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Laboratory investigations of viscous effects in replenished magma chambers

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Some laboratory experiments are described which investigate the dynamical effects of replenishment of a magma chamber containing high viscosity magma by hotter, denser and much more fluid magma. In the experiments a layer of hot KNO_3 solution is emplaced beneath cold glycerine, which has a viscosity 3000 times greater. Less dense fluid is released immediately and continuously from the interface as a result of crystallization in the lower layer and rises as plumes through the overlying glycerine. Further crystallization occurs in the plumes, and the crystals fall out; but there is little mixing between the two fluids and a layer of depleted KNO_3 solution forms at the top. The experiments demonstrate that interfacial processes begin to dominate where there are large viscosity differences between adjacent fluid layers as would be the case in a rhyolitic magma chamber replenished by basaltic magma.

The fluid dynamics of the cooling and crystallization of a magma chamber has recently been extensively investigated [1,2]. In one area of study Huppert and Sparks [3,4] put forward a theoretical model for the evolution of a homogeneous magma chamber replenished episodically at its base by the input of magma which is hotter yet, due to compositional differences, heavier than the resident magma. The model supposes that the new magma ponds at the base of the chamber and cools by the transfer of heat through the thin interface separating the two magma layers. Because the two magmas are envisaged to be of comparable viscosities, and the compositional diffusivity is so much less than the thermal diffusivity, there is a negligible transfer of matter across the interface. As the lower layer cools, it crystallizes and the density of the residual liquid decreases. After the temperature difference between the layers has decreased sufficiently, the density of the residual liquid in the lower layer can become equal to that of the upper layer. At that time the liquid magma of the lower layer will rise and mix with that of the upper layer.

The fundamental fluid dynamical principles of the model were confirmed in a series of laboratory experiments [5]. These used aqueous solutions, with comparable viscosities, of hot KNO_3 and cold $NaNO_3$ as the lower and upper layers respectively. Virtually no KNO_3 was transferred across the interface separating the layers until the interface became unstable. Then the residual aqueous KNO_3 rose and quite quickly mixed homogeneously with the upper $NaNO_3$ solution.

This note discusses the new features of a further series of experiments designed to investigate the effect of replacing the upper layer with a fluid of large viscosity. We have in mind modelling the replenishment of, say, a rhyolitic magma chamber by hotter and heavier basaltic magma of much smaller viscosity.

The lower layer in the current experiments, as

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in the previous ones, was an aqueous solution of KNO_3 whose initial temperature, density and viscosity were typically 61°C, 1.287 g cm^{-3} and 0.005 cm^2 s^{-1}. The upper layer was pure glycerine initially at 12°C, of density 1.260 g cm^{-3} and viscosity 16 cm^2 s^{-1}. The viscosity of glycerine is approximately an exponentially decreasing function of temperature [6] and to minimize effects due to horizontal temperature, and hence viscosity, gradients, we confined the lower layer to a region with smaller horizontal dimensions than the glycerine layer above it. Specifically, the lower layer was initially poured into a Perspex box 6 × 15.4 × 5 cm high which rested centrally at the base of a container 10.6 × 20 × 30 cm high. There was a false floor for the upper layer at the top of the box. Fig. 1 presents a plan and elevation of the container and inserted box. The glycerine was rapidly emplaced above the lower layer to a depth of typically 23 cm.

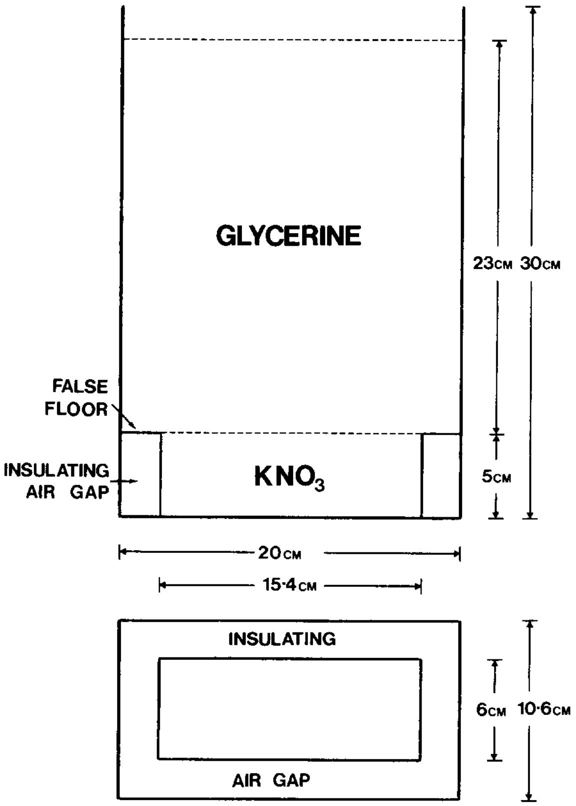

Fig. 1. Elevation and plan of the container and inserted box used in the experiments.

As soon as the cold glycerine comes into contact with the hotter lower layer, heat is transferred and the aqueous KNO_3 solution cools, convects and quite quickly becomes supersaturated and begins to crystallize. The crystallization occurs preferentially near the interface, and almost from the start some less dense KNO_3 solution is released and ascends into the glycerine. The intrusion into the glycerine is driven by viscous stresses at the interface. The light fluid rises in relatively inviscid, thin plumes in a very viscous environment. The tops of the plumes have a large spherical cap (see Fig. 2a), as has been observed previously when relatively inviscid fluid rises buoyantly through very viscous fluid [7]. They penetrate virtually to the top of the glycerine with the viscosity of the glycerine surrounding the plumes being decreased by the horizontal transfer of heat and water content from them. As the rising, residual liquid cools, it forms crystals which are initially carried up by the flow in the plumes, but eventually the crystals become sufficiently large that they sink back. After a time the plumes can become quite full of crystals and take on a rather tortuous shape, as shown in Figure 2b.

After some 20 to 30 minutes from the beginning of the experiment the release of light fluid is greatly accelerated and penetrates through the mat of crystals which have formed at the interface. The amount of crystals in the glycerine layer increases and a layer of light aqueous solution begins to form above the glycerine, as seen in Fig. 2c. Slowly, the lower layer is completely emptied of its KNO_3 solution, the crystals in the glycerine sink back and double-diffusive fingers form between the light released liquid at the top of the layer and the glycerine beneath it (Fig. 2d). The finger structure is due to the diffusion of glycerine into water being much larger than the diffusion of water into glycerine [6]. Thus glycerine diffuses into a downward moving fluid parcel to make it heavier, causing its descent to continue.

Comparing these experiments with the previous ones involving an aqueous, relatively inviscid upper layer, we see that there are a number of important differences. In the previous experiments

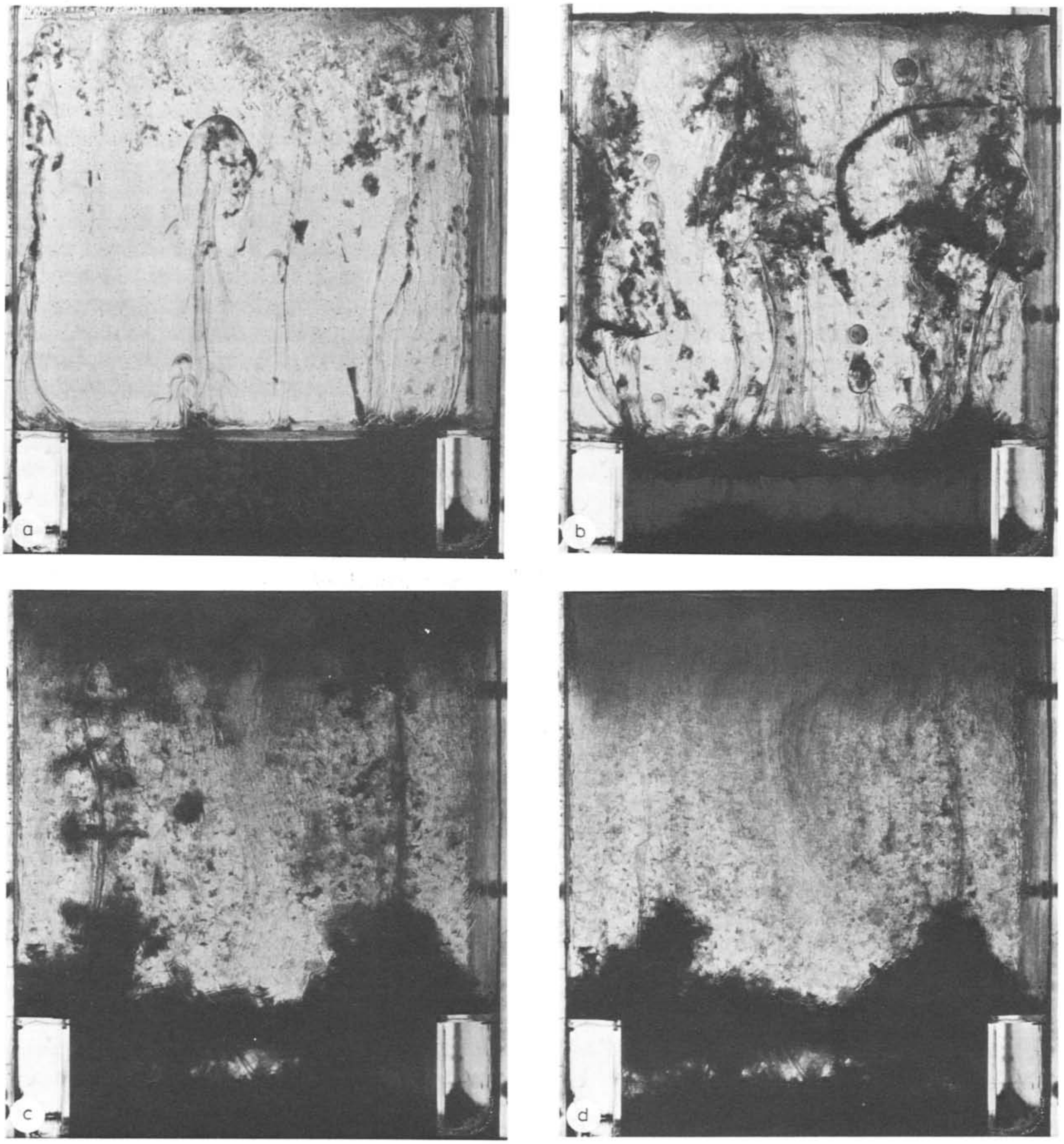

Fig. 2. Convection in a two-layer crystallizing system with large viscosity ratio (approximately 3000) of hot KNO_3 solution below cold glycerine. (a) 9 min 45 sec, plumes with mushroom shaped caps are rising into the upper layer. Crystallization of KNO_3 solution takes place within the plumes. (b) 18 min 25 sec, further crystallization takes place in the plumes and aggregates of crystals are falling back. Small, nearly spherical blobs are also rising, and mixing very little with the glycerine. Long, dendritic crystals of KNO_3 are also visible at the bottom and top of the lower layer. (c) 45 min 0 sec, plumes continue to rise, with further crystals falling out. (d) 1 hr, the plume activity has almost ceased, and a deep layer of residual fluid has built up at the top. Irregular piles of crystals remain on the floor.

the two layers remained distinct until, at a specific time, (when the density of the lower layer became less than that of the upper) the interface between them broke down and the two fluids mixed rather quickly to a homogeneous state. With a viscous upper layer, light liquid, depleted in KNO_3 due to crystallization within the lower layer, is continuously lifted into the upper layer due to viscous stresses at the interface. No sudden overturn takes place. Because of the large differences in viscosity this released liquid mixes very little with the upper layer as its rises through it and is deposited almost undiluted above it.

Other experiments, to be reported elsewhere [8], were designed to confirm that the release of less dense fluid at the interface was not due solely to local crystallization. In these experiments the density and temperature of the lower layer were controlled directly by either heating, or cooling it to produce crystallization. In both cases we observed that plumes of light fluid still ascended into the glycerine, irrespective of whether the light fluid was generated by heating or by crystallization. We also examined the effects of adding glycerine to both an aqueous KNO_3 lower layer and an aqueous $NaNO_3$ upper layer in order to increase the viscosities of both layers by an order of magnitude. This increase in viscosity did not change the process of crystallization and subsequent sudden overturning and mixing, as observed in the previous experiments with equal but lower viscosities [5]. This supports the notion that it is the viscosity difference across the interface, and not the magnitude of the viscosity itself, which causes the newly described effects.

This note concentrates on the fluid dynamical effects which can occur when a magma chamber is replenished by new, heavier magma whose viscosity is very much less than the resident magma. We have focussed on the fact that the large difference in viscosities causes the light fluid released from the lower layer to rise in a continuous manner. The transfer process is dominated by interfacial effects. The thermally driven motion in the viscous upper layer drives motion in the lower layer by the viscous stress exerted across the interface. The continuity of horizontal velocity and stress across the interface requires that the thickness of the influenced region in the lower viscosity layer be very much smaller than that in the upper layer. Small amounts of less dense, residual fluid in the lower layer are thus transported to the base of a plume and then rise into the upper layer. The large viscosity ratio between the rising elements and their surroundings then inhibits mixing and a layer of depleted, virtually unmixed fluid forms at the top of the chamber.

Circumstances in which hot dense magma is emplaced beneath cooler and much more viscous magma are commonly encountered in calc-alkaline magmatic systems [9,10]. Huppert et al. [10] presented a model for mixing by the crystallization and exsolution of volatiles from a lower layer of wet mafic magma. They envisaged behaviour similar to the experiments reported by Huppert and Turner [5] for fluid layers of comparable viscosity. However, when there is a large viscosity contrast between the magma layers, as for example between basalt and rhyolite, the new experiments indicate that interfacial processes will become dominant. Volatile exsolution in mafic magmas can reduce the density to values less than dry rhyolite. Thus crystallization and volatile exsolution along the interface may result in entrainment of vesicular mafic magma into the viscous rhyolite in a manner somewhat similar to that envisaged by Eichelberger [9]. Vesicular mafic inclusions with characteristic quench textures are common in silicic volcanic rocks and could be interpreted in terms of entrainment across an interface.

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