

THE EFFECT OF VISCOSITY DIFFERENCES ON THE DYNAMICS OF CONVECTIVE MIXING PROCESSES

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SUMMARY Recently there has been a growing interest in the fluid dynamics of various geological processes. In particular, double-diffusive convection and associated horizontal layering have been shown to be significant in large igneous intrusions as they solidify. The case considered here is that of a chamber containing liquid magma, replenished from below with hotter but denser magma of different composition which is cooled by convective heat transfer to the resident magma above. This process has been modelled in the laboratory using hot KNO_3 solution as a typical lower layer having the property (analogous to certain magmas) that the saturation density decreases as the temperature falls and crystallization occurs. The subsequent convective behaviour is sensitive to the viscosity ratio between the two layers, and a range of conditions has been examined to represent different compositions of the upper layer. The experiments also have more general implications for mixing between fluids of very different viscosities.

1 INTRODUCTION

At the previous conference in this series, Turner (1980) described laboratory experiments designed to model various fluid dynamical processes of geological interest. An earlier review by Turner and Gustafson (1978) had suggested that it would be useful to pursue various analogies between the now well understood processes leading to layering in the ocean, and those responsible for producing layers in large igneous intrusions. Double-diffusive convection can be effective in either system; it was proposed that the horizontally extensive layers in the rocks first formed in the fluid state, and that the growth of crystals as the magmas solidified was subsequently affected by these pre-existing layers.

This idea has led to a series of experiments in which crystallization has been added to previous investigations of double-diffusive processes. Aqueous solutions near room temperature have been used as convenient laboratory analogues of crystallizing rocks, and Chen and Turner (1980) and Turner and Gustafson (1981) have reported the results of cooling solutions in various geometries, from the top, bottom and sides. The most important new element common to all the experiments is the production of a cold, depleted residual fluid as denser crystals form. With a suitable choice of solutes, this fluid is less dense than the original solution because the concentration change more than compensates for the density increase due to cooling. The resulting "compositional convection" models analogous effects in solidifying magmas which have previously been neglected. A recent review of the present state of this field has been given by Sparks, Huppert and Turner (1983).

2 COOLING AT A SIDE WALL

With side wall cooling and crystallization, the net effect of the release of light fluid and the associated compositional convection in the boundary layer is to produce stratification and layering in an initially homogeneous experimental tank (or magma chamber), as previously described by Turner (1980). If there are several components in the solute or melt, then the same dynamical process leads to "differentiation", or a systematic vertical variation in composition, both in the fluid and in the crystalline products (Turner and Gustafson 1981). The results of such experiments have been used to interpret the observed vertical zonation of magma chambers, as indicated either by the variation with time of the erupted products (McBirney 1980) or

by the compositional changes in the solidified plutons (Hildreth 1981).

3 REPLENISHMENT FROM BELOW

Another direct way of producing stratification in a magma chamber is to introduce a layer of different density at the bottom or top. If the new magma is hotter but denser (because it has a different composition) it can remain isolated from the cooler magma above while it cools rapidly through the "double diffusive" interface between the two layers. The heat transfer takes place on a convective timescale, much faster than by conduction through the side walls. The associated crystallization again reduces the density of the residual fluid in the lower layer, so that it approaches that in the upper layer. Convection then transports the residual fluid upwards, finally leaving a layer of crystals on the bottom. The nature of the convective motions and the mixing behaviour vary greatly as the viscosity ratio of the two layers is changed, and selected examples of our laboratory observations are described below. A time lapse film will also be shown in conjunction with the verbal presentation of the paper.

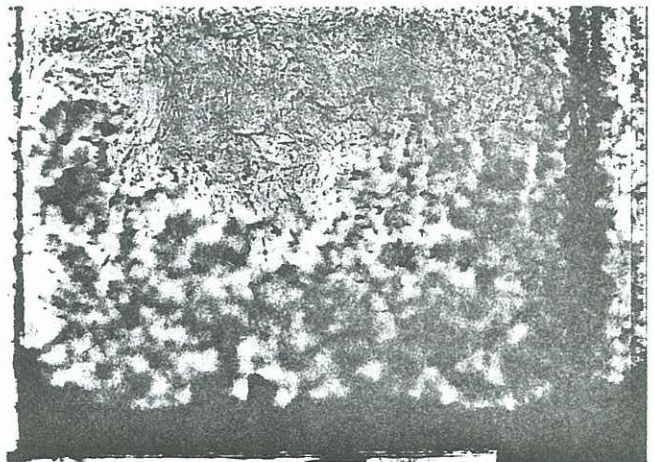


Figure 1 Shadowgraph showing a layer of hot KNO_3 below cold NaNO_3 solution. Cooling through the interface, and associated crystallization in the lower layer, has caused the density to decrease until overturning has occurred. The experimental tank is 400mm wide.

3.1 Two Homogeneous Layers of Equal Viscosity

All the experiments described here have used a lower layer of hot, crystallizing KNO_3 solution. Replenished basaltic magma chambers, in which the viscosity of the two layers remains nearly the same, have been modelled using an upper layer of cold NaNO_3 or K_2CO_3 (Huppert and Turner 1981). In this case, as crystallization brings the density of the residual fluid in the lower layer closer to that of the upper layer, there is a sudden overturning, with a rapid and intimate mixing between the two components. (See figure 1.) A layer of crystals is left at the base of the chamber, and the depleted liquid is mixed into the chamber above, so that its concentration is less than it would have been if the two layers had mixed immediately. Note also that no crystallization would have occurred at all if the hot input liquid were forcibly mixed initially with the colder fluid already in the chamber.

3.2 Density Gradient With Comparable Viscosities

When the upper homogeneous layer was replaced by a stable gradient of cold solution (e.g. K_2CO_3), heating of this gradient from below first produced a series of well-mixed convecting layers. The KNO_3 layer cooled and crystallized as before, and eventually overturned. In this case, however, the rise of the lower-layer fluid was constrained by the density gradient, so mixing took place only with the lower part of the upper gradient region, as shown in figure 2 (reproduced from Huppert, Turner and Sparks 1982).

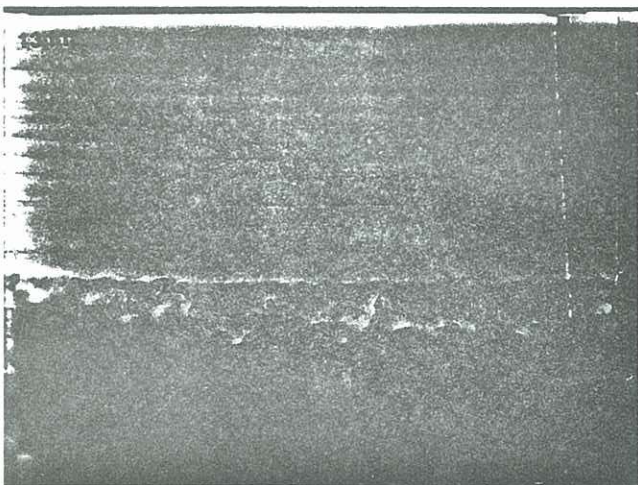


Figure 2 A layer of hot KNO_3 below a stable gradient of cold K_2CO_3 solution. The mixing following overturning is now confined to the lower part of the gradient region. (Compare with figure 1.)

3.3 Homogeneous Layers With Large Viscosity Ratio

The more recent experiments in this series have had in mind applications to magma chambers in which the upper magma is highly differentiated and silicic and hence more viscous than the mafic lower layer (Huppert, Sparks and Turner 1983). The upper layer fluid used to achieve the largest viscosity ratio of several thousand was cold glycerine, and various mixtures with aqueous solutions were used to cover intermediate values. The viscosity of glycerine varies strongly with composition; it is even more sensitive to temperature, as shown in figure 3. This property influences the form of convection in the upper layer, as described below.

With large initial viscosity ratios there was a dramatic change in behaviour from that described in section 3.1. As shown in figure 4, the release of fluid across the interface was continuous, rather than sudden. Crystals formed at the cooled interface, and residual

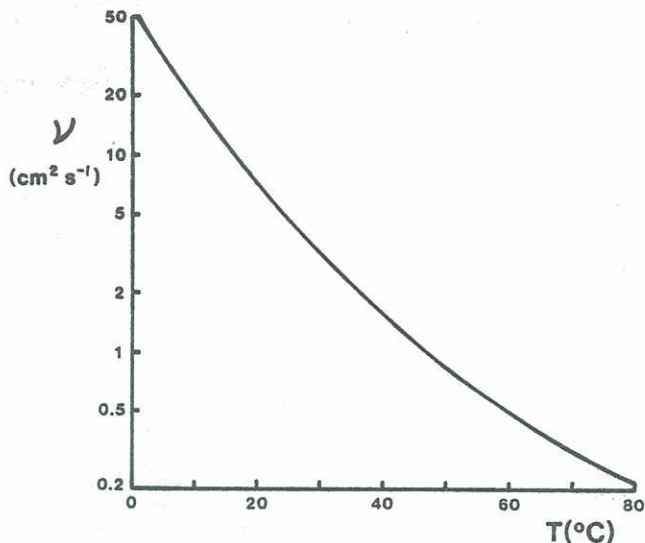


Figure 3 The viscosity of pure glycerine as a function of temperature. Note the logarithmic scale for v .

fluid rose up as very thin plumes above the crystals, aided by the decrease in viscosity due to the local heating. As this fluid cooled, more crystals formed in the plumes and slowly became detached and fell back. Further crystallization at the base of the tank reduced the density difference and increased the rate of release of fluid from the lower layer. At no time, however, was there a rapid overturning; there was very little mixing between the two layers when the viscosities were very different, and the final result was to deposit most of the original lower layer fluid, depleted in composition by the removal of crystals, at the top of the experimental tank.



Figure 4 An experiment in which KNO_3 solution at 60°C has been emplaced below glycerine at 11°C . Blobs and plumes of residual KNO_3 solution rise continuously from the interface where crystallization is occurring, to the top of the tank. Further crystals form in the plumes and fall back. The tank is 200mm wide.

The experiments with viscosity variations were extended to investigate the effects of a density and viscosity gradient in the upper layer, and of several distinct layers of different properties in the upper part of a chamber. The results indicate that whatever the stratification, whether it be in layers or continuous, the form of the initial motion in the upper fluid is determined by the viscosity ratio between the two fluids immediately adjacent to the interface.

This principle is illustrated in two contrasting experiments with two upper layers. When cold aqueous NaNO_3 solution was in the middle layer, below less dense glycerine, overturning and rapid mixing between the crystallizing KNO_3 solution and the middle layer of comparable viscosity took place with no further penetration upwards. When the middle layer was cold glycerine, and the upper layer was glycerine diluted with water, plumes of lower layer fluid, in which crystals were growing, penetrated continuously through the middle layer with little mixing. When there was a large density step between the two uppermost layers the residual fluid ponded below the interface, but if this density difference was small, upward penetration continued, with further cooling and crystallization, through to the top of the tank. For intermediate density differences some residual fluid was deposited both at the central interface and at the top, as shown in figure 5.



Figure 5 Two cold glycerine layers, with a 2% density step, above hot crystallizing KNO_3 solution. Most residual fluid is deposited at the interface, while some rises right to the top following further crystallization. (Compare with figure 4.)

The observations of a very different mixing behaviour with a large viscosity ratio raise several questions of more general interest. Fluid is transferred into the more viscous layer above an interface, firstly by the decrease in density due to crystallization, but also because of viscous coupling across the interface. Viscous stresses are set up by the slow convection in the upper layer, consisting of convergent flows in a warm, less viscous boundary layer. These break away to produce plumes which drag up some of the underlying low viscosity layer; the relative importance of thermal and compositional effects determines the later form of the rising plumes.

A large viscosity ratio inhibits mixing between the rising elements and their surroundings, but the precise mechanism is not understood. Other related questions worth further investigation are: How long can heterogeneities survive in a stirred fluid of variable viscosity? What is the relative importance of diffusion and disruption by shearing motions? Is there a characteristic stable size of elements of known viscosity subject to specified motions in a fluid of different viscosity? These are fundamental problems whose solution would be applicable to industrial mixing processes, and not only in the magma mixing context which prompted this study.

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