General Geomorphological Field Observations around Satopanth Glacier Area, Garhwal Himalaya, Uttarakhand

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Abstract: Upper Alaknanda valley from the head wall of Satopanth glacier, till village Mana houses distinct geomorphology which is full of glacical, glacio-fluvial and peri-glacial features. Starting from village Mana a distinct U-shaped valley is observed, the valley wall has a sharp contact with the glacial trough line making vertical cliffs over which there are hanging valleys from which waterfalls pour their water into the valley floor. The trough line roughly denotes first glacial advancement stage of the valley. Moving further in the valley various features like fluvial terraces are observed along the river bank concealed under thick veneers of slope wash material forming talus fans through which river Alaknanda has carved a V-shaped valley. The glacier out wash plain is filled with erratic boulders and other glaciogenic material like terminal and recessional moraines. The erosional and depositional features in this area indicate two more glacial advancements in this area. Further the valley takes sharp left turn with relatively steeper slope of 200-300 m after which snout and front of Satopanth glacier can be observed. Besides this numerous other features like lateral moraines, recessional moraines, supra-glacial moraines, ablation valleys, lateral basins, supra-glacial ponds, pro-glacial lake, lateral basin lakes, crevasses and Patterned ground etc., are observed which were formed due to various glacial and peri-glacial activities.

Key Words: *Geomorphology, Satopanth Glacier, Garhwal Himalaya*

Introduction

Study area lies in the upper Alaknanda basin in Chamoli district, Uttarakhand Himalaya. The major portion of study area falls in the Survey of India topographic map no. 53N/5, 53N/6, N/1 and is located between latitude 30°42´55´´-30°50´32´´N and longitude 79°13´55´´-79°29´40´´E (Fig.1). Satopanth glacier has five major tributary glaciers namely Luri Bamak, T1, T2, T3 and T4 glaciers, of these Luri Bamak meets the trunk glacier at the left bank whereas T1,T2, T3 and T4 meet the trunk glacier at the right bank. Satopanth glacier (SPG) and its adjoining Bhagirath Kharak (BKG) glacier are the sources of river Alaknanda and river Uttarganga respectively, both of which meet approximately 1 km downstream of Satopanth glacier just before Alkapuri, from where the river is known as Alaknanda. From Alkapuri after travelling ~8 kms River Alaknanda meets River Saraswati at Keshav Prayag near Mana village. The upper Alaknanda watershed covers an area of 234.35 km^2 out of which 70.70 and 107.22 km^2 are covered by Satopanth and Bhagirath Kharak watersheds respectively.

The E-W trending SPG and BKG are approximately 13 and 18.5 km long with an average width of 750-850 m, covering an area of ~19.0 and 31.0 km^2 respectively. The gradient of SPG (0.152) is comparatively higher than that of the BKG glacier (0.143) (Nainwal et al. 2008 & 2016). A linear ridge known as Balakun divides these two glacier trough and ends abruptly towards the eastern end near the junction of the lateral moraine of these two glaciers at Kunaling. The snouts of SPG and BKG glaciers are located at an altitude of around 3860 and 3760 m asl respectively. Both of these glaciers emerge from the eastern slopes of Chaukhamba group of peaks. The Pawegarh ridge (5288-6165 m asl) marks the northern boundary of the upper Alaknanda basin and is a water divide between Alaknanda and Saraswati catchments, Nilkanth (6596 m asl)– Chaukhamba (7138 m asl) ridge is the southern boundary which divides Alaknanda catchment from Rishiganga and Mandakini catchments. The Chaukhamba (~6288–7138 m asl) on the west, divides Alaknanda catchment from Bhagirathi catchment.

Geology

Geologically, the study area falls under Higher Himalayan Central Crystalline Zone, described as Himadri Complex. Lithology of the area is dominated by calc-silicate with sillimanite-kyanite-garnet-biotite gneiss and schist with tourmaline granite (Pegmatite and apatite veins) belonging to Pindari Formation (Valdiya, 1973, Valdiya, et al. 1999).

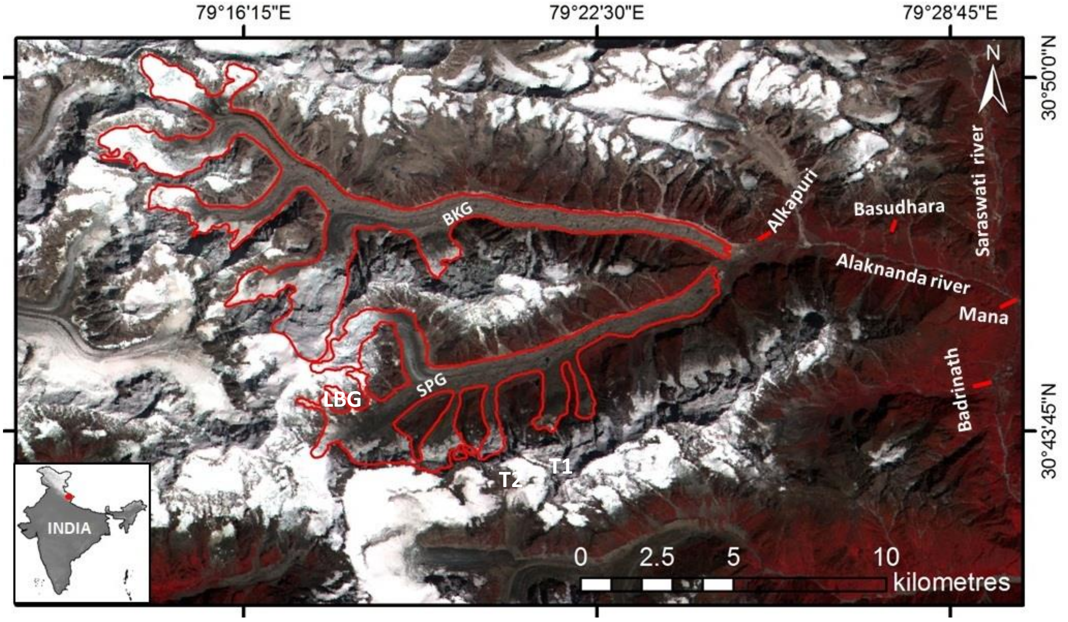

Figure 1: Satopanth (SPG) and Bhagirath Kharak (BKG) Glaciers. The red spot in the inset shows the location in India.

The Central Crystallines are separated from Calc-Zone of Chamoli by the Main Central Thrust (MCT) which passes near Helang, south of Joshimath (Fig 3.2). In the north, Central Crystallines are separated by Tethyan Sedimentary Rocks by NW-SE trending Tethyan Thrust. At Joshimath area the rocks are folded streaky psammitic gneisses and schists overlain by quartzite, mica-schist and para-gneisses from Vishnuprayag till Pandukeshwar (Heim & Gansser, 1939) belonging to Joshimath formation.

Table 1 Litho-tectonic succession of study area

Vaikrita Group	Higher	Badrinath Granite	Tourmaline Granite with Pegmatite-Apatite veins
		Pindari Formation	Calc-silicate with Siliminite-Kyanite-Garnet-Biotite Gneiss & Schist with Anatectic Granite (associated with Migmatites)
		----------------------------------Pindari Thrust----------------------------------	
		Pandukeshwar Formation	Biotite & Muscovite rich Quartzite intercalated with Schist and subordinate Gneiss
		Joshimath Formation	Streaky & Banded Gneiss, and Kyanite-Garnet rich Mica Schists
		----------------------------------Vaikrita Thrust----------------------------------	
MCT Zone		Munsyari Formation	Mylonitised Porphyritic Granites with subordinate Amphibolites, Chlorite-Sericite Schist & Limestone
--Munsyari Thrust--			
Lesser		Garhwal Group (Meta-sedimentary rocks)	

(Source Valdiya et al. 1999)

From Pandukeshwar till Hanumanchatti area the exposed rocks are massive Quartzites with intercalated Schist bands known as Pandukeshwar Quartzite belonging to Pandukeshwar formation. In this Quartzitic area Alaknanda forms steeply sloped valley. After Hanumanchatti moving towards north Gneisses and Schists with lenses of Calc-silicates are strikingly injected by tertiary Tourmaline bearing Pegmatites and granites with calcareous bands, which led to the development of Migmatites belonging to Pindari formation. These Leuco-granitic tourmaline bearing rocks are known as Badrinath Granite. Moving north from Badrinath schistose rocks of Budhi schist formation are found (Table 1). Rocks belonging to all the four formations come under Vaikrita Group (Valdiya & Goel, 1983).

Geomorphological Observations

The glacial geomorphology of upper Alaknanda valley is very interesting and can be divided into two groups, i.e., present and past glacial landforms and features. The present day glacier landforms/features include cirques, moraines, horn, arte, moraines ponds and lakes, supra-glacial channels, moulins, ablation valleys and lateral basins, while past glacial landforms/features are represented by hanging valleys, waterfalls, double U-shaped valleys, truncated spurs, dumped glacial deposits in basins and valleys, and erratic boulders etc. These features/landforms can also be classified according to the mode of action by which they are formed like erosion & deposition also depending on their location the glacial features/landforms can be classified in to glacial and peri-glacial features.

Following glacial features/landforms were observed in upper Alaknanda valley:

Moraines

One of the most important and prominent depositional features of a glaciated valley are the moraines which are formed by the accumulation of unconsolidated glacial debris (regolith, rock, sand, silt and clay) known as till. The types of moraines which were encountered in the area are as follows:

a. Lateral moraines: These are ridges of glacial debris which run parallel along the sides of a glacier (Fig. 2). The till which a glacier carries along after melting of the glacier gets deposited laterally along the margin in the form of ridges above the present level of the glacier. As they are deposited on top of the glaciers they do not encounter any postglacial erosion of the valley hence get preserved as high ridges with their top indicating the top of the glacier ice in the past. In Satopanth glacier lateral moraines of three categories were encountered i.e., active, recessional and static. Active lateral moraines are confined to the upper reaches of the glacier and associated with present day glacier movement. Its length varies from 1-3 km on the left bank (from Luri Bamak Glacier till base of Balakun peak opposite Satopanth Tal) whereas ~1 km on the right bank near Surajkund and Vishnukund area. These moraines are devoid of any vegetal or lichen growth indicating their active nature. Lateral recessional moraines in Satopanth glacier valley were not found except at one point near Alkapuri just before Bhagnyu nalla fan approximately at a height of 3650 masl. It has a length of 300-400 m with 40-50 m width and height at the ridge top ranging between 10-15 m. This recessional lateral moraine is composed of weathered semi-rounded leuco-granitic to granitic-Gneiss boulders.

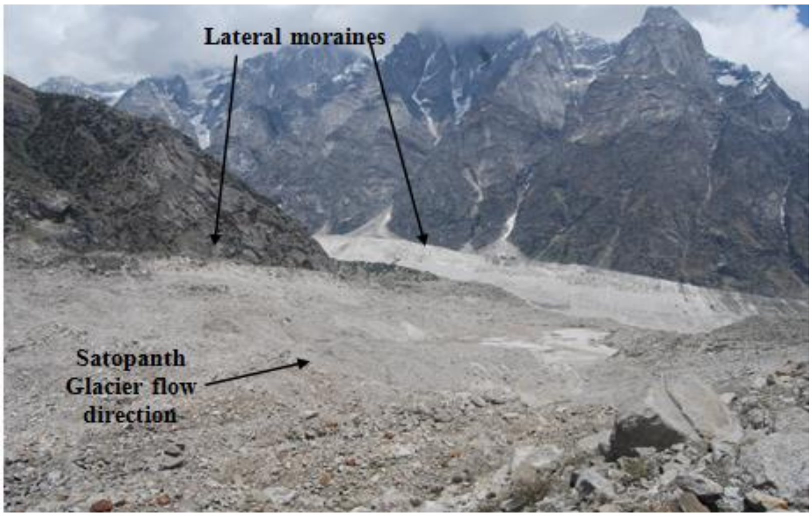

Figure 2 Lateral moraines of Satopanth and Bhagirath Kharak glaciers

The lateral static moraines which run on both sides of the glacier are the most important and apparent of above mentioned all moraines. These moraines have prominent and continuous ridge standing between the glacial valley wall and the present day glacier in the glacial trough. The right and left side lateral static moraines are ~9 km and ~6 km long respectively. Both of the moraines gradually attain height towards the upstream direction of the valley, with minimum height ~40 m near the snout and ~200-250 m near Chakrateerth and Satopanth Tal area. Both of these moraines have their steeper sides towards the glacier and the gentle and stable one towards the valley walls. The steeper sides are devoid of any vegetal growth suggesting continuous activity and mass movement of the material along the slope. The valley side which is relatively gentler possesses vegetation (Juniper and other shrubs) indicating relatively stable conditions of the slope. A number of talus cones cut through the lateral static moraines at several places especially along the left bank of the glacier whereas towards the upstream direction the lateral moraines are dissected by the tributary valley glaciers especially along the right bank of the glacier. Along the left bank at places the lateral static moraine gets vertical due to dominance of erosion and mass wasting activities at the toe which has left a sharp contact between the junction of upper dark and vegetated moraine and lower light and naked moraine, this sharp contacts acts as the trim line on the glacial trough. In the upper Alaknanda valley between snout of Satopanth glacier and village Mana former moraines and lateral basins are either completely or partially concealed under talus/scree cones and rockfall debris especially along the right bank of River Alaknanda.

b. Medial moraines: In Satopanth glacier medial moraines are confined to upper middle part of the valley which starts from the junction of Satopanth glacier with Luri Bamak glacier and can be traced till ~3 km downstream as a superficial deposit without much variation in the thickness (Fig 3).

Figure 3 Medial moraine

c. Supraglacial moraines (Debris cover): Supra-glacial moraines (Fig. 4) are created by debris accumulated on top of glacial ice. This debris can accumulate due to ice flow towards the surface in the ablation zone, melting of surface ice or from debris that falls onto the glacier due to avalanches from valley sidewalls. In Satopanth glacier the formation of ablation moraines can also be attributed to the disintegration of medial moraines due to divergent flow of the glacier (Sah, 1991).

In Satopanth glacier supra-glacial moraines are encountered in the initial ~8.3 km length between the altitudinal ranges of 3850 to 4500 m with an average width of this zone 700-750 m. The presence of supra-glacial moraines between two lateral moraines is the indicator of slow rate of movement and thickness shrinkage of a glacier without considerably affecting its snout position. In Satopanth glacier the supra-glacial moraines rest on the glacial ice in the form of mounds with gradual decrease in their size as we move towards the upstream direction of the glacier. Glacier health and behaviour can be understood by the presence of supra-glacial moraines which in case of Satopanth glacier suggest that it is under fast melting state.

d. Terminal Moraines: These are formed at the front edge of a glacier marking its maximum extent during a period of time (Fig 5). These are deposited transversely across the glacier valley below the snout of the glacier and often block the glacier melt water resulting in the formation of a pro-glacial lake. In Satopanth glacier one such moraine can be seen 350-400 m in front of the present glacier front. River Alaknanda cuts its way through this moraine by a narrow passage.

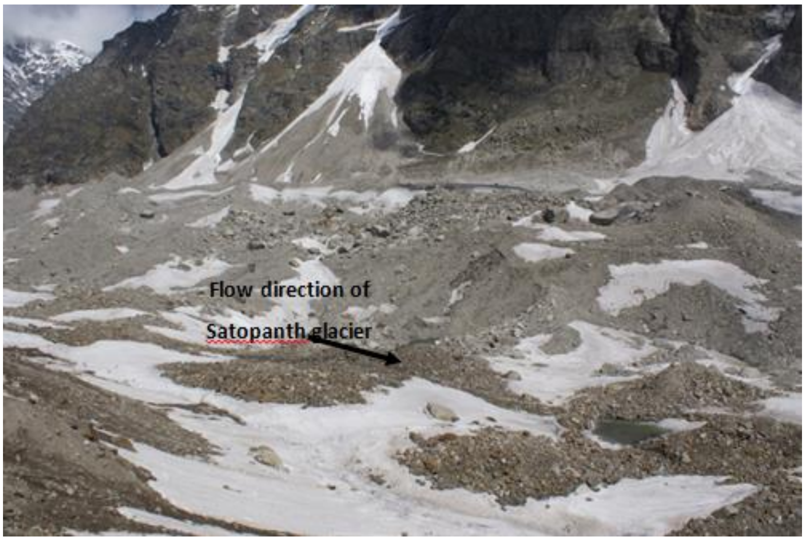

Figure 4 Supra-glacial moraine/debris cover over Satopanth glacier.

e. Recessional Moraines: These are series of small ridges running transversely behind the terminal moraine almost parallel to it. They represent temporary halts of glacial retreat. In Satopanth glacier two such moraines can be observed at 10-20 and 250 m in front of the present glacier front (Fig 5).

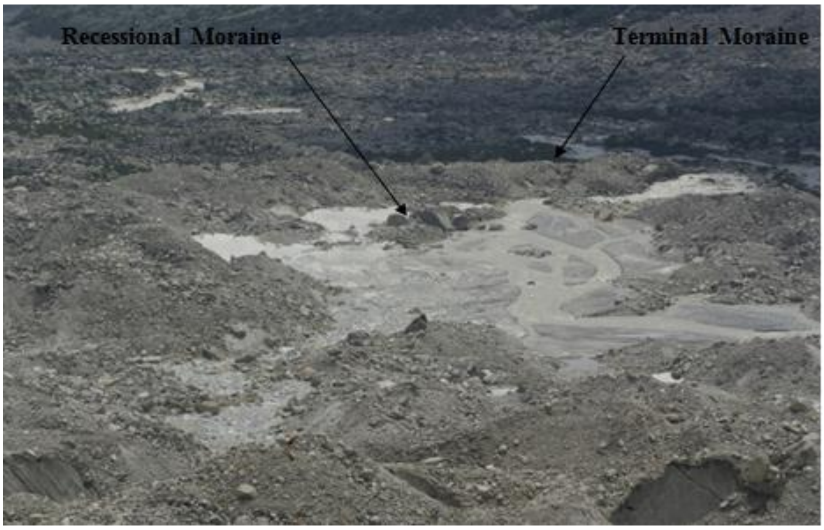

Figure 5 Terminal and recessional moraines.

Snout

The snout of the Satopanth glacier is located at an altitude of 3868 masl which is a small ice face towards the right bank of the glacier where the river emanates but along the glacier frontal terminal boundary there is a huge ice face named front (Fig 6 & 7). In case of Satopanth glacier the front is around 200-250 further ahead of its snout which is quite striking. The probable reason behind it is the glacial ice towards the left frontal margin of Satopanth glacier has melted fast due to the fluvial action by ice melt water of Bandhara waterfall that drains the significant portion of the right lateral basin of Satopanth glacier. At the front of Satopanth glacier the glacial ice exposed is well stratified representing different periods of ice accumulation.

Just ahead of the Satopanth front there is plain area half of which is composed of a small proglacial lake which is formed partially by ice melt and partially by a small diverged stream of Alaknanda River from the snout, the water in this lake is further blocked by a terminal moraine, further a stream through this lake turns and meets the main stream of River Alaknanda. River Alaknanda cuts its way through this terminal moraine by a narrow passage.

Figure 6 Snout of Satopanth Glacier (2013)

Figure 7 Satopanth Glacier Front (2014)

Ablation Valley/Lateral Basins

Ablation valleys are very narrow and long valleys formed between the glacial valley wall and lateral moraines. Formation of ablation valleys can be attributed to continuous shrinking of the valley glacier and prominence of lateral moraines followed by fluvial action by snowmelt lateral channels. At a few places these valleys get wider and are filled with lateral channels fine sediments due to this these appear like flat basins which are known as lateral basins. In Satopanth glacier Ablation valleys are present along both left and right lateral static moraines, among these the ablation valleys along the right lateral moraine are more prominent and defined. There are two lateral basins (Fig. 8) in Satopanth valley both of which are along right lateral moraine among these one is at the base of Neelkanth peak below Saudhara waterfalls which is smaller while the other one which is bigger and prominent is at Chakrateerth or Majna (older name of Chakrateerth). Chakrateerth lateral basin is approximately 1-1.25 km long and 200-250 m wide. I this lateral basin there are a few small snow melt channels which unite to form a single channel which drain its water in the lower extremity of the basin cutting through the lateral moraine in to the glacier. These channels have a minimum and maximum discharge during the dawn and dusk respectively. It appears that in Chakrateerth lateral basin once there was a lake similar to Satopanth Tal lake (Heim and Gansser, 1939) but it disappeared over a period of time as the lateral channels breached the lateral moraine, this is point is substantiated by the presence of damp, soggy and soft ground in the central part of Chakrateerth lateral basin below the valley wall.

Figure 8 Ablation basin (Chakrateerh Ground)

Lakes

There are different types of lakes and ponds which are formed in the glacial as well as peri-glacial areas of Satopanth glacier valley. The different types of Lakes/ponds which are encountered in Satopanth valley are as follows.

a. **Lateral basin ponds/lakes:** These ponds/lakes are formed when snow or ice melt water channels flowing in the lateral basin or ablation valley get blocked by the rock/debris fall, talus/scree or moraine itself. There are four such ponds/lakes in Satopanth glacial trough which are confined to right bank of the glacier. The most prominent among all the four lakes is Satopanth Tal Lake (Fig. 9.), which is a triangular lake with longest and shortest side ~275 and ~200 m respectively and a perimeter of around 750 m with approximate depth of around 20 m in the centre. This lake is situated in the lateral basin between the right lateral moraine of Satopanth glacier and left lateral moraine of T2 glacier about 35-40 m below the lateral moraine ridge top. This lake shows significant seasonal water level fluctuation (~10 m), with maximum level in the month of June and minimum during the winters. Apart from Satopanth Tal lake there are also three other small lateral basin ponds known as Chandrakund, Vishnukund (Sonkund) and Surajkund which are located upstream of Satopanth Tal between right lateral moraine of Satopanth glacier & right lateral moraine of T3 glacier, right lateral moraine of Satopanth glacier & left lateral moraine of T3 glacier and right lateral moraine of Satopanth glacier & left lateral moraine of T4 glacier respectively.

b. Supra-glacial ponds/lakes: Satopanth glacier is covered with thick to thin layer of Ablation or Supra-glacial moraines, at the places these moraines are deposited as mounds especially at the lower reaches of the ablation zone, at the steep slopes of these mounds sometimes due to the failure of the rock debris the underlying ice gets exposed and over a period of time forms a depression filled with melt water which appear as supra-glacial lakes/ponds (Fig, 10). These lakes/ponds many a times are also formed by the blockage of the moulins on the surface of the glacier which get filled with the water brought by supra-glacial or blocked sub-surface channels. There are several Supra-glacial lakes/ponds which are confined mostly over debris covered part of Satopanth glacier ie. from the confluence of Luri Bamak and Satopanth glacier till the snout of Satopanth glacier.

c. Pro-glacial Lake: These lakes are formed between front of the glacier and last recessional moraine (Fig.11). One such lake is formed near Satopanth glacier front partially by ice melt and partially by a small diverged stream of Alaknanda River from the snout, the water in this lake is further blocked by a recessional moraine.

d. Kettle ponds/lakes: These are the depressions containing water formed by melting of detached ice blocks separated from the main glacier. A couple of such Kettle ponds are formed ~250 downstream of Satopanth glacier front.

Figure 9 Satopanth Tal

Figure 10 Supra-glacial pond/lake

Crevasses

In Satopanth glacier the crevasses (Fig.12) are mainly confined to the central and upper parts of the glacier. In the upper reaches of Satopanth and its tributary glaciers like Luri Bamak, T1, T2 and T3 **transverse crevasses** are prominent as up there steep slopes suddenly get gentle causing longitudinal extension of the ice which puts extensional tensile stress parallel to the direction of flow of the glacier resulting in the formation of crevasses which stretch across the glacier transverse to the flow direction.

Transverse crevasses can easily be seen in Swargarohini region of Satopanth glacier. In the middle reaches of Satopanth glacier both **longitudinal and splashing crevasses** are can be observed. Longitudinal crevasses are formed by expansion of glacial width due to widening/bending of the valley resulting in the development of tensile stress which is perpendicular to the direction of flow of the glacier. The longitudinal crevasses are typically concave down the valley margin, forming an angle greater than 45° with the margin giving it a typical chevron shape with its apex pointing towards upstream direction. The splashing crevasses are formed as a result of shear stress at the glacier margin combined with and longitudinal compressing stress from lateral extension resulting in the cracks extending from the glacier's margin and are concaving up with respect to glacier flow, making less than 45°angle with the margin. All of these crevasses have width ranging between a few centimeters to a couple of meters and length ranging between a few metres to 250 m or more. At the centre the glacier is generally crevasse free as there is almost negligible shear from the margins.

Figure 11 Proglacial lake

Figure 12 Crevasses

Moulins or Glacial Mills

Moulins are the features which are found generally in the ablation zone of a glacier. These are well-like circular vertical shafts or holes on the glacier ice surface formed by the supra-glacial melt channels/streams (Fig.13) which erode the glacial ice and drain into these shafts and reach either the bottom of the glacier or end up in a crevasse bottom where it forms en-glacial channels. In Satopanth glacier moulins were observed in the upper ablation zone where there is relatively less or thin debris cover especially near the confluence of Satopanth glacier and its tributary Luri Bamak glacier (Fig. 14). There were three moulins which were mapped, one at the centre of Luri Bamak glacier and other two on the Satopanth trunk glacier opposite of Surajkund.

Figure13 Supra-glacial channel/stream in the upper ablation zone of SPG

Figure 14 Moulin near Surajkund area

Figure 15. Glacier table

Cryoconite Holes

Cryconite holes (Fig 16) are features formed on glacier ice or snow cover by dust, small rock particle and microbes which concentrate and settle on the bottom of these holes giving an appearance of dark spotted mass. These are formed by decrease in the albedo of the glacier due to concentration of dark particles which absorb more solar heat as compared to the surrounding clean ice. These holes were observed in the upper ablation zone of Satopanth glacier and its tributary Luri Bamak glacier where there is predominantly bare debris ice.

Figure 16 Cryoconite Holes

Glacial Trough

Satopanth glacier has a typical U-shaped glacial trough (Fig. 17) with a width ranging between 850-1200 m. The valley wall is almost vertical forming a 100-250 m high cliff from the trough line till the ablation valley/lateral basin in the lower reaches, which decreases in height to as low as to 50 m moving towards upstream direction of the valley. These vertical cliffs have numerous hanging valleys above them from which several waterfalls (Fig. 18) drain down especially along the right bank of the glacier till Chakrateerth. These waterfalls are fed by the melt water emanating from the cirques above the hanging valleys. The slope of Satopanth glacier rises very sharply in its headwall region. The satellite images also reveal very high and steep head and lateral walls along large ice-free vertical regions, which indicate that unlike other major glaciers, Satopanth glacier is dominantly fed by avalanches, which is also supported by the fact that the large area of Satopanth glacier is covered with debris (Banerjee and Shankar, 2013). A number of talus/scree fans and avalanche fans (Fig. 21) can be seen on the glacial trough walls on both banks of the glaciers which generally rest over static lateral moraines and ablation valley directly or on the lateral basins.

Figure 17 Typical U-shaped valley (looking downstream towards village Mana from Vsudhara area). Note the glacier Trough line is clearly visible.

Figure 18 View of Saudhara waterfalls. Note numerous streams emanating from hanging valley form waterfalls at the sharp contact of glacial trough with steep valley the wall

Cirques

Cirques (Fig. 19) are bowl shaped valleys s formed by glacial erosion. These are surrounded from three sides by cliffs of which the highest one is known as headwall. The fourth side of the cirque is open the end of which is known as the lip or threshold from which the glacier flows down from the cirque. In Satopanth glacier the cirques are mostly confined to the periphery with the ones on the right periphery face north and have their lip/threshold quite close to the valley walls at an average altitude of 4500-4600 masl where as the ones which face towards the south have their lip/threshold at an altitude 5300-5400 masl which confirms the obvious solar insolation effect. There are total 17 cirques which were mapped around Satopanth glacier out of which 5 were inactive. The basin ridges get typical jagged-knife appearance arête and horned peaks formed by the head ward erosion of cirque head walls.

At the higher reaches of the Satopanth valley in upstream direction, the glacial trough line loses its sharp contact with the valley slope and forms steeply sloping glacier due to bed erosion done by cirques and side glaciers. In the lower reaches of the Satopanth valley glacial stairway/steps are developed before the contact with the main glacial trough line.

Figure 19 Cirque at Swargarohini Satopanth glacier

Rock Glaciers

Rock glaciers (Fig.20) are noticeable geomorphological landforms in a glacial valley. Rockglaciers were often thought to be a form of debris-covered glaciers, which led to the term 'rock glaciers (Kaab, 2007). These are composed either of angular rocky debris frozen in interstitial ice (peri-glacial) or glaciers which have ice core draped by a thick layer of debris (glacial). These extend outward and down slope from glaciers or talus and debris cones. In Satopanth glacier valley two rock glaciers were observed both which are ice core type (glacial) and are confined to the right bank of the glacier. The first one is ~500 m in length and is situated near Satopanth Tal between T2 and T3 glaciers and forms a small hanging valley with a debris chute ending in a talus cone in the lateral basin of Satopanth Tal. The second one is ~300 m just adjacent to the first one along the right bank of T3 glacier.. The absence of any vegetation and lichen growth indicates that the rock glacier is under slow movement. Both of these rock glaciers have lie between altitudes of 4500-4700 masl.

Figure 20 View of a Rock Glacier near Satopanth Tal between T2 & T3 glaciers

Erratic Boulders

These are rocks and boulders which are contrastic to the native area in terms of size and composition. In Satopanth valley erratic boulders of Leuco-Granite, Migmatite/Gneiss can be observed around 1 km downstream of the glacier snout. These boulders are apparently remnants of the end moraine deposits of the past with its finer matrix washed out by erosion done by glacial melt water and precipitation.

Peri-glacial Features

In the upper reaches of Alaknanda valley various peri-glacial features like patterned ground, polygons, talus cones and fluvial deposits of past and present peri-glacial environment are found.

Talus / Scree Cones

In Satopanth glacier valley accumulation of numerous talus and scree cones (Fig. 21) at the base of glacial trough is quite common. These are deposited by mass wasting and avalanching activities (Fig. 22) during the summer/monsoons and the winter seasons respectively. The boulders and rocks fragments in these cones are mostly devoid of any vegetation and lichen cover confirming

their activeness. These cones show maximum density at the toe of South facing slopes and at places dissect through the lateral moraines.

These are formed due to solar insolation as there is rapid and considerable variation in diurnal temperature causing frequent freezing and thawing of water in the rock joints and cervices which increases frost action manifold times as compared to the north facing slopes where this process is very gradual.

Patterned Ground

In peri-glacial regions distinct, natural geometric pattern formed by ground material due to freezing and thawing of the soil is known as patterned ground (Fig. 23). In Satopanth valley these features are found at height >3500 masl where seasonal frost, freezing and thawing are quite common. Formation of these features can be attributed to permafrost or seasonal frost conditions in which due to repeated freezing and thawing the larger stones are forced up towards the surface by the groundwater (frost heaving) and smaller stones settle beneath the larger stones by outward flow. In water-saturated areas the finer sediments have a greater ability to expand (heave) and contract as freezing and thawing occur, resulting in development of lateral forces which stack up larger stones into clusters forming different shapes like polygons (Fig 24), circles, and stripes of patterned ground (Easterbrook, Don J. 1999).

Figure 21 View of Talus cones near Laxmivan area.

Circles are of two types sorted and unsorted, sorted circles have a circular stone boundary with finer sediments in the centre where as unsorted circles have fine sediments in centre surrounded by circular vegetation margin. In Satopanth valley circles are found ~4 Km downstream of the snout on the left bank between Bhagnyu nalla and Vasudhara on terraces where continuous moisture available from the mist generated by the Vasudhara falls. These are generally of unsorted type with ~0.5-1.0 m diameter as small humps with ~0.5 m height in the centre. They are poorly sorted because of high diurnal and seasonal temperature variability. At places where the slope gets steeper (10-20°) these circles get elongated and stretched forming stone strips of 2-3 m length. Polygons are formed due to frost heaving due to which polygonal rings of raised stones are formed. These polygonal rings can be observed in flat Chakrateerth ground lateral basin ~5-6 km up stream of the glacier snout on the left bank an altitude of ~4200-4300 masl. These are unsorted type with very small stone size having ~0.5-1.0 m diameter and 30-50 cm height in the centre and devoid of any border stone with shallow soil border indicating frequent frost cracking and sorting.

Figure 22 Avalanche fan below Balakun peak

Fluvial Activity

River Alaknanda emanates from the snout of Satopanth glacier after travelling ~600 m and crossing the terminal moraine there is a steep drop of 300-400 m after which it meets River Uttar Ganga which emanates neighbouring Bhagirath Kharak Glacier, from this point fluvial action becomes dominant. The valley width is ~800-1000 m and glacial trough line is 300-400 m high from the deepest part of the valley. The glacier trough which is filled by morainic deposits of the past is now mostly covered by recent talus material with a few exposures of older morainic deposits.

Figure 23. Patterened ground near Vasudhada Falls

River Alaknanda has carved a V-shaped valley on these talus covered morainic deposits by fluvial action, the evidence of which can be observed between Bhagnyu nalla fan and Vasudhara falls. In this area two to three distinct levels of fluvial erosional terraces can be observed. River Alaknanda flows 30-40 meters below the lowest river terrace. The uppermost terraces are either totally or partially concealed under talus/scree deposits. These deposits at places over the flat terraces are responsible for the formation of patterned ground due to freezing and thawing action. Above the topmost terrace the valley wall gets very steep with trough line 100-200 m above it making steep escarpment. From the trough line a number of waterfalls originating from cirques and snow covered slopes, some of which are as high as 125 m fall drain out in the valley. Between Alkapuri and Vasudhara falls on the left bank of the valley there is remnant of an old recessional lateral moraine whose remaining part has been eroded by a massive fluvio-glacial fan made by Bhagnyu Nalla. An episode of cloud burst took place in this nalla on 11th August 2007 which caused excessive accumulation of sediment in the channel. The large amount of water along with sediment load picked up other loose sediments enroute and moved towards Alaknanda River dammed the Alaknanda valley. After just a few hours damming was breached and devastated many structures in the downstream areas such as Keshavprayag suspension bridge near Village Mana. This incidence substantiates the dominant fluvial action in the lower reaches of Satopanth valley.

Figure 24. Polygons at Chakrateerth ground

Results and discussion

From observations in Satopanth glacier, upper Alaknanda valley till village Mana a distinct glacial trough was observed right from Mana till Swargarohini. The valley wall makes a vertical cliff between the trough line and the lateral moraine top, lateral basin or in the lower reaches flat terraces of past morainic deposits concealed under thick talus/debris cone cover. The height of these cliffs in the lower reaches (Mana-Vasudhara area) is ~300 m above the valley floor, in the snout area this height is around 200 m which decreases to 50 m as we move in the upstream direction of Satopanth Tal. This trough line roughly denotes the maximum height of the glacier ice in the past and represents the first glacial advance stage ie. Alaknanda (stage-I) (Nainwal et.al, 2007) (Fig. 4.17). Further depositional and erosional features observed between Satopanth glacier snout and village Mana indicate two more major glacial advances in the valley which represent Alkapuri (Stage-II) and Satopanth (Stage-III) (Nainwal et al. 2007) The evidences of Alkapuri (Stage-II) can be traced just before Bhagnyu Nalla fan where a recessional lateral moraine of ~300 m length can be observed, a few traces of this moraines can be observed after Bhagnyu nalla fan till Vasudhara. The evidence of the youngest Satopanth (Stage-III) is the most prominent and can be seen as lateral morainic ridges running along the glacier which are ~20-30 m above it and can be traced a few hundred metres below the present snout with the maximum reach at the left side of the glacial trough about 500 m before Alkapuri.

The snout (right frontal margin) and left frontal margin of Satopanth glacier shows contrasting recession as compared to eachother. This fast melting in the right margin was due to the fluvial action by ice melt water of Bandhara waterfall that drains the significant portion of the right lateral basin of Satopanth glacier (Nainwal et al. 2016). Also just below the recent terminal moraine of Satopanth glacier the valley slope gets quite steep for the next 200-300 m which is also suspected to have contributed in the faster rate of recession of Satopanth glacier in the recent times as compared to the neighbouring Bhagirath Kharak glacier which did not show such rate of recession.

The presence of wide lateral basins which are confined along the right bank with absence of such basins on the left bank indicates that in Satopanth valley the glacial ice is thrusting towards the left bank of the glacier trough also thrusting of glacial ice towards northeast near the snout and also by the orientation of recessional lateral moraine of youngest (Alkapuri Stage-III) substantiates the fact that the glacier had carved the Satopanth valley along the north-east strike of the bed rock along the left bank as the bed rocks are dipping in the north west direction. A number of hanging valleys and waterfalls are formed in Satopanth glacial trough due to its contiuous shrinkage (Fig. 4.18). On the bank of the glacial trough between lateral moraine and valley walls, lateral valleys were formed some of them especially in the right bank are quite wide. At a few places these lateral valleys were blocked by the debris brought by small tributary valley glaciers, rockfalls and talus deposits which led to the formation of lateral basins. These lateral basins were gradually filled by water and sediments brought by melt water channels resulting in the formation of ponds/lakes like Satopanth Tal, Chandrakund, Vishnukund (Sonkund) & Suryakund whereas at places where the debris blockade was breached by water or other activities or the melt water of lateral channels was not sufficient to get collected, were covered with sediments. On these sediments filled lateral basins distinct peri-glacial features called patterned grounds were developed due to prevailing conditions like frost heaving, freezing and thawing etc. Under these conditions the patterned grounds of circles, polygons are formed on the flat surface whereas strips on the surfaces which are inclined (10-20°).

Various morainic deposits like lateral recessional moraines & terminal moraines near Laxmivan-Vasudhara area and lateral static moraines on both sides of Satopanth glacier are the evidences of retreating trend of the past whereas outwash boulders, erractic boulders, a couple of recessional moraines and terminal static moraines near the present snout indicate the present retreating phase of Satopanth glacier. The shrunk and dry cirques and hanging ice falls are the indicators of receding snow line. The presence of debris and talus cones in the lateral valleys above the snout of the glacier and small patches of older morainic deposits exposed in between the thick debris and talus deposits downstream of the glacier snout show increase in mass wasting activities due to increase in relief due to glacial/ cirque ice vacation and permanent snow line recession which exposed the rocks on steep sloped to frost action.

In the lower reaches of the U-shaped glacier trough especially after Laxmivan River Alaknanda shows valley deepening and carves V-shaped valley through remnant of former morainic deposits covered by thick talus and debris deposits indicating dominance of fluvial action. The fluvial action dominance in the lower reaches is also shown by a massive fluvio-glacial fan made by tributary Bhagnyu Nalla which meets River Alaknanda on the left bank just after Laxmivan.

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