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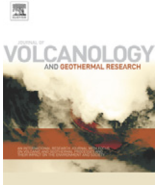

Numerical modeling of the development of small-scale magmatic emulsions by Korteweg stress driven flow

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The occurrence of micron to millimeter size globular heterogeneities in igneous rocks is frequently explained by processes of liquid immiscibility. However, such textures have also been documented in miscible magmatic pairs. In this study, the ability of miscible magmas to develop transient surface tensions and mimic the behavior of immiscible liquids is tested for the whole spectrum of magmatic compositions. We implemented a numerical model that includes the effect of gradient stresses (namely Korteweg stress) in order to investigate the role of such stresses in the evolution of diffusive interfaces. The results show that an initially elongated heterogeneity surrounded by a miscible and compositionally diverse magma will tend to minimize its contact surface by relaxing to a spherical shape, advected by a Korteweg stress driven flow. If the initial aspect ratio of the heterogeneity exceeds a critical value, surface minimization may be achieved by drop breakup. In addition, it is shown that two neighboring heterogeneities may coalesce to a single spherical drop. These results imply that even for fully miscible magmas, rheological barriers may prevent efficient mechanical intermingling and induce the formation of small-scale globular textures, analogous to those commonly observed in immiscible liquids. A better understanding of the role of Korteweg stress may be of the utmost importance for deciphering the textures generated by the interaction of compositionally diverse magmas.

1. Introduction

Small-scale (micron to millimeter) heterogeneities that consist of globules surrounded by a glassy matrix of different composition have been frequently observed in igneous rocks. Such globules may display more or less smooth interfaces and their spatial distribution may result in the development of an emulsion-like texture. The intimate spatial association and particular textural characteristics have led many petrologists to infer the existence of a genetic link between host rock and enclosed globules. For instance, it has been suggested that the occurrence of such textures may be associated with processes of immiscible separation from a common parent magma (e.g. Philpotts, 1979; Roedder, 1979; Veksler et al., 2007). The theory of immiscible separation became especially popular among carbonatite scholars. Small-scale carbonatite globules surrounded by silicate glass have been frequently documented in natural samples (e.g. Kjarsgaard and Peterson, 1991; Bailey et al., 2005, 2006) as well as in experiments (e.g. Freestone and Hamilton, 1980; Brooker, 1998). Occasionally, silicate globules immersed in a carbonatite matrix have also been observed (e.g. Macdonald et al., 1993). In particular, the development of carbonate globules in experimental products has lead to the definition of fields of miscibility between silicate and carbonatite magmas, although the textural interpretation of such globules may be ambiguous (Lee et al., 1994). Where the process of immiscible separation was not supported by geochemical evidence, it had been proposed that such textures resulted from the mechanical interaction of two immiscible and genetically unrelated magmas (Cooper and Reid, 2000; Chazot et al., 2003). In any case, textural evidence of liquid immiscibility has relied on the fact that the attainment of globular shapes must be related to the action of surface tension arising from a positive enthalpy of mixing (i.e. thermodynamic immiscibility). However, such textures are not unequivocally related to the dispersion of magmatic droplets in a pool of an immiscible magma. For instance, similar textures have been observed, both in natural samples and in laboratory experiments, in silicate–silicate magmatic pairs which have been proven to be mutually miscible (e.g. Yoder, 1973; Gourgaud and Maury, 1984; Mungall, 1994; Schreiber et al., 1999; Zimanowski et al., 2004). Recently, Zieg and Marsh (2005) advocated the development of a viscous emulsion between two miscible magmas as a possible petrogenetic process that might explain the formation of the Sudbury bimodal igneous complex.

The possibility for miscible liquids to develop a transient surface tension and mimic the behavior of immiscible liquids was first suggested by Korteweg (1901). Korteweg's mathematical formulation was generalized by Joseph and Renardy (1992) who added a second order tensor to the Navier–Stokes equations in order to account for the

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stress generated by compositional gradients at the interface between two miscible liquids. The concept of Korteweg stress was applied to magmas by Mungall (1994). He presented results of experiments in which smooth menisci formed at the interface between two miscible magmas and suggested that their formation was related to the action of gradient stresses. In the last decade both numerical models and fluid dynamic experiments have been devised in order to provide definitive evidence of the existence of transient interfacial tensions and assess the effects of Korteweg stress in more detail (e.g. Chen and Meiburg, 1996; Joseph et al., 1996; Petitjeans and Maxworthy, 1996; Chen et al., 2001; Chen and Meiburg, 2002; Kostin et al., 2003; Bessonov et al., 2004; Pojman et al., 2006, 2007; Zoltowski et al., 2007). The interest in Korteweg stress theory applied to geophysics was revived by a recent publication (Morra and Yuen, 2008) in which it was suggested that Korteweg stress may play a significant role in the Earth's dynamics wherever sharp compositional gradients exist. They envisaged that Korteweg stress may affect processes occurring at different scales, from subduction and plume rise to crystal lattice deformation. Although their study was mostly focused on large scale mantle dynamics, they stated that “it is almost impossible to assess the influence of K-stresses without quantifying the smallest scale effects. Evaluation of these effects of one scale to another will require accurate numerical modeling […]”. The numerical modeling of the effects of Korteweg stress at small scales is the main focus of this research. In particular, we present a model that includes the effect of Korteweg stress on two interacting miscible magmas at the micro-scale. The aim of our simulations is to investigate the effects of gradient stresses on small-scale heterogeneities surrounded by a miscible and rheologically distinct magma. In particular, we aim to establish whether such stresses may induce the development of instabilities such as drop relaxation, breakup and coalescence that may lead to the formation of globular textures, which are analogous to those observed in immiscible liquids. To the best of our knowledge this is the first application of Korteweg stress based simulations to the field of igneous petrology.

2. Consideration of magma interaction processes

It is well established that the interaction of diverse magmas plays a primary role in the evolution of magma chambers. However, the details of two-magma interaction dynamics may be difficult to assess, because evidence is rarely preserved in rocks. The geological record may be obliterated by the intrinsic dynamic nature of such processes and the tendency of perturbed systems to develop a new equilibrium.

Magmatic heterogeneities, occurring for instance as enclaves of various sizes as well as flow banding textures, may represent markers of magmatic interaction and have been successfully used in order to retrieve information about interaction dynamics (e.g. Perugini et al., 2003; Holtz et al., 2004; Ventura et al., 2006). However, the initial stages of magmatic interactions are still poorly understood. For instance, the physical mechanism leading a continuous magmatic body to be dispersed as a series of roughly spherical heterogeneities is still unclear (e.g. Ventura et al., 2006). Roedder (1979) argued that in the absence of a suitable mechanism capable of dispersing small-scale heterogeneities with sharp contacts, immiscible separation remains a more likely process. However, as we pointed out in the previous section, such textures have been observed in clearly miscible magmatic pairs. Moreover the existence of sharp contacts may be ascribed to prompt chemical diffusion being inhibited by quenching due to heat exchange between the interacting magmas or rapid ascent to the surface.

Recently, it has been suggested that the occurrence of viscous fingering patterns at the interface between distinct magmas may testify to the first stages of magmatic interaction after the injection of a new batch of magma into a magma chamber (Perugini and Poli, 2005; Perugini et al., 2005). Moreover it has been argued that the dispersion of small-scale heterogeneities characterized by spherical to more or less elongated shapes may result from the disruption of such viscous fingers (Perugini et al., 2007). The ability of discrete bodies to develop from the breakup of viscous fingers has also been shown numerically by De Wit and Homsy (1999).

Bearing in mind the above considerations, we attempt, with our numerical model, to contribute to a better insight of the initial stage of magmatic interaction. In particular, we aim to identify the mechanisms linking the incipient interaction of two discrete bodies of magma, to the development of a dispersion of one magma into the other in the form of small-scale globular heterogeneities and assess the role of Korteweg stress in such a scenario.

3. Theoretical model

In order to test the effect of Korteweg stress on interacting miscible magmas, we have modeled the evolution of small-scale magmatic heterogeneities enclosed in a miscible magma of contrasting composition. Our approach is similar to those used in the non-magmatic numerical models of Kostin et al. (2003) who described the temporal evolution of a prolate drop surrounded by a miscible liquid and of Lamorgese and Mauri (2006) who studied the evolution of neighboring spherical drops immersed in a miscible matrix. The set of equations, the values of the physical parameters and the scale of the domain adopted in our method are specifically adapted to the study of micron to millimeter size magmatic emulsions, in agreement with the textures observed in the literature cited in Section 1. The model is described by the following set of dimensionless equations that express the conservation of 1) mass 2) momentum and 3) chemical species:

$$\nabla \cdot v = 0 \tag{1}$$

$$\frac{1}{\mathrm{Sc}}\left(\frac{\partial v}{\partial t} + v \cdot \nabla \otimes v\right) = \nabla \cdot \left\{ -pI + [\exp(\lambda(c-1))]\left[\nabla \otimes v + (\nabla \otimes v)^T\right] - \frac{\lambda^2}{DB^2\mu_{\max}}\delta\left[(\nabla c)^T \nabla c\right] \right\} \tag{2}$$

$$\frac{\partial c}{\partial t} + v \cdot \nabla c = \nabla \cdot \nabla c \tag{3}$$

v, p, c, and t are dimensionless variables (velocity, pressure, composition and time) which are related to the corresponding physical variables by means of the following normalizations:

$$x_i = \frac{\hat{x}_i}{L} \tag{4}$$

$$t = \frac{\hat{t}D}{L^2} \tag{5}$$

$$v = \frac{\hat{v}L}{D} \tag{6}$$

$$p = \frac{\hat{p}L^2}{\mu_{\max}D} \tag{7}$$

$$c = \frac{\hat{c} - \hat{c}_{\min}}{\hat{c}_{\max} - \hat{c}_{\min}} \tag{8}$$

where the caret symbol denotes the physical variables; x_i represents the spatial coordinate; L is the largest side of the domain. The rest of