Degree of Magnetic anisotropy as a strain intensity gauge: An example from the Footwall of MCT Zone along Bhagirathi valley, Garhwal Himalaya, India

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In the Garhwal Himalaya, the footwall of the Main Central Thrust (MCT) Zone bears a wide zone (4 to 5 km) of mylonitic quartzite (Figure 1). These mylonites are inferred to have developed due to intense non-coaxial deformation followed by grain refinement through dynamic recrystalisation (Singh and Thakur 2001) and represent deep-level tectonites. These tectonites are devoid of strain markers (in the present case quartz clasts no longer preserved their outer boundaries). As a consequence, estimating finite strain in them is a challenge. Therefore, strain in such rocks needs to be estimated using some alternative techniques. The measurement of anisotropy of magnetic susceptibility (AMS) is one such technique that has been recently used to gauge strain in rocks that are devoid of strain markers (e.g. Hrouda 1993, Tarling and Hrouda 1993, Archanjo et al. 1995, Borradaile and Henry 1997, Mukherji et al. 2004, Sen et al. 2005, Sen and Mamtani 2006).

In the Garhwal Himalaya, MCT Zone is characterized by a 10-12 km thick NNE-dipping shear zone (Figure 1b). The lower boundary of MCT Zone corresponds to MCT (Heim and Gansser 1939) or Munsiari Thrust (MT: Valdiya 1980). The northerly dipping MCT or MT separates the crystalline rocks of the Munsiari Group (Metcalfe 1993) from the quartzites and metavolcanics of the Garhwal Group (Jain 1971). Further north, rocks of Munsiari Group are separated by the rocks of Vaikrita Group, of Higher Himalaya, along the Vaikrita Thrust (VT: Valdiya 1980). The area under investigation comprises of quartzites (referred as the Berinag quartzites; Valdiya 1980) and epidiorites of the Garhwal Group (Jain 1971) and form a part of the footwall of MCT Zone, along the Bhagirathi valley (Figure 1c). Further, these quartzites and epidiorites of the Garhwal Group are separated from the granitic gneiss and amphibolites of the Munsiari Group by the MCT.

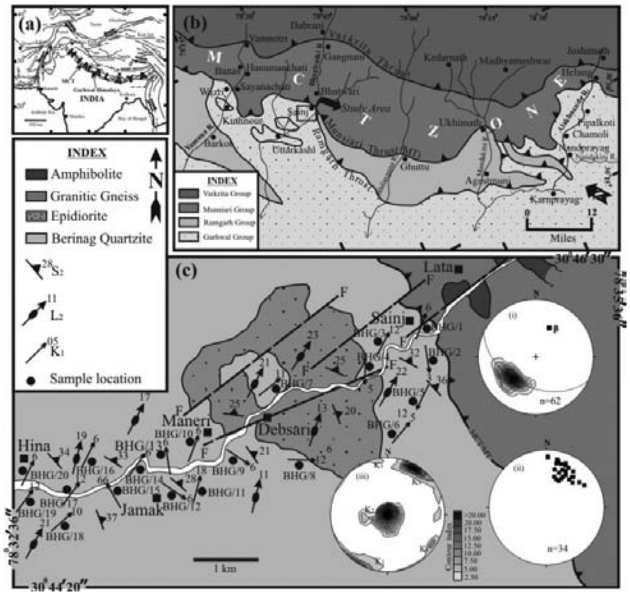

FIGURE 1. (a) Simplified tectonic map of the Himalaya (b) Simplified tectonic map of Garhwal Himalaya (modified after Valdiya 1980) (c) Geological map of the area, along Bhagirathi valley. Inset (i) and (ii) are lower hemisphere equal area projections of mylonitic foliation (S_2) and stretching lineation (L_2) and inset (iii) is the orientation of K_1 and K_3 axis in the footwall of MCT Zone of Bhagirathi valley.

Three phases (D1- D3) of deformation have been deciphered from the analysis of structural elements from the footwall of MCT Zone (Tripathy 2006). The earliest deformation (D1) is represented by co-axial strain. The D2 deformation is non-coaxial, characterized by ductile shearing but the degree of shearing varies considerably and has produced mylonites on either side of the MCT. Due to intense shearing, the early formed structures have reoriented and a strong mylonitic foliation (S2) and stretching lineation (L2) has developed on the pre-existing foliation plane (S1). D3 deformation, followed D2, has led to the development of non-penetrative structures mainly faults and joints.

Two-dimensional finite strain was determined using quartz clasts, for each of two mutually perpendicular thin sections (i.e. along XY, parallel to S2 and YZ is perpendicular to S2 and L2) prepared from 20 oriented hand specimens of mylonitic quartzite collected from different locations (shown in Figure 1c) from the area under study. The enlarged photomicrographs taken from thin sections and two-dimensional data were obtained by Center-

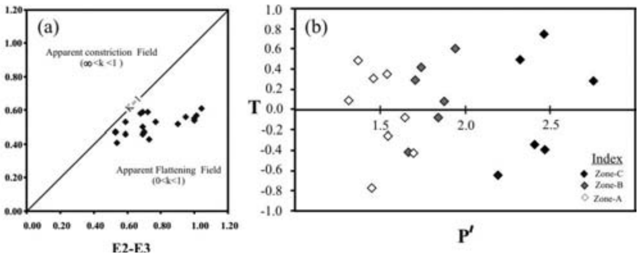

FIGURE 2. (a) Data from Rxy vs. Ryz of mylonitic quartzites from 20 samples plotted on a Flinn graph and (b) Jelinek plot (P’ vs. T) representing the shape of magnetic susceptibility ellipsoids in the investigated mylonitic quartzite

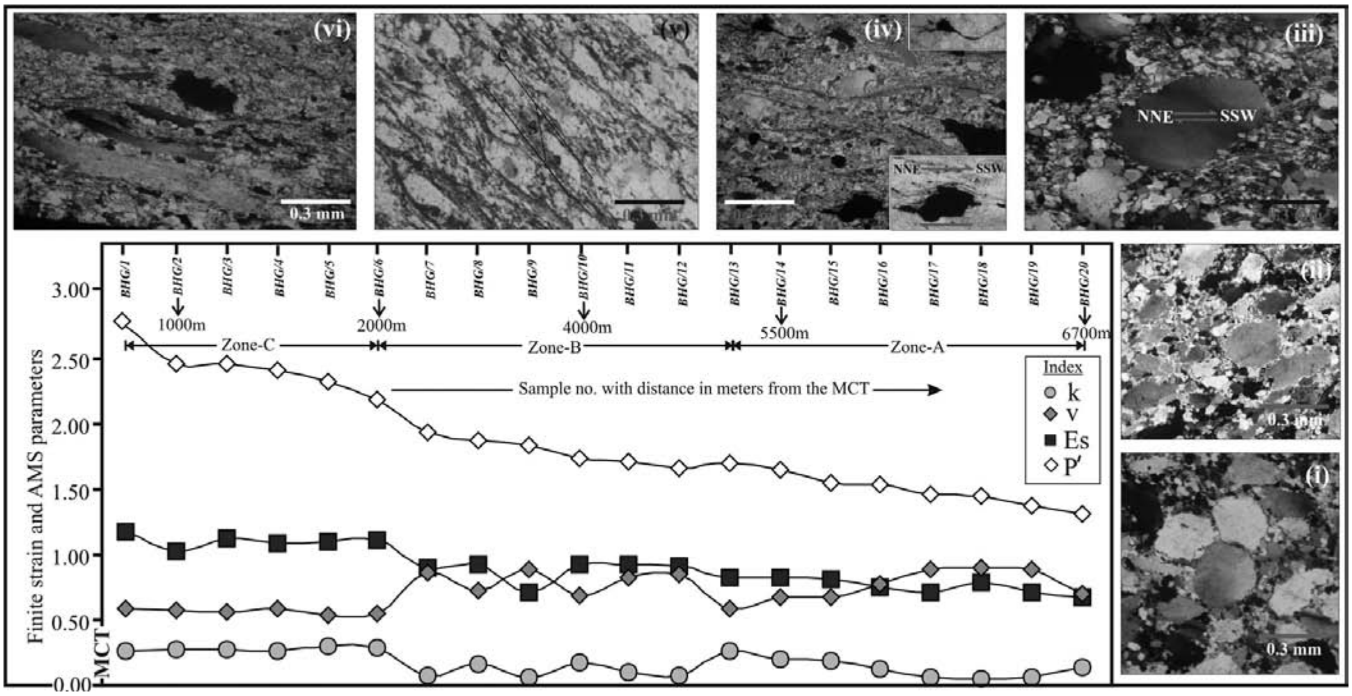

FIGURE 3. Plot showing the spatial variation of petrofabric strain parameters (Es, k and v) and AMS parameter (P') of the respective samples to the relative position from the Main Central Thrust (MCT). Inset-i to vi shows the progressive development of mylonitic structures with respect to increasing in strain (Es).

to Center method as suggested by Fry (1979). Three dimensional strain ellipsoids were calculated using two-dimensional strain data from the three mutually perpendicular planes and estimated different finite strain parameters i.e. Es, k and v (Ramsay and Huber 1983). The deduced shape of the strain ellipsoids falls in the apparent flattening field ($0< k<1$, $+1>v>0$) of Flinn plot (Figure 2a) (Flinn 1956) and exhibits a high strain intensity. Figure 3 is a plot of strain parameters (Es, k and v) with respect to the location of collected samples. In the present case the samples (BHG/1 to BHG/20) were collected up to 6700 m (perpendicular distance) from the MCT plane at regular intervals of distance. It has been observed that in between 6700 to 2000 m distance there is a gradual increase in strain towards the MCT. Further from 2000 m to close to the MCT (BHG/6 to BHG/1) there is no significant variation in strain values. In such a strain gradient the microstructural variation (inset-i to vi in Figure 3) was observed in accordance with the increase in strain intensity (Es).

For the purpose of present magnetic fabric analysis, multiple cylindrical cores were drilled from each oriented quartzite sample (previously used for finite strain analysis) and a total of 63 cores were obtained. AMS analyses of cylindrical specimens of quartz mylonites were carried out with a KLY-3S Kappabridge (AGICO, Czech Republic) at the Wadia Institute of Himalayan Geology (Dehradun, India). The analysis yields orientations and magnitudes of the three principal axes of the magnetic susceptibility ellipsoid viz. K_1, K_2 and K_3 ($K_1 \geq K_2 \geq K_3$). From these data, the mean susceptibility (K_m), degree of magnetic anisotropy (P≥) and shape parameter (T) are computed using the formulae given by Tarling and Hrouda (1993) and Hrouda et al. (2002). In order to know the source of anisotropy carrier for the development of AMS fabric, the cylindrical core samples were again selected for petrographical and rock magnetic studies: Isothermal Remanent Magnetization (IRM) and Saturation Isothermal Remanent Magnetization (SIRM).

Figure 2b is the Jelinek plot (P` vs. T). It graphically represents the shape of magnetic susceptibility ellipsoids in the aforesaid samples. The well scattered T values with respect to P` within the study area document L-S tectonites. The orientation of K_1 (magnetic lineation) and K (pole to magnetic foliation plane i.e., K_1-K_2 plane) in lower hemisphere equal area projection (inset-iii in Figure 1c), reveal that the magnetic fabrics are well in correspondence to the structural elements of the area under study (Figure 1c, inset-I and ii). It has been noticed that the P` value consistently increases in a finite strain gradient. Whilst the highest P` value is noted in sample no. BHG/1 located 500 m from the MCT, the lowest P` value is noted in the sample no. BHG/20 that lies farthest (6700 m) from the MCT (Figure 3). However, a significant variation in P` values (2.19 to 2.75) can be observed even if the finite strain values are saturated at a distance of 2000m from the MCT and the ductile zone acted as a strain observer (Figure 3).

The studied rock magnetic and chemical parameters; B0Cr (remanence coercivity), HIRM/μ_{lf} and IRM$_{soft}$, indicate a good proportion of ferrimagnetic and antiferromagnetic minerals (Figure 4A-C). Whereas, the low K_m (Figure 4D) values (2.52 μSI to 29.90 μSI) allow to guess that the total anisotropy is due to presence of magnetite as elongated porphyroclast and lattices inclusion in quartz and mica grains. Since the objective of the present study is to demonstrate weather P` can be used as a strain intensity gauge in a saturated finite strain zone, the study area was divided in to three zones i.e. Zone-A to C for better comparison and discussion of the results obtained from finite strain, rock magnetism and AMS fabrics studies.

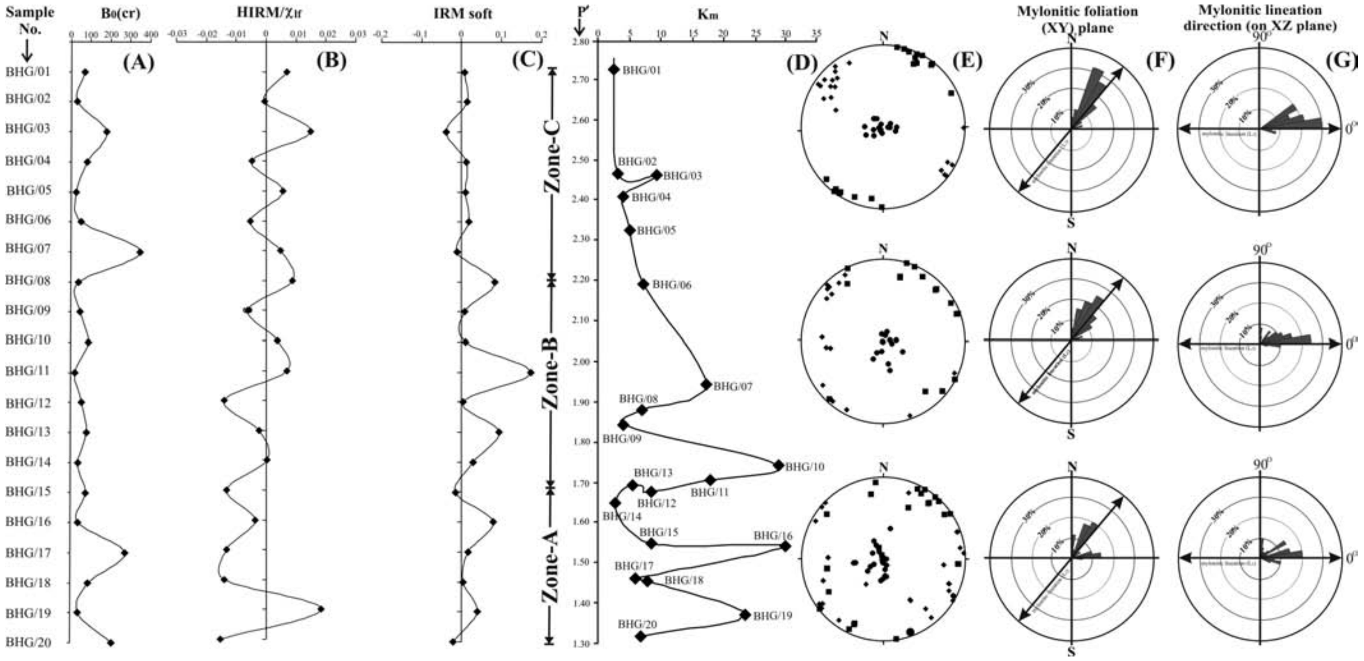

FIGURE 4. Plot of the rock magnetic and chemical parameters (A) B0Cr (remanence coercivity), (B) HIRM/μ_{lf}, (C) IRMsoft, (D) plot of Km vs. P´, (E) the distribution of susceptibility axes (K_1, K_2 and K_3) from multiple core samples within the site were plotted on equal area projection for all the three Zones and (F and G) Ross diagram of orientation of long axes of magnetite grains with respect to the mylonitic foliation plane (XY plane) and with respect to the mylonitic lineation (L_2) direction.

Correlation between P` and strain in quartz mylonites has been a matter of debate. To apply P` as a strain-intensity gauge, it is most important to demonstrate that P` is independent to Km. Moreover, it is essential to examine a consistent relationship between P` and shape ratio of magnetite grains which may lead to magnetic interaction in AMS fabric (Ruff et al. 1988, Archanjo et al. 1995). A comparison of P` values with Km reflects a considerable higher P` with low Km values in Zone-C than in Zone-A and B (Figure 4D). Again in Zone-A and B, Km values show much variation from one to another with low P`. This indicates the role of strain being responsible for high P` values rather than rock magnetic interaction. In consequence, the development of AMS fabric (directional data) due to the preferred orientation of the magnetite grains was examined by measuring the orientation of long axes of magnetite grains with respect to the mylonitic foliation plane (XY plane) and with respect to the mylonitic lineation (L2) direction (on XZ plane). The distribution of susceptibility axes (K_1, K_2 and K_3) from multiple core samples within the site were plotted on equal area projection for all the three zones (Figure 4E). In Zone-A, a prolate magnetic fabric has developed, resulting in well defined K1 axis directions whereas the K_2 and K_3 directions lie in the plane perpendicular to the K_1 direction, but are not isolated from each other. However, in an increasing strain gradient from Zone-A to Zone-C, the susceptibility axes have become increasingly isolated from each other. This suggests that with increasing finite strain and P` values from Zone-A (Es=0.67-0.83, P`=1.32-1.65) to Zone-C (Es=0.90-1.18, P`=1.94-2.75), elongate magnetite grains are rotated into the mylonitic foliation (Figure 4F) and towards the mylonitic lineation direction (Figure 4G). Thus, the development of preferred alignment is predominantly accomplished by rotation of mica cleavage planes into mylonitic foliation. Since much of the elongate magnetite is incorporated within the mica cleavage planes, rotation of the mica will also rotate the included magnetite into the mylonitic fabric. These observations suggest that the AMS fabric was controlled by the reorientation of originally randomly oriented elongate magnetite grains into the mylonitic foliation and lineation directions with increasing strain. Thus, the above observations suggest that the development of AMS fabric is influenced by the passive rotation of magnetite grains as a function of strain. Hence P` can be used as a strain-intensity gauge at least on the outcrop scale, where a systematic variation in P` values can be noticed.

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