RIGID PARTICLES IN SIMPLE SHEAR FLOW: IS THEIR PREFERRED ORIENTATION PERIODIC OR STEADY-STATE?

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ABSTRACT

The theory of the rotation of isolated rigid particles within a linearly viscous fluid deforming in progressive simple shear is often invoked in models of Shape Preferred Orientations (SPO) of crystals in igneous rocks. A classical result of the theoretical model is that the SPO should rotate and pulsate with increasing strain, with a periodicity equal to that of the rotation of an individual particle. However, the initial theoretical model makes a large number of assumptions, many of which are unlikely to be satisfied by actual crystalline suspensions in magmatic melts. The purpose of this note is to review three of the reasons why periodicity of rigid particle SPO may not really be expected in igneous rocks: (i) SPO in igneous rocks are generally defined by suspensions of crystals that are concentrated enough to allow mechanical interactions between the crystals; (ii) the porphyroblast/matrix interface may not always be coherent; and (iii) the aspect ratios of the crystals defining the SPO are unlikely to be unique and constant, as assumed in the model. The last point is discussed on the basis of some 2D simple calculations of the development of SPO defined by different types of heterogeneous populations of particles. The combined effects of these deviations from the standard model point to two fundamental conclusions: (i) there is no simple relationship between fabric and finite strain, and (ii) the SPO in magmatic rocks may be considered as good markers of the flow, whatever the significance of the inferred flow pattern in terms of geodynamics and/or emplacement processes.

INTRODUCTION

The use of fabrics as strain and/or kinematic markers in igneous rocks has now become a popular technique for the structural analysis of magmatic intrusions. Shape preferred orientations (SPO) are obtained in rocks either from direct field measurements (e.g. Fernandez, 1988; Hippert, 1994; Nicolas and Boudier, 1995) or from measurements and image analysis of sections/thin sections (e.g. Allard and Benn, 1989; Launeau et al., 1990; Philpotts and Asher, 1994). On another hand, the Anisotropy of Magnetic Susceptibility (AMS) technique is widely used for fabric measurements and has proved to be quite powerful when mapping fabrics otherwise difficult to recognize in the field (e.g. Gullet et al., 1983; Cogné and Perroud, 1988; Bouchez and Diot, 1990; Gleizes et al., 1993; Cruden and Launeau, 1994; Bouchez and Gleizes, 1995; Raposo and Ernesto, 1995).

It is widely recognized that fabrics in igneous rocks, when related to magmatic flow, are shape preferred orientations of rigid particles suspended in a viscous fluid (e.g. Blumenfeld and Bouchez, 1988; Paterson et al., 1989; Fernandez and Laporte, 1991; Nicolas, 1992). The theory of rotation of isolated rigid particles within a Newtonian fluid (Jeffery, 1922; Fernandez, 1987; Passchier, 1987; Jezek, 1994; Masuda et al., 1995) is invoked in models of SPO of crystals in rocks. A classical result of this model is that, in simple shear flow, the SPO should rotate and pulsate with increasing strain (Fernandez, 1987; Fernandez and Laporte, 1991; Ildefonse et al., 1992a; Jezek et al., 1994). This periodic behaviour contrasts with the steady-state orientation and progressively increasing intensity of the fabric obtained in a coaxial flow (Ildefonse et al., 1992a; Jezek et al., 1994; Masuda et al., 1995). In intermediate non-coaxial flows, the fabric develops towards a stable orientation or otherwise, depending on the ratio between the particle aspect ratio and the degree of non-coaxiality of the flow (Passchier, 1987; Jezek et al., 1994; Masuda et al., 1995).

Following this simple model, flow kinematics inferred from rigid particle SPO in igneous rocks may be highly questionable when the latter is periodic, i.e. when the flow is non-coaxial. However, the initial theoretical model makes a large number of assumptions, many of which are unlikely to be satisfied by actual crystalline suspensions in magmatic melts. The purpose of the present paper is to review some of the natural causes for a different rotational behaviour of rigid particle SPO in igneous rocks.

MECHANICAL INTERACTIONS

The most obvious modification of the rotational behaviour of the SPO is probably that due to mechanical interactions between the crystals of a magmatic suspension. The effect of interactions between rigid particles has been described experimentally (Ildefonse and Fernandez, 1988; Ildefonse et al., 1992a; Ildefonse et al., 1992b). It was shown that in concentrated suspensions, interactions are responsible for slowing down or blocking the rotation of neighbour particles, resulting in 1) the decrease in intensity of the SPO in both coaxial and non-coaxial flows, and 2) the break-down of the periodicity of the SPO development in simple shear flow. The latter is particularly important as the fabric then tends to align with the shear plane, resembling a passive fabric behaviour. This is best illustrated by figure 1, showing the difference in sub-fabric orienta-
tion between the disturbed and undisturbed particles of the same population (aspect ratio 2.5) in a given experiment (Ildefonse et al., 1992a).

More recent 2D experiments (Arbaret et al., 1996) have shown that the stabilising effect of interactions on the orientation of the fabric is still observed at lower concentrations of particles (as low as 13%).

![Graph](image)

*Figure 1.* Experimental test of the effect of mechanical interactions between rigid particles on the development of shape preferred orientations (after Ildefonse et al., 1992a). Particle aspect ratio is 2.5; the fabric orientation is given with respect to the shear plane. Particles are considered as undisturbed if they were able to rotate more than 90 degrees during the experiment (if no interaction occurs, a particle with aspect ratio 2.5 should have rotated 180 degrees after a shear strain of 9.11). The results are compared with the evolution of a passive fabric.

**SLIP AT THE PARTICLE/MATRIX INTERFACE**

Another important parameter when considering the rotation of rigid particles in a viscous medium is the cohesiveness of the particle/matrix interface. Following Jeffery’s model, the rigid particle suspensions in rocks have always been considered as a continuous medium, with a perfectly cohesive particle/matrix interface. However, it was argued in a previous paper (Ildefonse and Mancktelow, 1993) that this interface may be discontinuous and slipping in several geological situations, including the melt-lubricated porphyroblast boundaries in a partially molten rock or a crystallising magmatic mush. The effect of slip at the rigid particle/matrix interface has been studied experimentally using analogue paraffin wax models (Ildefonse and Mancktelow, 1993). In spite of the low maximum shear strain ($\gamma = 3$) that could be obtained in the simple shear apparatus, the result showed a marked tendency for the particles to rotate toward a stable orientation close to the shear plane, similar to passive markers. Compared to the case with a cohesive interface, the particle rotation becomes slower when approaching the shear plane; rotation may even be reverse (Fig. 2) for particles initially oriented between 0° and -30° (Ildefonse and Mancktelow, 1993). The corresponding SPO will thus be stronger at a given shear strain, and it will tend to acquire a stable orientation, approximately parallel to the shear plane.
VARIABLE CRYSTAL ASPECT RATIOS

So far, most theoretical and experimental studies of the development of rigid particle SPO considered the case of populations of particles with a unique aspect ratio. However, this obviously does not apply to natural situations, where crystals in a suspension will usually display variable aspect ratios. Heterogeneous populations have been considered by Fernandez et al. (1983) and Fernandez and Laporte (1991), but they only discuss the resulting SPO in non-coaxial flow in terms of symmetry and 3D shape of the fabric. The effect of having variable particle aspect ratios on the orientation of the global fabric as a function of strain was not discussed. We address this problem, on the basis of simple 2D calculations of SPO developed in simple shear flow with various types of heterogeneous populations (theoretical or real) of non-interacting particles.

![Graph](image)

*Figure 2.* Experimental test of the effect on rigid particle rotation of slipping at the particle/matrix interface (after Ildefonse and Mancktelow, 1993). The rotation of rigid particles with various orientations and slipping interface (black lines) is compared with the rotation calculated using Jeffrey's model (grey lines). Particle aspect ratio is 2.5; the orientation gives the angle of the particle's long axis with respect to the shear plane. Reverse rotations were observed for particles initially oriented between 0° and -30°.

The angle $\theta'$ of each particle of the considered population with vertical is calculated, at any time, as a function of the shear strain $\gamma$, its aspect ratio $n$ and its initial angle $\theta$, using the equation given in Fernandez et al. (1983):

$$\frac{\sqrt{1-X^2}}{2} \gamma + \arctg \left( \frac{\sqrt{1-X}}{\sqrt{1+X}} \tan \theta \right) = \arctg \left( \frac{\sqrt{1-X}}{\sqrt{1+X}} \tan \theta' \right)$$

with $X = \frac{n^2 - 1}{n^2 + 1}$ (shape parameter).
At each calculated increment of deformation, the fabric intensity $D$ and its orientation $\alpha$ are given respectively by the eigenvalues ratio and the first eigenvector of the orientation tensor (Harvey and Laxton, 1980).

**BIMODAL POPULATIONS**

We first calculated the evolution of a fabric developed within a mixture of two populations of particles with aspect ratios 6/1 and 6/5. The low aspect ratio particles have a period of rotation (which is a function of the particle aspect ratio; Fernandez et al., 1983) approximately three times shorter than the high aspect ratio particles. Calculations were performed for various proportions of the two sub-populations (Fig. 3).

![Graph showing evolution of SPO with various mixtures of two homogeneous populations of non-interacting particles in a simple shear flow (aspect ratios 6/5 and 6/1). The fabric intensity $D$ and its orientation $\alpha$ are obtained respectively from the eigenvalues ratio and the first eigenvector of the orientation tensor (Harvey and Laxton, 1980).](image)

*Figure 3. Evolution of SPO with various mixtures of two homogeneous populations of non-interacting particles in a simple shear flow (aspect ratios 6/5 and 6/1). The fabric intensity $D$ and its orientation $\alpha$ are obtained respectively from the eigenvalues ratio and the first eigenvector of the orientation tensor (Harvey and Laxton, 1980).*

The fabrics developed within the mixtures are significantly different from those calculated for the two end-member homogeneous situations. Within the $\gamma$ range corresponding to the period of rotation of the high aspect ratio particle ($\gamma = 19.37$), the fabrics evolve following an intermediate and more complicated pattern than the single cyclic rotation calculated for homogeneous populations; the fabric intensity presents 3 dif-
ferent maxima. The most remarkable point is the reverse rotation of the fabric, which stays within a range of \( \gamma = \pm 20^\circ \) around the shear plane approximately from \( \gamma = 4 \) to \( \gamma = 12 \). It is also noteworthy that the mixed fabric momentarily disappears (D=1) when passing through the orientation 90° (perpendicular to the shear plane), instead of \( \pm 45^\circ \) in end-member situations, when reaching the critical shear strain for the high aspect ratio particles.

GAUSSIAN POPULATIONS

In the preceding example, the calculation was made with a mixture of two distinct populations with a given aspect ratio. Practically, such a mixture may easily be divided into two sub-populations that can be analysed separately. Fernandez et al. (1983) have shown how one can use this situation to find the sense of shear. In nature, however, each determined sub-population (for instance each mineral phase) usually presents a heterogeneous distribution of aspect ratios. As a first attempt to estimate the effect of this heterogeneity on the development of the fabric, the calculation was made with a Gaussian distribution of aspect ratios.

Populations of 1080 particles have been chosen, in order to maintain an isotropic distribution of the orientations in the initial stage (6 particles/degree). The mean aspect ratio was 2.5 in every population, the standard deviation ranged from 0 to 0.5 (Fig. 4).

Results of the calculation show that with increasing standard deviation (i.e. increasing departure from the ideal homogeneous population) the curves slightly deviate from the classical cyclic behaviour inferred from Jeffery's model (Fig. 5); the fabric intensity D varies less and the fabric orientation evolves progressively within a shorter range of orientations around the shear plane. Again, one can note that when defined by a heterogeneous population of particles, the fabric undergoes a reverse rotation instead of disappearing at \(-45^\circ\) and instantaneously reappearing at \(45^\circ\). However, the deviation from the homogeneous case remains weak.

![Figure 4](image)

**Figure 4.** Normalized Gauss distribution representing the variation of particle aspect ratio in the chosen populations. \( s = \) standard deviation; the mean value is 2.5.
Figure 5. Evolution of SPO with heterogeneous populations of non-interacting particles in a simple shear flow. The particle aspect ratios vary following a Gaussian distribution (Fig. 4). The curve $s = 0$ corresponds to the end-member homogeneous distribution (aspect ratio 2.5). $D$ and $\alpha$ are the same as in Figure 3.

NATURAL POPULATIONS

In order to have a better idea of the effect of the heterogeneity of particles aspect ratio on the development of the shape preferred orientation, the same calculation as in the previous examples has been performed with distributions of aspect ratios measured on natural populations of biotites and amphiboles (Fig. 6).

Figure 6. Distributions of the measured aspect ratios of 100 biotites (A) and 100 amphiboles (B) used as models of heterogeneous populations in the calculations.
These populations have been taken from 3D analogue experiments (Arbare, this volume). The main characteristic of such natural populations is the heterogeneity of the measured shape, as shown by the histograms of the aspect ratios of the minerals (Fig. 6). Note that the distributions grossly display a Gaussian shape, with high standard deviations, but also show an important asymmetry with respect to the mean value.

Results are shown in comparison with the curves obtained for homogeneous populations with an aspect ratio equal to the mean value of the natural populations (Figs. 7 and 8). The discrepancy between the two situations is spectacular, in both cases (biotites and amphiboles). As soon as the fabric approaches the shear plane, the cyclic rotation inferred from Jeffery's theory totally disappears; the fabric remains sub-parallel to the shear plane, with a shorter range of orientations for the elongated particles (biotites, ± 5°; Fig. 7) than for the shorter particles (amphiboles, ± 10°; Fig. 8). The intensity of the fabric rapidly decreases and remains around the same value as strain increases. Again, the best stability is achieved with the particles having the higher aspect ratio (biotites, Fig. 7); fluctuations of the fabric intensity are more pronounced in the amphibole case (Fig. 8).

![Figure 7](image)

*Figure 7. Calculated evolution of SPO with a heterogeneous population of non-interacting biotites (see Fig. 6a) in simple shear flow. The grey curve shows the evolution of a homogeneous population of particles with the mean aspect ratio (6.14), for comparison. The evolution is displayed for shear strain up to 50, in order to illustrate the quasi-steady-state nature of the SPO. D and ω are the same as in Figure 3.*

**DISCUSSION AND CONCLUSION**

The calculations presented herein demonstrate the influence of the variation in particle aspect ratio on the development of shape preferred orientation in a simple shear flow. The fabric tends to be more-or-less parallel to the shear plane while its intensity is decreased. This is due to the fact that any elongated particle rotates slower when parallel to the shear plane than when perpendicular to the shear plane. Furthermore the longer the particle the longer the time of residence around the shear plane. Consequently, when combining a number of different periods of rotation, corresponding to the different particles, there is always a larger number of particles more-or-less aligned with the shear plane. The only case where this effect is not very important is that of the Gaussian
distribution, because of the symmetry of the aspect ratio distribution around the mean value 2.5, the slower rotation of the longer particles being then balanced by the faster rotation of an equal amount of the shorter particles.

Figure 8. Calculated evolution of SPO with a heterogeneous population of non-interacting amphiboles (Fig. 6b) in simple shear flow. The grey curve shows the evolution of a homogeneous population of particles with the mean aspect ratio (3.1) for comparison. The evolution is displayed for shear strain up to 50, in order to illustrate the quasi-steady-state nature of the SPO. D and O are the same as in Figure 3.

The heterogeneous distribution of the particles aspect ratio has an effect on the development of SPO similar to the mechanical interactions and to a slipping particle/matrix interface, as reviewed above. Many deviations from the Jeffery’s model may occur in rocks, and the present review is far from exhaustive. For example, the continuous input of new particles into the system, which is probably the normal situation in a crystallising magma, will have exactly the same effect as the variability of the particle aspect ratios (P.Y. Robin and P. Launeau, personal communication; Launeau et al., 1995). The triaxial shape of crystals, instead of the axisymmetrical shape assumed in Jeffery’s model, should also be taken into account (Freeman, 1985; Jezeck et al., 1994).

The various processes, suggested by the observation of rocks, and that modify the rotational behaviour of rigid particles and/or of corresponding fabrics, point to the inadequacy of the Jeffery’s model to account for natural SPO. The major observed effect, clearly illustrated by Figures 7 and 8, is a break-down of the assumed pulsating fabric evolution: instead of undergoing its predicted cyclic development, the fabric tends to be a nearly steady-state feature. This implies two fundamental consequences:

1- there is no simple relationship between the fabric (both intensity and orientation) and finite strain,

2- the SPO in magmatic rocks may be considered as indicating the local flow direction, without any preconceived idea of the significance of the inferred flow pattern in terms of geodynamics and/or emplacement processes (see other contributions in this volume).

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Rigid particles in simple shear flow: in their preferred orientation periodic or steady-state?  R. Ildefonse, L. Abreau and M. Diniz

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