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The relation between magnetite and silicate fabric in granitoids of the Adamello Batholith

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ABSTRACT

The link between the macroscopic silicate fabric and the magnetite-controlled AMS (anisotropy of magnetic susceptibility) fabric in ferromagnetic rocks was investigated through a comprehensive comparison between different fabric measurement techniques. Sample lithologies include tonalites and granodiorites from the Lago della Vacca Complex, Adamello Batholith, Italy. The datasets used to assess the link between subfabrics and the coherence between methods include: 1) macroscopic silicate fabric measured directly in the field; 2) macroscopic silicate fabric derived from image analysis (IA) of outcrop pictures and sample pictures; 3) shape-preferred orientations (SPO) of mafic silicates, 4) SPO of magnetite, and 5) calculated distribution of magnetite grains from computer-assisted high-resolution X-ray tomography (X-ray CT) images; 6) fabrics derived from the AMS. Macroscopic mineral fabrics measured in the field agree with the IA results and with the SPO of mafic silicates obtained from the X-ray CT imaging. The X-ray CT results show that the SPO of the magnetite grains are consistent with the AMS data whereas the spatial distribution of the magnetite grains is less compatible with the AMS fabric. This implies that the AMS signal is mainly controlled by the shape of the magnetic carrier mineral rather than by the spatial arrangement of the magnetite grains. An exception is the presence of magnetite clusters. Furthermore, the SPO of mafic silicates and the SPO of the magnetite grains are consistent with the AMS data. Another finding of this study is that the magnetic susceptibility correlates linearly with the amount of magnetite in the samples. The coherent results obtained from a variety of methods reinforce the application of both AMS measurements and IA as robust tools to analyse fabrics in granitic intrusions.

1. Introduction

Anisotropy of magnetic susceptibility (AMS) has been widely applied to analyse fabrics in magmatic intrusions (e.g. Archanjo et al., 2012; Bouchez, 1997; Cruden et al., 1999; Gleizes et al., 1998; Launeau and Cruden, 1998; López de Luchi et al., 2004; Petronis et al., 2012; Raposo et al., 2012; St Blanquat et al., 2001), lava flows (e.g. Cañón-Tapia and Coe, 2002; Cañón-Tapia, 2004; Loock et al., 2008), and dykes (e.g. Archanjo and Launeau, 2004; Cañón-Tapia and Chávez-Álvarez, 2004; Eriksson et al., 2011; Geoffroy et al., 2002). Many studies showed that the magnetic fabric obtained by AMS measurements is commonly coaxial with the macroscopic silicate fabric in ferro- and paramagnetic rocks (e.g. Aranguren et al., 2003; Archanjo et al., 1994; Hrouda et al., 1999; Petronis et al., 2004) and hence can be used to gain information about magma flow, emplacement related strain and/or tectonic strain. However, the AMS signal cannot be compared directly to the shape-preferred orientation (SPO) of the main silicate minerals that determine the macroscopic fabric of the rock. The relation between AMS fabric and strain is not simple either (Hrouda and Ježek, 1999): Arbaret et al. (2013) showed that AMS and SPO fabrics in simple shear flow tend to stabilise parallel to the shear plane only at high strain and that the amount of strain required for fabric stabilisation depends on the aspect ratio of the particles and their initial orientation. Adding further complexity, the magnetic axes and the three-dimensional shape of the magnetic minerals are not always clearly associated (Bouchez, 1997).

Theoretical and experimental work has been conducted to explore the nature of the AMS signal in ferromagnetic igneous rocks where magnetite is the main magnetic carrier mineral of the AMS. Two theories explaining how the AMS signal is controlled were developed:

i) The AMS signal is attributed to the shape anisotropy of the magnetite grains (O'Reilly, 1984). Although magnetite crystallises in

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the cubic system the grains are not necessarily isometric. It was demonstrated that the AMS ellipsoid and the shape ellipsoid of the magnetite grains (SPO) are closely related in terms of orientation and intensity of the ellipsoids' axes (Grégoire et al., 1998).

ii) The AMS signal is attributed to the irregular distribution of the magnetite grains and their tendency to form clusters (Hargraves et al., 1991; O'Reilly, 1984; Stephenson, 1994). The distribution anisotropy of the magnetites leads to varying magnetic interactions between the magnetite grains and create the AMS signal (Cañón-Tapia, 1996). Clusters of magnetite grains result in an increased or decreased magnetic susceptibility along the clusters' longest axes, depending on whether the grains are aligned or side-by-side (Grégoire et al., 1995). Therefore, the grain shape of the magnetites and the magnetic anisotropy degree might not be closely related.

To synthesise these two concepts about the origin of the AMS signal, studies showed that the AMS signal is controlled by several factors, such as the proportion of grains that interact magnetically or not, the shape of these grains, and intrinsic material properties of the magnetic grains (Cañón-Tapia, 2001). Numerical models and experiments suggest that the two end-members of magnetic interactions between grains are i) small magnetite grains, which form clusters and interact magnetically, determine the AMS signal by their distribution, and ii) large, dispersed magnetite grains do not interact magnetically and control the AMS signal by their preferred shape orientation (Gaillot et al., 2006). Quantifying the contributions of each of these factors to the AMS signal remains a major challenge as the signal only gives integrated information over the whole volume of the sample.

A recent study uses high-resolution X-ray tomography (X-ray CT) as a non-destructive technique to shed light into the distribution and shape of magnetite grains in tonalites (Floess, 2013). The conclusion of this work is that the distribution of the magnetite grains only influences the AMS signal if the magnetites are arranged in clusters, in agreement with Gaillot et al. (2006). If a strong AMS is present in the rock, the AMS ellipsoid is identical to the shape and the preferred orientation of the magnetite grains. However, the connection of AMS fabric to the SPO of the main silicate phases (i.e. macroscopic fabric) remains solely observational.

Like this non-quantified relation, the link between the magnitude of the mean magnetic susceptibility K_m and the amount of iron has not been investigated in detail for highly ferromagnetic rocks. It has only been proposed for rocks with K_m smaller than 10^{-3} SI that K_m correlates positively and linearly with the iron content of those rocks (Bouchez, 1997; Rochette, 1987).

Building upon the work of Floess (2013), this paper presents a detailed comparison between different fabric analysis measurements in ferromagnetic granitoids of the Lago della Vacca Complex (LVC), Adamello Batholith. The aims of this study are to test the applicability of the methods to characterise fabrics, to explore the link between AMS fabric and the macroscopic silicate fabric, to determine the origin of the AMS signal and to explore the relation between the magnetic susceptibility and the magnetite content. The purpose of this paper is not to discuss the fabric results in the context of the regional geology of the LVC, which is covered in another paper (Schöpa et al., submitted for publication).

2. Samples and methods

2.1. Samples

The 12 samples selected for this study were taken in the LVC, a silicic intrusion in the southern Adamello Batholith (Fig. 1). The samples are made up of Lago della Vacca tonalite, Galliner granodiorite and marginal tonalites. A full description of the microstructures of these rocks is given by John and Blundy (1993) and will be summarised here.

The Lago della Vacca tonalite shows an equigranular texture with 1–3 mm large prismatic hornblende, subhedral plagioclase, subhedral biotite, euhedral titanite and anhedral apatite (samples 11AS11, 11AS25, 11AS38, 11AS39, 11AS53). Quartz and alkalifeldspar smaller than 2 mm are present in the interstices. The hornblende and the titanite occasionally contain inclusions of plagioclase, pyroxene and oxides.

The equigranular Galliner granodiorite is characterised by prismatic hornblende crystals and subhedral plagioclases of 2–3 mm in size (samples 11AS47, 11AS58). Subhedral biotite with apatite, plagioclase and oxide inclusions is subordinately present. Interstitial quartz and alkalifeldspar are usually smaller than 3 mm.

Marginal tonalites of the LVC include two varieties: i) highly foliated tonalite, where up to 6 mm large plagioclase and lath-shaped hornblende crystals define the macroscopic foliation (samples 11AS12, 11AS28, 11AS40, 11AS52), and ii) tonalite with equigranular hornblende crystals up to 4 mm in size with inclusions of anhedral plagioclase, pyroxene and oxides (sample 11AS46). Interstitial plagioclase, biotite, quartz and alkalifeldspar measure 0.2–1 mm in both marginal tonalite varieties.

Oxides, predominately pure magnetite, are present in the tonalites and granodiorites of the LVC as individual grains or grain clusters. Single oxide grains occur in the groundmass, fill in the interstices between the silicate minerals and are included in larger hornblende, plagioclase, biotite and titanite crystals. The magnetite inclusions are occasionally located parallel to the rims of the host crystal. If large hornblende crystals have a preferred orientation single magnetite crystals and magnetite clusters follow this alignment (Fig. 2). Individual magnetite grains measure between 30 and 500 μm, average ~150 μm, and magnetite clusters can be up to 550 μm large.

2.2. Field measurements and image analysis (IA)

The macroscopic silicate fabric in the LVC granitoids is determined by the preferred orientation of mafic silicates such as lath-shaped hornblendes and subordinate, anhedral biotites. Magmatic foliations were measured directly in the field with a geological compass; mineral lineations could not be resolved at outcrops.

IA with the intercept method in grey levels (Launeau et al., 2010) quickly analyses the whole crystal shape anisotropy of a rock by a smoothed detection of boundaries between contrasted mineral phases. The division of the area of analysis (or mineral area when available) by the number of boundaries counted in each direction gives the mean intercept length rose. This is the mean shape preferred orientation of the minerals (SPO) because it is proportional to the preferred orientation of the minerals' shape towards a main direction. Since most of the fabrics or SPO are ellipses in 2D, we can calculate the 3D SPO ellipsoid with a minimum of three mutually perpendicular images (Launeau and Robin, 2005; Robin, 2002). It includes an adjustment of the size in sections to make them compatible with a common ellipsoid. The method finally provides a preferred orientation of crystal population along a main direction, expressed as the longest axis of the SPO fabric ellipsoid.

The intercept method was applied to two image datasets to determine the macroscopic SPO of mafic silicate crystals marked by their contrast to quartz and feldspar. One image dataset was taken of rock surfaces in the field (IA-F) and the second dataset was obtained from rock samples (IA-S) cut in the laboratory (Fig. 3). These were the same samples that were cored for the AMS analysis and used for the X-ray CT measurements.

The intercept method in grey levels can rapidly quantify the macroscopic silicate fabric. However, the method can only be used if sufficient minerals of different brightnesses are present in the images. In addition, the SPO of the IA is sensitive to shape variations of the mafic silicates. In our sampled lithologies, the general habit of the hornblende and biotite crystals does not change significantly in individual samples or across