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Fabric analysis of quartzites with negative magnetic susceptibility – Does AMS provide information of SPO or CPO of quartz?

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ABSTRACT

We ask the question whether petrofabric data from anisotropy of magnetic susceptibility (AMS) analysis of deformed quartzites gives information about shape preferred orientation (SPO) or crystallographic preferred orientation (CPO) of quartz. Since quartz is diamagnetic and has a negative magnetic susceptibility, 11 samples of nearly pure quartzites with a negative magnetic susceptibility were chosen for this study. After performing AMS analysis, electron backscatter diffraction (EBSD) analysis was done in thin sections prepared parallel to the K_1K_3 plane of the AMS ellipsoid. Results show that in all the samples quartz SPO is sub-parallel to the orientation of the magnetic foliation. However, in most samples no clear correspondance is observed between quartz CPO and K_1 (magnetic lineation) direction. This is contrary to the parallelism observed between K_1 direction and orientation of quartz *c*-axis in the case of undeformed single quartz crystal. Pole figures of quartz indicate that quartz *c*-axis tends to be parallel to K_1 direction only in the case where intracrystalline deformation of quartz is accommodated by prism <c> slip. It is therefore established that AMS investigation of quartz from deformed rocks gives information of SPO. Thus, it is concluded that petrofabric information of quartzite obtained from AMS is a manifestation of its shape anisotropy and not crystallographic preferred orientation.

1. Introduction

The measurement of low-field anisotropy of magnetic susceptibility (AMS) is a useful tool for petrofabric analysis of deformed rocks (Tarling and Hrouda, 1993). This method involves inducing magnetism in an oriented sample in different directions and measurement of the induced magnetization in each direction. AMS of an individual mineral depends on its crystallography (crystalline anisotropy) and/or shape (shape anisotropy). In case of minerals of the cubic crystal system (e.g., magnetite), shape anisotropy is the dominant controlling factor because these minerals lack a crystallographic anisotropy. In minerals of all the other crystal structures, induction of magnetization is believed to take place along the long crystallographic axis (the "easy" axis) (Tarling and Hrouda, 1993; Borradaile and Jackson, 2010). In addition, if the crystalline "*easy*" axis and long (shape) axis share the same orientation, then the magnetic anisotropy of the mineral is maximized. Thus, if a rock contains minerals with shape and/or crystallographic preferred orientation (CPO), it possesses a stronger magnetic susceptibility in the direction of the preferred orientation as compared to other directions. This anisotropy is visualized as AMS ellipsoid, which is a second rank tensor. In most rocks the orientations of principal axes of AMS ellipsoid ($K_1 > K_2 > K_3$) correlate well with orientations of structural features (finite strain axes), flow axes or some axis of kinematic importance (Borradaile and Jackson, 2010; Mamtani, 2014). This has made AMS a useful tool in Structural Geology research because in rocks where deformation related fabric elements are not visible to the human-eye, they can be deduced from orientations of the AMS ellipsoid.

Although studies integrating AMS and CPO data are relatively scarce, it has been theoretically understood that orientations of principal axes of AMS ellipsoid and crystal axes are parallel in orthorhombic and tetragonal crystals; this relationship becomes complex in monoclinic and triclinic crystal systems, more so in rocks that are commonly polycrystalline and polymineralic (Borradaile and Jackson, 2010). AMS of a rock has contribution from all the different mineral phases present in it viz. paramagnetic, diamagnetic and ferromagnetic *sensu lato* (*s.l*). If a rock has positive

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magnetic susceptibility, it implies that the AMS is dominated by the paramagnetic minerals (e.g., biotite, hornblende etc.) and/or ferromagnetic (*s.l*) minerals (e.g., magnetite, hematite etc.) present within it (Rochette et al., 1992; Tarling and Hrouda, 1993; Raposo and Berquó, 2008). There are several studies on deformed rocks with positive magnetic susceptibility that document (a) similarity between shape of AMS and strain ellipsoid (b) parallelism between shape preferred orientation (SPO) of elongated para/ferromagnetic minerals and magnetic fabric, and (c) positive correlation between strain intensity gradient and variation in degree of magnetic anisotropy (e.g., Rathore, 1979; Hrouda, 1982; Borradaile and Alford, 1987; Archanjo et al., 1995; Mukherji et al., 2004; Sen et al., 2005; Sen and Mamtani, 2006; Borradaile and Jackson, 2010; Raposo et al., 2014; Mamtani, 2014).

Compared to AMS studies on rocks with positive susceptibility (high para/ferro-magnetic mineral content), there are only a few investigations on rocks with negative magnetic susceptibility (such as pure/nearly pure quartzite and marble). AMS in such rocks is controlled by diamagnetic mineral phases such as quartz (in quartzite) and calcite (in marble). Although the crystallography of these minerals is well established, and there exists considerable knowledge about the relation between deformation and active slip systems in them (e.g., Hobbs et al., 1976; Nicolas and Poirier, 1976), there are only a few studies aimed at correlating their CPO with AMS data. In the case of calcite bearing rocks, an integration of AMS with Electron Backscatter Diffraction (EBSD) data has shown a good correlation between CPO and AMS (e.g., de Wall et al., 2000; Almqvist et al., 2010). However, similar studies dealing with quartz and quartzite are lacking. Moreover, of the limited studies done on quartzites, almost all of them dealt with samples having positive magnetic susceptibility (e.g. Mamtani et al., 1999; Tripathy et al., 2009; Mamtani and Sengupta, 2010; Vishnu et al., 2010; Mamtani and Vishnu, 2012). Quartz is diamagnetic, and has a negative magnetic susceptibility of -13.4×10^{-6} SI units (Tarling and Hrouda, 1993). This implies that in quartzites with positive magnetic susceptibility, there is a dominant contribution from para/ferro-magnetic minor mineral phases as compared to the major diamagnetic mineral phase (quartz). To the best of our knowledge there are no significant AMS studies of (nearly) pure quartzites that have a negative magnetic susceptibility. Experiments done on single crystal of quartz indicate that the ratio of magnetic susceptibility along *c*-axis to basal plane is very low (1.01; Nye, 1957; *cf* Hrouda, 1986). This was experimentally reconfirmed by Hrouda (1986). The latter also reported that in some cases magnetic susceptibility of single quartz crystal is higher along the *c*-axis than in the *ab* plane, while in some cases it is the reverse (also see Rochette et al., 1992). Borradaile and Jackson (2010) have stated that in a single undeformed crystal of quartz, the longest axis of the AMS ellipsoid (i.e., the direction with the most negative susceptibility) corresponds to the *c*-axis. Magnetic susceptibility along *c*-axis is -13.7 μSI while in the basal plane it is -12.5 μSI (see Fig. 7c of Borradaile and Jackson, 2010). However, the above authors state that because quartz undergoes basal glide under most tectonometamorphic deformation conditions, *c*-axis of deformed quartz occurs at high-angle to the foliation, thus producing inverse fabric. However, there is no detailed investigation and documentation on how the CPO, SPO and AMS in pure/nearly-pure quartzites (with negative magnetic susceptibility) are related to one-another. Some of the important questions that remain to be fully answered in quartzites with negative susceptibility are:

(a) Is K_1 direction parallel to the *c*-axis of quartz (the easy axis)?
(b) What is the relation between SPO and CPO of quartz?
(c) How are CPO and SPO related to the principal directions of the AMS ellipsoid?
(d) How does the dominant slip system (and hence temperature of deformation) influence the relationship between CPO and AMS?

The present study involves an integration of AMS, SEM based electron backscatter diffraction (SEM-EBSD) and SPO analysis of quartzite samples that have negative magnetic susceptibility to address the above listed questions.

2. Sample description and *modus operandi*

To fulfill the objectives of the present investigation, quartzites with negative magnetic susceptibility from two different regions have been studied.

2.1. Quartzites from Rengali region (India)

Quartzite samples from the Rengali Province located in eastern part of India were collected for this study. These rocks lie in the northern part of Eastern Ghats Mobile Belt in eastern India (inset, Fig. 1a). The samples were taken from a quartzite ridge that strikes in NW–SE direction, and extends for a distance of ~70 km situated to the north of the Kerajang Shear Zone (KSZ). The rocks of the region are known to have undergone three deformation events (D_1 to D_3). According to Misra and Gupta (2014), D_1 and D_2 took place during the late Archaean time under amphibolite to granulite facies conditions. D_3 took place under greenschist facies conditions at 490–470 Ma, and was accompanied with shearing and mylonitization along the KSZ (see Misra and Gupta, 2014 and references therein). Nine oriented blocks (each having dimension, *ca.* 10 cm × 10 cm × 10 cm) were collected for AMS as well as microstructural investigations. Since the rocks did not possess well-defined visible foliation (Fig. 1b), they were ideal for AMS investigation in order to recognize the orientation of fabric elements.

Cylindrical cores of 25.4 mm diameter and 22 mm height were drilled from each oriented block. AMS analysis was done using the KLY-4S Kappabridge (AGICO, Czech Republic) housed in the Department of Geology & Geophysics, Indian Institute of Technology (IIT) Kharagpur (India). Multiple cores were analyzed from each block; the programme SUFAR (AGICO, Czech Republic) was used for the measurement of AMS parameters viz. K_m (mean susceptibility), P_j (degree of magnetic anisotropy), T (shape parameter), and orientations of three principal axes of the AMS ellipsoid ($K_1 > K_2 > K_3$). Subsequently, the programme Anisoft 4.2 (AGICO, Czech Republic) was used to calculate Jelínek statistics, and determine mean values of AMS parameters for each block (using AMS data from individual cores of every block). The calculated values of all parameters are tabulated in Table 1. The reader is referred to Appendix A.1 for a more elaborate description of the AMS methodology and formulae used for calculation of various parameters. As listed in Table 1, all the investigated quartzite samples from Rengali have a negative magnetic susceptibility ranging between -13.6×10^{-6} SI units to -3.06×10^{-6} SI units; this implies negligible contribution from other mineral phases. Microstructural studies also reveal that the samples are almost pure quartzites and contain <3% of other (minor) mineral phases. In most of the samples, muscovite is the minor phase, which is known to be paramagnetic with a susceptibility of 165×10^{-6} SI units (Borradaile et al., 1987). Since the susceptibilities of all the samples are negative, it can be assumed that the presence of minor amounts of muscovite does not affect the AMS significantly. In the quartzite sample Rn258B, sillimanite is the minor phase. This sample has a mean susceptibility of -13.3×10^{-6} SI units (Table 1), which is almost identical to that of pure quartz crystal. This also implies that the presence of minor amount of