

*On the changed composition of an anorthoclase-bearing
rock-glass.¹*

(With Plate VI.)

By L. HAWKES, D.Sc., F.G.S.

Reader in Geology, Bedford College, London University.

and H. F. HARWOOD, M.Sc., Ph.D., A.I.C.

Lecturer in Chemistry, Imperial College of Science, London.

[Read March 15, 1932.]

THE present investigation began with an attempt to isolate and analyse the small sparse anorthoclase insets (phenocrysts) of the chilled glassy selvage of a felsite dike. On comparison of the compositions of the insets and the host rock it was found that the relationship was abnormal and that the insets could not have grown in a magma represented by the glass. The composition of the felsite interior of the dike, however, represents a magma which could have yielded the anorthoclase, and full consideration leads to the conclusion that the glass, though absolutely fresh and unaltered in appearance, has suffered marked changes in composition.

In east Iceland a rugged mountain ridge trending ESE. separates Faskrudsfjord from Stoðvarfjord. To the west of Sandfell (2428 feet), a prominent hill of light-coloured felsite on the Faskrudsfjord side, the ridge can be crossed at about 2000 feet by the Stoðvarskarð Pass, immediately to the east of which is a considerable development of acid lavas and tuffs including glasses and splendid spherulitic rocks, interbedded in the normal Tertiary basalts, here dipping 9° W. The acid series is at least 700 feet thick, and is petrologically distinct from the other Tertiary acid extrusives in east Iceland, in that the dominant felspar constituent is anorthoclase and not acid plagioclase.

¹ Unless otherwise stated, the chemical analyses given in this paper were made by Dr. H. F. Harwood. The remainder of the work was carried out by Dr. L. Hawkes who has written the paper.

The rocks to be described occur as an irregular vertical dike-like intrusion into the basalts below the acid extrusives, to which latter series the dike clearly belongs. At the western end of Stoðvarfjord the valley of Jafnadal leads NW. to the pass, and the specimens were taken from an exposure at about 1100 feet in the first notable tributary met on the northern side on ascending the valley. Here, abutting against the basalts, is a vertical wall 1-3 feet thick of a lustrous black glass with perlitic structure, the larger perlite ellipsoids measuring $8 \times 5 \times 3$ inches. The glass grades evenly away from the contact through a duller rock to a fine-grained grey felsite; all varieties contain anorthoclase insets averaging 1-2 mm. in length. Further exposures of the dike occur in the stream course below this locality.

The contact facies appears in thin section as a faintly brown glass crowded with microlites in fluxion parallelism, many of pyroxene averaging 0.002 mm. across, with some broader feldspar. The insets are mainly anorthoclase, forming 2.8 % by volume (3.2 % by weight) of the rock, some pyroxene (0.05 % vol.) together with minute magnetites and zircons. There is some tendency to glomero-porphyritic aggregation of the four minerals. The pyroxene exhibits a very feeble pleochroism— α clear grass-green, γ slightly brownish-green; $\gamma - \alpha$ about 0.03, $\gamma : c$ (on microlites) 55° . These properties indicate a slightly sodic pyroxene.

The anorthoclase insets are euhedral, although some are bent or fractured as a result of the differential flow accompanying the intrusion of the magma. They are short rectangular prisms elongated along the a -axis: some are tabular, parallel to (001). The forms observed were $c(001)$, $b(010)$, $a(100)$, $y(\bar{2}01)$, $m(110)$, and $n(021)$. Cleavage, (001) dominant, (010) good, ($\bar{2}01$) subordinate. Carlsbad, Manebach, and Baveno twinning occurs. The optic axial plane is normal to (010), and the acute bisectrix α is near the a -axis. In thin section the feldspar exhibits the characteristic irregular patchy extinction of anorthoclase, particularly well marked on (001) sections which show a minute discontinuous albite twinning. Sections normal to the acute bisectrix show cross-hatching due to albite twinning together with bands parallel to the (001) edge. Cleavage flakes (010) are normal to γ and give an extinction $\alpha : (001) = 9^\circ$; (001) cleavage flakes are nearly optic normal sections and show fine albite twinning and extinction $\alpha : (010) = 1-2^\circ$. Refractive index $\gamma = 1.531$. Many measurements of birefringence on cleavage

flakes gave: on (010), $(\beta-\alpha) = 0.0061 \pm 0.0003$; on (001), (near $\gamma-\alpha) = 0.0072 \pm 0.0002$. Measurement of the optic axial angle on an acute bisectrix section gave $2E = 83^\circ \pm 5^\circ$; optically negative.

The glass, refractive index 1.490, shows a birefringence which is slightly enhanced in the neighbourhood of the insets, where values of 0.0012 were measured. All parts of the glassy field of each thin section extinguish simultaneously, except near the insets, where the direction of vibration of the α ray swings round, always lying normal to the boundaries of the crystals and the flow lines round them. The streaky and mottled appearance of the polarization greys (plate VI, figs. 6, 7, 9, 10) is partly due to the microlites and partly to the presence around the larger microlites of small negative birefringent fields which are small-scale reproductions of the effect noted round the insets. The orientation of the vibrations of the α ray in the neighbourhood of the insets is that which would accompany the existence of radially compressive stress around the crystals. The phenomenon can be demonstrated experimentally by adding mineral grains (but not quartz) or fragments of 'vitreosil' to melted borax and allowing the preparation to cool, when negative figures appear around each grain, the state of radial compression in the borax glass being sometimes further revealed by the growth of a system of radial cracks within the birefringent zone. The strain is due to the circumstance that on vitrification with falling temperature the contraction of the glass is greater than that of the inclusions, and, in the case of the rock-glass, of the anorthoclase.¹ The rock-glass is now no longer in a state of mechanical strain but the optical effect remains, and if the rock is crushed to pass 90 mesh the fragments will still retain their birefringence. Ninety per cent. of the water in the rock-glass can be expelled without affecting the birefringence, which latter disappears at red heat. The birefringence shown outside the influence of the insets must have some other origin and be due to stresses operating over a larger field.

It was thought that where it is unaffected by the presence of phenocrysts the birefringence of the glass as a whole would be related to the strains governing the perlitic fracturing, but examination of a thin section 77 sq. cm. in area, cut through one of the large perlite ellipsoids with concentric cracks, shows that this is not the case, for the whole field extinguishes in one position. The

¹ T. H. Waller, The phenomena of strains, etc., observable in obsidian. Geol. Mag., 1885, p. 91.

birefringence is of uniaxial negative character. We are unaware that an optical phenomenon of this kind has been noticed before, and discussion of its causation must await further study in the field.

One end of a large perlite ellipsoid is greenish-grey in colour and in thin section exhibits dark brown devitrification patches and streaks; the alteration of the latter has been guided by cracks (plate VI, fig. 8).

The felsite in section shows the same anorthoclase insets as the glass, with magnetite and zircon, but the pyroxene is represented by opaque dust, and the groundmass is holocrystalline with small felspar laths and larger quartzes which may enclose the felspar poikilitically.

The contact-rock is a favourable one for an investigation of the relationship of the composition of the first formed felspar to that of the groundmass. The insets form but 3 % of the rock and include one kind of felspar only which can be readily separated from the vitreous groundmass and other crystals. The separation was made by Mr. A. F. Hallimond, who suggested the use of his electro-magnetic separator,¹ the glass being more magnetic than the felspar. The rock was crushed to a size between 60 and 90 mesh, and 375 grams were passed through the machine to yield 4.5 grams of a white, least-magnetic product, which, after suspension in a bromoform mixture and removal of the small sunken and floating fractions, proved to be 87 % felspar, a satisfactory result considering the small size of the crystals. In table I is given the analysis of the contact-rock (no. 1), and that of the felspar separation (no. 3), and also the calculated norms.

The amount of glass present in the felspar preparation is estimated in two ways: (a) In the rock norm 29.26 parts of free silica are equivalent to 97 parts of glass (allowing 3 % of insets), and the felspar preparation norm gives 4.15 % free silica, which is then equivalent to $(97 \times 4.15)/29.26 = 13.7$ % of glass; (b) the rock analysis gives 5.88 parts H₂O+ in 97 parts of glass, and 0.71 % H₂O+ in the felspar preparation is then equivalent to $(97 \times 0.71)/5.88 = 11.7$ % glass. Adopting a figure of 13 %, this proportion of no. 2 was subtracted from no. 3, and the result recalculated to 100 % is given in no. 3a, which is then the composition of the anorthoclase with the glass eliminated. Removing the non-felspathic constituents

¹ A. F. Hallimond, An electro-magnetic separator for mineral powders. *Min. Mag.*, 1930, vol. 22, p. 377.

TABLE I.

	1.	1a.	2.	3.	3a.
SiO ₂	70.55	76.19	77.77	66.30	65.48
Al ₂ O ₃	11.82	12.76	11.61	18.86	19.86
Fe ₂ O ₃	0.55	0.59	0.79	0.23	0.18
FeO	1.06	1.14	0.40	0.20	0.07
MgO	0.03	0.03	trace	none	—
CaO	0.74	0.80	0.33	1.16	1.22
Na ₂ O	5.08	5.49	3.91	6.95	7.21
K ₂ O	2.58	2.78	4.34	4.97	5.31
H ₂ O-(110°)	1.40	—	0.06	none	—
H ₂ O+(110°)	5.88	—	0.56	0.71	—
CO ₂	0.03	0.03	none	—	—
TiO ₂	0.09	0.10	0.09	—	—
P ₂ O ₅	trace	—	0.02	—	—
Cl	trace	—	trace	—	—
S	trace	—	0.01	—	—
MnO	0.04	0.04	0.02	trace	—
SrO	trace	—	none	0.04	0.05
BaO	0.03	0.03	0.02	0.54	0.62
Li ₂ O	none	—	trace	—	—
NiO	none	—	none	—	—
F	0.04	0.04	—	—	—
	99.92	100.02			
O less F	0.02	0.02			
	99.90	100.00	99.93	99.96	100.00
Specific gravity ...	2.307	—	2.565	2.584	—
Norms.					
Quartz	29.26	31.56	38.35	4.15	0.51
Orthoclase	15.23	16.43	25.68	29.41	31.42
Albite	42.92	46.29	33.06	58.74	60.88
Anorthite	1.78	1.92	1.39	4.45	4.86
Celsian	—	—	—	1.31	1.53
Strontium-felspar	—	—	—	0.13	0.14
Hypersthene	0.60	0.65	—	—	—
Diopside	1.67	1.80	—	0.73	0.41
Ilmenite	0.17	0.18	0.15	—	—
Magnetite	0.79	0.85	1.16	0.32	0.23
Symbols	I. '4.1.4.	—	I. 3(4).1.3''.	—	—

1. Glassy contact facies of the dike. Jafnadal, Stoðvarfjord, Iceland.

1a. Analysis no. 1 recalculated to 100%, with water eliminated.

2. Felsite. Interior of the Jafnadal dike.

3. The separation (containing 87% of anorthoclase insets) obtained from the rock-glass no. 1.

3a. The composition of the anorthoclase insets, being no. 3 recalculated after subtraction of 13% of no. 1.

from the norm of no. 3 *a*, the composition of the anorthoclase becomes:

Albite	...	...	...	61.60
Orthoclase	...	...	...	31.80
Anorthite	...	...	...	4.90
Celsian	...	...	...	1.55
Strontium-felspar	...	...	...	0.15
				100.00

This is the composition of a normal potash-rich anorthoclase with 32 Or, 68 Ab + An. From his study of the Ab + An + Or of anorthoclases Vogt finds 32 to be the maximum recorded percentage of Or.¹ The felspar shows a notable content of baryta present as celsian which is known as a constituent of many anorthoclases.² Comparison of the baryta content of the felspar (0.62 %) with that of the whole rock (0.03 %) shows that 0.019 %—more than half of the baryta of the magma—has entered into the first 3.2 % of the rock to crystallize. The specific gravity of the anorthoclase, being that of the separated product recalculated to eliminate 13 % of glass, is 2.63, a value which is probably a little too high owing to the glomero-porphyritic tendency of pyroxene and magnetite to accompany the felspar.

Comparing the composition of the felspar with that of the whole rock, and considering the alkalis, the surprising result is obtained that the rock rich in soda bears insets relatively richer in potash, so that differentiation appears to be proceeding towards a soda-rich rest magma. This runs counter to the general rule deduced by Vogt from consideration of a great mass of data, that, in acid magmas with small contents of anorthite and an orthoclase content of less than about 40 % of the Ab + An + Or, the first formed felspar is poorer in orthoclase than the magma.³ The figures for the insets and the rock are given in table II (nos. 1 and 2), and to demonstrate the abnormality of their relationship both as regards alkalis and lime, they are plotted on fig. 1, which is a copy of part of Vogt's

¹ J. H. L. Vogt, The physical chemistry of the magmatic differentiation of igneous rocks. II. On the felspar diagram Or:Ab:An. *Skrifter Norske Vidensk.-Akad. I. Mat.-nat. Kl.*, Oslo, 1926, no. 4, p. 28. [Min. Abstr., vol. 3, p. 379.]

² N. Orlov, *Analysen einiger Silikate aus der Gegend von Pjatigorsk.* *Neues Jahrb. Min.*, 1912, vol. 1, p. 421.

D. Beliankin, Contribution à la chimie des feldspaths. *Bull. Acad. Sci. U.S.S.R.*, 1929, p. 571. [Min. Abstr., vol. 5, p. 70.]

³ J. H. L. Vogt, loc. cit., p. 82.

diagram illustrating the relationships between the first-formed feldspars and their host rocks.¹

TABLE II. The calculated relative proportions of Or, Ab, An, in (1) the anorthoclase insets, (2) the glassy contact-rock, (3) the holocrystalline interior felsite.

		1.	2.	3.
Orthoclase	...	32.3	25.4	42.7
Albite	...	62.7	71.6	55.0
Anorthite...	...	5.0	3.0	2.3
		100.0	100.0	100.0

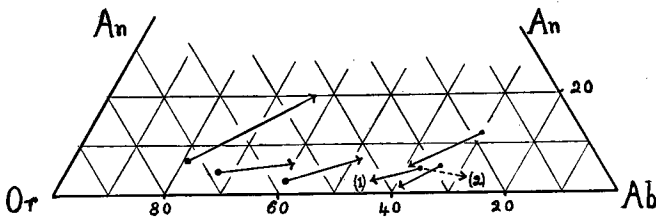


FIG. 1. Felspar diagram adapted from Vogt. The arrow-heads indicate the Or, Ab, An ratios of the rocks, and the dots to which they are joined the ratios of their respective insets. Arrow-head (1) indicates the ratios of the interior felsite, and (2) those of the contact facies of the Jafnadal dike, the dot to which they are joined representing the composition of their anorthoclase insets.

To ensure that no analytical error was responsible for these results, Iceland was revisited, and another sample of the glass obtained, from which 1.1 gram of felspar was separated magnetically as before and analysed, giving :

		Felspar separation.	Rock.
Na ₂ O	...	6.88	5.07
K ₂ O	...	4.89	2.54

These figures substantiate those previously found.

The clue to the solution of the problem is given by a comparison of the analyses of the felspar and the dike interior felsite (table I, no. 2), for the anorthoclase now appears as a normal first-formed constituent of the felsite magma, as is seen when the results (table II, no. 3) are plotted on the diagram (fig. 1). The orthoclase content of the felsite is rather greater than the 40 % given by Vogt as the upper limit for rocks yielding feldspars richer in soda than themselves,

¹ J. H. L. Vogt, loc. cit., fig. 10, p. 81.

but the data are not sufficiently precise to permit a very exact determination of the eutectic point. We conclude, then, that the magma of the dike rocks contained about 3% of insets—mainly anorthoclase, and that it had the composition of the felsite, and that the differences between the analyses of the felsite and chilled contact glass are due to subsequent changes in the composition of the latter.

The hypothesis that the composition of the glass has remained unchanged and that the insets were introduced into the liquid (now glass) as the result of crystal settling from another magma is rejected on the following grounds: (1) It has not yet been demonstrated that settling of such small feldspars—some are 0.2 mm. across—does occur in acid magmas; (2) the insets are evenly distributed throughout the rock; (3) the insets are euhedral, and there is no resorption or overgrowth to indicate that they have existed out of equilibrium with their liquid environment; (4) the proportion of insets in the glass is the same as that in the felsite; (5) the abnormal rock is restricted to the glassy facies. Both this and (4) would be highly fortuitous circumstances on the settling hypothesis. (6) The contact-rock, as is to be expected if soda has replaced potash, is abnormal in that with marked excess of soda over potash (2.50%) there is a small content of lime (0.74%). In fig. 2 are shown the lime contents of all (27) those analysed acid rocks from the British and Icelandic Tertiary province with soda in excess of potash. All those rocks are included which have more than 66% of silica, and soda in excess of potash by any amount up to 3%. The diagram shows that with increasing excess of soda the minimum contents of lime rise, and that no rock of the Jafnadal type is known in the province. Whereas none of these criteria is in itself conclusive the cumulative evidence is decisive, and there are no grounds for rejecting the most straightforward view that the glassy facies is derived from the same liquid, which in the interior of the dike has crystallized to form the felsite.

We pass to a consideration of the considerable water content shown by the glass. The amount of water which can be held in solution in magma is governed by pressure and temperature, diminishing with decreasing pressure and with increasing temperature. From Goranson's data¹ we discover that the water found in the glass ($H_2O + 5.88\%$) could, between the temperatures of 700 and

¹ R. W. Goranson, The solubility of water in granite magmas. Amer. Journ. Sci., 1931, ser. 5, vol. 22, p. 481.

900° C., be held by an acid magma at depths not less than between 3-4 km. The Jafnadal dike is petrologically allied to the acid extrusives above it, and there can be little doubt that it was emplaced at the time when the surface of the country was at or near the top of the acid extrusive series. A half kilometre is a liberal estimate of the original depth below the surface of the glass analysed—at which depth the maximum possible water content at 900° is

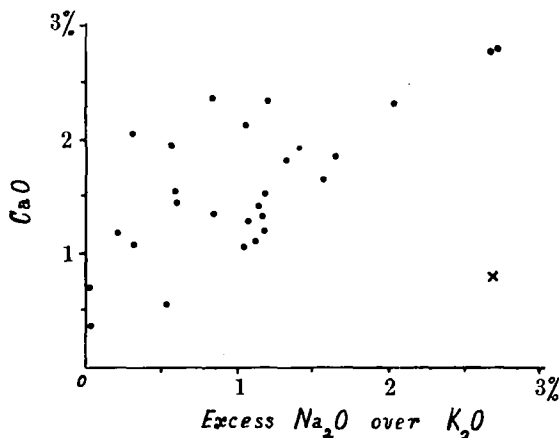


FIG. 2. The lime contents of the acid rocks of the North Atlantic province plotted against the excess of soda over potash. The cross gives the relationship for the Jafnadal contact-glass.

about 1%. Had the temperature of the magma on intrusion been as low as 700° the water content could not have been more than 2%, so it is clear that the bulk of the water now in the glass was not held in the magma on emplacement, but has been added later. An even more striking case is that of the glass which outcrops at the Stoðvarskarð Col, for this is the upper part of an acid lava flow which in its original liquid form can have held only a negligible amount of water, whereas the rock now shows $\text{H}_2\text{O} + 6.92\%$.

The capacity of glass for water increases with falling temperature, and it would be reasonable to suppose that the water was added from the interior of the dike or lava, from which it was expelled on crystallization, and that the other changes in composition were effected at the same time. In this connexion we may note that the glassy casing of the Stoðvarskarð acid lava (also with anorthoclase

insets) gives K_2O 2.50 %, Na_2O 3.63 % (L. H. anal.), or Or : Ab 33:67. The optical properties of the inset anorthoclase are the same as those of the analysed felspar, and if their compositions are the same this extrusive glass as compared with the contact dike rock has suffered a similar but smaller alkali exchange.

To further compare the felsite and glass compositions the latter is recalculated to a water-free basis (table I, no. 1 α). The notable differences remaining for consideration are those relating to silica and alumina. The excess of silica in the felsite is 1.58 %, but it is the normative free silica which is significant, and this shows an excess in the felsite of 6.79 %. Recalculation of the felsite norm after replacement of potash by soda to give the proportions present in the glass shows that about 7 % of free silica has been extracted—one may surmise in water solution. This silica loss accounts for the increased alumina of the glass.

That the changes in composition have been effected in the glass and not in the crystalline felsite is in accordance with the fact that 'glass in general has a lower resistance towards chemical agencies than mineral of the same composition'.¹ In many cases changes in the glass are accompanied or succeeded by devitrification, as is exemplified in a rock from Borgarfjord, east Iceland, in which unaltered spherulites occur in a groundmass exhibiting perlitic marking, but which is composed of a mosaic of quartz crystals (figs. 3 and 4), and a similar example of this selective silicification is provided by the well-known spherulitic rock of Lea, Shropshire. It is not as a rule difficult in the case of a crystalline rock to detect alteration when this has occurred, but the example given in this paper shows that a rock-glass which neither macroscopically nor microscopically shows the slightest trace of alteration—even retaining the strain polarization set up on vitrification—has yet suffered considerable changes in composition, viz. loss of silica, addition of water, and replacement of potash by soda.

Fenner gives an example of a basic pillow lava in the 'nearly unaltered' glassy skin of which potash has replaced soda, and 'these results make one dubious whether any basaltic or doleritic glass, if not of absolutely fresh appearance, can be assumed to have the composition it had at the beginning'.²

¹ J. H. L. Vogt, loc. cit., III (second half), 1931, p. 192.

² C. N. Fenner, The residual liquids of crystallizing magmas. *Min. Mag.*, 1931 vol. 22, p. 556.

Not only by reason of its instability, but also from the circumstances governing its formation, rock-glass is especially liable to attack, for it seldom occurs as a single intrusive mass, but predominantly as a chilled casing of a larger enclosed volume of magma, and this on crystallization releases products to the action of which the glass must be subject. Petrologists attach great importance to the apparently unaltered chilled glassy facies as

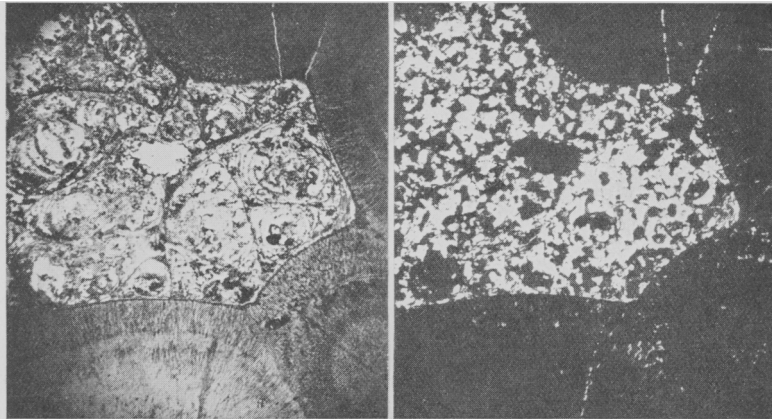


FIG. 3.

FIG. 4.

FIG. 3. Spherulitic rhyolite from the Helgá valley, Borgarfjord, east Iceland. Between the curved borders of the spherulites lies an area with perlitic markings. Ordinary light, $\times 25$.

FIG. 4. The same between crossed nicols. The perlitic area is seen to be composed of a mosaic of granular quartz.

representing the original intruded magma—being undisturbed by crystallization-differentiation, but caution is necessary, and to Bowen's statement¹ 'They [i.e. glassy rocks] are the only rocks of which we can say with complete confidence that they correspond in composition with a liquid', we would add 'provided their composition has remained unchanged'. In the field, glasses have a deceptively fresh appearance as compared with the crystalline rocks, but to discover the original composition of the liquid it is safer to take the fine-grained holocrystalline contact-rock, rather than a glass.

In his study of the dacite mass of Hamarfjord, east Iceland, the

¹ N. L. Bowen, *The evolution of igneous rocks*. 1928, p. 125.

author (L. H.) in order to arrive at the composition of the original magma took the fresh glassy casing for analysis, the alkalis found being Na_2O 4.27 %, K_2O 1.59 %.¹ In the light of the present investigation this result was reviewed with suspicion, especially as the lime content of the rock is low (1.85 %). Accordingly, the alkalis of the finely crystalline dacite have now been determined with the following result: Na_2O 4.60, K_2O 2.96 %, showing that here also alkali exchange has occurred in the glass.

We make acknowledgement to Mr. A. F. Hallimond for his separation of the anorthoclase insets.

EXPLANATION OF PLATE VI.

FIG. 5. The analysed contact-rock, Jafnadal dike, Iceland. Anorthoclase insets in glass with microlites. Ordinary light, $\times 10$.

FIG. 6. The same between crossed nicols, the cross-lines marking the planes of vibration of light through the nicols. The glass in this position exhibits the maximum birefringent effect.

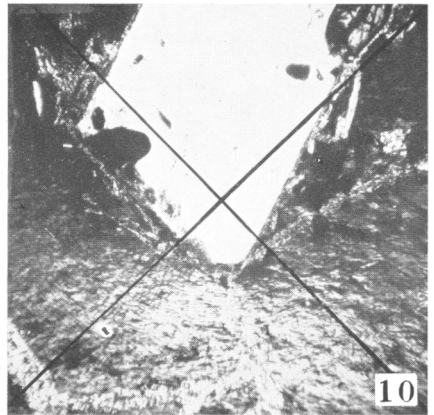
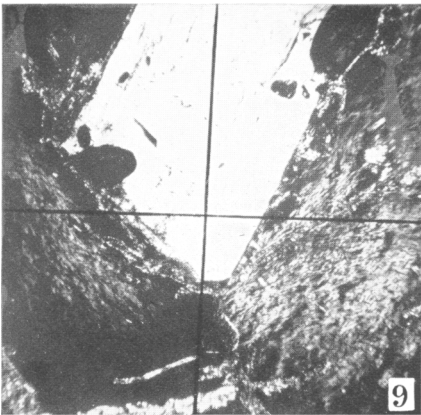
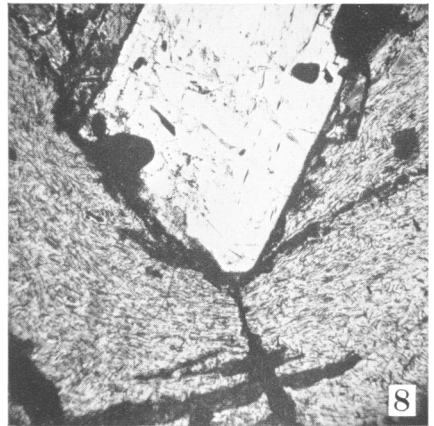
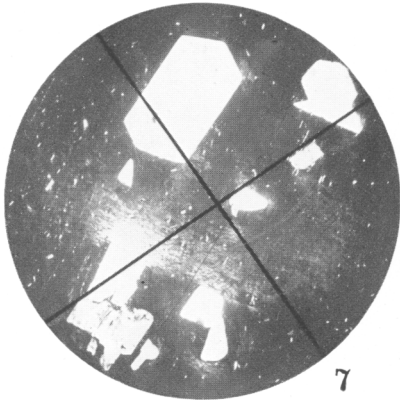
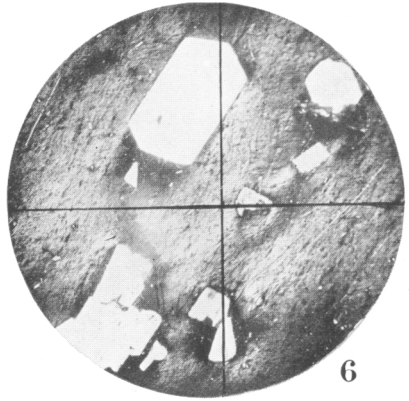
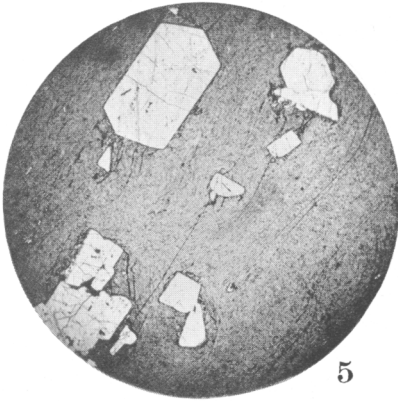
FIG. 7. The same. The crossed nicols have been rotated through 45° to show the main body of the glass in extinction, and light patches due to local strain at the insets.

FIG. 8. The Jafnadal dike contact-rock. Anorthoclase inset in glass with microlites in fluxion parallelism to the inset boundary. The black streaks represent brown devitrification bands. Ordinary light, $\times 33$.

FIG. 9. The same between crossed nicols. The cross-lines mark the planes of vibration of light through the nicols. The patchy birefringence shown in the glass near the inset is due to strain. The white streaks mark the devitrified bands.

FIG. 10. The same. The crossed nicols have been rotated through 45° . Comparison with fig. 6 shows that in the glass the plane of polarization of one ray (a) lies normal to the boundary of the inset and to the flow-lines.

¹ L. Hawkes, On an olivine dacite in the Tertiary volcanic series of eastern Iceland. *Quart. Journ. Geol. Soc.*, 1924, vol. 80, p. 560.



L. HAWKES AND H. F. HARWOOD: ANORTHOCLASE-BEARING ROCK-GLASS.