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The role of compositional convection in the formation of adcumulate rocks

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The origins of cumulate rocks are re-examined in the light of new concepts in the fluid dynamics of crystallising systems. We propose that during the formation of adcumulate rocks, compositional convection allows continuous exchange of melt in the pores of a cumulus pile with the main magma reservoir. We consider this explanation to be physically more plausible than that proposed in the conventional cumulus theory. We present an experimental study of crystallisation in a porous medium to illustrate the process, and a theoretical analysis to demonstrate its applicability to magma chambers. We also consider factors which may inhibit convection and thus lead to the formation of meso- and orthocumulates. Finally we suggest how these ideas may be used to understand the distribution of these different rock types in layered intrusions.

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Introduction

One of the most intriguing features of many igneous intrusions is the formation of adcumulate rocks. Nearly mono-minerallic rocks, such as dunite and anorthosite, are formed, which contain virtually no remnant of the melt from which the cumulus crystals precipitated. Further, in many cases the crystals do not show chemical zonation, indicating that they grew from a magma in which the local composition did not change significantly as the rock solidified. At the other extreme orthocumulate rocks show evidence for the entrapment of substantial amounts of liquid in the pores between cumulus crystals. Such rocks show chemical zoning of the primocrysts and precipitation of new minerals in the interstices. Wager et al. (1960), who suggested textural and chemical criteria for identifying these different kinds of cumulate, recognised a continuum of rock types from extreme adcumulates through mesocumulates to orthocumulates. Irvine (1982) suggested numerical limits for the volume fraction of interstitial minerals (P) to distinguish these types: $P < 0.07$ (ad-), 0.07–0.25 (meso-) and 0.25–0.50 (ortho-). These textural criteria may be supplemented by measurement of the whole-rock concentrations of incompatible elements, i.e. those excluded from the structures of the cumulus minerals (Henderson, 1970; Irvine, 1979).

Until recently the crystal settling model (Jackson, 1961; Wager and Brown, 1967) was considered the most satisfactory explanation for the origins of the different types of cumulate. This theory envisaged that crystals precipitated from the magma and accumulated on the floor of the intrusion. If the accumulation rate was high, the growth of the cumulus pile trapped melt in between the settled crystals, which crystallised out to form orthocumulates. Low accumulation rates allowed the melt in the pore space to remain at a constant composition by diffusional exchange with the overlying magma reservoir. Thus continued growth of the cumulus crystals was in an isochemical environment and adcumulates were formed.

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Recent geological studies of layered intrusions have made clear that crystal settling is not an adequate explanation for the origin of many layered igneous rocks (Campbell, 1978; MacBirney and Noyes, 1979). Indeed, the evidence indicates that in many cases, crystals grew in situ at the margins of magma chambers. However, melt can still be trapped during in situ crystallisation, and the adcumulate to orthocumulate classification remains useful and valid irrespective of the mechanism of rock formation (Irvine, 1982). Further, Hess (1972) has argued convincingly that diffusional exchange between the magma reservoir and interstitial melt is too slow for it to be a quantitatively plausible mechanism for effecting the necessary chemical exchange. These observations and ideas suggest that accumulation rate and static diffusion may not be the important factors in controlling postcumulus crystallisation.

Hess (1972), suggested that convection in the interstitial liquid can provide more effective chemical transport than diffusion. Here we develop this idea more fully. We discuss the main influences tending to promote and inhibit convection and show how the balance between these can potentially explain the occurrence of different cumulate types in layered intrusions.

Compositional convection in magmas

Experimental studies of convective effects caused by crystallisation in saturated solutions (Chen and Turner, 1980; MacBirney, 1980; Huppert and Turner, 1981) together with theoretical arguments (Sparks and Huppert, 1984; Sparks et al., 1984) suggest an alternative to crystal settling as a mechanism for fractional crystallisation: the convective separation of melt from growing crystals. When a crystal grows from a multi-component melt, the liquid is locally depleted in light or heavy components which results in a change in melt density next to the crystal. Under suitable conditions, for example when light melt is produced by crystallisation on the floor or walls of magma chambers, this depleted melt can be convected away. This process has been termed convective fractionation (Sparks et al., 1984). Theoretical analyses indicate that the compositional convection associated with crystal growth will often be of prime importance in silicate melts, metallic melts and the aqueous solutions used in many experiments (Roberts and Loper, 1981; Sparks et al., 1984; Sparks and Huppert, 1984).

Sparks and Huppert (1984) have introduced the term fractionation density, which can be defined as the fluid density of the chemical components being removed by fractional crystallisation. The fractionation densities of mafic minerals such as olivine and pyroxenes are usually greater than basaltic melt densities which consequently decrease during crystallisation of these phases. Assemblages in which plagioclase is a major component sometimes have fractionation densities less than basaltic melt densities and so an increase in liquid density occurs during fractionation. It is important to realise that during fractionation of magmas the compositional effects on melt density are generally much larger than the associated thermal effects. Compositional convection should therefore be anticipated in magmas.

Experimental study

The formation of adcumulates and orthocumulates involves crystallisation in a porous medium. The question arises as to whether the convective effects observed during crystallisation in open containers (e.g. Chen and Turner, 1980; MacBirney, 1980; Huppert and Turner, 1981; Turner and Gustafson, 1981) can also occur in porous media.

A series of experiments has been carried out to gain understanding of compositional convection in porous media. Only one particular experiment is described here because qualitatively similar behaviour was observed in all cases. The laboratory system chosen was closely related to that studied by Huppert and Turner (1981) in their model of a replenished magma chamber. In their experiments cooling and crystallisation was induced by emplacing an aqueous solution of potassium nitrate beneath a less dense and colder solution of sodium nitrate. A sharp double-diffusive interface was formed between the two fluid layers across which heat was transferred. Convective cooling of the lower layer resulted in crystals of KNO_3 growing on the sides of the container. Compositional convection augmented the effects of thermal convection maintaining a well-mixed lower layer. Crystallisation of potassium nitrate caused the residual fluid in the lower layer to decrease in density (Huppert and Turner, 1981, fig. 1). The density of the residual fluid eventually became equal to that of

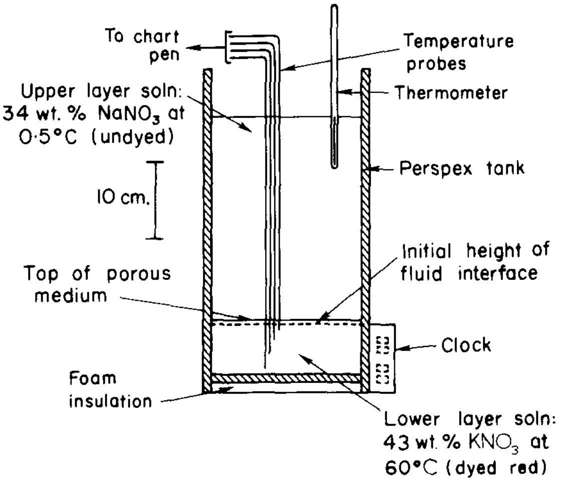

Fig. 1. Arrangement of apparatus and initial conditions of the experiment.

the overlying sodium nitrate solution. At this time, the potassium nitrate solution ascended rapidly into the overlying layer and mixed thoroughly with it.

In the experiment reported here the same system was used, except that the lower KNO_3 layer was contained in a porous medium of randomly packed glass beads (diameter 1.5 mm). The tank was made of 1 cm thick Perspex and was 20 X 20 X 50 cm deep. The base was insulated though for viewing purposes the walls were not. Conductive heat losses were found to be negligible on the time scale of an experiment. Fig. 1 shows the apparatus and initial conditions of the experiment. The bed of glass beads was pre-heated to the same temperature (60°C) as the KNO_3 solution which was immediately poured into the porous medium until the top of the fluid was just beneath the top of the beads. The $NaNO_3$ solution was then poured on top, through a float. The porous medium was virtually opaque, but fluid motions above it were readily observed by the standard shadowgraph technique. Temperatures in the porous medium were monitored by an array of four thermistors (Fig. 1) whose output was fed to a chart recorder. The upper layer temperature was periodically measured with a thermometer. Samples of fluid were taken from the upper layer and subsequently analysed for their sodium and potassium content.

Immediately after the establishment of the two-layer system, turbulent thermal convection was observed in the upper layer. After 2–3 minutes plumes of fluid slightly darker than the surroundings were seen rising in the upper layer, indicating the dyed potassium nitrate solution was being released from the porous medium (Fig. 2). Flame photometric analysis of the upper layer samples (Fig. 3), confirmed that potassium nitrate was indeed being continually released into the upper layer. Transfer of potassium nitrate by compositional convection continued until all the residual fluid from the lower layer had mixed with the upper layer (after about 100 minutes).

The interface between the fluid layers fell slowly in height, but was difficult to observe visually due to the opacity of the porous medium. However, the temperature difference between the layers allowed

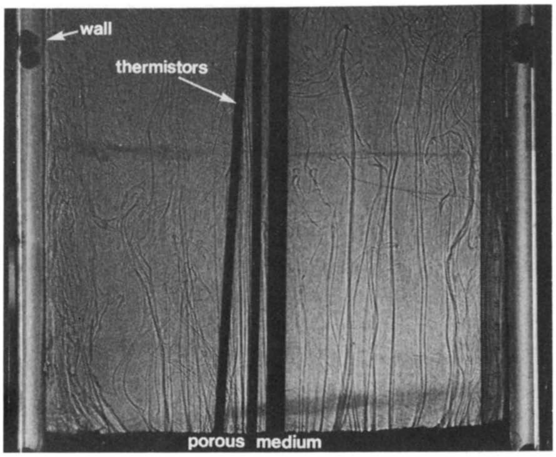

Fig. 2. Photograph at time 20 minutes shows buoyant compositional plumes rising from the porous medium.

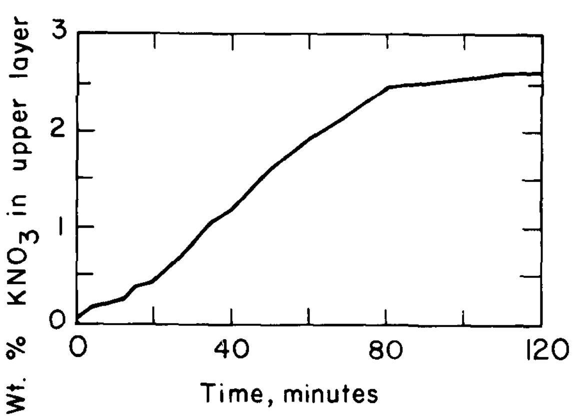

Fig. 3. Results of flame photometric analysis of fluid samples withdrawn from the upper layer. Values accurate to ± 0.03 wt.%. Potassium nitrate.

the position of the interface to be approximately monitored, by suspending temperature probes at different heights (Fig. 1). Thus, as the interface moved steadily downward past the probe tips, they each in turn recorded a rapid temperature drop. Fig. 3 shows the immediate and continuous transfer of potassium nitrate solution from the porous medium into the upper layer by compositional convection. This contrasts with the behaviour observed by Huppert and Turner (1981) who reported a stable "diffusive" interface across which negligible chemical transfer occurred until a time of sudden overturn. The reason for this difference is that in their experiments, the lower layer convected turbulently and light residual fluid formed at the crystals was quickly mixed into the bulk of the lower layer. This prevented overturn until the entire lower layer had a density equal to that of the upper layer. In the present experiments the porous medium inhibited convective mixing in the lower layer so that where local crystallisation had produced sufficiently light residual fluid, this immediately ascended into the upper layer.

Other experiments were carried out in which homogeneous saturated solutions of potassium nitrate were cooled from below. In these experiments only the lower half of the solution was contained in a porous medium. Crystals grew near the floor between the glass balls and released light fluid which migrated upwards to be continually replaced by fluid richer in potassium nitrate. The crystals eventually filled all the pore space between the balls. The experiments demonstrate that crystallisation in a porous medium can release light residual fluid and result in convective exchange with an overlying fluid reservoir. They suggest a mechanism whereby the interstitial liquid in a cumulus pile can be held at a constant composition by continuous convection.

Theory

When a crystal grows in a melt, an exponential compositional gradient is set up in a thin film adjacent to the crystal face (Donaldson, 1975; Coriell et al., 1980). In the absence of convection this film has a characteristic thickness of D/V, where D is the diffusion coefficient and V is the growth velocity of the crystal face. For a horizontal crystal face (g vertical), if a critical Rayleigh number is exceeded the film is unstable and will convect. The compositional Rayleigh number can be expressed for this situation as:

$$Ra_{\mathrm{S}} = g \Delta\rho D^2 / \mu V^3 \qquad (1)$$

where μ is the viscosity, and $\Delta\rho$ is the density difference across the film. For values of D in the range 10^{-7} to 10^{-9} cm^2 s^{-1}, V in the range 10^{-7} to 10^{-9} cm s^{-1}, $\Delta\rho = 0.01$ g cm^{-3} and $\mu = 100$ g cm^{-1} s^{-1} the Rayleigh numbers are all much greater than the critical value of around 10^3. This implies that convective instability should occur during crystallisation of basaltic magma. It is important to note just how thin these unstable films will be. At the critical Rayleigh number and $D = 10^{-8}$ cm^2 s^{-1}, the film thickness will be approximately 450 μm. For a vertical or inclined crystal face no stable condition exists and fluid in this film will always tend to flow away from its point of origin. Thus even in the pore spaces between cumulus crystals, convective instabilities will arise as crystals grow. Fuller discussions of the convection next to a growing crystal face can be found in Coriell et al. (1980) and Sparks and Huppert (1984).

A macroscopic approach to the convective instability of a fluid in a porous medium can be taken by adapting experimental and theoretical work on thermal convection produced by heating a saturated medium from below (e.g. Lapwood, 1948; Wooding, 1957; Elder, 1967). Overall convective instability in a porous medium will occur when the Rayleigh number exceeds a critical value. This may be defined as:

$$Ra_{\mathrm{p}} = k \Delta\rho g H / D \mu \qquad (2)$$

where k is the permeability and H is the vertical thickness of porous medium. Typical values of these parameters for basaltic systems are set down in Table 1, which give a range in Ra_{p} of 10^2 to 10^9, with most probable values in the region 10^4 to 10^5.

TABLE 1

k	(cm^2)	10^{-5}
$\Delta\rho$	(g cm^{-3})	10^{-2}
D	(cm^2 s^{-1})	10^{-7} to 10^{-9}
μ	(g cm^{-1} s^{-1})	10 to 10^3
H	(cm)	10^2 to 10^5

Thus for basaltic magmas all of these values are greater than the critical value of approximately 10 for the onset of instability. This supports the idea that convection can take place in a cumulate pile.

The permeability coefficient (k) requires some comment. The value of k given in Table 1 (10^{-5} cm^2) is calculated for a randomly packed assemblage of crystals with diameter 0.2 cm and 40% pore space. Theoretical and empirical studies, Carman (1956), suggest that the relationship between permeability and porosity (ϵ) is of the form:

$$k \propto \epsilon^3/(1-\epsilon)^2 \tag{3}$$

Thus in cumulate piles, permeability would be reduced to 10^{-8} cm^2 for 4% pore space and to 10^{-11} cm^2 for 0.4% pore space. Hence it would seem that for magmas with the properties listed in Table 1, permeabilities would become too low for convection to occur when porosities decreased to a few percent. Similarly if the viscosity of the interstitial melt becomes too high, convection will be inhibited or will cease, despite the presence of unstable density distributions. During the progressive solidification of a cumulus pile with depth, we term the level at which convection ceases either due to high melt viscosity or low porosity the permeability/viscosity barrier.

Formation of adcumulates and orthocumulates

Fig. 4a depicts the situation where crystallisation on the floor of a magma chamber gives rise to an unstable density distribution throughout the depth of porous material. This can occur during crystallisation of assemblages of minerals which have a fractionation density greater than the melt density. Examples of such assemblages would be those containing mafic minerals such as olivine and pyroxene and in some cases olivine-plagioclase assemblages (Sparks and Huppert, 1984). Our calculations suggest that Rayleigh numbers will often be greater than critical in basaltic systems. Under these circumstances pore fluid may continuously exchange with liquid from the magma reservoir by convection. This mechanism enables the pore melt to maintain a uniform composition and adcumulus growth to take place. The ability of convective exchange to occur will be limited by a viscosity/permeability barrier. Beneath this barrier there will be no motion (Fig. 4a).

Fig. 4b depicts the situation where crystallisation of the cumulus minerals on the floor of the chamber causes an increase in the interstitial melt density with depth. This can often be the case in basaltic systems, in which plagioclase is a major component of the fractionating assemblages (Sparks and Huppert, 1984). Convective exchange with the magma reservoir cannot occur as the density distribution in the pore liquid is statically stable. We propose that orthocumulate rocks can form in such circumstances. An example of this mechanism could be represented by the orthocumulates of the Lower Zone in the Skaergaard intrusion, where the magma density certainly increases during crystallisation: melt compositions from Wager and Brown (1967).

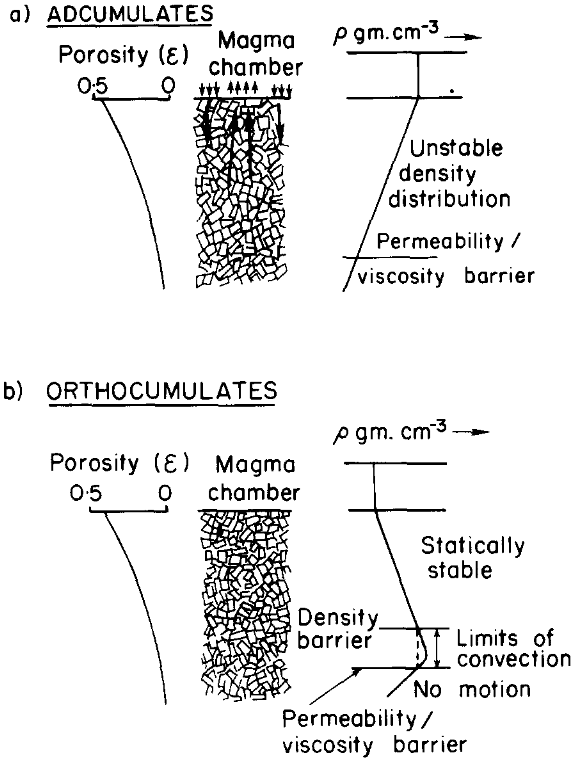

Fig. 4. Density distributions in the pore fluid produced by different paths of intercumulus crystallisation, which give rise in (a) to adcumulates, and in (b) to orthocumulates.

Fig. 4b also illustrates another kind of physical barrier, which could be important. Although melt density often increases during differentiation of basaltic magma, the trend is usually reversed in highly fractionated magmas (Stolper and Walker, 1980; Sparks and Huppert, 1984) causing a density maximum. This maximum typically arises because iron-titanium oxides enter the fractionating assemblage. In Fig. 4b we show how the progressive evolution of intercumulus melt with depth may cause a density maximum to be reached. Convection should occur provided this maximum is above the viscosity/permeability barrier. This convection will not reach the surface, because of the stable density distribution in the overlying fluid. Motion will be limited by a density barrier above, and a viscosity/permeability barrier beneath.

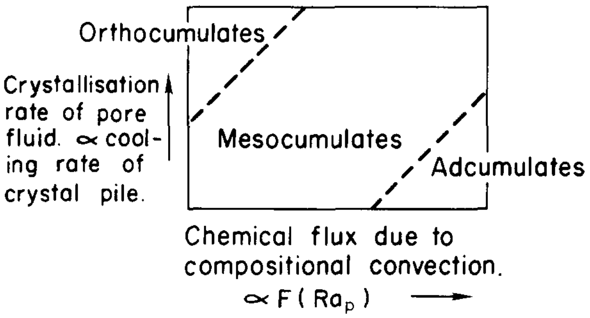

Fig. 5. Shows the qualitative relationship between the regimes in which the three main cumulate types are formed.

Another constraint on adcumulus growth arises out of the balance between the rate of removal of chemical components from the interstitial melt by crystal growth and the flux of those components through the crystal pile due to the convection. If the crystallisation rate is too high, convection may not be sufficiently vigorous to maintain a constant melt composition next to the growing crystals. Crystallisation rate is proportional to the cooling rate of the crystal pile and therefore proportional to the heat flux from the system. Consequently meso- and ortho-cumulates could form in situations of rapid cooling despite an unstable density distribution. A series of unpublished experiments on crystallisation in porous media in the system $CuSO_4$-Na_2SO_4 by R. Kerr and S.R. Tait, designed to examine the dynamic balance between convection and crystallisation rate, have confirmed this analysis. An example of this process may be provided by units described from the Jimberlana intrusion by Campbell (1978). He records units which are adcumulate in the centre of the intrusion but which become progressively more orthocumulate when traced to the margins. This could be due to more rapid cooling and crystallisation of the interstitial melt near the margins of the intrusion compared to the central regions. Fig. 5 shows these ideas schematically.

Discussion

The principles outlined in this paper provide important physical constraints on the occurrence of different kinds of cumulate rock. Adcumulus growth can occur, provided that appropriate conditions exist for convection in the cumulus pile. Ultramafic rocks formed on the floors of intrusions predominantly have adcumulate textures, which is consistent with the mechanism we propose, because fractionation of mafic minerals makes residual melts lighter. An example of this would be the very large thicknesses of adcumulates in the ultramafic zone of the Great Dyke in Zimbabwe. Even when an unstable density distribution exists in the pore fluid, at porosities of a few percent the permeability can be too low to allow convection to take place. Hence, this mechanism will not provide efficient exchange between pore fluid and reservoir during crystallisation of the last fraction of interstitial liquid.

If conditions for convection exist on the floor of the chamber the same mineral assemblage will produce static conditions at the roof. Thus in these circumstances we would predict that adcumulus growth would occur at the floor while orthocumulates simultaneously form at the roof. Judging from the P_2O_5 contents of the Skaergaard rocks, Wager (1963), this is the case in Upper Zone times with adcumulates forming in the layered series and orthocumulates in the Upper Border Group. Unfortunately the compositions of magmas at this stage are still poorly known Chayes (1970), and so we cannot confirm that the density relationships are as predicted.

When a fractionating assemblage contains a large proportion of plagioclase, crystallisation can produce an increase in the residual liquid density. At least in the simple form proposed here, convection in the intercumulus liquid cannot account for plagioclase adcumulates formed on the floor of an intrusion. Where such rocks form at the roof, compositional convection could assist the formation of adcumulates. It may also be an important process in the crystallisation of lunar anorthosites, thought to form whilst floating on top of their parental magma. Morse (1982) discussed these rocks, but considered that molecular diffusion played the major role in providing the conditions for adcumulus growth.

Other postcumulus processes have been postulated, and we emphasize that the model presented here does not conflict with the occurrence of other mechanisms. Upward expulsion of interstitial liquid due to compaction of the cumulus pile has been suggested (Irvine, 1981). MacKenzie (1984), in recent work, has analysed the compaction of a partially molten slab, controlled by the viscous flow of the crystalline matrix. He has shown that provided the pore space remains interconnected, which may be the case down to very low values of porosity, interstitial melt can be efficiently squeezed out, in slabs a few hundreds of metres thick. His analysis implies that compaction could be a very effective means of generating monomineralic rocks. Cameron (1969) has demonstrated that grain size changes have occurred in certain rocks of the Eastern Bushveld intrusion by postcumulus recrystallisation. Growth of some grains at the expense of others and annealing may destroy original textures and compositional zoning in minerals.

In summary, an important factor in determining whether adcumulus growth can occur is if efficient convective exchange can occur between intercumulus liquid and magma reservoir. An unstable density distribution in the pore fluid can be generated by the crystallisation of certain phases from a basaltic melt. Rayleigh number criteria applied both at the microscopic level (at a growing crystal face), and at the macroscopic level (to the whole porous medium), indicate that convective condititions will occur in many basaltic systems. Orthocumulates are formed when the density distribution is stable. We have also described how compositional convection can be inhibited if the melt viscosity is too high, the permeability too small or the crystallisation rate (equivalent to the heat flux) too high. The ideas presented here may be tested against field data if enough is known about the physical properties of the magmas involved and the cooling history of the intrusion.

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