volume composition was found with the Shand recording micrometer. Considerable variations were given by eight sections: quartz 12·8–25·7, felspar 21·6–41·4, groundmass 41·7–52·7 %, the mean result being:

Phenocrysts	Quartz . . .	18·2 %
	Felspar . . .	35·4
Groundmass		46·4.

The origin of the structure is best studied from a consideration of the groundmass. This cannot represent a later impregnation of a granitic rock, for the borders of the aggregates, although parallel, do not fit one another, and it would be difficult to explain why an invading liquid had never failed to penetrate any quartz-felspar contact.

The texture of the groundmass is identical with that of many quartz-porphyries. These latter rocks of dominant quartz-felspar composition have originated either (*a*) by intrusion and rapid cooling of a magma holding phenocrysts, or (*b*) by sudden increase in viscosity of a partially crystallized magma under conditions of steady cooling. With regard to (*a*), as considerable corrosion of phenocrysts has taken place, the amount of liquid must have been less than 46·4 %, and the intrusion of such a crystal mixture would have been attended

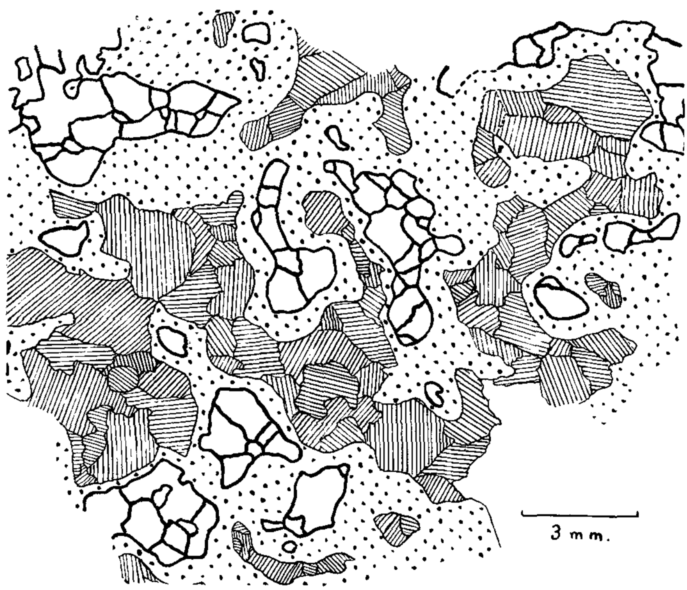


FIG. 1. Drawing from a thin section of the Kvosafoss porphyry. Felspars lined, quartzes clear, groundmass stippled.

by disturbance of the crystalline portion, whereas although slight displacement of some phenocrystal areas has occurred, there is no sign of fracture even in those with marked elongation (pl. VII, fig. 2). A consideration of (*b*) provides no clue to the abnormal corrosion that has obtained, for although the quartz of porphyries is commonly corroded, the felspar never shows such marked effects as in this rock.

The narrowness of the groundmass veins—especially in relation to the size of the phenocrysts—and the close parallelism of their borders, indicate that the phenocrystal areas were originally in contact, i.e. that the rock was holocrystalline and coarse-grained, and has suffered partial fusion with the crystallization of the melt to a finer grain. The monomineralic composition of the coarse-grained areas is significant. Fusion has been restricted to the quartz-felspar contacts, neither quartz nor felspar show signs of melting. The phenomenon is clearly one of corrosion.

That fusion may take place at the contacts of different solids if the temperature rises above the eutectic point, though not to the melting point of the most easily fusible constituent, was established by Hallock,[1] who prepared a liquid globule of Wood's metal by heating the requisite proportions of 'fine filings' of cadmium (melting point 320°), tin (m. p. 232°), lead (m. p. 326°), and bismuth (m. p. 269°) at 100°. Hallock also found that when a piece of tin was placed on a carefully cleaned piece of lead and heated in an air-bath to 190° melting occurred at the contact in a few hours, and he formulated the law: 'An alloy can be produced out of its original constituents without considerable pressure if the temperature be above the melting point of the alloy, even though it be far below the melting point of the most easily fusible constituent.' This conclusion is confirmed by the work of Benedicks and Arpi.[2] The principle has proved of value in the hands of the investigators at the Geophysical Laboratory in Washington in the determination of the equilibrium diagrams of silicate mixtures, in which undercooling so easily obtains that it may be impossible to find the true temperature of crystallization of a melt. Superheating, however, is rare, and many examples could be cited of silicate mixtures in which it has been shown that fusion begins at a temperature below the melting point of the most easily fusible constituent.

In the Icelandic rock the quartz shows no sign of inversion to tridymite or cristobalite. Under atmospheric pressure this would indicate that the temperature has not exceeded 870° for longer than a few days at any rate.[3] The inversion-point is raised with increased pressure by an amount which has been calculated at 100° for a depth of 2½ miles in the crust,[4] which depth would be a liberal estimate for the original thickness of the cover of the rock. We may thus consider 970° as an upper limit for the temperature to which the rock has been raised. The orthoclase-albite-silica eutectic temperature is not known. Vogt suggests 975° for the albite-silica and orthoclase-silica eutectics,[5] and that of the ternary eutectic point would be lower

[1] W. Hallock, Bull. U.S. Geol. Survey, 1890, no. 60, pp. 147–148.

[2] C. Benedicks and R. Arpi, Revue de Métallurgie, 1907, vol. 4, p. 416.

[3] R. B. Sosman, The properties of silica, 1927, p. 783.

[4] N. L. Bowen in E. E. Fairbanks, The laboratory investigation of ores, 1928, p. 181.

[5] J. H. L. Vogt, Journ. Geol. Chicago, 1921, vol. 29, p. 336.

than this, showing that there is no reason to doubt the possibility of the fusion of the rock in the dry state within the range of the stability of the quartz.

Dr. J. A. Smythe of Armstrong College, Newcastle-upon-Tyne, has conducted some experiments to ascertain whether the operation of Hallock's law could be demonstrated with quartz and felspar. Specimens of granite and granophyre from the Slaufrudal stock, composed largely of quartz and perthite with rare acid oligoclase, were heated under the conditions described below and examined afterwards in thin section:

1,000° for 3 hours: no change.

1,020° for 2½ hours: no change.

1,050° for 6 hours, with a possible rise to 1,100° during the last hour: almost complete fusion of the perthite only.

1,060°–1,070° for 5 hours; partial fusion of perthite only.

1,170° for 4 hours: perthite fused, oligoclase showing partial fusion.

Smoothed pieces of quartz and orthoclase bound together with platinum wire were heated for 6 hours at 1,050° with no change, and for 4 hours at 1,200°–1,230° with partial fusion of the felspar. Cones were made of mixtures of finely ground quartz and felspar in the eutectic proportion and heated at 1,050° for 6 hours with no change. In all these experiments no sign could be detected of any corrosion of quartz, although the temperature was well above that of the eutectic. We may conclude that the action is too sluggish to give results under the comparatively short duration of the experiments, whereas fusion may well occur under the prolonged influence of contact-metamorphism assisted by the intimate granular contact which must obtain under the pressures existing in the earth's crust. One cannot rule out the possibility that the fusion of the rock was assisted by the presence of water, although in that case signs of solution might have been expected at the contacts of grains of the same mineral-species.

It has commonly been assumed that the acid rocks require higher temperatures for fusion than the basic, but if we accept dry fusion for the Kvosafoss rock we must conclude that granites of quartz-orthoclase-albite eutectic composition will fuse completely at a temperature not higher than 970°. In this connexion we note that Bowen in combating the idea that dry granite melts at a higher temperature than dry basalt, writes: 'It has been demonstrated experimentally in the dry way by Shepherd and by Greig that granite is converted into glass at a temperature well below that at which basalt begins to show any change'.[1]

If the suggested explanation is correct, the groundmass, being derived from the solution of quartz and felspar in one another, must be of eutectic composition. From the data given of the composition of the Icelandic graphic granites[2] the eutectic volume ratio quartz/felspar may be taken as 0·4, which applied to the groundmass gives the composition:

	Quartz.	Felspar.
Phenocrysts	18·2	35·4
Groundmass	13·2	33·2
	31·4 %	68·6 %

This gives a quartz/felspar ratio for the original rock of 0·46, the ratios for the granitic types of the stock varying from 0·49 to 0·56. Having regard to the considerable proportion of groundmass and the uncertainty of the exact eutectic ratio, the agreement of the deduced composition to that of the granitic types may be considered satisfactory.

Dr. H. H. Thomas has drawn my attention to the resemblance of the structure of the Kvosafoss rock to that of a Mull gneiss (Geol. Survey Coll., no. 18,025) which has suffered partial fusion from a dolerite intrusion.[3] There is a similar parallelism of monomineralic areas of quartz and felspar separated by glass, only in this case the temperature must have been higher, as the felspar shows incipient melting phenomena.

I am indebted to Dr. Smythe for his experimental work and also for helpful criticism during the consideration of this problem.

Glomero-granular Texture.

Whatever explanation be adopted of the origin of the Kvosafoss porphyry, one characteristic of the crystallization history is evidenced in the coarse-grained part of the rock, viz. that in some areas quartzes only have grown, in others felspars only. The disposition of the groundmass between these areas at once draws attention to this

[1] N. L. Bowen, The evolution of the igneous rocks, 1928, p. 298.

[2] H. K. Cargill, L. Hawkes, and J. A. Ledeboer, 1928, loc. cit., p. 529.

[3] Mem. Geol. Survey Scotland, 1911, no. 35, The geology of Oronsay with part of the Ross of Mull.

feature, which had not been noted in the previous study of the granite types of the Slaufrudal stock; but a re-examination of them revealed that there is a distinct tendency to aggregation of this kind, giving rise to monomineralic clusters of several individuals in anhedral intergrowth. Many sections of different granites were examined, and this texture—for which the name 'glomero-granular' is suggested when occurring in non-foliated rocks—was found to be common in

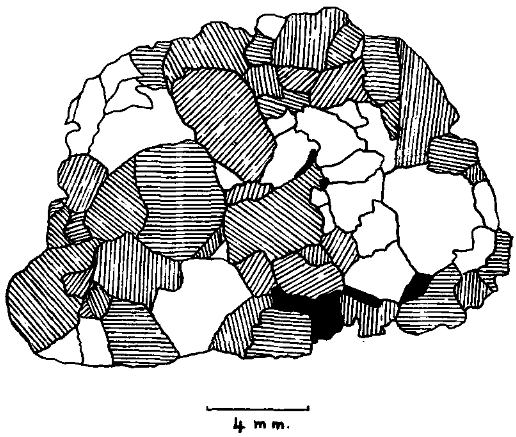


FIG. 2. Alkali-granite, Quincy, Mass., U.S.A. Felspar lined, quartz clear, iron-ore and ferromagnesian constituents black.

the coarser grained types. An illustration of this is given from a thin section of the Quincy granite (fig. 2).

The texture is well developed in the west of England granites, of which Teall writes: 'Quartz generally occurs in the form of grains and granular aggregates'.[1] It is well known that dynamic metamorphism may result in the breaking up of larger crystals into smaller ones, even if it has been insufficient to produce foliation, and this is probably in part the explanation of the texture of the Quincy granite, as the quartz gives undulose extinction; and Dale writes of this rock, 'this [mechanical] strain has been carried far enough to granulate the quartz'.[2] The glomero-granular texture is, however, also found in rocks which show no sign of having been subjected to strain, and in these the texture must be original, a conclusion which may be supported from a study of the normal quartz-porphyries.

[1] J. J. H. Teall, British Petrography, 1888, p. 314.
[2] T. N. Dale, Bull. U.S. Geol. Survey, 1908, no. 354, p. 56.

The monomineralic glomero-porphyritic clusters of quartz-felspar-porphyries appear to represent an early stage in the production of the glomero-granular texture. An examination of a large number of sections of these rocks bearing large phenocrysts showed that whereas the felspar, and more rarely the quartz, commonly occur in groups of two and three or more intergrown individuals, it is rare to find quartz and felspar in contact, excluding those rare cases of felspar phenocrysts which enclose quartz in graphic intergrowth. Also the phenocrysts of one kind may exhibit a segregation in small areas, an arrangement which is illustrated from the Armboth dike (fig. 3). The continuous growth of quartz and felspar in the delimited areas would result in the glomero-granular texture. Should these phenocrysts be intratelluric, their segregation, despite flow disturbance, is none the less significant.

The causation of the texture, when it cannot be related to granulation of larger individuals, is obscure. One would expect the centres of crystallization of the first constituent to form to be evenly spaced, and when, as in the porphyries and granites, the two main constituents crystallize at the same time the phenomenon of their segregation is all the more remarkable.

In 'synneusis' texture small early-formed crystals of one or more species 'swim together', but there is no evidence that the larger individuals do so, and their monomineralic attachments render such an explanation improbable. The coarse anhedral texture of the groups indicates that there has been a definite clustering of the centres of crystallization. Liquid immiscibility cannot be invoked in explanation of the phenomena. No concentration of quartz and felspar is to be detected in separate areas of the groundmass of the porphyries; and furthermore, in the crystallization of an association of two immiscible liquids, the first solid phase to appear in each liquid is one and the same component.[1] Thus for immiscible liquids giving quartz and felspar, crystallization of one constituent—say felspar—will begin in one liquid and continue until that liquid is used up, when felspar will grow in the remaining liquid until the eutectic point is reached with final crystallization of quartz and felspar together. The product will be composed of clusters of felspar crystals and a quartz-felspar aggregate: the separation of the two constituents now under consideration will not obtain. Application of the phase rule shows that it is impossible for the two components of a binary

[1] See N. L. Bowen, 1928, loc. cit., pp. 8–10.

system, or the three of the ternary one, to crystallize simultaneously in an association of two liquids, and this excludes any application of immiscibility to the present case. The structure would result if the original centres of crystallization were far apart and the growing crystals in some way initiated new centres near to them, but this

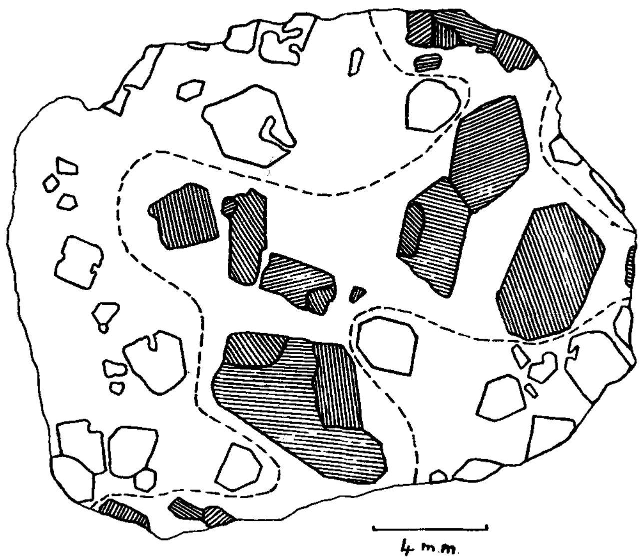


FIG. 3. Quartz-porphyry, Armboth dike, Thirlmere, Cumberland Felspar lined, quartz outlined, groundmass remainder. The broken lines delimit the areas of quartz and felspar phenocrysts.

would be difficult to understand, unless with movement in the magma the crystals set up new centres in their wake.

The glomero-granular and the graphic are contrasted textures: in the former the tendency is for contact of different species to be avoided until the later stages of solidification; in the latter there is intimate association from the first. The conditions which it has been suggested favour the granular rather than the graphic texture are slow rate of cooling and abundance of mineralizers.[1] The presence of the glomero-granular disposition in the coarser granular types harmonizes with this view, but the occurrence of graphic intergrowth phenocrysts in some porphyries presents a difficulty, unless such

[1] H. K. Cargill, L. Hawkes, and J. Ledeboer, 1928, loc. cit., p. 528.

phenocrysts grew at an earlier stage in a larger body of magma poorer in mineralizers.

Whatever the cause, it is clear that in the normal undisturbed crystallization of a granite magma under conditions giving rise to coarse grain there is a tendency for aggregation of minerals of the same kind. This phenomenon has not been studied in other rocks, but its recognition calls for caution in adopting for all occurrences of monomineralic nodules explanations which are based upon accidental or abnormal circumstances, such as liquid immiscibility, the breaking up of monomineralic rock, and the accumulation of crystals in restricted parts of channels.

It is important to distinguish between glomero-porphyritic textures due to the aggregation of one, and those of more than one mineral.[1] In acid rocks the former are commonly a consequence of normal crystallization of the enclosing magma, whereas the latter represent, or are derived from, true xenoliths.

The glomero-granular texture is of significance in connexion with the origin of those granite-gneisses in which the foliation is due to a variation in the relative proportions of different constituents in different layers. Discussing the formation of gneiss from granite, Teall writes: 'Lenticular folia of quartz should alternate with corresponding folia of felspar; the grains of each separate folium representing collectively one of the larger individuals of the granular aggregate.'[2] A primary segregation of quartz and felspar in the granite would emphasize this tendency, and the larger folia commonly met with probably result from the metamorphism of glomero-granular rocks.

[1] Some authors use 'glomero-porphyritic' for monomineralic clusters, but this is not universal, neither is it the original sense in which the term was used by J. W. Judd (Quart. Journ. Geol. Soc. London, 1886, vol. 42, p. 71). A similar confusion exists regarding the term 'cumulophyric', which has been adopted for clusters of more than one mineral (A. Holmes, Petrographical methods, 1921, p. 343), although it was first applied to clusters of equant crystals (Cross, Iddings, Pirsson, and Washington, Journ. Geol. Chicago, 1906, vol. 14, p. 703).

[2] The geological structure of the north-west Highlands of Scotland. Mem. Geol. Survey, 1907, p. 65.

EXPLANATION OF PLATE VII.

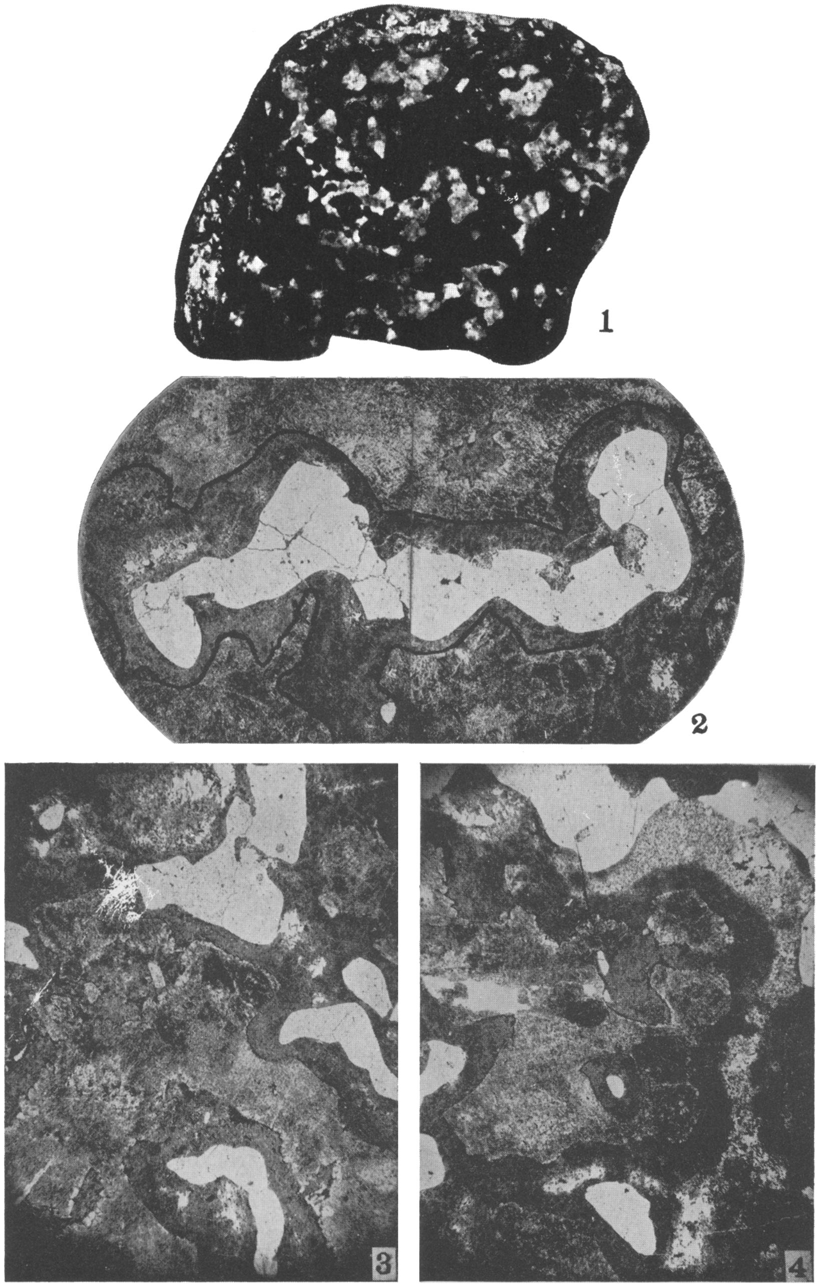
Partially fused granite from Kvosafoss, Iceland.

FIG. 1. Photograph of the polished rock. $\times 1\frac{3}{4}$.

FIG. 2. Photomicrograph showing elongated quartz aggregate in the middle. The boundaries of the felspar aggregates are marked in with black lines. The area between the two borders is groundmass. Ordinary light. $\times 8$.

FIG. 3. Irregular patches of quartz and felspar with groundmass between. Ordinary light. $\times 9$.

FIG. 4. Illustrates the segregation of the groundmass quartz at the phenocrystal quartz borders. Note the central small quartz separated from the felspar area by groundmass. Ordinary light. $\times 9$.



L. HAWKES: PARTIALLY FUSED GRANITE.