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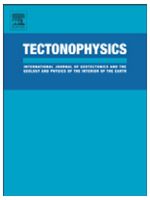

Characterisation of grain-size, shape and orientation of plagioclase in the Rooi Rand dyke swarm, South Africa

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ABSTRACT

Magmatic (type-A) fabric co-exists with dyke-orthogonal (type-B) fabric in both the plagioclase and opaque grain fractions in dykes of the Rooi Rand dyke swarm (RRDS). We present new data from the RRDS pertaining to the size, shape, texture and orientation of plagioclase. Texturally, the samples range from intersertal to sub-ophitic and phenocrystic (plagioclase-phyric). More than 90% of plagioclase grains are <33 μm in size and the modal size is 12.3 μm. The smallest, most abundant grains have modest shape ratios ($1.40<r<1.95$). Larger grains have relatively low shape ratios although grain-size and shape in the RRDS are essentially independent. Additionally, we investigate the angle between individual grains and the respective dyke margins in (sub-) horizontal thin-sections. This apparent imbrication angle, A_i, in conjunction with three dimensional fabric shape tensors and grain-size and shape data, shows that the most common grain-size class, with modest shape ratios (1.80–2.20), is predominantly associated with type-A fabric. The interaction of grains attempting to rotate in even-textured samples appears to have resulted in the lack of correlation between shape and size parameters and the orientation or intensity of the fabric, whilst grains with increasing r values show a tendency towards type-B fabric. Based on textural information and crystal size distribution, we suggest that plagioclase <80 μm in size grew as a result of a late-stage nucleation event, becoming increasingly anisotropic as a result of relatively rapid undercooling. Thus, late-stage, rapid nucleation of the plagioclase groundmass significantly affected the final fabric that developed, and the interaction of large, anisotropic grains has not played as significant a role in the development of type-B fabric as previously thought.

1. Introduction

There have been many studies quantifying fabric development in igneous rocks, whether using anisotropy of magnetic susceptibility (AMS) (Cañón-Tapia, 2004 and references therein) or the shape preferred orientation (SPO) of minerals (Baer, 1995; Blanchard et al., 1979; Blumenfeld and Bouchez, 1988; Cruden, 1990; Ferguson, 1979; Gay, 1966, 1968; Kattenhorn, 1994; Launeau, 2004; Launeau and Cruden, 1998; Launeau and Robin, 1996; Nicolas et al., 1988; Ramsay, 1989; Romeo et al., 2007; Willis, 1977). Lattice preferred orientations (LPO / CPO) and electron back-scattered diffraction (EBSD) studies have also been applied to the study of igneous petrofabrics in gabbro (Benn and Allard, 1989), volcanic flows (Bascou et al., 2005) and dykes (Chadima et al., 2009; Romeo et al., 2007). In the study of dykes these techniques are primarily applied to determine the original flow direction of magma as this has important geodynamic implications, particularly when dealing with a dyke swarm (Aubourg et al., 2008; Callot et al., 2001; Ernst, 1990; Ernst and Baragar, 1992; Ernst and Duncan, 1995; Kissel et al., 2010).

The development of flow-related petrofabrics in mafic dykes follows the general premise that a statistically significant number of grains will become imbricated (tiled) against the dyke walls during magma flow (Blanchard et al., 1979). The recognition of this flow-related fabric is typically based on the angle between the dyke and the tiled grains being in the range ~10–30°. These grains may be phenocrysts or they may be part of the finer grained groundmass in the solidified dyke. The most basic formation of a flow-related magmatic fabric in a dyke occurs under conditions of simple shear in a magma in which constituent grains become tiled against the walls of an intrusion. This would typically develop fabric symmetrical with respect to the dyke plane. Non-symmetrical fabrics may develop for a number of reasons, including but not limited to deformation of the dyke during emplacement and grain interaction (Callot and Guichet, 2003; Correa-Gomes et al., 2001). Oblate shaped AMS fabrics have been shown to develop intersection lineations and S/C type relationships (Callot and Guichet, 2003).

There are, however, many factors which may complicate the acquisition of such an ideal magmatic fabric. This has become evident from petrofabric studies as well as proposed quantitative models

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which attempt to account for simultaneous grain growth, rotation, interaction and overall magmatic fabric acquisition (Amenta, 2001; Archanjo and Launeau, 2004; Benn and Allard, 1989; Callot and Guichet, 2003; Correa-Gomes et al., 2001; Dragoni et al., 1997; Launeau and Cruden, 1998; Willis, 1977). The study of sub-fabrics and the role of grain shape and rotation is well documented (see citations above and Fernandez et al., 1983; Ildefonse et al., 1992; Jezek et al., 1994). In this paper we present directly observed, two-dimensional (2-D) data pertaining to the size, shape and orientation of plagioclase grains which define the igneous petrofabric in dolerite dykes of the Rooi Rand dyke swarm (RRDS).

In a recent study, the magnetic fabric and the mineral SPO fabric of the RRDS of South Africa was presented (Hastie et al., 2011a). Inverse fabric (referred to as type-B fabric) exists in the mineral SPO of plagioclase grains in ~40% of the data. This is an igneous petrofabric in which the foliation defined by plagioclase (and some opaque grains) is orthogonal to the dyke plane. A model of late-stage fabric acquisition owing to grain interaction has been proposed to explain this fabric orientation. It was also shown that finer grain sizes (<10 μm), particularly those measured by AMS, appeared to preserve the earliest, relict fabric (similarly to Romeo et al., 2007).

From visual inspection alone there seems to be no apparent relationship between the orientation of grains and their morphology (specifically the grain-size and shape ratio) in the RRDS. In one case (Fig. 4b of Hastie et al., 2011a) it was demonstrated that the type-B fabric component could be digitally separated from the type-A (normal) fabric component. The overall fabric comprises a type-A component defined by the majority of the grains and a type-B component defined by the less abundant fraction. It is difficult to judge visually whether particular fabrics are occupied by finer, or coarser grains than the average, or by grains of a particular shape.

2. Grain shape and flow fabric

Benn and Allard (1989) have quantified igneous fabrics in gabbro of the Oman ophiolite using mineral SPO and LPO. These authors found differences in fabric orientation according to grains of different shape ratios. In particular, low shape ratios ($r<1.5$) were less likely to reach an imbricated angle — where r is the ratio of long (L) to short (S) axes. A similar finding has been made by Ildefonse and Fernandez (1988) as well. A study of grain-size and magmatic fabric development in a single dyke of the RRDS by Kattenhorn (1994) revealed that grains of relatively high shape-ratio ($3<r<10$) were found predominantly within 30° of the dyke plane. Furthermore, there is evidence that continued crystallisation (i.e. an increasing number of grains) leads to grain interaction, and therefore a higher degree of grain imbrication is achieved (stable fabric of Ildefonse et al., 1997). Laminar flow also increases the likelihood of grain imbrication. The magnitude of shear (γ) is also important, particularly when considering the magnitude of shear imparted to each of the grain populations with different shape ratios (Launeau and Cruden, 1998).

Dragoni et al. (1997) demonstrated that magma flow typically produces cyclical rotation of grains. Indeed these authors showed that, when considering AMS fabrics, the orientation of the magnetic foliation (the $K1$–$K2$ plane) oscillates between vertical and horizontal positions in mafic sills of the Ferrar Province, Antarctica. Importantly these authors were able to show that these oscillations were dependant on the value of r. For example, as r increased, the greater the time interval $K3$ spent in a vertical position — which essentially defines a type-B fabric. This is contrary to the findings of Ildefonse and Fernandez (1988) and Kattenhorn (1994).

Launeau and Cruden (1998) provide a thorough analysis of grain orientation, fabric intensity and direct measurement of igneous fabric development in the Lebel syenite (Ontario, Canada) using both AMS and mineral SPO. These authors explore the factors involved in the progressive development of the igneous petrofabric in the Lebel syenite. These include free grain rotation, grain interaction and progressive crystallisation. They find that (1) the rate of rotation of grains is proportional to r. Thus, different populations of grains, with differing shape ratios will tend to develop their own preferred orientations provided the grains do not interact. Grains with the smallest r values will have rotated most, (2) fabric anisotropy (P') increases with increasing γ, particularly when there is a component of pure shear (i.e. flattening). Additionally, a pure shear component greatly increases the degree of preferred orientation (Rf_φ) for grains of high shape ratio, (3) at high shear magnitudes ($\gamma>6$) preferred orientations begin to show cyclicity; whereby populations of grains with differing values of r have more intense or less intense degrees of preferred orientation. Thus, obliquities between sub-fabrics are a function of their shape ratio and the shear magnitude, (4) progressive simple shear in a nearly crystallised magma (involving grain interaction) will result in anisotropic grains rotating into the shear plane. These grains will most likely maintain a stable orientation irrespective of grain-size and shape and (5) if grain-size is related to time then each grain-size population will have its own range of shape ratios and distribution of preferred orientation. The authors, however, indicate that the distribution of grain sizes in the Lebel syenite appears to be independent of grain shape and preferred orientation. It is thus the product of magmatic, progressive crystallisation, with strong interaction of grains during the final stages of emplacement.

More recently, Cañón-Tapia and Chávez-Álvarez (2004) performed an investigation of simulated grain movement and rotation — primarily in the context of AMS. The orientations of the principal axes of the susceptibility tensor ($K1$, $K2$ and $K3$) were monitored during continuous deformation (in this case grain rotation in a viscous medium). The simulations of particle movement focused on using groups of data with different initial orientations, and increasing shear strain. The results of these simulations showed that (1) the grain shape (r) primarily controls the periodicity of particle rotation, (2) the fabric intensity (anisotropy) fluctuates with particle rotation due to the original orientation and shape (r) of the grains, (3) oblate particles are more likely to be imbricated with $K3$ normal to the dyke plane, which is consistent with the model of Geoffroy et al. (2002) who showed that oblate fabrics tend to be "normally" imbricated, with the foliation being within ~30° of the dyke plane and (4) prolate grains are more likely to produce correctly imbricated, type-A magnetic fabric irrespective of the amount of shear. However, areas of little or no deformation (e.g. the centre of a dyke) yield poorly grouped AMS irrespective of the value of r.

There are number of ways in which the above findings may be applicable to the study of the RRDS. Firstly, one might expect to find that the large, most anisotropic grains will tend to be restricted in their movement owing to their larger size, and later interaction during simple shear. Secondly, there should then be a strong relationship between the grain shape (r) and preferred orientation. Thirdly, the distribution of grain-size may provide, at least qualitatively, an indication of the crystallisation behaviour. The sliding of grains past one another will be important in the shear plane, presumably most evident in the foliation plane. Finally, the fabric studied in the solidified dykes is unlikely to be representative of the early history in the fabric development. Given that the Lebel syenite is of a different composition and not a sheet-like intrusive, however, it is prudent to be cautious about inappropriate comparison. The above brief synthesis suggests that there is a correlation between the orientation of a fabric and its scalar parameters — although it has not been shown previously if this can be directly applied to the grains which constitute the fabric, as we attempt to do here.

3. Aim

We explore the interdependence of grain-size, shape and orientation of plagioclase within the igneous petrofabric of the RRDS in an