Petrography, geochemistry and regional significance of crystalline klippen in the Garhwal Lesser Himalaya, India

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Uphalda gneisses (UG) is a crystalline klippe located near Srinagar in Garhwal Himalaya. These gneisses are compared with Debguru porphyroids (DP) ($\approx$ Ramgarh group) of Garhwal–Kumaun Himalaya and Baragaon mylonitic gneisses (BMG) of Himachal Himalaya. Petrographic study reveals that the deformation of UG was initiated at higher temperature (above 350°C) and continued till lowering of temperature and deformation led to the mylonitization.

Geochemically, these granitic gneisses (UG, DP and BMG) exhibit similar composition. Features such as high molecular A/CNK value (>1), presence of normative corundum and absence of normative diopside, enhanced Rb/Sr, Rb/Zr ratios, enrichment of Th and containing rounded zircons support their crustally-derived S-type granitic nature. The linear plot in major oxides is interpreted in terms of fractional crystallization processes. Mantle normalized multi-element spider diagram of UG illustrates depletion of Ba, Nb, Sr, P and Ti and enrichment of Th and show similarities with DP and BMG.

Similarities were observed in lithology, petrographic characters and chemical composition of UG, DP, BMG and Ulleri augen gneisses (Nepal). Comparison with the rocks of Higher Himalayan crystallines ($\approx$ Vaikrita), suggests that these rocks (UG) are not transported from Higher Himalaya as understood earlier. This study however proposes that, these gneissic bodies represent an older basement occurring as a tectonic sliver which emplaced within the cover sequence as wedges at different structural levels. This is a regional phenomena observed throughout the Lesser Himalayan region.

1. Introduction

The Garhwal–Kumaun Himalaya stretches from the Kali river in the east to Tons–Pabbar valleys in the west. The region is approximately 300 km long and 125 km wide. Pioneering studies have been carried out on Garhwal–Kumaun Himalaya by Medlicott (1864), Oldham (1883, 1885) and Middlemiss (1885, 1887, 1890). In the 20th century, significant studies were carried out by Auden (1934, 1937) and Heim and Gansser (1939). Valdiya

(1980) gave a comprehensive picture on the structure and stratigraphic details of the region.

In recent years, considerable number of studies have been carried out on the Main Central Thrust (MCT) after its early discovery by Heim and Gansser (1939). This structure is widely responsible for the development of the Himalaya; however its location is highly debated (Kohn *et al* 2002; Searle *et al* 2002). The lower and upper bounding faults of MCT zones have been termed as MCT-I and MCT-II in Nepal (Hashimoto *et al* 1973;

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Arita 1983), Munsiri and Vaikrita thrust in the Garhwal–Kumaun region (Valdiya 1980).

The Lesser Himalayan sequence is restricted to a zone between Main Boundary Thrust (MBT) in the south and Vaikrita thrust ($\approx$ MCT) in the north. Ahmad *et al* (2000) studied the combined isotope and trace elements of major lithologies of the Garhwal–Kumaun sector in order to identify the location of the MCT and traced the entire length of the Himalayan orogen. Many workers have divided Lesser Himalaya into older and younger regions (Valdiya 1980; Srivastava and Gairola 1990; Srivastava and Mitra 1994; Ahmad *et al* 2000; DeCelles *et al* 2001; Richards *et al* 2005; Clerier *et al* 2009).

In between MBT and Vaikrita thrust ($\approx$ MCT), there lie a number of thrusts such as Ramgarh thrust, North Almora thrust, Tons thrust and Munsiri thrust; often some of these are folded. Structurally, there lie two major thrust sheets in Lesser Himalaya, viz., Ramgarh thrust sheet and Munsiri thrust sheet. In addition, there are several klippen (e.g., Almora, Satengal, Banali, Amri, Bijni, etc.) located in the parautochthonous zone of Lesser Himalaya with their root zone lying in the Higher Himalaya. A few of these klippen have been re-examined in terms of modern concepts of thrust tectonics and the earlier models revised (Bali and Bhattacharya 1988; Dubey and Bhat 1991; Srivastava and Mitra 1994; Jayangondaperumal and Dubey 2001; Devrani and Dubey 2008). Consequently, their origins are still enigmatic and are yet to be deciphered in terms of their source region. In Garhwal–Kumaun Himalaya at Srinagar, a small klippe named as Uphalda gneisses (UG) (Doval and Saklani 1980) is present and correlated to Muliagaon gneisses of Pratapnagar (Saklani 1972). A suite of granitic porphyry termed as Debguru porphyroids (DP) (Heim and Gansser 1939; Valdiya 1980) is located at the base of the Ramgarh thrust sheet; their stratigraphic position and origin is a matter of disagreement which is yet to be resolved. Compositionally and texturally, DP ($\approx$ Ramgarh) are different from Augen gneisses of the Almora klippe (Valdiya 1980). Similarly, a sheet-like body occurs at the basal part of the Chail thrust sheet with a maximum thickness of 800 m known as Baragaon mylonitic gneisses (BMG) in Himachal Himalaya (Gururajan 1990). Compositionally, DP and BMG are similar to UG.

The main purpose of this study is to comprehend the origin and source of the UG based on field and laboratory data and its comparison with DP of Garhwal–Kumaun and BMG of Himachal Himalaya; and to unravel the occurrence of these gneisses as tectonic slivers within the metasedimentary piles of the Lesser Himalaya. This may lead to an understanding of the status of various klippen existing in various sectors of the Lesser Himalaya.

2. Geological setup

The Lesser Himalayan region (figure 1a) is divided into Inner and Outer Lesser Himalayan sequences, separated by North Almora thrust (NAT)/Tons thrust (TT) (Ahmad *et al* 2000). The investigated area is located in the Outer Lesser Himalayan zone of Garhwal Kumaun Himalaya around Srinagar. The Inner Lesser Himalaya is more proximal to the south of the Indian shield than the Outer Lesser Himalaya (Ahmad *et al* 2000). The autochthonous unit of the Proterozoic sediments of Damtha and Tejam groups is exposed at the vast window in the inner (northern) belt of the Lesser Himalaya. The Outer Lesser Himalaya mostly consists of the Jaunsar and Mussoorie group (Valdiya 1980). Lithostratigraphically, it comprises Mandhali at the base, succeeded by the Chandpur and Nagthat formations of the Jaunsar group, forming the bulk of the tectonic unit and are capped by the Late Neoproterozoic Krol (mostly limestones) and Tal (mostly siliciclastics) formations. The trilobite fossils from the Tal formation belong to the Early Cambrian (Hughes *et al* 2005). Cretaceous to Paleocene shelly limestone and sandstone of Bansri and Subathu formations have limited exposure to the south of the TT in the Garhwal Lesser Himalayan sequence.

The northern boundary of Almora klippe marked by the NAT acts as a barrier between Outer and Inner Lesser Himalaya and separates Chandpur phyllites from Khirsu quartzite (Rautgara of Valdiya 1980) of Kumar and Agarwal (1975). Below the NAT, a thick succession of phyllites of Chandpur Formation is exposed and severed by small basic dykes at Killeshwar (3 km south of Srinagar). Lens-shaped mylonitized granitic gneiss bodies which are exposed at Uphalda are named as UG (figure 1b) by Doval and Saklani (1980). The contact between UG and Chandpur formation is thrust. These UG are broadly similar to the suite of quartz porphyry of Valdiya's DP.

Chandpur formation consists of phyllite, slate, shale and quartzite. The Chandpur phyllite of Srinagar area is also referred to as Pauri phyllite. These rocks are greyish green to dark green in colour and are folded and schistose in nature at Uphalda. The crenulation cleavage is quite prominent. A patchy outcrop of ferruginous quartzite appears in the form of a tectonic window, 4.5 km SE of Srinagar (Doval and Saklani 1980). The basic dykes are hard and compact and cut across the phyllites of Chandpur formation. Dykes are foliated at the margin and the core portion is fresh and compact.

The UG are biotite-rich mylonitic augen gneisses and are characterized by alternate bands of quartz, feldspar and micas. These rocks are intensely and

Figure 1. (a) Geological and structural map of the Garhwal–Kumaun Lesser Himalaya. It represents the major structure of the region, various klippen, a series of stacked thrust sheets, major drainages and township of the region. Abbreviations – MBT: Main Boundary Thrust; MCT: Main Central Thrust (modified after Valdiya 1980; Clerier *et al* 2009). (b) Geological map of the study area, shows the various locations, structural details such as Uphalda klippe, etc. (modified after Doval and Saklani 1980). Rectangle in the map (a) shows the location of (b).

pervasively mylonitised, sheared, foliated and strongly recrystallized to blastomylonites. The UG is in direct contact with Chandpur phyllite and the contact is sharp.

3. Petrography

The UG show characteristics of mylonite that is defined by grain-size reduction of quartz and

feldspars with a well-developed foliation plane. The rock has a mineral assemblage of quartz, alkali feldspar, plagioclase, biotite and muscovite with minor amount of apatite, zircon, calcite, epidote

and Fe-oxide. The preferred orientation of mica defines the foliation plane.

Quartz commonly occurs as coarse porphyroblast with small recrystallized grains at the

Figure 2. Representative photomicrograph of UG of Garhwal Lesser Himalaya showing various mylonitic characters of the rock. (a) Quartz porphyroblast with small recrystallized grains at the margin, (b) undulose extinction and deformation lamellae in UG, (c) quartz (at the centre) showing core-mantle structure, (d) ribbon structure observed in UG, (e) completely recrystallized quartz ribbon, (f) recrystallized grains having straight boundaries meet at triple-point junction, (g) polycrystalline quartz with irregular grain boundaries, and (h) recrystallized quartz grains and calcite are in the pressure shadow region. (All photographs are taken under XPL.)

margin with fine grained groundmass (figure 2a). The porphyroclast is wrapped by foliation and shows ductile deformation features such as undulose extinction, deformation lamellae and development of sub-grains (figure 2b). It exhibits core-mantle structure as well as ribbon structure that is elongated and stretched along the foliation (figure 2c, d). At a few places, totally recrystallized quartz ribbons are also observed (figure 2e). The recrystallized grains form small equate patches of polygonal grains having straight or sutured grain boundaries (figure 2f) and meet at triple-point junctions. Irregular grain boundaries in quartz suggest grain boundary migration phenomena (figure 2g). At places, recrystallized quartz grains and

calcite are concentrated in the pressure shadow regions of the quartz porphyroclast (figure 2h). Fractures filled with mica and fine-grained quartz in porphyroclast are also present. Microstructural features suggest that the quartz have undergone both ductile and brittle deformations.

Alkali feldspar occurs as coarse porphyroclast in the form of augen and small grains associated with quartz and micas as groundmass. The porphyroclast is wrapped up by the foliation defined by the alignment of fine-grained mica and exhibits cross-hatched twinning and perthitic texture (figure 3a). It also shows undulose extinction and at places, the foliation passes through the porphyroclast (figure 3b). Along the fracture(s) the K-feldspar is broken into

Figure 3. Representative photomicrograph showing (a) K-feldspar porphyroclast wrapped by foliation, (b) foliation passing through the K-feldspar porphyroclast, (c) microcline twinning and the porphyroclast is broken into small grains and distributed in the groundmass, (d) displaced twin lamellae along the fracture (arrow) of plagioclase porphyroclast and broken into small grains, (e) folded foliation and development of crenulation cleavage, and (f) rounded grains of zircon support their sedimentary parentages. (All photographs are taken under XPL except (e), (f) taken under PPL). Mineral abbreviations are after Kretz (1983): quartz (Qtz), K-feldspar (Kfs), plagioclase (Pl), muscovite (Ms), biotite (Bt), calcite (Cal).

small grains and disseminated in the groundmass, suggesting that fracturing occurs later than the early crystal ductile deformation (figure 3c). The K-feldspars are less altered than the plagioclase.

Plagioclase occurs both as porphyroblast and fine-grained groundmass. In most of the samples, the plagioclase is completely altered. Plagioclase porphyroblasts are subhedral to anhedral with sutured boundaries and highly altered at the rim. They show undulose extinction and tapering deformation twins. In some cases, the fractures in the porphyroblast of plagioclase are developed by cutting across the twin lamellae and displacing the twin lamellae along the fracture and breaking the porphyroblast into small grains (figure 3d). Patches of plagioclase occur as islands in K-feldspar. The alteration product calcite shows twinning. Both plagioclase and K-feldspar are plastically deformed, however fracturing mechanism is more dominant in these minerals. Dynamic recrystallization of feldspars is not observed because the dissolution processes were dominant or the recrystallized domains around the feldspars have been dissolved or replaced by micas under low temperature conditions aided by flow of fluids.

Muscovite shows a strong preferred orientation and defined main foliation. It is very fine grained. At places, the main foliation is folded with development of crenulation cleavage (figure 3e). Sericite, which is the alteration product of feldspar, is also present. Biotite occurs as fine flakes lying along the foliation. The modal content of biotite is less than muscovite. More likely, the biotite has been destabilized and converted into secondary minerals. Similar types of petrographic characters are observed for DP and BMG.

The mineral assemblages in the UG exhibit greenschist facies condition. The mineral assemblages in the surrounding Chandpur formation are also metamorphosed to greenschist facies condition. The micas, especially recrystallized biotite are affected by chloritization. Albite, microcline and quartz also exhibit recrystallization phenomena. Crystallized plagioclase is of albitic composition indicating that recrystallization has occurred at lower temperatures. Recrystallization of muscovite, epidote, quartz and albite from the deformation-induced retrogression of plagioclase reveals that the deformation has taken place at greenschist facies conditions.

4. Analytical techniques

Sixteen samples representing UG (11) of Srinagar area, DP (2) and BMG (3) were collected. These samples were analysed for major, trace and rare

earth elements (REE) at Wadia Institute of Himalayan Geology, Dehradun. Geochemical analyses were performed using standard X-RF techniques, analysed by wavelength dispersive X-RF system (Siemens SRS 3000) and inductively coupled plasma-mass spectrometry (ICP-MS). The calibration of X-RF system was done by matrix correction based on intensities (Lucas-Tooth and Pyne 1964). Using a number of international standards (such as G2, GSP-1, JG-1, JG-2, DG-H) along with the samples, we monitored the quality of the analysis. Trace and REE analyses were carried out on ICP-MS (Perkin Elmer), with 0.4 g of the sample, following a long process of acid digestion that involved repeated treatment with HF-HClO₄ in the ratio of 2:1. The samples were dissolved in the acid mixture for two to three treatments until a clear solution was obtained. The residue was dissolved in 1N HNO₃ and 100 ml solution was then ready for analysis. Precision for the major oxides was always better than 1.5%, for P₂O₅, MnO and trace elements it was better than 5%, and for REE better than 10% (Ahmad *et al* 1996).

5. Geochemical characteristics

The geochemical analysis of UG, DP and BMG are presented in table 1. The overall major oxide behaviour of UG, DP and BMG are identical. These rocks are rich in SiO₂ content, ranging between 65 and 70 wt%; Al₂O₃ exhibits a narrow range (15–18 wt%). UG are also rich in Fe₂O₃ and K₂O content. To demonstrate the nature of these rocks, A/CNK ratios were derived (where molecular A/CNK = {mol. [Al₂O₃/(CaO+Na₂O+K₂O)]}, which range between 1.24 and 2.37 (UG: 1.39–0.37, DP: 1.28–1.45, BMG: 1.24–1.46), suggesting their peraluminous nature. The more leucocratic samples are very peraluminous. All the samples show the presence of normative corundum and absence of normative diopside; presence of round zircon grains support their sedimentary parentages (figure 3f). Alkali content (Na₂O+K₂O) of UG is high (>6 wt %). K₂O content is always greater than Na₂O. High K₂O content suggests preponderance of microcline in these rocks. DP and BMG also exhibit similar characteristics. The major oxide composition of UG along with DP and BMG are plotted in Harker's variation diagram. TiO₂, Al₂O₃, Fe₂O₃, MgO and Na₂O exhibit negative trend with SiO₂, whereas CaO and K₂O do not show linear trend (figure 4). Owing to similar composition, the characteristics of these rocks are similar. The Fe₂O₃ *vs.* MgO plot (figure not shown) exhibit a positive trend indicating that they are constantly controlled by biotite crystallization. Relatively high Ti concentration, but lack

Table 1. Representative major and trace elements composition of Uphalda gneisses (UG), Debquru porphyroids (DP) and Baragaon mylonitic gneisses (BMG) (major oxides in weight %, trace elements in ppm, total iron as Fe_2O_3 and $Eu/Eu^* = Eu_N / \sqrt{(Sm_N * Gd_N)}$).

Sp. no.	Uphalda gneisses										Baragaon mylonitic gneisses			Debquru porphyroids		
	UP1	UP2	UP3	UP4	UP5	UP6	UP7	UP8	UP8A	UP9	UP10	AM1	BM10	CM1	NM4	BM2
SiO ₂	66.5	67.6	68.5	67.0	65.9	68.4	67.0	64.3	69.9	70.3	67.3	69.7	71.4	63.7	68.5	69.6
TiO ₂	0.3	0.2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.6
Al ₂ O ₃	17.2	18.4	17.7	15.4	18.6	15.5	15.3	18.6	15.1	17.1	15.3	15.4	14.7	16.5	16.4	14.9
Fe ₂ O ₃	3.3	3.6	2.6	4.4	4.7	4.5	4.6	4.3	4.3	2.4	4.4	2.4	1.8	5.9	1.8	2.6
MnO	0.04	0.04	0.07	0.07	0.05	0.06	0.06	0.05	0.07	0.06	0.08	0.03	0.02	0.07	0.03	0.03
MgO	0.77	0.61	0.67	0.86	0.43	0.96	1.01	1.01	0.39	0.46	0.87	0.39	0.41	1.38	0.36	0.41
CaO	0.26	0.25	0.90	1.76	1.05	1.27	1.77	1.24	2.01	1.61	1.10	1.05	0.51	2.15	0.87	0.97
Na ₂ O	2.10	1.07	0.99	1.43	1.89	1.63	1.12	2.15	0.72	1.44	0.09	2.35	1.33	2.74	2.47	2.13
K ₂ O	6.34	5.14	6.00	4.97	5.14	5.32	5.45	5.38	5.31	4.76	5.69	6.15	6.36	4.52	5.23	5.86
P ₂ O ₅	0.11	0.11	0.12	0.12	0.12	0.11	0.12	0.11	0.11	0.11	0.11	0.10	0.07	0.23	0.15	0.12
LOI	2.19	2.54	2.68	3.23	2.46	2.44	3.26	2.69	1.36	2.38	4.54	2.09	2.45	2.02	3.26	1.98
Total	99.08	99.60	100.71	99.81	100.89	100.65	100.24	100.36	99.79	101.08	99.98	100.12	99.45	99.84	99.64	99.05
Sc	8	6	8	9	6	7	8	8	8	8	10	9	7	7	10	9
Co	7	8	17	9	8	12	8	9	10	9	12	8	8	11	12	8
Ni	33	17	35	37	37	32	38	32	31	32	34	29	28	38	27	16
Ba	918	838	864	869	801	796	776	783	864	791	890	650	524	961	690	653
Rb	319	328	314	296	284	271	286	277	245	260	295	58	291	266	302	239
Sr	89	54	99	155	170	179	175	136	143	178	97	19	60	170	66	110
Y	27	23	27	25	25	27	25	26	27	27	23	34	50	32	27	44
Zr	197	278	209	208	202	193	193	177	188	199	184	247	122	262	94	225
Nb	24	26	26	26	26	26	25	24	24	24	24	21	11	24	22	16
Pb	26	110	43	35	28	30	21	21	19	36	21	20	22	22	43	35
Th	29	24	27	28	30	28	29	28	28	25	28	16	65	38	10	77
La	45.09	56.64	52.20	58.45	52.81	48.18	48.14	41.46	44.72	49.95	43.61	42.69	47.73	52.12	27.38	58.20
Ce	85.07	106.13	99.30	109.82	99.12	91.50	92.80	80.34	73.96	95.55	83.32	90.54	118.80	107.70	59.79	133.10
Nd	34.00	39.30	38.08	43.18	37.81	34.89	35.40	30.90	30.88	36.53	31.60	39.14	45.24	42.65	25.08	57.01
Sm	6.39	6.75	7.12	7.96	7.12	6.54	6.75	5.70	5.95	6.87	6.06	9.99	10.42	11.06	5.60	12.67
Eu	1.69	2.21	2.08	2.28	1.80	1.58	1.69	1.41	1.54	1.80	1.57	0.56	0.60	1.01	0.66	0.57
Gd	4.66	4.68	5.21	5.81	5.24	4.99	5.11	4.23	4.20	5.07	4.39	6.83	6.82	7.78	4.23	8.27
Dy	5.20	4.44	5.18	5.73	5.10	5.18	5.42	4.47	4.21	5.31	4.61	9.30	6.88	6.67	4.47	7.10
Er	2.61	2.21	2.60	2.85	2.48	2.69	2.84	2.28	2.21	2.70	2.41	5.53	2.91	3.09	2.28	3.16
Yb	2.19	1.86	2.12	2.32	1.91	2.10	2.30	1.83	1.71	2.04	1.99	4.90	2.29	2.90	1.83	2.66
Lu	0.32	0.29	0.33	0.35	0.29	0.32	0.35	0.27	0.27	0.31	0.31	0.56	0.24	0.28	0.27	0.33
A/CNK	1.59	2.37	1.81	1.41	1.76	1.44	1.39	1.60	1.43	1.63	1.83	1.24	1.46	1.24	1.45	1.28
K/Rb	199	157	191	168	181	196	191	194	217	183	193	1060	219	170	173	245
Rb/Sr	3.59	6.09	3.15	1.91	1.67	1.52	1.64	2.04	1.72	1.46	3.04	3.05	4.85	1.56	4.58	2.17
(La/Yb) _N	14.74	21.81	17.64	18.06	19.84	16.50	14.99	16.28	18.77	17.57	15.72	6.25	14.95	12.89	29.76	15.69
Eu/Eu*	0.39	0.42	0.40	0.31	0.40	0.31	0.36	0.25	0.33	0.42	0.34	0.21	0.22	0.33	0.41	0.17

Figure 4. Harker's variation diagram of UG (black plus), BMG (empty rhomb) of Himachal Himalaya and DP (filled dots) of Garhwal Lesser Himalaya, showing binary relationship with SiO_2 vs. all major oxides.

of titanium phase, suggests the involvement of biotite during melting. Among the trace elements, Ba, Sr, Zr, Th and Nb show a negative trend with SiO_2 and Rb does not show any trend but cluster at one place in Harker's variation diagram (figure 5), however these elements show a comparatively better trend with Zr. In general, the UG are rich in Rb, Ba, Zr, depleted in Sr and transition elements (Co, Ni, etc.). Similar characteristics are also exhibited by BMG and DP ($\approx$ Ramgarh group of rocks). The general enrichment of LILE (K, Rb, etc.) and depletion of HFSE (Zr, Y, Nb) support their crustal source. To demonstrate crystal fractionation of feldspar and biotite, Sr and Ba are plotted against Rb/Sr ratio (figure 6) and Ba vs. Rb plots (figure 7a). A very good negative trend is observed particularly in the Sr vs. Rb/Sr diagram. The bulk distribution coefficient (K_d) for Ba and Sr will be >1 and for Rb <1 , hence the fractional crystallization will result in decreasing Sr and Ba and enhancement

Figure 5. Harker's plots of SiO_2 vs. trace elements of UG (black plus), BMG (empty rhomb) of Himachal Himalaya and DP (filled dots) of Garhwal Lesser Himalaya.

of Rb. The depletion of Sr is in accordance with plagioclase fractionation. The above cited trends suggest that fractionation was dominated by K-feldspar and biotite and are increasingly important in more evolved stages. Further, positive correlation between Zr and TiO_2 is best explained by fractional crystallization processes (figure 7b).

REE of UG, BMG and DP are analysed and their values are normalized after Sun and McDonough (1989) and are presented in table 1. UP are characterized by high LREE abundances (chondrite normalized La 100–290X) and the HREE abundances vary between $10\times$ and $20\times$ Lu (figure 8a). The ratios of $(\text{La/Yb})_N$, $(\text{La/Sm})_N$, $(\text{Gd/Yb})_N$ and Eu_N/Eu^* (where Eu^* is the square root of the products Sm_N and Gd_N) are calculated and suggest moderately fractionated nature of UG. Similar characteristics are also exhibited by BMG and DP. The concentration of total REE and degree of fractionation increases from leucocratic to melanocratic variety of rocks. Involvement of REE-rich accessory minerals such as monazite and zircon are abundant in UG, DP and BMG. Variations in REE patterns can also be explained in terms of simple crystal fractionation. Positive correlations between

Figure 6. LILE covariation plots of UG, DP and BMG. Symbols are as in figure 4.

Figure 7. Variation diagrams of Sr vs. Ba. (a), Zr vs. TiO₂ (b), Zr vs. Th (c), and Zr vs. Ce (d) of UG, DP and BMG. Symbols are as in figure 4.

Zr and both Th and Ce suggest that fractionation of zircon and monazite may have been involved (figure 7c, d). As these phases are much denser than the parental magma and can also form inclu-

Figure 8. (a) Chondrite normalized REE patterns of UG, DP and BMG. (b) Mantle normalized multi-element spider diagram of UG, DP and BMG. Normalized values (in a, b) are after Sun and McDonough (1989).

sions armoured in major fractionating phases such as biotite. Monazites are rich in LREE and zircons are rich in HREE. Variable fractionation of these phases can play an important role in affecting the REE patterns in the residual melts even if the amount of these minerals is small (Yurimoto *et al* 1990). Crystallization of these minerals assemblages are favoured in Ca-poor peraluminous granitic rocks such as UG, DP and BMG. Drastic similarities in REE concentration between UG, BMG and DP suggest that the source materials are similar in composition before their emplacement.

6. Discussion

6.1 Tectonic implications and regional correlation in the Himalaya

The preceding description on field geology, petrography and geochemistry of UG, DP and BMG suggests that they are the products of crustal melting of older sedimentary protolith. Petrographic studies of associated Chail metamorphics and the mylonitic augen gneiss show greenschist facies

condition. The micas, especially biotite, are affected by chloritization in spite of recrystallization. However, albite, microcline and quartz show recrystallization. The crystallized plagioclase is of albitic composition indicating that recrystallization has occurred at lower temperatures. Also the recrystallization of muscovite, epidote, quartz and albite caused by the deformation-induced retrogression of plagioclase reveals that the deformation has taken place in greenschist facies condition. The deformation was initiated at higher temperature (above 350°C) and continued till lowering of temperature. A similar situation observed in UG suggests that before their emplacement as a klippe, these rocks were subjected to deformation that led to the mylonitization of these gneisses.

Geochemically, these granitic gneisses exhibit high molecular A/CNK value, presence of normative corundum and absence of normative diopside, enhanced Rb/Sr, Rb/Zr ratios, enrichment of Th and contain round zircons; which supports their crustally-derived S-type granitic nature and matches well with S-type granites of White and Chappell (1988). Sedimentary parentage also evident from similarities in REE patterns of granites to those of Post-Archaean Average Australian Shale and North American Shale Composite. The linear plot in major oxide binary plots is interpreted in terms of fractional crystallization processes. Their compositions are controlled by source material, however significant amount of crystal fractionation also played a role in the evolution of these granitoids.

To compare their geochemical similarities, we have used mantle normalized multi-element spider diagram for UG, DP, Ramgarh group of rocks (Ahmad *et al* 2000) and BMG; and observed drastic similarities in terms of REE and spider diagram such as depletion of Ba, Nb, Sr, P and Ti and enrichment of Th (figure 8b).

Mylonitic gneiss is a distinct rock of Lesser Himalaya which occurs as an isolated tectonic sheet within the metasedimentary package such as Chail metamorphites in Himachal Himalaya. The mylonitic gneisses are dated in various sectors of the Himalaya starting from the western sector in the Himachal Himalaya (BMG) to the eastern sector of the Himalaya, Nepal (Ulleri gneisses) and it has yielded Rb–Sr whole rock ages between 1800 and 1000 Ma (Bhanot *et al* 1976, 1978, 1982; Frank *et al* 1977; Paul *et al* 1982; Sinha-Roy and Sengupta 1986; Miller *et al* 2000).

In the western sector of the Himalaya, at the base of the Chail formation, highly deformed gneisses are exposed and are termed as mylonitic augen gneiss. These rocks belong to green schist to lower amphibolite facies metamorphic grades. Further, the protolith of this mylonitic augen gneiss

did not intrude into the Haimanta group (Miller *et al* 2000). Interestingly, Haimantas are considered equivalent to Chails (Islam *et al* 1999). The mylonitic augen gneisses represent the basement of these Proterozoic metasediments (Trivedi *et al* 1984; Srivastava and Mitra 1994; Grasemann *et al* 1999). The whole rock Rb–Sr isochron ages of ca. 1800 Ma for gneisses of Ramgarh thrust hanging wall by Trivedi *et al* (1984) led Valdiya (1995) to argue that schistose gneisses represent the basement sequence of the Lesser Himalaya. The characteristic association of mylonitic augen gneisses with carbonaceous-graphitic schist and phyllite has been assigned different names in different sections (e.g., Bajjura nappe: Frank *et al* 1973; Outer granite band: Bhatia and Kanwar 1973; Baragaon gneiss: Bhanot *et al* 1978; Sewa paragneiss: Sharma *et al* 1973; Gahr–Manjrot formation: Bassi 1989 and the Ulleri Augen gneiss in the Annapurna region in Nepal: Le-Fort 1975a, 1975b; Pecher and Le-Fort 1977).

Figure 9. (a) Th–Sc–Zr ternary plot for UG, DP, BMG, Ramgarh and Vaikrita gneisses/HHCs (Ahmad *et al* 2000) (after Bhatia and Crook 1986). (b) $(Zr \times 10^5)/Al_2O_3$ vs. TiO_2/Zr ratio plot of same dataset as in (a) and Ulleri gneisses and Ramgarh (schistose gneiss) data of Célérier *et al* 2009 (after Fralick and Kronberg 1997).

To demonstrate that the UG have distinct lithology and can be distinguished from the Higher Himalayan crystallines (HHC), we attempted a ternary plot of immobile elements such as Th, Sc, and Zr (figure 9a) for the UG, DP and BMG and compared it with data on HHCs (~Vaikrita group) and Ramgarh group by Ahmad *et al* (2000). The ternary plot indicates that the HHCs rocks are distinct from the UG, DP and BMG. Further, the data on Ramgarh group by Ahmad *et al* (2000) are compatible with our data. In addition, the ratio of immobile elements can distinguish the source region and such plots remain robust even during high-grade metamorphism (Fralick and Kronberg 1997; Ahmad *et al* 2000). $Zr \times 10^5 / Al_2O_3$ vs. TiO_2 / Zr plots (figure 9b) of UG, DP, BMG and the data on Ramgarh group by Ahmad *et al* (2000), Célérier *et al* (2009) (sample no. 0602006 of Mandakini valley and Ulleri gneisses of Nepal) plotted along with HHCs display a distinct identity and can be distinguished from the Lesser Himalayan rocks. The elemental ratio plots are also in conformity with Nd–Sr isotopic studies (Ahmad *et al* 2000; Martin *et al* 2005) and suggest that UG are comparable with DP, BMG and Ramgarh group of rocks.

Schistose gneisses are widely exposed in the Garhwal–Kumaun region and considered as the basement to the Lesser Himalayan sequence (Valdiya 1995). Crystalline schistose gneiss sample 0602006 of Mandakini valley of Garhwal Himalaya (Célérier *et al* 2009) was collected from the same locality/lithology of our DP. These retrogressed schistose gneiss (0602006 of Célérier *et al* 2009), DP, UG and BMG also suggest an older age for these rock units. Here we suggest UG represent a basement sliver and are emplaced within the cover sequence as wedges in the Lesser Himalaya.

The UG of Srinagar occur as a detached tectonic sheet within the metasedimentary piles of Lesser Himalayan Chandpur phyllites. In the southern parts of UG, the Chandpur formation consists of banded green shale and phyllite; whereas in the northern part, these rocks (Pauri phyllite) gradually change to chlorite–sericite phyllite, followed by chlorite biotite schists and show very well-developed foliation and crenulation cleavages (figure 3e). Resemblance in mineralogy and grade of metamorphism of these rocks is more likely correlatable to the Chail metamorphites of Himachal Himalaya which appears to be reasonable. Similar types of klippen are also observed in Sutlej valley in the Himachal Himalaya. A small gneissic klippe with mylonitic gneissic characters over the Rampur parautochthonous is observed around Shatahal ($31^{\circ}24'41''$: $77^{\circ}37'30''$; Viridi 1976). The surrounding rocks of Shatahal klippe resemble the Lesser Himalayan rocks of

Srinagar. Therefore, the occurrence of this type of klippe is a regional phenomenon throughout the Lesser Himalayan region.

7. Conclusions

Similarities in lithology, petrographic characters and geochemical composition of UG with DP and BMG of Himachal Himalaya suggest that these rocks are not transported from Higher Himalaya as understood earlier (Pilgrim and West 1928; Gansser 1964 and Valdiya 1980). Structural and stratigraphic relations of UG of the Garhwal Himalaya indicate that it represent(s) an older basement sliver which may be tectonically emplaced within the cover sequence as wedges at different structural levels.

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