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Magnetic and shape fabrics of magnetite in simple shear flows

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ABSTRACT

The magnetite fabrics measured by anisotropy of magnetic susceptibility (AMS) and by shape preferred orientation (SPO) optical methods are classically used as flow kinematics indicators in lava flows. The development of magnetite fabrics during simple shear strains $\gamma \leq 20$ was performed using a suspension of 1% volume fraction of multidomain magnetite randomly contained in a mixture of silicone and wax. We measured AMS fabric and SPO ellipsoids by calculating a quadratic shape tensor from oriented thin-sections. For $\gamma < 8$, fabrics obey to the theoretical model of rotation of Jeffery (1922). Fabrics are usable to determine the flow kinematics, including the amount of applied finite strain. For $\gamma > 8$, fabric elements, foliation and lineation, are stabilised closely parallel to the flow plane and the shear direction, respectively. Two- and three-dimensional numerical simulations using measured aspect ratios of magnetite point out that the large scattering of aspect ratios and the initial orientation distribution of particles are together responsible for a wide-ranging loss of periodicity. The stable AMS and SPO fabrics observed at large strains in experiments are the result of these primary fabric properties combined to collisions between particles and, possibly, their complex three-dimensional shapes. In addition, the constant angular relationship observed at large strains between fabrics and flow components is related to the transient collisions.
Consequently, the determination of the lava flow kinematics by using fabric properties measured either by AMS or by SPO analyses should be indubitably associated to a detailed study of the three-dimensional shape of the solid carriers. Regularly shaped populations of low elongated particles will be capable to produce cyclic to oscillating fabrics, while the fabric of elongated particles will be more sensitive to the shape parameters and collisions, ultimately favouring stable fabrics at large strains.

1. Introduction

Magmas flowing from their source are usually regarded as suspensions of crystals that behave as active (rigid) markers crystallising and rotating in a matrix (the melt) submitted to deformation. From decades, both shape preferred orientation (SPO) and anisotropy of magnetic susceptibility (AMS) of crystal populations are fabric components widely used as flow direction and deformation regimes indicators (Cañón-Tapia, 2005; Borradaile and Jackson, 2010 for recent reviews). AMS is used in the case of paramagnetic and ferrimagnetic crystals such as biotite and multidomain magnetite respectively, for which the magnetic ellipsoid closely corresponds to the shape of the crystal (Borradaile, 1988; Rochette et al., 1992; Tarling and Hrouda, 1993; Borradaile and Henry, 1997; Hrouda and Ježek, 1999; Borradaile and Jackson, 2010). Two-dimensional image analysis on rock-sections gives direct quantification of the SPO fabric ellipse (Launeau et al., 1990), while tensorial reconstruction applied to any three perpendicular sections yields the SPO ellipsoid (Owens, 1984; Launeau and Cruden, 1998; Launeau and Robin, 2005). Many studies have applied, sometimes combining, these two approaches to determine the flow dynamics during magma emplacement in dikes (Philpotts and Asher, 1994; Tauxe et al., 1998; Callot et al., 2001, Aubourg et al., 2002; Geoffroy et al., 2002; Féménias et al., 2004; Poland et al., 2004; Bascou et al., 2005, Philpotts and Philpotts, 2007; Aubourg et al., 2008, Hastie et al., 2011), lava flows (Cañón-Tapia et al., 1995; Cañón-Tapia, 2005; Loock et al., 2008) and domes (Arbaret et al., 1993; Cañón-Tapia and Castro, 2004; Závada et al., 2009). When identical, AMS and SPO fabric properties are linked to magma flow dynamics by applying the theory of the motion and rotation of the crystals in the sheared medium (Dragoni et al., 1997).

The theoretical evolution of the SPO of rigid markers with progressive strain is based on Jeffery (1922) giving the cyclic motion of a uniaxial particle in a matrix submitted to deformation. Analytical solutions of these equations have been determined for different flow geometry such as simple shear (Jeffery, 1922), pure shear (Gay, 1968, Reed and Tryggvason, 1974) and axial flattening (Debat et al., 1975, Ježek et al.,

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1996; Freeman, 1985 for general systems). The model considers that; (1) the matrix has a Newtonian behaviour as recorded for silicate melts in the natural shear strain rates range (Petford, 2003); (2) the particle populations exhibit random initial orientations, homogeneous aspect ratios; and, finally, (3) never interact. Moreover, the influence of newly appearing and growing crystals during cooling is not taken into consideration (Launeau and Cruden, 1998). Among these simplifications, shape distribution and mechanical (for SPO) and magnetic (for AMS) interactions between particles have been recognised for a long time as critical parameters favouring fabric deviation from theory (Blumenfeld and Bouchez, 1988; Tikoff and Teyssier, 1994; Grégoire et al., 1995; Arbaret et al., 1996; Gaillot et al., 2006).

The influence of the grain shape distribution on SPO development at large simple shear strains γ remains poorly quantified. The numerical 2D simulations of Ildefonse et al. (1997) have evidenced a departure from a homogeneous population for normal log and Gaussian distributions having variances higher than 0.3. In particular, for $\gamma>10$, the SPO lineation stabilises parallel to the flow direction. A similar result is produced if new grains are added by continuous crystallisation in a melt during deformation (Launeau and Cruden, 1998).

In addition, contact-interactions and distribution anisotropy of magnetite grains have been extensively invoked as two factors that could potentially change the SPO, and more particularly, the AMS fabric properties (Hargraves et al., 1991; Grégoire et al., 1995; Cañón-Tapia, 2001; Gaillot et al., 2006). Borradaile and Puumala (1989) point out experimentally the good link between AMS fabrics of low concentration suspensions of magnetite and flow kinematics during moderate pure shear deformation (25% shortening). Similar conclusions were proposed by Cogné and Canot-Laurent (1992) for hematite suspensions submitted to simple shear $\gamma\leq1.4$. Recent works concluded that magnetic interactions, contact interactions through clustering, and intrinsic shape all play a role on AMS and SPO magnetite fabrics acquisition (Borradaile and Puumala, 1989; Hargraves et al., 1991; Grégoire et al., 1995; Grégoire et al., 1998; Cañón-Tapia and Pinkerton, 2000; Cañón-Tapia, 2001; Gaillot et al., 2006). When particles are nearly isotropic in shape the AMS tensor is controlled by the distributions of grains (Hargraves et al., 1991). Grégoire et al. (1998) and Cañón-Tapia (2005) concluded that the AMS fabric remains mainly controlled by the shape of magnetite when their average aspect ratio is larger than 1.6. This conclusion has been also reached by Gaillot et al. (2006) from analytical models and experiments on magnetic interactions. So far, however, the link between both AMS and SPO fabrics and flow dynamics remains debated in particular for large finite strains that are often recorded in lava flows and dykes.

In this contribution we study the behaviour of low concentrations (1% volume) of magnetite particles undergoing large simple shear deformations ($\gamma\leq20$). Although many different deformation regimes are found in lava flows (Merle, 1998; Loock et al., 2008) and domes (e.g. Závada et al., 2009), we will focus on the simple shear deformation as it corresponds to the most common deformation regime encountered along conduit margins and bases of lava flows where large finite strains are achieved (Merle, 1998). In addition, the simple shear is used as a case study in many analogue (Fernandez et al., 1983; Ildefonse et al., 1992); numerical (Ježek et al., 1996) and experimental previous works (Borradaile and Puumala, 1989; Cañón-Tapia and Pinkerton, 2000). Since the link between AMS and SPO of a magnetite-alone suspension may be a function of intrinsic susceptibility (Archanjo et al., 1995) or shape geometry (Hrouda, 1982; Borradaile, 1991; Tarling and Hrouda, 1993; Borradaile and Henry, 1997; Grégoire et al., 1998; Cañón-Tapia and Castro, 2004), we combined AMS measurements with image analysis of SPO on oriented thin-sections. A three-dimensional SPO ellipsoid was calculated using the quadratic shape tensor of Shimamoto and Ikeda (1976) by combining three mean grain inertia tensors measured on three perpendicular sections (Owens, 1984; Launeau and Cruden, 1998). Two- and three-dimensional numerical simulations are used to investigate the influence of both aspect ratio distribution and contact interactions on SPO and AMS fabric development. A third numerical simulation is developed in order to estimate the probability of collisions of particles during shearing. Relationships between SPO and AMS fabrics and consequences of shape distribution and contact interactions on the use of fabrics as flow kinematics indicators at large strain regimes ($\gamma\leq20$) are discussed.

2. Apparatus and starting material

2.1. Apparatus

In order to ensure homogeneous, large simple shear strain ($\gamma>4$) within the magnetite suspension, we used a ring-shear apparatus composed of two concentric cylinders, which rotate with the same angular velocity but in opposite directions (Passchier and Sokoutis, 1993; Arbaret et al., 1997, Arbaret et al, 2001; Mancktelow et al., 2002; technical description of the apparatus is in Arbaret et al., 1996). The fixed bottom of the ring shear rig is covered with a 2 mm thick layer of low-viscosity mineral oil acting as a lubricant. The fixed external reference frame used for measurements is defined with XY the surface of the undisturbed shear flow parallel to the surfaces of the cylinders and X the direction of the shear (Fig. 1a).

In the ring shear apparatus the simple shear strain is not constant but depends on the radial distance r between the centre of the sampling area and the rotation axis of the ring (Reiner, 1960). The shear strain rate $\dot{\gamma}$ applied at the sample position can be calculated with the equation proposed by Masuda et al. (1995) and experimentally confirmed by Arbaret et al. (2001) in a Newtonian matrix:

$$\dot{\gamma}=\frac{-2\left(\dot{\Omega}_i-\dot{\Omega}_e\right)}{\frac{1}{R_i^2}-\frac{1}{R_e^2}}\frac{1}{r^2}, \tag{1}$$

where R_e and R_i are the radii and $\dot{\Omega}_e$ and $\dot{\Omega}_i$ are the angular velocities of the external and internal boundaries respectively. In the ring shear used for these experiments, R_e is 149.5 mm and R_i is 96.0 mm. The strain gradient affecting the sampling zone centred between the two cylinders was calculated by measuring the displacement rate of solid markers disposed at the surface of the material. We found a strain ranging from $\gamma=18.5$ to $\gamma=21.7$ for a maximum mean finite strain $\gamma=20$.

2.2. Starting material

The apparatus was filled with a suspension of 1% volume fraction of magnetite grains (Fig. 2). The magnetite grains were extracted from the basalt of the Tiretaine lava flow (Chaîne des Puys, French Massif Central, Loock et al., 2008). We selected the largest sieved crystal fraction ranging from 50 to 100 μm. Microprobe analysis of 50 grains showed that the compositions are ulvospinel-magnetite solid solution with the following average composition: $Mg_{0.2}\,Fe^{II}_{1.3}\,Al_{0.2}\,Fe^{III}_{0.3}\,Ti_{0.5}\,O_3$ calculated on 3 cations. This result is consistent with Curie temperatures at 90 °C and 120 °C found by Loock et al. (2008). The particle size, the chemistry and the Curie temperatures indicate that the main susceptibility carrier for these experiments is multidomain titanomagnetite. Such mineral is known to have a normal magnetic fabric with an AMS dominated by the shape of the crystal. The 1% concentration of magnetite was chosen (1) to insure that the apparatus used for AMS measurements as described below is not saturated; and, (2) the particles are statistically far enough from each other in the starting product to reduce the magnetic interactions between neighbouring magnetite that can change the principal axes of the AMS ellipsoid (Hargraves et al., 1991; Grégoire et al., 1995; Grégoire et al., 1998). Furthermore, although magmas emplaced near, or at the surface, usually contain oxide up to 5% volume fraction (Hargraves et al., 1991), the chosen volume fraction used for our experiments is comparable to magnetite concentrations found in many