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Magnetic fabric as a vorticity gauge in syntectonically deformed granitic rocks

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ABSTRACT

A concept is presented to quantify vorticity using magnetic fabric data determined from anisotropy of magnetic susceptibility (AMS) analysis in syntectonic granites, whose emplacement is synchronous with tectonics of adjacent shear zones. The latter is considered to define the direction of extensional flow apophysis (A_e). It is suggested that the magnetic foliation traces the direction of maximum instantaneous stretching axis during the final stage of ductile deformation. Hence, the angle between mean orientation of magnetic foliation and A_e gives the kinematic vorticity number (W_n). This concept is tested in two granites from India — Godhra Granite (western India) and Chakradharpur Granitoid (eastern India). The analysis explains the kinematics of fabric development within the granites and also the evolution of structural elements in the surrounding rocks. It is also suggested that in cases where granite margins get mylonitized synchronously with tectonic activity along adjacent shear zones, the angle between mean magnetic foliation of the granite margin samples and the shear zone can help calculate W_n. The example of Malanjkhand Granite (central India) is discussed to highlight this. Using magnetic fabric, a value of $W_n = 0.98$ is recorded for granite margin samples implying their deformation by dominantly simple shear. Oblique quartz foliation recorded on the microscale in the granite margin samples yields $W_n = 0.94$, which is similar to the value obtained using AMS. It is thus concluded that magnetic fabric provides a possibility to quantify vorticity in syntectonic granites in 2-dimension.

1. Introduction

Kinematic analysis is of fundamental importance in structural geological investigations. This requires quantification of the degree of non-coaxiality (or amount of rotation) of flow by calculating the kinematic vorticity number (W_n) (Means et al., 1980), which is characteristic of the geometry of particle paths for individual flow types. Flow is commonly visualized to have theoretical lines (flow apophyses) that define material lines that do not rotate with respect to instantaneous stretching axes (ISAs) during progressive deformation. Depending upon whether material points/lines are attracted or repulsed, two apophyses are defined — extensional (A_e) and shortening (A_s), and the angle (α) between them gives W_n ($= \cos\alpha$; Passchier, 1986). Alternately, $W_n = \sin 2\xi$ (ξ is the angle between ISA_{max} and A_e; Weijermars, 1991). Fig. 1 is a schematic diagram explaining the determination of W_n using the above two formulae. For any flow type W_n lies between two end-members — pure shear ($\alpha = 90°$; $W_n = 0$) and simple shear ($\alpha = 0°$; $W_n = 1$). Deformed sets of veins/dykes, rigid porphyroclasts, quartz c-axis fabrics etc. have been used for vorticity analysis (Passchier, 1987, 1990; Wallis, 1995; see Xypolias, 2010 and references therein). It is well established that a large number of granites emplace and develop fabrics syntectonically with regional deformation (Druguet and Hutton, 1998; Solar et al., 1998; Vigneresse, 1995, 1999; Vigneresse and Tikoff, 1999), and hence vorticity quantification can provide useful information about the kinematics of fabric development in them. However, application of the above methods in granitic rocks is a challenge because they do not always contain the above markers that are a pre-requisite for vorticity analysis. The present paper explores the use of magnetic fabric determined from anisotropy of magnetic susceptibility (AMS) studies in granitic rocks as a vorticity gauge.

2. Fabric analysis in granites using AMS — the background

Granitic plutons generally occupy large area and commonly lack visible fabric elements (foliations/lineations). As a consequence, fabric in them is often analyzed using AMS, which is a useful petrofabric tool (Borradaile, 1988, 2001; Borradaile and Jackson, 2010; Bouchez, 1997; Hirt and Almqvist, 2012; Raposo and Gastal, 2009; Tarling and Hrouda, 1993; Tripathi et al., 2012). AMS involves induction of magnetism in an oriented sample in different directions and measurement of the induced magnetization in each direction. The analysis yields magnitudes and directions of the three principal axes of the AMS ellipsoid — K1, K2 and K3 (K1 ≥ K2 ≥ K3), the mean susceptibility, strength of magnetic foliation and lineation, degree of magnetic anisotropy and shape of AMS (see Tarling and Hrouda for formulae). K1, K2 and K3 of the AMS ellipsoid are often visualized as X, Y and Z

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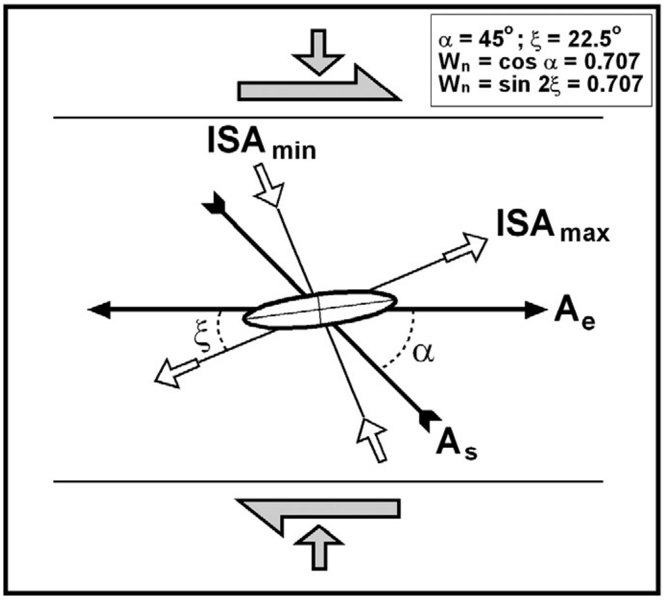

Fig. 1. Schematic diagram showing the method (along with formulae) to determine the kinematic vorticity number (W_n) in a dextral general shear zone. A_e and A_s are, respectively, the extensional and shortening flow apophyses. ISA_{max} and ISA_{min} are the maximum and minimum instantaneous stretching axes, respectively. The ellipse shown in the center represents the strain ellipse. As an example, the angle α between A_e and A_s is considered to be 45°, thus giving W_n as 0.707. The angle ξ between ISA_{max} and A_e is 22.5° thus giving the same W_n. The diagram is simplified after Fig. 4a of Xypolias (2010).

axis of the strain ellipsoid, where K3 is the pole to the magnetic foliation (K1–K2) plane while K1 the magnetic lineation (Tarling and Hrouda, 1993). Thus, AMS helps recognize fabric in granites. It is known that crystallization occurs during emplacement and cooling of granite. If this takes place syntectonically, then the crystallizing minerals develop a fabric that can be related to the deformation responsible for their formation. However, in cooling/crystallizing granite, the crystal fraction goes on increasing and there is progressive superimposition of low-T over high-T fabrics. As a consequence, a magmatic fabric (e.g. preferentially oriented feldspar laths) that developed at high-T, gets obliterated/completely destroyed during syntectonic cooling. Therefore in a majority of syntectonic granites, the preferred orientation of minerals is largely related to the last stage of cooling (just before solidification), which is recorded by the AMS. Thus, orientation of the magmatic and magnetic fabric is representative of respectively the early and late stage of syntectonic crystallization. Moreover, regional deformation may continue even after a granite has fully solidified, in which case there can be development of a field foliation oblique to the magnetic foliation, particularly in the granite margin. The question is, can these fabrics — magmatic, through magnetic to solid-state field foliation, be used to determine W_n in syntectonic granite? This paper addresses the above by discussing available field and magnetic data from two granites from India — Godhra Granite and Chakradharpur Granitoid.

3. Available data

In the past, field, AMS and microstructural studies have been carried out by the author on two granites located in different parts of India viz. the Godhra Granite (Aravalli region, western part of India; Mamtani and Greiling, 2005, 2010; Mamtani et al., 2011; Sen and Mamtani, 2006) and the Chakradharpur Granitoid (Singhbhum region, eastern part of India; Mamtani, 2013; Mamtani et al., 2013) (Fig. 2). Both have been inferred to be syntectonic with regional deformation and formation of regional-scale shear zones in their respective vicinities. In both the granites, the magnetic foliation is steeply dipping and the magnetic lineation is moderate to gently plunging. The interested reader is referred to the above cited works for details about regional geology/stratigraphy, as well as complete AMS data. Here the available orientation data necessary for vorticity analysis are only summarized.

3.1. Godhra Granite

The Godhra Granite (955 ± 20 Ma in age; ~5000 km^2 area) is known to have developed its fabric synchronously with Grenvillian age tectonic rejuvenation of the Central Indian Tectonic Zone (CITZ) that lies to its south (inset in Fig. 2a). Magmatic fabric defined by preferentially oriented feldspar laths is preserved in some parts; the strike of this magmatic fabric is dominantly N123° (Fig. 3b). Older polydeformed banded gneisses are located to the east of the granite. The main field foliation recorded is S3 that is related to D3 deformation. Strike of axial plane (AP3) varies between WNW and WSW, with the maximum being 113°, which is sub-parallel to the orientation of the feldspar laths in the Godhra Granite. The granite preserves high-T solid-state deformation fabrics (chessboard pattern in quartz) as well as medium to lower-T fabrics (deformation twins in feldspar and kinked micas). The superimposition of low-T over high-T fabrics is significant in the southern part (Mamtani and Greiling, 2010). AMS studies have revealed that the mean susceptibility in many samples is high (>500 × 10^{-6} SI units), and it has been established that paramagnetic minerals such as biotite (and in some samples hornblende), and ferromagnetic (sensu lato) magnetite are the important phases that contribute to the AMS (Mamtani and Greiling, 2005; Mamtani et al., 2011). Magnetic foliation in Godhra Granite is dominantly ENE–WSW (Fig. 3a,c), which is parallel to magnetic foliation in the banded gneiss, as well as orientation of CITZ (Sen and Mamtani, 2006). Older polydeformed metasedimentary rocks (quartzites and mica schists; Lunavada Group) lie to the northeast of Godhra Granite (Mamtani et al., 2000). These have NE–SW striking D2 structures (S2 foliation and AP2 axial planes; mean orientation = N58°E). The D3 folds have NW–SE strike in the northern parts (mean orientation N309°E), which becomes WNW–ESE/E–W in the southern parts (Fig. 2a). Singly folded quartzites and phyllites (Champaner Group) lie to the southwest of the granite with axial plane striking E–W (Fig. 2a). Fig. 3d is a synoptic diagram representing all orientation data from Godhra Granite and adjacent rocks. These data have been used to conclude that fabric development in Godhra Granite was synchronous with D3 deformation of the banded gneiss, D3 deformation of the Lunavada Group and D1 deformation of the Champaner Group rocks; globally, this is related to the formation of Rodinia during the Grenvillian times (Mamtani and Greiling, 2005).

3.2. Chakradharpur Granitoid

The Chakradharpur Granitoid (~250 km^2 area) has developed its fabric syntectonically with evolution of the Singhbhum Shear Zone (SSZ) that lies to its south. It belongs to the Precambrian, but accurate geochronological data are not available. It is surrounded by rocks of the North Fold Belt (quartzites and schists). SSZ has formed at the junction between North Fold Belt in the north and relatively rigid Archaean age Singhbhum Granitoid lying to its south. In the vicinity of Chakradharpur Granitoid, SSZ has N70°E strike (Fig. 2b, 4a). In areas distant from SSZ, folds in North Fold Belt are sub-horizontal to gently plunging. The folds become overturned to the south, fold axes become steeper and foliations develop down-dip (northerly plunging) mineral lineations in the southern parts close to SSZ (Ghosh and Sengupta, 1987, 1990; Sengupta and Ghosh, 1997). The Chakradharpur Granitoid does not have well-developed magmatic fabrics. However, at places, a field foliation with mean strike N70°E dipping 54° towards NW (Fig. 4b) is recorded, which is parallel to strike of SSZ (Mamtani et al., 2013). AMS studies have shown that mean susceptibility of this granitoid is low (<500 × 10^{-6} SI units), and it has been inferred by Mamtani et al. (2013) that biotite is the main paramagnetic phase that contributes to the AMS. Magnetic lineation (K1) plunges towards the NE,