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Anisotropy of Magnetic Susceptibility in the Almora Crystalline Zone Lesser Himalaya, India: A Case Study

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Abstract: The Almora Crystalline Zone (ACZ) in the Kumaun Lesser Himalaya is disposed in the form of a large thrust sheet over the unfossiliferous Precambrian-Palaeozoic sedimentary sequences and have tectonic contacts, known as North Almora Thrust (NAT) and South Almora Thrust (SAT). The rocks are metamorphosed under greenschist and amphibolite facies and contain mainly diamagnetic and paramagnetic minerals. The structural and fabric data collected from the field has been found to be matching with the newly generated magnetic data of crystalline rocks from the vicinity of the NAT and SAT. Anisotropy of Magnetic Susceptibility (AMS) measurements has become an important tool for fabric study based tectonic evolution of metamorphic terrains. These rocks show a very strong preferred orientation of lineation (k_{max}) and the mean shape of the strain ellipsoid is prolate due to the late stage thrust sheet movements. However, in places, a few samples show high mean susceptibility due to the presence of ferromagnetic minerals.

Key words: AMS, mylonites, ACZ, Lesser Himalaya, India

INTRODUCTION

The Lesser Himalaya is characterized by the occurrence few crystalline outcrops of varying dimensions, of which Almora Crystalline Zone is the largest. These crystalline rocks occur as remnants of a large thrust sheet that derived from the Central Crystalline Zone of the Higher Himalaya along the Main Central Thrust (MCT) and now rest over the Lesser Himalayan Sedimentary Sequences (Fig. 1) (Gansser, 1964; Valdiya, 1979; Coward *et al.*, 1986; Pecher and LeFort, 1986). The rocks of the ACZ are generally comprised of low to medium grade metamorphics belonging to the greenschist and amphibolite facies. The dominant lithology is slate, phyllite and various varieties of schists, quartzites, granites and their mylonite derivatives (Valdiya, 1980; Bhattacharya and Agarwal, 1985; Bali and Bhattacharya, 1988; Bali and Agarwal, 1999). The major tectonic boundaries are NAT and SAT, exposed on the surface as floor thrusts, though there are a number of other thrusts, branching out from these two main thrusts and are of local nature. These thrust planes are mapped at different places by many earlier workers (Merh and Vashi, 1976; Trivedi *et al.*, 1984). Zones of mylonitic rocks have also been identified within and outside the ACZ. Many earlier workers focused their attention to delineate tectonic evolution, deformation and the microstructures

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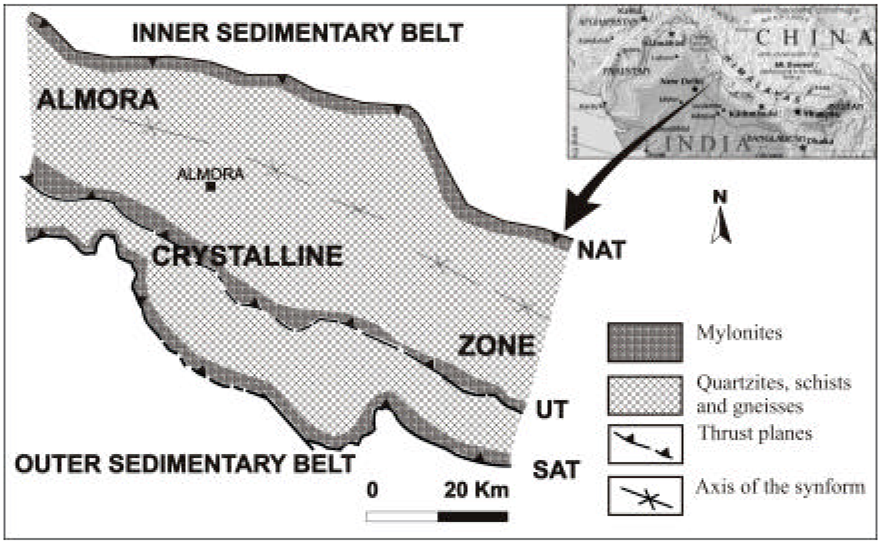

Fig. 1: Location map showing the Almora Crystalline Zone, Kumaun Lesser Himalya. Inset shows the location of the area within India

of the rocks (Misra and Sharma, 1972; Jain, 1975; Bhattacharya and Agarwal, 1985; Agarwal, 1986, 1994; Srivastava and Mitra, 1996; Bali and Agarwal, 1999; Joshi, 1999; Agarwal and Bali, 2008; Agarwal *et al*., 2010; Joshi and Tiwari, 2009).

The present study is part of the work being carried out in the ACZ to study the tectonics, deformation pattern, strain analysis and the micro-fabrics. During this study, it was felt to establish a correlation between the deformational structures, the fabrics observed from the outcrop and from thin section study and the magnetic fabric developed during the last phase of deformation. Considering these objectives, 5-6 cores of 2 cm diameter were drilled from individual oriented samples from the vicinity of the thrust zones for the AMS analysis.

STRUCTURE AND STRAIN ANALYSIS OF MYLONITES

The thrust planes are characterized by the presence of zones of mylonites of variable thickness. The mylonites in general are present within the crystalline rocks, though the foot-wall rocks also show effects of pulverization and recrystallisation (Agarwal, 1994). A variety of micro-structural fabrics developed within the mylonites. Following the classification of Spry (1969), it is observed that a number of mylonite types like Protomylonites, Orthomylonites, Ultramylonites (Fig. 2a-c) and Phyllonites are developed (Bhattacharya and Agarwal, 1985; Bali and Agarwal, 1999). In this study, it is observed that a number of fabric elements developed during the various stages of the evolution of ACZ (Bali and Agarwal, 1999). The mylonitic foliation is prominently developed close to major tectonic planes. Near NAT, this feature dips 15° to 65° towards S/SSW and 10° to 40° due NNE/NE at SAT. The mylonitic foliation at places becomes undulating due to the influence of another fabric termed as C-Surface. In some of the ultramylonite especially these bordering the SAT, the C and S fabric (mylonitic foliation) attain parallelism due to intense shearing activity that seems to have taken place during the emplacement of thrust

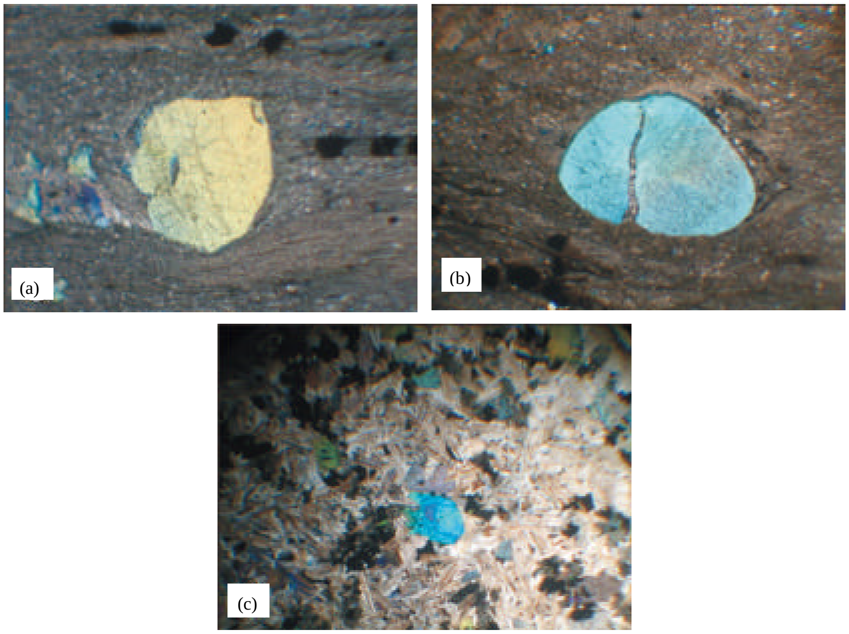

Fig. 2: (a-c) Photomicrograph of Mylonite types showing intense pulvirization and deformed porphyroclasts

sheets. A still younger fabric referred to as S_b fabric is developed in mica rich rocks. This fabric too is found to be prominently developed within the mylonitic rocks bordering the SAT. Mineralogically, quartz shows imprints of deformation during the process of mylonitization. The dynamic recrystallisation achieved during the thrust sheet emplacement seems to have changed the earlier quartz porphyroclasts into recrystallised augen structures. It is also observed that the ultramylonites located away from the thrust planes show strong recrystallisation. In addition to such plastically deformed features, quartz also shows evidences of brittle deformation. Mechanically broken quartz fragments measuring less than 0.4 mm sizes are present within the ortho- and ultramylonite bordering the SAT.

Strain analysis in this part of Himalaya has been carried out by Bhattacharya and Agarwal (1989), using folded tectonites and elliptically deformed porphyroclasts. Various parameters like flattening of folds, apparent strain ratio and buckle shortening were estimated using the folds.

Flattening in minor folds was measured by the method suggested by Ramsay (1962). Quantative assessment in folds has been carried out along two N-S traverses across the strike of South Almora Thrust (SAT). Flattening values have been found to range from 19- 56% along these traverses (Agarwal and Bhattacharya, 1987). Though these values do not show any regular increase or decrease in the trends from North to South.

The apparent strain ratio ($\sqrt{\lambda_1}/\sqrt{\lambda_2}$) was estimated for the (flattening) folds of the area by the method suggested by Ramsay (1967). The ($\sqrt{\lambda_1}/\sqrt{\lambda_2}$) values for the folds of the area range from 0.1 to 2.65 along these traverses. The buckle shortening (De Sitter, 1964) for the folds varies from 40-90%.

Elliptically deformed porphyroclasts have also been used especially around the SAT for the estimation of strain at the mesoscopic as well as microscopic (thin section) levels. The

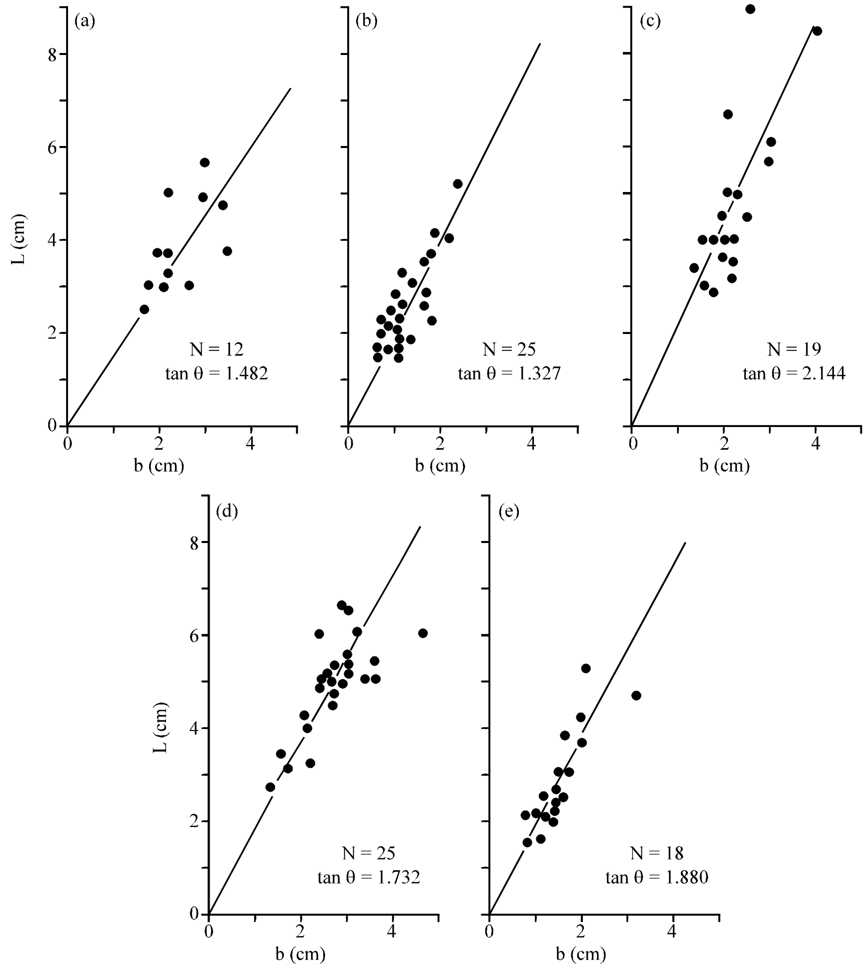

Fig. 3: (a-e) Measurements of strain ratio from the thin sections on the longest (L) and shortest (b) axis of the elliptically deformed feldspar porphyroclasts of the area (modified after Bhattacharya and Agarwal, 1985, 1989)

elliptically deformed porphyroclasts of quartz and feldspar occur with their long axis parallel to sub parallel (very rarely oblique) alignment with the prevailing foliation plane. The values of strain ratio for these porphyroclasts for the four traverses range between 1.804-2.050 (Fig. 3a-e).

The above study shows that the ellepsoidally deformed quartzofeldspathic porphyroclasts are oriented along the x-y plane of the local strain ellipsoid. Their maximum orientation correspond to the longest strain axis of the strain ellipsoid. It must be noted that the strain values are more near the SAT and NAT as compared to the other places.

ALMORA CRYSTALLINE ZONE AND AMS ANALYSIS

Anisotropy of Magnetic Susceptibility (AMS) or the magnetic fabric of a rock has great importance for understanding the fabric of the deformed rocks. Graham (1954) first

Table 1: Anisotropy of magnetic susceptibility parameters computed at each site

Sample site	K_{mean} (SI unit)	K_{max}	K_{int}	K_{min}	F	L	P'	T	K1	K2	K3	N
Almora Southeast-I	8.87×10^{-4}	1.075	1.009	0.915	1.103	1.065	1.176	0.216	23.3/38.2	123.5/12.7	228.5/49.0	13
Almora Southeast-II	2.14×10^{-4}	1.045	1.017	0.938	1.085	1.027	1.119	0.051	1.73/38.3	284.7/25.1	39.0/41.3	11
Almora Northwest	4.96×10^{-4}	1.062	1.008	0.931	1.083	1.053	1.142	0.210	184.2/9.1	297.0/27.5	77.6/60.8	9
Almora Southwest	1.52×10^{-4}	1.035	1.026	0.939	1.092	1.009	1.114	0.814	358.0/24.5	91.2/7.1	196.3/64.4	23
Almora Northeast	1.63×10^{-4}	0.831	0.807	0.761	1.600	1.030	1.093	0.330	202.2/46	300.2/7.6	37.3/43.0	10

Notes: K1, K2, and K3: Intensity of maximum, intermediate and minimum susceptibility axes. K_{mean}: Mean susceptibility. L: Magnetic lineation (K1/K2), F: Magnetic foliation (K2/K3), P': Corrected anisotropy degree, T: Shape factor, N: No. of samples

understood this property of the rocks and its potential to study the fabric of a rock especially for otherwise homogeneous looking granite plutons and deformed rocks. This method can thus be applied on a greater scale to different rock types with much precision and speed for solving many problems than most conventional methods. Many workers discussed the applicability of AMS to record the structure and fabric of tectonites e.g., Tarling and Hrouda (1993), Borradaile and Henry (1997), Greiling and Verma (2001), Tripathy (2009) and Tripathy *et al*. (2009).

The application of AMS technique to correlate the meso- and microscopic structural elements of the tectonites and mylonites from the Himalaya is the first attempt so far. The magnetic susceptibility (k) is a physical property, which denotes the acquired magnetization (M) in an applied field (H). Low field anisotropy of magnetic susceptibility is a second rank tensor and is expressed in terms of an ellipsoid with principal axes k_{max}; k_{int}; k_{min}. The average volume susceptibility is [$k = (k_{max} + k_{int} + k_{min})/3$], mean shape and anisotropy factors are directly calculated from directional measurements taken in 15 different sample positions using the software (Anisoft-42) for the MFK Kappabridge (Hrouda *et al*., 1990). The mean shape of the ellipsoid is expressed by the parameter T; the value of it between 0 to +1 represent an oblate, 0 for neutral and < to -1 for prolate shapes respectively (Jelinek, 1981). The anisotropy degree of the ellipsoid is descried by the P' value. The magnetic lineation expresses to the direction of maximum susceptibility (k_{max}) and the direction of minimum susceptibility (k_{max}) is the pole of the magnetic foliation plane (containing k_{max} and k_{int}). The analytical data of the AMS for about 30 oriented samples are selected from the vicinity of the NAT and SAT comprising a representative of mylonites and are shown in Table 1. The mean susceptibility (average value 3.82×10^{-4}----SI units) of the samples mainly shows the presence of paramagnetic minerals as the rocks normally fall under schists, though few quartz rich rocks show very low values also (1.52×10^{-4}). One sample indicates the presence of ferromagnetic minerals (susceptibility value 8.87×10^{-4}), which is pure magnetite (sample No. KM 14) as the thermomagnetic behavior show strong decrease in susceptibility at temperatures of 589°C (Fig. 4).

Shape of Ellipsoid

In the present study mainly mylonites were subjected to AMS analysis. The microstructural features of these mylonites were studied in great details from different sectors of the Almora Crystalline Zone (Agarwal, 1994; Agarwal and Bali, 2008; Bhattacharya and Agarwal, 1985; Bali and Agarwal, 1999). The AMS data provide a more detailed picture of the fabric element and their variations. It also gives an opportunity to interpret the fabric of the deformed rocks with greater amount of confidence. The data show not very significant variation in shape (T), which is ranging between 0.051 and 0.814 and degree of anisotropy (P') ranging between 1.093 to 1.176 (Table 1). This variation is shown in the T-P' plot (Fig. 5a-e) of Jelinek (1981). The shape of the strain ellipsoid of most of the samples is of oblate type owing to the fact that a very strong mylonitic foliation is characteristic for these rocks (Bhattacharya and Agarwal, 1985; Agarwal, 1994; Bali and Agarwal, 1999). The

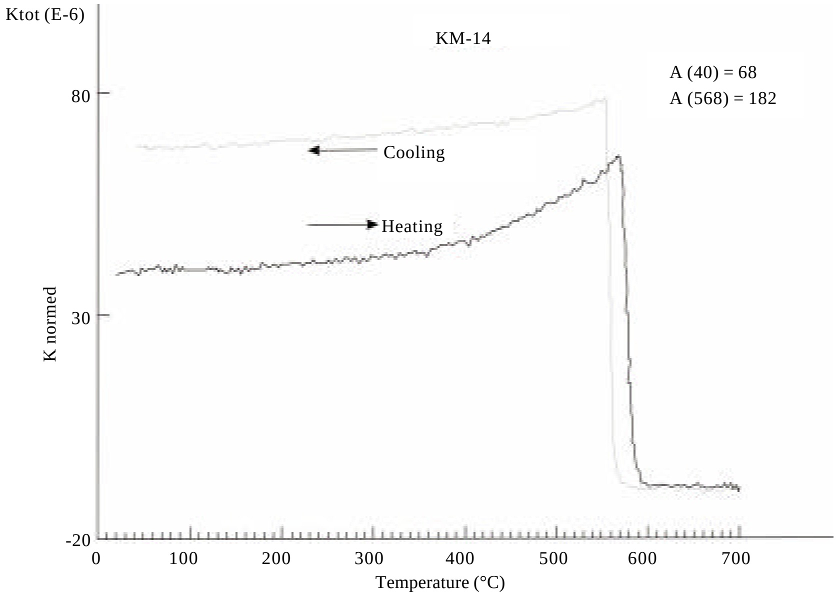

Fig. 4: K-T curve obtained for a ferromagnetic mylonite (Sample KM-14) documenting the presence of multidomain (MD) magnetite as an important mineral phase

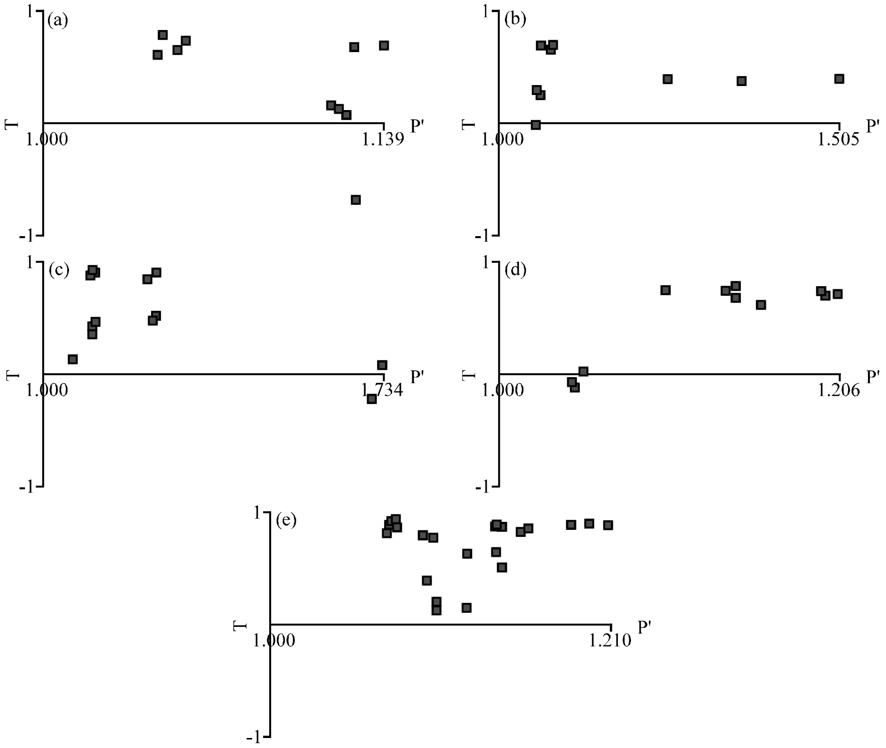

Fig. 5: (a-e) T vs. P' plot of the mylonite samples

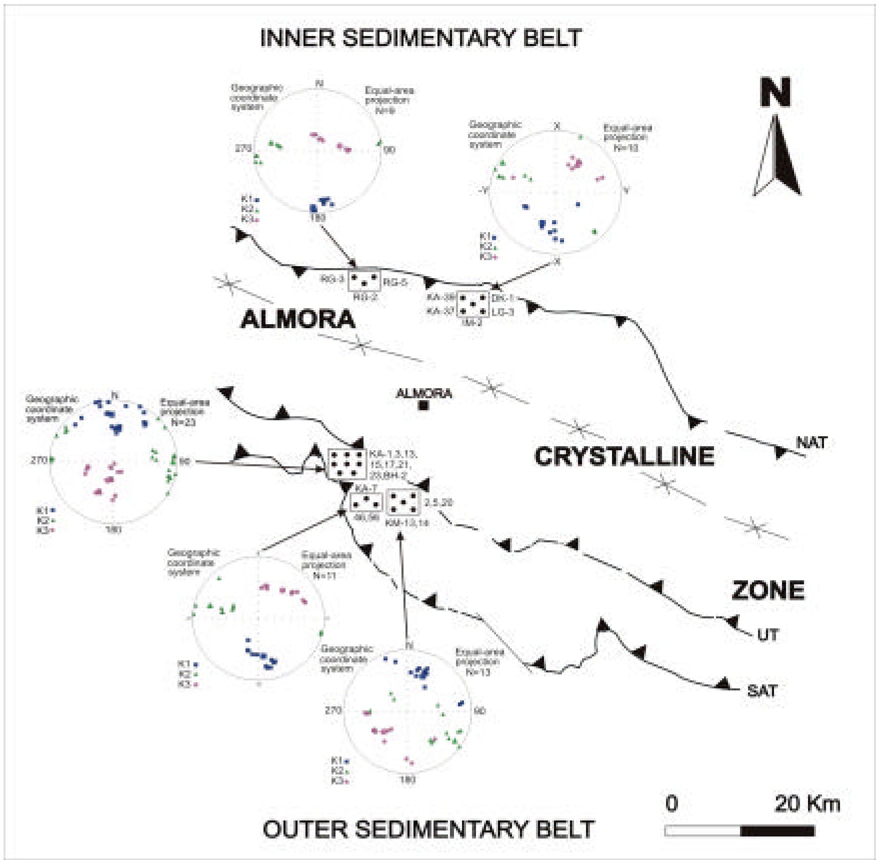

Fig. 6: Location of the sampling sites and their AMS plot

variation in shape (T) and anisotropy (P') is due to the inhomogeneity of the rocks. The paramagnetic minerals of a few samples near the thrust planes form a strong mineral lineation/stretching lineation, which is the cause of the prolate shape of the strain ellipsoid (Fig. 2). Though a few samples away from the thrust planes which lack a distinct mineral lineation show scattering of the shape factor values is because of the variation in the fabric through out the crystalline thrust sheet. Such variations in the rock fabric have been recorded earlier from the field. The magnetic foliation in all the samples is mostly oriented in NW-SE direction dipping either to the N or to the S at a regional scale which compares well with the field measured foliation data. The directional data for the whole area is given in Table 1 and are also shown on the map in the form of stereoplots (Fig. 6).

RESULTS

The present study deals with a comparative analysis of field observations, micro-structural, strain distribution and anisotropy of magnetic susceptibility in the Almora Crystalline Zone. The magnetic fabric data indicate a very strong foliation and the mean susceptibility varies from low to medium owing to the presence of mainly dia- and paramagnetic minerals in the rocks. The shape of the ellipsoid chiefly falls in the field of oblate type of ellipsoid. This indicates the presence of a strong mylonitic foliation in these rocks. The AMS fabric of the representative rock samples mainly from the areas close to major thrust planes broadly show a prolate type of ellipsoid, which is due to the presence of a strong lineation developed due to the thrusting and match with the field data, though at places it shows significant variations. This can be interpreted in the light of late stage thrust adjustment. The orientation of k_{max} is significant either in NE or SW directions along the northern limb and the southern limb of the Almora synform, the fact which is now well established by the field evidences of both stretching lineation (Agarwal, 1994) and the top to North sense of shear (Agarwal and Bali, 2008).

DISCUSSION

The rocks of Almora Crystalline Zone Kumaun Himalaya are disposed in the form of a large thrust sheet representing the part of the up heaved basement along a major crustal level shear zone known as Main Central Thrust (MCT). The rocks of ACZ are metamorphosed under the greenschist and amphibolite facies and show a very well defined foliation and stretching lineation (Agarwal, 1994). The AMS fabric of the Mylonites from ACZ along identified traverses show a similar pattern of fabric development as recorded earlier from the field data. The overall AMS fabric in all the samples show an oblate strain ellipsoid indicating a strong magnetic foliation (Fig. 5, Table 1). The other important point to be mentioned here is that the tectonic strain data recorded from these rocks does not show any specific pattern of distribution (Bhattacharya and Agarwal, 1985, 1989). This fact is also corroborated by the mean susceptibility which varies throughout the area and has no definite distribution pattern. A strong magnetic lineation is observed, though, along the thrust planes which is also recorded earlier in the form of a strong stretching lineation from near the thrust planes (Agarwal, 1994).

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