

Crystallization of basaltic magma as recorded by variation of crystal-size in dikes.

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IT is a familiar fact that in dikes, lava-flows, and sills the grain-size of the individual minerals normally varies according to the distance from the contacts. At or near the margins of the igneous body the grain-size is usually very much less than in the centre, and this phenomenon has been attributed to differences in the cooling-velocities at these spots. On the basis of measurements carried out by Queneau (8) the opinion seems to have been formed that the crystal-size always shows a progressive increase from the contacts towards the centre. This is not so, however, for as Lane (6) has shown, the crystal-size may increase to a maximum at a certain distance from the margin, and thereafter decrease again towards the centre of the intrusion. Apart from these investigations, carried out by Queneau and Lane, the only additional quantitative data on crystal-size variation known to the writer concerns a series of measurements made on an olivine-diabase by B. H. Dollen, under the direction of H. L. Alling (1).

The crystal-size variations in the three dikes (minette, quartz-diabase, and olivine-diabase) measured by the authors cited have recently been interpreted by the writer (12) on the basis of:

- (a) calculated cooling-velocities for various temperature ranges at different distances from the contact;
- (b) experimental work on the relationship between cooling-velocity and crystal-size.

From these the relationship between distance from the contact and crystal-size can be derived. It has been shown, moreover, that the curves representing the relationship between grain-size variation and distance from the walls for various minerals also give an indication of the temperature ranges throughout which the individual minerals have crystallized in a magma (11) (12).

The present paper deals with the application of these principles to the Cleveland dike, a representative of the tholeiitic magma-type,

which can be traced from Yorkshire to the island of Cumbrae, in the Firth of Clyde, throughout a distance of 310 km. Mull constitutes the intrusion centre, and the dike thus has a total length of about 400 km. Before dealing with this intrusion, however, it is necessary to outline briefly the principles employed in the interpretation of crystal-size variations in dikes (12).

Relationship between cooling-velocity and distance from the cooling-wall.

A dike intruded into colder country-rock can be regarded as a plate of a certain thickness subjected to cooling. In a vertical dike cooling

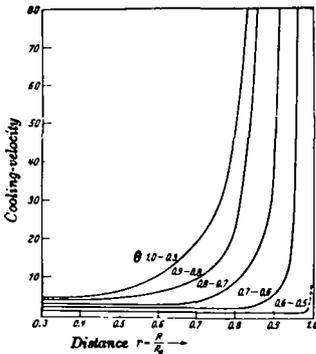


FIG. 1.

FIG. 1. Relationship between cooling-velocity and distance from the margin in a dike for various temperature ranges (θ -values).

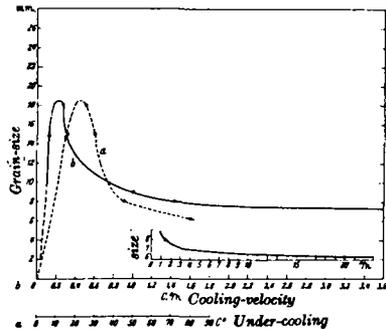


FIG. 2.

FIG. 2. Relationship between crystal-size and (a) under-cooling and (b) cooling-velocity.

will be symmetrical with respect to both walls, so that only one-half of the intrusion, from margin to centre, need be considered. If we assume that the conductivity of heat is the same in the magmatic body as in the country-rock, and omit complications due to convective currents, then it is possible to calculate mathematically the cooling-velocity at different distances from the margin. This has been done for various temperature ranges, using the following data:

- Specific gravity = 2.9,
- Conductivity of heat = 0.006 cal. cm.⁻¹ sec.⁻¹ centigrade⁻¹,
- Specific heat = 0.2 cal. g.⁻¹ centigrade⁻¹.

The results for various temperature ranges are given in table I and partly in fig. 1. They refer to a dike of a thickness of 2 metres, i.e. half thickness $R_0 = 1$ m. Since cooling-velocity is reciprocal to the

square of the thickness, the given values are to be multiplied by a certain factor if thicknesses other than $R_0 = 1$ m. are to be dealt with.

For a dike of $R_0 = 2$ m. this factor is $1/4$
 „ „ $R_0 = 3$ m. „ „ $1/9$
 „ „ $R_0 = 4$ m. „ „ $1/16$, &c.

It is impossible to account accurately for the liberated heat of crystallization. If it is assumed that during crystallization of the main constituents heat is almost evenly liberated, then the given values for cooling-velocity will become smaller by a constant factor (Lovering (7)). Thus the ratio of cooling-velocities which actually suffice to explain our observations concerning crystal-size variation will not be affected, and this factor need not be considered.

TABLE I. Mean cooling-velocities in °C./h prevailing in indicated temperature ranges. Infinite plate of half thickness $R_0 = 1$ m.

r	θ -values.								
	1.0- 0.9.	0.95- 0.85.	0.90- 0.80.	0.85- 0.75.	0.80- 0.70.	0.75- 0.65.	0.70- 0.60.	0.65- 0.55.	0.60- 0.50.
0.95	—	—	320	300	165	120	28	6.24	1.08
0.90	180	160	149	100	50	16.6	6.0	2.02	0.99
0.85	108	83	72	29	15.4	7.6	3.3	1.52	0.99
0.80	53	37	22.5	14	8.3	4.4	2.09	1.48	0.99
0.75	31	21.5	14.5	9.5	5.4	3.2	2.06	1.44	0.99
0.70	20.5	15.0	10.4	6.3	4.0	2.6	2.03	1.40	0.99
0.65	14.8	11.0	7.3	4.9	3.5	2.50	2.00	1.35	0.99
0.60	11.2	8.0	6.1	4.1	3.0	2.47	1.98	1.35	0.99
0.55	8.5	6.2	5.2	3.8	3.0	2.44	1.98	1.35	0.99
0.50	6.5	5.4	4.8	3.6	3.0	2.41	1.98	1.35	0.99
0.45	5.7	4.8	4.3	3.6	2.9	2.39	1.98	1.35	0.99
0.40	4.8	4.6	4.1	3.6	2.9	2.37	1.98	1.35	0.99
0.30	4.7	4.5	4.0	3.6	2.9	2.37	1.98	1.35	0.99
0.20	4.6	4.4	4.0	3.6	2.8	2.37	1.98	1.35	0.99
0.10	4.5	4.3	4.0	3.6	2.8	2.37	1.98	1.25	0.99
0.00	4.5	4.3	4.0	3.6	2.8	2.37	1.98	1.35	0.99

r	0.90- 0.70.	0.85- 0.65.	0.80- 0.60.	0.75- 0.55.	0.70- 0.50.
0.95	305	180	56	14	2.15
0.90	59	32.6	10.8	3.64	1.74
0.85	24.5	12.2	5.4	2.40	1.58
0.80	12.4	6.7	3.5	2.07	1.52
0.75	7.6	4.8	2.8	1.98	1.52
0.70	5.80	3.7	2.56	1.90	1.52
0.65	4.75	3.15	2.44	1.89	1.52
0.60	4.09	3.05	2.35	1.89	1.52
0.55	3.69	3.00	2.35	1.89	1.52
0.50	3.57	2.95	2.35	1.89	1.52

TABLE I (cont.)

	0.90-	0.85-	0.80-	0.75-	0.70-
<i>r</i>	0.70.	0.65.	0.60.	0.55.	0.50.
0.45	3.44	2.91	2.35	1.89	1.52
0.40	3.37	2.88	2.35	1.89	1.52
0.30	3.37	2.85	2.35	1.89	1.52
0.20	3.37	2.85	2.35	1.89	1.52
0.10	3.37	2.85	2.35	1.89	1.52
0.00	3.37	2.85	2.35	1.89	1.52

	0.90-	0.85-	0.80-	0.75-	0.70-
<i>r</i>	0.75.	0.70.	0.65.	0.60.	0.55.
0.95	—	280	114	44	9.2
0.90	114	65	25	8.6	2.8
0.85	35	20	9.5	4.37	1.91
0.80	18.3	9.4	5.7	2.77	1.70
0.75	10.4	6.45	3.77	2.28	1.58
0.70	7.2	5.09	3.05	2.23	1.56
0.65	5.8	4.05	2.78	2.19	1.56
0.60	5.0	3.55	2.68	2.19	1.56
0.55	4.2	3.42	2.60	2.19	1.56
0.50	4.06	3.33	2.60	2.19	1.56
0.45	3.79	3.24	2.60	2.19	1.56
0.40	3.78	3.15	2.60	2.19	1.56
0.30	3.78	3.15	2.60	2.19	1.56
0.20	3.78	3.15	2.60	2.19	1.56
0.10	3.78	3.15	2.60	2.19	1.56
0.00	3.78	3.15	2.60	2.19	1.56

Fig. 1 shows the cooling-velocity at different distances from an igneous contact. The abscissa represents distance in terms of $r = R/R_0$, in order to facilitate comparison in dikes of various thicknesses. R is the distance from the centre of a dike to a point in the cross-section, and R_0 the distance from the centre to the margin. Thus $r = 0.0$ is the centre and $r = 1.0$ the margin. (For example, assuming a dike of total thickness 6 m. then $R_0 = 3$ m. A specimen taken at a distance of 2.1 m. from the centre (in the cross-section) equals $R = 2.1$ m.; $r = 2 \times 1/3 = 0.7$.) The ordinate gives the cooling-velocities in $^{\circ}\text{C./h}$. At constant distance the cooling-velocity diminishes continuously with progressive cooling of the body, but for our purpose successive steps of temperature ranges have been chosen for which the *mean* cooling-velocity is given. These temperature ranges are designated by θ -values. $\theta = (T - T_c)/(T_m - T_c)$, where T_c is the temperature of the country-rock immediately before intrusion, T_m is the temperature of the magma immediately after intrusion, and T is the temperature deriving from θ , T_c and T_m . Assuming, for simplicity, $T_m = 1000^{\circ}\text{C}$. and $T_c = 0^{\circ}\text{C}$., then θ 1.0-0.9 indicates the temperature range from 1000° to 900°C .,

θ 0.9–0.8 = 900°–800°, &c. The curves in fig. 1 and the values in table I represent the mean values of the cooling-velocity in the designated temperature ranges at different distances from the centre of the dike.

Relationship between cooling-velocity and crystal-size.

The interpretation of variation in crystal-size at different distances from the centre of a dike depends on (a) the relationship between cooling-velocity and distance from the centre, and (b) the relationship between cooling-velocity and crystal-size. When these two relationships are known, curves can be constructed to show the variation of crystal-size with distance.

The mean of the maximum crystal-size (that is, the mean size of the crystals when crystallization is completed) has been determined experimentally for various degrees of under-cooling (11). A silicate melt was used from which the rock-forming mineral nepheline crystallized. The size is given as the mean diameter of the crystals measured from one prism face to the opposite one. The crystal-size itself depends on two factors: (a) the rate of formation of crystal nuclei, and (b) the velocity of growth. Both have been experimentally determined for different degrees of under-cooling and the quantitative relationship between these two primary factors has been worked out. The crystal-size equals

$$\text{Constant} \times \sqrt[4]{(\text{velocity of growth}/\text{rate of formation of nuclei})}.$$

For the present purpose, however, these two primary factors governing crystal-size need no longer be dealt with (cf. (11)). Velocity of growth and rate of formation of nuclei vary with under-cooling, and therefore crystal-size varies with it also. This is shown in fig. 2 by curve *a*, broken line. As under-cooling decreases crystal-size increases up to a maximum and then falls to the zero-point of the co-ordinate system, at which point no crystals form.

There is obviously a close connexion between under-cooling and cooling-velocity, for similar effects are produced by a marked degree of under-cooling on the one hand and high cooling-velocity on the other. In both cases small crystals develop. This connexion has been worked out and it is possible to correlate crystal-size, developed at a certain degree of under-cooling, with a certain cooling-velocity (11) (12). The result is shown in fig. 2, curve *b*, full line. It should be noted that with decrease in cooling-velocity there is merely a small increase in crystal-size over a wide range until certain low cooling-velocities are approached,

when rapid increase takes place. At very low cooling-velocities there is a rapid decrease in crystal-size. This fact has not previously been observed, but is experimentally and thermodynamically well founded, and is of great significance in the interpretation of the phenomena observed in nature. (Discussion of Queneau's and Lane's conceptions (in 12).)

Relationship between crystal-size and distance from margin.

Although the actual values given in fig. 2 refer only to nepheline crystallized in a certain system, it can reasonably be assumed that the same relationship between crystal-size and cooling-velocity, as represented by curve *b*, will hold for other rock-forming minerals. This assumption is supported by the agreement between the observed and calculated curves expressing the relationship between crystal-size and distance from the centre in dikes. Such curves, based on the outlined relationship between (*a*) cooling-velocity and distance from the centre, and (*b*) cooling-velocity and crystal-size, have been constructed for dikes of various thicknesses (12). The results for dikes of $R_0 = 1$ m., 2 m., 3 m., 4 m., 5 m., and 6 m., all belonging to the same magma and having the same viscosity, are here again produced as graphs. These have been constructed as follows. Assuming a dike of $R_0 = 3$ m., and regarding the temperature range of $\theta 1.0-0.9$, the cooling-velocity at a distance of $r = 0.7$ (corresponding to the distance of 2.1 m. from the centre) is obtained from table I; it is 20.5 °C./h multiplied by $1/9 = 2.28$ °C./h. From fig. 2, curve *b*, it is found that the crystal-size of 7.5 mm. diameter corresponds to this cooling-velocity. This value is plotted at the distance $r = 0.7$ in fig. 5. When similarly derived values for other distances are plotted, a curve is obtained which shows the variation of crystal-size with distance for the case of a mineral crystallized within the temperature range of $\theta 1.0-0.9$. The same procedure is carried out for other temperature ranges indicated on the corresponding curves in the diagrams. (Figs. 3-8 represent various thicknesses.)

Having regard to the diagrams for various thicknesses it is noticed that in thin dikes ($R_0 = 1$ m.; fig. 3) hardly any change in crystal-size takes place; this has often been observed in nature. In thicker dikes ($R_0 = 2$ m.; fig. 4) the crystals become larger with increasing distance from the margin, and maintain the maximum value in the central portion of the dike. If still thicker dikes are considered, however, crystals which have grown within certain temperature ranges no longer attain a maximum size at the centre of the dike, but show a pronounced maximum

at a certain (intermediate) distance from the margin. This has been observed by Lane (6) in the Medford dike at Cambridge, Massachusetts, and has been interpreted by the writer (12).

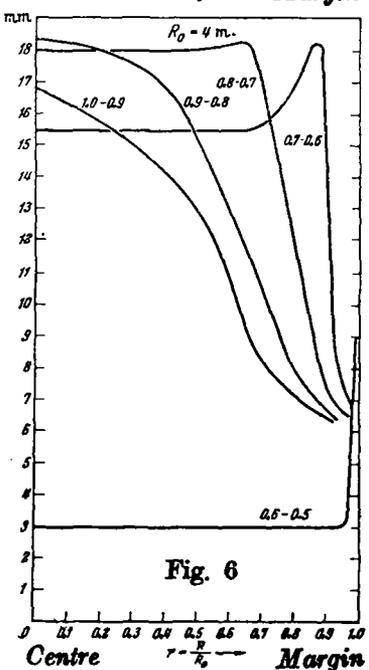
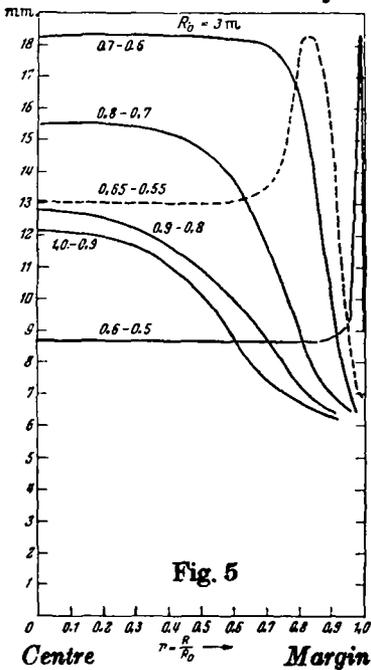
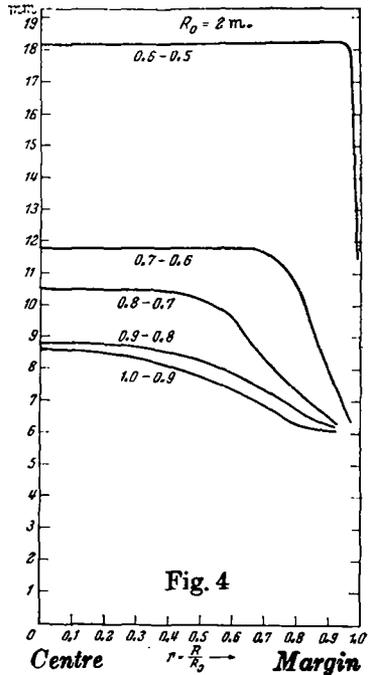
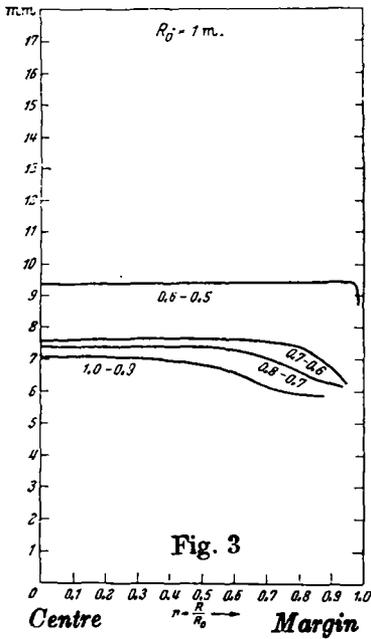
When the temperature of the intrusion has fallen to half or less than half of its original value (T_m) no differences in cooling-velocity exist across the dike, and hence there is no variation in crystal-size.

Grain-size measurements carried out on naturally occurring dikes can be interpreted on the basis of the data incorporated in the constructed curves, and afford valuable information concerning the temperature ranges within which individual minerals have grown, and even provide some indication of the viscosity of the various magmas (12). There is one point which must be stressed, however, viz. that in speaking of temperature ranges in which various minerals have crystallized, it is not implied that, quantitatively, all of a mineral has crystallized within a certain range of temperature, but that by far the greater quantity did so. It is not possible to be more precise (except in individual cases, as we shall see below, page 571, as the method employed is based on the determination of the mean diameter of a great number of crystals. If, for instance, after the bulk of a mineral has crystallized in a certain temperature range a further 15% crystallizes out later, this will often not influence to any extent the crystal-size of the earlier formed 85%. This should be born in mind when comparing the results of crystal-size interpretation which lead to the deduction of crystallization ranges with those derived from the study of ternary and quaternary systems (see p. 570).

In the following pages new measurements of grain-size in a tholeiite dike are given and interpreted.

Crystal-size variation in the Cleveland dike.

The rock.—One of the localities which afford a complete section of the Cleveland dike, from one margin to the other, is Great Ayton, south of Middlesborough, in Yorkshire. The dike is there exposed in underground workings, and is seen to be almost vertical and with a total thickness of 54·5 feet, or 16·6 m. Specimens have been taken from one margin to the other at intervals normally of 1·5 feet except in the central parts of the dike (15–42 feet from the south margin) where the distance between successive specimens was increased to 3 feet. The orientation of all specimens was marked, and thin sections were cut in such a way that the plane of the section is horizontal and perpendicular to the walls of the intrusion.



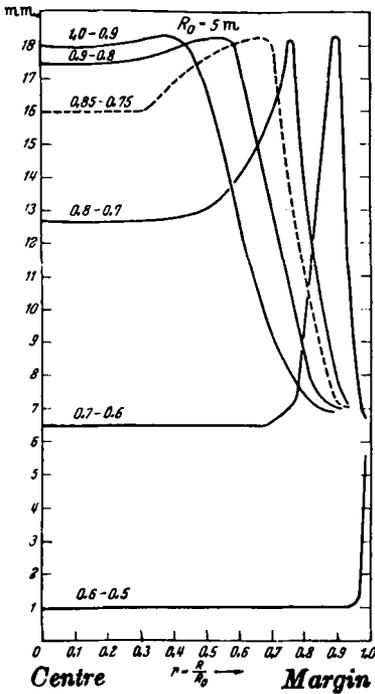


Fig. 7

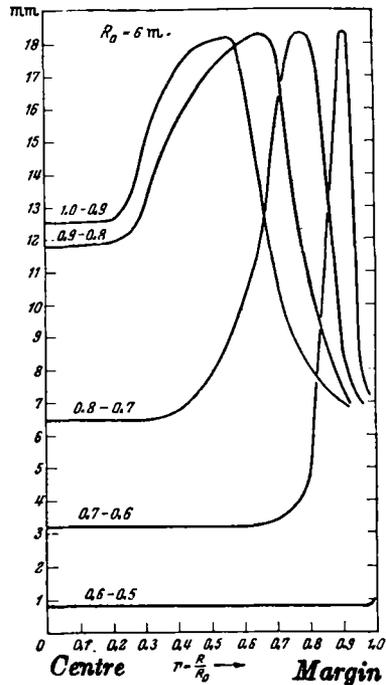


Fig. 8

FIGS. 3-8. Crystal-size variation in dikes from the centre to the margin for various temperature ranges and thicknesses (R_0 being half of the total thickness).

The rock of the Cleveland dike has previously been fully described by J. J. H. Teall (9) and A. Holmes (4). It is a typical tholeiite characterized by basaltic composition and the development of intersertal texture. A very fine-grained variety near the margin is always distinct from the coarser-grained rock of the main mass, but apart from this no further variation in grain-size can be detected in the hand-specimens. Typically porphyritic crystals of plagioclase, ranging in size up to 2×4 mm., are as well developed, and of the same size, at and near the margins as in the centre of the dike. These constitute on an average 3 or 4% of the rock. Very subordinately scattered porphyritic crystals of enstatite-augite are also distributed throughout the rock. The groundmass is made up of plagioclase laths ranging in composition from labradorite to oligoclase, and with only slight zoning. The interstices are occupied by augite, magnetite, very little quartz, biotite, and much

mesostasis. The latter is devitrified, and comprises about 30-40 vol. % of the rock. Magnetite is evenly distributed as idiomorphic and sometimes as skeleton forms, and the augite occurs as grains and slender prisms.

Although the texture must be described as intersertal there are some exceptions from the point of view of an ideal intersertal texture, in that magnetite and, more often, pyroxene crystals are occasionally partly intergrown with the felspar laths of the groundmass. This indicates that crystallization of some plagioclase took place after some individual crystals of magnetite and augite had already developed. This observation will be discussed further, below.

Measuring of crystal-sizes.—A number of methods have been used in the measurement of the diameters of crystals in thin sections. Some of these have been described by H. L. Alling (1), who himself uses, for accurate work, a camera-lucida and polar-planimeter equipment, with which the area of fifty grains of each mineral in each slide is measured. From the mean area of all grains measured the diameter of a circle equal to this area is calculated, and this is taken as the mean diameter of the crystals. In the present investigation the writer used an integrating stage, and, as the crystals are randomly distributed, measured 350 to 400 crystals of each mineral in each slide. The total sum of diameters divided by the number of crystals gives the mean diameter.

In the specimens taken from the margin of the dike and at a distance of 1.5 feet inwards the plagioclase laths of the groundmass tend to be orientated with their longer axis almost perpendicular to the cooling-wall. (This is a growth effect due to the great heat transport and consequently molecule diffusion towards the wall.) In these cases the section was measured in two directions, one perpendicular to the other, and the mean value determined from both sets of measurements. It would appear, moreover, that in addition to this orientation there is still another orientation effect, in which the two longest axes of the felspar laths lie more or less in a horizontal plane (floating effect). This is also the plane of the slides. Thus the mean crystal-size of plagioclases measured in these two sections is not the true mean diameter, but is too great. This may explain the observation that the two values at and close to the margin do not fit the general trend of the curve, which is accurately determined by the other points (see broken line in fig. 9).

As shown by the calculated curves, conspicuous changes in crystal-size must be expected especially at distances extending from the margins inwards up to about one quarter of the total thickness of the dike.

Specimens have therefore been taken at closer intervals in these marginal parts than in the middle portion of the dike. This is essential in order to obtain an accurate curve of crystal-size variation. It would be advisable to choose even smaller intervals, because all specimens taken represent chance sections and may depart to some extent from the true mean value. This, however, can be interpolated graphically if enough points are available for the graph.

In the present instance 27 specimens have been taken across the whole dike, but since the northern part of the cross-section (extending 12.5 feet from the north margin into the dike) contained mainly decomposed augites which could not always be distinguished individually, only the southern half of the dike, involving 15 thin sections, has been investigated.

Results of measurements.—The results of the measurements are plotted in fig. 9. The abscissa represents the distance from the margin to the centre of the dike. The ordinate gives the mean diameter of the crystals in millimetres. Since the graph would have become too long the curves for augite and magnetite have been displaced upwards; and the ordinate on the right-hand side refers to these two minerals, while the left ordinate refers to plagioclase. Only the three minerals of the ground-mass are considered, the porphyritic crystals of intratelluric origin being ignored.

As the specimens have been taken at rather small intervals, the curves which link up the individual values represent crystal-size variation with a comparatively high degree of accuracy, and so a reliable interpretation is possible. It is noticed from fig. 9 that the curves for plagioclase, augite, and magnetite are very different in character. Proceeding from the margin to the centre, the plagioclase curve rises steeply to a maximum and thereafter remains constant, whereas the magnetite and, more conspicuously, the augite curves show a definite size maximum followed by a decrease at a certain distance from the margin.

Interpretation of crystal-size variation in the tholeiite dike.

The observed crystal-size variation of the minerals plagioclase, augite, and magnetite can be compared with curves constructed independently by methods based on the principles responsible for the variation of crystal-size in dikes. In so doing, merely the character of the curves has to be compared, disregarding the absolute crystal-size. Furthermore, the three curves for plagioclase, augite, and magnetite, as determined in the dike, must all be represented in one of the constructed diagrams.

If the curves of fig. 9 are compared in this way with the constructed diagrams of figs. 3-8, it is seen that the three curves are not represented in any of the diagrams of figs. 3, 4, 5, and 8. Fig. 7, however, shows a slight resemblance, while in fig. 6 there are curves which resemble more

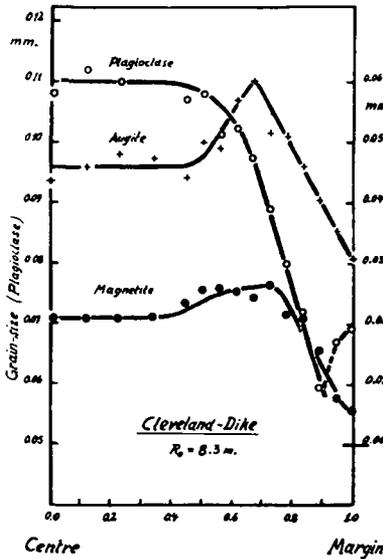


FIG. 9

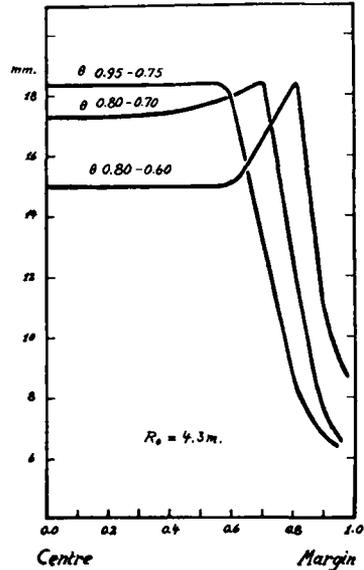


FIG. 10

FIG. 9. Crystal-size variation in the Cleveland dike (Great Ayton, Yorkshire) of plagioclase, augite, and magnetite.

FIG. 10. Constructed diagram showing crystal-size variation in a dike of $R_0 = 4.3$ metres for various temperature ranges.

closely those which have been observed in the dike (fig. 9). The curve for plagioclase resembles the curve constructed for θ 0.9-0.8, magnetite that for θ 0.8-0.7, and augite that for θ 0.7-0.6. It must be expected, therefore, that the measured curves will very closely resemble curves constructed for a dike of half a thickness R_0 , somewhere in between $R_0 = 5$ m. (fig. 7) and $R_0 = 4$ m. (fig. 6), but nearer to the latter thickness. Curves have been constructed for various thicknesses, and it is found that a dike of $R_0 = 4.3$ m. shows curves of crystal-size variation which give the best coincidence with those observed in nature: the plagioclase curve is the same in type as the one constructed for the temperature range θ 0.9-0.8, the magnetite curve resembles closely the

curve for θ 0.8–0.7, and the augite curve that for θ 0.75–0.65. This would mean that the bulk of these minerals has crystallized approximately in the respective temperature ranges. In order to be more accurate, however, the textural relationship of the minerals has to be taken into account. It is obvious that most of the augite and magnetite has crystallized after the plagioclase, although sometimes a mutual intergrowth of magnetite and augite with plagioclase is observed. This illustrates that part of the plagioclase had not finished growth at a time when some of the magnetite, as well as the augite, had already developed. The temperature range in which plagioclase crystallized, therefore, should extend lower down, and the one for augite higher up.

Curves for $R_0 = 4.3$ m. have been constructed, representing variation of crystal-size when crystallization took place in correspondingly wider temperature ranges. (Cooling-velocities for such wider ranges are given in table I). Omitting all constructed curves which do not fit the curves of fig. 9, a diagram of those which fit is given in fig. 10. It is arranged side by side with fig. 9 to simplify comparison.

As nearly as possible the plagioclase curve corresponds in type to that constructed for a temperature range of θ 0.90–0.75, the one for magnetite to the curve for θ 0.80–0.70, and the augite curve to the curve constructed for θ 0.80–0.60. This means that in a tholeiitic magma *most* of the groundmass crystals have crystallized in the following temperature ranges. The temperatures in °C. corresponding to the θ -values are calculated on the assumption of an intrusion temperature $T_m = 1000^\circ$ C. and an initial country-rock temperature $T_c = 25^\circ$ C.

plagioclase in θ 0.90–0.75 = 903–756° C.

magnetite in θ 0.80–0.70 = 805–708

augite in θ 0.80–0.60 = 805–610

These results are in conformity with the intersertal texture and its slight deviations. They are also in agreement with petrographical observations. It has often been noticed that in basaltic magmas the crystallization ranges of plagioclase and augite must have overlapped each other. Concerning magnetite, it has often been assumed that magnetite always crystallizes very early in magmas. This does not hold for gabbroic magmas, as H. L. Alling (1) and others have pointed out. A. Streng observed sixty years ago that, in certain German diabases, magnetite had crystallized after plagioclase and olivine. In the tholeiite, magnetite has definitely crystallized after the crystallization of plagioclase had commenced.

It has to be considered now if the results derived from interpretation of crystal-size variation are in agreement with our knowledge derived from physico-chemical data. On the basis of N. L. Bowen's (3) investigation of the ternary system albite-anorthite-diopside, T. F. W. Barth (2) has further developed a picture of crystallization of basaltic magma. According to him, a basaltic magma can be regarded, at a first approximation, as a point within the quaternary system albite-anorthite-diopside-hypersthene. It depends on the chemical composition of the magma if either plagioclase or pyroxene starts to crystallize first. During the process of crystallization the composition of the melt changes gradually, and when the cotectic surface is reached simultaneous crystallization of both minerals along the two-phase plane takes place. Barth (2) has fixed the position of the cotectic surface within the interior of the quaternary system and has expressed its position by the equation

$$\text{Ab}' + 2 \text{Di}' + 2.3 \text{Hy}' = 123.$$

In applying this equation, the norm of the rock has first to be calculated from the chemical analysis, then An, Ab, Di, and Hy are recalculated to 100, which gives Ab', Di', and Hy'. If the sum of these terms in the above equation is greater than 123 pyroxene has crystallized first, if less plagioclase.

This calculation has been carried out for the rock from Great Ayton (chemical analysis in (4) and (9)) and from two other localities of which A. Holmes (4) gives the norms. The sum of the above equation for rocks of different localities but all representing the tholeiite of the Cleveland dike is: Great Ayton, Yorkshire, 95.5; Bolam, Durham, 115.9; Boldon, Durham, 107.0. The sum is always less than 123 and therefore, according to Barth, plagioclase should start to crystallize before pyroxene. This also is the conclusion drawn from the interpretation of crystal-size variation.

While plagioclase crystallizes, the composition of the system is gradually altered towards the cotectic surface. When this is reached, both plagioclase and pyroxene crystallize together. The same conclusion has been arrived at from our method. But from this it follows that *most* of the plagioclase finished crystallization well before the bulk of the pyroxene. This can be understood, as plagioclase crystallization was initiated much earlier, and a good deal of the mineral had already separated before pyroxene started to grow. According to the quaternary system, plagioclase cannot completely cease to crystallize before pyroxene. It should be stressed here, again, that the temperature range

given for the crystallization of plagioclase, for example, does not refer quantitatively to all the plagioclase but, according to the method, to the majority of these crystals. Therefore, this method does not exclude the possibility that a smaller percentage of the plagioclase has crystallized at temperatures below θ 0.75 along with pyroxene, until the end of the crystallization. The percentage of plagioclase which might have crystallized below θ 0.75 until θ 0.60 can be approximately calculated from our curves.

The percentage of crystals growing at lower temperatures and having consequently a mean size different from that of the majority of crystals crystallized in the higher range of θ 0.90–0.75 cannot have been greater than the percentage which would markedly alter the character of the curve. The calculations show that up to 25% of the plagioclase crystals could have grown in the lower temperature range of θ 0.75–0.60; and a good deal, or perhaps all, of this percentage may have done so. On the other hand, at least 75%, or by far the greater part, has crystallized in the range of θ 0.90–0.75.

Corresponding calculations have been made for magnetite and augite. It was concluded that not more than 5% of augite could have crystallized in the higher range of θ 0.9–0.8, and probably none has done so. Concerning magnetite, up to 30% could have crystallized in the lower temperature range of θ 0.7–0.6, and some of it may have done so.

Thus the conception of crystallization in a tholeiitic magma, which has been mainly derived from the study of crystal-size variation in a dike, can be summarized in a diagram showing the temperature ranges in which the major and minor quantities of the groundmass minerals have crystallized. If the sharp steps in this diagram (fig. 11) are smoothed out into a curve, as done for plagioclase, the picture is likely to give a good idea of the crystallization process. It should be borne in mind, however, that about 40% of the magma has not crystallized at all during the cooling process, but has remained as a glass, which is no longer of basaltic composition.

In fig. 11 all of *each* groundmass crystal is represented as 100%. Let us now consider the crystallization process by taking all constituents of the rock as 100%. The tholeiite of Great Ayton shows the following composition in vol. %. These measurements agree with the data of Cleveland dike rocks from other localities which have been provided by Holmes (4), viz. phenocrysts 4, plagioclase 29, pyroxene 22, magnetite 4, mesostasis 41 vol. %. Using the results represented in fig. 11 the

following steps of crystallization with decreasing temperature are obtained:

TABLE II. Amounts of crystallized materials in the Cleveland dike at temperatures indicated by θ -values.

	$\theta 0.9$.	$\theta 0.8$.	$\theta 0.7$.	$\theta 0.6$.	$\theta < 0.6$.
Phenocrysts	4	4	4	4	4 vol. %
Plagioclase	—	15	26	29	29
Pyroxene	—	—	11	22	22
Magnetite	—	—	3	4	4
Mesostasis... ..	—	—	—	—	41
Remaining melt in vol. %	96	81	55.5	40.5	0

In this table the figures represent volume %. It is also clearly seen how in the remaining melt the importance of the 41% of highly siliceous material which later forms the mesostasis becomes greater with progressing crystallization.

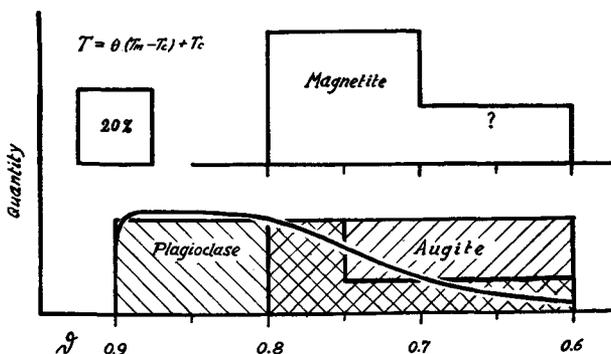


FIG. 11. Diagram showing crystallization of the groundmass minerals in the tholeiitic magma. (Quantity of crystals and temperatures, θ -values, are represented. All of each individual mineral is given as 100%.)

The general outline of crystallization is, as has been discussed, in full agreement with physico-chemical deductions. It should be noted, however, that in the first stage of crystallization of a basaltic magma, the quaternary system gives quite a reliable idea of the process, but with progressing crystallization the composition of the melt changes markedly, so that the late differentiates of tholeiitic magma are sub-alkalic, almost granitic in character as has been shown by W. Q. Kennedy (5) and F. Walker (10). This means that during crystallization the composition of the remaining melt changes gradually from the basalt- to the granite-system, which is a rather complicated process to deal with synthetically.

But synthetic work in connexion with the results derived from the interpretation of crystal-size variation will be undertaken.

Comparison of the tholeiitic magma with other magmas should be of great interest. This will be done first of all with the olivine-basalt magma, thus making possible a comparison between the two primary parent basaltic magmas postulated by W. Q. Kennedy (5). The ranges of crystallization of the bulk of the main constituents will probably be different. This presumption is supported by the interpretation of size variations across an olivine-diorite dike measured by H. L. Alling (1). A preliminary and approximate evaluation of temperature ranges in which most of the olivine, plagioclase, and augite crystallized has been communicated by the writer (12). But more accurate results are expected from the study of olivine-dolerite dikes from Scotland which is in progress.

Viscosity of magmas.

The curves of figs. 3-8, representing crystal-size variation with distance from the margin, refer to a certain equal viscosity for all the various dike thicknesses for which curves have been constructed. These dikes may be called 'comparison dikes'. If the viscosity of a magma was different from that of the comparison dike, then the size variation will not be the same in the natural as in the comparison dike if both are of the same thickness. A dike of $R_0 = 8$ m., for instance, having a greater viscosity than the comparison magma, shows crystal-size curves which are not similar to those constructed for a dike of the same $R_0 = 8$ m., but for a dike of $R_0 < 8$ m. This has been observed with the Cleveland dike. It is of $R_0 = 8.3$ m. and the crystal-size curves have been found to be similar to those of a comparison dike of $R_0 = 4.3$ m. (figs. 9 and 10). This means that the tholeiitic magma has had a higher viscosity than the comparison magma. On the other hand, for an olivine-diorite dike at Ausable Forks, Essex Co., New York, (1) of $R_0 = 1.7$ m., the crystal-size curves were found to resemble those of a comparison dike of $R_0 = 4$ m. (12). This means that the viscosity of this olivine-diorite magma has been smaller than that of the comparison magma, and thus has been definitely smaller than that of the tholeiitic magma. This deduction is in full accord with our current conception on viscosities of magmas.

Imagining an olivine-dolerite magma of low viscosity and a tholeiitic magma of higher viscosity each forming dikes of the same thickness, let us say $R_0 = 2$ m., the olivine-dolerite will show pronounced varia-

tions of crystal-size with distance from the margin (corresponding about fig. 7; $R_0 = 5$ m.), while the tholeiite dike will show hardly any (corresponding about fig. 3; $R_0 = 1$ m.). This has often been observed in the field and is due to the differences in viscosity of these two magmas.

A little more on viscosity of magmas has been said in (12), and it is proposed to deal with it more fully when further investigations on basaltic and other dikes are completed.

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