Mesoscopic, magnetic and petrofabric study of the High Himalayan gneisses and leucogranite along oblique and frontal ramps of the Vaikrita Thrust in Satluj and Bhagirathi valleys: Thrust locking and superposed folding

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Field, microstructural and anisotropy of magnetic susceptibility (AMS) studies were performed along the oblique thrust ramp of the Satluj river valley and frontal thrust ramp of the Bhagirathi river valley. The presence of asymmetric and sheath folds indicates intense shearing near the thrust. The simple shear gradually decreases with an increase in distance from the thrust and pure shear with upright folds becomes prominent. The AMS studies suggest slightly higher pure shear in the frontal ramp region as compared to the oblique ramp region where oblique slip was predominant. The sense of shear criteria and orientation of superposed folds indicate locking of the thrust. Normal faults are the youngest structure.

Keywords. Thrust locking; young normal faults; deformation structures; orogenic belt; anisotropy of magnetic susceptibility; microstructures.

1. Introduction

Oblique ramps and fault-bend structures appear to be scale independent and have several structural associations. Oblique ramps inhibit the motion of thrust sheets by macroscopic folding because they represent topography along otherwise subplanar faults and serve as a mechanism of displacement transfer by linking en-echelon frontal thrusts (Pfiffner 1981; Goldberg 1984) and of displacement termination as in the bounding faults to duplexes (Boyer and Elliot 1982; Lageson 1984). Oblique ramps may be associated with basement buttresses where thrust belts interact with foreland style deformation and localise anomalous deformation of

the hanging wall (Couples and Lewis 1988; Schmidt *et al.* 1988). Folds over oblique ramps are generally oblique to the regional trend and are linked to frontal ramp folds at potentially complex intersections (Wilkerson *et al.* 1991; Apotria *et al.* 1992). Previous studies suggested that motion over an oblique ramp requires that the hanging wall undergoes regional strike parallel extension (as opposed to local, over the intersection zones) as the hanging wall moves from the lower footwall flat through the oblique ramp. Documentation of the occurrence of oblique ramps is already carried out globally; until now, work related to the details of deformation processes involved is limited. The following studies suggest that oblique ramps are important

features in the areas of thrusting and superposed deformation events.

Mean magnetic susceptibility (K_m) is an indicator of minerals that controls the magnetic fabric of a rock. In this sequence, anisotropy of magnetic susceptibility (AMS) is an important tool to evaluate fabric in rocks that do not have visible, mesoscopic fabric, and it also helps to decipher signatures of deformation episodes that are not easily discernable in the field (Borradaile and Henry 1997; Zak *et al.* 2008; Majumder and Mamtani 2009; Dubey 2014). The AMS data have also been used to decipher the mechanism of folding (Hrouda 1978). Earlier studies carried out by Aranguren *et al.* (1996) and Tomezzolli *et al.* (2003) have shown that magnetic fabric for granitic mylonites or granitic gneiss may represent an intermediate fabric between 'S' and 'C' fabrics or depict a weak fabric developed at later stages of deformation (Ono *et al.* 2010). In the case of Himalaya, a complexly deformed terrane, comparison between the magnetic fabric and their corresponding mesoscopic foliation is important as it can reveal multiple deformation events (Jayangondaperumal *et al.* 2010; Sen *et al.* 2012; Tripathi *et al.* 2012; Singh *et al.* 2017).

The Himalayan mountain chain initiated as a result of India–Eurasia collision at ca. 50 Ma (Patriat and Achache 1984). This led to the formation of a series of major fault systems of regional dimensions, viz., South Tibetan Detachment (STD), Main Central Thrust (MCT), Main Boundary Thrust and Himalayan Frontal Thrust. The MCT is one of the most significant north dipping intracontinental thrusts that mark a boundary between the High Himalayan crystalline (HHC) sequence and the Lesser Himalayan crystalline sequence. The crystalline rocks are separated from the Tethyan metasedimentary rocks (Precambrian to Eocene) by the STD and the nature of the contact has been described variously as conformable, unconformable (Gansser 1964), thrust fault (Valdiya 1987; Thakur 1992), normal fault (Burchfiel and Royden 1985; Herren 1987) and early thrust fault reactivated as a normal fault (Gururajan and Islam 1991; Patel *et al.* 1993). Structural and geochronological studies indicate that thrusting and normal faulting on the margins of the High Himalayan slab are broadly synchronous and the faulting initiated with Miocene prograde metamorphism and has moved episodically since then (Hodges *et al.* 1992; Murphy and Harrison 1999). Searle *et al.* (2008) have also suggested

that the MCT had evolved both in time (early–middle Miocene) and space from a deep-level ductile shear zone to a shallow brittle thrust fault. However, most of the earlier studies have ignored the structural features along the oblique ramp of the thrusts and superimposed folding in the region. Hence, the present study was performed along the oblique and frontal fault ramps of the STD and Vaikrita thrust (VT) along the Satluj (Himachal High Himalaya) and Bhagirathi valleys (Garhwal High Himalaya). One of the objectives of the present study was to understand the simultaneous versus sequential development of thrust and superposed folds.

2. Regional geological setup

The regional geological setup is broadly divided into four major lithotectonic units, e.g., (i) Neogene Siwalik Group, (ii) Proterozoic Lesser Himalayan sequence, (iii) Proterozoic to Ordovician Greater or HHC sequence and (iv) Proterozoic to Eocene Tethyan Himalayan sequence (Le Fort 1996). The MCT separates the gneisses, migmatites and schists of the HHC from the lower grade metasediments of the root zone of the allochthonous klippen of the Lesser Himalaya (Dubey 2004). The HHC represents a core of the Himalaya where Neoproterozoic to Cambrian rocks were brought from deeper levels. A thick slab of ~40 km was metamorphosed up to partial melting condition during the Eocene and early Miocene times (Vannay and Grasemann 2001; Dipietro and Pogue 2004). The unit is bounded by prominent oblique fault ramps of the MCT at the bottom and STD at the top (figure 1) (Dubey 1999; Vannay *et al.* 2004; Yin 2006). A number of shear zones, observed in the uppermost part of the HHC, show a sense of shear from top to N/NE (Godin *et al.* 2006).

The present study area in figure 1(c) shows that the HHC rocks along the Satluj and Baspa valleys are intruded by tourmaline and garnet-bearing leucogranite and those intrusions have taken place along the foliation planes. Felsic veins have small garnet and tourmaline crystals in leucosome of the gneisses. These felsic veins are folded and their axial surfaces are parallel to pre-existing foliations. The field foliations of granitic gneisses trend in NE–SW and NW–SE with moderate to gentle dips. The amphibolite within banded gneisses is also intruded parallel to the foliation

Figure 1. (a) The location of the study area in India's map. (b) The two rectangles (A and B) represent location of the present study area. FR: Frontal ramp, OR: Oblique ramp, SD: Sangla Detachment, MCT: Main Central Thrust, MT: Munsiri Thrust (modified after [Vannay and Grasemann 2001](#)), (c) a simplified geological cross-section along the Satluj valley (modified after [Dubey 1997](#)) and (d) a simplified geological cross-section along the Bhagirathi valley.

(towards 90°/30°). In the Satluj and Baspa valley sections (figure 1b), the Sangla Detachment (SD) represents a segment of the STD and separates the HHC from the Tethys Himalaya. The Palaeozoic (500 Ma) Kinnaur Kailash

Granite (KKG) (porphyritic or coarse-grained two-mica granite) lies on hanging wall of the STD and is in contact with metasediments of the Tethys Himalaya (figure 1b). In the Satluj and Baspa valley sections, rocks occurring near Karcham

consist of graphitic schist with intercalated layers of quartzite and garnet-bearing marbles and staurolite. The upward succession consists of garnet mica schist. The SD corresponds to a ductile shear zone affecting the contact between the KKG, at the base of the Tethys Himalaya, and the underlying migmatitic paragneiss of the HHC (figure 1c). This shear zone is revealed by a marked strain gradient from the top to the base of the KKG.

In the Bhagirathi valley section, Garhwal Himalaya rocks consist of granitic gneiss, augen gneiss, mica schist, phyllonites, calc-silicates, amphibolites, migmatites and quartzite with Palaeozoic (500 Ma) Bhaironghati granite (BG) (Metcalf 1993; Singh and Thakur 2001; Tripathi *et al.* 2009; Mukherjee 2013). Towards bhaironghati and further north, i.e., Gangotri, two types of granites are exposed, i.e., biotite granite or BG and tourmaline-bearing leucogranite. In figure 1(b) towards Jangla, close to the contact with Harsil metamorphic rocks, the BG is porphyritic in nature with occasional xenoliths and absence of foliation. Augen gneiss occurs in lensoidal form near Bhaironghati. The intrusive relationship of the overlying BG with the low-grade Harsil metamorphics can be seen at Bhaironghati. The quartzite is hard and compact with alternate bands of phyllites and schists. The metamorphic rocks at Harsil trend in NE–SW direction with gentle dips. In figure 1(d), almost E–W trending contact between overlying BG and Harsil metamorphics is well exposed near Harsil. Towards Harsil, the river takes a turn of 90° and flows almost parallel to the regional trend of Harsil metamorphics.

3. Mesoscopic structures of the study area

3.1 The Satluj valley

The HHC unit from VT at its base to top of the unit towards STD consists of granitic gneiss, augen gneiss, migmatite, mylonite, kyanite ± garnet-bearing schist and gneiss, and HHC leucogranite (figure 1c). The mesoscopic foliations in the granitic gneisses trend NW–SE, with moderate to gentle dips. Later on due to superposed deformation, some of the field foliations reoriented to NE–SW. Lineation in the granitic gneiss is trending towards SW with moderate plunge. Field foliations of granite and granitic gneiss are almost parallel. Isoclinal to tight folds deforming the mylonitic schistosity along the granite and gneiss contact in the Baspa valley reveal two phases of ductile

deformation. The inclined and asymmetric folds indicate shearing along the VT. The earlier deformation is related to southward thrusting, as indicated by shear sense criteria including normal drag shear bands; S-C fabrics preserved in mylonites and K-feldspar porphyroclast in granitic gneiss (figure 2e). These contractional mylonitic structures of the VT zone are superposed by extensional normal drag shear bands associated with eastward dipping mineral lineation. Axial surfaces of the folds and gneissosity of the rock follow a similar trend at many places. The mesoscopic fabric is related to axial plane foliation of the early (F_1) folds. The felsic veins within the granitic gneiss are folded and their axial planes are parallel to pre-existing foliations. Slickenside observed at some places shows up dip as well as lateral movements in both the sections.

In the Sangla and Powari sections of the Satluj and Baspa valleys (figure 2), most of the early fold axes trend towards NW–SE. The central part of the HHC shows multilayer folds in granitic gneiss with nearly NW–SE trend of the early fold axes (F_1) and axial plane (AP1) dip towards NE. However, the trend of fold axes near Tapri (towards Karcham) is nearly NE–SW. The variation in the trend can be seen in folds produced by buckling within granitic gneiss. The superposed folds (F_2) in the granitic gneiss show NE–SW trend of fold axes with axial plane (AP2) dip towards NW or SE (figure 2a). Asymmetric folds are very prominent mostly near the shear zones. Harmonic and disharmonic folds are seen at many sites in the Akpa–Powari section along the Satluj valley. At few places near Karcham (31°26′31.6″N and 78°13′92.7″E), asymmetric boudins show overlapping with the sense of shear from top to west. The asymmetric folds above the boudins have developed at a later stage (figure 2b) and axial plane of these folds dips towards SE. At Karcham (31°26′31.6″N and 78°13′92.7″E), a felsic quartz vein shows normal faulting with NE trend of the fault plane and 3 cm of displacement (figure 2c). At Karcham (31°29′01.0″N and 78°10′39.3″E), displaced boudins show normal faulting with displacement of 4 cm and fault plane is trend towards N–S (figure 2d). The N dipping fault plane indicates the late stage superposed deformation. In the Satluj valley section near Powari, book shelf gliding can be observed in sheared boudin with top towards north sense of shear. Similarly, in the Baspa valley section near Sangla, quartz porphyroclast rotation shows sigmoidal structure and

Figure 2. Fold structures from the Satluj and Baspa valleys. The trends of the axial planes (AP) are marked on the photographs: (a) internal buckling in the alternate layers of quartz and feldspar with NW trend of axial plane (AP2) near Karcham ($31^{\circ}26'40.7''\text{N}$; $78^{\circ}13'37.4''\text{E}$), (b) overlapping boudins and symmetric folds with NE trend of the hinge lines near Karcham ($31^{\circ}26'31.6''\text{N}$; $78^{\circ}13'92.7''\text{E}$), (c) felsic quartz vein showing small scale normal faulting near Karcham ($31^{\circ}26'31.6''\text{N}$; $78^{\circ}13'92.7''\text{E}$), (d) displaced boudins near Karcham ($31^{\circ}29'01.0''\text{N}$; $78^{\circ}10'39.3''\text{E}$), (e) sigmoidal quartz porphyroclasts show top to south sense of shear and (f) flanking structure in the granitic gneiss.

top towards SW sense of shear. Near Karcham ($31^{\circ}29'01.0''\text{N}$ and $78^{\circ}10'39.3''\text{E}$) quartz porphyroclasts show top towards south sense of shear (figure 2e). The sense of shear is parallel to the thrust displacement. Asymmetric boudins in granitic gneiss show top towards south sense of shear near Powari ($31^{\circ}35'36.2''\text{N}$ and $78^{\circ}17'32.6''\text{E}$). Asymmetric folds with top towards east sense of shear are associated with simple shear along the thrust and flanking structure in the granitic gneiss (figure 2f). The superposed folding is evidenced by NE–SW trending fold hinge lines with the NW or SE dipping axial surfaces (figure 3).

3.2 The Bhagirathi valley

The rocks of the area are sheared and deformed. Main foliation of the Harsil metamorphics is nearly E–W with moderate dip towards north (figure 1d). The BG is a coarse grain granite which shows close contact with granitic gneiss and Harsil metamorphics. At many places, Harsil metamorphics show development of S–C structures and lineation in the granitic gneiss plunging $\sim 20^{\circ}$ towards NE. A few felsic veins intruded within the gneiss show late stage superposed deformation (F_2). Small-scale ductile–brittle structures have

Figure 3. Lower hemisphere equal area projections showing distribution of fold hinge lines and axial surfaces around: (a) Akpa and (b) Sangla section. '+', early (F_1) folds and 'x', superposed (F_2) folds.

also been observed at many places representing late stage deformation.

Small kinks and asymmetric folds are developed near the contact of metamorphics with the granites. Quartz boudins are aligned parallel to the main foliation of the mica schist. An upright fold in granitic gneiss at Harsil forest guest house ($31^{\circ}02'46.1''\text{N}$ and $78^{\circ}49'16.6''\text{E}$) shows NW trend of fold hinges with SW dipping axial surfaces (AP1) (figure 4a). Folded quartz boudin close to Harsil shows NW trend of early fold hinges with NE trend of axial planes. At Jangla ($31^{\circ}02'19.7''\text{N}$ and $78^{\circ}53'55.6''\text{E}$), tight folds in the granitic gneiss show refolded limb with N–S trend of fold hinge lines and axial plane dip towards east (figure 4b). Quartz porphyroclast rotation in augen gneiss shows top to SW sense of shear near the Bridge towards Bhaironghati ($31^{\circ}02'10.5''\text{N}$ and $78^{\circ}51'25.3''\text{E}$) (figure 4d). Normal fault in the mica schist shows NE–SW trend of the fault plane near Gangnani at hanging wall of the VT (figure 4e). Isoclinal folds in fine grained granitic gneiss (figure 4c). All these folds show NW–SE trend of early fold hinge

lines. The hanging wall rocks of the VT suggest dominance of early (F_1) folds (figure 5).

4. Sampling sites and analytical techniques

For magnetic fabric studies, oriented block samples were collected from both Satluj and Bhagirathi valleys (figure 6a and b). AMS was measured by KLY-3S Kappabridge (Agico, Czech Republic). Oriented cylindrical cores with 2.54 cm diameter and 2.2 cm height were used for measurements in spinner mode. The results provide orientation and magnitude of three principal axes of the magnetic susceptibility ellipsoid ($K_1 \geq K_2 \geq K_3$), the mean magnetic susceptibility (K_m), degree of magnetic anisotropy (P') and shape parameter (T) (Jelinek 1981). The magnetic lineation is attributed to K_1 , and pole to the magnetic foliation (K_1 – K_2 plane) is K_3 (table 1) (Tarling and Hrouda 1993). The 'SUSAR' software supplied with KLY-3S Kappabridge was used to obtain the above parameters. The isothermal

Figure 4. Folds in Harsil-Jhala section, Bhagirathi valley: (a) upright folds in granitic gneiss near Harsil, (b) refolded quartz vein in granitic gneiss showing isoclinal fold with axial plane (AP2) dip towards east near Jangla ($31^{\circ}02'19.7''\text{N}$, $78^{\circ}53'55.6''\text{E}$), (c) isoclinal folds in the granitic gneiss, (d) quartz porphyroclast rotation in augen gneiss showing top to southwest sense of shear and (e) normal fault in the mica schist with NE-SW trend near Gangnani.

Figure 5. Lower hemisphere equal area projections showing distribution of fold hinge lines and axial surfaces of Harsil section along Bhagirathi valley. '+', early (F_1) folds and 'x', superposed (F_2) folds.

Figure 6. (a) Geological map showing locations of (27) samples in the HHC, Satluj valley, different colours of circles represent different lithology of the area (modified after Vannay *et al.* 2004) and (b) simplified geological map shows locations of samples exposed along the Bhagirathi valley (modified after Jain *et al.* 2002).

remanent magnetisation (IRM) analysis was also carried out on Bartington Kappabridge (KLY-3S) Instruments equipment at Department of Geology, University of Pune, India, for a total of 13 selected cores obtained from both the valleys to identify the magnetomineralogy of the rocks. Results obtained from the Kappabridge (KLY-3S) analyses are expressed in terms of volume susceptibility as it focuses upon the geometric elements, whereas the data from the Bartington analyses are presented in mass susceptibility as it needs mass normalisation to evaluate the ferrimagnetic concentration and grain size dependency of susceptibility.

A total of 27 samples were collected from Satluj valley and 12 samples from Bhagirathi valley (figure 6a and b). The samples from Satluj valley include 23 samples of the High Himalayan gneiss (HHG) and 4 samples of High Himalayan leucogranite (HHL). A total of 286 cores (255 cores of HHG and 31 cores of HHL) were analysed. Twelve samples from the Bhagirathi valley includes seven from High Himalayan granitic gneiss and five from leucogranites. A total of 59 cores of the HHC and 35 cores of leucogranites were analysed, and the data are presented in tables 1 and 2. Jelinek statistics (Jelinek 1978) was performed using the Anisoft-42 software. One core from each sample was used for magnetomineralogy of the rock samples and to prepare oriented thin sections for

microstructural studies. Rock orientation, optical parameters, field of view and locations of the samples were recorded for each photomicrograph.

5. Results

5.1 Mineralogy and microstructures of the HHCs

The general petrography of the HHC suggests that the rocks are mainly composed of quartz, plagioclase, K-feldspar, biotite, muscovite (with some medium- to high-grade rock forming minerals such as garnet, kyanite, tourmaline and sillimanite) calcite, garnet, iron oxide, etc. Accessory minerals include rutile, zircon, apatite and magnetite. Quartz, plagioclase and K-feldspar are present as porphyroclasts within matrix of quartz, feldspar, biotite and sometimes hornblende. Two types of microstructures observed from both the sections are described below.

5.1.1 High-temperature solid-state deformation microstructures

The high-temperature solid-state deformation microfabric includes lobate contact between quartz and feldspar, and chess-board microstructure in quartz and myrmekite formation in plagioclase. The quartz grains are subhedral, and their grain boundaries are highly fractured with the

Table 1. Site mean values of AMS parameters calculated by using Jelinek statistics.

Sample no.	Rock type	Field foln.	n	K_m	P'	T	K_1 (D/I)	Conf. angl.	K_3 (D/I)	Conf. angl.
APR5/2	Granitic gneiss	75/15	10	46	1.147	0.359	287/51	6.7/3.4	177/16	6.3/3.6
APR5/3A	Granitic gneiss	50/35	11	64.9	1.085	0.193	286/48	21.9/6.9	18/2	18.9/7.3
APR5/4B	Granitic gneiss	100/75	15	219	1.166	-0.12	319/24	2.6/1.2	228/2	4.2/1.3
APR6/7C	Granitic gneiss	60/40	8	234	1.338	0.751	84/40	34.1/1.1	230/45	2.7/1.2
APR6/8	Granitic gneiss	60/40	11	303	1.259	0.646	145/36	4.1/2.4	300/51	4.9/1.5
APR6/9A	Granitic gneiss	40/20	13	759	1.447	0.178	301/36	2.1/1.3	194/21	7.1/1.9
PK8/2	Granitic gneiss	40/30	9	213	1.698	0.434	312/44	4.0/1.7	73/28	3.0/2.0
KS10/1	Banded gneiss	110/30	12	118	1.174	0.404	140/41	2.4/2.0	275/39	5.3/1.7
KS10/4A	Granitic gneiss	70/20	9	61.2	1.098	0.629	337/3	38.9/8.1	218/84	12.3/7.9
KS10/5	Gneiss	90/30	9	43.3	1.128	0.152	253/31	4.6/2.5	347/6	7.3/1.6
KS10/6	Mylonites	90/30	7	230	1.107	0.256	78/77	22.3/6.4	341/2	15.6/10.0
KS10/10	Granitic gneiss	100/35	12	126	1.24	0.638	280/30	2.3/2.0	174/27	5.3/1.8
KS12/1	Gneiss	90/20	12	128	1.321	0.892	5/22	8.3/1.1	265/22	2.0/1.2
KS12/3	Banded gneiss	105/15	13	54.9	1.352	0.925	6/20	19.0/1.3	269/17	1.4/1.1
KS12/5D	Gneiss	110/15	12	142	1.224	0.384	291/83	1.6/0.8	170/4	7.5/0.9
KS12/6	Mylonites	20/30	7	132	1.189	0.333	45/48	9.0/5.1	233/41	5.8/2.8
CS11/11	Gneiss	40/30	8	120	1.201	0.711	127/11	8.3/7.5	225/38	7.6/3.6
No.3	Granitic gneiss	50/33	6	224	1.262	0.378	38/26	3.9/3.1	293/27	10.1/2.9
No.4	Banded gneiss	40/29	15	337	1.13	- 0.039	292/14	11.9/6.2	54/64	26.1/9.0
No.9	Granitic gneiss	230/38	16	6.28	1.34	0.414	42/39	9.7/2.8	292/23	3.1/2.8
No.10	Granitic gneiss	0/20	8	259	1.219	0.868	350/60	14.1/1.6	225/19	2.0/1.3
No.11	Granitic gneiss	130/37	17	120	1.225	0.708	154/43	22.5/2.2	274/28	3.9/1.8
No.18	Granitic gneiss	65/35	15	173	1.283	0.802	292/49	3.8/5.1	164/29	2.1/1.6
KS10/7	Hhc leucogranite	200/40	10	50.4	1.139	0.023	(2)/59	1.9/1.2	192/31	5.7/1.3
KS10/11A	Hhc leucogranite	110/70	11	109	1.197	0.328	142/84	2.9/1.0	344/6	5.9/1.1
KS10/3A	Hhc leucogranite	60/40	5	44.5	1.201	0.406	327/14	6.0/3.0	232/19	8.2/3.1
KS10/3B	Hhc leucogranite	60/40	5	52.8	1.266	0.252	323/33	23.2/4.2	221/17	8.6/6.6

Note: n , total number of samples used for arithmetic mean; K_m (10^{-6} μ SI), mean magnetic susceptibility; L, lineation (K_1/K_2); F, foliation (K_2/K_3); P' , corrected anisotropic degree; T , shape parameter; K_1 , magnetic lineation; K_3 , magnetic foliation, K_1 (D/I) confidence angle and K_3 (D/I) confidence angle.

Table 2. AMS and field foliation data of the gneisses and leucogranite samples.

Sample no.	Rock type	Field foln.	n	K_m	P'	T	K_1 (D/I)	Conf. angl.	K_3 (D/I)	Conf. angl.
HB1	Augen gneiss	130/60	7	76.3	1.248	0.847	239/35	10/2.3	148/2	8.8/1.5
HB3	Augen gneiss	220/35	9	165	1.202	0.728	322/26	9.8/4.1	229/6	43.0/3.5
BH6/3	Augen gneiss	155/40	10	87.3	1.171	0.864	22/45	71.0/5.5	182/43	8.8/3.3
BH6/4	Gneiss	155/40	10	79.4	1.167	-0.123	191/31	5.9/2.0	81/29	7.4/4.0
HB12/1	Augen gneiss	(10)/50	8	17.2	1.406	0.638	354/38	15.7/5.8	190/51	9.4/4.4
HB12/3	Augen gneiss	40/40	8	225	1.247	0.627	290/44	10.7/7.3	174/24	11/8.1
HB12/5	Augen gneiss	0/50	7	351	1.096	0.055	325/44	40.6/7.1	184/39	12.2/7.0
HG2	leucogranite		9	132	1.054	0.017	60/4	40/10.8	319/58	11.4/8.2
BH8/5B	leucogranite		7	30.8	1.019	0.011	101/14	35.5/15.1	3/31	36.7/13.8
BH8/5C	leucogranite		6	24.6	1.02	0.008	319/1	24.4/11.1	51/44	53.6/15.3
SH10/3	leucogranite		5	20.7	1.012	0.005	143/9	39.5/6.1	47/33	43.7/20.1
SH10/4	leucogranite		8	25.6	1.033	0.012	199/54	16.0/10.3	15/36	16.7/8.1

Note: K_m : mean magnetic susceptibility; P' : corrected degree of magnetic anisotropy; T : shape parameter; K_1 : magnetic lineation; K_3 : pole to magnetic foliation; conf. angle: confidence angle; n : number of cores analysed per site.

development of deformation bands. The highly serrated crystal boundary in quartz is a characteristic feature of higher mobility and migration of grain boundaries. This also suggests that new grain crystallisation is related to primary dynamic recrystallisation via strain hardening (White 1977). Dynamic recrystallisation occurs in the form of Bulging recrystallisation (figure 7a). At certain places, quartz grains show chess-board microstructures (figure 7b) (cf. Kruhl 1996; Stipp *et al.* 2002). At certain places, quartz grains show grain boundary migration with adjoining K-feldspar grain indicating temperature range >600°C. The plagioclase grain boundaries are highly serrated and show prominent Carlsbad twinning (figure 7c). Fractures are also present within the plagioclase grains that show lobate contact with the adjoining quartz grains, and marginal replacement is evident by myrmekite intergrowth (figure 7d) (cf. Rosenberg and Stünitz 2003). K-feldspar grains show dynamic recrystallisation in the form of perthite and fracture filling by secondary minerals such as quartz or calcite (figure 7e).

5.1.2 Low-temperature solid-state deformation microstructures

The superposed microfabric includes undulose extinction in quartz and deformation twin in plagioclase (figure 7f). At many places, K-feldspar is surrounded by recrystallised matrix of quartz and feldspar. Biotite flakes are fractured and show one set of cleavage. Development of kink band and marginal replacement with the feldspar grain (figure 7g) is also observed in many of the biotite grains. Near the MCT mylonite zone, the biotite and muscovite flakes show south verging tight folds (figure 7h).

5.2 Anisotropy of magnetic susceptibility

5.2.1 Magnetomineralogy of Satluj valley rocks

The mean susceptibility values of the High Himalayan granitic gneisses range from 6.28 μ SI (sample 9) to 759 μ SI (sample Apr6/9a). Two samples from Satluj and Baspa valleys (Apr5/2 and Cs11/11) show very low values of $K_m < 500 \mu$ SI (46 μ SI and 132 μ SI). In central part of the area, sample Apr6/9a shows $K_m > 500 \mu$ SI, whereas towards the hanging wall of the VT, the gneiss samples show $K_m < 500 \mu$ SI. The mean susceptibility values (K_m) of the HHC leucogranite

Figure 7. Photomicrographs of the HHC gneisses from both the valleys: (a) bulging recrystallization, (b) chess-board microstructure in quartz, (c) grain boundary migration recrystallisation in quartz, (d) lobate shape (quartz grain connected with plagioclase) and marginal replacement by myrmekite intergrowth, (e) recrystallisation of feldspar and development of myrmekite with microcline twinning, (f) deformation bent twin in plagioclase, (g) Kink bands in biotite with marginal recrystallization and (h) muscovite and biotite flakes showing tight fold. Sample numbers are marked on each photomicrograph.

vary from $44.5 \mu\text{SI}$ (sample Ks10/3a) to $109 \mu\text{SI}$ (sample Ks10/11a). Mean magnetic susceptibility (K_m) is an indicator of minerals that control the magnetic fabric of a rock. The bulk susceptibility values of granitic gneisses and leucogranites suggest dominance of paramagnetic mineralogy (figure 8a). However, one sample (Apr6/9a) from

central part of the present study area reveals ferromagnetic ($K_m > 500 \mu\text{SI}$) mineralogy. Most of the susceptibility and IRM data from the analysed samples show low mean Xlf ($0.59 \times 10^{-8} \text{ m}^3/\text{kg}$) varying between 1.9 and 0.05 with low variability depicting weakly ferromagnetic in nature (figure 9). The anhysteretic remanent magnetization (ARM)

Figure 8. (a) Relationship between K_m vs. P' , (b) relationship between P' (corrected degree of magnetic anisotropy) and T (shape parameter), (c) K_m vs. T graph and (d) Hrouda double plot for the HHC gneisses.

and susceptibility of ARM ($XARM = ARM/DC$ bias field) was estimated as parameter. $XARM$ values are also very low vis-à-vis the Soft IRM and saturation isothermal remanent magnetisation (SIRM), indicating weak ferromagnetic nature of the samples suggesting that the susceptibilities are also affected by diamagnetic nature of silica. A greater control of paramagnetic minerals might have controlled the susceptibility and hence AMS of these rocks. The coercivity of remanence shows a median value of 56 mT and varies between 18 and 124 mT. This indicates a large variability among hard and soft ferromagnetic and antiferromagnetic assemblages, and the rock contains biotite and muscovite as the main paramagnetic minerals.

5.2.2 Parameters of magnetic anisotropy

The degree of anisotropy (P') of the HHC gneisses and leucogranite is high (>1.15) and shows weak linear correlation with the corresponding susceptibility value (table 1). The degree of

magnetic anisotropy (P') of granitic gneisses ranges from 1.085 (sample APR5/3a) to 1.698 (sample Pk8/2). For the HHC leucogranite, P' values range from 1.139 (KS10/7) to 1.266 (sample Ks10/3b) (figure 8a). In the central part of the area, a granitic gneiss sample Ps8/2 shows high P' value (1.698), whereas K_m (213 μSI) is very low. It is observed that samples with low K_m can have high P' and vice versa. Samples from the HHC leucogranite also show high (P') values with low K_m ($<500 \mu SI$). In the central part of the HHC, samples show high P' values in comparison with the samples close to the STD and VT. Only two samples from hanging wall of the VT (Ks12/6) (1.189) and footwall of the STD (Apr5/4b) (1.166) show high values of P' , whereas their respective K_m values are very low. The central part of the area shows high P' values with low K_m values. This result indicates that values of P' are not influenced by the magnetic mineralogy; hence, the strong magnetic anisotropy is related to the deformation. Jelinek plot shows that most of the susceptibility ellipsoids of Baspa valley fall

Figure 9. Isothermal remanent magnetisation (IRM) curves for the representative HHC gneiss samples, from the Satluj Valley.

in the oblate field, whereas two samples of Satluj valley fall in prolate field (figure 8b). The distribution of shape parameter (T) with the degree of anisotropy (P') indicates that the samples that are closer to the STD have low P' values and prolate shapes, and rest of the samples show high P' values with oblate shapes. The HHC leucogranites follow the similar trend, i.e., high P' values with oblate shape ellipsoids. The K_m/T graph represents dominance of oblate shapes with respect to low magnetic susceptibility values in both the valleys. Only one sample in the Satluj valley has high $K_m > 500 \mu\text{SI}$ with oblate shape ellipsoid (figure 8c), whereas only two samples of the Satluj valley, which are close to the STD, show prolate shape with very low values of K_m . The Hrouda double plot of the HHC gneiss shows a relatively low degree of anisotropy (≥ 1.5), and the angle between magnetic foliation and mesoscopic foliation is variable ($0-75^\circ$), but dominantly the dip values are low (figure 8d). This suggests a combination of simple shear and lateral shortening for deformation in the area (Tarling and Hrouda 1993).

5.3 Magnetic fabric analysis

5.3.1 Relationship between mesoscopic and magnetic fabrics

HHCs of Satluj and Baspa river valleys show large variation in orientations of magnetic fabrics at different sites. Sites Apr5/2, Apr5/3a, Apr6/9a Ks10/5, Ks10/6, No.18, Ks10/7, Ks12/5d, Ks10/10 and Ks10/11a (total 10) occur close to the STD and a normal fault east of the VT (figure 10a and c). The field and magnetic foliations are oriented in different directions with sub-vertical dip, with random orientation of magnetic lineation (i.e., northeasterly, northwesterly and southwesterly). The variation in orientation (figure 10a) may be a result of interference of the superposed fold hinge lines with the reactivated normal fault. At site (Cs11/11), close to the STD in Baspa valley, the field and magnetic foliations are parallel or nearly parallel to each other. The trend is nearly NW–SE with moderate dips and southerly plunging magnetic lineation. A number of sites (e.g., Apr5/4b, Apr6/7c, Apr6/8, Pk8/2, No.3 No.4, No.9, No.10, Ks10/4a and Ks12/6) show that the field and magnetic foliations are randomly oriented with gentle to moderate plunge. The two fabrics intersect each other, and no systematic

pattern can be observed in this area, suggesting superposed deformation (figure 10b).

The HHC leucogranite (sites Ks10/3a and 10/3b) shows NW–SE striking magnetic foliation with northwesterly and southerly plunging magnetic lineation. In rest of the HHC gneisses (sites Ks10/1, Ks12/1, 12/3 and No.11), the field foliation trends around N–S and NE–SW and is gentle to moderately dipping. The orientation indicates that some of the fold hinge lines have been rotated to nearly N–S direction in vicinity of the fault oblique ramp (figure 10a). The magnetic foliation trends from N–S to NW–SE with moderate dips. The two foliations intersect each other at acute angles. The angle is somewhat larger at site 12/1, which is situated at some distance from the VT. The magnetic lineation plunges at steep angles, indicating the formation of nearly upright superposed folds and maximum extension in sub-vertical direction parallel to axial surfaces of the developing folds.

5.4 Bhagirathi valley

5.4.1 Magnetomineralogy of Bhagirathi valley

Magnetic susceptibility of the HHC gneiss shows a large variation from $17.2 \mu\text{SI}$ (Hb12/1), $165 \mu\text{SI}$ (Hb3) to $351 \mu\text{SI}$ (Hb12/5). The HHC gneiss contact with BG towards northern side also shows low values of K_m , i.e., 79.4 (Bh6/4) and 87.3 (Bh6/3) (table 2). Similarly, HHC leucogranites also show a large variation in the distribution of mean magnetic susceptibility and suggest dominance of paramagnetic mineralogy, i.e., $K_m < 500 \mu\text{SI}$ (figure 11a). Near the contact with Harsil metamorphics, the HHC leucogranite shows variation in their K_m values from $20.7 \mu\text{SI}$ (Sh10/3) to $132 \mu\text{SI}$ (Hg2). The sites reveal very low K_m values, indicating the dominance of paramagnetic mineralogy. Most of the susceptibility and IRM data from the analysed samples show low mean Xlf ($0.59 \times 10^{-8} \text{ m}^3/\text{kg}$) varying from 1.16 to 0.04 with low variability depict weakly ferromagnetic nature (figure 12). The ARM and XARM are also very low. The soft IRM and SIRM values indicate weakly ferromagnetic nature of all the samples. It is probably that the susceptibilities might be affected by the diamagnetic nature of silica. It suggests a greater control of paramagnetic minerals (micaceous) on the overall susceptibility and confirms that the gneissic rock contains biotite, amphibole, mica and pyroxene as the main paramagnetic minerals.

Figure 11. (a) Relationship between K_m/P' , (b) Jelinek plot for the HHC gneisses and leucogranite, (c) relationship between K_m/T for HHC gneisses and leucogranite and (d) Hrouda double plot for HHC gneiss.

5.4.2 Parameters of magnetic anisotropy

The P' values of the HHC gneisses range from 1.096 (Hb12/5), 1.248 (Hb1) to 1.406 (Hb12/1) (table 2). The spatial distribution of degree of anisotropy (P') in all the sites suggests a decrease in the P' values towards the VT. Samples at some distance from the VT have high P' values, whereas the K_m values are relatively low. The K_m/P' graph of the HHC and leucogranite shows a weak linear relationship (figure 11a). The area suggests dominance of paramagnetic mineralogy, whereas the corresponding P' is high, indicating that eccentricity of the susceptibility ellipsoid is controlled by deformation near the thrust zone. The shapes of the susceptibility ellipsoids for most of the gneiss samples fall in the oblate field, except two samples, which fall in the prolate field (figure 11b). Susceptibility ellipsoids are dominantly oblate for the HHC gneisses and leucogranite. This indicates that the shapes of the susceptibility ellipsoids are not controlled by magnetic mineralogy of the samples. The K_m/T graph shows that the HHC gneisses and leucogranite have oblate shapes with very low

values of K_m (figure 11c). The Hrouda double plot (figure 11d) shows that the degree of anisotropy (>1.15) is relatively high and the angle between magnetic foliation and bedding plane is variable (0° – 50°) but mostly low. This suggests that a combination of simple shear and lateral shortening is responsible for deformation in the area (Tarling and Hrouda 1993).

5.4.3 Relationship between mesoscopic and magnetic fabrics

The magnetic fabric of the HHC gneisses and leucogranite shows well-developed clustering of three susceptibility axes and variation in orientation of magnetic fabric at different sites (figure 13a). In the northern part of the area, near the contact with BG, a large variation in orientation of the two foliations can be observed even in adjacent sites. Sites Bh6/3 and Bh6/4 are adjacent to each other, but Bh6/3 site shows E–W orientation of the magnetic foliation, whereas Bh6/4 shows N–S orientation of the magnetic foliation with

Figure 12. Isothermal remanent magnetisation (IRM) curves for the representative HHC gneiss samples, from the Bhagirathi Valley.

northeasterly and southerly plunging magnetic lineations, respectively, despite having similar mesoscopic foliation, which strikes E–W with moderate plunge towards south (figure 13b). Some of the sites (Hb1; Hb3; Hb12/1; Hb12/3) are adjacent to one another but the mesoscopic foliation varies from E–W to NW–SE to NE–SW with moderate dips in different directions. The magnetic foliation also strikes from nearly E–W to N–S with moderate to steep dips in different directions. The two sites (Hb12/1, Hb12/3) have a concordant as well as discordant relationship in their field and magnetic foliations (figure 13a). The magnetic lineation shows gentle to moderate plunge towards southwest (Hb1), northwest (Hb3, Hb12/3) and north (Hb12/1). The gentle to moderate plunge of

magnetic lineation reveals that superposed folding, not thrusting, is the controlling factor at late stages of deformation; otherwise, the magnetic lineation should have been sub-vertical.

The leucogranite present within the gneisses also shows E–W and NW–SE to NE–SW striking magnetic foliation with moderate dip towards SW and SE. The orientation of magnetic lineation is randomly distributed with gentle to moderate plunge in different directions. Site Hb 12/5 shows two (mesoscopic and magnetic) foliations parallel as well as intersecting each other at acute angles (figure 13c). Therefore, the orientations of the foliations do not show any systematic patterns throughout the area indicating superimposed deformation.

Figure 13. (a) Mesoscopic, magnetic foliation and magnetic lineation map of the HHGs, (b) distribution of magnetic susceptibility axes (K_1 , K_2 and K_3) for all the samples in lower hemisphere equal area projection along with confidence ellipses and (c) composite field (broken line), magnetic foliations (solid line) and magnetic lineation ('star') of samples of the HHC gneisses of Bhagirathi valley. Open circles are pole to field foliation and black squares are pole to magnetic foliation.

6. Significance of composite magnetic fabric

Previous studies by Housen *et al.* (1993) suggest that one significant component of composite magnetic fabric in a deformed rock is orientation of magnetic lineation along the intersection of two planar fabrics. As discussed earlier, for granitic mylonites, the magnetic fabric may represent an intermediate fabric between the 'S' and 'C' fabric (Aranguren *et al.* 1996; Tomezzoli *et al.* 2003) or weakly mimic a fabric developed at later stages (Ono *et al.* 2010). The magnetic fabric studies from the oblique and frontal ramps of the VT have high P' values despite having very low magnetic susceptibility. Magnetic fabric data can be affected by

thrust zone shearing, folding and later by faulting (Hallwood *et al.* 1992; Tarling and Hrouda 1993; Nakamura and Nagahama 2001; Mamtani and Sen-gupta 2010). The magnetic fabric is sensitive to small changes in the stress regime. Hence, the magnetic foliation and magnetic lineation reflect the superposed deformation. Curvature of the superposed fold surfaces as a result of interference is reflected in different orientations of the magnetic foliation.

The described features indicate that magnetic fabric anisotropy does not have any systematic variation with respect to distance from the thrust or fault zones. At many sites, magnetic lineation is developed in the form of intersection lineation

with gentle to moderate plunge, and random distribution of magnetic lineations suggests the superposed deformation. Sub-vertical to vertical magnetic foliation planes with variable orientations represent the later developed fabrics due to continuous horizontal compressional forces. The shape fabric from the oblique ramp reveals a strong oblate shape of susceptibility ellipsoid, whereas the frontal ramp shows combined prolate and oblate susceptibility ellipsoids. Sites from both the studied sections of the HHCs also indicate that the magnetic lineation generally coincides with the intersection lineation of field and magnetic fabrics, suggesting the effect of superposed folding rather than thrusting. The only lineation observed in field is intersection lineation developed as a result of intersection of two foliations. This can be attributed to a large variation in trends of fold hinge lines as a result of interference between simultaneously developing folds (Dubey and Cobbold 1977), between early and superposed fold hinge lines, and interference between folds and simultaneously developing faults. The fold curvatures are also reflected in orientations of the mesoscopic foliations. Curvature of the superposed fold surfaces as a result of interference is reflected in different orientations of the magnetic foliation in most parts of the study area (figures 10 and 13). AMS analysis of most of the sites from HHC reveals a strong oblate shape of susceptibility ellipsoid (figures 8 and 11). The oblate ellipsoids are most likely to result from axially symmetric shortening under the general strain condition (Hobbs *et al.* 1976), whereas prolate ellipsoids result from axially symmetric extension. It is noted that the axially symmetric extension is associated with large-scale displacement along thrusts, whereas the axially symmetric shortening and general strain conditions are more associated with development of folds. The absence of the prolate susceptibility ellipsoids suggests that the magnetic fabric reveals interference of mild superposed deformation with upright superposed folds over pre-existing asymmetric early folds. Moreover, the study suggests a greater role of pure-shear deformation as compared with simple-shear deformation. Therefore, the field, AMS and microstructure-based study of the gneisses and leucogranites along the oblique and frontal ramp of the STD and VT do not show any significant thrust-related consistent movement and preserve signature of ductile deformation and superposed folding.

7. Discussion

The present field, microscopic and magnetic fabric studies around the oblique and frontal fault ramps provide significant information on deformation in a part of the western Himalaya. The structural observations around the oblique ramp (Satluj valley) of the STD and VT show a large variation in the direction of fold hinge lines, sense of shear, foliations and trend of faults. The early deformation (D_1) folds (F_1) from the oblique ramp show a uniform orientation of fold hinge lines, i.e., NW–SE to E–W with sense of shear from north to south. The sense of shear is oblique to the general trend of the VT (NW–SE). The superposed folds (F_2) show NE–SW to N–S orientation and sense of shear from top to NW, which is parallel to the general trend of the VT. Small kink and non-cylindrical mesoscopic folds are present with two sets of foliations and formation of intersection lineation. Stretching mineral lineations are rare. As the thrust-related lineations are steep, the gently plunging lineations are regarded as indicator of the superposed deformation (D_2). The presence of asymmetric, isoclinal, transposed and sheath folds in vicinity of the VT (oblique ramp) and upright folds at some distance from the VT suggests simple shear along the thrust. Folds from the frontal ramp show predominance of early folds with NW–SE to NNW–SSE orientation of fold hinge lines with axial surface dip towards NE, whereas the superposed folds show NE–SW orientation of fold hinge lines. The superposed folds are more pronounced in the late stage quartz veins and close to the VT. The NE trending normal fault is nearly orthogonal to the general trend of the STD and VT (NW–SE), suggesting a late stage superposed deformation (D_2). In that particular area, folds and faults show mutual interference patterns between early and superposed folds and oblique fault ramps (Dubey 1997). The development of early folds is simultaneous with the thrusts, and their geometry is compatible with the northward movement of the Indian Plate. The superposed folds are described as cross folds because their trend (NNE–SSW) is generally orthogonal to the early folds (Dubey and Bhakuni 2007). Development of non-cylindrical folds in vicinity of the oblique fault ramp is characterised by a systematic curvature of fold hinge lines towards or opposite to the tectonic transport direction, depending on the location of the fold with reference to the oblique ramp geometry (Dubey 2014). Orientation of fold

hinge lines across a fault can be used to distinguish between a thrust fault and a later strike-slip fault. The effect of a later superposed deformation is to produce extra curvature of fold hinge lines by fold interference or fold-fault interference, reversal of displacement (oblique slip) along the oblique ramp and strike-slip displacement along the early frontal thrust ramp. The fold hinge curvature in various directions displays a characteristic pattern with reference to the adjacent frontal fault ramp. Absence of early folds close to thrust on the hanging wall is a known phenomenon (Raj 1983; Dubey and Bhat 1991), but the random orientation of superposed folds is a significant feature. The study area shows that the early folds geometry at a distance from VT is characterised by asymmetric, overturned and recumbent folds. The sense of shear indicated by asymmetric superposed folds is sinistral (top to NW) and parallel to the general trend of VT. The minor early folds are absent close to the thrust, and observed superposed folds show moderate to gentle plunge towards E or NE with their axial surfaces dip towards N or NW. The superposed folds show a large variation in their orientation because of interference and their development of initially undulatory surfaces. The superimposed folds distributed uniformly in the area provide evidence that they have formed as buckle folds due to compression rather than interference between two propagating thrust sheets (cf. Coward and Potts 1983). The minor normal faults are formed at different stages of evolution and strike-slip faults are formed after the locking of the major thrusts. Thrusting and superimposed folding are predominant structures.

The microstructural studies of the gneisses and leucogranite along the oblique and frontal fault ramps of both the valleys suggest that during the tertiary Himalayan orogeny, the rocks underwent an early stage of deep level ductile deformation (due to grain boundary migration and chess board microstructure with growth of myrmekites $>600^{\circ}\text{C}$) along with thrusting. This was later superimposed by shallow level brittle deformation (formation of biotite, development of subgrains, fracturing in feldspars, alteration and kinking in biotite and at 250°C) during exhumation at a later stage of deformation. The presence of S-C fabrics also indicates an increase in strain adjacent to the VT. The thermochronological data from different sectors of the High Himalaya suggest that the last stage of tectono-metamorphic evolution from Pliocene to late Pleistocene was

associated with rapid exhumation and cooling of the rocks. Exhumation of the HHC was also associated with brittle extensional structures (figures 2 and 4) (Hodges *et al.* 1992; Dezes *et al.* 1999; Searle *et al.* 1999; Vannay *et al.* 2004). These structures cannot be developed along with the ductile compressional structures; therefore, these should be post-superposed deformational events. Previous studies by Grujic *et al.* (1996), Beaumont *et al.* (2001) and Vannay and Grasemann (2001) suggest that the exhumation of the HHC is caused by simultaneous extensional faulting along the STD and thrusting along the MCT. Moreover, this is coupled with focused erosion and presence of southward-directed channel flow of mid-crustal to lower crustal layer of partially molten material that is bound by the STD and the MCT. The pseudo-section thermochronology-based studies by Caddick *et al.* (2007) and field, microstructural and AMS-based studies by Tripathi *et al.* (2012) support that deep underthrusting along the MCT did not take place after thrust locking, and the superposed (folding) deformation was the only manifestation of deformation at the late stage.

8. Conclusions

- Simple shear has played an active role in rapid exhumation of the HHC rocks along the MCT zone.
- The microfabric studies from oblique and frontal ramps of the STD suggest pre-existing magmatic fabric followed by high-temperature solid-state deformation fabric superposed by low-temperature solid-state deformation fabric.
- The presence of normal faults indicates late stage extensional regime in the area.
- The magnetic fabric study within the ramps of the STD and VT does not show any signature of thrusting but late stage strikes parallel displacement along the thrust zone.
- Field data from the oblique ramp (Satluj valley) indicate predominance of both early and superposed folds in the area. On the contrary, frontal ramp (Bhagirathi valley) reveals predominant early folds, with few secondary quartz veins showing late stage superposed deformation. The observation suggests that the oblique ramp structure has led to an early thrust locking in the Satluj valley.

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