

Cooling rate studies of rocks from two basic dykes

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SYNOPSIS

NUCLEATION and crystal growth of plagioclase have been studied in two basaltic melts by one atmosphere, constant-rate and variable-rate cooling experiments using the wire-loop technique (Donaldson *et al.*, 1975). Constant-rate cooling studies indicate that the length of the incubation period prior to nucleation varies systematically with the degree of supercooling and with the cooling rate. Attempts to determine the rates at which the marginal parts of two dykes (from the Isle of Arran, SW Scotland) cooled, by the attempted reproduction of the natural textural features, in constant-rate cooling experiments suggest that for one of the

dykes, plagioclase phenocrysts at the contact could have grown at a cooling rate of approximately 3 °C/hour and the groundmass plagioclase laths at faster cooling rates in excess of 10 °C/hour. For the other dyke the plagioclase laths in the rocks 0.5 cm from the dyke contact probably grew at rates slower than 2 °C/hour. Attempts to validate experimentally the Jaeger (1957) cooling model for the two dykes suggest that the dykes cooled at much slower rates than the theory predicts.

REFERENCES

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COOLING RATE STUDIES OF ROCKS FROM TWO BASIC DYKES

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Many experimentalists have used non-equilibrium studies in preference to equilibrium studies to try to evaluate the rates at which natural rocks could have cooled (e.g. Lofgren et al., 1974, 1975). In this study constant rate and variable rate cooling experiments have been used to try to simulate as closely as possible the mineralogy, grain size and textures of the marginal parts of two basaltic dykes from the Isle of Arran in S.W. Scotland.

The constant rate cooling experiments had a dual purpose in that firstly, they were a study of the effects of cooling rate on the initiation of nucleation; secondly, they were used to obtain a first approximation of the rates at which the marginal parts of two basaltic dykes cooled. The variable rate cooling experiments were performed to simulate as closely as possible the cooling of natural rocks as predicted by the Jaeger cooling model (Jaeger, 1957).

THE DYKES

The two dykes from the Isle of Arran consist of one olivine tholeiite (dyke 1) and one tholeiite (dyke 2). Each dyke was sampled at intervals from one of its contacts to its centre. In each case only half the width of each dyke was sampled in detail on the not unreasonable assumption that the dykes are compositionally symmetrical. Orientated samples cut parallel and perpendicular to the walls of the dykes showed that there was generally no preferred mineral orientation within either of the two dykes. The whole rock analyses for the major elements of the dyke rocks are given in Table 1.

Table 1. Chemical Analyses of Samples from Dykes 1 and 2.

Sample Number	Dyke 1		Dyke 2	
	G.1	G.9	G.13	G.18
	Major Elements (wt.%)			
SiO ₂	45.39	45.74	49.38	46.94
Al ₂ O ₃	17.46	17.96	13.01	13.25
TiO ₂	1.55	1.43	2.28	2.19
Fe ₂ O ₃	4.39	2.96	7.16	4.68
FeO	7.24	8.60	8.28	10.59
MnO	0.19	0.19	0.24	0.21
MgO	6.20	8.47	5.05	5.24
CaO	10.69	10.31	9.03	9.71
Na ₂ O	2.75	2.47	2.58	2.58
K ₂ O	0.17	0.15	0.79	0.64
P ₂ O ₅	0.15	0.14	0.20	0.18
S	0.09	0.05	0.21	0.12
CO ₂	2.73	0.20	1.07	0.41
H ₂ O ⁺	1.38	1.32	1.18	0.97
Total	100.38	99.99	100.46	99.71

Sample G.1 = 0.41m from W. contact of dyke 1.
Sample G.9 = 1.83m from W. contact of dyke 1 (i.e. centre).
Sample G.13 = 0.215m from N.E. contact of dyke 2.
Sample G.18 = 2.34m from N.E. contact of dyke 2 (i.e. centre).

The variation in modal percentages of plagioclase, clinopyroxene, olivine and iron oxides across each dyke is given in figs. 1 and 2. From Table 1 it can be seen that dyke 2 shows no evidence of fractionation even though the modal variations of olivine and iron oxides across this dyke (fig. 2) do suggest possible fractionation; a possible explanation for this is discussed later on in the text. From Table 1, dyke 1 shows some degree of fractionation with FeO increasing with crystallisation.

EXPERIMENTAL METHODS

The experiments were carried out in an ordinary 30mm bore, Pt-20%Rh wound, vertical quench furnace in which the f_{O₂} was controlled by a CO₂-H₂ mixture. The wire-loop method (Donaldson et al., 1975a) was used. For the constant rate cooling experiments 0.2mm diameter Ag₄₀Pd₆₀ wire was used and for the variable rate cooling experiments 0.15mm

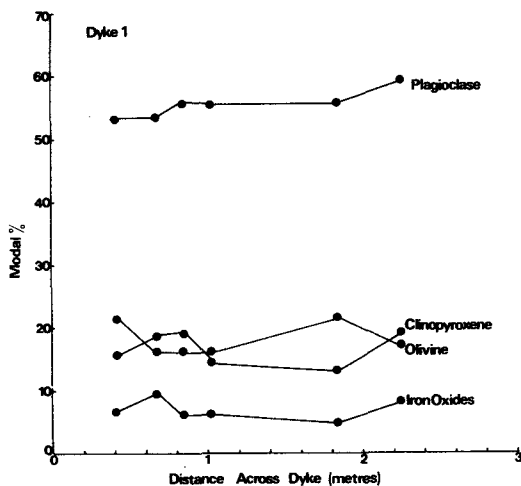


Fig. 1. Variation in modal percentages of plagioclase, clinopyroxene, olivine and iron oxides across dyke 1.

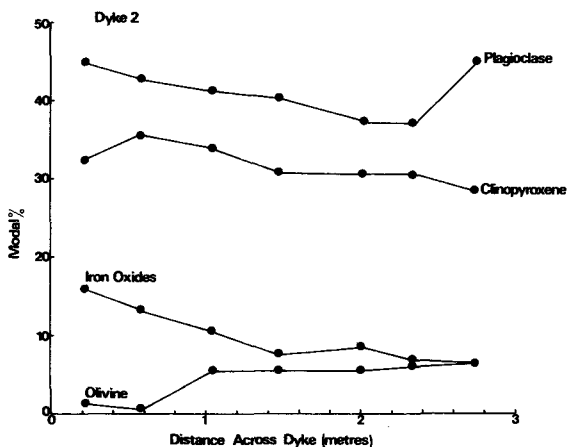


Fig. 2. Variation in modal percentages of plagioclase, clinopyroxene, olivine and iron oxides across dyke 2.

diameter Ag₄₀Pd₆₀ wire was used in an attempt to reduce iron losses to a minimum (Corrigan and Gibb, 1979). In the variant of the wire-loop method used in this work the powdered starting materials (50-80mg) were pressed into pellets 5mm in diameter and 2-3mm thick, a length of annealed wire was gently twisted around the pellet and the entire pellet was partly fused to form a bead by holding it substantially above its liquidus temperature (between 100-150°C) for a short interval (between 2 and 6 minutes). During this initial fusion the muffle furnace atmosphere was controlled by mixtures of CO, CO₂ and N₂ to minimize oxidation of the iron and also oxidation of silver in the wire. It was later found that the initial fusion of the pellets could be satisfactorily achieved in air using a muffle furnace so long as heating times were reduced to 2-3 minutes, otherwise serious weakening, and in

extreme cases failure of the wire resulted. At the end of the experiment the sample (complete with suspending wire and ceramic insulator; see Donaldson et al., 1975a, fig. 2) was quenched into cold water. Where the pellets remained intact they were cut horizontally, i.e. perpendicular to the suspending wire and made into thin sections. In the case of shattered pellets a small amount of the charge was crushed under a liquid (acetone or water) and then coarsely ground and mounted on a glass slide. This expedited preliminary identification of the silicate phases and the consequent decisions regarding the conditions necessary for subsequent experiments. Thin sections were made from the remaining fragments of the shattered beads.

In both the constant rate and variable rate cooling experiments the temperature was lowered by using a variable speed electro-mechanical stepping device to continuously increase the output from a DC millivolt source by extremely small increments (either 4.5×10^{-5} mv or 1.39×10^{-6} mv). This signal was added to that from the control thermocouple in the furnace to simulate a gradual rise in furnace temperature, thus inducing the control system to cool the furnace at the required rate by attempting to maintain the total signal at a constant level. This method was used as manual or mechanical adjustments of the set point of the controller could not give the precision required and, in any case, was liable to give 'overshoot'.

In both types of experiments the charges were heated above their liquidus temperature to set values of $+\Delta T$ (superheat) for 12 to 24 hours with the gas mixture set to give an f_{O_2} of 10^{-9} atmospheres (dyke 1) or 10^{-8} atmospheres (dyke 2) at this temperature (these are the f_{O_2} values determined experimentally, at which the dykes are thought to have formed (Corrigan, 1960)). In the constant rate cooling experiments the charges were then cooled rapidly to 10^{-15}°C above the liquidus, with an adjustment in the gas mixture to give the same f_{O_2} at the liquidus temperature. The charges were then cooled at the predetermined rates through the liquidus temperature to various degrees of $-\Delta T$ (supercooling) and quenched. In the variable rate cooling experiments the samples were cooled rapidly to the liquidus temperature, maintaining a constant f_{O_2} by a readjustment of the CO_2/H_2 gas mixture and then the charges were cooled at the required rates through the liquidus temperature. The CO_2/H_2 ratio in the atmosphere was not altered during the runs, so that the f_{O_2} decreased slightly with cooling. This procedure is justifiable since Hamilton and Anderson (1967) have shown that anhydrous basaltic magma cooling under conditions of constant total composition will have a small decrease in f_{O_2} .

CONSTANT RATE COOLING EXPERIMENTS

Nucleation of phases

Constant rate cooling studies on sample G.18 (dyke 2) have shown that the order of appearance of liquidus plagioclase (1166.5°C) and second phase clinopyroxene ($1147 \pm 4.5^\circ\text{C}$) is the same as under equilibrium conditions although the nucleation temperature of each phase is lowered. The experimentally derived supercooling relationships for sample G.18 superheated to $+\Delta T = 34.5 \pm 4^\circ\text{C}$ (fig. 3) indicate that the temperature at which plagioclase nucleates from the melt is dependent on the cooling rate, and that the length of the incubation period for both the liquidus phase and the second phase increases as the cooling rate decreases. Also the amount of $-\Delta T$ required prior to nucleation decreases as the cooling rate decreases. This relationship is consistent with the findings of Donaldson (1978, 1979) for the delay in the nucleation of olivine from a basaltic melt, with the work of Walker et al. (1976) on a lunar picrite composition and also with the crystallisation studies of Lofgren and Donaldson (1975).

For sample G.18 olivine did not nucleate in any of the experimental charges except for two runs cooled at $1^\circ\text{C}/\text{hour}$ and quenched from $-\Delta T$ s of 110°C and 105°C respectively (fig. 3). In dyke 2 there are no olivine phenocrysts and granular groundmass olivine increases in amount from the dyke margin to the dyke centre (fig. 2) with olivine absent from the actual contact. Since there are no olivine phenocrysts flowage differentiation cannot account for the distribution of olivine in the dyke. The experimental data (fig. 3) suggest the possibility that the modal increase in olivine towards the dyke centre might be attributable to variation in the cooling rate (and supercooling) across the dyke and not be a result of a differentiation mechanism (other than flowage differentiation which has already been discounted). This is supported by the fact that the margin and centre of dyke 2 are almost identical chemically (Table I) which would not be the case if any true fractionation had occurred. It is also tenable that the olivine distribution in the dyke could be due to the nucleation of iron oxides in preference to olivine at the dyke margin, either because of the faster cooling rate or because of a higher f_{O_2} at the dyke contact. Such iron oxide nucleation would act to deplete the melt in the iron necessary for olivine growth. In support of this latter idea, there is a marked increase in modal iron oxides from the centre towards the

contact of the dyke (fig. 2). Whichever explanation is favoured it does not detract from the fact that the olivine content varies across dyke 2 without any obvious corresponding variation in the bulk composition which is undoubtedly an important phenomenon.

The simplest explanation to account for the absence of olivine at the actual dyke contact is that the constituents of the olivine are quenched into the glass. A more complex hypothesis is that the gradual increase of olivine from the contact could be due to slower cooling towards the dyke centre allowing the iron oxides to be resorbed and replaced by iron-rich olivine.

Reproduction of grain sizes and nucleation densities

Non-equilibrium experiments in which basaltic melts were cooled at constant rates have been successful in the reproduction of the textures and mineral chemistry of basaltic rocks, and in obtaining estimates of cooling rates by the comparison of the natural rock and the experimental products (e.g. Donaldson et al., 1975b). The lack of crystal/liquid equilibrium during natural crystallisation is especially characteristic of dyke 2, as evidenced by clinopyroxene fan spherulites, skeletal iron oxides and skeletal plagioclase. It is also evident in dyke 1 which contains skeletal olivine and clinopyroxene fan spherulites. As a result, experiments designed to study equilibrium crystallisation are not strictly applicable and therefore, non-equilibrium conditions have been investigated to determine the approximate rates at which parts of the two dykes could have cooled. It is realised that natural cooling is not linear but linear rates are a good first approximation (variable rate cooling experiments will be discussed later).

The variations in crystal sizes and nucleation densities in igneous

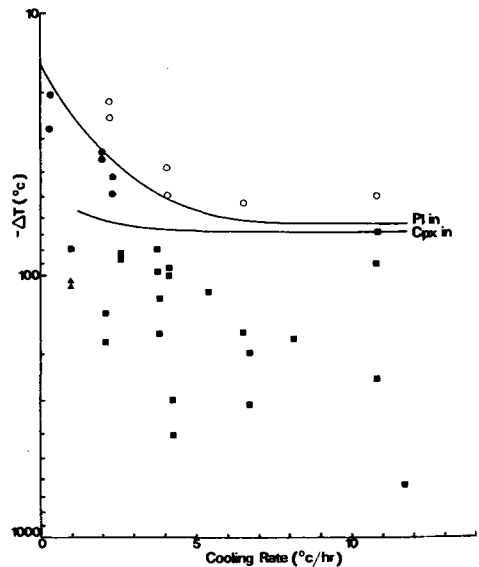


Fig. 3. Phase relationships for sample G.18 as a function of $-\Delta T$ and cooling rate. The symbols are as follows: open circle = glass; solid circle = glass + plagioclase; solid square = glass + plagioclase + clinopyroxene; solid triangle = glass + plagioclase + clinopyroxene + olivine.

bodies are attributed to different cooling rates within the magmatic body (Lane, 1898; Queneau, 1902; Gray, 1968, 1970). The mean sizes of the twenty largest plagioclase crystals in thin sections ($3.4 \times 2\text{cm}$) of the rocks were determined by measurement of their 'widths' perpendicular to the (010) plane on the universal stage. The twenty largest crystals were measured in preference to averaging large numbers of crystals as it is likely that the first few crystals to form in the melt will have nucleated homogeneously, whereas the size of later generations of crystals seems likely to be governed to some extent by the remaining space in the melt and they may well have nucleated heterogeneously on pre-existing crystals. The largest error in this method probably arises from the fact that the largest crystal may be missed in sampling a limited area such as a thin section.

To check on the consistency of the crystal size measurements in the two dykes, replicate measurements were made on different thin sections and sometimes from different points along the length of the dyke as follows: for dyke 1 three thin sections were used to measure the 'width' of the plagioclase crystals at 0.5cm from the W. contact and they gave 84.5 μ , 83.5 μ and 86 μ respectively; for dyke 2 samples at 0.5cm from the S.W. contact were taken from two areas (one area of four thin sections and the other of five thin sections) and each gave respectively 48.9 μ and 53.2 μ . The results of the crystal size measurements are given in fig. 4 where it is shown that there is a general increase in the 'width' of the plagioclase crystals from the margin to the centre of the two dykes. The differences in crystal size across the dykes are attributed to different cooling rates within the magmatic bodies.

In the experimental charges the plagioclase crystals were measured

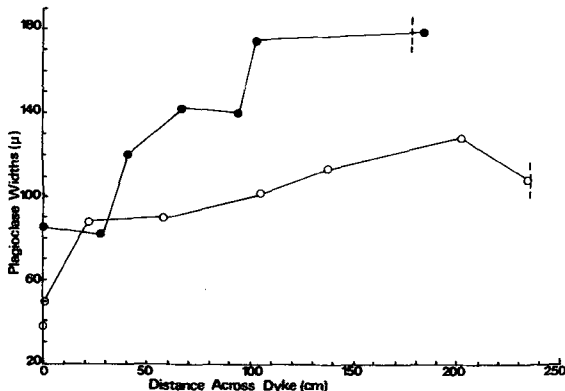


Fig. 4. Mean 'widths' of the twenty largest plagioclase crystals (see text) perpendicular to the (010) plane at various distances across dykes 1 and 2. solid circles = dyke 1, open circles = dyke 2. The centre of each dyke is indicated by the dashed line.

in exactly the same way as in the natural dyke rocks. Great care was taken not to measure crystals touching the supporting wire as they might represent heterogeneously nucleated crystals. A notable feature of the constant rate cooling experiments on sample G.1 (dyke 1) was the existence of a bimodal plagioclase crystal size distribution. It seems probable that the larger plagioclase crystals in such charges have grown heterogeneously and so only the smaller 'interstitial' plagioclases were measured. Their sizes must be considered as minima as the presence of larger heterogeneously nucleated plagioclases would have placed limitations on the growth of subsequent plagioclases. To check on the precision of such measurements two charges of sample G.1 were cooled at 10.8°C/hour and then quenched from 1016°C and 965°C and both gave plagioclase crystal 'widths' of 2.6 μ .

Since nucleation and growth in the melt are inter-related a textural analysis of a rock should also take into account crystal nucleation densities, but there is really no satisfactory method of obtaining a value for nucleation density.

Dyke 1

For sample G.1 the charges used for the plagioclase crystal size measurements were cooled to temperatures such that no significant amount of glass remained. Cooling at 2.1°C/hour and quenching from 1016.5°C ($-\Delta T = 241.5^\circ\text{C}$) gave a plagioclase crystal 'width' of 11.5 μ . Clearly to produce plagioclase crystal 'widths' of 86 μ at 0.5cm from the western margin of the dyke (fig. 4) cooling would have had to be at a rate considerably slower than 2°C/hour.

Dyke 2

Fig. 5 shows that a relationship exists between plagioclase crystal size and cooling rate for charges quenched from the same $-\Delta T$ value. This relationship may not be particularly instructive, however, since the crystal size attained at any set cooling rate may well depend more upon the growth time in the melt than the $-\Delta T$ value from which it is quenched (i.e. if two charges are cooled at different rates and then quenched at the same $-\Delta T$ value the crystals in the more slowly cooled charge will have had a longer growth time than those in the more quickly cooled charge). If the relationship shown in fig. 5 is meaningful it follows that a calibration of this variation could be used to determine

cooling rates. To try and determine for sample G.18 at what temperature below the liquidus temperature plagioclase crystal growth ceases, several runs were performed at a cooling rate of $2.3 \pm 0.5^\circ\text{C}/\text{hour}$ and then quenched after various times and therefore from different temperatures below the liquidus temperature. The results of this experiment are shown in fig. 6 where the mean plagioclase crystal size is plotted against the total time (t_c) spent in excess of that required to reach the nucleation temperature and that necessary for incubation and nucleation. To calculate t_c the experimental cooling rate curve for this sample was used (see fig. 86, Corrigan, 1980). The result was that after 18 hours the crystal size had increased no further and after 51 hours it had levelled off. The anomalous point 'A' on fig. 6 with a larger crystal width could be due to the measurement of heterogeneously nucleated crystals which were not identified as such. It is possible.

however, that the mean width might go through a maximum (point 'A') since in the last stages of nucleation and growth the growth of many small crystals could have stopped before they had time to attain larger sizes. The time at which the plagioclase crystals increase no further in size corresponds to $-\Delta T = 142.5^\circ\text{C}$ (i.e. 1024°C) and thus a calibration of crystal size against cooling rate for charges quenched from or below 1024°C should be meaningful. In support of this, isothermal supercooling experiments (see Corrigan, 1980) indicate that the solidus of G.18 is at $-\Delta T = 145^\circ\text{C}$.

In fig. 7 the relationship between cooling rate and plagioclase crystal size is shown. A regression curve of the form $y = a \times b^x$ ($y = 66.60 \times 0.8147^x$) is shown as a dashed line and a visual fit curve is shown by the solid line. It is evident from the data points 'A', 'B' and 'C' that the true curve is not just a simple exponential curve, but should in fact rise much more steeply at slow cooling rates (since the charges 'A' and 'B' were quenched from 1056°C and were thus not held as long as the other charges their crystal size must be a minimum and the true curve may be even steeper at slower cooling rates). Initially it seemed likely that the curve could be asymptotic to the crystal size axis since at very slow cooling rates the nucleation of small numbers of crystals would enable them to grow into very large crystals. It is, however, unlikely that the true curve is asymptotic to the cooling rate axis because at some critical rate the charge would consist only of glass.

When the variation in natural plagioclase crystal 'width' across dyke 2 (fig. 4) is used in conjunction with fig. 7 it can be deduced that at 0.5cm from the dyke's south-west margin the plagioclase crystal 'width' of 51 μ could have been produced at a constant cooling rate of 2.2°C/hour. Directly at the south-west contact the dyke rock consists of plagioclase phenocrysts in a dominantly glassy groundmass with sparse groundmass plagioclase, with the former having a mean 'width' of 38 μ and the latter having a mean 'width' of 3.5 μ . Such plagioclase phenocrysts would correspond to cooling rates of 3°C/hour and the groundmass plagioclase to cooling rates faster than 10°C/hour. Due to the unreliability of the curve (fig. 7) at very slow cooling rates it can only be said that the plagioclase crystal 'width' of 86 μ at 21cm from the dyke contact could correspond to cooling rates slower than

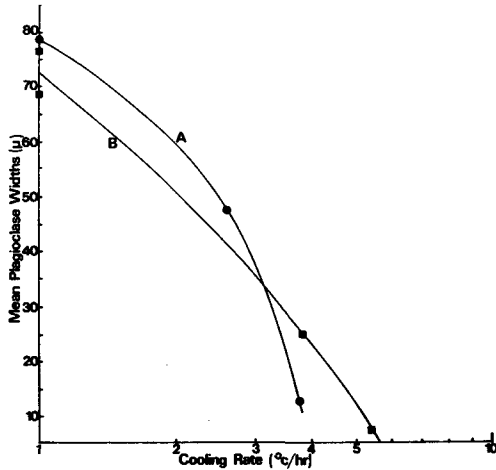


Fig. 5. Mean 'widths' of the twenty largest plagioclase crystals perpendicular to the (010) plane as a function of cooling rate for sample G.18. Each solid symbol refers to a charge. The charges (curve 'A', solid circles) were all quenched from $-\Delta T = 80 \pm 1^\circ\text{C}$ and the charges (curve 'B', solid squares) were all quenched from $-\Delta T = 112.5 \pm 2^\circ\text{C}$.

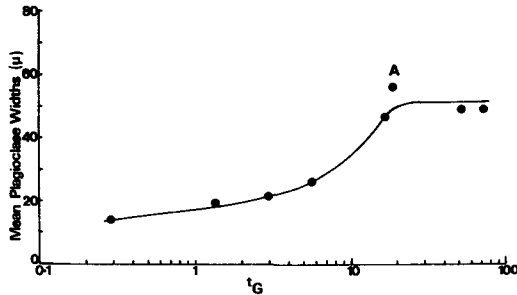


Fig. 6. Mean 'widths' of plagioclase crystals (in some cases less than twenty crystals were measured as fewer crystals than this were observed in the charges) perpendicular to the (010) plane as a function of the total time spent in excess of that required for incubation and nucleation (t_G) for sample G.18. Each solid circle refers to a charge cooled at a rate of $2.3 \pm 0.5^\circ\text{C}/\text{hour}$.

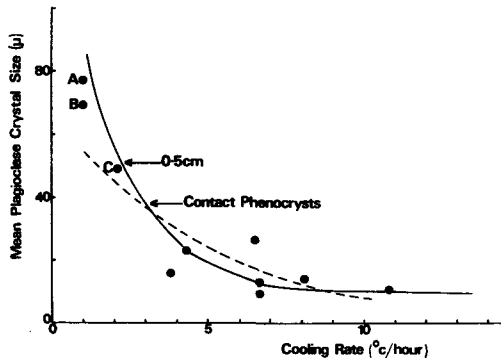


Fig. 7. Mean 'widths' of the twenty largest plagioclase crystals (perpendicular to the (010) plane) as a function of cooling rate for charges of sample G.18. Solid circles refer to charges cooled to less than 1024°C and quenched (except for charges 'A' and 'B' which are explained in the text). The diagram indicates at what cooling rate plagioclase crystals of a certain size could have grown at the contact and 0.5cm from the contact of dyke 2.

$1.5^\circ\text{C}/\text{hour}$ and that the plagioclase crystal 'width' of 150μ at 201cm from the dyke contact could correspond to cooling rates slower than $1^\circ\text{C}/\text{hour}$.

Conclusions

It is apparent from the experiments reported above that the duplication of coarse-grained rocks (i.e. at constant cooling rates slower than $1^\circ\text{C}/\text{hour}$) is difficult because of the long cooling times and large sample sizes which would be necessary. The constant rate cooling experiments on sample G.18 from dyke 2 have shown, however, that sizes of crystals found to occur naturally in dykes can be reproduced in realistic times in the laboratory.

VALUABLE RATE COOLING EXPERIMENTS

Reproduction of crystal sizes

These experiments were conducted to try to duplicate the cooling conditions predicted for each dyke by the Jaeger (1957) cooling model as closely as possible. The model is based on the following assumptions: firstly, the intrusive body has the form of a flat sheet of thickness 'd' in one direction and it extends indefinitely in the perpendicular directions, with the country rock extending indefinitely on either side at a constant temperature, which is taken as 0°C ; secondly, intrusion takes place very rapidly, with the magma being intruded at a constant temperature (this temperature is taken as the liquidus temperature of the composition concerned); thirdly, the thermal properties of the country rocks and the solidified magma are considered to be the same and to be independent of temperature; fourthly, the loss of heat due to escaping volatiles is ignored; fifthly, the effects of convection in the magma are ignored and cooling is assumed to be only by conduction into the wall rocks. For a full description of this theoretical model (including the equations used) the reader is referred to Jaeger (1957). In order to try to update the numerical values used by Jaeger (1957) and to differentiate between the thermal properties of the liquid and solid magma, most of his input parameters were replaced by more recent and appropriate data (Table II). The liquidus temperature for each of the compositions used was determined experimentally. Due to the extreme difficulty in identifying accurately the small quantities of glass in experiments heated to just above the solidus temperature and hence in determining the solidus temperature, approximate values were determined from isothermal supercooling experiments (Corrigan, 1980). These latter experiments showed that for sample G.1 there was less than 10% glass at 1100°C ($-\Delta T = 158^\circ\text{C}$), for sample G.18 there was no detectable glass at 1024°C ($-\Delta T = 145^\circ\text{C}$) but about 10% glass at 1044°C ($-\Delta T = 125^\circ\text{C}$). In view of the uncertainty surrounding the solidus temperatures, three values have been used for each of the dykes in the calculations to cover the whole of the likely range. The latent heat

Table II. Numerical Values used in the Jaeger Cooling Model.

Parameter	Rock	Liquid Magma	Parameter	Solid Magma
Density ρ_2 (gm/cm^3)	G.1	2.85	ρ_1	2.88
	G.18	2.92		(b)
(a)				
Total Specific Heat c_2	G.1	0.3	c_1	0.25
(c)	G.18	0.3	(d)	0.25
Thermal Conductivity	G.1	0.0068	K_1	0.00506
(e)	G.18	0.0061		(f)
K_2 ($\text{cal}/\text{cm}/\text{sec}^\circ\text{C}$)				

- (a) = The densities of the liquid magmas at their liquidus temperatures which were calculated using the method of Bottings and Weill (1970).
- (b) = This value is the one used by Jaeger (1957) for the density of the solid rock (the measured densities of the rocks ($2.6 - 2.7 \text{ gm}/\text{cm}^3$) are slightly lower and may not be the true values since the rocks have undergone a certain degree of weathering).
- (c) and (d) = These values were taken directly from Jaeger (1957).
- (e) = The values for the thermal conductivity of the liquid magmas at their respective liquidus temperatures were derived by extrapolation of the data compiled by Clark (1966).
- (f) = The value for the thermal conductivity of the solid dolerites was taken from Clark (1966) as this value was the most appropriate for the solid rock densities used here.

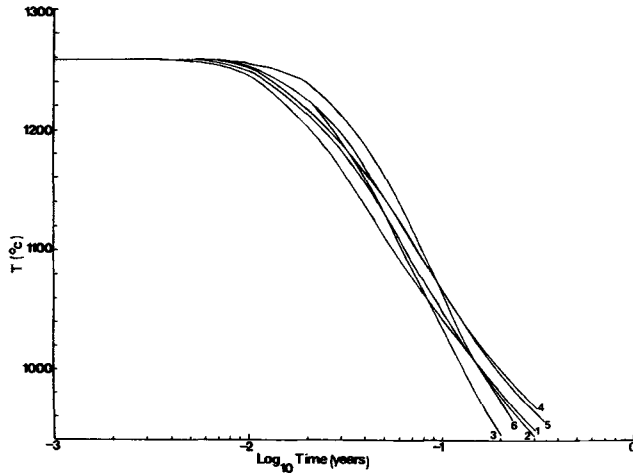


Fig. 8. Time/temperature curves for dyke 1 calculated for a point 101.5cm from the contact. The numbers on the curves refer to the case numbers (see Table III).

Dyke 1

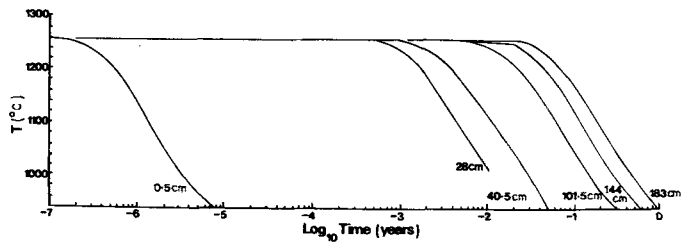


Fig. 9. Variation of temperature with time for six points in dyke 1. The distances of these points from the dyke contact are indicated on the curves. The curves are based on case 2 (Table III).

Dyke 2

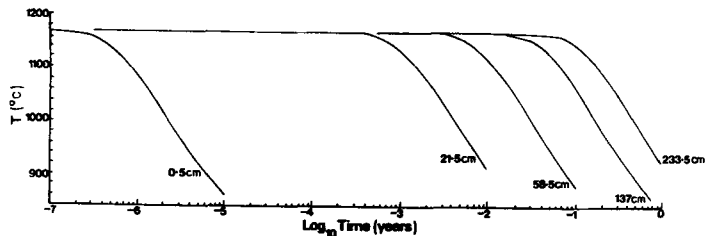


Fig. 10. Variation of temperature with time for five points in dyke 2. The distances of these points from the dyke contact are indicated on the curves. The curves are based on case 11 (Table III).

values of 80 and 100 cal/gm as used by Jaeger (1957) have been utilised here, since it is believed that such values are likely to form the maximum and minimum limits of the true range.

In the Jaeger cooling model several factors have been neglected which could well lead to errors in the predictions of the natural cooling rates of the two dykes studied. These include, firstly, the effect of superheating; secondly, possible preheating of the country rocks; thirdly, a decrease in the latent heat parameter with time as crystallisation proceeds; fourthly, changes in temperature due to the escape of volatiles, and fifthly, it was assumed that the injection of

magma was instantaneous and that it remained at a uniform temperature throughout its period of intrusion. These factors are discussed more fully elsewhere (Corrigan, 1980).

For the theoretical modelling of the cooling of the two dykes, twelve cases (Table III) were calculated to show how variation in the latent heat values and estimated solidus temperatures could affect the temperature/time curves (see fig. 8 for the dyke 1 data). For dyke 1 the near-contact rock G.1 was used, as the dyke shows some degree of differentiation and for dyke 2, which is more chemically homogeneous the central sample G.16 was used, so that any chemical changes due to

weathering would be reduced to a minimum. For the experimental modelling of parts of dykes 1 and 2 cases 2 and 11 were chosen as being closest to the estimated solidus temperatures, but the latent heat value (i.e. 100 cal/g^m) was chosen arbitrarily for reasons already stated. In figs. 9 and 10 the temperature/time curves are shown for cases 2 and 11 respectively for various values of x (i.e. distance from the dyke margin). It is clear from these curves that the centres of dykes 1 and 2 (figs. 9 and 10) had cooled by 1 to 2°C after 0.02 and 0.05 years respectively and that at 0.5cm from the dyke contact dyke 1 had cooled by 195°C after 63 seconds (11,142°C/hour) and dyke 2 by 150°C after 61.5 seconds (8,781°C/hour). At 28cm from the contact of dyke 1 195°C of cooling was reached after 56.1 hours and at 21.5cm from the contact of dyke 2 150°C of cooling was attained after 31.1 hours. A comparison of these cooling rates predicted by the Jaeger cooling model with the approximate linear cooling rates deduced previously suggests that the theoretically predicted rates are much too fast (by orders of magnitude for samples at distances of 0.5cm). Nevertheless, since parts of the two dykes can be cooled in times attainable in the laboratory, modelling of the theoretical cases 2 and 11 were undertaken for x = 0.5cm (for both dykes) and for x = 28cm for dyke 1 and for x = 21.5cm for dyke 2.

The limiting factor in duplicating the Jaeger cooling model experimentally for the centres of the two dykes was the smallest temperature interval that the electromechanical cooling rate device could cope with. At the slowest part of the cooling curve this temperature interval occurred after 53 minutes, therefore the temperature changes were calculated at 53 minute intervals and the cooling rates at these intervals were then determined. To try to duplicate the textures and grain sizes at 0.5cm from each of the two dyke contacts the furnace was switched off which gave uncontrolled cooling but was the only way to cool fast enough.

Figs. 11a and 11b show the calculated temperature/time curves (for rocks at 28cm and 21.5cm from the contacts of the two dykes) and the experimental temperature/time curves which were an attempt to duplicate

twinned, sometimes skeletal but more often non-skeletal plagioclases which were sometimes zoned; subsequent rosette spinel; a mafic phase(s) (olivine and/or clinopyroxene were too fine-grained for optical identification and there was not enough material for identification by x-ray diffraction), and less than 10% interstitial glass. The groundmass

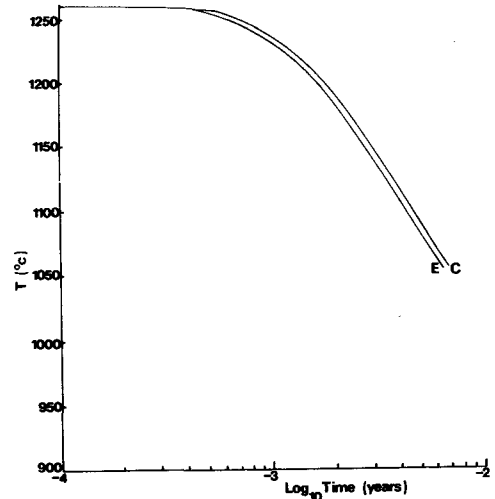


Fig. 11a. The experimental (E) and calculated (C) temperature/time curves for dyke 1 using case 2 (x = 28cm).

Table III. Parameters used for the Theoretical Modelling of the Cooling of Dykes 1 and 2 as Predicted by the Jaeger Cooling Model.

Case	T ₁ (°C)	T ₂ (°C)	Comments
1	1063.35	1258.35	Dyke 1 L = 80
2	1108.35	1258.35	Dyke 1 L = 80
3	1158.35	1258.35	Dyke 1 L = 80
4	1063.35	1258.35	Dyke 1 L = 100
5	1108.35	1258.35	Dyke 1 L = 100
6	1158.35	1258.35	Dyke 1 L = 100
7	991.52	1166.52	Dyke 2 L = 80
8	1016.52	1166.52	Dyke 2 L = 80
9	1066.52	1166.52	Dyke 2 L = 80
10	991.52	1166.52	Dyke 2 L = 100
11	1016.52	1166.52	Dyke 2 L = 100
12	1066.52	1166.52	Dyke 2 L = 100

T₁(°C) = Solidus Temperature

T₂(°C) = Liquidus Temperature

the former. In figs. 11a and 11b the time at which the temperature first decreased for both the calculated and experimental curves is taken as the same thus allowing for the lag time at the beginning of the cooling sequence at very slow cooling rates and also the thermal inertia of the furnace. The result is that the maximum discrepancy between the calculated and the experimental temperature/time curves, which was as much as 12°C without this correction, is reduced to 2 to 3°C, which is almost within the limits of error of the furnace temperature measurement. The temperature/time curves of the experiments for rocks at 0.5cm from the margins of the two dykes are shown in fig. 12, where the temperature readings were taken at two minute intervals.

For dyke 1 a characteristic feature of the experiments designed to duplicate the cooling rates predicted by the Jaeger cooling model at a distance of 28cm from the dyke contact is that, as in some of the constant rate cooling experiments, plagioclase crystallised in a bimodal size distribution. Since it is uncertain whether the larger crystals represent true phenocrysts or whether they are heterogeneously nucleated crystals (some are undeniably located in the vicinity of the supporting wire), those crystals were ignored in the crystal size measurements and only groundmass crystals were used. For dyke 1 two samples were run together and both were quenched from 1060°C (-ΔT = 198°C) after cooling as shown in fig. 11a. They contained lamellar

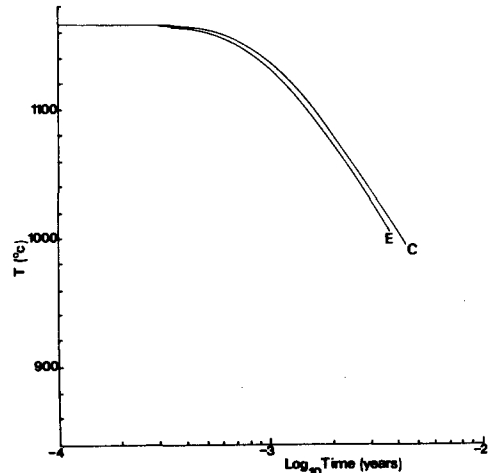


Fig. 11b. The experimental (E) and calculated (C) temperature/time curves for dyke 2 using case 11 (x = 21.5cm).

plagioclase 'width' was consistent in both charges (21μ and 19μ respectively). A comparison of the grain sizes of the natural rock at 28cm from the dyke contact and the recrystallised rocks produced in the experiment showed that the experiment had failed to reproduce the texture and grain size of the natural rock.

The two charges for dyke 2 run to try to duplicate the textural relationships at 21.5cm from the dyke contact were quenched from 1004°C (-ΔT = 162°C) and from 1014°C (-ΔT = 152°C) after cooling as shown in fig. 11b. Both the charges were holocrystalline and contained very dense clinopyroxene fan spherulites which were intergrown with thin acicular plagioclase laths. Trace amounts of an interstitial granular phase with second order birefringence (olivine?) were observed and iron oxides were present in skeletal form. The plagioclase crystal 'widths' in both charges were 3μ. A comparison of the grain sizes of

the natural rock at 21.5cm from the dyke contact and the recrystallised rocks produced in the experiment showed that the experiment had failed to reproduce the texture and grain size of the natural rock.

For dyke 1 charges of sample G.1 were quenched from 1027°C ($-\Delta T = 23^\circ\text{C}$) and from 962°C ($-\Delta T = 29^\circ\text{C}$) respectively after cooling as shown in fig. 12. Both charges were holocrystalline and consisted of exceptionally fine-grained intergrown fan spherulites of clinopyroxene and plagioclase accompanied by evenly disseminated rodlet and granular to subequant iron oxides. No olivine was observed. The charge quenched from the slightly higher temperature contained plagioclase with a crystal 'width' of 7 μ and the plagioclase crystal 'width' in the other charge was 1.3 μ .

For dyke 2 a charge of sample G.18 was quenched from 989°C

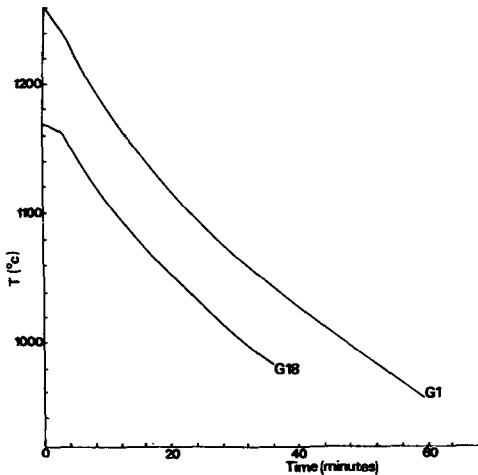


Fig. 12. Cooling profiles for samples G.1 and G.18 resulting from switching off the furnace power system.

($-\Delta T = 177^\circ\text{C}$) after cooling as shown in fig. 12, and the thin section of the bead was observed to consist of 95% glass with four fine-grained clinopyroxene fan spherulites occurring in a cluster in one part of the section. No plagioclase was observed. If the clinopyroxene fan spherulites were a result of homogeneous nucleation, this charge is direct evidence that at extremely fast cooling rates the liquid phase (plagioclase) may fail to nucleate in preference to the second phase (clinopyroxene).

For both dykes none of the charges produced at such fast cooling rates bore any resemblance to the natural dyke rocks.

Thus, a comparison of the experimentally produced charges with the appropriate natural dyke rocks indicates that they are quite different and thus the dykes must have cooled at much slower rates than the Jaeger cooling model predicts to attain their natural plagioclase crystal sizes. Further, the results confirm that the cooling rates predicted by the Jaeger cooling model are much too fast and are not compatible with the experimentally determined linear cooling rates. Clearly much longer experiment times than those indicated by the Jaeger model (i.e. slower cooling rates) are required to reproduce the natural dyke rocks by variable rate cooling and such times would be impractical in the laboratory. However, as a first approximation the much slower linear cooling rates determined for the dykes can be accepted.

FACTORS POSSIBLY INFLUENCING THE CRYSTALLISATION OF MELTS

Certain factors which could affect nucleation and growth in the experiments but do not apply to natural systems and equally others

which could affect these processes in the natural system but not in the experimental case must be considered as they could well result in differences in texture and grain size between the experimental and natural systems. The former include: firstly, the sample container used during the experiment and the mass ratio of the sample to the container (clearly the larger the sample mass relative to the container mass the less likelihood of heterogeneous nucleation); secondly, iron loss from the sample to the supporting wire which could act to change the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio of the melt (Corrigan and Gibb, 1979), and thirdly, iron loss from the sample to the supporting wire with the resultant release of O_2 which could alter the f_{O_2} . Factors of the second type include: firstly, the presence of a volatile phase during natural magmatic crystallisation which could significantly affect the resultant textural features (Lofgren and Donaldson, 1975) indicated that the nucleation rate could be increased by a little H_2O in the gas phase, and secondly, Buckley (1951) indicated nucleation could be promoted by turbulence which could be present during magmatic intrusion. In view of these factors some caution is necessary in drawing comparisons between recrystallised rocks produced in the laboratory and natural rocks.

CONCLUSIONS

The constant rate cooling studies have shown that the temperature at which liquidus plagioclase nucleates from the melt is dependent on the cooling rate, and that the length of the incubation period for both the liquidus phase and the second phase increase as the cooling rate decreases. At fast cooling rates the nucleation of certain phases may be suppressed and this phenomenon might offer an explanation for the absence of certain phases at the margins of intrusions.

Attempts to reproduce the textural relations of two basic dykes in constant and variable rate cooling experiments had only limited success. The dykes must have cooled at much slower rates than those predicted by the Jaeger cooling model, suggesting that the model is inadequate or that the dykes were continuously supplied with magma and acted as feeders for lava flows and/or sills.

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