
The Formation and Cooling of Dikes

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Introduction

When molten (igneous) rock forces its way, or is squeezed up, into a vertical or near-vertical crack in other rocks, be they flat-lying sedimentary rocks such as sandstone or shale, or folded metamorphic rocks such as schist or gneiss, or other igneous rocks, the crack is usually forced apart and the molten rock cools in the space to form a tabular igneous intrusion cutting across the surrounding rocks that is known as a dike (or dyke, depending on which country you live in!). The molten rock (magma) crystallizes as it cools, the most common dike rocks being diabase (or dolerite), basalt, and fine-grained granitic rocks. Although dike formation and magma cooling in dikes have not been observed and timed, prolific studies have still been directed towards understanding the mechanism of magma intrusion to form dikes and the timing of magma cooling in them.

Issues such as the rate of cooling of magmas are critical to young-earth creationists, since the timescales usually envisaged for the cooling of such large bodies of magma as granite batholiths are usually quoted in the order of from hundreds of thousands of years to tens of millions of years. Anti-creationists and theistic evolutionists have pointed to such apparent contradictions with the young-earth timescale, thus insisting that young-earth creationists and Flood geologists are “obviously” wrong and so their viewpoint is untenable. It is thus clearly appropriate that the data on these topics be reviewed. Dikes perhaps represent the simplest example of a cooling magma body because of their limited dimensions, and so are an appropriate place to start in our investigations.

Magma Intrusion

Szekely & Reitan (1971) maintain that the width of a dike places a limit on the possible vertical distance of magma transport (that is, the distance from the source of the dike material), provided that the

magma viscosity, and the temperature and thermal properties of the surroundings and the magma, are known or can be estimated. In many cases dike compositions indicate that the source of the magmas is the lowermost crust or uppermost mantle. The geological environment of emplacement may then dictate a distance of transport of only about thirty kilometers.

In order to define the combination of variables compatible with dike formation by magma intrusion, Szekely & Reitan considered a simplified physical picture, as shown in Figure 1. A fissure through the earth's crust is represented by a rectangular slot of width W , which connects a magma chamber or source (with the magma at $h=0$ when $t=0$) to the free surface at $h=H$. At time $t=0$, which corresponds to

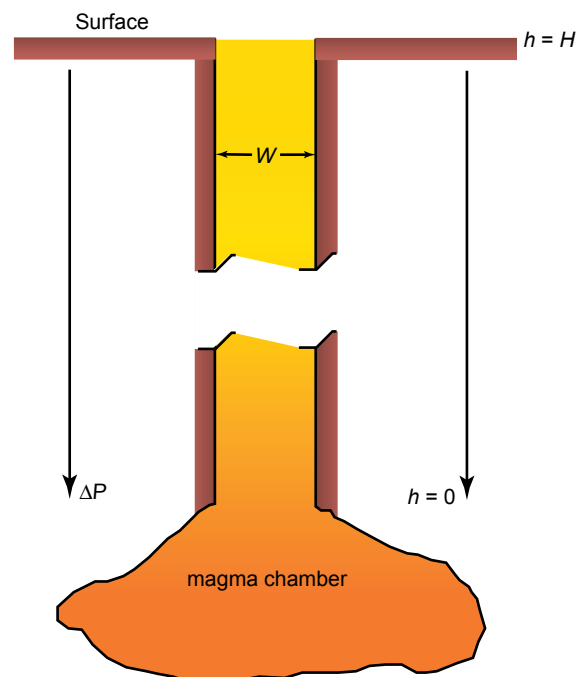


Figure 1. Physical model for the intrusion of a dike into a fissure from a magma chamber at depth below the crust (after Szekely & Reitan, 1971).

the opening of the fissure, the static pressure acting on the magma ΔP will force the magma upward through the fissure.

As the magma rises it encounters wall rock of progressively lower temperature. The resultant heat loss causes a substantial increase in viscosity and at least partial crystallization. The increase in viscosity, the partial blockage of the slot, and the reduction in the effective driving force will hinder upward flow. Should crystallization be completed before the free surface (or any other elevation of h above the magma chamber that is of interest) is reached, the mechanism is ruled out for the given geometry.

A rigorous formulation of the problem, where allowance is made for the two-dimensional nature of the velocity and temperature fields, and simultaneously, account is taken of the interaction of the velocity field with rate of crystallization and inward-moving (from the walls of the fissure) solidification front, results in a rather complex set of partial differential equations. Thus Szekely & Reitan considered it preferable, at least as a first approximation, to examine the asymptotic behavior of the system. They first considered the rise of magma in a rectangular slot without crystallization and developed expressions relating the rate of rise of the magma toward the free surface to other parameters, such as width of the slot, viscosity, etc. Then they determined the time required for complete crystallization as a function of dike width, for given values of the latent heat of fusion and the difference of temperature between the wall rock and the solidus temperature of the magma (that is, that temperature at which the originally liquid magma has completely solidified).

Using the parameters already depicted in Figure 1, at $t=0$ magma enters the slot from the magma chamber and is forced upward owing to the pressure of the overburden acting on the walls of the magma chamber. To describe the rise of the magma within the slot, Szekely & Reitan made the following assumptions:—

1. the flow is laminar throughout;
 2. entrance and inertial effects can be neglected;
 3. there are no radial gradients within the slot;
 4. for the effect of gradual cooling of the magma throughout its rise, the viscosity can be considered as a given function of the vertical position h , varying over a specified permitted range;
- and
5. frictional heat generated by viscous flow can be neglected.

Although restrictive, the assumptions represent a reasonable compromise between faithful representation of reality and the desired mathematical simplicity. Assumptions 1, 2, and 5 can be justified in

hindsight from their computed results, which show that the rise time is only significantly affected by the passage of the magma in the upper portion of the slot, where the assumptions would appear to be valid. Assumption 3 is very reasonable for most cases, in view of the fact that the ratio between H (the height the magma rises from the magma chamber to the free surface) and W (the width of the dike) is very much greater than 1.

Within the framework of these assumptions and their physical model, Szekely & Reitan concluded that the position of the top of the magma within the slot is readily described by a first-order differential equation which relates the rate of rise of the magma to the width of the dike, the static pressure due to the overburden load, the magma density, the acceleration due to gravity, the distance risen by the magma, and the position-dependent viscosity. The variation of viscosity as a function of position in the crust is dependent on the following facts:—

1. the viscosity is an exponential function of temperature;
 2. the ambient temperature increases with depth;
- and
3. viscosity is dependent on pressure, which increases with depth.

After integration of their first-order differential equation, Szekely & Reitan derived a simplified equation which they then used to perform computations, substituting in appropriate property values:—

- the static pressure, $\Delta P = 8 \times 10^9$ dynes cm^{-2}
- the magma density, $\rho = 2.7$ g cm^{-3}
- the viscosity at $h=0$, $\mu_0 = 10^5$ g $\text{cm}^{-1} \text{sec}^{-1}$
- the viscosity at $h=H$, $\mu_H = 10^{10}$ g $\text{cm}^{-1} \text{sec}^{-1}$

Their computations were then used to construct curves relating the time of rise of the magma to the width of a dike for six different heights above the top of the magma chamber (Figure 2). Also shown in this figure are curves relating time required for complete crystallization to the width of a dike, for two different values of the latent heat liberated by crystallization.

In their computation of the time of crystallization, Szekely & Reitan assumed that heat transfer is by conduction only and solely in the direction perpendicular to the dike in a semi-infinite medium. Parameters used were:—

- the thermal diffusivity of the magma 4×10^{-3} $\text{cm}^2 \text{sec}^{-1}$
- the thermal diffusivity of the surrounding rock 6×10^{-3} $\text{cm}^2 \text{sec}^{-1}$
- the initial temperature of the magma, taken to represent the liquidus temperature (the lowest temperature at which the magma is still totally liquid) 1200°C

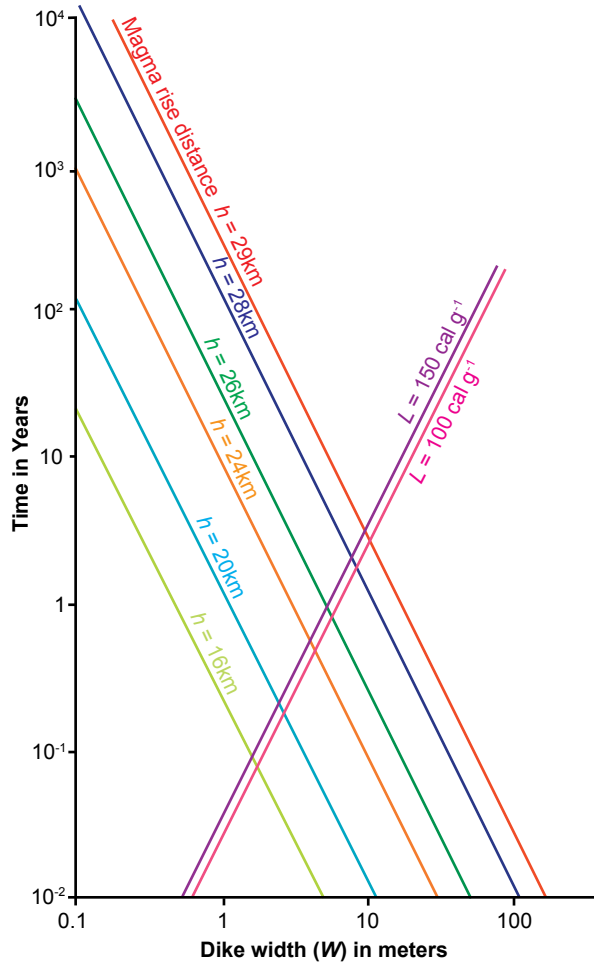


Figure 2. Graph showing the time of rise of magma versus dike width W , with height of rise of the magma through the earth’s crust as the parameter h , and also time of complete crystallization versus dike width, with the latent heat of crystallization as the parameter L (after Szekely & Reitan, 1971).

- the temperature at which crystallization is assumed to be completed 1000°C
- the latent heat of fusion liberated uniformly over the temperature range 1200°C to 1000°C 150 or 100cal g^{-1}
- the initial temperature of the surrounding rock 600°C

These assumptions made by Szekely & Reitan avoid **underestimating** the time required for complete crystallization.

Assessing the results as plotted on Figure 2, it should be noted that the region to the lower left of the lines labeled with values of h is ruled out, as the magma would not have reached the height in the time available. Similarly, the region to the upper left of the lines labeled with values of L (the latent heat) is ruled out, since complete crystallization of the dike will have occurred. Critical limiting values of dike width for any combination of latent heat fusion and height above the magma chamber are given by the intersections of the

lines. The locus of such intersections, relating height of rise of magma to dike width for values of L , is shown in Figure 3. The curves define an “impossible” region to the upper left and a “feasible” region to the lower right.

Of particular interest are the timescales involved in the rise of the magma from the considerable depths of the lowermost crust and for crystallization to occur. Since the region to the left of the lines labeled with values of latent heat L is ruled out, this imposes a **maximum** time for the rise of a magma into a fissure and subsequent crystallization. Taking the critical limiting values of dike width for any combination of latent heat fusion again (but this time the intersections of the lines give the timespans involved) the locus of such intersections, relating time of rise and crystallization to dike width for values of L , is shown in Figure 4. Again, the curves define an “impossible” region to the upper left and a “feasible” region to the lower right.

Comparing Figures 2 and 4, it is thus possible to calculate that for a dike of width 12 meters, the time taken for the magma to rise from a depth of around 29 kilometers and then crystallize is definitely less than five or six years, and probably less than three years. Significantly, most dikes are narrower than twelve meters, so this represents a limiting timespan for dike formation. Furthermore, Szekely & Reitan concluded that their approach, and their selection of values for

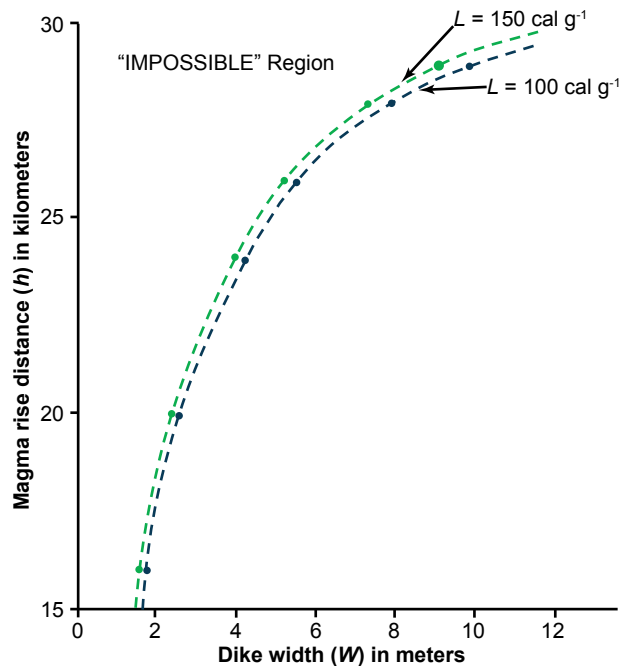


Figure 3. Graph showing the locus of intersections of height of rise of the magma h versus width of the dike W in Figure 2, defining an “impossible” region above and/or to the left of the curves and a “permitted” region below and/or to the right of the curves (after Szekely & Reitan, 1971).

their computations, tended to underestimate.

At dike widths greater than 12 meters, Szekely and Reitan's analysis appears to be inadequate. On Figure 2 it can be seen that it is impossible to relate the height of the magma rise parameter to the time and width parameters, but even a dike as wide as 100 meters, ignoring the height of rise parameter, can be seen, according to the graph, as taking less than 300 or 400 years to form and crystallize.

Cooling Times

In an earlier study, Jaeger (1957) modeled the cooling by conduction of an intrusive sheet of magma—a dike (or sill, in the case of a horizontal sheet)—taking into account the effect of heat of solidification. As in any analysis of this type, a number of general assumptions must be made. Jaeger assumed that:—

1. the intrusive body is in the form of a flat sheet extending indefinitely in the perpendicular direction—a reasonable approximation to most dikes.
2. the intrusion takes place rapidly, that is, in a time which is very short compared to the time of solidification.
3. the country rock is at constant temperature which will be taken to be zero. (If it is not zero, Jaeger concluded that the results of his analysis should be added to the initial country rock temperature.)
4. the magma is supposed to be intruded at a constant temperature, which, for simplicity, will be taken to be the liquidus temperature appropriate to its composition. (There is good geological evidence that this is frequently the case.)
5. the thermal properties of the country rock and solidified magma are the same and are independent of temperature. (This assumption was again made for simplicity, but it is a reasonable one in view of the uncertainty of these quantities.)
6. heat removed by escaping volatiles need not be considered. (Since the effects of volatiles are dispersed over a region whose thickness is many times that of the magma sheet, it is reasonable to assume that the heat conveyed by them is also dispersed over a large region and so will make little contribution to the temperature in the narrow region which is heated by conduction from the cooling sheet.)
7. the effects of convection in the magma can be neglected and cooling is by conduction only.

After developing a numerical solution from first principles, Jaeger presented his results as families of curves of temperature against time. Solutions for three typical cases are presented in Figures 5, 6,

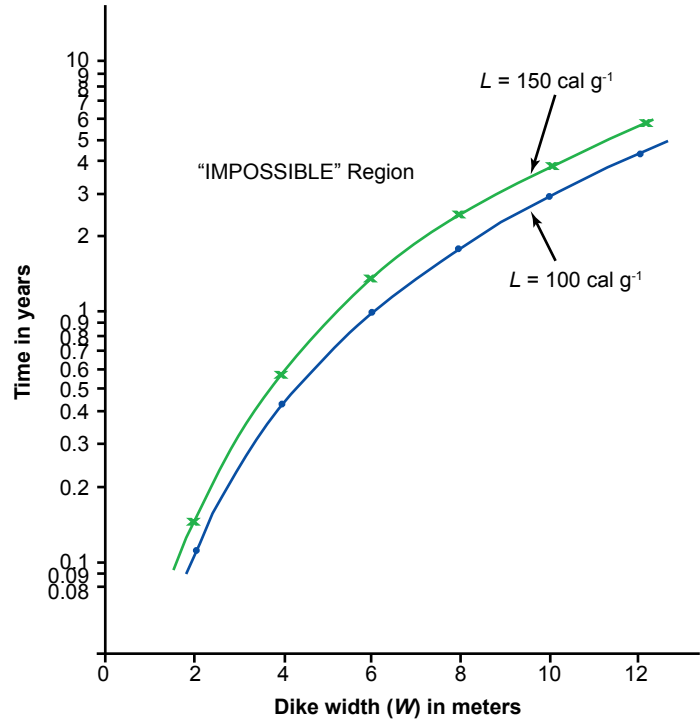


Figure 4. Graph showing the locus of intersections between time in years for rise and cooling of the magma versus width of the dike W as derived from Figure 2, again defining an "impossible" region above and/or to the left of the curves and a "permitted" region below and/or to the right of the curves.

and 7. In each case the temperatures are plotted as functions of the time in years for selected points of the dike, measured from the centre of the dike as distances $0, 0.1D, 0.2D, 0.3D, \text{ and } 0.4D$ (in the dike), $0.5D$ (which is the edge of the dike and the contact with the country rocks), and then $0.6D, 0.7D, 0.8D, 0.9D, \text{ and } 1.0D$ (in the country rock), where D is the thickness of the dike in meters. The timescale is expressed as a factor of D^2 .

Figure 5 represents the family of cooling curves for a typical granitic dike, where the temperature of the magma at the time of intrusion $T_2 = 700^\circ\text{C}$, the temperature of solidification $T_1 = 500^\circ\text{C}$, the latent heat of solidification (or fusion) $L = 80 \text{ cal g}^{-1}$, and the density of the magma $\rho = 2.7 \text{ g cm}^{-3}$. The cooling time for complete crystallization (or solidification) is the time taken for the temperature of the magma at the center of the dike to fall from its initial temperature T_2 to the temperature of solidification T_1 . In this case it is the time taken for the magma at the center of the dike to fall from 700°C to 500°C , and can be read directly from the graph as $0.016D^2$ years, where D is the thickness of the dike. Thus a granitic dike one meter wide would take 0.016 years to crystallize, a two meter wide granitic dike would take 0.064 years, a five meter wide granitic dike would take 0.4 years, and a ten meter wide granitic dike would take 1.6 years to crystallize, etc.

However, this does not take into account complete cooling to ambient temperatures from the temperature of crystallization of 500°C. Once the granitic dike reached that crystallization temperature at its center, it would then take still further time for the dike and the surrounding country rock to cool right down again to ambient temperatures. This of course is depicted in the diagram by the partial extension of the family

of curves beyond the time of crystallization. If the curves are projected (extrapolated) even further until the dike is completely cooled, the time taken would appear to be about $0.09D^2$ years. In the case then of a ten meter wide granitic dike, complete cooling would appear to take about nine years.

Figures 6 and 7 correspond to a typical diabase (dolerite) dike. In Figure 6 the initial temperature of the magma T_2 is 1000°C, while in Figure 7 it is 1100°C. Otherwise, the other parameters—the

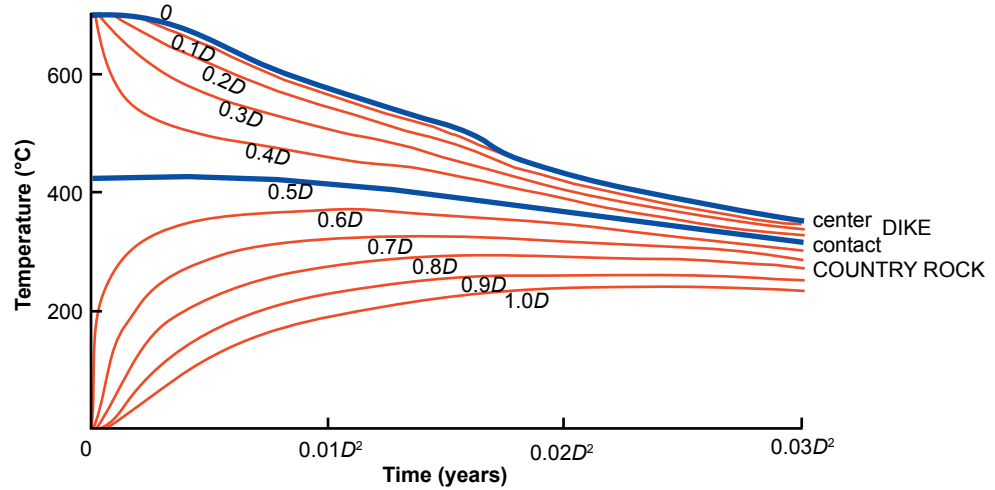


Figure 5. Graph showing the family of curves for the cooling history of a dike of thickness D meters for which the intrusion temperature is 700°C, the solidification temperature 500°C, and the latent heat of solidification is 80 cal g^{-1} . The labels on the curves are partial distances from the center of the dike measured as fractions of the thickness D (after Jaeger, 1957).

temperature of solidification $T_1=800^\circ\text{C}$, the latent heat of solidification $L=100\text{ cal g}^{-1}$, the density of the magma $\rho=2.8\text{ g cm}^{-3}$ —are the same in both examples. The times for complete solidification (crystallization) are $0.012D^2$ and $0.014D^2$ years respectively. Thus, a dolerite dike intruded at a temperature of 1000°C which is one meter wide would take 0.012 years to cool to 800°C, a two meter wide dike would take 0.05 years, a five meter wide dike would take 0.3 years, and a ten meter wide dike would take 1.2 years, etc. Similarly, a diabase dike one meter wide intruded at 1100°C would take 0.014 years to cool (crystallize completely) to 800°C, a two meter wide dike would take 0.056 years, a five meter wide dike would take 0.35 years, and a ten meter wide dike would take 1.4 years, etc.

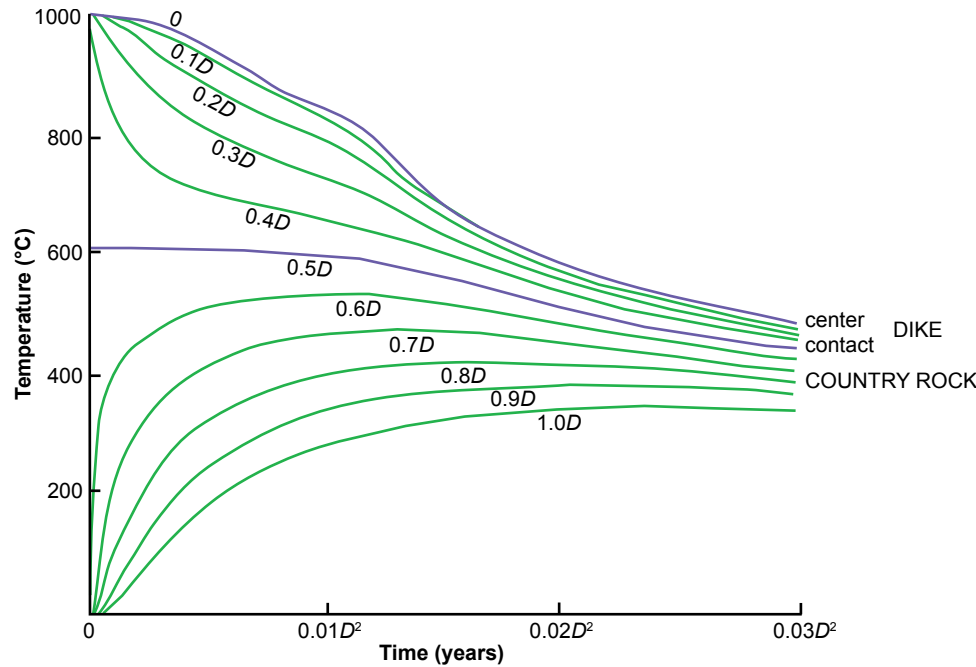


Figure 6. Graph showing the family of curves for the cooling history of a dike of thickness D meters for which the intrusion temperature is 1000°C, the solidification temperature 800°C, and the latent heat of solidification is 100 cal g^{-1} . The labels on the curves are distances from the center of the dike measured as fractions of the thickness D (after Jaeger, 1957.)

Again, the dikes need to then cool from 800°C to ambient temperatures, and so some further time is needed for complete cooling. If the families of curves are again projected until the dikes are completely cool, the time taken in both the examples of Figures 6 and 7 would again be

about $0.09D^2$ years. Thus a ten meter wide diabase dike would also appear to take about nine years to completely cool.

The results set out in Figures 5, 6, and 7 apply to deeply buried dikes, where the magma has not reached the surface and there is a considerable amount of rock cover above the top of the dike. Of course, nearer the surface cooling will be more rapid, so the results of this analysis represent an upper time limit on crystallization. In any case, Jaeger concluded that his results should be applicable at depths below the surface greater than the thickness of the dike.

In a subsequent study, Jaeger (1968) confirmed his earlier calculations and results. His additional comments are of importance here too. For example, he states that if volatiles (principally gases) are liberated on solidification and escape rapidly (for example, through cracks), the heat carried by them away from the dike will have the effect of accelerating the process of cooling of the dike. Additionally, if the dike has intruded into sediments or metamorphic rocks that are wet, because of either ground or pore water, the effect will be to lower the contact temperatures by amounts of up to 50°C and slightly shorten the times of solidification and complete cooling.

Jaeger also reported a simplified expression for cooling time, which encompasses all the relevant parameters:—

$$\tau = \kappa t / a^2$$

where

τ is a Fourier number or dimensionless time;

κ is the thermal diffusivity (and accounts for thermal conductivity, magma density and the specific heat);

t is the time in years; and

a is half the width of the dike ($D=2a$).

Substituting in what Jaeger described as a reasonable value for κ ($0.01\text{cm}^2\text{sec}^{-1}$), and rearranging the equation to calculate cooling time, he found that

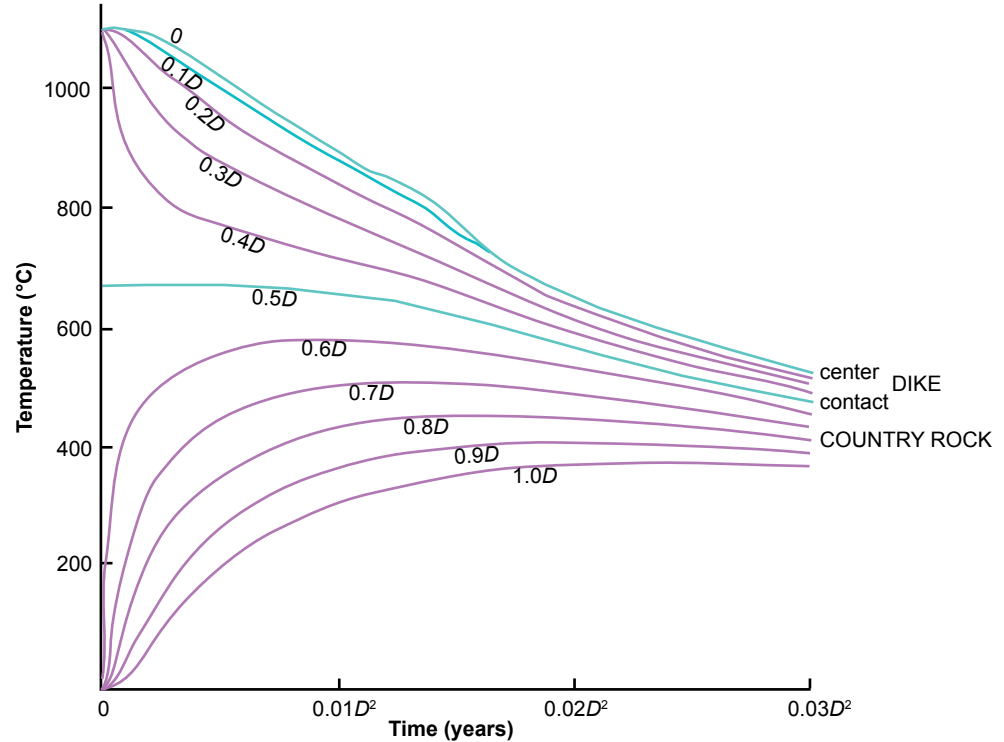


Figure 7. Graph showing the family of curves for the cooling history of a dike of thickness D meters for which the intrusion temperature is 1100°C , the solidification temperature 800°C , and the latent heat of solidification is 100calg^{-1} . The labels on the curves are distances from the center of the dike measured as fractions of the thickness D (after Jaeger, 1957).

$$t \approx \frac{\tau a^2}{31.5}$$

Furthermore, he suggested that for $\tau < 0.01$ cooling is only superficial; for $\tau = 0.1$ it will have penetrated to the center of the dike; for $\tau = 1$ there is substantial cooling at the center; and for $\tau > 10$ cooling is practically complete. Consequently, if a value of τ for complete cooling is set at twelve, then a ten meter wide dike ($a=5$) would cool completely in approximately 9.5 years, a similar estimate to the extrapolation of Jaeger's families of curves.

A Field Example

The calculations and results reviewed here, derived as they are from theoretical considerations and first principles, have successfully been used in practical situations where they correlate well with other field observations.

Perhaps one of the most unusual field examples of dikes are those studied by Wiebe (1973) along the northern coast of Cape Breton Island, Nova Scotia, Canada. At this locality are found a number of dikes, some consisting of homogeneous basalt, and some of homogeneous granite, but yet others consisting of a composite granite-basalt mixture. The latter are unusual, since basaltic and granitic magmas are not normally known to co-exist like this. The geological setting of these composite dikes allows reasonable

estimates to be made of the time required for solidification of each magma. Indeed, the solidification time had to have been short, otherwise the basaltic and granitic magmas in these composite dikes would have begun to mix, which the field observations, petrographic observations, and geochemical analyses indicate has only just begun on a very small scale.

Wiebe observed that at least one of these composite dikes varied gradually over a distance of 25 meters along its length from homogeneous basalt, to pillowed basalt (rounded blobs of basalt that look like pillows) with granitic veins between the pillows, to granite with less than 50% pillow-like inclusions of basalt. In all the composite dikes, mixing of the two magmas appears to have formed by a progression from simple curved contacts to intimate granite veining of the basalt, to ultimate subdivision of basalt into smaller pillows and lenses. These and many small-scale features suggest that the basalt and granite were magmas when they initially made contact with each other in the composite dike. Because the granite clearly remained mobile longer than the basalt, the latter must have cooled first, even though the basalt magma may have been intruded at a higher temperature than the granite.

Temperature and pressure in the country rock at the time of dike emplacement were difficult for Wiebe to estimate, the chilled margins of most dikes suggesting low temperatures and probably low pressures. The existence of the mineral hornblende in the basalt suggested load pressures greater than 1 kilobar (kb) were likely. Wiebe thus estimated the temperature of the country rock to have been 200°C and the pressure 2kb. Initial temperatures of the basaltic and granitic magmas would have been 1100°C and 750°C respectively, such high temperatures in the dikes thus ensuring that even if there was a variation of as much as 200°C in the temperature of the country rock, this would affect the cooling times of these magmas by less than 50%. Mineralogical observations suggested that at the time of injection the temperatures of the magmas were slightly below these liquidus temperatures for each rock.

Wiebe then proceeded to use the standard cooling calculations of Jaeger as already outlined above. In so doing, he adopted Jaeger's values for the other properties of the magma and country rock. Other parameters used were an average dike thickness of 50cm (some portions of these dikes were over one meter wide), an average dike composition of about 70% granite and 30% basalt, an initial average temperature of the dike segments of approximately 850°C (even though the initial temperature of the basalt and granite magmas would have been 1100°C and 750°C respectively), solidification temperatures of the basalt and granite of 900°C

and 700°C respectively, a solidification temperature therefore of the dike as a whole of 700°C, an overall density of 2.6gcm⁻³, a thermal conductivity of 0.005calcm⁻¹sec⁻¹deg⁻¹, a specific heat of 0.28, and a latent heat of crystallization of 80calg⁻¹.

Based on the 70:30 ratio of granite and basalt, and the average initial temperature estimated at 850°C, solidification of the composite (or average) dike is thus assumed to have been complete when the 700°C isotherm reached the center of the dike, that is, when all the granitic component was solid. Using the methods of Jaeger and the conditions already specified, Wiebe thus calculated that the composite dike would have solidified completely in 27.8 hours, although he cautioned that this time must be considered only as an estimate value for a dike of homogeneous average composition and width, since it cannot be applied specifically to any point in the real dike. Portions of basaltic composition would have solidified more rapidly, and granite very near to the basalt would have solidified more slowly than this average value. Thus the calculated time of solidification based on the average initial temperature is probably a moderate overestimate of the actual time.

The basalt pillows particularly would have become solid much more rapidly than the granite host, and because of their discrete sizes a cooling history time frame can be calculated. A basalt pillow would have solidified when the 900°C isotherm reached its center, so in contact with a granite magma at 750°C the approximate time necessary for solidification of a pillow with a 5cm radius would have only been thirty-five minutes. Similarly, a pillow with a 10cm radius would have cooled in about 140 minutes. Thus Wiebe concluded that the 900°C isotherm would have reached the center of a typical pillow within less than one hour. He also found that these short time frames for cooling of both the basalt and granite magmas were supported by the geochemical data on the transfer during magma cooling of various elements between the basalt and granite components of these composite dikes.

Conclusions

For creationists the cooling times for fine-grained igneous rocks such as basalt and diabase (dolerite) have never been considered to be a real problem, although the time frames involved have never been really documented in the relevant creationist literature. This review therefore has endeavoured to supply this documentation of the cooling times involved in such thin igneous bodies as dikes.

We have seen that by the application of standard cooling theory for solid bodies, the time frames involved are indeed relatively short, and that even for a granitic dike ten meters wide, which is fairly rare,

the cooling time for crystallization (solidification) to occur is only of the order of 1.6 years, and cooling to ambient temperatures is completed in about nine years. It is also good to see that these estimates are confirmed by field studies such as the example cited. Since the intrusion of dikes into other rocks is an event which can be much later than the formation of the rocks into which the dike intrudes, dike formation in many instances could still have occurred after Noah's Flood, so these time frames greater than the duration of the Flood year do not generate an additional problem. We have also seen that even the time taken for a magma to rise from depths as much as thirty kilometers down in the earth's crust and crystallize is also only a matter of a few years.

While such thin bodies of igneous rock would appear to be a simple solvable challenge for creationists, they provide the easiest place to start in this whole

investigation of the cooling of igneous rocks. Further studies will need to delve into the cooling times for larger bodies of igneous rock, such as one kilometer thick sills and granite batholiths up to tens of kilometers wide.

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