Analogue modelling of segregation and ascent of magma

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Abstract: Segregation and ascent of magma was simulated in analogue experiments in which wet sand and stiff gelatine formed the analogues for solid rock. The liquid magma phase was simulated with either air that was pumped into the sample (ascent simulations) or CO_2 gas that was produced by fermentation within the sample (segregation simulations). The experiments were carried out in an upright flat glass tank to enable filming of the processes. Movies that are shown here indicate that the segregation and ascent is highly dynamic and non-linear, with intimately linked stepwise transport and accumulation. We suggest that stepwise transport and accumulation are part of a continuous process that links initial small scale melt formation and segregation to ascent through crust or mantle by dykes.

Introduction

Magma is generated by partial melting on the µm to mm-scale in its source rocks and may accumulate and ascend to form > km-scale volumes in the form of batholiths, magma chambers or volcanic outpourings. The whole process involves often over 25 orders of magnitude in scale and deals with a variety of processes on different scales and different levels within the crust and mantle. Time scales also vary over many orders of magnitude, from seconds to hours for hydrofracture propagation involved in ascent of dykes (Emerman & Marrett 1990, Lister & Kerr 1991, Clemens & Mawer 1992) to one or more millions of years for a thermal event that causes partial melting (see discussion in Brown et al. 1995, Petford et al. 2000). The sheer range of scales involved inhibits any numerical or experimental modelling of the whole process. This has limited most modelling to only one aspect or one step of the whole process.

One the smallest scale, melting experiments have been done on real rocks (van der Molen & Paterson 1979, Dell'Angelo & Tullis 1988, Rushmer 1995) and on analogue materials (Means & Park 1994, Park & Means 1996, Grujic & Mancktelow 1998, Rosenberg & Handy 2000). Ascent by dyking has been extensively modelled numerically (Weertman 1971, Spence & Turcotte 1985, Lister & Kerr 1991, Petford et al. 1993, Rubin 1995a; 1998, Mériaux & Jaupart 1998, Dahm 2000) and with analogue models using gels (Maaløe 1987, Takada 1990, Lister & Kerr 1991, Dahm 2000). The alternative to dyking, diapirism, has been modelled for decades, most famously by Ramberg (1967), and more recently by, for example, Whitehead & Helfrich (1990) and Anma & Sokoutis (1997).

A limitation to most of these models is that they do not provide much insight into how one step links to the next. For example, numerical models on dyke ascent usually assume a certain influx or pressure at the base of a dyke (e.g. Lister & Kerr 1991, Rubin 1993, Mériaux & Jaupart 1998). Similarly, analogue models for dyking use a certain flux of the magma analogue (e.g. air, water) from an outlet to start a "dyke". Such models assume that influx or pressure is sufficient and can apparently be maintained to make the model work. Such models normally do not explain how the previous step in the sequence links with the one under consideration. It appears as if it is tacitly assumed that each step does not influence the next step.

Here we present movies of analogue experiments of melt segregation and magma ascent. Although the experiments are physically restricted to model only a certain scale, we argue that they represent steps in a step-wise process of segregation and ascent on an ever increasing scale. The movies should thus be envisaged as "snap shots" taken along the road that a magma may take from initial formation to ascent as dykes.

Analogue experiments of stromatic migmatites

To simulate melt segregation in partial melts, we used a simple mixture of sand, sugar water and bakers' yeast.

Fermentation of sugar by yeast produces ethanol and CO_2 gas. The gas is the analogue of melt. The experiments were done in a semi-2 dimensional glass tank (40 x 40 x 1.5 cm) (Fig. 1). The glass tank was filmed with a digital video camera (756x512 pixels, 25 frames/s).

Initial fluid-filled porosity was about 25%. Fermentation produced gas at a steady rate of about $5 \cdot 10^{-3}$ %/s. The gas partly replaced the pore fluid and after about two to three hours the total porosity settled around 40%, half of which was gas-filled. Figure 2 shows the highly dynamic evolution of the system over a two hour period. Gas accumulates in horizontal hydrofractures to form a structure similar to a stromatic migmatite. Hydrofractures, fractures that are propped open by the internal fluid pressure (Hubbert & Willis 1957, Secor 1965), are also thought to occur in otherwise ductile partial melts, owing to high melt pressure induced embrittlement (Nicolas & Jackson 1982, Sleep 1988). The hydrofractures do not grow and link to create a percolating network through which the gas can steadily escape the sample, as envisaged by, for example, Nicolas (1986). Instead, hydrofractures grow slowly and coalesce or drain into others in sudden events (Fig. 3) in between periods of quiescence.

At any time it is difficult to tell from the current structure where large hydrofractures once resided. The deformation caused by the formation of a hydrofracture is usually largely reversed upon collapse and drainage. Figure 3 and 4 shows an interesting exception to this. Opening of a very large lopolithic hydrofracture causes stretching of the overlying layers. Collapse of the hydrofracture necessitates shortening of these layers, which occurs by a thrust fault. Some gas remains trapped along the thrust. Similar structures of leucosomes along reverse faults or axial planes of folds are frequently found in migmatites (e.g. fig 9b in McLellan 1988, fig. 1e in Brown et al. 1995). The experiments show that these may result from collapse and escape of melt volumes.

Wet sand is a Mohr-Coulomb type material. The observed segregation and accumulation behaviour is, however, not restricted to this mechanical behaviour of the solid matrix. Similar experiments in stiff gelatine (purely elastic-brittle) with sugar and yeast yielded similar results (Figure 5).

Analogue experiments of magma ascent

Magma ascent experiments were performed in a similar tank to the one shown in figure 1, but measuring 100 x 100 x 0.8 cm. The tank was filled 40 cm deep with gelatine, which is an elastic-brittle material with a Young's modulus of about 10^3 Pa, a Poisson's ratio of 0.5 and a tensional strength of about 10^2 Pa (Takada 1990). Instead of producing gas in the sample by fermentation, air was pumped into the gelatine through one of up to six tubes with upwards pointing syringe needles fixed to the ends. A thin wire was inserted in some of the needles and suspended

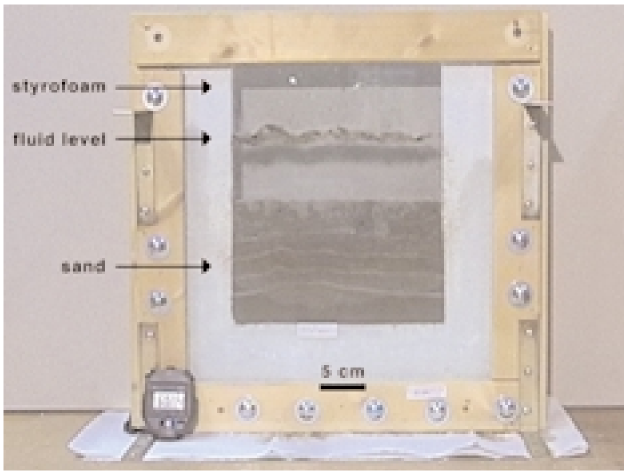

Figure 1. Glass tank that was used for the segregation experiments. The simple set-up consists of a wooden frame that holds together two glass plates that are separated by styrofoam, to create a 1.5 cm wide sample chamber. Ascent experiments were carried out in a similar, but larger tank.

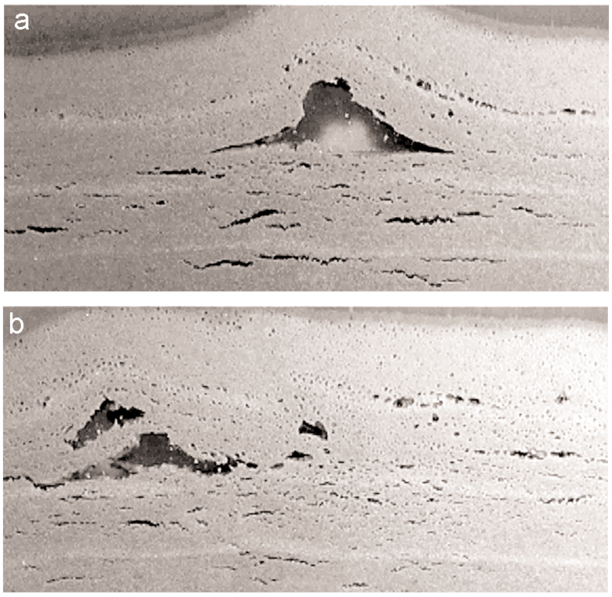

Figure 2. Movies of the growth and collapse of gas-filled hydrofractures. **(a)** Second hour of the experiment. **(b)** Third hour of the experiment. Time between frames is 1 minute. Width of view is 21 cm. **View Movie**

Figure 3. Movie of the collapse of a large lopolithic hydrofracture, which grew over a period of about half an hour and collapsed within less than a second. The collapse produces a thrust fault, with some remaining air pockets, although there is no bulk horizontal shortening of the sample. Movie length in real time is 4 s, with frames 0.04 s/frame. Width of view is 16 cm. **View Movie**

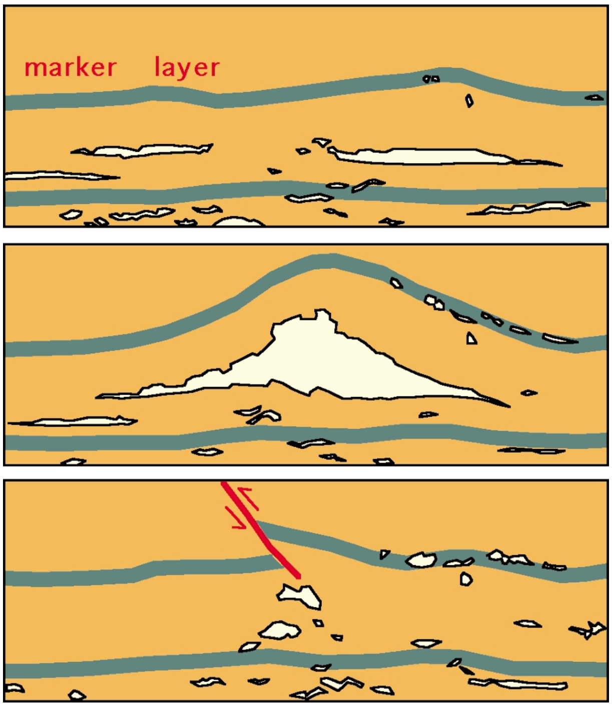

Figure 4. Drawings of three stages of the collapse of a large lopolithic hydrofracture (Fig. 3a) to show the formation of a thrust structure in a marker horizon due to collapse of the hydrofracture. Notice that there is no overall horizontal shortening of the sample.

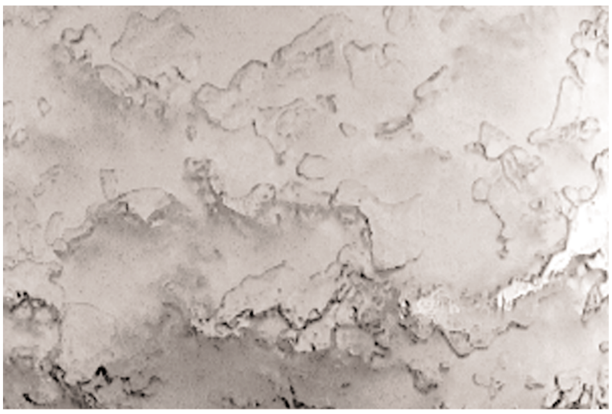

Figure 5. Segregation of gas from fermenting sweet gelatine in a glass jar. Contrary to the Mohr-Coulomb wet sand, gelatine is purely elastic-brittle. Gas accumulates in irregular hydrofractures that occasionally collapse and expulse their gas content. One frame per minute. Width of view is 3.6 cm.

vertically to avoid clogging of the needle during settling of the gelatine and to induce a straight vertical ascent path for the air.

Figure 6 shows the ascent of series of air lenses along a path created by the first ascending air lenses (Fig. 7). Although air flow from the syringe at the bottom was constant, air first accumulated to reach a critical size for ascent (Weertman 1971, Secor & Pollard 1975, Dahm 2000). The ascending air lenses are hydrofractures that move with their content and have been termed "mobile hydrofractures" by Bons (2001), to separate them from the dyke-type hydrofractures that only propagate at their upper tip, but do not close at their rear end. The air-filled mobile hydrofractures have a roughly constant shape and velocity. Obstacles along the path can stop or slow down ascending batches, which leads to accumulation of air batches (Fig. 6 c&d). Arrested batches can become mobile again when enough batches have accumulated to overcome the obstacle. Large mobile hydrofractures move faster than small ones (cf. Dahm 2000).

Discussion

Both types of experiment show one common characteristic: both movement and accumulation is step-wise and in batches. In the fermentation experiments, gas is produced on the smallest microscopic scale and accumulates in small bubbles and hydrofractures. These in turn occasionally collapse and migrate to merge with others in ever larger volumes, until escape is achieved. The second type of experiment can be regarded to follow from this stage. Batches that escaped from the source area (partial melt) make their way up as mobile hydrofractures. Here the step-wise accumulation of batches continues by two processes: (1) larger and faster batches catch up and merge with smaller and slower ones and (2) obstacles slow down or arrest ascending batches until enough have accumulated to pass the site of high propagation resistance. This step-wise ascent and accumulation is similar to that proposed by Maaløe (1987) and Sleep (1988) from analogue experiments and theoretical modelling.

An interesting observation of both types of experiments is that transport occurs without full connectivity of the mobile phase. Connectivity is only transient and local in the segregation experiments. This is in contrast to popular models of melt segregation that envisage flow through an interconnected network of pores or fractures (e.g. Nicolas 1986, Collins & Sawyer 1996, Brown & Solar 1998). In that case, the Darcian equation of flow is valid, where flux is proportional to permeability and the gradient in hydraulic head. However, the permeability is zero most of the time in our experiments and flow cannot be described by Darcian flow. The concept of a "critical melt fraction" (van der Molen & Paterson 1979, Vigneresse et al. 1996), the melt fraction at which connectivity is reached and Darcian flow is possible, becomes irrelevant if transport can occur without connectivity.

Some comments on the validity of the experiments

The general model of magma ascent in mobile hydrofractures that close at the rear (Weertman 1971, Maaløe 1987, Takada 1990) and the use of air or liquids and gelatine to simulate dykes (Maaløe 1987, Takada 1990, Lister & Kerr 1991, Dahm 2000) has been strongly criticised by Lister & Kerr (1991) on the grounds that (1) hydrofractures cannot close at the rear end due to the infinitely high stress needed to squeeze out all fluid from between two parallel plates, and (2) the propagation velocity of dykes is determined by the viscous drop along the dyke, not by fracture toughness as is supposedly the case in the gelatine experiments. Dahm (2000), on the other hand, argues that viscous forces in the rear end of a tear-drop shaped propagating hydrofracture are in fact ascent rate controlling, not the fracture toughness. The flow in the air-filled hydrofractures is laminar, but close to turbulent (Reynold's number ≈ 100 to 1000), as is envisaged for ascending magma in dykes (Emerman et al. 1986, Bruce & Huppert 1990). Most of the rate controlling viscous pressure drop along the hydrofracture occurs in the very narrow (µm's) tail (point 2), where minute amounts of air may be left behind, due to imperfect closure (point 1). More importantly, ascent rate is also controlled by irregularities in the fracture surface. The resistance to propagation clearly plays a role here and would in nature if fractures are not as ideal as most mathematical models envisage them to be. It appears that the gelatine+air system is indeed a good analogue for the ascent of magma. It should also be noted that the gelatine experiments reported by Lister & Kerr (1991) are indeed "in the wrong physical regime" to quote the authors, as the liquid-filled hydrofracture was not long enough to close at the rear end to enable a viscous pressure drop to be rate controlling and the glycerol-liquid used, in combination with very slow propagation (10^{-4} m/s), may have softened the gelatine to give it a high effective resistance to fracture propagation. It should be noted that the fracture tip in the experiment of Lister & Kerr (1991; Fig. 7) was blunt, while ascending hydrofractures in our

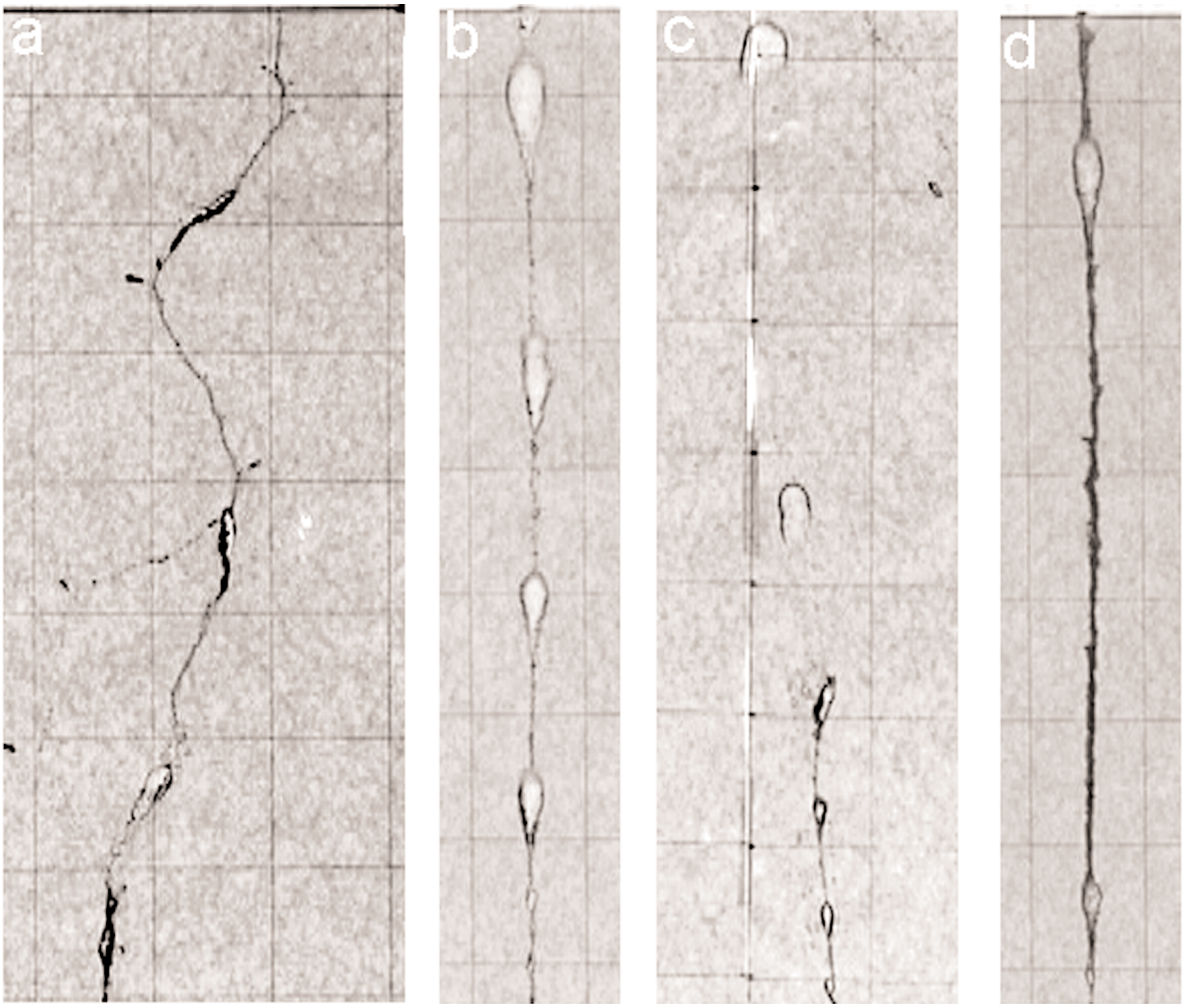

Figure 6. Movies of ascending air lens trains along pre-existing fractures, formed by earlier ascending lenses. **(a)** Regular ascent. Time between frames 0.2 s. (**b**) Regular ascent along vertical fracture, enforced with wire that was connected to syringe during stiffening of the gelatine and then pulled out. Some accumulation due to variations in lens size and speed occurs. Time between frames 0.04 s. **(c)** Accumulation at obstacle. Small lenses ascend to an obstacle, where they get halted. Only when enough have accumulated, can the air proceed upwards again, now in a fracture parallel to the glass plate. Also note the shedding of air by imperfect closure and the incorporation of shed air in the next passing lens. Time between frames 0.08 s. **(d)** Another example of accumulation lenses that accumulate due to variable ascent speeds. Time between frames 0.04 s. Grid spacing is 5 cm. **View Movies**

experiments had pointed tips (Fig. 8), as envisaged by Rubin (1995b) and Dahm (2000) and indicative of low resistance to fracturing (Lister & Kerr 1991)

The volume change in the fermentation experiments is unrealistically high. However, the advantage of this is that the process can be studied in its extreme form and for a prolonged period. It should also be taken into account that the effective volume change for any part of a partial melt system can be far more than only caused by local partial melting, if melt is added from other parts of the system. Analogue experiments are never perfect in all aspects, but we think that the fermentation experiments can give valuable insight in the processes that might occur in partial melt systems.

Conclusions

Our analogue experiments on magma accumulation and ascent suggest that both are part of a continuous chain of step-wise movement and mergers of hydrofractures. The process is highly dynamic and non-linear, with periods of quiescence interspersed by sudden bursts of transport and accumulation. Transport occurs before full percolation of the melt phase is reached. Popular concepts, such as steady-state Darcian melt flow and a critical melt fraction appear to be inappropriate to describe such a system.

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Figure 7. Propagation of initial hydrofracture in unfractured gelatine in 0.8 cm wide glass tank. Air is slowly pumped in from a syringe that is located at the bottom of the image. The fracture is mostly parallel to the glass plates (plane of view). Notice the far-field elastic deformation which can be seen by the offset of a trace of small bubbles to the right of the fracture. Grid spacing is 5 cm; time between frames 0.08 s.

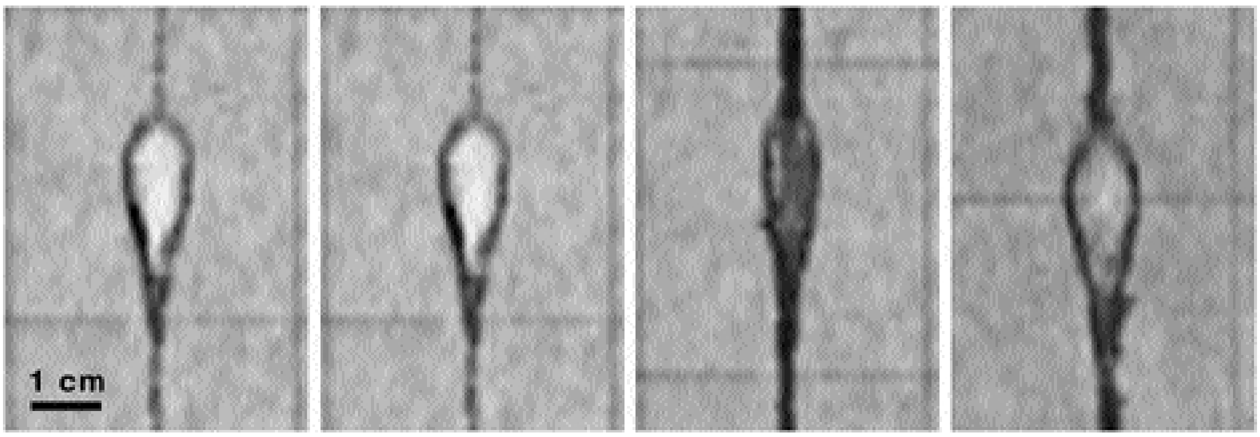

Figure 8. Close-ups of individual ascending air lenses, showing their tear shape with a narrow tail, as modelled by Dahm (2000). Left two images are from Figure 6b, right two from Figure 6d.

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