Back-thrusting in Lesser Himalaya: Evidences from magnetic fabric studies in parts of Almora crystalline zone, Kumaun Lesser Himalaya

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The present study aims to understand evolution of the Lesser Himalaya, which consists of (meta) sedimentary and crystalline rocks. Field studies, microscopic and rock magnetic investigations have been carried out on the rocks near the South Almora Thrust (SAT) and the North Almora Thrust (NAT), which separates the Almora Crystalline Zone (ACZ) from the Lesser Himalayan sequences (LHS). The results show that along the South Almora Thrust, the deformation is persistent; however, near the NAT deformation pattern is complex and implies overprinting of original shear sense by a younger deformational event. We attribute this overprinting to late stage back-thrusting along NAT, active after the emplacement of ACZ. During this late stage back-thrusting, rocks of the ACZ and LHS were coupled. Back-thrusts originated below the Lesser Himalayan rocks, probably from the Main Boundary Thrust, and propagated across the sedimentary and crystalline rocks. This study provides new results from multiple investigations, and enhances our understanding of the evolution of the ACZ.

1. Introduction

The continental–continental collision of the Indian and Asian plates, ~55 Ma ago, motored the evolution of the ~2400 km long belt of the Himalaya mountain chain, which is the loftiest in the world (Gansser 1964; Molnar and Tapponnier 1975; Valdiya 1998). The collision shortened the crust and developed three major south-verging thrust systems known as Main Central Thrust (MCT) (active from 20.8 ± 1.1 to 15.0 ± 2.4 Ma, Tobgay *et al.* 2012), Main Boundary Thrust (MBT) (~11 Ma, Meigs *et al.* 1995), and Himalayan Frontal Thrust (HFT) (initiation age between 500 and 100 Ka, Thakur 2013), from north to south respectively (see Seeber and Armbruster

1981; Srivastava and Mitra 1994; Mukherjee *et al.* 2015; Dubey 2014). The MCT and MBT delineate the Lesser Himalayan sequence in Kumaun region from the Higher Himalaya in north and the Siwalik (sub-Himalaya) in south, respectively (Nakata 1989; Jayangondaperumal *et al.* 2010). The sedimentary formations of the Lesser Himalayan sequence (LHS) are tectonically overlain by several klippen consisting of largely amphibolite facie metamorphic rocks, and intrusive and basement granites, belonging to the Precambrian Almora group. The Almora group consists of granite, granodiorite and augen gneiss that are intruded into Saryu, Gumalikhhet and Munsiri formations (Valdiya 1980). The intrusive and basement granites within the klippen have been dated

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as 560 ± 20 Ma and 1865 ± 60 Ma, respectively (Rb/Sr whole rock; Trivedi *et al.* 1984). On the one hand, some workers established the klippen as remnants of a once more extensive Munsiri thrust sheet, which lies structurally below the MCT (e.g., Valdiya 1980; Srivastava and Mitra 1994; Moharana *et al.* 2013). On the other hand, Jayangondaperumal and Dubey (2001) proposed that the klippen are pop-up or para-autochthonous.

1.1 Geological setting

The Almora klippen, also known as the Almora Crystalline Zone (ACZ), is the largest among all Lesser Himalayan thrust sheets. The intensely deformed ACZ trends WNW–ESE and is separated from the Damta–Tejam Group of rocks in the north and the sedimentary Krol belt in south by the North Almora Thrust (NAT) and South Almora Thrust (SAT), respectively (Valdiya 1980) (figure 1). Another important tectonic plane referred to as Mukteshwar dislocation (MD) or as Ramgarh Thrust/Uprari Thrust (Valdiya 1980; Robinson and Pearson 2013) is exposed in the north of SAT (figure 1).

The Almora crystalline zone is regionally folded into a giant synform having approximately an E–W axis. The southern limb of the Almora synform, with north dipping metamorphic rocks, has been divided into two: a lower Ramgarh Formation in the south (with mylonites, garnetiferous mica-schist, inter-bedded quartzite and phyllites, some lenticular exposers of gneisses and thin bands of amphibolites), separated by the MD, and from an upper Mukteshwar Formation in the north with quartzites, garnetiferous chlorite schists and subordinate phyllites and gneisses (Bhattacharya and Agarwal 1985; Agarwal 1994; Bali and Agarwal 1999). The rocks are usually trending ESE–WNW and dipping $\sim 30^\circ$ towards north in the southern limb and around 50° or more in the northern limb.

The two tectonic contacts, NAT and SAT separate the ACZ from the sedimentaries in the north and the south, respectively. A fairly thick zone of the mylonitic rocks (6–8 km wide) fringing the SAT (Bhattacharya and Agarwal 1985), falling in the Ramgarh Belt of Valdiya (1980), and another thin zone of mylonites bordering the NAT (Bali and Agarwal 1999) are present on the two sides. The SAT can be correlated with the Ramgarh Thrust of Valdiya (1980) and overlying rock units between SAT and Uprari Thrust (UT) can also be referred to the Ramgarh Belt. However, a variety of other rock types, viz., garnetiferous mica-schist, quartzite, phyllites, occasionally gneisses and gneissic granites, and thin bands of amphibolites with well-developed planar and linear fabrics are

Figure 1. (a) Geological map of the Kumaun Lesser Himalaya showing regional extent of the Almora crystalline zone and other lithotectonic units (modified after Valdiya 1980). The arrows mark the cross-section line. (b) Generalised cross section of Kumaun Lesser Himalaya showing different lithounits and major thrust sheets and (c) tectonic disposition of Almora thrust sheet (Agarwal 1994; Pant *et al.* 2012), where 'MD' is Mukteshwar Dislocation and 'MCT' is Main Central Thrust. Note that the Damta and Tejam Group and the Jaunsar and Musoorie Group belong to the inner and the outer Krol Belt, respectively.

also present. A variety of structural elements have been observed, e.g., small scale folds, shear zones (mainly showing overall top-to-south sense of shear, but also show top-to-north sense of shear occasionally along the northern limb near NAT) and other minor structures.

1.2 Motivation

Unlike the strike slip tectonics-dominated syntaxes at the two sides, the Kumaun Lesser Himalaya lies near the central part of the Himalayan belt

and is, therefore, a critical area for studying the typical characteristics of the Himalayan fold-and-thrust belt (Srivastava and Mitra 1994) and brittle deformation (Mukherjee and Koyi 2010a, b). Some published reports suggest that the NAT and SAT are two exposures of the same folded sole-thrust, over which the ACZ was thrust south from the Munsiri Formation (Valdiya 1980; Thakur 1992; Agarwal 1994; Srivastava and Mitra 1994); while the others treat NAT as the thrust contact between inner and outer Lesser Himalaya (Ahmad *et al.* 2000). Furthermore, some reports propose that since the western edge of NAT is juxtaposed with Tons thrust, both of them are exposure of the same thrust (Clerier *et al.*

2009a, b; Webb 2011); however, the emplacement relations are still unclear. Furthermore, back-thrusting in the Himalayan collisional zone is significant to appreciate that a bivergent kinematics rather than a monovergent deformation operated in this orogeny (e.g., Bose and Mukherjee 2015). A comparative study of the deformation structures and magnetic fabrics may, therefore, reveal the similarities and differences in the deformation mechanism active at the NAT and SAT. It is important to note that there are no published or established ages for NAT and SAT. The comparison may further help in understanding the evolution of Lesser Himalaya in general and ACZ in particular.

Figure 2. Geological map of the Bhowali–Ramgarh and Bhimtal–Dhanachuli section across the SAT, modified after Bhattacharya and Agarwal (1985). The map shows geological units, their trends and magnetic foliations, and the sample locations.

2. Methodology

2.1 Field based studies and sampling

The orientation of the beds and the metamorphic foliation were recorded by a geological compass. Block samples, oriented using a compass, were collected from each site. A minimum of five cylindrical cores (25.4 mm in diameter and 22 mm in length) were drilled from each block sample in the laboratory.

Geological map for the study area near SAT (figure 2) has been modified after Bhattacharya and Agarwal (1985). Geological map of the study area near NAT, the Dhaulchhina–Goniagad road section, has been prepared during the present study (figure 3).

2.2 Rock magnetic measurements

For magnetic fabric studies, the AMS was measured using a KLY-4S Kappabridge (AGICO,

Brno, Czech Republic) at Department of Strukturgeologie und Tektonophysik, Institut für Angewandte Geowissenschaften, Karlsruher Institut für Technologie, Karlsruhe, Germany. The data were processed through the Anisoft 4.2 software, and plotted in lower hemisphere stereographic projections. We calculate the AMS parameters, such as mean bulk susceptibility (k_m); corrected degree of magnetic anisotropy (P'); mean of shape factor of AMS ellipsoid (T_{mean}). The following equations, after Tarling and Hrouda (1993), represent these parameters:

$$k_m = (k_1 + k_2 + k_3)/3 \quad (1)$$

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

$$T_{\text{mean}} = (2\eta_2 - \eta_1 - \eta_3)/(\eta_1 - \eta_3) \quad (3)$$

where

$$\eta_1 = \ln k_1; \quad \eta_2 = \ln k_2; \quad \eta_3 = \ln k_3$$

Figure 3. Geological map of Dhaulchhina–Goniagad section near NAT. The map shows geological units, their trends and magnetic foliations, and the sample locations.

and

$$\eta_m = k_2[(\eta_1)(\eta_2)(\eta_3)]^{1/3}. \quad (4)$$

We denote the maximum, intermediate and minimum principal magnetic susceptibility axes as k_1 , k_2 and k_3 . The T_{mean} , k_m and P' were studied as a function of distance from the thrusts, SAT and NAT. Furthermore, we plotted T_{mean} against P' (Jelinek 1981) and k_m against P' to understand the relationship among them.

For investigating the magnetic mineralogy, temperature dependent low-field magnetic susceptibility (χ - T) experiments were carried out. The measurements were done in two runs on powdered samples using a Kappabridge (KLY-4S) (AGICO, Brno, Czech Republic) at Department of Strukturgeologie und Tektonophysik, Institut für Angewandte Geowissenschaften, Karlsruher Institut für Technologie, Karlsruhe, Germany. For low temperature (-194°C to room temperature) measurements, the Kappabridge was equipped with CS-L (AGICO, Brno, Czech Republic) cryostat and the sample was cooled to -194°C using liquid nitrogen, which was then flushed out of the holder using a blast of argon. The bulk susceptibility of the sample was measured as it gradually warmed up to the room temperature. For high temperature (40° – 700°C) measurements, the Kappabridge was equipped with a CS-2 furnace (AGICO, Brno, Czech Republic). The sample was first heated from 40° – 700°C (at a rate of $10^\circ\text{C min}^{-1}$) and was then cooled back. The bulk susceptibility was measured during the entire cycle of heating and cooling. An argon environment (flow rate of 60 ml min^{-1}) was maintained in the sample holder to minimize the risk of oxidation of the sample while heating. The temperature of the sample was measured with a Pt resistance thermometer, placed within a distance of 1 mm. The first derivative curve of the χ - T measurements was calculated to determine the Curie temperature (T_C) and Verwey transition temperatures (T_V). The reversibility of the χ - T curves was also tested.

3. Results

3.1 Macroscopic observations on the rocks in ACZ

ACZ comprises of quartzites, mica schists, garnetiferous mica schists, gneiss and their mylonitic products, belonging to Ramgarh Formation and Saryu Formation which commonly show up to amphibolite facie metamorphism (figure 1) (Valdiya 1980; Srivastava and Mitra 1994, 1996; Bhattacharya 1999; Joshi 1999; Joshi and Tiwari 2004, 2009).

Rocks north of SAT, dip northward; however, those to south of SAT and close to the MBF dip

steeply (35° – 75°) in various directions (figure 2). In contrast, the rocks south of the NAT consistently dip south (figure 3). The northward dip of rocks north of SAT and southward dip of the rocks south of NAT agree to the synformal model of ACZ (figures 1c, 5). Deformation structures, such as boudins, tensional gashes, lateral ramps, large to small scale folds, formed at brittle–ductile transition are common in the studied area (cf. Bali and Agarwal 1999). ACZ rocks are deformed intensely into two 6–8 km thick mylonite zones along NAT and SAT. The mylonite zone along SAT is thicker and more intensely deformed than that along NAT. Previous pseudo-tachylite based studies are in agreement that SAT is more intensely deformed than NAT (Agarwal 1994; Agarwal *et al.* 2011). In vicinity of SAT, mylonites demonstrate both brittle and ductile top-to-south shear sense (figure 4a, b). While near NAT they mostly show top-to-south shear sense (figure 4c), however at few spots top-to-north shear sense is also recorded (figure 4d, e, supplementary figure S1). Generally the slip surfaces, C' -surfaces, make small angles (25° – 35°) with respect to the shear boundaries (Grasemann *et al.* 2003). In ACZ rocks, the angle between C' -surfaces and the shear boundaries is within this range (figure 4).

3.2 Microscopic observations on the rocks in ACZ

In general, the mylonites show a prominent schistosity defined by the alignment of ellipsoidal quartz and sometimes by feldspar grains and their aggregates. However, evidences of heterogeneous deformation due to variation in mechanical properties of the rock are common, such as rotation of quartz grains while fracturing of weaker biotites (figure 4f, g, h). In general, under the microscope the deformation ranges from brittle to semi-brittle in ACZ rocks. In coherence, Bali and Agarwal (1999) describe numerous grains that are plastically deformed or fractured. Grinding of larger quartz and plagioclase grains into smaller grains is common (figure 4f, g) (cf. Bali and Agarwal 1999). Along the SAT, in consequence to intense grinding, only a residue of fine grained, dark coloured material is observed and the clast density is very low, some times less than a couple of grains in a rock-thin section ($\sim 5 \text{ cm}^2$). These rocks may, thus, be classified as ultramylonites. The clast density increases gradually with distance from the thrusts. Larger quartz clasts, near the SAT, show delta (δ) (figure 4f) and sigma (σ) (figure 4g) structures. The ductile shear sense deduced from these grains is top-to-south. Chlorite and biotite as secondary minerals define secondary foliation. The chlorite and biotite have either a syn- or pre-deformation origin, because they demonstrate

Figure 4. (a) Quartz veins in mylonites near SAT demonstrating top-to-south shear. Angle between S and C' planes is 33° . (b) Garnitiferous quartz mica schist dipping 22° towards 045 showing top-to-south shear sense along with a sheared quartz vein. Angle between S and C' planes is 29° . (c) Shear zone showing top-to-south shear sense (white rectangle) in mylonites near NAT. Angle between S and C' planes is 23° (see Trouw *et al.* 2009 for similar examples). (d) Shear zone showing top-to-north shear sense (white rectangle) in mylonites, which is opposite to the general shear sense along NAT. Angle between S and C' planes is 27° . (e) A shear zone visible near Kaflegair village, developed in vicinity of NAT. The beds dip southwards. The sense of shear is top-to-north (up-dip). Angle between S and C' planes is 27° . (f) Sigma structure formed by a dextrally rotated quartz grain and pressure shadow of fine grained mica. The structure shows a top-to-north shear sense. (g) Quartz grain in finer matrix forming a delta structure and showing dextral shear sense. (h) Mica-fish in micaceous quartzite near NAT showing a micro-shear zone, having a sinistral shear sense (black arrows), enclosed by dextral micro-shear zone. N and T mark the north and top of the images, respectively.

conspicuous shear zone microfabric. The chlorite grain from a sample near NAT is most interesting as it shows sinistral offset, antithetic with respect to the main dextral microshear zone (figure 4h). Since the micrograph is from an XZ (parallel with

the lineation and perpendicular to the foliation) thin-section, which is oriented in its original position, the sinistral and dextral shear sense are analogous to top-to-north and top-to-south (cf. Trouw *et al.* 2009).

3.3 Magnetic fabrics in rocks near SAT and NAT

The rocks near SAT show oblate magnetic fabrics (figure S2) which, in general, strike E–W (figure 2) and have moderately to gently plunging northwardly dip (figure 5). In accordance, k_3 axis plunge moderately southwards (figure 5). Similar to those near the SAT, rocks in vicinity of the NAT have oblate magnetic fabrics (figure S2) striking roughly E–W (figure 3). Most k_3 s have steep N to NNE plunge, but a few plunge steeply to SE

(figure 5). Along the SAT and NAT the magnetic lineation has a down-dip attitude with respect to the magnetic and field foliation.

It is noteworthy that with decreasing distance from the thrusts, SAT or MD, the magnetic fabrics become progressively less oblate, in other words more neutral (T_{mean} decreases on closeness with SAT and MD; figure 6). However, no such relation is observed between T_{mean} and distance from NAT (figure 6). While k_m increases with distance from SAT; no such relationship is observed in case of NAT (figure 7). P' , on the other hand, shows

Figure 5. Lower hemisphere projections of the maximum (k_1) and minimum (k_3) principal magnetic susceptibility axes. All samples were collected near the SAT and the NAT. The dip (d) of the beds/metamorphic foliation is also presented. The density contours are calculated by cosine sum method, considering 20 as cosine exponent and 15 cosine intervals.

Figure 6. Graphs showing variation in shape factor of the AMS ellipsoid (T_{mean}) with distance from the thrusts. T_{mean} increases with distance from SAT until the sampling sites get too close to MD, when T_{mean} decreases. Each data point is a mean of at least five samples, collected from a sampling site.

direct correlation with the distance from both SAT and NAT. For example, P' increases with distance from the SAT and the NAT (figure 8). Increase in P' with distance from the thrusts implies that the rocks are becoming magnetically less anisotropic due to thrusting. To the north of the SAT, in three farthest samples, P' decreases with distance (figure 8). Gradually increasing closeness of these

samples with the MD may have caused decrement in P' (figure 8).

In all lithologies near SAT and NAT, presence of only paramagnetic minerals is revealed by absence of Verwey and Curie transition and the substantial noise in the χ - T curves (figure 9a, b). In consequence these rocks have low magnetic susceptibility, typically less than 1.00×10^{-3} SI units

Figure 7. Graphs showing variation in mean of bulk susceptibility (k_m) with distance from the thrusts. k_m increases with distance from the SAT. Each data point is a mean of at least five samples, collected from a sampling site.

Figure 8. Graphs showing increase in mean of corrected magnetic anisotropy (P') with distance from the SAT and NAT, until, in the case of SAT the sampling sites were too close to the MD. Each data point is a mean of at least five samples, collected from a sampling site.

Figure 9. Susceptibility (χ) normalised to susceptibility at 40°C vs. temperature curves. The solid curves (black and grey) represent high temperature measurements, while the black dotted curve represents low temperature measurements. Representative curve for rocks (a) near the SAT and (b) near the NAT.

(table S1). Occasionally in rocks near SAT, susceptibility in cooling curve (black dotted curve in figure 9a) is lower than in the heating curve (black and grey solid curves in figure 9a). Such a behaviour may be attributed either to destruction of paramagnetic phases during heating or to an artefact induced due to low susceptibilities (e.g., Petrovský and Kapička 2006; Agarwal *et al.* 2015). The peak in the beginning of cooling curve at about -180°C is an artefact introduced by the cryostat (figure 9a).

4. Discussion

The Himalayan orogeny has led to more compression after the ACZ emplacement of Munsiri Thrust either as remnants (Valdiya 1980; Srivastava and Mitra 1994, 1996) or as pop-up or para-autochthonous (Jayangondaperumal and Dubey 2001). The late stage compression may have superimposed the original rock and magnetic fabric, thus either overprinting or intensifying it. Comparison of field and magnetic foliation, and examination of deformation structures in field and under microscope may reveal the superimposition of the late stage deformation and thus decode information on the emplacement mode of the NAT.

4.1 Structural trends of rocks in the ACZ

Structures such as shear zones, plastically deformed quartz grains and meso-to-micro scale fractures were frequently observed. These brittle and plastic deformation structures and the distribution of mylonites in the ACZ indicate that the deformation regime possibly reached the brittle-ductile transition zone. The brittle-ductile transition was marked by development of S-C' fabric and shear band foliation (figure 4).

The deformation pattern near the SAT can be more-or-less well constrained. The beds and the metamorphic foliations consistently dip northwards (figures 2, 5), which agree well to the synformal model of the ACZ (e.g., Agarwal 1994; Agarwal *et al.* 2010). The shear zones and structures observed in field and under microscope demonstrate top-to-south shear sense (figure 4a, b, g). This shear sense is in agreement with the southward thrusting model of ACZ (Jain and Anand 1988), and is common in most of the Himalayan terrains (Mukherjee *et al.* 2012).

The situation near the NAT is complex. Both the metamorphic and magnetic foliations consistently dip southwards (figure 5) which agrees well to the synformal model and southward thrusting of ACZ. However, some shear zones and structures observed

in field and under microscope demonstrate top-to-south shear sense; while the other demonstrate top-to-north shear sense. Rheological complications and reorientation of shear zones can produce reverse shear (Mukherjee 2012). Although the top-to-south shear sense is more frequent and agrees to the southward thrusting model of ACZ, we cannot overlook the less common top-to-north shear sense, which is observed only in patches near NAT. The antithetic, top-to-north, shear sense may be argued as a flanking structure with reverse shear sense (e.g., Grasemann *et al.* 2003). However, the reverse shear sense is also observed in the magnetic fabrics, thus, suggesting that the top-to-north shear sense is not due to flanking.

Sporadic albeit conspicuous micro- and meso-structural evidences indicate that the top-to-north shear sense is younger and has overprinted the top-to-south shear sense (figure 4f). This late stage deformation is antithetic to the original southward thrusting. However, absence of such structures near SAT implies that the younger episode of deformation was more active near the NAT. We therefore propose that, after the emplacement of ACZ as a thrust sheet, northern margin of the klippen thrust, NAT (i.e., the roof thrust) reactivated and back-thrusts developed to accommodate the continued compression. There are two possible origin of back-thrusts: (i) NAT suffered reactivation and inversion of shear sense. Thus the NAT 'modified' in to back-thrusts. A similar model was proposed by Agarwal (1994). (ii) Root of back-thrusts lies much below the ACZ and LHS, most probably at the Main Boundary Fault (MBF) and the NAT was not reactivated.

4.2 Magnetic fabrics of rocks in ACZ

The magnetic fabrics near the SAT dip northwards and k_3 vary in trend from SW to SE (figures 2, 5). Near the NAT the magnetic fabrics strike E-W, most of which dip towards S (figures 3, 5). These magnetic fabrics, near SAT and NAT, approximate the metamorphic foliation (figures 2, 3). It is important here that, the orientation of sedimentary beds in ACZ is similar to the metamorphic foliation and the magnetic fabrics (figure 2). We therefore, ascribe such orientation of the magnetic fabrics to the synformal geometry of ACZ. The synformal curvature, introduced in the ACZ after its emplacement, rendered the field and the magnetic fabrics with similar trends. A small fraction of k_3 , near the NAT, plunge SE (figure 5). This trend is reverse of the prominent southward plunge in ACZ, and can neither be explained by synformal geometry of ACZ nor by its southward thrusting. Along the SAT and NAT, the magnetic lineation has a down-dip attitude with respect to the magnetic and field

foliation. This may have been caused by shearing during the ductile deformation.

Shape and anisotropy of the AMS ellipsoid (T_{mean} and P') and the mean bulk susceptibility (k_m) decrease in vicinity of SAT and MD (figures 6, 7, 8). In spite of these conspicuous relationships of magnetic properties with distance from the SAT, we do not observe any relationship of P' with either T_{mean} or k_m (figure S2). Lack of such relationships imply that the variation in the magnetic parameters with distance from the SAT is not due to intrinsic rock properties, such as change in grain size and/or in mineralogy, but owes itself to thrusting-related phenomenon. We attribute decrease in the magnetic properties, k_m , T_{mean} and P' , to increase in brittle deformation and mylonitization with closeness to SAT. Brittle deformation may have fractured the paramagnetic carrier minerals. Absence of such relationships near NAT are, in particular, noteworthy and imply that during the emplacement of ACZ either the brittle deformation was active only along the SAT, or both along SAT and NAT but was subsequently obscured along NAT (figures 6, 7, 8). We suggest that the previously proposed back-thrusting along NAT was realised as a swarm of thrusts, rather than a unique plane/zone. Deformation implied by them, therefore, lacked a systematic gradient with respect to distance from NAT, as was observed in the case of SAT. Lack of gradient meant that deformation intensity did not decrease continuously with distance from the NAT.

It may be concluded that, a relationship between magnetic parameters and distance from NAT, similar to that observed in case of SAT, was present after the emplacement of ACZ. However, later back-thrusting obscured these relationships and overprinted some k_3 such that their plunge changed from northward to southward.

4.3 Evolution of ACZ

We propose that the evolution of ACZ is marked by at least two stages, with characteristic metamorphic and mutually antithetic deformation pattern. The southward thrusting of the ACZ was accompanied by metamorphism that grew secondary paramagnetic minerals, such as chlorite, presumably by shear heating (Mulchrone and Mukherjee 2016). Due to southward thrusting all the mineral grains were preferentially aligned (e.g., Passchier and Trouw 1996) and a prominent metamorphic and magnetic foliation developed. It is important here that due to the southward thrusting, initial shear sense in ACZ was top-to-south, and the metamorphic and magnetic foliations had southward dip, with k_3 plunging

northward. To accommodate further compression, due to active Himalayan orogeny, NAT reactivated and back thrusts developed. The reactivation motored the overprinting of the original top-to-south shear sense with younger, antithetic, top-to-north. The overprinting and younger shear sense is, thus, observed in shear zones and microstructures (figure 4d, e, f, h) and in some k_3 with southward plunge (figure 5).

5. Conclusions

We compare the structures and rock magnetic properties of rocks near the SAT and NAT and discuss the origin of ACZ. The investigations reveal that

- magnetic fabrics of all the rocks in ACZ are carried by secondary paramagnetic minerals, such as chlorite, which are sometimes fractured.
- Near SAT the sedimentary beds and the metamorphic and magnetic foliations have similar orientation, i.e., northward dip. The situation near NAT is complex. Here the general trend of the magnetic and metamorphic fabric is southward dipping and corresponding k_3 plunge northward; however, some k_3 demonstrate a southward plunge.
- Deformation near SAT has a consistent top-to-south shear sense. However, near NAT, both top-to-south and top-to-north (at microscale and in the outcrop) shear sense are recorded, although the former is more common. We thus propose after the ACZ emplaced, Lesser Himalayan NAT was back-thrust.

The present study deals with the gap in our understanding of the evolution of ACZ. It provides an appropriate model to explain the present and previous observations from the sedimentary and crystalline rocks in Lesser Himalaya. It emphasizes on the need of exhaustive studies by employing parallel techniques, to unequivocally understand the evolution of Himalaya.

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