Sedimentological and mineralogical characteristics of active glacial sediments in the Indian Himalaya regions

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ABSTRACT
Glaciated sediments are a significant source to know the glacier environment processes. Glacial meltwater streams draining from the Himalayan glaciers carry with a different type of sediment sizes, because of the supraglacial, englacial, and subglacial debris, as well as formation of sediments from erosion by the movement of the ice. This study examines mineralogical and textural characteristics of sediments transported in the selected Indian Himalayan glacier meltwater streams. The results indicate that various sedimentological diversity occurring within proximity of active glaciations due to glacio-hydrological processes. Sedimentological and mineralogical characteristics suggest that sediments of the proglacial area are polygenetic in nature. A comparative change in feldspar/quartz among bedrock, sand, and clay suggested that the active geochemical weathering regime at a low-temperature environment maturing the sand composition. The less clay fraction in glacier sediment indicates limited generation of clay minerals in the glacier environment. Change in clay composition from supraglacial moraine to proglacial environment indicated a chemical alteration in glaciated valley assisted by low slope glacio-fluvial environment.

Introduction
Sediments derived from various Himalayan uplands, which form the biggest Indus-Ganga-Brahmaputra floodplains in the world. The sources of this sediment come through different geo-morphological processes in the upland area which are covered with snow and ice. Glacial processes are a significant source of chemically immature sediments that contribute to the fertility of the soil in floodplain areas (Ahmad & Hasnain, 2007). The supraglacial sediments lay over the glacier play a major role in the melting of snow and ice below the glacier. Debris cover protects the glacier melting from thickly covered sediments and enhances the ice melting due to thinly covered sediments. It has long been recognized that physical weathering act as essential processes in producing vast volumes of sediments because glaciers are very active agents of weathering and erosion. Plucking, quarrying, crushing, shearing, and abrasion are the physical weathering processes in alpine basins.

Along with active glaciological processes high seismicity, steep valleys with frequent avalanching, intense monsoonal rainfall, and glacial activities support high erosion rates in the Himalayan catchments (Pandey et al., 1999; Hasnain & Thayyen, 1999; Singh & Hasnain, 1998). Himalayan glaciers also produced a large amount of rock debris consist of gravel, sand, silt/clay, etc., stored on supra-glacier and paleo-moraines compared to other glacier regions. Such glaciers are thought to be the main active agents of erosion and transporting sediment in regional denudation systems (Gardner, 1986). Numbers of studies have demonstrated that specific yield may increase downstream due to the remobilization of sediments pushed by the glaciers (Ferguson, 1984; Hasnain & Chauhan, 1993; Warburton, 1990). Although plenty of literature and data are available on sediment and soil attributes in the middle and lower catchments of the Himalayan rivers (Pandey et al., 1999). The sediment characteristics in river water at upland catchments are extremely sparse. For mountain studies, textural, mineralogical, and geochemical characteristics of the sediments at glacier surface are extremely important for revealing the tectonic process and also dealing with the problems of soil erosion, flash flooding, quality of water supply in the downstream regions, transport of chemical pollutants and degrading of natural habitats. To recognize the relationship between glacier-hydrological-sedimentological interactions processes a detailed analysis has studied. The sedimentological characteristics and mineralogical composition of various types of sediments were chosen to reveal these interactions processes. The supra-glacier, old recessional moraine of the pro-glacial stream bed, and meltwater suspended sediments were collected in glacier environment at some selected locations in the Indian Himalaya. The present studies can also be used to interpret ancient landforms and sediments for paleo-environmental
reconstructions, and aid in understanding different processes which are operating on glacier sediments.

Study area

The study area comprises of five Himalayan glaciers which are basically Parkhachik and Drang-Drung glacier in western Himalaya, Pin-Parbati and Gangotri glacier in middle Himalaya, and Zero point glacier in eastern Sikkim Himalaya. All these Himalayan glaciers bounded by latitudes (26°34’41”–34°51’23”) and longitudes (75°59’12”–89°34’45”) in the northern peninsular region of India (Figure 1).

For collecting glacier surface samples, numerous field campaigns were conducted in these selected Himalayan glaciers. The samples were collected from Gangotri glacier basin (30.926074°, 79.080370°), Bhagirathi valley, Garhwal Himalaya, Pin-Parbati glacier (31.799362°, 77.374058°), Parbati valley, Himachal Pradesh in central Himalaya. In western Himalaya, the samples were collected from Parkhachik glacier (34.050942°, 76.024245°), Drang-Drung glacier (33.861900°, 76.362755°), Indus valley, Kashmir Himalaya, and Zero point glacier in eastern, Sikkim Himalaya.

Geologically, the basement rocks of all these glaciers are leucogranite and gneisses of the central crystalline zone. These extensive glaciers were characterized by variable size typically ranging from 30-km-long Gangotri glacier, 9-km Pin-Parbati glacier, 14 km Parkhachik glacier, 22 km Drang-Drung glacier, and 5-km-long Zero point glacier. All these glaciers were densely covered with debris except Drang-Drung glacier. The frontal portion of this glacier was also covered with debris along with a small size lake at glacier front.

Methods

To know the textural and mineralogical characteristics of glacier sediments we have collected a different fraction of sediment samples from glaciated moraines and stream bed sediments during the post-monsoon period. Samples were assembled in zip-lock polythene bags using a plastic scoop to avoid any types of contamination. The grain size distributions were determined by sieve shaker (Fritsch Analysette 03.502) and textural analysis was carried out using Folk and Ward (1957).

The medium grains sand fraction of sediments samples were analyzed to determine the major mineral composition, and Trinocular Stereo zoom microscope (Nikon-SMZ1500) were used for this purpose. In each sample, minerals were identified and performed mineral counting analysis based on a physical method for the 200 particles in each sample (Ingersoll et al., 1984). The mineralogy of clay fraction of sediment samples was studied using an X-ray diffractogram instrument (Carrols, 1970; Gibbs, 1970). The samples were used as a powder and run diffractometer along with Ni-filter and Cu, Ka-radiation with the chart drive speed of 1 cm⁻¹/min.

The pebbles size fraction of bed sediment samples were examined under petrography analysis under thin section studies. These thin sections were prepared by cutting a section of the rock sample followed by grinding and polishing before fixing on a petrography slide (Hamphries, 1992). The different gravel samples were viewed under thin sections and photographed under the microscope with a magnification factor of 20 μm and 50 μm.

Results and discussion

Sedimentological characteristics of the glaciated sediments

Basic statistical grain size parameters like graphics mean, standard deviation skewness, and kurtosis were calculated for different sediments fraction from Gangotri, Pin-Parbati, Parkhachik, Drang-Drung, and zero-point glaciers regions (Table 1).

Figure 1. Location map of the sediments samples site in the active glacial region of Indian Himalaya (After Carosi et al. 2018).
Table 1. Sedimentological characteristic in the Himalayan glacier environment.

| Supra-glacial moraine          | Mean size (ϕ) | Sorting (ϕ) | Skewness (ϕ) | Kurtosis (ϕ) |
|-------------------------------|---------------|-------------|--------------|--------------|
| Pin-Parbati (HP)              | 0.8           | 1.04P       | 0.13FS       | 0.76P        |
| Drang-Drung (J&K)             | 0.56          | 1.9P        | 0.544FS      | 0.57P        |
| Drang-Drung (J&K)             | 0.51          | 1.8P        | 0.505FS      | 0.56P        |
| Parkachik(J&K)                | 0.4           | 1.67P       | 0.485FS      | 0.62P        |
| Parkachik(J&K)                | 0.38          | 1.04P       | 0.85FS       | 1.58L        |
| Gangotri (GH)                 | 0.383         | 0.99P       | 0.854VFS     | 0.66P        |
| Gangotri (GH)                 | 1.218         | 1.276P      | 0.334VFS     | 0.479VPL     |
| Gangotri (GH)                 | 1.243         | 1.25P       | 0.2945K      | 0.478VPL     |
| Zero-point (SH)               | 2.789         | 1.081P      | -0.3815CK    | 3.818VPL     |
| Near snout                    |               |             |              |              |
| Parkachik (J&K)               | 2.16          | 1.28P       | -0.465CK     | 2.94VL       |
| Drang-Drung (J&K)             | 1.93          | 1.82P       | 0.081 SMK    | 0.66VPL      |
| Gangotri (GH)                 | 1.531         | 1.283P      | 0.0218CK     | 0.466VPL     |
| Zero-point (SH)               | 2.789         | 1.081P      | -0.3815CK    | 3.818VPL     |
| Suspended sediments           |               |             |              |              |
| Dudu (GH) Ahmad, 2000         | 5.34          | 1.43P       | 0.16FS       | 1.02 L       |
| Dokriani (GH) Thayyen et al., 1999 | 4.25     | 1.65P       | 0.15FS       | 0.87PL       |
| Pindar (KH) Pandey et al., 2002 | 5.08     | 1.6P        | 0.34VFS      | 1.1 M        |
| Satopanth (GH) Chauhan, 1993  | 5.14          | 1.7P        | 0.41VFS      | 0.85 M       |

P = Poorly Sorted, FS = Fine Skewed, VFS = Very Fine Skewed, SCK = Strong Coarse Skew, CK = Coarse Skew, SMK = Symmetrical Skew, PL = Platykurtic, VPL = Very Platykurtic, L = Leptokurtic, VFS = Very Leptokurtic, M = Mesokurtic.

The mean grain size is an important parameter that defines the overall grain size characteristics. The mean values of sediments from supraglacial moraines, old recession moraines, snout, and suspended sediments are 0.71ϕ, 2.01ϕ, 2.12ϕ, and 4.95ϕ respectively (Figure 2). The mean size of supraglacial moraines ranges from 0.38 to 1.24ϕ indicating a predominance of coarse sand which was larger than among all collected sediment samples in different glaciated regions.

The supraglacial moraines are characterized by loose rock debris on the surface of glacier and dust settling out from the atmosphere. Sorting of supraglacial moraines ranges from 0.99 to 1.9ϕ with STD (Standard Deviation) of 0.36ϕ showing poorly sorted. The average sorting value of suspended sediments is 1.5ϕ with STD of 0.11ϕ indicating very well-sorted sediments; it may be due to low energy conditions prevailing in the glacial environment during post-monsoon seasons (October to November). The other researchers have reported that the poor sorting in the glacial meltwater of suspended sediments due to the high flow conditions of glaciers meltwater (Pandey et al., 2002; V.B. Singh et al., 2014).

The skewness values of sediments indicate negatively skewed near snout area and old lateral moraine, which shows the admixture of relatively coarse to strongly coarse skewed sediments (Figure 3). Supraglacial moraine sediments tend to be near symmetrical (>0.5) with a relatively small abundance of fine particles which indicates a large admixture of medium to fine sediments while suspended sediments are characterized by positive/fine skewed (0.26) which indicates a relatively high proportion of fine sediments.

The kurtosis expresses the peakedness of the grain-size distribution. If the central portion is better sorted than the tails, the frequency curve is said to be excessively peaked or leptokurtic. If the tails are better sorted, the curve is said to be flat peaked or platykurtic. The average kurtosis of supraglacial sediments is 0.71ϕ, followed by 1.3ϕ for side old moraine, 1.9ϕ near the snout, and 0.9ϕ for suspended sediments (Figure 4). The individual location is showing local variation because suspended sediments fall in the mesokurtic category and sediments from the near snout area are very leptokurtic in character (>1.9).

![Figure 2. Textural characteristics showing of different glaciated environment sediments.](image-url)
Mineralogical characteristics of the glaciated sediments

Average sediments mineralogy of the gravel fraction from the Pin-Parbati, Drang-Drung, Parkhachik, Gangotri, and Zero point glaciers areas were subjected to the petrological microscopic studies. The minerals identified were quartz, plagioclase biotite, and muscovite. The volume percentages of identified minerals in the thin section are presented in (Table 2). Quartz is the most dominant mineral comprising 57% followed by biotite 18%, muscovite 8%, and plagioclase 13% (Figure 5).

The average mineralogy of the sand fraction of the sediments from the Pin-Parbati, Drang-Drung, Parkhachik, Gangotri, and Zero point glaciers were subjected to the stereomicroscope studies in order to determine the bulk mineralogy. The volume percentage of identified minerals was presented in (Table 3). Quartz is the most dominant mineral, comprising 73%, followed by muscovite 16% and plagioclase 10%.

The average sediments mineralogy of silt/clay fraction of the Pin-Parvati, Parkhachik, and Drang-Drung glaciers meltwater were subject to the X-ray Diffraction studies in order to the bulk mineralogy determination. The volume percentage of identified minerals in clay fraction (< 63 µm) is given in (Table 4). It shows that quartz is the most dominant mineral, comprising 40%, followed by micas 9%, plagioclase 29%, and chlorite 5%.

The volume percentages of identified minerals of suspended sediments in glacier streams are presented in (Table 5). Minerals percentages of suspended sediments were compiled from various studies (Ahmad, 1995, 2000; Chauhan, 1995; Pandey, 1999; Raju, 1993). Quartz is the most dominant mineral, comprising 30.3%, followed by mica 20%, plagioclase 31.2%, Sericite/illite 18.2%, and calcite/dolomite 5%. The comparative analysis of the mineral composition from different fractions of the sediment suggests that the bedrock and the fine

Figure 3. Bivariate plots showing different particle size mean size vs. kurtosis.

Figure 4. Bivariate plots showing different particle size mean size vs. skewness.
fraction are near the same concerning mineral composition. However, a contrast was found for the composition of the sand fraction that was associated with a high percentage of quartz. The changes in the relative abundance of minerals in fine fractions have been used to reveal the earth surface processes (Haldar & Tišlar, 2014; Montgomery et al., 2000; Nicholas, 1997; Viers et al., 2007). A change in relative intensities of peaks of the minerals was recognized along with the new peak X-rays diffractograms. The X-rays diffra-ctograms peak of sediments indicates that the bulk mineralogy may change significantly from supra-glacial sediments to pro-glacier bed sediments.

**Discussion**

Numerous workers particularly in Western Himalaya, Nepal Himalaya, and the Khumbu Himalaya of Nepal have described the characteristic of supra-glacial debris on glaciers (Bishop et al., 1999, 1995; Kick, 1962; Owen, 1988; Scott, 1992) and the Khumbu Himalaya of Nepal (Inoue, 1977; Iwata et al., 2000; Moribayashi & Higuchi, 1977). Bishop et al. (1995, 1999), and Shroder et al. (2000) highlighted the importance of supra-glacial debris cover in the glacial system. Facies over the glaciers particularly the lateral and terminal sediment deposits were described by (Benn & Owen, 2002). Supraglacial processes are responsible

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**Table 2.** Mineral composition % of gravel in the selected Himalayan glacier and pro-glacial environment.

| S. no. | Latitude | Longitude | S. no. | Quartz | Plagioclase | Biotite | Muscovite |
|--------|----------|-----------|--------|--------|-------------|---------|-----------|
| Pin-Parbati (Himachal Himalaya) | | | | | | | |
| PP-1 | 31.92416° | 77.90361° | 1 | 55 | 12 | 25 | 9 |
| PP-2 | 31.89194° | 77.90777° | 2 | 56 | 6 | 13 | 3 |
| Parkachik (Jammu & Kashmir Himalaya) | | | | | | | |
| P-1 | 34.11416° | 76.00750° | 3 | 68 | 6 | 26 | 0 |
| P-2 | 34.13472° | 76.02277° | 4 | 67 | 10 | 13 | 8 |
| P-3 | 34.12583° | 76.03916° | 5 | 60 | 0 | 28 | 3 |
| P-4 | 34.12527° | 76.04194° | 6 | 59 | 9 | 32 | 0 |
| Drang-Drung (Jammu & Kashmir Himalaya) | | | | | | | |
| D-2 | 34.04722° | 76.39833° | 8 | 51 | 3 | 6 | 40 |
| D-7 | 33.96833° | 76.36805° | 9 | 51 | 3 | 6 | 40 |
| D-8 | 33.99583° | 76.44555° | 10 | 45 | 8 | 5 | 14 |
| D-10 | 34.03861° | 76.57194° | 11 | 52 | 6 | 35 | 3 |
| D-12 | 34.05277° | 76.62472° | 12 | 76 | 0 | 21 | 3 |
| D-17 | 33.93388° | 76.39722° | 13 | 59 | 30 | 10 | 0 |
| Gangotri (Garhwal Himalaya) | | | | | | | |
| G-1 | 30.98980° | 78.92275° | 14 | 54 | 5 | 22 | 18 |
| G-6 | 30.98298° | 79.01977° | 15 | 58 | 17 | 11 | 16 |
| G-15 | 30.92554° | 79.08517° | 16 | 64 | 10 | 19 | 8 |
| G-22 | 30.99648° | 78.95406° | 17 | 60 | 14 | 10 | 15 |
| Zero-point glacier (Sikkim Himalaya) | | | | | | | |
| S-4 | 27.92098° | 88.68856° | 18 | 53 | 20 | 20 | 7 |
| S-5 | 27.92168° | 88.69006° | 19 | 48 | 29 | 23 | 0 |
| S-6 | 27.90600° | 88.69035° | 20 | 54 | 29 | 17 | 0 |
| S-7 | 27.91856° | 88.69275° | 21 | 59 | 21 | 20 | 0 |
| S-8 | 27.9739° | 88.69417° | 22 | 54 | 27 | 19 | 0 |
| S-9 | 27.90600° | 88.69035° | 23 | 51 | 25 | 22 | 0 |

**Figure 5.** Average mineral percentages showing of different sediment fraction in glaciated environment.
Table 3. Mineral composition % of sand in the selected Himalayan glacier and pro-glacial environment.

| S. no. | Latitude | Longitude | Quartz | Plagioclase | Mica | S. no. | Latitude | Longitude | Quartz | Plagioclase | Mica |
|--------|----------|-----------|--------|-------------|------|--------|----------|-----------|--------|-------------|------|
| Pin-Parbati (Himalchul Himalaya) | 31.97500° | 78.05972° | 94 | 2 | 4 | G-11 | 30.94277° | 79.06287° | 73 | 11 | 16 |
| PP-4 | 31.97500° | 78.05972° | 94 | 2 | 4 | G-12 | 30.93676° | 79.06745° | 54 | 15 | 31 |
| PP-6 | 31.91805° | 77.88777° | 97 | 0 | 3 | G-13 | 30.93276° | 79.07343° | 74 | 17 | 9 |
| Parkachik (Jammu & Kashmir Himalaya) | 34.13472° | 76.02277° | 90 | 0.5 | 9 | G-14 | 30.92548° | 79.08381° | 78 | 9 | 13 |
| P-2 | 34.13472° | 76.02277° | 90 | 0.5 | 9 | G-15 | 30.92554° | 79.08517° | 47 | 28 | 25 |
| P-4 | 34.12527° | 76.04194° | 94 | 3 | 2 | G-16 | 30.92663° | 79.08221° | 39 | 7 | 54 |
| P-12 | 34.12444° | 77.24972° | 87 | 4 | 8 | G-17 | 30.92638° | 79.08098° | 70 | 12 | 18 |
| Drang-Drung (Jammu & Kashmir Himalaya) | 34.01638° | 76.55111° | 90 | 2 | 8 | G-18 | 30.92988° | 79.07591° | 67 | 13 | 20 |
| D-3 | 34.01638° | 76.55111° | 90 | 2 | 8 | G-19 | 30.94314° | 79.06244° | 71 | 11 | 17 |
| D-8 | 33.99583° | 76.44555° | 86 | 0 | 14 | G-20 | 30.94913° | 79.05617° | 64 | 15 | 20 |
| D-9 | 33.97972° | 76.46333° | 66 | 5 | 29 | G-21 | 30.96934° | 79.03705° | 76 | 15 | 9 |
| Gangotri (Garhwal Himalaya) | 30.99880° | 78.92275° | 72 | 12 | 15 | G-22 | 30.99648° | 78.95406° | 76 | 10 | 14 |
| G-1 | 30.9974° | 78.93984° | 54 | 16 | 29 | S-1 | 27.92708° | 88.69421° | 69 | 11 | 20 |
| G-2 | 30.9974° | 78.93984° | 54 | 16 | 29 | S-2 | 27.90172° | 88.69254° | 68 | 13 | 19 |
| G-3 | 30.99450° | 78.94143° | 69 | 13 | 18 | S-3 | 27.91928° | 88.69169° | 92 | 3 | 5 |
| G-4 | 30.99553° | 78.98103° | 73 | 14 | 13 | S-4 | 27.91308° | 88.73502° | 80 | 7 | 12 |
| G-5 | 30.98850° | 79.00380° | 50 | 22 | 27 | S-5 | 27.91366° | 88.73524° | 87 | 5 | 7 |
| G-6 | 30.98298° | 79.01977° | 69 | 14 | 16 | S-6 | 27.79303° | 88.70769° | 88 | 5 | 7 |
| G-7 | 30.96686° | 79.03790° | 85 | 5 | 9 | S-7 | 27.90298° | 88.68856° | 76 | 8 | 15 |
| G-9 | 30.94930° | 79.05145° | 60 | 15 | 25 | S-8 | 27.92168° | 88.69006° | 82 | 6 | 12 |

Table 4. Mineral composition % of Clay/silt fraction in the selected Himalayan glacier and pro-glacial environment.

| S. no. | Latitude | Longitude | Quartz | Plagioclase | Mica | K-feldspar | Chlorite | Carbonate |
|--------|----------|-----------|--------|-------------|------|------------|----------|-----------|
| Pin-Parbati | PP-1 | 31.92416° | 77.90361° | 62 | 20 | 9 | 5 | 4 | 0 |
| PP-4 | 31.97500° | 78.05972° | 45 | 16 | 12 | 9 | 17 | 0 |
| PP-6 | 31.91805° | 77.88777° | 50 | 27 | 5 | 13 | 4 | 0 |
| Parkachik | P-2 | 34.13472° | 76.02277° | 35 | 15 | 11 | 11 | 0.16 |
| P-4 | 34.12527° | 76.04194° | 44 | 17 | 18 | 7 | 10 | 0.04 |
| P-12 | 34.12444° | 76.24972° | 52 | 28 | 12 | 4 | 0 | 0.03 |
| Drang-Drung | D-3 | 34.01638° | 76.55111° | 34 | 25 | 19 | 16 | 6 | 0 |
| D-8 | 33.99883° | 76.44555° | 46 | 24 | 12 | 18 | 0 | 0 |
| D-9 | 33.97972° | 76.46333° | 59 | 31 | 0 | 6 | 0 | 0 |
| Gangotri | SM-1 | 30.92097° | 79.08448° | 8 | 22 | 0 | 68 | 1.4 | 0 |
| SN-1 | 30.927224° | 79.078257° | 18 | 71 | 4 | 6 | 0.7 | 0 |
| BOH-3 | 30.939266° | 79.062659° | 26 | 53 | 0.9 | 18 | 1 | 0 |

Table 5. Mineral Composition of suspended sediments draining from different glaciated regions.

| Minerals composition | Satopanth n = 5 | Gangotri n = 7 | Bagni n = 5 | Dokriani n = 8 | Dudu n = 2 | Pindari n = 10 |
|----------------------|-----------------|----------------|-------------|---------------|-------------|---------------|
| Quartz | 13 | 17 | 57 | 21 | 28 | 45 |
| Feldspar | 40 | 32 | 26 | 51 | 32 | 6 |
| Sericite/Illite/Kaolinite | 11 | 47 | 12 | 11 | 15 | 13 |
| Mica | 37 | 4 | 2 | 19 | 24 | 35 |

Taken from different literature sources.

for the sedimentological characteristics of glacier surface debris. Much of the supraglacial debris on Himalaya was derived by valley sides mainly lateral, medial, and old moraines, either falling directly on ablation zone or undergoing englacial transport. The steep slopes of lateral and median moraine continuously supply the sediment on the glacier surface. Further, this debris interacts with supra-glacial melting processes that redistribute the sediment and associated with numerous ponds, lakes, Moulin, crevasse, and related supraglacial channels and spread with meltwater. The finer sediments are removed by the continuous flow of supraglacial streams channels due to a steep gradient that promotes unstable situation for the accumulation of finer sediments on the glacier surface. The selective removal of the fine particle from debris results in coarsening of the supraglacial sediments (Figure 6a–d).

Delivering of the meltwater through supra-glacier channels into Moulin add the fine sediments to fully developed a subglacial system in peak ablation system (Hasnain et al., 2001). The fine size sediments provided by supraglacial channels, the subglacial abrasion activity, unstable moraines, and alluvial cones at snout
region, which reflected positively skewed and highly leptokurtic nature of the sediments. During the ablation season, huge quantities of sediment are released from the margin of debris-covered glacier deposits by a combination of mass movement and glacio-fluvial processes (Hewitt, 1967). Sometimes these sediments are under-covered by subglacial till which exposed by deglaciation and erosion processes. This subglacial till associated with fine silt and contribute into glacier meltwater stream and result in fine skewed glacier fluvial deposits in front of the glacier snout (Figure 7). The glacio-fluvial environment of the Himalayan region is mostly surrounded by paleo lateral moraine. The silt and clay from lateral moraine also mobilized along with slope and contributed fine sediments in the proglacial environment.

Sedimentological and mineralogical characteristics suggest that sediments of the proglacial area are polygenic in nature. The reworking of the old and new supraglacial sediments processes indicates mature sand composition. The location of the sand in Dickinson plot suggested, the stable shield area are the sources of the sediments, but the maturing of sand composition in glacier environment due to the

![Dickinson diagram showing the provenance of sediments sources.](image)

**Figure 6.** Dickinson diagram showing the provenance of sediments sources.

![Images of Himalayan region and sediment sources](image)

**Figure 7.** (a) Supraglacial debris derived by valley side erosion and falling on ablation zone. (b) Lateral erosion contribute the sediments on glacier surface. (c) Medial moraine contribute the sediments near glacier surface. (d) Fine material removed by Moline and coarsening the sediments at the glacier surface.
recycling of available quaternary glacial sediments near glacier area (Figure 8). The high percentage of quartz in sand fraction than gravel fraction suggests that the reworking of sand grade sediment in meltwater stream drain from glacier environments. The detritus mineralogy of the bed sediments of river Ganga in central Ganga basin also suggested that the detritus mineral mainly derived from recycled orogen provenance with granite-gneisses (S.K. Singh et al., 2008).

Geochemical weathering processes were assessed by using feldspar/quartz minerals ratios of different sediments fractions. The mean values were shown 0.34$\phi$, 0.16 $\phi$, and 0.8 $\phi$ for the bed rock, sand, and clay/silt fraction samples respectively. Loss of feldspar in sand fraction of sediment indicates a geochemical weathering of the active minerals in the glaciated environment. The high viscosity of meltwater at low temperature, high hardness, and less geochemical activity of quartz grain has limited production of fine particles of quartz. During these processes, it leads to higher feldspar/quartz ratio in clay/silt fraction at glacier region environment. Further, the high feldspar/quartz ratios of the suspended sediment in the glacial stream were observed that the selective removal of the feldspar, biotite, and muscovite and increase the fine particle in glacier meltwater. The less clay fraction in glacier sediment indicates limited generation of clay minerals in the glacier environment. The X-ray diffractograms showing a variation in mineralogy near the glacier snout and downstream regions (Figures 7(b,c) and 9(a)). The result indicates that the decomposition of clay mineral in the proglacial stream caused by the sediment moisture and stable hydraulic condition in low slope area in most of the year. In low slope regions near the glaciated environment were shown that the strong leveling of the topography by the glacier action.

Conclusions

The present study provide a research platform to analysis the sediments characteristics of glacial meltwater streams and their origin. The major findings of this study summarized as follows:

- Supraglacial-meltwater interaction processes are responsible for the sedimentological characteristics of glacier surface debris. The selective removal of a fine particle from debris results in coarsening of the supraglacial debris. These fine particle sediments further mixes with the weathered subglacial material, unstable moraines, and alluvial cones at snout region, which results in a positive skewed and highly leptokurtic nature of sediment in glacio-fluvial region.
- The reworking of the old and new supraglacial sediments results in mature sand composition in glacier environment.
- A comparative change in feldspar/quartz ratio for the bed rock, sand, and clay/silt fraction indicate the geochemical weathering and limitation of a generation of the clay-size particle in glacier environment.
- Moisture content in glacial, fluvial sediments, and stable hydraulic condition along with low slope in the glaciated area provides an ideal
Figure 9. (a) XRD (Diffraction graph) of the samples collected from the Drang-Drung glacier. (b) XRD (Diffraction graph) of the samples collected from the Parkhachik glacier. (c) XRD (Diffraction graph) of the samples collected from the Pin-Parbati glacier.
place for the change in minerals composition in the proglacial stream.

Therefore, based on present investigations the current results suggest that, textural and mineralogical characteristics of Himalayan glaciers sediment provides detailed information on glacier dynamics, erosion rates, sediment transport, hydrological processes, etc. Therefore, future studies should follow homogenous time periods that are analogous to other studies during

Figure 9. (Continued)
the ablation season over the Indian Himalayan glaciers.

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The authors declare that they have no conflict of interest.

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