CRYSTAL-MELT DIFFERENTIAL BEHAVIOURS DURING MAGMA ASCENT IN DYKES: INSIGHTS FROM 2-D NUMERICAL MODELLING

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Summary

We present the results of 2D numerical models of flow in a two-phase medium, composed by crystals carried by a viscous melt, subject to a vertical pressure gradient condition. These simulations of magma migration in a vertical dyke show that presence of crystals and their proportion perturb the flow velocity. As shown in previous analytical studies, the presence of crystals leads to a significant drop in vertical velocity. However in our case, this global displacement is accompanied neither by obvious crystal rotation nor by a significant horizontal displacement of crystals towards the dyke centre. Moreover, our results show that separation between crystal and melt occurs under certain conditions, which can lead to geochemical differentiation of magmas during their ascent. We provide, through a quantitative parametric study, the range of values leading to crystal-melt segregation and compare the obtained differentiation rates to natural observations. Consequently, our results have fundamental implications regarding the causes of geochemical heterogeneities in magmatic suites. They provide constrains on differentiation processes during ascent, which is often neglected in comparison with the two classical end-members (i.e., source-related processes vs. emplacement-related processes differentiation).

Introduction

Dykes are common geological structures and are a record of magma migration into the brittle crust (e.g., Clemens & Mawer, 1992). Magmas are composed by melt carrying a solid fraction of suspended crystals. Up to a critical solid fraction, depending on particle size, shape and distribution in the magma, silicate melts are considered as Newtonian fluids. This maximum crystal content varies for example from 30 to 50% (Petford, 2003), but could be as low as 16% (Champallier et al., 2008). Indeed, at crystal contents near 20%, a flowing magma has to be considered as a multiphase flow. Despite important consequences for the inference of granite petrogenesis, processes acting during magma flow are poorly understood. As crystals and melt have different properties (e.g., viscosity, density…), their behaviour during magma ascent will differ. In a stationary magma, crystals will fall since they have a higher density than the melt. Conversely, in a high velocity ascending magma, we can imagine that crystals would be transported passively by the melt. In intermediate cases, crystals and melt behaviour might be different, leading to crystal-melt segregation.

One of the most efficient process to segregate crystals in a flowing magma results from the interactions between them (Bagnold, 1954; Komar, 1972; Barrière, 1976). Experiments made by Bhattacharji (1967), and supported by analytical studies (e.g. Komar, 1972), have shown that magma flow leads to an accumulation of the solid particles toward the centre of the dyke, due to the Bagnold effect (Bagnold, 1954), even at low crystal content of ca. 15 vol.%. The size of the phenocrysts is an important parameter in this process; the bigger the size is the more efficient the sorting is (Komar, 1972; Barrière, 1976). This process of flow differentiation leads to magma "partitioning" between a "solid cumulate" in the centre of the dyke and an evolved crystal-poor liquid fraction along the edges. From a chemical point of view, this induces a differentiation between chemically relatively primitive dyke cores and the more chemically evolved margins. Parallel to the flow direction, segregation of crystals from granitic magmas, for example, induces differentiation: the melts being more and more evolved ascending towards the surface (Tartèse and Boulvais, 2010).

Magma dynamics in dykes is thus disturbed by the presence of crystals, and it diverges from the simple Newtonian ascent of crystal-free melts. From field observations, analytical calculations and analogue modelling of crystal-melt decoupling in ascending magmas were made under simple configurations. The aim of this study is to extend understanding of the magma dynamics in dykes. To reach that goal, we propose to use a mechanical numerical model that can take into account more realistic flow behaviour.

Numerical model and Setup

In order to examine the influence of crystals on an ascending magma flow, we build a simple 2D mechanical code using finite difference methods. This code solves the Stokes equations of continuity and momentum in the incompressible formulation. This common choice in earth sciences is also justified here because the flow in the dyke is laminar (Reynolds number largely lower than 1).

Our model setup (Fig. 1) simulates a slice in the dyke perpendicular to the channel. Assuming a dyke much longer than its thickness, we set periodic velocity boundary conditions in the vertical direction. A pressure gradient P is applied at the bottom of the model box. The left and the right sides are fixed at zero velocity.

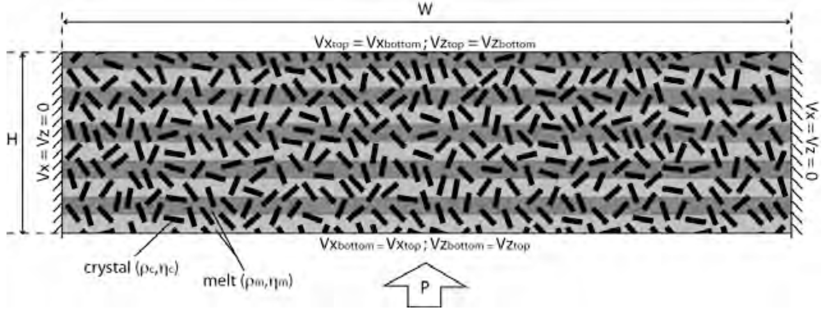


Figure 1 : Setup for the numerical experiments. H and W correspond respectively to the thickness and the width of the model box. Vx and Vz are the velocity components in the horizontal and the vertical direction, respectively. Boundary conditions are explained in details in the text.

In the crystal-free simulation (vertical laminar flow of a viscous fluid), our model exactly fits the existing analytical solution and the velocity field is Newtonian. In order to test the effect of crystal loading on this Newtonian flow, we performed 4 different experiments, testing two sizes of crystals (5 cm x 2 cm and 2.5 x 1 cm) in two different proportions (20 and 40%). Crystals are all considered homogeneous (i.e., same size and shape) and W = 4*H = 1 m. In the reference model, viscosity ratio (η_c/η_m) is set to 10^6 and densities are $\rho_m = 2400$ kg.m^{-3} and $\rho_c = 2700$ kg.m^{-3} for the melt and the crystals, respectively.

Results

Considering the general evolution of the model (Fig. 2), our numerical experiments show neither crystal rotation nor significant horizontal displacement of crystals toward the centre of the dyke. Nevertheless, despite these unexpected observations, our model reproduces other interesting features of the solid particles driven by a viscous fluid. All our experiments reach quickly a steady state. It is thus possible to study the dynamic of the system after only few time steps. The orders of magnitude for the vertical velocity are always the same at each time step for each experiment (Fig. 2).

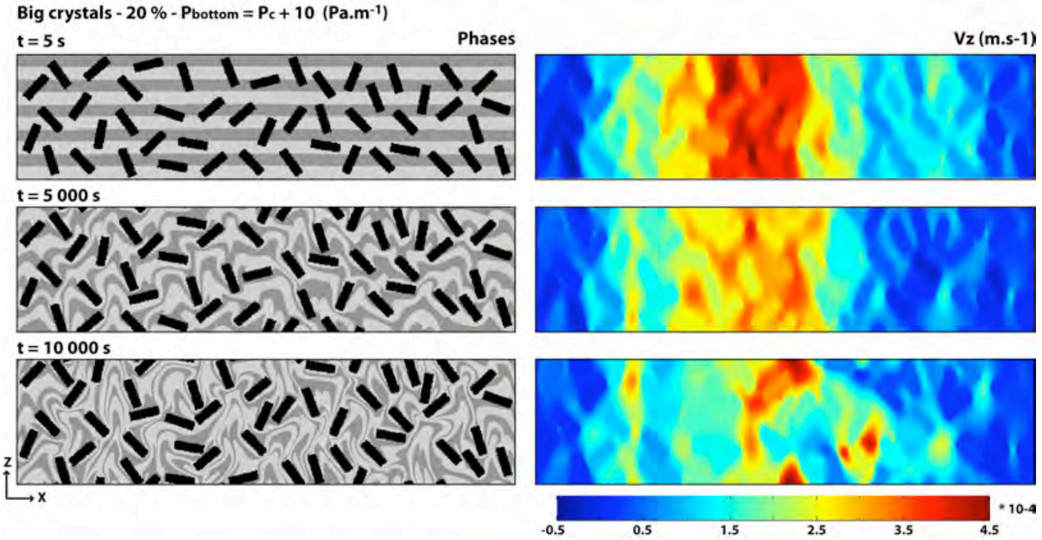


Figure 2: Phase evolution (left) and vertical velocity component (right) for an experiment where partitioning between melt and crystals occurred (10 Pa.m^{-1} more than the P_c value, see text). W = 1m and H = 0.25m. Viscosity ratio between crystals and melt is 10^6. Density of the crystals and the melt are 2700 and 2400 kg.m^{-3}, respectively.

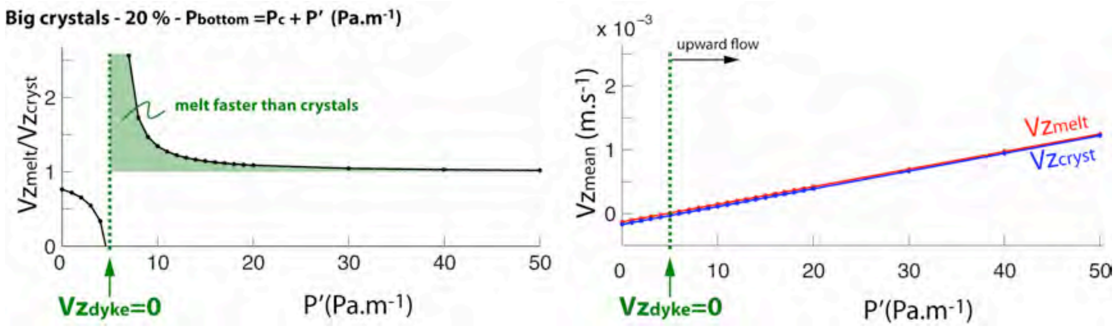
Our simulations show that dyke evolution is entirely controlled by the pressure gradient. Considering the melt only, the pressure gradient P_0 needed to balance its weight is $P_0 = \rho_m * g$, where ρ_m is the density of the melt and g the gravity constant. At P_0, addition of denser crystals in the system leads to negative (downward) vertical velocities. To counterbalance this effect, the pressure gradient (P) has to be higher. Hence, if the dyke is completely filled with crystals (100%), the pressure required to balance the whole system is $P_{100} = \rho_c * g$, where ρ_c is the density of the crystals. At $P > P_{100}$, all the material contained in the dyke is transported toward the surface at high velocity.

Between these two end-members (P_0 and P_{100}), a critical pressure gradient P_c can be defined where the system is balanced ($Vz_{dyke} = 0$). For $P < P_c$, the velocity field is downwards within the dyke, due to gravity. For $P > P_c$, the velocity field is upwards. This P_c value can be approximate by:

$$P_c \sim P_0 + (\rho_c - \rho_m) * X_c * g$$

where X_c constitutes the fraction of crystals in the dyke. Indeed, due to the heterogeneous distribution of the crystals across the dyke width, this theoretical P_c value can be slightly different but is always close to this P_c value (Fig. 3).

The major result presented here concerns crystal-melt segregation during magma ascent. We show that for a pressure gradient slightly higher than P_c, the melt velocity can be more than two times higher than the crystals velocity (Fig. 3). When the pressure gradient increases, this partitioning capacity decreases and the time needed to separate melt and crystals becomes larger. At the same time, the velocity of the whole magma increases and thus, a longer vertical transport distance is required for partitioning.



Big crystals - 20 % - $P_{bottom} = P_c + P'$ (Pa.m^{-1})

Figure 3: Vertical velocity characteristics of melt and crystals. Left: Ratio between Vz_{melt} *and* $Vz_{crystal}$ *vs. P'. P' corresponds to the pressure gradient added to Pc to reach the total pressure gradient imposed* ($P'=P_{total} - P_c$)*. The green area corresponds to the zone where melt ascents faster than crystals; Right:* Vz_{mean} *for melt and for crystals vs. P'. All other parameters are the same as on Fig. 2. P'= 0 corresponds to the theoretical value where* $P = P_c$*.*

Other results from our parametric study (e.g., the effect of the density difference between crystals and melt, the viscosity ratio effect, the effect of the heterogeneity in crystals size) will also be presented.

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