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Convection and Mixing in Replenished Magma Chambers

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ABSTRACT

This paper describes a series of laboratory experiments, in all of which a denser fluid is added through a small source to the bottom of a tank of homogeneous or stratified fluid. The problems discussed arose originally in the geological context of magma chambers refilled from below, but they have a more general fluid dynamical interest.

Depending on the rate of inflow, there can be little or a great deal of mixing between the input and resident fluids, to produce either a homogeneous or a stratified layer at the bottom. A hot but dense lower layer, in which crystallization is occurring, evolves as it is cooled through the interface. When its density reaches that of the layer above, it mixes with the overlying fluid in a manner which depends on the viscosity contrast between the two layers. Viscosity differences also have a strong effect on the initial mixing between an inflow in the form of a "fountain" and the surrounding fluid, even when the inflowing fluid is fully turbulent. These effects of viscosity variations raise further fundamental questions about the mechanism of turbulent entrainment.

INTRODUCTION

There has been a growing interest over the past few years in the fluid dynamics of various geological processes. In particular, knowledge about double-diffusive convection has been transferred from its original oceanographic context to the study of layering in large igneous intrusions, and laboratory experiments with crystallizing aqueous solutions have been used as analogues of solidifying liquid magmas. Chen and Turner (1980), for example, have reported the results of cooling solutions in various geometries, from the top, bottom and sides. Several aspects of these geologically motivated studies have been described at previous Conferences in this series. (Turner 1980, 1983), and for more general reviews of the background and the geological applications see Sparks et al. (1984) and Turner and Campbell (1986). The problems discussed in the present paper all relate to magma chambers replenished from below with magma which is compositionally denser (though it is usually hotter) than the resident magma. Even in this simple geometry, a wide range of dynamical processes has been identified and studied. The major factors determining the behaviour are the rate of inflow, and the relation between the viscosities of the two fluids. All of these experiments have been recorded on time-lapse films as well as in still photographs, and these will be used to illustrate the talk.

SLOW REPLENISHMENT

Two layers of comparable viscosities

The first case of interest is a tank or magma chamber refilled with hotter, denser fluid, slowly enough for there to be little mixing, but fast enough for negligible crystallization to occur during replenishment. Many magmas have the property that the first crystals to form are denser than the melt, and so the depleted residual fluid becomes less dense as crystallization proceeds. A convenient laboratory analogue is a solute like KNO_3, for which the solubility in water increases strongly with temperature (as shown in Fig. 1, reproduced from Huppert and Turner (1981)). A hot, saturated layer of KNO_3 cools rapidly through the double-diffusive interface with an upper colder layer (of $NaNO_3$ for instance). It crystallizes as it does so, and the density of the lower layer fluid therefore decreases.

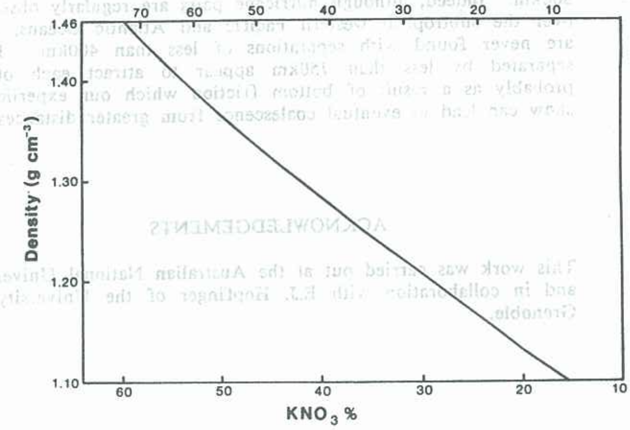

Fig. 1: The density of saturated solutions of KNO_3 as a function of composition and temperature.

If the viscosities of the two fluid layers are comparable, the lower layer gradually evolves towards a state where its density approaches that of the upper layer, but the interface remains sharp during this time, and there is little transfer of composition between the layers. When the densities become equal, the interface breaks down and the two layers mix intimately together, as shown in Fig. 2. This model is appropriate for basaltic magma chambers in which there is little contrast in viscosity between the resident and incoming magmas.

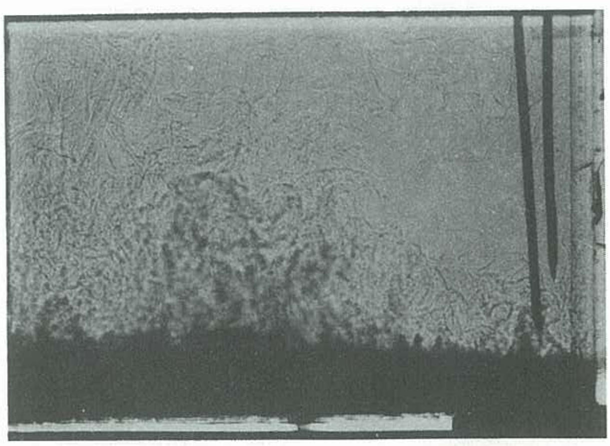

Fig. 2: Shadowgraph showing the sudden breakdown of an interface between hot KNO_3 below cold $NaNO_3$, after cooling has produced crystallization and hence a decrease in density of the lower layer. The tank is 400 mm wide.

Several variations on this experiment have also been carried out with magma mixing in mind. When a layer of hot, nearly saturated KNO_3 is put in below a fluid having a vertical compositional (and hence density) gradient, for example a gradient of K_2CO_3 or $NaNO_3$, the lower layer at first cools and evolves as before. When overturning occurs, however, the rise of the lower-layer fluid is constrained by the gradient to the lower part of the tank. When there are gradients of composition of several components in the tank, or layers of different composition which crystallize from below, a sequence of overturning events may take place. Horizontal layers of crystals form, the composition of which reflects the composition of the fluid in contact with the crystals as they grow (Kerr and Turner (1982)). When the lower layer contains a component (e.g. HNO_3) which can react with a dilute extra solute in the upper layer (K_2CO_3), the evolution proceeds as before, since the transport of these components through the interface is very slow. When overturning occurs, however, the thorough mixing leads to a reaction and rapid release of CO_2. This experiment provides a good analogue of the exsolution of gas from inclusions of water-rich mafic magma, following mixing and quenching in the cooler magma above.

More viscous upper layer

If the viscosity of the upper layer is much greater than that of the lower, as it would be with a rhyolitic magma in the chamber and an input of a basaltic layer below this, the behaviour is very different to that described above. The laboratory model used hot KHO_3 solution emplaced below cold glycerine solutions, which have a viscosity up to 3000 times greater. (More details of this experiment and variations on it which include density and viscosity gradients are given in Huppert et al. (1983) and Turner (1983).) In this case, instead of evolving with a sharp interface until overturning takes place, the lower layer releases less dense fluid continuously into the upper layer, as shown in Fig. 3. As a result of crystallization, light fluid is deposited against the interface (which acts as a nearly rigid lid), and rises through it in the form of plumes into the upper layer. Further crystallization occurs in these plumes, and the crystals fall out, but there is little mixing between the two layers. The final result is that a layer of depleted KNO_3 solution is deposited at the top, reversing the original sense of compositional stratification.

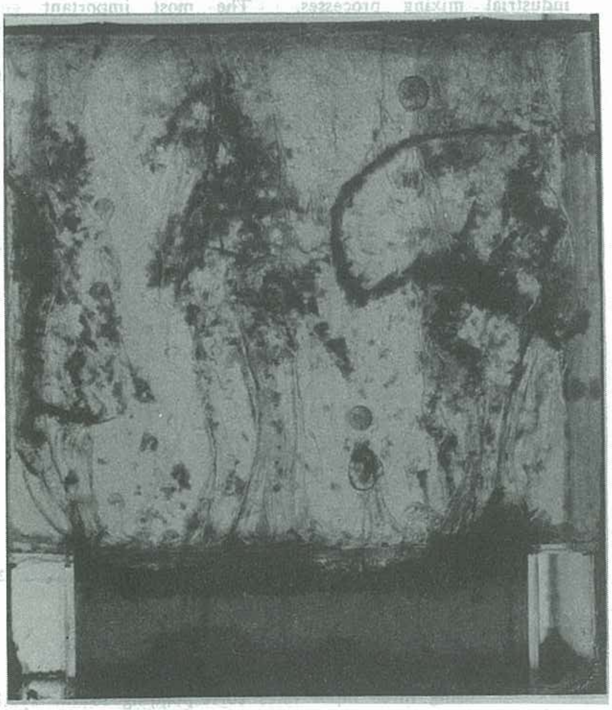

Fig. 3: An experiment in which KNO_3 solution at 60°C, below much more viscous glycerine at 11°C, crystallizes and releases plumes of light fluid continuously into the upper layer. The tank is 200 mm wide.

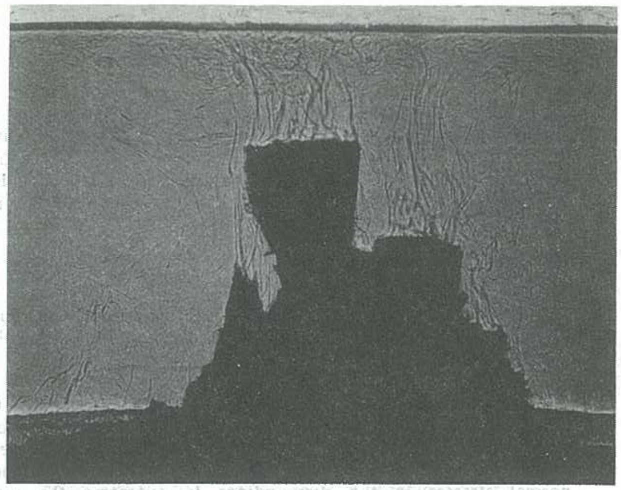

Fig. 4: A group of "chimneys" growing above a source of hot KNO_3 solution released slowly under a homogeneous layer of cold K_2CO_3. Crystallization blocks the outlets near the base, forcing hot fluid upwards.

Very slow inputs, with quenching

When the rate of input of hot, saturated KNO_3 below a cold less dense solution of comparable viscosity is very slow indeed, much of the input fluid is "quenched" and crystallizes immediately during refilling. Not all the input fluid crystallizes, however, and some lighter residual fluid is released to mix convectively with the homogeneous layer above. In time, some hot dense input fluid spreads along the bottom to form a layer as before. When this crystallizes further, some of the input channels between the crystals become blocked, and columns of crystals or "chimneys" build up above the input vents, as shown in Fig. 4, reproduced from Huppert et al. (1982). Hot fluid is forced upwards through a cluster of thin-walled conduits, and the nearly horizontal top indicates that denser fluid was ponding at that level, and causing further crystal growth as it flowed over the edges and down the sides.

RAPID REPLENISHMENT

Comparable Viscosities

The opposite extreme to the case just described is a rapid turbulent inflow of denser fluid directed upwards. When the input momentum is large in relation to the density difference, (i.e. when an internal Froude number is large), this flow forms a fountain which rises high into the surrounding fluid and falls back. If the viscosities of input and resident fluids are comparable, there is rapid mixing with a much larger volume of the surrounding fluid. A hybrid layer of this mixture builds up at the bottom, producing a stratified region even in a tank or magma chamber which was originally homogeneous (Fig. 5). If the input fluid is hot as well as compositionally dense, a series of "double-diffusive" layers can form, each of which is convecting and well-mixed. All of these features, and especially the efficient mixing between incoming sulphide-rich liquid and large volumes of resident silicate magmas containing low concentrations of metals, are significant for understanding the formation of layers of chromium and platinum ores in large igneous intrusions (Campbell and Turner (1986).

Large viscosity ratios

When the kinematic viscosity ν_2 of the fluid in a tank (or magma chamber) is much greater than that of the input fluid (ν_1), mixing can be inhibited, even though the inflow remains turbulent. The boundary between the turbulent fountain and the upper viscous layer is smooth, with only the larger scales of turbulent motion distorting the interface, and none of the smaller scales penetrating into the outer fluid (Fig. 6). Theoretical arguments outlined by Campbell and Turner (1985) and Turner (1986) have shown that, provided the inflow is fully turbulent, the rate of mixing is unaffected by the viscosity of the outer fluid if

$$Re_2 = wd/\nu_2 > k, \text{ a constant.} \quad (1)$$

Explicitly, provided $Re_1 = wd/\nu_1 > 400$, the criterion for uninhibited entrainment is determined by a Reynolds number based on the velocity w and diameter d of the inflow and the kinemetic viscosity ν_2 of the *outer* fluid, and is independent of the viscosity ν_1 of the inflow. It can be written in the more symmetrical form

$$Re_1 = wd/\nu_1 > k\nu_2/\nu_1 \quad (2)$$

which states that as the viscosity ratio increases, the inflow Reynolds number must increase in proportion if mixing is to remain possible.

The above results imply that it is the response of the fluid outside the turbulent region to the disturbances imposed on it which determines the rate of entrainment. Inertial forces in the turbulent flow must be able to generate large enough normal stresses in the surroundings to overcome the viscous stresses and distort the boundary in the manner necessary for mixing to be initiated.

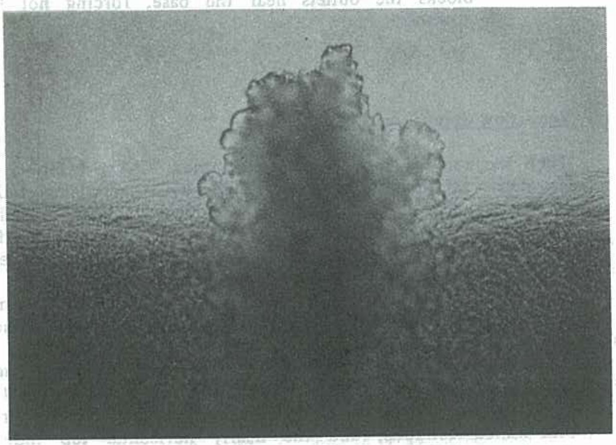

Fig. 5: A fountain of NaCl solution mixes vigorously with the surrounding fresh water of nearly equal viscosity and falls back to form a stratified layer. The tank is 400 mm wide.

The relation (1) has received support from the results of laboratory experiments shown in Fig. 7. The mixing rates into fountains having three different values of wd were measured, with the surrounding fluid having a range of ν_2 values in each case. For each value of wd there is a critical value of $\nu_2 (= \nu_2^c)$ corresponding to $k \approx 100$ below which changes of ν_2 have no influence on mixing. When $\nu_2 > \nu_2^c$ there is a rapid decrease in the entrainment rate, which has fallen to half at k=30 and is negligible when $\nu_2 \gg 10\nu_2^c$. The higher the value of wd, the higher is the value of ν_2 at which the viscosity of the host fluid first influences entrainment. If the "entrainment midpoint" for the curve of highest input Reynolds number is scaled to the conditions of the other two experiments, the arrows mark the corresponding viscosities at which the entrainment is predicted (using (1) with k = 30) to fall to half their maximum values. The displacement of these arrows from the experimental curves is a measure of the direct effect of ν_1 in reducing entrainment. The difference between the experiment and prediction is just outside the experimental error for the intermediate flow rate, but the increasing disagreement at lower wd values indicates a real effect of low Re_1, which has been documented in a further series of experiments.

It is to be expected that the principles established in this study will be more generally applicable to other turbulent flows surrounded by more viscous fluids, though comparable detailed results still need to be obtained for plumes, for example. For the particular geological application which motivated the

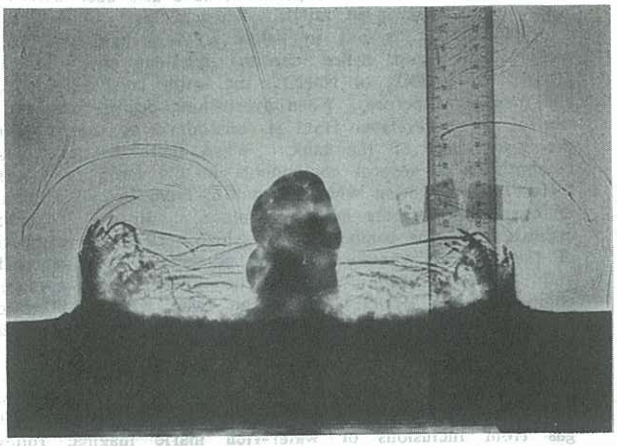

Fig. 6: A fountain of K_2CO_3 solution injected upwards into much more viscous glycerine does not mix at all with its surroundings, and the interface remains smooth. (The annular plume at larger radius is due to a double-diffusive effect which is irrelevant in the present context but will be explained in the oral presentation.)

"fountain" study the conclusions are already very clearcut, however. If a primitive basaltic magma is injected into a chamber containing fractionated basaltic magma, the viscosity of both magmas will be low and not very different. The flow will be turbulent unless the feeder pipes are very small, and the two magmas will mix readily. However, if basaltic magma is injected into a much more viscous silicic melt, little or no mixing will occur, except in the uncommon situation where the feeder dyke is several hundres of metres wide.

CONCLUSIONS

The experiments described here have led to results which are of direct interest to geologists and volcanologists, but they should also be more widely applicable, for example to various industrial mixing processes. The most important general conclusion is that mixing between two fluids can be greatly inhibited if there is a large viscosity ratio between them. Further work is in progress using a different geometrical configuration, in order to obtain a better understanding of the physical mechanisms involved.

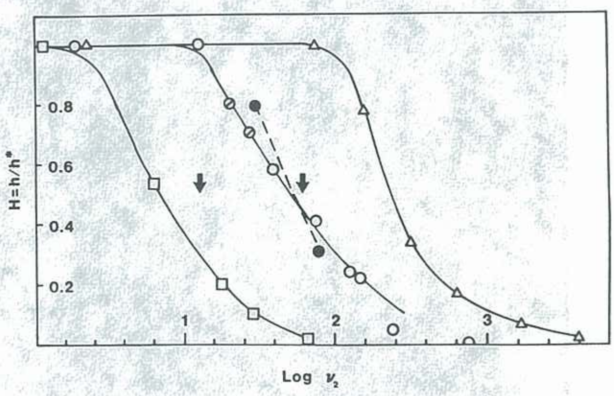

Fig. 7: The results of "fountain" experiments carried out using three input rates corresponding to the symbols: triangles, wd=68 cm² s⁻¹, circles, wd=18 cm² s⁻¹, squares, wd=3.9 cm² s⁻¹. The ordinate is a normalized measure of entrainment, and it is plotted against the kinematic viscosity ν_2 of the host fluid in centistokes, on a logarithmic scale. For more details see Campbell and Turner (1985, 1986).

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