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Significance of AMS analysis in evaluating superposed folds in quartzites

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Abstract – Quartzites tend to be compositionally homogeneous, and because of this, deformation related fabric elements (foliations and lineations) are poorly developed in them. This makes structural analysis of deformed quartzites challenging. The measurement of anisotropy of magnetic susceptibility (AMS) is useful for recognizing structural imprints in rocks that lack mesoscopic fabrics and the present study is carried out with an aim to demonstrate the robustness of AMS in analysing such deformation imprints in quartzites. AMS data of samples from folded quartzites located in an approximately 10 km^2 area around Galudih (eastern India) are presented. Although on a regional scale, superposed deformation and ductile shearing are known from the area, the investigated quartzites do not preserve mesoscopic evidence of these large-scale features and have developed folds that plunge gently towards the SE with a vertical NW–SE-striking axial plane. The magnetic foliation recorded from AMS analysis is parallel to the axial plane, while the orientation of the magnetic lineation varies from SE through vertical to NW. This is similar to the large-scale fold axis variations recorded in various regional domains mapped over an area of about 200 km^2. It is concluded that although the imprint of regional superposed deformation is not obvious on the mesoscopic scale in the quartzites around Galudih, this imprint can be detected from the magnetic fabric. The present study thus highlights the usefulness of AMS in analysing superposed folds in quartzites.

Keywords: anisotropy of magnetic susceptibility, folds, deformation, quartzites.

1. Introduction

Quartzites commonly occur in various geological terrains in different parts of the world. Owing to their compositional homogeneity, they often do not develop axial planar fabric elements such as axial plane foliations on the mesoscopic scale. Moreover, if such quartzites undergo polyphase deformation (superposed folding), then analysing their superposed fold history is challenging, due to the absence of structures such as refolded secondary foliations at outcrop scale. The measurement of anisotropy of magnetic susceptibility (AMS) is a useful tool for petrofabric analysis (e.g. Hrouda, 1982; Tarling & Hrouda, 1993; Zhang & Piper, 1994; Bouchez, 1997; de Wall, Greiling & Sadek, 2001; Jayangondaperumal & Dubey, 2001; Borradaile & Jackson, 2004; Mamtani & Greiling, 2005; Žák, Schulmann & Hrouda, 2005; Kratinová *et al.* 2007; Žák, Verner & Týcová, 2008; Mamtani & Sengupta, 2009; Majumder & Mamtani, 2009, among others), and often deformations that do not leave mesoscopic-scale imprints can be recognized from AMS data (e.g. Stacey, Joplin & Lindsay, 1960; Mamtani *et al.* 1999; Mukherji, Chauduri & Mamtani, 2004; Mamtani & Arora, 2005). In the eastern part of India (~ 30 km SE of Jamshedpur; see inset of Fig. 1a for location) there are folded quartzites with fold axes plunging gently to the SE. On a regional scale these quartzites show superposed folding and shearing. The deformational history of the quartzites has been deciphered earlier (e.g. Naha, 1959, 1965; Mukhopadhyay & Sengupta, 1971; Ghosh, Mukhopadhyay & Sengupta, 2006), based on detailed structural analysis in different parts of the terrain (~ 200 km^2). The western part of this region (around Galudih; see Fig. 1a for location) has folded quartzite bands that do not contain mesoscopic-scale manifestations of the regional superposed folding and shearing. The main objective of the present study is to perform AMS analysis of samples taken from various parts of the folded quartzites (limbs and hinges) over an approximately 10 km^2 area and to test the robustness of the AMS data for detecting imprints of the regional superposed deformation.

2. Geology of the study area

The study area comprises metasedimentary rocks (quartzites and intercalated schists) that belong to the Proterozoic mobile belt of eastern India and lie between the Dalma synclinorium in the north and the Singhbhum Shear Zone in the south (Fig. 1a). The reader is referred to the work of Dunn & Dey (1942) for an older account of regional geology of the area; a recent review has been given by Saha (1994). Structural geological investigations have been carried out by various workers (e.g. Naha, 1959, 1965; Mukhopadhyay & Sengupta, 1971; Mukhopadhyay, Ghosh & Chattopadhyay, 2004; Mamtani *et al.* 2004; Ghosh, Mukhopadhyay & Sengupta, 2006). On a regional scale, imprints of three deformation events have been reported in the

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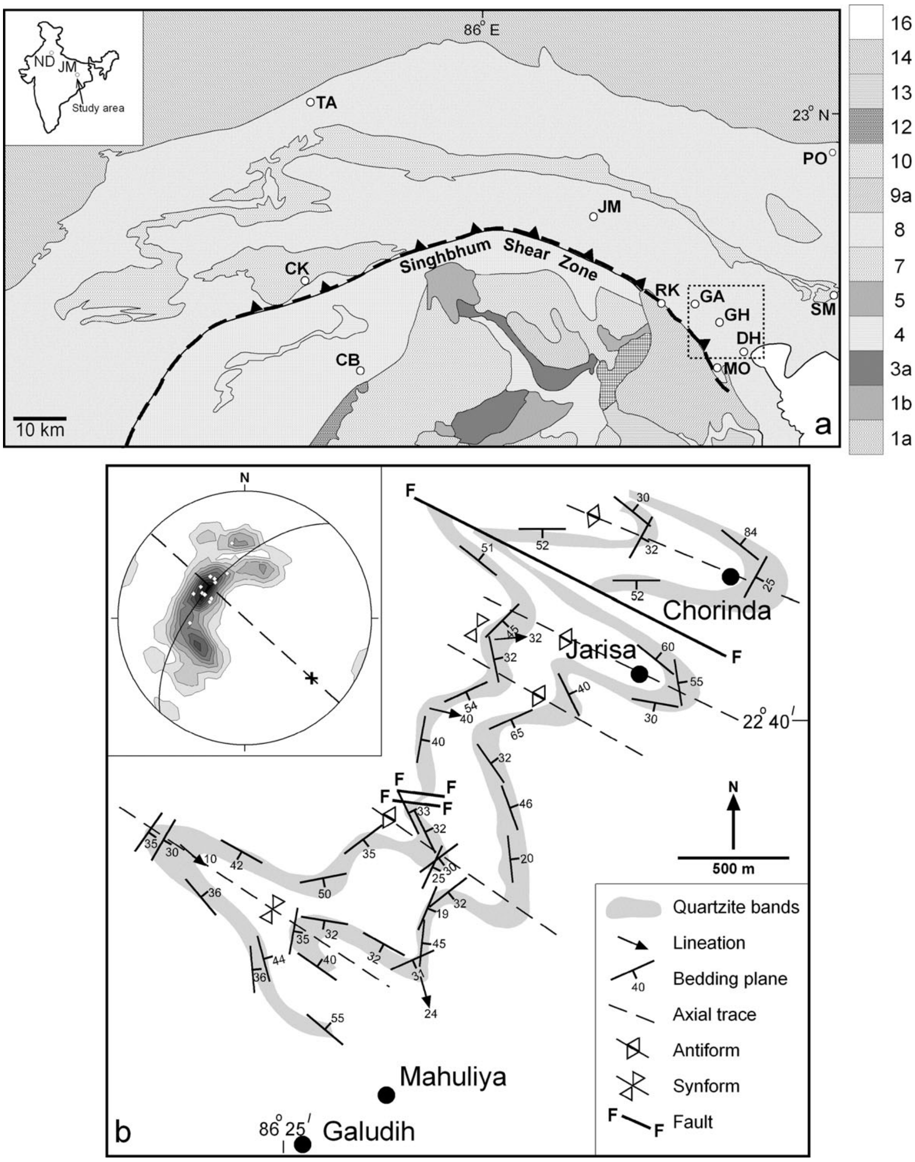

Figure 1. (a) Generalized lithological map of the area around Galudih, Ghatshila and Dhalbhumgarh (dotted box in the eastern part of the map). ND – New Delhi; JM – Jamshedpur; GA – Galudih; GH – Ghatshila; DH – Dhalbhumgarh; SM – Simulpal; TA – Tamar; CK – Chakradharpur; CB – Chaibasa; RK – Rakha Mines; MO – Mosabani; PO – Porapahar. Index: 1a – Older Metamorphic Group; 1b – Older Metamorphic Tonalite group; 2 – Pallahara Gneiss; 3a – Singhbhum Granite Phase I; 4 – Iron Ore Group Lavas; 5 – Iron Ore Group Shales; 7 – Singhbhum Granite Phase III; 8 – Singhbhum Group; 9a – Dhanjori Lavas; 10 – Dalma Lavas; 12 – Kolhan Group; 13 – Mayurbhanj Granite; 14 – Chotanagpur Granite Gneiss; 16 – Alluvium. (b) Structural map of the quartzite bands around Galudih. Inset in (b) is the lower hemisphere equal area projection of poles to bedding planes (S_0; $n = 42$). White rhombs are poles to S_0 at hinges of folds. Cross represents the π-axis (fold axis plunging 30° towards 132°). NW–SE-striking dashed line represents the average orientation of the axial plane. Bedding plane symbols indicate degree of dip.

Galudih–Ghatshila–Dhalbhumgarh region (Fig. 1a for locations). The area comprises the Ghatshila syncline in the west and Dhalbhumgarh syncline in the east; a culmination separates the two depressions. In the vicinity of Galudih, two quartzite bands are clearly traceable, with the western one being older than the eastern one (Naha, 1965; Fig. 1b). The quartzite bands are folded with the fold axis plunging moderately towards the SE and with vertically dipping NW–SE-striking axial planes (Fig. 1b). The quartzites are jointed and NE–SW-striking joints dominate. These have been considered as cross-joints (Mamtani *et al.* 2004). The folds in these quartzites (vicinity of Galudih) were mapped as D_1 structures by Naha (1965). Around Ghatshila (SE of Galudih), the fold axis plunges steeply to the NW defining a canoe-shaped geometry, which was attributed to variation in the configuration of the sedimentational trough (Naha, 1965; see Fig. 2). In the eastern extremity of the area (around Simulpal; see Fig. 1a for location), Mukhopadhyay & Sengupta (1971) mapped a continuation of the quartzites of the Galudih–Ghatshila region as D_2 structures. According to these authors, D_1 structures are preserved as rootless isoclinal folds defined by quartzose lenses in schists. They also reported crenulation cleavage in the schists to infer that the major folds and

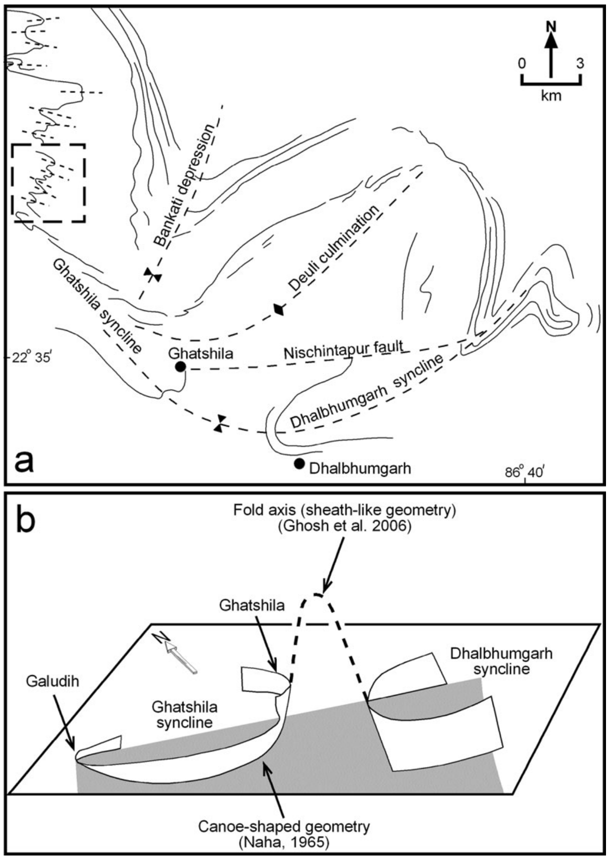

Figure 2. (a) Regional geological map of the study area showing the regional synclines as well as culminations and depressions (after Ghosh, Mukhopadhyay & Sengupta, 2006). Dashed box in the western part of the map marks the area shown in Figure 1b that was investigated in the present study. (b) Schematic diagram showing the sheath-like geometry of the regional folds in the Galudih–Ghatshila–Dhalbhumgarh area (after Ghosh, Mukhopadhyay & Sengupta, 2006). The folds around Galudih plunge due SE, while those around Ghatshila plunge due NW, thus resulting in a canoe-shaped geometry (Naha, 1965). See text for discussion.

axial planar foliation in the region belong to D_2 folds.

To the southeast of Ghatshila lies the Dhalbhumgarh syncline. The D_2 folds here plunge steeply to the ENE with the schistosity striking ESE–WNW (Mukhopadhyay, Ghosh & Chattopadhyay, 2004). Ghosh, Mukhopadhyay & Sengupta (2006) have documented the presence of ductile shear structures such as shear bands and mylonitic foliations associated with D_2 structures. From this evidence they concluded that ductile shearing occurred during the later stages of D_2 deformation. The U-shaped synclinal fold closures of the Ghatshila and Dhalbhumgarh synclines face in opposite directions and have steep westerly and easterly plunges, respectively, defining an acute culmination of the D_2 fold axis (Fig. 2). According to Ghosh, Mukhopadhyay & Sengupta (2006), this culmination and depression defines the overall geometry of the Dhalbhumgarh–Ghatshila region as a sheath-like fold (Fig. 2a, b) that developed due to movement on D_2 schistosity. D_2 was followed by D_3 deformation that resulted in broad curving of D_2 axial traces (Banakati Depression in Fig. 2a).

Thus, it is clear from the above description that the regional deformation history of the area is complex. The objective of the present investigation is to carry out AMS analysis of quartzites in the vicinity of Galudih (boxed area in Fig. 2a) and see the extent to which magnetic fabric of the rocks developed on a relatively small scale of an approximately 10 km^2 area preserves evidence of the regional deformation events that can be deciphered from mesoscopic fabrics developed on a much larger scale over an approximately 200 km^2 area.

3. AMS analysis of folded quartzites around Galudih

The analysis of AMS involves inducing magnetism in a sample in different directions and measurement of the induced magnetization in each direction. The results can be approximated in terms of an ellipsoid that is referred to as the AMS ellipsoid with three principal axes K_1, K_2 and K_3 ($K_1 \geq K_2 \geq K_3$). Subsequently, the mean susceptibility, [$K_m = (K_1 + K_2 + K_3)/3$], the strength of the magnetic foliation, [$F = (K_2 - K_3)/K_m$], and strength of the magnetic lineation, [$L = (K_1 - K_2)/K_m$], are calculated. Moreover, following Jelinek (1981), the degree of magnetic anisotropy P′ and shape parameter (T) are calculated as follows:

$$P' = \exp\surd\{2[(\eta_1 - \eta_m)^2 + (\eta_2 - \eta_m)^2 + (\eta_3 - \eta_m)^2]\}\ \text{and}$$

$$T = (2\eta_2 - \eta_1 - \eta_3)/(\eta_1 - \eta_3)$$

Here, $\eta_1 = \ln K_1$, $\eta_2 = \ln K_2$, $\eta_3 = \ln K_3$ and $\eta_m = (\eta_1.\eta_2.\eta_3)^{1/3}$. While P′ is a measure of the eccentricity of the AMS ellipsoid, T defines the shape of the AMS ellipsoid. The latter varies from −1 to +1; a prolate shape yields a negative T value and oblate shape a positive value (Tarling & Hrouda, 1993).

In the present study, AMS was measured using the KLY-4S Kappabridge (AGICO, Czech Republic) in the Department of Geology & Geophysics, Indian Institute of Technology, Kharagpur (India). The instrument has an operating frequency of 875 Hz and the measurements were made in the spinner mode in a field intensity of 300 Am^{-1}. In this spinner mode, the AMS of a spinning specimen fixed in the rotator is measured. The specimen rotates with a speed of 1 revolution per 2 seconds inside the coil of the Kappabridge and the susceptibility is measured 64 times during one revolution. The measurements are made along three perpendicular axes and the above-mentioned AMS parameters are calculated using the program SUFAR that runs the measurements. The sensitivity of AMS measurement in the spinner mode is 2×10^{-8} (SI units). Oriented samples from a total of 18 sites from different locations around the folded quartzite bands in the vicinity of Galudih were taken. Multiple cores (2.54 cm diameter, 2.2 cm length) were investigated from each site; a total

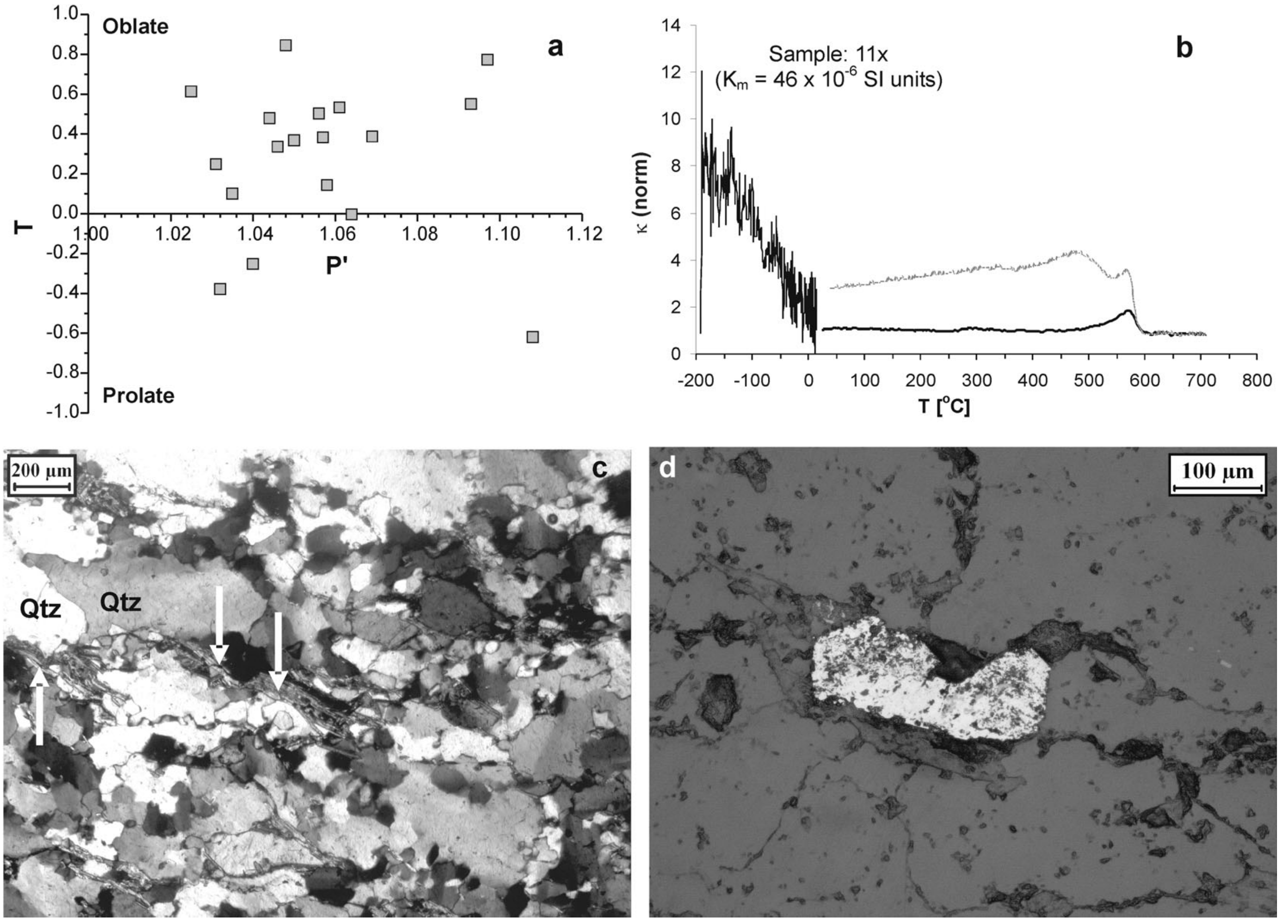

Figure 3. (a) Jelinek (P′ v. T) plot of the quartzites analysed in the present study. (b) Temperature variation of magnetic susceptibility (κ–T) curve of a quartzite sample. (c) Photomicrograph showing presence of mica (muscovite and biotite; white arrows) in the quartzite of the study area. Qtz – quartz. (d) Photomicrograph (polished thin-section; reflected light) showing magnetite in the quartzite sample. The magnetite is martitized (see text for details).

of 108 cores from 18 sites were analysed. Data from all cores from a particular site were used to calculate the mean values of the various AMS parameters (Jelinek statistics: Jelinek, 1981). The program Anisoft (version 4.2; AGICO, Czech Republic) was used for this calculation. The results of the analysis are described below.

The quartzites have low K_m values (between 10.1×10^{-6} SI for site 10 and 141×10^{-6} SI for site 5; Table 1). Figure 3a is the Jelinek plot (Jelinek, 1981) for the samples, which indicates that the shape of AMS ellipsoid in most of the samples is oblate. Quartz, being diamagnetic, has a negative magnetic susceptibility (-13.4×10^{-6} SI units: Tarling & Hrouda, 1993). Positive K_m values of the quartzites (Table 1) are indicative of the presence of some Fe-bearing minerals along with diamagnetic quartz. Temperature variation of magnetic susceptibility (κ−T) analyses were performed on powdered samples of some of the quartzites using the CS-3 furnace (from room temperature to 700 °C) and the CS-L cryostat (from −196 °C to 0 °C) attached to the KLY-4S Kappabridge in the magnetic laboratory of Universität Karlsruhe (TH), Germany. The κ−T curve (Fig. 3b) implies the presence of traces of magnetite. Further, it is noted that the susceptibility increases during heating (above 500 °C), which points to some formation of magnetite during the heating experiment. Transmitted light petrographic studies (Fig. 3c) revealed the

Table 1. AMS data of the quartzite samples analysed from the area around Galudih (eastern part of India)

Site number	K_m (10^{-6} SI)	P′	T	K_1 (D/I)	K_3 (D/I)
1	57	1.097	0.773	102/62	224/16
1b	74.6	1.035	0.101	102/77	219/6
1c	69.5	1.061	0.534	192/75	36/14
3	42.4	1.056	0.503	173/1	263/14
3x	78	1.046	0.336	241/77	61/13
5	141	1.048	0.846	302/21	205/1
7	16	1.04	−0.252	288/71	64/14
8	13.4	1.031	0.249	162/55	52/14
9	51.9	1.064	−0.003	0/90	64/0
10	10.1	1.108	−0.619	115/22	212/15
11	75.5	1.057	0.383	125/18	234/30
11x	46.0	1.05	0.368	320/36	56/6
12	16.5	1.093	0.551	112/0	7/36
13	33.9	1.058	0.144	129/18	221/7
14	19.9	1.025	0.614	179/88	46/1
15	69	1.032	−0.378	50/52	274/29
16x	15.8	1.069	0.387	136/64	323/26
17	54.9	1.044	0.480	115/22	207/4

K_m, P′ and T are the mean susceptibility, (corrected) degree of magnetic anisotropy, and shape parameter respectively. D/I refers to the declination/inclination of the maximum (K_1) and minimum (K_3) principle axis of the AMS ellipsoid.

presence of micas (muscovite and biotite). Moreover, ore petrography of polished thin-sections showed the presence of some magnetite grains (Fig. 3d) that have undergone martitization. Thus, it is confirmed that the positive susceptibilities of the investigated quartzites are due to traces of Fe-bearing minerals (magnetite and biotite).

Parts a to r of Figure 4 show lower hemisphere equal area projections of mean K_1, K_2 and K_3 orientations for the 18 sites investigated here. As stated above, mean values were calculated using Anisoft 4.2 (AGICO, Czech Republic). Magnetic foliation plane (K_1K_2 plane defined by common great circle containing K_1 and K_2) and bedding plane for each site (dashed great circle in Fig. 4a–r) are also plotted on each individual projection. It is noted that the magnetic foliation is dominantly NW–SE striking. The authors have also contoured K_1 orientations as well as plotted K_1, K_2 and K_3 orientations of individual cores ($n = 108$) for all the sites (Fig. 4s). This also reveals that the magnetic foliation is NW–SE oriented. It may be noted that the plunge of K_1 varies from SE through vertical to NW. The significance of this variation is discussed in Section 4.

Figure 5b, c shows the magnetic foliation and lineation maps of the quartzite bands (see Fig. 5a for locations of AMS sampling sites). Figure 5d is a synoptic diagram showing the lower hemisphere equal area projection of the mean orientations of K_1 (magnetic lineation) and K_3 (pole to magnetic foliation) recorded in the samples. It is noted that on average the magnetic foliation (K_1K_2 plane) is vertical with a NW–SE strike. Naha (1965) divided the region in the vicinity of Galudih and Ghatshila into several domains and performed a detailed structural analysis of planar and linear structural elements. The orientations of lineations recorded in the different domains by Naha (1965) are also plotted in the same lower hemisphere equal area projection (Fig. 5d), the significance of which is discussed in the following Section.

4. Discussion

Hrouda (1986) discussed the problem of using AMS data from quartzites as a measure of magnitude of strain. Accordingly, the degree of magnetic anisotropy in quartzites may be used as a proxy of strain if $K_m > 50 \times 10^{-6}$ SI. However, Hrouda (1986) stated that the orientations of K_1, K_2 and K_3 can be used for structural geological interpretations even if $K_m < 50 \times 10^{-6}$ SI. In the present study, many quartzites have very low susceptibilities ($< 50 \times 10^{-6}$ SI). Therefore, following Hrouda (1986), the authors have preferred to base their interpretations on orientations of AMS data.

4.a. Magnetic foliation and axial plane orientation

On the mesoscopic scale, the folded quartzites are largely devoid of axial planar fabric elements, such as axial plane cleavage. Using field planar data from limbs of the mesoscopic folds, the mean axial plane orientation of the folds is determined to be NW–SE striking with vertical dip (Fig. 1b; also see Naha, 1965). The mean orientation of the magnetic foliation recorded in the Galudih quartzites is subparallel to the axial planar direction of the mesoscopic folds recorded around Galudih (Fig. 5d). This indicates that although the quartzites of the study area have not developed an axial planar foliation on the mesoscopic scale, there was development of fabric in the axial planar direction, which is recognized from the AMS analysis.

Naha (1965) stated that the folds in the study area developed as a consequence of flexural folding. Most of the samples produce an oblate shape of the AMS ellipsoid, which indicates a flattening strain. Moreover, the magnetic foliation is steep and is parallel to the axial plane direction of the folds. This indicates (a) shortening perpendicular to the axial plane direction and (b) apart from flexural folding, homogeneous shortening must have been dominant to result in the development of a magnetic fabric that is parallel to the axial plane direction. This supports the inference of Mamtani *et al.* (2004), who suggested that the interlayered sequence of quartzites and schists in the study area developed Class 1C geometry folds that were further enhanced by homogeneous shortening.

4.b. Magnetic lineations and superposed folding in Galudih quartzites

The rocks in the region around Galudih, Ghatshila and Dhalbhumgarh (see Fig. 1 for locations) have been extensively mapped in the past and, as discussed in Section 2, the superposed fold history on a regional scale is well established. On a regional scale, the rocks have undergone three episodes of deformation. All the mesoscopic folds in the quartzite bands around Galudih show a fold axis plunging uniformly to the SE. On a regional scale, there are culminations and depressions. Near Ghatshila (SE of the study area), the folds plunge steeply towards the NW, thus resulting in a canoe-shaped geometry, which was attributed to variation in the configuration of the sedimentational trough by Naha (1965), but is considered to be an indication of superposed deformation by Mukhopadhyay, Ghosh & Chattopadhyay (2004) and Ghosh, Mukhopadhyay & Sengupta (2006). The latter workers have also demonstrated that to the southeast of Ghatshila, around Dhalbhumgarh, there is evidence of ductile shearing and the regional folds plunge towards the ENE. This variation in regional structure to the southeast of Ghatshila is due to a sheath-like regional folding. According to the present study, the AMS data from the Galudih quartzites provides evidence in favour of the regional sheath-like geometry and superposed deformation.

In the present study, AMS analysis was performed on samples from quartzite bands near Galudih, which lies in the western part of the region. The π-axis (fold axis) lies almost on the mean orientation of the magnetic foliation plane (Fig. 5d). Although a

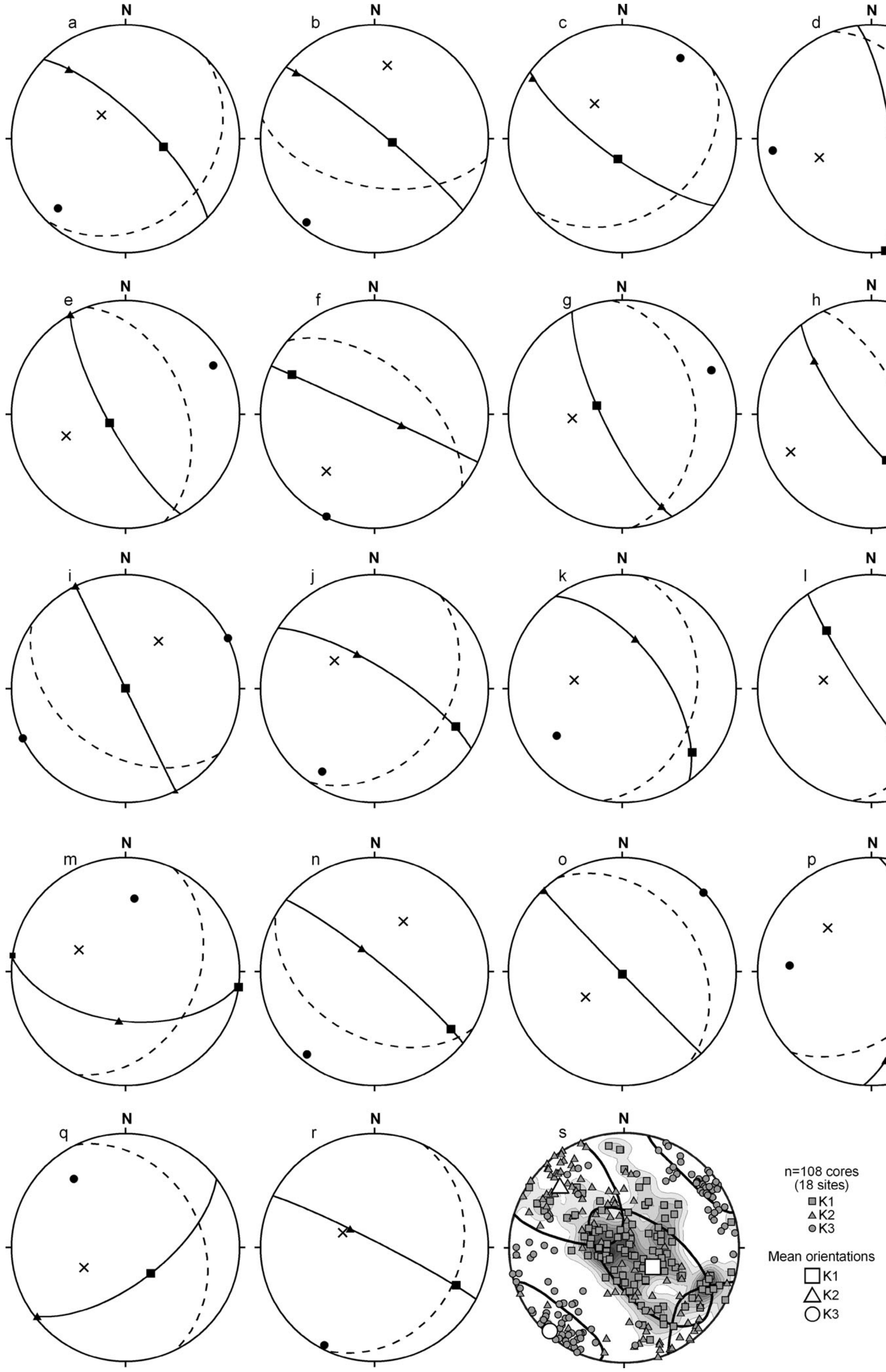

Figure 4. Lower hemisphere equal area projections of K_1 (square), K_2 (triangle) and K_3 (circle) orientations recorded in the investigated quartzites. (a) to (r) show mean orientations for sampling site 1, 1b, 1c, 3, 3x, 5, 7, 8, 9, 10, 11, 11x, 12, 13, 14, 15, 16x and 17, respectively. Magnetic foliation (common great circle containing K_1 and K_2) is plotted in each projection. The orientation of the bedding plane at each site is also plotted as a pole (cross) as well as great circle (dashed). (s) Lower hemisphere equal area projection of K_1, K_2 and K_3 for individual cores ($n = 108$ cores) studied from 18 sites. Mean orientations of K_1, K_2 and K_3 calculated using Anisoft 4.2 (AGICO, Czech Republic) from data of all cores are also plotted. K_1 orientations of individual cores were contoured and are also shown in the same diagram. Note that the magnetic foliation is NW–SE striking and the plunge of K_1 varies from SE through vertical to NW. See text for discussion.

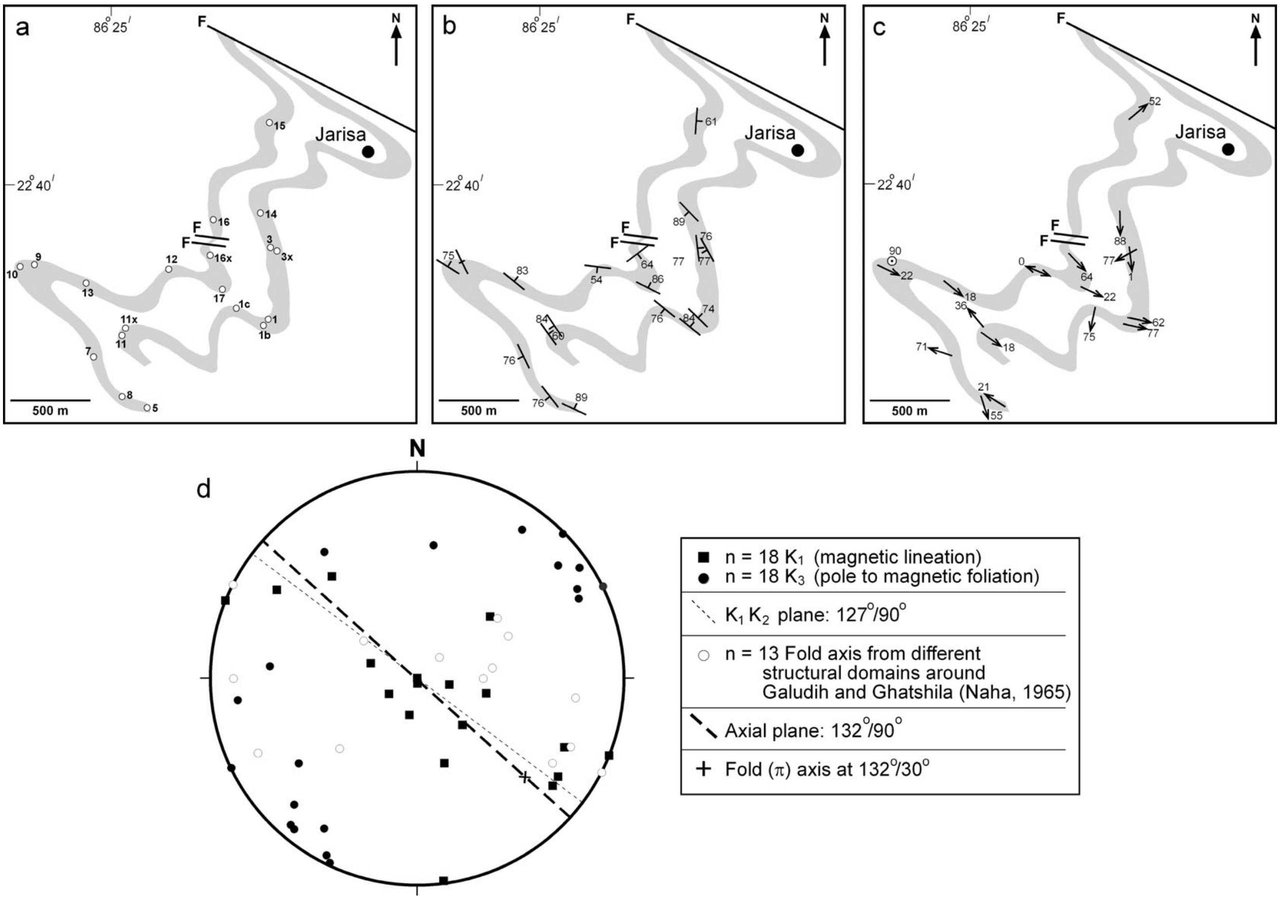

Figure 5. (a) AMS sampling site map of the quartzites investigated. (b) and (c) are magnetic foliation and magnetic lineation maps, respectively, of the quartzites. (d) Lower hemisphere equal area projection of orientation of magnetic lineation (K_1) and pole to magnetic foliation (K_3) of the samples investigated. Index gives explanation of the symbols. See text for discussion.

few magnetic lineations (K_1) plunge gently to the SE, with orientations sub-parallel to the fold axis, most K_1 orientations vary from SE through vertical to NW (Fig. 5d). This variation is also noted in Figure 4s, where K_1 orientations from all the individual cores ($n = 108$) were plotted as well as contoured. The authors have plotted the orientations of fold axes in different structural domains in the region around Galudih and Ghatshila (as reported by Naha, 1965) in the same lower hemisphere equal area projection along with the magnetic data (open circles in Fig. 5d). It is noted that the variation in orientation of K_1 from quartzites around Galudih is similar to the variation of the fold axis orientations on a regional scale. This implies that although the Galudih area, which occupies the westernmost part of the terrain, did not develop mesoscopic-scale superposed folds, there was some influence of the regional deformation on the quartzites that is manifested in the variation of the magnetic lineations. This would also imply that the variation in orientation of the fold axis on a regional scale must be tectonic in origin and cannot be attributed to variations in basin configuration. It was suggested by Mukhopadhyay, Ghosh & Chattopadhyay (2004) and Ghosh, Mukhopadhyay & Sengupta (2006) that regional D_2 deformation was responsible for the development of superposed folds (culminations and depressions) as well as sheath-like geometry in the vicinity of Ghatshila and Dhalbhumgarh. We infer that the variation in the orientation of the K_1 axis (from SE through vertical to NW) in the Galudih area is an imprint of this regional-scale superposed deformation. Thus, the present study indicates that the regional-scale superposed folding influenced fabric development in the quartzites around Galudih. Although this did not lead to a mesoscopic-scale superposition/variation of structures, it is manifested in the variation of magnetic fabric orientation data.

5. Conclusions

The present study demonstrates the robustness of measuring AMS to decipher superposed fabrics in quartzites that are devoid of mesoscopic-scale evidence of multiple deformation events. The analyses of quartzites from the folds in an approximately 10 km^2 area around Galudih (eastern India) reveals that the fold axis plunges gently to the SE. However, the orientation of the magnetic lineation varies from SE through vertical to NW. This variation in the orientation of the magnetic lineation correlates well with the regional-scale variation in the fold axis in different structural domains located in an approximately 200 km^2 area between Galudih, Ghatshila and Dhalbhumgarh (reported by earlier workers); this variation has been attributed to development of sheath-like geometry on a regional scale due to shearing related to D_2 deformation (Ghosh, Mukhopadhyay & Sengupta, 2006). Thus, it is concluded that the magnetic fabric developed in folded quartzites around Galudih preserves within it evidence of regional-scale superposed deformation and shearing.

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References

BORRADAILE, G. J. & JACKSON, M. 2004. Anisotropy of magnetic susceptibility (AMS): magnetic petrofabrics of deformed rocks. In *Magnetic Fabric: Methods and Applications* (eds F. Martín-Hernández, C. M. Lüneburg, C. Aubourg & M. Jackson), pp. 299–360. Geological Society of London, Special Publication no. 238.

BOUCHEZ, J. L. 1997. Granite is never isotropic: an introduction to AMS studies of granitic rocks. In *Granite: From Segregation of Melt to Emplacement Fabrics* (eds J. L. Bouchez, D. W. H. Hutton & W. E. Stephens), pp. 95–112. Dordrecht, The Netherlands: Kluwer Academic Publishers.

DE WALL, H., GREILING, R. O. & SADEK, M. F. 2001. Post-collisional shortening in the late Pan-African Hamisana high strain zone, SE Egypt: field and magnetic fabric evidence. *Precambrian Research* **107**, 79–194.

DUNN, J. A. & DEY, A. K. 1942. The geology and petrology of eastern Singhbhum and surrounding areas. *Geological Survey of India Memoir* **69**, 281–450.

GHOSH, M., MUKHOPADHYAY, D. & SENGUPTA, P. 2006. Pressure–temperature-deformation history for a part of the Mesoproterozoic fold belt in North Singhbhum, Eastern India. *Journal of Asian Earth Sciences* **26**, 555–74.

HROUDA, F. 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophysical Survey* **5**, 37–82.

HROUDA, F. 1986. The effect of quartz on the magnetic anisotropy of quartzite. *Studia Geophysica et Geodaetica* **30**, 39–45.

JAYANGONDAPERUMAL, R. & DUBEY, A. K. 2001. Superposed folding of a blind thrust and formation of klippen: Results of anisotropic magnetic susceptibility studies from the Lesser Himalaya. *Journal of Asian Earth Sciences* **19**, 713–25.

JELINEK, V. 1981. Characterization of the magnetic fabric of rocks. *Tectonophysics* **79**, T63–7.

KRATINOVÁ, Z., SCHULMANN, K., EDEL, J.-B., JEŽEK, J. & SCHALTEGGER, U. 2007. Model of successive granite sheet emplacement in transtensional setting: Integrated microstructural and anisotropy of magnetic susceptibility study. *Tectonics* **26**, TC6003.

MAJUMDER, S. & MAMTANI, M. A. 2009. Magnetic fabric in the Malanjkhand Granite (central India) – implications for regional tectonics and Proterozoic suturing of the Indian shield. *Physics of the Earth and Planetary Interiors* **172**, 310–23.

MAMTANI, M. A. & ARORA, B. R. 2005. Anisotropy of magnetic susceptibility – a useful tool for analyses of naturally deformed rocks. *Himalayan Geology* **26**, 175–86.

MAMTANI, M. A. & GREILING, R. O. 2005. Granite emplacement and its relation with regional deformation in the Aravalli Mountain Belt (India) – inferences from magnetic fabric. *Journal of Structural Geology* **27**, 2008–29.

MAMTANI, M. A. & SENGUPTA, A. 2009. Anisotropy of magnetic susceptibility analysis of deformed kaolinite: implications for evaluating landslides. *International Journal of Earth Sciences* **98**, 1721–5.

MAMTANI, M. A., GREILING, R. O., KARANTH, R. V. & MERH, S. S. 1999. Orogenic deformation and its relation with AMS fabric – an example from the southern Aravalli mountain belt, India. In *The Indian subcontinent and Gondwana: a palaeomagnetic and rock magnetic perspective* (eds T. Radhakrishna & J. D. A. Piper), pp. 9–24. Geological Society of India, Memoir no. 44.

MAMTANI, M. A., GHOSH, A., CHAUDHURI, A. K. & SENGUPTA, D. 2004. Joint Pattern in Precambrian rocks around Galudih (India): implications for fold mechanism. *Gondwana Research* **7**, 579–83.

MUKHERJI, A., CHAUDHURI, A. K. & MAMTANI, M. A. 2004. Regional scale strain variations in the Banded Iron Formations of eastern India: results from anisotropy of magnetic susceptibility studies. *Journal of Structural Geology* **26**, 2175–89.

MUKHOPADHYAY, D. & SENGUPTA, S. 1971. Structural geometry and time relation of metamorphic recrystallisation to deformation in the Precambrian rocks near Simulpal, Eastern India. *Geological Society of America Bulletin* **82**, 2251–60.

MUKHOPADHYAY, D., GHOSH, M. & CHATTOPADHYAY, A. K. 2004. Structural pattern in the Dhalbhumgarh–Kokpara region and its bearing on the tectonics of the Proterozoic fold belt of North Singhbhum, Eastern India. *Geological Survey of India, Special Publication* **84**, 43–60.

NAHA, K. 1959. Steeply plunging recumbent folds. *Geological Magazine* **96**, 137–40.

NAHA, K. 1965. Metamorphism in relation to stratigraphy, structure and movements in parts of east Singhbhum, eastern India. *Quarterly Journal of the Geological Mining & Metallurgical Society of India* **37**, 41–95.

SAHA, A. K. 1994. Crustal Evolution of Singhbhum–North Orissa, Eastern India. *Geological Society of India Memoir* **27**, 341 pp.

STACEY, F. D., JOPLIN, G. & LINDSAY, J. 1960. Magnetic anisotropy and fabric of some foliated rocks from S. E. Australia. *Pure and Applied Geophysics* **47**, 30–40.

TARLING, D. H. & HROUDA, F. 1993. *The Magnetic Anisotropy of Rocks*. London: Chapman and Hall, 217 pp.

ŽÁK, J., SCHULMANN, K. & HROUDA, F. 2005. Multiple magmatic fabrics in the Sazava pluton (Bohemian

Massif, Czech Republic): a result of superposition of wrench-dominated regional transpression on final emplacement. *Journal of Structural Geology* **27**, 805–22.

ŽÁK, J., VERNER, K. & TÝCOVÁ, P. 2008. Multiple magmatic fabrics in plutons: an overlooked tool for exploring interactions between magmatic processes and regional deformation? *Geological Magazine* **145**, 537–51.

ZHANG, J. & PIPER, J. D. A. 1994. Magnetic fabric and post-orogenic uplift and cooling magnetizations in a Precambrian granulite terrain: The Datong-Huai'an region of the North China Shield. *Tectonophysics* **243**, 227–46.