

**Keywords:** Late Quaternary glaciations, optical dating, periglacial features, Satopanth and Bhagirath Kharak glaciers.

THE seasonal distribution of precipitation in Himalayan glaciers is of summer accumulation-type, i.e. maximum accumulation and ablation occurs during summer<sup>1,2</sup>. Towards the growth of the glaciers, the Indian Summer Monsoon (ISM) is a major source of moisture<sup>3</sup>. Hence changes in the extent of valley glaciers can be used to reconstruct the past precipitation and temperature conditions. These changes are manifested in the pattern of distribution of the glacial sediments, particularly the lateral moraines. In a valley glacier, the highest point of lateral moraines coincides with the Equilibrium Line Altitude and terminates at the snout<sup>4</sup>.

In the Trans-Himalayan region, evidence for past glaciations is preserved in the form of well-developed moraines and valley fills that exceed several tens of metres in thickness. According to Owen *et al.*<sup>5</sup>, the extent of valley glaciations varied considerably throughout the Late Quaternary. Although most studies indicate multiple events of glaciation in the Himalaya, quantitative estimate on their timing is lacking due to scarcity of organic material that precludes the use of standard radiocarbon-dating techniques. Recent advancement in luminescence dating has opened up the possibility of proving the timing of the Late Quaternary in the region<sup>3</sup>. There exists some estimate on the timing of various glacial advancements from the Central Himalaya<sup>6,7</sup>, which provides insight into the fluctuations in ISM during the Late Quaternary. This study is a contribution towards understanding the magnitude and variability in the Late Quaternary glaciation in the Upper Alaknanda basin, in which an attempt has been made to reconstruct the pattern of glaciation. Lateral moraines associated with three glacial advances are well preserved in the Upper Alaknanda basin. These are named as Alaknanda (Stage-I), Alkapuri (Stage-II) and Satopanth (Stage-III) glacial advances. The oldest Stage-I was the most extensive glaciation in the basin that reached south of Badrinath (2604 m asl). Compared to this, the other two glaciations were terminated around 3550 and 3700 m asl respectively, in the N-S trending Upper Alaknanda basin. Preliminary estimate based on limited optical dating suggests the Stage-I predates the Last Glacial Maximum (LGM). An indirect age estimate based on the chronology of recessional moraine dated to 12 ka suggests that Stage-II was deposited during the LGM whereas Stage-III is dated to 4.5 ka. Conical heaps in the vicinity of the present-day snout are attributed to the recent recession probably associated with the Little Ice Age.

## Chronology of the Late Quaternary glaciation around Badrinath (Upper Alaknanda Basin): Preliminary observations

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**Reconstruction based on the presence of lateral moraines and other relict periglacial features in Upper Alaknanda basin indicates three phases of glaciation during the Late Quaternary. From oldest to youngest, they are named as Alaknanda (Stage-I), Alkapuri (Stage-II) and Satopanth (Stage-III) glacial advances. The oldest Stage-I was the most extensive glaciation in the basin that reached south of Badrinath (2604 m asl). Compared to this, the other two glaciations were terminated around 3550 and 3700 m asl respectively, in the N-S trending Upper Alaknanda basin. Preliminary estimate based on limited optical dating suggests the Stage-I predates the Last Glacial Maximum (LGM). An indirect age estimate based on the chronology of recessional moraine dated to 12 ka suggests that Stage-II was deposited during the LGM whereas Stage-III is dated to 4.5 ka. Conical heaps in the vicinity of the present-day snout are attributed to the recent recession probably associated with the Little Ice Age.**

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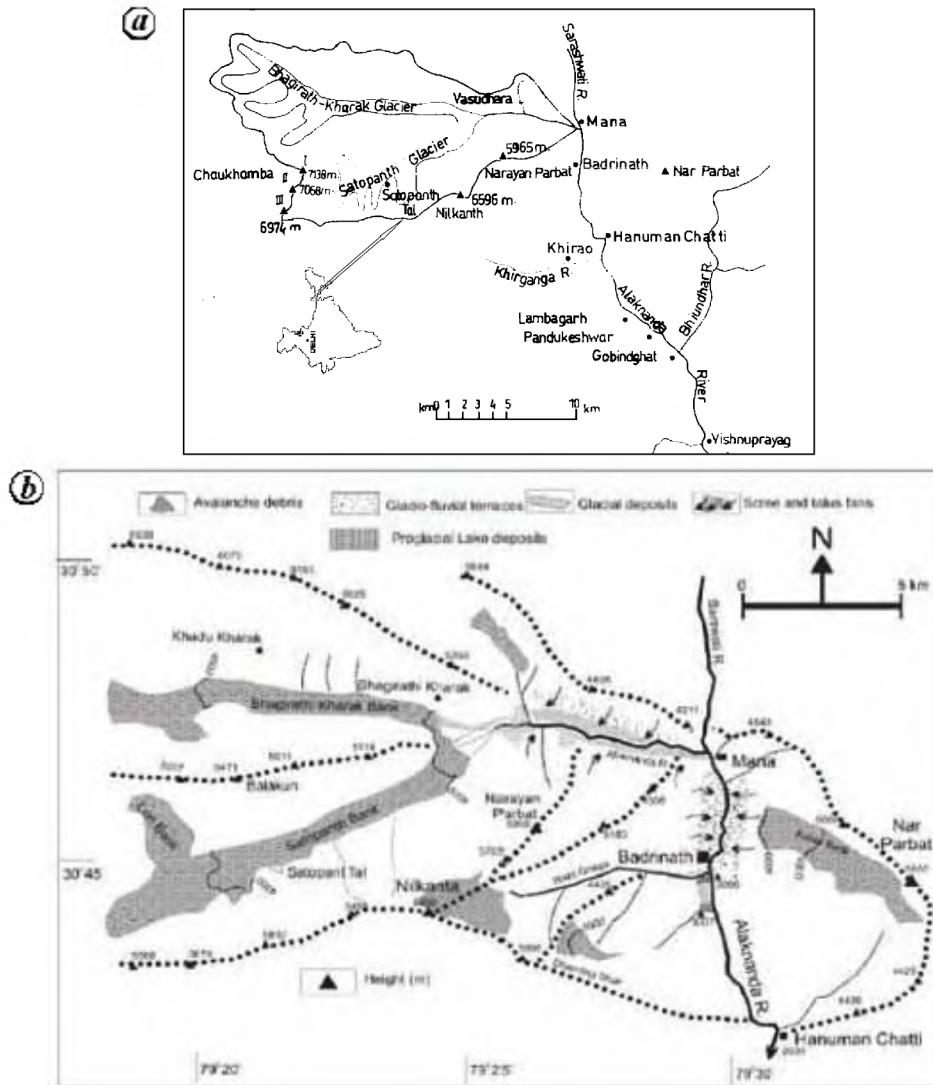


Figure 1. *a*, Location of the study area. *b*, Geomorphological map of the Upper Alaknanda basin.

The E-W trending Satopanth (21.17 sq. km) and Bhagirath Kharak (31.17 sq. km) are approximately 13 and 18.5 km long glaciers with an average width of 750 to 850 m (Figure 1 *a*). These glaciers are separated by a linear ridge (Balakun) which terminates abruptly on the eastern proximity. Snouts of Satopanth and Bhagirath Kharak glaciers are located at 3868 and 3768 m asl respectively. The Alaknanda river originates from the Satopanth glacier and meets Saraswati river near Mana village. From here onwards, the Alaknanda flows as a braided meandering river in Badrinath basin, whereas after leaving the Badrinath basin, it becomes a torrential-cascading river that has carved a deep gorge in the crystalline rocks.

The southern flank of the basin is surrounded by a linear ridge (>5000 m asl) on which lies the highest Nilkanth peak (5960 m asl). From this, the ridges bifurcates into two spurs, one extending towards NE and terminating near the confluence of the Alaknanda and Saraswati rivers, whereas the other takes a southeasterly turn along the Dhamling

Dhar (Figure 1 *b*). Compared to the northern ridge (above Bhagirath Kharak and Khadu Kharak), concentration of cirque glaciers is more on the southern ridge. The wide U-shaped basin between the glacier snout and Badrinath is filled with glaciogenic sediments, outwash gravel, cones of mass movement and avalanche debris. A relict glaciated basin (hanging basin) above the 4000 m asl contour can be observed, particularly between Mana and Badrinath. However, much of the features carved during palaeoglaciation are either obliterated or concealed by subsequent geomorphic processes.

The landforms present in this area are the result of polycyclic endogenic and exogenic processes operating at varying intensities through time. Genetically, two major processes can be observed in the study area and their resultant landforms are shown in Table 1.

The present study focuses on the periglacial features in order to reconstruct the pattern of Late Quaternary glaciations in the Upper Alaknanda Basin. Towards this, features

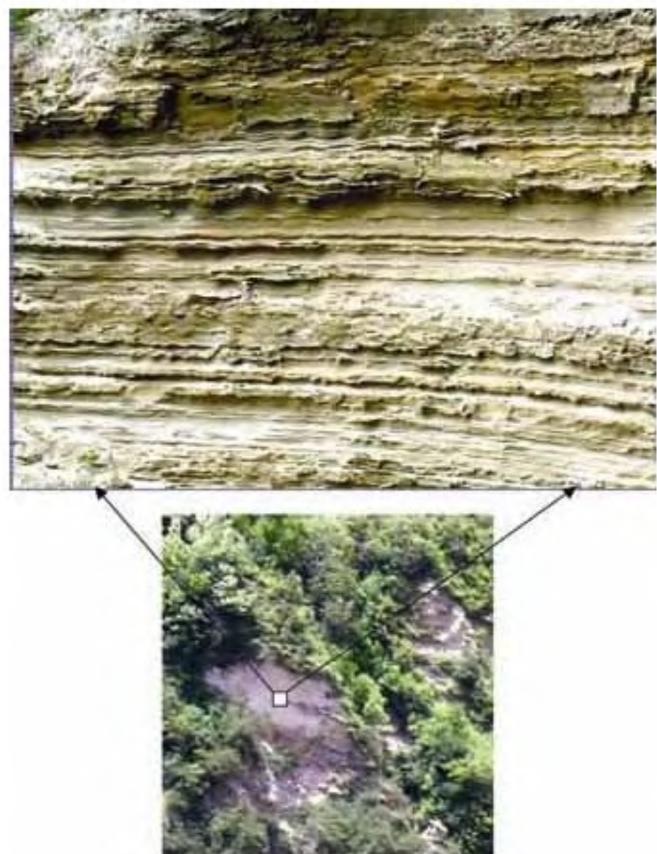
like lateral moraines, proglacial relict lake deposits and patterned ground were used. Such features have been conventionally used to reconstruct Late Quaternary glacial advancement and retreats, particularly lateral moraines<sup>4</sup>.

Based on the nature of occurrence, degree of weathering and morphology of morainic ridges, three generations of lateral moraines were identified.

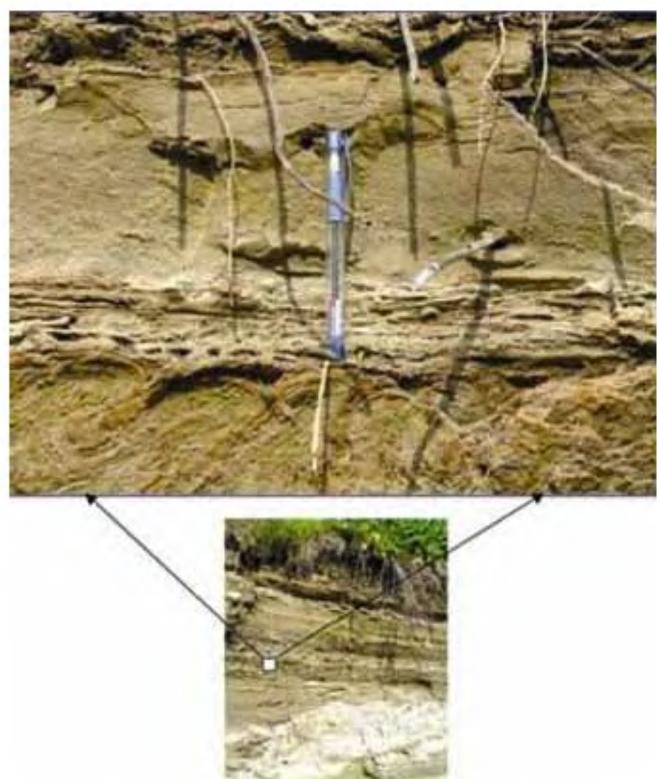
The longest and oldest moraines of Stage-I are partially lithified and degraded. They occur as patches between the confluence of the Alaknanda and Saraswati rivers (3132 m asl) and were traced ~5 km downstream at 3007 m asl (Figure 1 b). Downstream of Badrinath, these moraines appear as linear, hummocky ridges covered with birch and junipers. Poor preservation of Stage-I moraine is due to the subsequent fluvial process and frequent debris avalanches, which has either eroded or concealed them. The farthest occurrence of this moraine is located at 3007 m asl. Two generations of relict proglacial lake sediments were identified, one occurring near the terminus of this stage at 3007 m asl (on the opposite bank of Rarang Chatti) having thickness of ~100 m, dominated by varve and rythmites, whereas the other succession of lesser thickness (10–15 m) was observed upstream of Bamni village at 3090 m asl on the right bank of the Alaknanda river (Figures 2 and 3).

In addition, an isolated, sharp, crested, morainic ridge is located near Hanuman Chatti at 2604 m asl. This was earlier reported by Khan<sup>9</sup> and Puri *et al.*<sup>10</sup>, who suggested that it represents the maximum extent of valley glaciation. However, in the absence of lateral continuity (with that of the Stage-I moraine) and geomorphic evidences of glaciation between the termination of Stage-I (at Rarang Chatti) and end moraines at Hanuman Chatti, it is difficult to ascertain its antiquity. Morphologically it is more close to Stages-II or III (sharp-crested). This is plausible considering that the morainic ridge lies proximal to a fast-cascading stream, which originates from an abandoned cirque. However, till further investigations are carried out, it would be speculative to assign its stratigraphic position.

The Stage-II lateral moraine, which is quite prominent in the basin, emanates east of Bhagirath Kharak at 3700 m asl and could be traced east of the Vasudhara where it terminates with a curvilinear ridge at 3550 m asl,



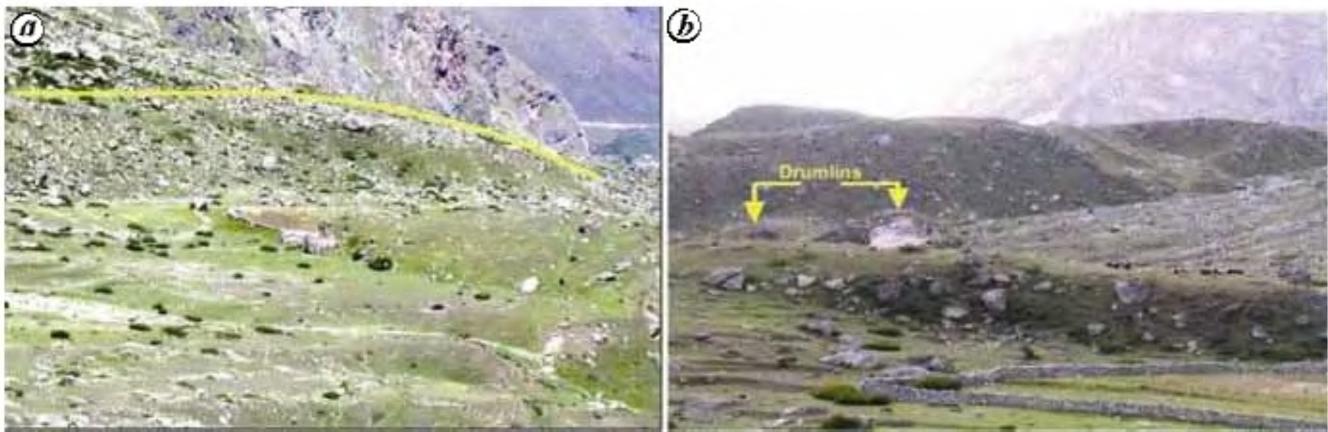
**Figure 2.** Field photograph of glacial lake deposit located on the right bank of Alaknanda river, 2 km downstream at Badrinath.



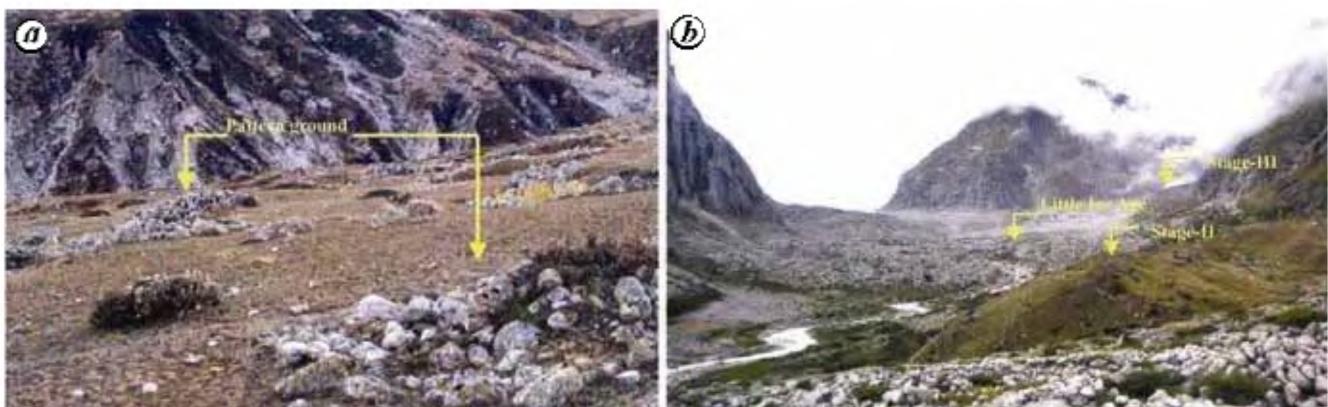
**Figure 3.** Field photograph of glacial lake deposit located on the right bank of Alaknanda river at Bamni village.

**Table 1.** Description of major and minor glacial and periglacial landforms present in the study area

Process	Landform
Glacial	Moraines, proglacial lakes, avalanche chute and fans, ice caves, arêtes horns, cirques, hanging and U-shaped valleys.
Periglacial	Outwash plains, morainic terraces, patterned ground, proglacial relict lake deposits, drumlins, talus cone, alluvial fan, solifluction lobes, debris cone and talus fans.



**Figure 4.** Curvilinear morainic ridge (a) and drumlins (b) near Vasudhara associated with Alkapuri glacial advance (Stage-II).



**Figure 5.** a, Patterend ground (stone circle) associated with Stage-II glacial advance. b, Limit of Satopanth glacial advance (Stage-III).

preceded by a prominent depression (Figure 4a). Compared to the Stage-I, the lateral moraine of Stage-II is less vegetated but relatively well preserved in the basin. Associated with this moraine are two distinct proglacial features, viz. the drumlins and patterned ground. Drumlins are observed resting on the modified lateral moraine of Stage-II (Figure 4b), whereas the patterned ground was found in the depression immediately west of the curvilinear ridge (Figure 5a). Patterned ground are formed by the sorting out of material on diurnal thermal effect and may be classified as circles, nets, polygons, steps and stripes<sup>11</sup>. They are not developed over slopes steeper than 30°. On nearly flat surfaces, circles, nets and polygons are developed, while stripes and steps are better developed on the slopes having 15° to 30° and 6° to 15° inclinations. Unsorted circles are frequently observed on the left bank of Alaknanda near Vasudhara fall and they are confined to 3500 to 3700 m asl.

The Stage-III (youngest) lateral moraine was observed 10–20 m above the modern glacier, running parallel to it. This moraine emanates from 5000 m asl in Bhagirath Kharak glacier and 4700 m asl in Satopanth glacier and terminates at 3700 m asl (few hundred metres below the

present-day snout), where it forms a broken curvilinear ridge (Figure 5b). Morphologically, Stage-III moraine is sharp-crested, loose and sparsely vegetated. A prominent depression was observed between the moraine ridge and valley wall.

Besides this, a conical heap of assorted boulders and pebbles (3–5 m in height) is observed in the vicinity of the modern snout. Morphologically, they are similar to push moraines, but lack fine sediment. Therefore, we refer to them as ablation moraines, as suggested by Sah<sup>12</sup>.

In addition to the moraines, a prominent outwash gravel terrace is preserved in this basin (near the helipad at Badrinath), which presents evidences of temporary ponding during historical time. Laterally, the outwash gravel terrace can be traced upstream near Mana village. Further west of Mana village, fluvial energy is largely utilized in vertical incision and surfacial modification of the moraines, as observed around Vasudhara.

A preliminary attempt towards chronology of glacial stages is made using optical dating technique. This method relies on the principle that during the transportation of sediment, geological luminescence (trapped charges) is reduced to a residual level (bleaching). Once the sedi-

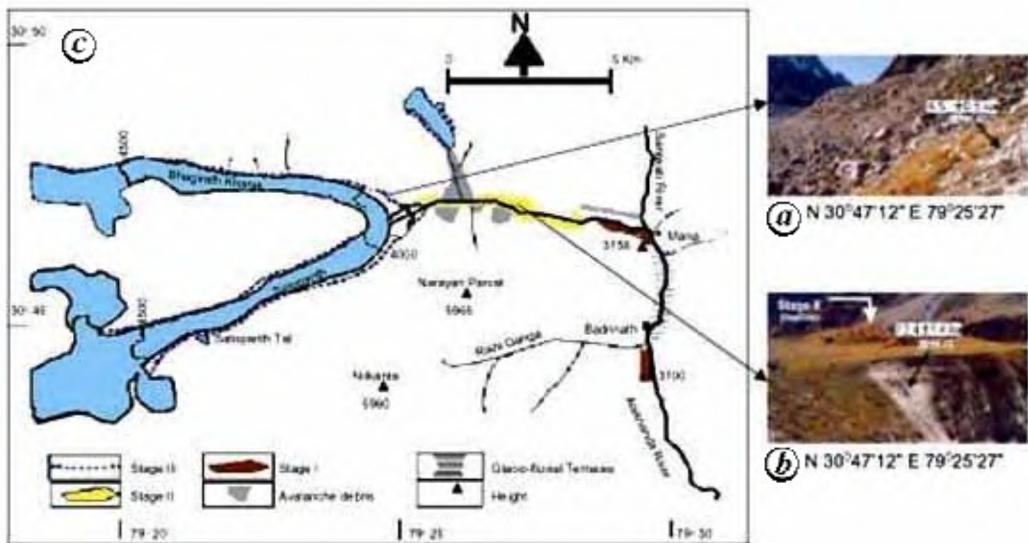


Figure 6. Map showing various stages of glacial advances and dated horizons.

ment is buried, accumulation of luminescence occurs due to the ionizing radiation arising from the ambient radioactivity. Hence the luminescence build-up in the mineral is a function of burial time and the concentration of radioactivity in the sample environment. Thus, the time elapsed since mineral grains were buried can be determined by measuring both the luminescence signal and estimating the flux of ionizing radiation to which it has been exposed since burial<sup>13</sup>. In case of moraine, bleaching of mineral grains remains a suspect because at the depositional site, the sediment will be an admixture of whole continuum of environmental conditions, e.g. basal lodgment, melt-out till, englacial and supraglacial till<sup>14</sup>. In order to minimize the uncertainty in the depositional environment, we have collected samples from well-developed lateral moraines and fluvially modified recessional moraines (Figure 6a and b). Samples were sequentially pretreated in order to extract pure quartz. Details regarding chemical extraction can be found elsewhere<sup>15</sup>.

Single aliquot regeneration (SAR) protocol of Murray and Wintle<sup>16</sup> was used on coarse-grain quartz (125–90 and 150–210  $\mu\text{m}$ ) extracted from the sample. In SAR method, estimation of palaeodose is made on single aliquots by recording its natural luminescence and then reconstructing a regenerated luminescence versus dose growth curve corrected for the sensitivity changes using a fixed test dose. Typically about 50–60 discs were measured and out of these around 10–20 satisfied the criterion of a recycling ratio of 0.90–1.10. The palaeodose for age calculations was based on a weighted mean of values in the region defined by the minimum value and the minimum value + (2  $\times$  errors).

Out of the two samples, the regenerated luminescence signal from sample Bhagirath Kharak-I (BKH-I) was weak

(low sensitivity) resulting into large scatter in regenerated dose points, poor recycling ratio and growth curves. Therefore, the sensitivity of quartz was enhanced by subjecting it to high-temperature annealing (450°C/1 min). As suggested by Thomas *et al.*<sup>17</sup>, this was done after the measurement of natural signal and first test dose. This led to marginal improvement in the quartz sensitivity, giving rise to few growth curves with adequate recycling ratio (0.9 to 1.10). However, BKH-II responded linearly to regeneration doses. In both the samples, it was observed that sensitivity of quartz is not adequate enough to provide large number of equivalent dose. This was also observed by Thomas *et al.*<sup>17</sup> for eastern Himalayan samples. In the present study the percentage of aliquots that fulfilled the criteria of SAR protocol was 15–20. Sample BKH-I gave  $4.5 \pm 0.5$  ka, whereas BKH-II was dated to  $12.4 \pm 1.4$  ka. The ages are consistent with the lateral morainic stratigraphy reconstructed in the field (Table 2).

In the study area, the terminus of three glacial advancements is well preserved in the form of terminal or ground moraines (Figure 6c). The former is represented by a degraded curvilinear ridge. Additionally, the presence of two relict proglacial lake deposits that are associated with recession of Stage-I glaciation implies that recession was pulsating because proglacial lakes are genetically related to the proximity of the valley glaciers and respond in accordance with the glacier advancement and retreat<sup>18</sup>. Absence of moraine intercalation in the relict lake succession further indicates that following the Stage-I advancement, subsequent glaciation remained above 3007 m asl which accords well with the observation made in the Kali river and Goriganga basins<sup>7,19</sup>. This is also expressed in the broad, U-shaped valley morphology which becomes V-shaped below 3000 m asl. Sah<sup>12</sup> showed development of

**Table 2.** Details of radioactivity assays, dose rate (DR), equivalent dose (De) and single aliquot regeneration (SAR) ages obtained

Sample no.	U (ppm)	Th (ppm)	K (%)	DR	De	SAR age (ka)
BKH-I	4.38 ± 0.71	5.95 ± 2.45	2.5*	3.7 ± 0.3	17 ± 1	4.5 ± 0.5
BKH-II	9.67 ± 1.42	9.97 ± 5.07	2.9 ± 0.15	5.5 ± 0.6	69 ± 3	12.4 ± 1.4

Cosmic ray dose 250 ± 50 µGy/a. Water content 10 ± 5%.

knick point at this location, which he attributed to neotectonic activity. Interestingly, the zone of contrasting valley morphology is associated with the location of the Pindari Thrust. Based on the sudden change in the course of the Alaknanda from N-S to NW-SE contrasting lithology, viz. calc silicates overriding the gneisses and quartzite, and development of deep gorge, indicates activity along the Pindari Thrust in the recent geological time. This would imply that the southern extent of valley glaciation in the basin was structurally controlled, as observed in the Kali and Goriganga basins<sup>7,19</sup>.

Termination of Stage-II moraine is well persevered as a curvilinear ridge representing the snout position at around 3550 m asl. This advancement has additionally preserved two prominent periglacial features, viz. the smooth whale-back forms – the drumlins and stony circles – the patterned ground. Drumlins are basically accretionary forms which occur behind the terminal moraines, indicating that their streamline forms are lodgment till with subsequent overriding and re-trapping by the ice and possibly relate to the rapid ablation process<sup>20</sup>. Similarly, the sorted, stony circle are formed by repeated frost heaving that brings large rocks to the surface and the repeated freeze and thaw process pushes the rocks to the sides forming sorted circles<sup>21</sup>. Such features indicate lowering of periglacial environment and have been used to reconstruct the palaeo temperature depression<sup>18</sup>. In the Higher Central Himalaya the above processes are operative above ~4000 m asl. Hence their occurrence in areas around 3500 m asl suggests significant lowering of temperature during the Stage-II glaciation.

The Stage-III lateral moraine runs parallel to the modern glacier, but is much above its influence<sup>12</sup>. The lateral moraine of this stage emerges from around 4700 m asl and terminates at around 3700 m asl, forming a degraded loop. Presence of small terminal morainic ridges and mounds associated with Stage-III indicates that the glacier could not build up large terminal morainic ridges owing to its rapid retreat. The ice retreat was probably sporadic. It is estimated that during Stage-III the glacier reached ~2 km from the present snout position, which is similar to the observation made in the adjoining Gangotri glacier<sup>22</sup>. However, a careful mapping of Stage-III moraines and comparing them with the modern counterpart can help in a realistic estimate of the reduction in glacier ice volume.

In a classical model of glaciation, each retreat should be associated with the outwash gravel terrace<sup>23</sup>. Geomor-

phological consideration and field evidences suggest that outwash terrace gravels associated with Stage-I are non-existent because the valley glacier extended south of the Badrinath basin. Compared to this, Stages-II and III glaciations terminated well above Badrinath. In view of this, the clast-supported, well-rounded outwash terrace gravels around Badrinath are equated with the Stage-II deglaciation. The youngest and less extensive Stage-III deglaciation snout was much closer to the present-day snout. Incised glacio-fluvial deposits (10–20 m) in the otherwise gently gradient valley between Stage-III terminus and Mana village, suggest that during deglaciation, high sediment discharge probably raised the thalweg between Satopanth and Mana village, which was subsequently incised by the Alaknanda river in order to equilibrate with the trunk valley gradient (Badrinath). This could be the reason for poor development of outwash terraces and deep incision of the glacio-fluvial sediments.

Luminescence age of 12 ka is obtained on the recessional moraine (Stage-II) located at around 3600 m asl and is separated from the terminus of Stage-II by a prominent depression. This would imply that during the recessional phase, there was a temporary hiatus which is also indicated by the presence of drumlins above the dated horizon (Figures 4b and 6)<sup>24</sup>. It is suggested that due to the weakening of the ISM, valley glaciers were less extensive during the Last Glacial Maximum (LGM). Hence a reasonable assumption can be made that Stage-I predates the LGM, whereas the less extensive Stage-II corresponds to the LGM and the recessional moraine represents post-glacial cooling associated with the Younger Dryas (YD). Evidence of YD has already been reported from the relict lake and speleothem deposits from the Central Himalaya and Ganga plain, suggesting temporary cooling<sup>19,25</sup>. It is likely that during this period deglaciation following Stage-II was either halted temporarily or marginally re-advanced.

Geomorphological mapping supported by TS survey indicates that the Satopanth glacier extended in the past (Stage-I) about 17 km downstream in the Alaknanda valley from the present position of snout. Similarly, extension of Stages-II and III was mapped 6.05 and 2.10 km downstream respectively.

There is increasing evidence from the Higher Central Himalaya suggesting that maximum extent of valley glaciers predate the LGM<sup>6,7,19</sup>. In view of this, the present study is not only important by way of confirming the earlier

observations, but also presents evidence for temporary hiatus during deglaciation around 12 ka, which is first of its kind from the Central Himalaya. Stage-III dated to 4.5 ka, indicating marginal re-advancement in the valley glacier. Similar advancement of lesser extent was identified in the adjoining Gangotri glacier – the Shivling Glacial Stage of Sharma and Owen<sup>6</sup>. Based on pollen study in the vicinity of Dokriani glacier<sup>26</sup>, this period was identified with significant reduction in the ISM.

Considering the above, it can be suggested that the poorly organized heap of moraines (ablation moraine) lying in the vicinity of the present-day snout appears to have been deposited during the historical time, as observed around the Mount Everest<sup>27</sup>. It can be broadly correlated with the Little Ice Age as reported from the Himalaya and other parts of the world<sup>28–30</sup>. Recent peat bog study in the Pindari Valley (Central Himalaya) indicates prevalence of extended cool and moist condition that started around 400 years ago and lasted till the end of the 19th century; it is attributed to the Little Ice age<sup>31</sup>. However, this needs to be validated by firm chronology. Until then, inferences towards their genesis and antiquity will remain speculative.

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