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PAUCITY OF MAFIC RING-DIKES—EVIDENCE FOR FLOORED POLYMAGMATIC CHAMBERS

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ABSTRACT. A common misunderstanding of the buoyancy principle has led geologists to believe that mafic ring-dikes are rare because lighter felsic blocks will not sink in heavier mafic melt.

It is shown that according to the conventional concept of a monomagmatic chamber mere density difference between country rock and magma is not directly the controlling factor, for if it were, mafic ring-dikes would be the rule and not the exception.

If a polymagmatic chamber is postulated with an upper layer of felsic and a lower of mafic melt, the chances of forming mafic ring-dikes in contrast to felsic ones are greatly reduced. But the chances are still in favor of mafic ring-dikes even when the most favorable realistic density relations are assumed.

The most significant problem regarding ring-dike genesis, which has never been explained, is why the subsiding central block, after once being released by a ring-fracture in the roof zone, is brought to a halt in time for a ring-dike to form. In an attempt to solve this problem, an explanation for the paucity of mafic ring-dikes is also found.

The simplest and perhaps most logical solution appears to be that the magma chamber has a floor only a short distance below its roof and that the subsiding block comes to rest upon this floor or upon a layer of xenolithic debris deposited on it.

INTRODUCTION

There appears to be a common misunderstanding by geologists in dealing with the formation of ring-dikes about the behavior of large blocks of country rock set free from the roof zone above magmas of different densities. Illustrative of the consequences of this misunderstanding is the idea, commonly expressed or implied, that mafic ring-dikes are rare features because felsic blocks freed by ring-fractures will not sink in heavy mafic magma.

I agree that a felsic block would not sink *in* a heavier melt, but this does not mean it would not sink *into* such a melt. The distinction though apparently slight is fundamental and may be clarified by the analogy of the iceberg. A block of ice falling from the front of a glacier will not sink in the ocean but will sink until all but roughly one-ninth of its volume is covered. We commonly say the iceberg floats.

The problem appears to stem from the semantics of the word "sink". It seems advisable, therefore, to distinguish these two different concepts of sinking by more definitive terms. For the present, the expressions "to submerge completely" and "to submerge partially" may be more meaningful substitutes for the expressions "to sink in" and "to sink into" respectively. Again it seems advisable to employ the term "suspend" in preference to the term "float".

A rather typical example of the misunderstanding the writer has in mind is illustrated by Professor Wager's discussion of Turner's paper (1963, p. 365) on some Nigerian ring-structures. Here it is pointed out that "Ring-dykes of the form described in the paper . . . required that the central block should sink into the magma. For this to take place the magma must be of lower density than the subsiding block and therefore it was more likely to be of acid than basic type". Further, in his reply to Wager's comments, Turner (1963, p. 366) agrees ". . . that the absence of basic ring-dykes is the result of the high specific gravity of the magma . . . ".

Billings (1945, p. 56-57) also apparently felt that a low country rock-magma density ratio prevented the formation of mafic ring-dikes. He pointed out that in New Hampshire, ring-dikes apparently could not form until the magma had evolved to the stage where it had a lower density than that of the overlying rocks.

In the present paper the writer intends to examine the problem of ring-dike formation in the light of density control and frequency of petrographic make-up. A number of alternative postulated models will be examined. An attempt will be made to deduce the consequences of the principal limiting conditions involving different combinations of ring-fracture mechanics and magma type and to test the validity of each model by comparing the probable results with field observations.

The conventional model of ring-dike formation assumes the development of a ring-fracture in the roof rocks above a magma reservoir. Vertical displacement of the block bounded by the curved fracture is largely responsible for admission of magma along the fracture zone and the formation of the ring-dike.

In our discussion the following assumptions will be made:

1. The ring-dikes are magmatic.
2. The magma chamber is roughly circular in ground plan. It may have no inferrable floor, it may have a deep floor, or it may have a shallow floor.
3. The chamber may be monomagmatic and filled with either a felsic or a mafic melt, or it may be polymagmatic.
4. Ring-fractures lead to the formation of three types of central blocks: (a) cylindrical, (b) paraboloidal, and (c) inverted conical. Although the third type departs markedly from the ideal conical form, particularly in its lower portion, it seems best to retain the term "conical" to express this shape.
5. The central block of felsic rock is considerably heavier than the chosen felsic melts but slightly lighter than the chosen mafic magma.

Only a few of the aspects of ring-dike genesis can be treated here. Numerous further implications and problems will arise, but these are not germane and must be treated separately later.

DENSITY RELATIONS AND RING-FRACTURE CONTROL

Following Daly's (1933, p. 276) calculations let us assume the density of basaltic magma at 1100° C to be 2.70 g/cm^3 and that of granitic melt to be 2.32 g/cm^3. Let us take 2.68 g/cm^3 as a reasonable value for the average density of felsic rock at 20° C. Assume the average level of ring-dike formation to be 3 miles beneath the surface and the average temperature at that level to be roughly 150° C, then by interpolation we arrive at 2.66 g/cm^3 as the average density of the subsiding block. It should be noted that after subsidence the density of the central block may be reduced somewhat as the rock becomes heated by the adjacent melt. This thermal expansion is particularly important, as we shall see, in the case of small xenoliths whose density may be reduced to 2.56 g/cm^3. The above values hold for a confining pressure of one atmosphere. Since the compressibilities of rock and melt are roughly the same at the level with which we are concerned, the relative density values will not be greatly affected.

From these data it is apparent that a block of felsic rock would become completely submerged in granitic melt, but it would be suspended in basaltic melt with less than 2 percent of its volume standing above the heavier liquid. Although the density values used above are rather arbitrary, they are believed to be sufficiently accurate for the present purpose. The main point to bear in mind is that average felsic rock near the surface is at most only slightly lighter than basaltic melt and will, therefore, be suspended in the latter with all but a very small proportion of its volume immersed. In some localities of course the crustal rock may be heavier than mafic melt and will tend to be completely submerged in it. Such may have been the case at Mull (Bailey and others, 1924), Ardnamurchan (Richey and Thomas, 1930), and Mount Desert Island, Maine (Chapman, 1962).

In the present problem we will be concerned with what is a very general siutation in which the roof block above the magma chamber is believed to be completely freed by some type of ring-fracture. Until, in this rather ideal situation, the fate of the released block is satisfactorily understood, we need not concern ourselves with more special problems such as the origin of partial or incomplete ring-dikes.

To date three principal types of ring-fractures have been recognized: (1) cylindrical, (2) paraboloidal, and (3) conical; and it is believed that all three types have served to localize intrusions of the ring-dike type. The control of the first two types has become a classical concept since the early studies at Glen Coe (Clough, Maufe, and Bailey, 1909) and Mull (Bailey and others, 1924) in Scotland. Whereas the cylindrical and paraboloidal fractures will be treated as distinctly separate types, it is realized that there are probably all gradations between the two. Nearly complete paraboloidal fractures seldom develop, and the steeply dipping lower portions of paraboloidal fractures are usually truncated upward by gently inclined or horizontal cross fractures. Evidence for this opinion cannot be given here. A modification of the role of cylindrical fractures was suggested by Billings (1945, p. 52), and Reynolds (1956) has shown that ring-dikes may be controlled by cone-fractures. Although the writer agrees with Reynolds that cone-fractures have controlled the formation of many ring-dikes, the mechanism visualized by him is quite different from the one she proposes. Unfortunately, however, no explanation of this mechanism can be given in the present publication.

Let us now consider the behavior of felsic blocks formed by each of the three principal types of fractures in the roof rocks of monomagmatic chambers. First, consider chambers filled with a magma of felsic composition and lighter than the felsic block; later, consider chambers of mafic magma, a melt heavier than the felsic blocks.

FELSIC MAGMA CHAMBERS

In the first case let us assume a model magma chamber (fig. 1a) filled with felsic melt and well-fitted at the top with a cylindrical plug of felsic rock. Two possibilities arise: the chamber may remain tight or it may become vented to the surface. If the containing walls remain tight and no melt can escape along the cylindrical surface, the position of the plug will be controlled by the pressure of the melt within the chamber. Increased magma pressure, due for example to deformation of the chamber, will cause the plug to rise (fig. 1b); conversely decreased magma pressure will permit the plug to drop (fig. 1c).

If a small vent is drilled along the cylinder axis, purely for the purpose of determining the new level of the magma, a different situation is created (fig. 2a). The plug will now begin to settle as melt flows upward through the central vent (fig. 2b). Due to the higher density of the plug as compared with that of the felsic melt, the cylinder will fall completely free of the cylindrical opening and settle to the base of the chamber (fig. 2c). Such would be the fate of a sialic plug regardless of the magma pressure, provided of course the plug was not blown out of the cylindrical opening before it could settle. We should expect the same results if a cylindrical fracture formed above a felsic magma due to sudden change in chamber pressure and if the melt were permitted to escape upward along the fracture rather than along a central vent.

In the second case, if a paraboloidal fracture forms over the magma chamber (fig. 2d), the isolated block will settle as before to the base of the chamber and felsic melt will be displaced upward to fill the space vacated (fig. 2e, f). Once a paraboloidal fracture forms the block becomes unstable and will settle under any pressure conditions within the chamber.

In the third case, a steep cone-fracture might be formed in the roof rocks if the chamber pressure were sufficiently and suddenly increased (fig. 2g), and the fracture might be injected with felsic magma. Due to the higher density of the conical block, however, most of the felsic melt would be squeezed back out of the fracture as the conical block settled back into place (fig. 2h). At best then, only a thin or discontinous cone-sheet resembling a ring-dike at the surface would be apt to form. Considerable rubble caught along the fracture, however, might wedge the walls apart sufficiently to form a somewhat wider intrusion (fig. 2i).

Mechanisms exemplified by cases one and two would be more apt to lead to formation of felsic stocks than to ring-dikes because the subsiding block cannot be arrested in time. Although the mechanism represented in the third case might form a ring-intrusion (apparent ring-dike), the body would probably be very thin and perhaps discontinuous.

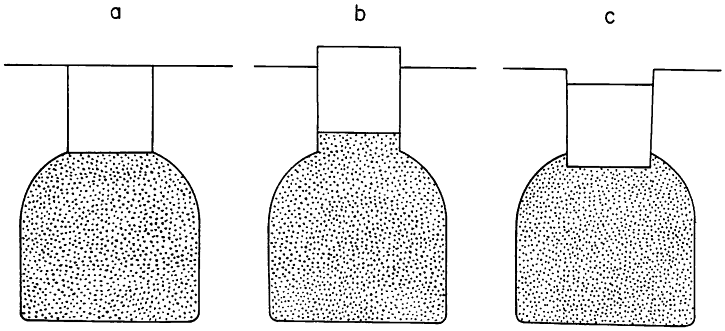

Fig. 1. Hypothetical, closed magma chamber tightly fitted with a cylindrical plug of felsic rock.

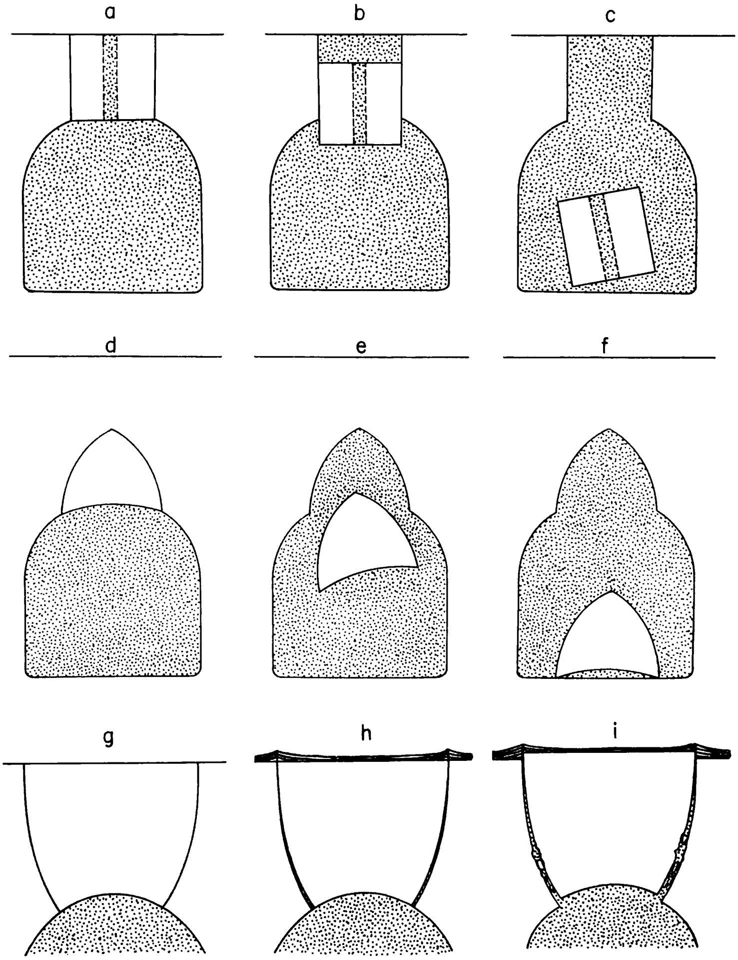

Fig. 2. Behavior of felsic blocks formed by ring-fractures above hypothetical chambers of felsic magma.

MAFIC MAGMA CHAMBERS

Again in the first case let us assume our model magma chamber (fig. 1), but this time filled with mafic melt. Here again the chamber may remain tight or become vented to the surface. When the plug is properly seated and no magma is permitted to escape, again we find the stable position for the plug will depend upon the pressure developed in the magma chamber.

If a vent is drilled along the cylinder axis, the mafic magma will flow up nearly to fill it. When the system is stabilized, the melt will fill all but less than 2 percent of the vent (fig. 3a). The cylindrical plug will be truly suspended in the mafic magma. The level of the plug however will depend on the chamber pressure. Increased magma pressure, due for example to deformation, would cause the plug to rise (fig. 3b), but the level of the melt within the vent would tend to remain fixed relative to the top of the plug. In other words the plug would still be suspended in the magma. With decreased magma pressure the plug would be lowered (fig. 3c).

If a complete cylindrical fracture or fracture-zone should develop above a mafic magma chamber, an adjustment between the cylindrical block and the heavier magma would be made to bring the mafic melt up along the sides of the block until it came to within a short distance of the top of the block. The felsic block would be suspended in the mafic melt. This vertical adjustment might come about by mafic melt forcing its way up the fracture and spreading

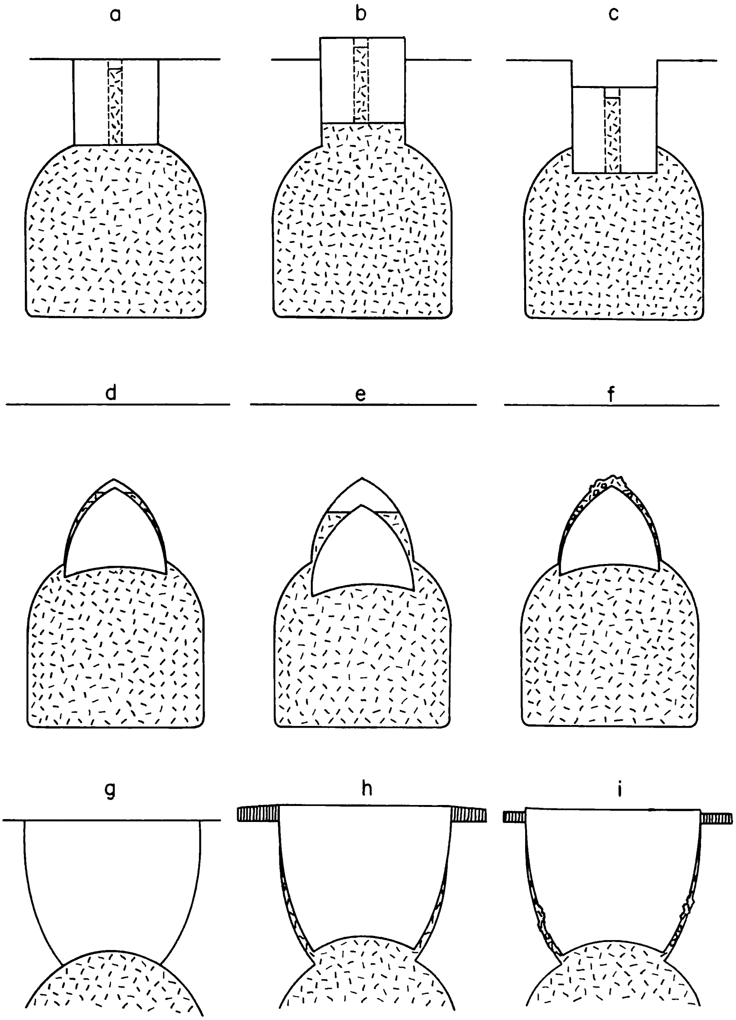

Fig. 3. Behavior of felsic blocks formed by ring-fractures above hypothetical chambers of mafic magma.

the walls apart or by piecemeal stoping along the fractured zone. Either mechanism could lead to formation of a vertical mafic ring-dike. The level at which the cylindrical block would finally come to rest would depend on the chamber pressure at the time the block became frozen in place as the ring-intrusion congealed.

In the second case let us assume a suddenly reduced pressure in the magma chamber and temporary loss of roof support so that a paraboloidal ring-fracture develops. Slight reduction of magma pressure over that necessary to hold the block in place would permit slight subsidence of the paraboloidal block and concomitant rise of mafic melt into the fracture so as to immerse the sialic mass almost completely (fig. 3d). Greater reduction of magma pressure would permit the block to subside farther (fig. 3e). Due to the tapering form of the fracture, mafic magma would come to within 4 percent roughly of the distance to the top of the paraboloidal block. Under these conditions, if the lowered pressure could be maintained long enough, the melt along the fracture could freeze to form a mafic ring-dike. If the melt in the open fracture did not completely crystallize before pressure was restored to raise the block again, then some would be squeezed back out of the fissure. Rock rubble caught along the open fracture, however, could prevent complete closing of the fissure and facilitate formation of a ring-dike (fig. 3f). Under proper conditions, therefore, ring-dikes of the paraboloidal type could be formed in the roof zone above a mafic magma chamber.

In the third case a suddenly increased chamber pressure might form a steep cone-fracture along which mafic melt could rise (fig. 3g). If the pressure were sufficiently intense and sustained, magma could rise and flood the land surface to build a thick layer of mafic flows (fig. 3h). The conical (more truly paraboloidal) block would be buoyed up less than 1 percent of its own height but would be raised an additional distance equal to the vertical thickness of the volcanic layer. This would permit formation of an apparent ring-dike. If the chamber pressure were insufficient to lift the mafic melt at least to the surface and hold it there until it crystallized, the block would settle back, squeezing out all the mafic material except that quickly frozen to the fracture walls. Rock rubble caught along the cone-fracture, however, could help to prevent the fracture from closing (fig. 3i).

Mechanisms exemplified by cases one and two would be more apt to lead to formation of mafic ring-dikes than to any other type of intrusion; the mechanism represented in case three would be likely to lead to formation of an apparent ring-dike.

From our analysis so far we might conclude that the conventional picture of a monomagmatic chamber and the mode of formation of ring-dikes do not harmonize with field observations. Based on the generally accepted theory, felsic magmas should greatly favor the development of stocks whereas mafic melts should form real or apparent ring-dikes. In other words felsic stocks and mafic ring-dikes should be the rule.

Finding the models of monomagmatic chambers inadequate, let us examine a more complex model, that of the polymagmatic chamber.

POLYMAGMATIC CHAMBERS

For many decades geologists have recognized the close association of felsic and mafic rocks in what are commonly called igneous central complexes. Furthermore, the coexistence of felsic and mafic melts in regions of igneous activity has long been recognized (Bunsen, 1851). The composite dikes and sills of the Scottish Tertiary province, made classic by Harker (1904), are forceful testimony for such coexistence. The coexistence of felsic and mafic melts formed the foundation for much of Daly's (1933) petrogenic reasoning. Holmes (1931) developed the concept of polymagmatic chambers most admirably and even applied it to the formation of ring-dikes. Unfortunately, however, this concept has played only a minor role in petrologic thinking over the last 35 years, and as a result virtually no progress has been made in solving the truly fundamental problem of ring-dike genesis.

If we accept the view that, by the time magma chambers reach the upper part of the Earth's crust, the heavier melt is capped by a layer of lighter felsic melt formed largely by fusion, we may be led to conclusions quite different from those just considered for monomagmatic chambers.

For this discussion we assume that the felsic and mafic melts are respectively granitic and basaltic in composition. The same general relations will hold, however, if a syenitic melt is substituted for the granitic one or if the basaltic melt is replaced by a slightly less mafic one. The essential requirement is that one melt be heavier and the other lighter than felsic rock.

Now let us consider the behavior of large roof blocks set free above our polymagmatic chamber by each of the three principal types of ring-fractures: (1) cylindrical, (2) paraboloidal, and (3) conical.

From what we have already seen, subsidence of cylindrical or paraboloidal blocks into felsic melt is readily accomplished. In a two-layer magma chamber with a felsic upper layer, subsidence could be initiated equally well, and the freed sialic block would settle through the felsic melt and into the mafic one far enough to attain hydrostatic balance (fig.4a to f). Upon coming to rest the block would be suspended mostly within mafic melt and only slightly within felsic melt. The amount of subsidence would depend on the amount of felsic melt in the chamber. After crystallization, erosion would most likely expose either a stock of granite or a ring-dike of mafic rock. Even under these conditions mafic ring-dikes and granitic stocks should be the rule so long as at least a little felsic melt occurs in the chamber prior to subsidence. The position of the felsic-mafic melt interface relative to the block depends upon the relative densities of the melts and block. As the density difference between block and mafic melt decreases and/or the density difference between the block and felsic melt increases, the block will become more deeply depressed into the heavier melt. On the basis of the density values suggested earlier, roughly 10 percent of the block volume will stand above the mafic melt. Thus the chances of forming a mafic ring-dike are very good, but those of forming a felsic ring-dike are very poor.

A steep cone-fracture or fracture-zone might free a large block of roof rock if a pressure increase developed suddenly in the magma chamber. Melt injected into this fracture would likely be drawn from the top of the magma chamber first and would therefore be felsic (fig. 4g). As we have already seen, only a thin or interrupted cone-sheet resembling a ring-dike at the surface would be apt to form because the heavier block would tend to settle back into place and extrude the lighter magma. If the increased magma pressure were prolonged, however, enough of the lighter melt might be driven from the chamber to permit mafic melt to enter the cone-fracture and raise the block sufficiently to form a thicker and more continuous intrusion (fig. 4h, i). Again it would be the mafic melt and not the felsic one that would form the better annular dike.

In conclusion it appears that ring-dikes formed above a two-layer magma chamber, like those formed above a monomagmatic chamber, would most like-

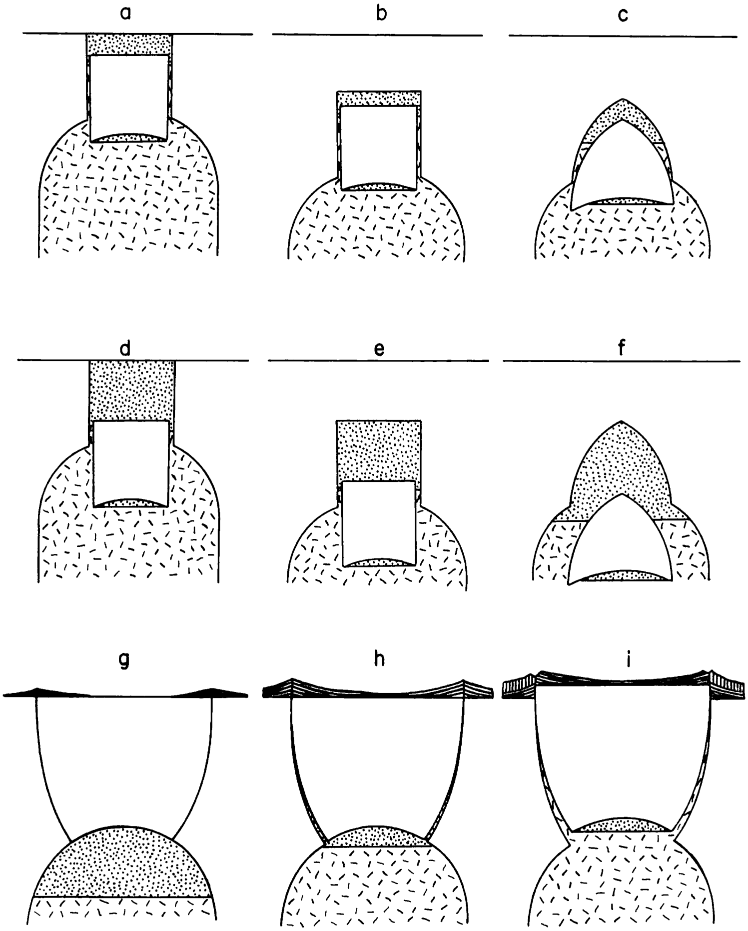

Fig. 4. Behavior of felsic blocks formed by ring-fractures above polymagmatic chambers. Felsic magma—stipple; mafic magma—dashes; felsic flows—ruled; mafic flows—vertically ruled.

ly be of mafic rather than felsic composition. Because the density of the subsided block is likely to be very close to that of mafic magma, the block is unlikely to be suspended high in the mafic melt. In many cases perhaps the block may even be heavier than the mafic melt and would become completely submerged. For a block to be suspended half immersed in mafic and half in felsic melt, its density would have to be half-way between those of the two melts.

Even assuming the block to have a specific gravity as low as 2.63 and the granitic melt as high as 2.40, the specific gravity of the mafic melt would have to be 2.86. But the value of 2.40 for the felsic melt is greater than that for cold obsidian, and the value of 2.86 for the mafic melt is as great or greater than that of most diabases and gabbros at the same temperature. More realistic maximum values might be 2.35 for the felsic and 2.80 for the mafic melt. Under these conditions we would expect the subsiding block to stop when three-fifths of its volume was immersed in the mafic melt. Only in such extreme cases, therefore, would the chances of felsic ring-dikes forming begin to approach those of forming mafic ones.

So far in our consideration nothing seems to lead to results comparable with those in nature, and it is obvious that something fundamental must be missing in our model.

In the foregoing analysis we have considered only one means, that of buoyancy, whereby a completely detached roof block may eventually be stabilized within the magma chamber. We have been led to believe, contrary to field observations, that mafic ring-dikes should be common features and perhaps much more common than felsic ones. The paucity of such mafic bodies may be due only in part to the fact that they may form at lower levels than felsic ones and may not be as frequently exposed by erosion.

In the case of cylindrical and paraboloidal blocks, subsidence may be limited by a major obstruction in the magma chamber. A common explanation of why the subsiding block comes to a halt is that of wedging along the ring-fracture. Although wedging would be extremely unlikely in the case of paraboloidal blocks with outward flaring boundaries, it is a feasible explanation in the case of some cylindrical blocks. Nevertheless, when we consider the large number of relatively wide and nearly complete ring-dikes, the wedge hypothesis is not good enough.

It is time now to take another look at our model of the polymagmatic chamber and to make some assumptions about a possible floor.

FLOORED MAGMA CHAMBERS

Two alternatives will be considered. (1) The subsiding block may come to rest on the floor of a shallow magma chamber or on a thick layer of xenolithic debris resting on the chamber floor. (2) The block may be stopped by a constructed floor consisting of a thick zone of inclusions incrusting the upper part of the mafic melt. Let us consider the second possibility first.

A constructed floor of xenolithic material could form along the mafic-felsic magma contact if stoping by the felsic melt, immediately prior to cauldron subsidence, had been extensive. Cold xenolithic material, showered down much faster than the mafic melt could sweep it away by convection or could destroy it by melting or reaction, could chill the top of the mafic melt and form a rather rigid crust or floor across the magma chamber. Such a mechanism is conceived to have been operative in the Scottish Tertiary province and in north central Nigeria. Accumulation of xenolithic debris near the top of the mafic melt would be enhanced as the smaller fragments, which had settled well into the mafic melt, were thermally expanded and buoyed up again.

This concept of an intramagma crust or floor has broad implications most of which must await later publication. For the immediate problem, however, such a floor appears to offer a reasonable solution. As the subsiding block comes to rest on the floor or on xenolithic debris piled on the floor, only a granitic melt is permitted to occupy the ring-fracture, mafic melt having been sealed off by the floor below (fig. 5a to c).

Repeated subsidence and ring-fracturing might result from: (1) readjustment in the loose breccia layer above the floor, due to settling and closer packing of fragments under the weight of the huge subsided block; (2) rupturing of the xenolithic crust under the load of the subsided block; (3) weakening of the xenolithic crust by fusion or reaction with the underlying magma; and (4) pressure changes in the underlying magma chamber.

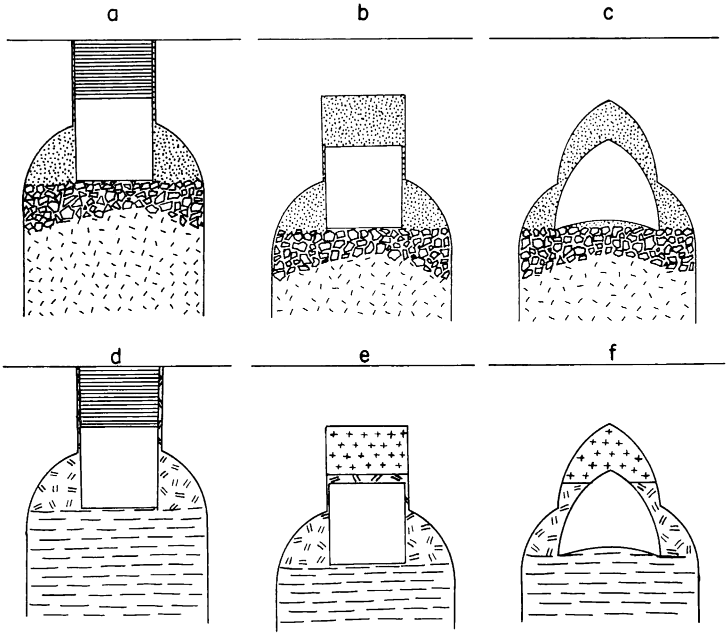

Fig. 5. Surface and subsurface cauldron subsidence over hypothetical, floored, polymagmatic chambers. Felsic magma—stipple; mafic magma—dashes; felsic flows—ruled; xenolithic floor—blocky; granitic magma—crosses; synitic magma—double dashes; layered crystallized rock—long dashes.

In contrast to the granitic-basaltic association of the Scottish Tertiary province is the White Mountain Magma Series of New Hampshire in which syenitic ring-dikes predominate and mafic rocks are extremely rare. Although granites are by far the most abundant rocks of the plutonic phase, granite is quite subordinate to syenite in the ring-dikes.

To explain these relations the following brief outline is offered. During the rise of mafic magma chambers in New Hampshire, a layer of granitic melt developed. By the time these chambers came to within their diametral distance of the Earth's surface (3 to 8 miles), the heavier melt had approached a syenitic composition. No mafic melt, consequently, was available for high level intrusion and ring-dikes. At the syenitic stage most of the lower melt in the chamber was crystallized. Only a thin layer of syenitic liquid remained above the chamber floor and below the lighter granitic melt.

Ring-fracture and subsidence under these conditions should favor the development of granitic stocks and syenitic ring-dikes in accordance with field observations. The subsiding block would be stopped on the chamber floor or on the xenolithic material accumulated on the floor. The lower and heavier syenitic melt would be last to enter the ring-fracture and form a ring-dike. The lighter granitic melt would be driven above the block to form volcanic eruptions (fig. 5d) or to occupy the cupola formed by subsidence and to develop a stock-like form (fig. 5e to f).

This concept of a floored polymagmatic chamber helps to understand many puzzling relations found in central magmatic complexes. Only a few of the problems have been considered here; others await publication in the near future.

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