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Process of magnetite fabric development during granite deformation

Manish A. Mamtani [a,*], Sandra Piazolo [b,c], Reinhard O. Greiling [d], Agnes Kontny [d], František Hrouda [e,f]

[a] *Department of Geology & Geophysics, Indian Institute of Technology, Kharagpur 721302, India*
[b] *Department of Geological Sciences, Stockholm University, Stockholm, Sweden*
[c] *Department of Earth and Planetary Sciences, GEMOC ARC Key National Centre, Macquarie University, 2109 NSW, Australia*
[d] *Lehrstuhl für Strukturgeologie und Tektonophysik, Institut für Angewandte Geowissenschaften, Karlsruhe Institute of Technology, Hertzstrasse 16, 76187 Karlsruhe, Germany*
[e] *Institute of Petrology and Structural Geology, Charles University, Albertov 6, CZ-128 43 Prague, Czech Republic*
[f] *AGICO Inc., Ječná 29a, Box 90, CZ-621 00 Brno, Czech Republic*

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ABSTRACT

This study evaluates the fabric defined by magnetite grains in a syntectonically deformed granite and deciphers the processes that led to magnetite fabric development. Anisotropy of anhysteretic remanence magnetization (AARM) analysis is performed in samples taken from different parts of the granite to establish that the magnetite grains define a fabric. Along with microstructural studies, the AARM data help conclude that this fabric is on account of shape preferred orientation (SPO) of the magnetite grains. The intensity of magnetite fabric (degree of anisotropy of the AARM ellipsoid) is higher in the southern parts as compared to the north, which is inferred to indicate a strain gradient. Electron back scattered diffraction (EBSD) analyses of magnetite grains were performed to determine if there are intracrystalline deformation features that could have influenced magnetite shape and SPO, and thus AARM data. Detailed crystallographic orientation data coupled with orientation contrast imaging did not reveal any subgrains and/or significant variations in crystallographic orientations within magnetite grains. Instead, grains exhibit fractures and are in places associated with quartz pressure fringes. Hence, neither the SPO nor the variation in the magnetite fabric intensity in the granite can be attributed to intracrystalline deformation of magnetite by dislocation creep. It is concluded that the magnetite grains were rheologically rigid and there was relative movement between the magnetite and the matrix minerals (quartz, feldspar and biotite). These matrix minerals actually define the fabric attractor and the magnetite grains passively rotated to align with it. Thus it is demonstrated that the magnetite fabric in the granite stems from rigid body movement rather than dislocation creep.

1. Introduction

Research on granites in the past few decades has revealed that although many of them lack clear mesoscopic evidence of a deformation fabric, this can be recognized by performing anisotropy of magnetic susceptibility (AMS) studies (e.g., Bouchez, 1997; Tarling and Hrouda, 1993). As a consequence, an integration of field, microstructural and AMS data has helped infer the time-relationship between fabric development and tectonic deformation in several granites (e.g. Archanjo et al., 1995; Greiling and Verma, 2001; Majumder and Mamtani, 2009a; Rochette et al., 1994; Žák et al., 2009). Many granites are magnetite bearing and AMS on its own does not analyze fabric defined by only the magnetite grains in the rock. This is because all the mineral phases present in the rock irrespective of being diamagnetic (e.g. quartz), paramagnetic (e.g. biotite) or ferromagnetic *sensu lato*/ferrimagnetic (e.g. magnetite) contribute to its AMS. Thus, whilst AMS provides information about the bulk fabric in the rock that can be linked to deformation, it does not indicate whether the magnetite grains also develop a fabric due to the same deformation. The fabric defined by magnetite can be determined by performing anisotropy of magnetic remanence (AMR) analysis (e.g., Jackson, 1991; McCabe et al., 1985; Petitgirard et al., 2009; Raposo and Gastal, 2009; Raposo et al., 2007; Trindade et al., 1999). AMR essentially stems from the shape anisotropy of ferrimagnetic magnetite (e.g. Tarling and Hrouda, 1993). Commonly used methods to determine AMR in rocks are measurement of IRM (isothermal remanence magnetization) and ARM (anhysteretic remanence magnetization) (e.g., Jackson, 1991). However, these methods do not provide any insight about the process/mechanism of magnetite fabric development. During fabric development, minerals can undergo rigid body rotation and/or recrystallization and may accommodate intracrystalline deformation by dislocation creep. With regards to magnetite, theoretical/experimental data (deformation mechanism map) indicate that at temperatures (T) > 600 °C it may undergo plastic deformation by dislocation creep (Ferré et al., 2003; Housen et al., 1995). Owing to its cubic crystallography and opaque nature, optical microscopy cannot help in recognizing intracrystalline plastic deformation features such as substructures i.e. systematic crystal bending

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* Corresponding author at: Tel.: +91 3222 283388; fax: +91 3222 255303/282700.
E-mail address: mamtani@gg.iitkgp.ernet.in (M.A. Mamtani).

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and subgrain boundaries within magnetite grains. However, such crystallographic features can be recognized by EBSD (electron back scattered diffraction) analysis (e.g., Agar and Lloyd, 1997; Boyle et al., 1998; Menegon et al., 2011; Piazolo et al., 2004; Prior et al., 2000; Storey and Prior, 2005). Thus, to quantify magnetite fabric and identify the processes that led to its formation AMR, microstructural, and EBSD data need to be integrated. Such an integrated approach has been adopted in this study with an aim to address the following questions.

(a) Does high temperature deformation of magnetite embedded in a deforming granite matrix lead to development of subgrains and/or other evidences of intracrystalline deformation and dynamic recrystallization?
(b) To what extent does such deformation influence the shape as well as shape preferred orientation (SPO) of magnetite in granite, which, in turn, is expected to influence the fabric intensity of magnetite petrofabric in the rock?

We address these questions by studying samples from the syntectonically deformed, Grenvillian age (955 ± 20 Ma; Gopalan et al., 1979) Godhra Granite located in the southern parts of the Aravalli Mountain Belt (northwest India; Fig. 1). This granite is taken as an example because it is ideal for a study focusing on the processes responsible for magnetite fabric development since it has been shown (Mamtani and Greiling, 2005, 2010; Sen, 2006; Sen and Mamtani, 2006; Sen et al., 2005) that (a) the emplacement and fabric development in the granite is syntectonic (b) intensity of AMS fabric as well as lineation varies from low in the north to high in the south, which is linked to the proximity of the southern part to the Central Indian Tectonic zone (c) high to low temperature deformation fabrics have been observed, where high-T fabrics such as chessboard pattern in quartz (>650 °C), although present throughout the granite, are dominant in the north, while medium-T (recrystallized feldspars; 450–600 °C) and lower-T fabrics such as deformation twins in feldspars (400–500 °C) and kinked biotites (≤300 °C) dominate the southern part (Fig. 1c), (d) many samples of the granite are magnetite-bearing and have high mean magnetic susceptibility ($>500\times10^{-6}$ SI units) (e) magnetite occurs in association with ilmenite indicating that the magnetite formed at T>600 °C (Ghiorso and Sack, 1991; Haggerty, 1991). In this study the magnetite fabric (and its variation in the granite) is evaluated from petrographic and anisotropy of anhysteretic remanence magnetization (AARM) analysis. Subsequently, EBSD analysis is performed to evaluate the possible role of intracrystalline deformation in the fabric development of magnetite.

2. Magnetite fabric analysis

2.1. Petrography—grain size and aspect ratio data

The granite is dominantly coarse grained to porphyritic and a mesoscopic foliation is generally absent. Therefore, in earlier studies the fabric of the granite was identified from AMS analysis (Mamtani and Greiling, 2005; Sen and Mamtani, 2006; Sen et al., 2005). AMS gives orientation of three principal axes K_1, K_2 and K_3 ($K_1>K_2>K_3$) of the AMS ellipsoid and the K_1K_2 plane represents the planar fabric (magnetic foliation) of the rock. For petrographic investigations, thin sections were prepared parallel to this magnetic foliation plane. Observations under transmitted light reveal that quartz, feldspar and biotite are the major mineral phases present. Opaque minerals comprise the minor phase, and ore petrography was performed on several polished thin sections from the northern and southern parts of the Godhra Granite. Samples were stained brown with ferrofluid for accurate identification of magnetite. Ferrofluid is a stable colloidal suspension of magnetite particles that range in size from 11 to 20 nm in a liquid medium (e.g. Kletetschka and Kontny, 2005). Magnetite grains, which are larger than a few micrometers have magnetic domains that generate large magnetic gradients above the polished surface and attract the particles of the ferrofluid. Hence, magnetite is stained brown with the ferrofluid and this allows its quick and clear distinction from other opaque phases under an optical microscope. Using this method, 6 different samples from different parts of the Godhra Granite were studied in detail. Altogether the grain size d (equal area diameter) and aspect ratio R (long/short axis ratio) of 225

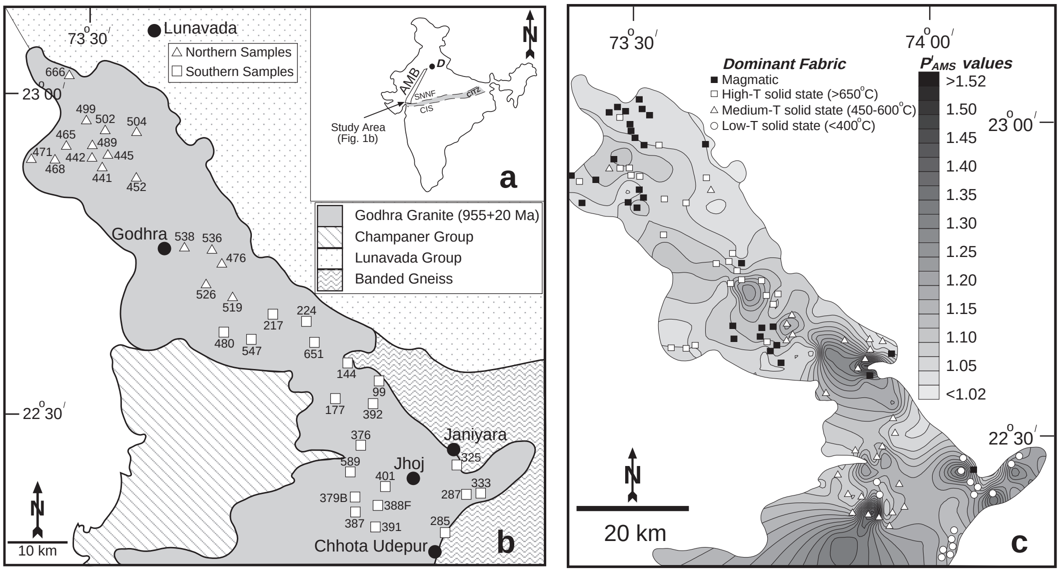

Fig. 1. (a) Map of India showing the Aravalli Mountain Belt (AMB) that lies to the north of the Central Indian Tectonic Zone (CITZ). The latter formed due to accretion of the northern and southern Indian shields during Palaeoproterozoic times (Yedekar et al., 1990). SNNF and CIS are the Son-Narmada-North Fault and Central Indian Suture that demarcate the northern and southern margins of the CITZ, respectively. (b) Geological map of the study area around the Godhra Granite. Locations of sampling sites in the north (triangles) and south (squares) on which anisotropy of anhysteretic remanance magnetization (AARM) analyses were made are shown. (c) Degree of anisotropy of magnetic susceptibility (P'_{AMS}) map of the Godhra Granite. Dominant fabrics identified in different parts of the granite based on petrographic study are also shown along with the temperature range of the various high-T solid-state fabrics (after Sen, 2006).