Chicory is being used as vegetable, coffee blend, metabolite of medicinal and cosmetic value, viz. esculin and esculetin[24,25] and as hepatoprotective agents[26]. This has led to large-scale cultivation of this crop and there is interest to genetically engineer them to obtain higher yields and for newer potentials. Male sterile lines of chicory have been obtained by incorporating barnase gene[27].

The present study led to floral induction in chicory plants. These plants, which would otherwise flower biennially, can be induced to flower precociously for studies on *in vitro* pollination and seed development (Figure 5 *g*). *In vitro* obtained seeds from both transformed and untransformed plants were found to be viable on testing them for their germination efficiencies on MS basal medium (Figure 5 *h*).

This crop being amenable to genetic manipulation would be the crop of choice for genetic manipulation. The information already generated in terms of available transformation protocols, *in vitro* morphogenesis, including flowering and seed set will make the target of genetic transformation for crop improvement. In future this approach would enhance the potential of this crop for economic benefits.

1. Petit, A., Beraloff, A. and Tempe, J., *J. Mol. Genet.*, 1986, **202**, 388–393.
2. Chilton, M. D., Tepfer, D., Petit, A., Casse-Dalbert, F. and Tempe, J., *Nature*, 1982, **295**, 432–434.
3. Tepfer, D., *Cell*, 1984, **37**, 959–967.
4. Ooms, G., Bossen, M. E., Burrell, M. M. and Karp, A., *Potato Res.*, 1986, **29**, 367–369.
5. *Wealth of India* (revised), Council of Scientific and Industrial Research, 1992, vol. 3, pp. 161–169.
6. Bais, H. P., Sudha, G. and Ravishankar, G. A., *J. Plant Growth Regul.*, 2000 (in press).
7. Murashige, M. and Skoog, T., *Physiol. Plant.*, 1962, **15**, 473–497.
8. Vereliet, G., Holsters, M., Teuchey, H., van Montagu, M. and Schell, J., *J. Gen. Virol.*, 1975, **26**, 33–48.
9. Dellaporta, S. L., Wood, J. and Hicks, J. B., *Plant Mol. Biol. Rep.*, 1983, **1**, 19–21.
10. Hamill, J. D., Rounsley, S., Spencer, A., Todd, G. and Rhodes, M. J. C., *Plant Cell Rep.*, 1991, **21**, 221–224.
11. Chi, C. L. and Pua, E. C., *Plant Sci.*, 1989, **64**, 243–250.
12. Sevon, N., Drager, B., Hiltunan, R. and Oksmann-Caldenty, K. M., *Plant Cell Rep.*, 1997, **16**, 605–611.
13. Kumar, V., Jones, B. and Davey, M. R., *Plant Cell Rep.*, 1991, **10**, 135–138.
14. Morgan, A. J., Cox, P., Turner, D. A., Peel, E., Davey, M. R., Gartland, K. M. A. and Mulligan, B. J., *Plant Sci.*, 1987, **49**, 37–49.
15. Rech, R. L., Golds, T. J., Hammatt, N., Mulligan, B. J. and Davey, M. R., *J. Exp. Bot.*, 1988, **39**, 1275–1285.
16. Bais, H. P., Sudha, G. and Ravishankar, G. A., *Planta*, 2000 (communicated).
17. Gerats, A. G. M., Keye, C., Collins, C. and Malmburg, R. L., *Plant. Physiol.*, 1988, **86**, 390–393.
18. Fierer, R. P., Mignon, G. and Litvay, J. D., *Science*, 1984, **223**, 1433–1435.
19. Meijer, E. G. and Simmonds, J., *J. Exp. Bot.*, 1988, **39**, 787–794.
20. Torrigiani, P., Altamura, M. M., Pasqua, G., Monacelli, B., Serafini-Fracassini, D. and Bagni, N., *Physiol. Plant.*, 1987, **70**, 453–460.
21. Tanguy, J. M., Tepfer, D., Paynot, M., Burtin, D., Heisler, L. and Martin, C., *Plant Physiol.*, 1990, **92**, 912–918.
22. Bais, H. P., Madhusudan, R., Bhagyalakshmi, N., Rajasekaran, T., Ramesh B. and Ravishankar G. A., *Acta Physiol. Planta*, 2000, **22**, 151–158.
23. Limami, M. D., Sun, Li-Yan, Douat, S., Helgeson, J. and Tepfer, D., *Plant Physiol.*, 1998, **118**, 543–550.
24. Bais, H. P., George, J. and Ravishankar, G. A., *J. Plant Growth Regul.*, 1999, **18**, 33–37.
25. Bais, H. P., Sudha, G. and Ravishankar, G. A., *J. Plant Growth Regul.*, 1999, **18**, 159–165.
26. Zafar, R. and Mujahid Ali, S., *J. Ethanopharmacol.*, 1998, **21**, 227–231.
27. Zoden, B., Notification number C/NL/94/25, 1998.

ACKNOWLEDGEMENTS. HPB gratefully acknowledges CSIR (New Delhi) for the award of Senior Research Fellowship. This work was supported by a research grant from Department of Biotechnology, Government of India, New Delhi.

Received 28 June 2000; revised accepted 27 September 2000

Geomorphological evidences of retreat of the Gangotri glacier and its characteristics

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The Gangotri glacier which has the 258.56 sq km of glacierized area is receding as evidenced by various geomorphological features and morphometry parametric. Because of subsidence and the fast degenerating nature of the glacier, middle part of ablation zone is full of supraglacial lakes. The study shows that retreat was much slower before, compared to what was after 1971. Series of hummocky moraines indicate a faster retreat of the ice.

THE Gangotri glacier is one of the largest Himalayan glaciers, which is about 30.20 km long[1] with its width varying from 0.5 to 2.5 km. It is a valley-type glacier, situated in the Uttarkashi district of Garhwal Himalaya, Uttaranchal (Figure 1) and it flows to NW direction. This glacier is bound between 30°43′22″–30°55′49″ (lat.) and 79°4′41″–79°16′34″ (long.), extending in height from 4120 to 7000 m.a.s.l. This area is situated north of the Main Central Thrust (MCT) and comprises bed rocks of

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granites, garnet mica schist, quartz biotite schist, kyanite schist, augen gneiss and banded augen gneiss[2]. The southwest Indian monsoon with an average annual precipitation of 1550 mm (ref. 3) influences the climate of the area. The microclimate of this region may be affected by both the valley aspect and altitude. The broadleaf thick forests are rare in this valley, upstream to Harsil (2400 m.a.s.l.), may be due to the sharp turn of the valley lying at right angles to the advancing monsoon front direction and consequently a decrease in rainfall. Here the arid element Himalayan cedar (*Cedrus deodara*) dominates the vegetated slopes up to timberline. The tree which reaches to the highest elevation of about 4100 m.a.s.l. near Bhojbasa is Indian birch, bhojpatra (*Betula utilis*).

This glacier comprises three main tributaries, namely Raktvarn (15.90 km), Chaturangi (including Kalandini bamak) (22.45 km) and Kirti (11.05 km) and more than 18 other tributary glaciers are almost transverse to subtransverse (Figure 2 and Table 1). The Raktvarn system contains 7 tributary glaciers; among them Thelu, Swetvarn, Nilambar and Pilapani are important. Similarly the Seeta, Suralaya and Vasuki are the major tributaries which make up the Chaturangi system, while the Kirti system comprises only three tributary glaciers. Besides these three major tributary systems, some other tributary glaciers of this area are directly draining into Gangotri glacier; among them Swachand, Miandi, Sumeru and Ghanohim are important. Four other glaciers, which are directly draining into the river Bhagirathi, are Maitri, Meru, Bhrigupanth and Manda. The total glacierized area of the catchment is 258.56 sq km, out of which the Gangotri system comprises 109.03 sq km, followed by Chaturangi (72.91 sq km), Raktvarn (45.34 sq km) and Kirti (31.28 sq km). The remaining four glaciers contain 29.41 sq km of glacierized area; among them maximum contribution is from Bhirgupanth glacier (14.95 sq km). The gradient of Gangotri glacier is lowest (0.045), followed by Chaturangi and Raktvarn (0.146 and 0.210 respectively), while Kirti glacier has the highest gradient, viz. 0.317.

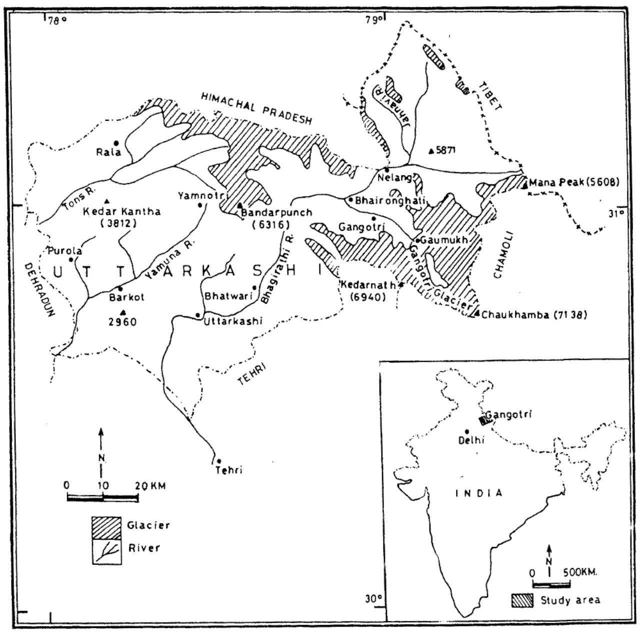

Figure 1. Location map of the study area.

The present landforms are results of polycyclic endogenic and exogenic processes operating at varying intensities through time. Erosional and depositional glacial–periglacial features are well developed all around the study area. The important depositional features are talus cones, snow-avalanche fans, snow-bridges, dead ice mounds, debris deposited by terminal, lateral, media, ground and surface moraines, boulders and bogs. The erosional features are U-shaped valley, truncated spurs with shorn-off faces, aretes, horns, pyramidal and conical peaks, serrated crests of ridges, cirques, glacial troughs, cols, smooth rock walls, steep head walls, crags and tails, rock steps in the longitudinal profiles at the junction of tributaries, waterfalls, rock basins, gullies and glacial lakes. All along the Gangotri glacier, several longitudinal and transverse crevasses were formed along which ice blocks have broken down. The ablation zone of the Gangotri glacier is covered by a thick pile of supraglacial moraines and is characterized by several serrac ice sections, melting into pools of supraglacial lakes. Because of subsidence and fast degenerating nature of the glacier, the middle part of it is full of supraglacial lakes.

A number of hanging valleys and prominent peaks form prominent features of this glacier. In this part of higher Himalaya, glacial melt-water dominates the fluvial system. In this valley, mass wastings is common all over the area and is initiated by heavy monsoon rains and active fluvial incision along the lower steep valley slopes[4]. Low frequency, high magnitude events such as earthquake-induced mass wastings are also important in the landscape evolution of this area. The total ice cover is approximately 200 km^2 and has about 20 km^3 of ice in volume[5].

A quantitive morphological analysis (morphometric) of the glaciers in this area is being attempted in this paper, in order to evaluate the evidence for retreat in the glacier. Very little literature is available regarding glacier morphometry. Since the classic work of Doornkamp and King[6], Prasad has made an attempt to study the glacier morphology[7]. Various parameters have been measured and calculated from the available toposheets and satellite geocoded data (IRS 1D, 1999). Various parameters are given in Table 2.

The general geomorphic evidence[8] suggests that an advancing glacier has a lobate front, viz. possesses a wider snout. On the other hand, a retreating glacier is less wide, viz. has a low width/length ratio. Therefore, these two parameters are important indicators of retreat of glaciers. The main glacier in this area is Gangotri. This glacier is assumed to be static, and a comparison is being made with other glaciers in this area. The width of snout of the Gangotri is 1.50, and only two tributary glaciers Swachand 1.55 and Sumeru 1.25, have wider snouts. Therefore, all other glaciers appear to be receding in comparison to Gangotri. The W/L ratios (shape) of the glaciers give some clue regarding the recession. If we assume Gangotri glacier as static, the values for Sumeru, Swachand, Ghanohim and Kirti I and II are higher and therefore, it appears that these glaciers are in the process of receding. However, all these glaciers are very small, except Sumeru and Swachand, and their values may not be conclusive indicators.

The Bhagirathi River originates at the snout known as Gaumukh (4120 m.a.s.l.) of the glacier located at the northern most end of the glacier[9]. Subterranean channels also feed the Bhagirathi at Gaumukh, below the glacier[10]. In the toposheet no. 53N/1 of Survey of India of 1962, Meru glacier also drains into the Gangotri glacier just before its snout, but at present due to the retreat of the glacier, it is meeting the Bhagirathi River downstream to

Figure 2. Geomorphological map of the Gangotri area.

the snout. At present the snout of the Meru glacier is at 4600 m.a.s.l., having retreated by 1.75 km. The total area vacated by the glacier during this period is 1.15 sq km. Prior to 1971, Chaturangi glacier also joined Gangotri glacier[11], but has since retreated by over 250 m from 1971 to 1999.

The Gangotri glacier in the past had extended up to the Sukhi, below Jhala (40.5 km downstream of Gaumukh) in Bhagirathi valley, as indicated by the remanents of moraine (Figure 3) at an altitude of about 2300 m.a.s.l. (refs 12, 13). This is the oldest terminal moraine of this glacier and its position probably represents the position of the snout during Pleistocene. This resulted in the expansion of the glacierized area in the form of a long valley glacier system covering a minimum area of 685 sq km, during Bhagirathi glacial stage (10^5 years ago)[14]. The most extensive landform, either in the form of the relicts of Pleistocene or the present glacial deposition in various forms is frequently encountered in this valley. There are three distinct forms of such deposits, viz. lateral, medial and terminal moraines. At present one can see the remanents of lateral moraines on both sides of the valley up to Gangotri (3000 m), 18 km from Gaumukh. The lateral morainic terraces are well-preserved up to Bhujgari (3600 m) 7 km downstream of Gaumukh. During the early part of its history, the glacier extended up to the Bhujgari ridge as large dimensions of the ridge indicate the existence of the snout at this level for a considerable time. The presence of old high moraine (4092 m) indicates the height to which this glacier had once risen. It appears that, there were five stages of the lateral moraine deposition between the present position of the snout and the Tapoban (4290 m). These lateral moraines are equivalent to the Shivling glacial advance (10^4 to 10^3 years ago) and Bhujbasa advance (10^2 years ago) of Sharma and Owen[14]. They are similar to Ghulkin-type glacier descried by Owen and Derbyshire[15] in the Karakoram mountains. The older lateral moraines are well stabilized, with vegetational growth over them. Between Gaumukh and Bhojbasa, there are a number of terminal morainic ridges and mounds of small dimensions, and it is probable that the glacier had not been able to build up its large terminal

Table 1. Physiographic position and trend of the glaciers

Name of glacier	Latitude (N)	Longitude (E)	Trend
Details of glaciers or bamaks present in the catchment of Gangotri glacier			
Gangotri	30°43′22″–30°55′49″	79°4′41″–79°16′34″	SE-NW
Raktvarn and its tributary glaciers/bamaks (TG)			
Raktvarn	31°0′20″–30°56′20″	79°11′30″–79°7′34″	N30°E-S30°W and N68°E-S68°W
Thelu	30°58′25″–30°56′57″	79°5′20″–79°6′6″	N18°W-S18°E
Swetvarn	30°59′28″–30°56′58″	79°6′–79°8′	N17°W-S17°E
I TG of Raktvarn	31°0′13″–30°57′10″	79°8′26″–79°9′4″	N23°W-S23°E
II TG of Raktvarn	30°59′10″–30°57′50″	79°9′36″–79°10′10″	N38°W-S38°E
Nilambar	30°54′27″–30°58′10″	79°11′8″–79°10′42′	N-S and NE-SW
III TG of Raktvarn	30°57′23″–30°57′10″	79°12′40″–79°10′51″	N54°E-S54°W
Pilapani	30°57′26″–30°57′	79°12′50″–79°10′33″	N50°E-S50°W and S70°E-N70°W
Chaturangi and its tributary glaciers/bamaks (TG)			
Chaturangi	30°54′8″–30°54′28″	79°15′19″–79°6′18″	E-W
I TG of Chaturangi	30°56′41″–30°54′30″	79°13′27″–79°12′49″	N30°W-S30°E and N37°E-S37°W
Seeta	30°52′26″–30°54′28″	79°16′34″–79°6′18″	S31°E-N31°W
Suralaya	30°50′36″–30°53′55″	79°15′–79°13′	S72°E-N72°W and N28°W-S28°E
II TG of Chaturangi	30°51′5″–30°54′3″	79°9′40″–79°11′38″	W-E and S-N
Vasuki	30°52′18″–30°54′28″	79 °8′26″–79°9′47″	S-N
Bhagirath Parvat I	31°0′20″–30°56′20″	79°8′–79°6′34″	E-W
Bhagirath Parvat II	3°58′25″–30°56′57″	79°8′26″–79°7′25″	E-W
Bhagirath Parvat III	30°59′28″–30°56′58″	79°10′–79°8′8″	NEE-SWW
Bhagirath Parvat IV	31°0′13″–30°57′10″	79°10′47″–79°9′28″	NE-SW
Swachand	30°59′10″–30°57′50″	79°10′38″–79°14′32″	E-W and N60°E-S60°W
Miandi	30°54′27″–30°58′10″	79°13′ 8″–79°14″	N25°E-S25°W
Sumeru	30°57′23″–30°57′10″	79°8′–79°9′40″	S-N to S60°W-N60°E
Ghanohim	30°57′26″–30°57′	79°5′19″–79°7′15″	S40°W-N40°E
Kirti and its tributary glaciers/bamaks (TG)			
Kirti	30°49′10″–30°52′	79°1′22′–79°5′32″	S20°E-N20°W and S53°W-N53°E
I TG of Kirti	30°48′30″–30°51′2″	79°4′40′–79°4′22″	S9°E-N9°W
II TG of Kirti	30°47′53″–30°50′	79°4′7′–79°2′50″	S28°E–N28°W
III TG of Kirti	30°52′18″–30°50′20″	79°0′9′–79°2′30″	N53°W-S53°E
Details of bamaks or glaciers present in the study area and directly draining into Bhagirathi river			
Maitri	31°–30°3′42″	79°5′–79°4′	N58°E-S58°W
Meru	30°51′7″–30°55′16″	79°2′21′–79°4′37″	S14°W-N14°E
Bhrigupanth	30°52′37″–30°57′15″	79°1′24′–79°2′25″	S37°W-N37°E
Manda	30°57′3″–30°58′7″	79°–79°1′43″	S25°W-N25°E

moraine owing to its rapid retreat since 1780 (Bhujbasa advance stage). There is no break in the continuity between the oldest and the youngest terminal moraines, which indicates that the retreat has been gradual (Figure 4). The lateral moraines from Jhala to Tapoban are diachronous[16] in nature, above Chirbasa; they are less eroded and have a sparse forest cover than those down the valley suggesting that, above Chirbasa they are younger. This, in turn, suggests that ice retreat was probably sporadic, an initial retreat progressed as far as Gangotri, where the ice had remained for a relatively long time. The medial moraines are present only on the tributary glaciers of the main Gangotri glacier.

Large morainic ridges and smaller inset morainic ridges provide evidence for a major glaciation. Glacial retreat and the redeposition of moraines have led to the formation of impressive river terraces and paraglacial fans. The lateral moraines form a series of discontinuous ablation valleys which are filled with scree and debris flow, and lacustrine triangular plain is present at an altitude of 4880 and 4292 m.a.s.l. The Tapoban (Figure 5) comprises lacustrine silts capped by 0.5 to 1.0 m thick fluvial silt and sands[14]. This flat area is bounded to the east by the left lateral moraines of the Gangotri glacier, to the west by the valley walls and to the north by the right side lateral moraines of Meru glacier. Historical documents contain descriptions of a large lake at Tapoban from 7th century AD[17].

A number of debris cones and talus fans are present all along the valley. Spectacular paraglacial fans are common in the upper part of the valley. These comprise debris flow and fluvial sediments, the source of which is erosion of the adjacent moraines. On the basis of these landforms, the former positions of Gangotri glacier were recon-

Table 2. Morphometric parameters of the Gangotri glaciers

Name of glacier or bamak	z	Z	L	W	Ws	A	H	Rh	ELA	Sh
Details of glaciers or bamaks present in the catchment of Gangotri glacier										
Gangotri	4120	7000	25.15	1.63	1.50	52.25	2880	0.045	5560	0.057
Raktavarn and its tributary glaciers/bamaks (TG)										
Raktavarn	4500	6200	15.90	0.85	0.99	13.53	1700	0.106	5350	0.053
Thelu	5040	5800	02.95	0.67	0.60	01.80	760	0.230	5420	0.227
Swetavarn	4760	6000	06.58	0.51	0.55	06.83	1240	0.188	5380	0.077
I Unnamed TG of Raktvarn*	5100	6200	06.30	0.82	0.50	06.28	1100	0.292	5650	0.130
II Unnamed TG of Raktvarn*	5240	6400	03.15	0.25	0.23	01.65	1160	0.241	5820	0.079
Nilamber	5300	6000	05.05	0.82	0.62	04.58	700	0.139	5650	0.162
III Unnamed TG of Raktvarn*	5200	6600	04.10	0.66	0.45	03.05	1400	0.341	5900	0.160
Pilapani	5080	5880	05.55	0.81	0.61	05.15	800	0.144	5480	0.146
Chaturangi and its tributary glaciers/bamaks (TG)										
Chaturangi	4400	5960	22.45	0.88	0.93	30.29	1560	0.070	5180	0.038
I Unnamed TG of Chaturangi*	5120	5800	05.50	0.56	0.49	06.98	680	0.124	5460	0.102
Kalindi	5440	5960	06.25	0.83	0.99	12.14	520	0.083	5700	0.133
Seeta	5400	6000	04.18	0.75	0.76	05.30	600	0.144	5700	0.178
Suralaya	5120	6230	08.95	0.81	1.04	16.35	1110	0.124	5675	0.090
II unnamed TG of Chaturangi*	5190	7080	05.60	0.48	0.75	02.95	1890	0.338	6135	0.086
III unnamed TG of Chaturangi*	4980	6360	10.00	0.71	1.05	11.67	1380	0.138	5670	0.071
Vasuki	4800	5800	06.95	0.35	0.58	05.25	1000	0.144	5300	0.050
Bhagirath Paravat (BP) I (6512)*	4520	5400	03.25	0.48	0.65	01.13	880	0.271	4960	0.147
Bhagirath Paravat (BP) II (6556)*	4600	5600	03.05	0.50	0.70	01.05	1000	0.328	5100	0.164
Bhagirath Paravat (BP) III (6195)*	4710	6220	05.15	0.33	0.57	01.33	1510	0.293	5465	0.064
Bhagirath Paravat (BP) IV (6625)*	4820	6000	04.05	0.62	0.86	01.95	1180	0.291	5410	0.153
Swachand	4880	6190	10.15	1.05	1.55	17.70	1310	0.129	5535	0.103
Miandi	4980	6000	06.00	0.76	0.97	05.28	1020	0.170	5490	0.126
Sumeru	4900	5840	04.60	1.28	1.25	03.18	940	0.204	5370	0.278
Ghanohim	4740	5840	06.30	1.52	1.95	14.38	1100	0.175	5290	0.241
Kirti and its tributary glaciers/bamaks (TG)										
Kirti	4520	6580	11.05	1.02	1.42	13.40	2060	0.186	5550	0.092
I Unnamed TG of Kirti *	4570	6830	05.05	1.43	0.61	06.98	2260	0.448	5700	0.283
II Unnamed TG of Kirti*	4860	6940	05.20	1.70	0.75	07.55	2080	0.400	5900	0.327
III Unnamed TG of Kirti*	4860	6400	06.55	0.98	1.10	03.35	1540	0.235	5630	0.150
Details of bamaks or glaciers present in the study area and directly draining into Bhagirathi river										
Maitri	4000	6200	09.20	0.54	0.73	04.60	2200	0.239	5100	0.058
Meru	4720	5800	03.05	0.42	0.46	06.48	1080	0.354	5260	0.137
Bhrigupanth	3720	6080	10.70	0.52	0.53	14.95	2360	0.221	4900	0.048
Manda	3880	5440	03.55	0.49	0.51	03.38	1560	0.439	4600	0.138

z: Altitude at snout in metres, Z: Maximum altitude in metres, L: Length in km, W: Width in km, Ws: Width at snout in km, A: Area in sq km, H: Relief in metres, Rh: Relief ratio, ELA: Present equilibrium line altitude in metres, Sh: Shape of basin.
* No specific name of the glacier is available on map.

structed (Figure 6). The older debris cones exhibit consolidated material with dense grass cover. Possibly the older phase of the glacier retreat, which led to formation of the older moraine, the older generation of debris cone came into existence. Sometimes, the older debris cones are partially overridden by younger talus cones or exposed deep gullies and ravines at the core of the younger ones, such examples are common in Chirbasa and Bhujbasa areas.

The younger debris cones/talus fans are formed by unconsolidated debris. A number of younger debris cones/talus fans were identified between Bhujbasa and Gaumukh. They have longer dimensions up to 500 m or so, with a higher gradient (> 40°). Sometimes, a number of stone streams were also traced along such cones. On the right side of the snout a huge young talus fan was noticed, which might have developed after the recession of the snout.

Figure 5. Series of lateral moraines, with Gangotri glacier to the left and lacustrine valley fill of Tapoban to the right.

Figure 3. The end moraine at Sukhi at an altitude of 2300 m, indicates the extent of the Gangotri glacier.

Figure 4. Position of snout in 1891, 1937, 1962 and 1971 as indicated by the end moraines and palaeochannels. The height (A) indicates the glacier, main advance stage.

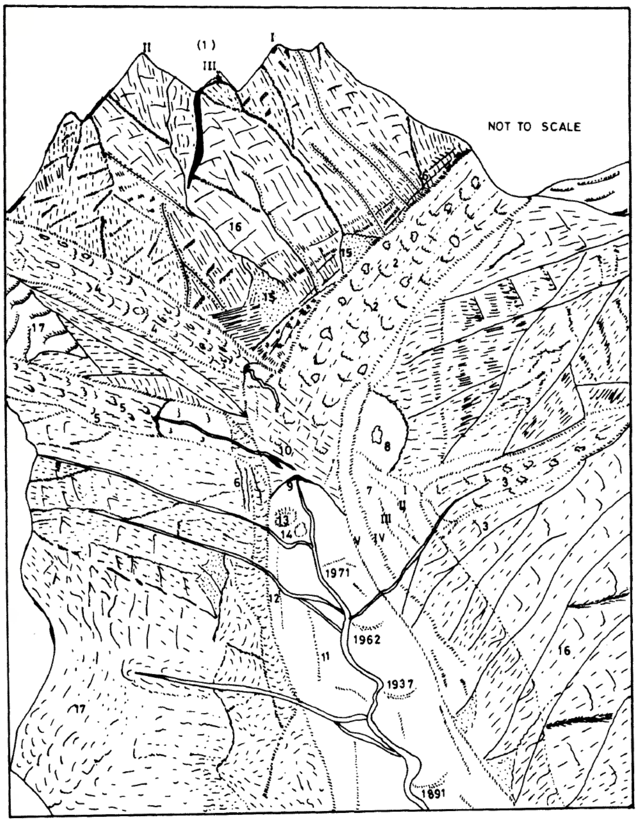

Figure 6. Sketch map of the Gaumukh area showing various glacial and fluvio-glacial features. 1 (I, II, III), Bhagirathi peaks; 2, Gangotri glacier covered with supraglacial moraine and lakes; 3, Meru glacier; 4, Chaturangi glacier; 5, Raktvarn glacier; 6, Glacial striations; 7, Five levels of lateral moraine between Gaumukh and Tapoban; 8, Tapoban lacustrine plain; 9, Gaumukh; 10, Crevasses; 11, U-shaped valley; 12, Remanents of lateral morainic ridges; 13, Hummocks moraine; 14, Proglacial lakes; 15, Debris cones and talus fans; 16, Rock wall; 17, Cirque or corrie; 1971–1891 position of snout over the years.

Proglacial lakes are well preserved in this area. These have fluvio-glacial deposits found at and close to the margin of a glacier. This is the favourable condition, and in particular, where the movement of the ice is contrary to the slope of the land, so that natural drainage from the ice margins is impeded or blocked altogether, for the development of pro-glacial lakes. These are large bodies of freshwater lake fed both by streams draining the unglaciated slopes and by melt-water from the surface and the ice. When melting is particularly intense, as during deglaciation, pro-glacial lakes will be at their largest and are most numerous. Some of the pro-glacial lakes of this area are dry, may be because of the ongoing neotectonic activities.

Recently the snout of the Gangotri glacier was observed to have undergone marked changes in its shape and position (Figure 7). The ice cave that was active during 1962 (ref. 18) has become extinct and new ice caves have been formed along the easternmost and westernmost edges of the snout. From 1962 to October 1999, the snout has retreated by 1.25 km. The main glacial stream emerges out from the easterly ice cave and now is treated as the main snout. The ice cave is nearly 35 m wide at its opening and becomes narrow towards the interior. The ice cliff at the mouth of the ice cave is about 45 m high from the stream level. A detailed examination of the snout surface suggests that there is some layering in ice and each layer varies in thickness from 0.5 to 1.5 m. The sides of the ice cave show chopping surfaces and the individual layers are, at places, slightly puckered and varved, indicating thereby differential load pressures of ice and moraine along the vertical plane or due to the exertion of pressure along the horizontal plane. Huge blocks of ice cover the floor of the cave. The stream water flows at considerable pressure along the eastern wall of the cave. Along the margin of the ice cave, two prominent crevasses have formed along the N30°W and W-E directions. They incline almost vertically and the surface moraines tumble down into such crevasses. The crevasses along the upper surface of the glacier extend over 400 m upstream (Figure 8). Minor longitudinal crevasses have been found within the ice cave. When the longitudinal and transverse crevasses intersect, they form huge blocks of ice, which get detached from the main glacier in short periods of time. The glacier surface near the snout is covered with surface moraine and is very uneven with mounded depressions. The surface moraine varies in thickness, approximately from 0.9 to 2 m. It is composed predominantly of the fragments of granitic rocks.

Just before 200 m and 50 m of the present snout, on the right side of the glacier, a large hummock with an ice core and a superimposed cover of well-rounded and polished boulders and fine sand, is met. On the left side of the glacier, a one 100-m long dead ice ridge is also present. The hummocks occur both as circular and elliptical mounds and arcuate ridges with flanks sloping at an angle of 30°. One of these mounds shows a depression in the centre with raised rims all around. The vertical section of such a typical mound shows alternating coarse and fine sandy layers of varying thicknesses, with frozen sand layer just above the dead ice core. The ice cores are found to be well-stratified and characterized by well-developed bubble lineation, but pebble fabric within the hummocks is very diffusive and has been reoriented. Within 1.0 km of the snout, a chaotic assemblage of hummocky moraines and dead ice, with small ponds and lacustrine deposits, indicates rapid ice retreat since 1971. This is the place where Vohra[5] marked the snout position in 1971.

During the last phase of the glacier advance, i.e. 200 to 300 year ago[9,11,19,20], the glaciers reached 2 km beyond the present snouts, and can be broadly correlated with the Little Ice Age as reported in other parts of Himalaya[21–23] and in other parts of the world[24]. Since then, there has been progressive glacial retreat, leaving successive morainic ridges. Sharma and Owen[14] reconstructed the ice thickness model of western Garhwal Himalaya. Their study showed that, prior to 1890, there had been progressive retreat and down-wasting of Gangotri glaciers. Since then, however, down-wasting has been relatively insig-

Figure 7. A view of the snout of the Gangotri glacier in June 1999.

Figure 8. Position of crevasses at the snout of the Gangotri glacier causing failure in the block form.

nificant and frontal retreat has dominated. In the forefield of the Gangotri glacier, moraines formed prior to 1971 are well-developed, with sharp-crested ridges and tills with strongly oriented fabrics. In contrast, the moraines formed after 1971 are hummocky and have a weak fabric strength. Over the last 25 years, Gangotri glacier has retreated 850 + (approx.) m, compared to 2 km over the last 200 years[14]. This suggests that retreat was much slower before compared to what was after 1971, and that the glacier must have been stationary or in a seasonally advancing condition (during 10^5 to 10^3 years ago) for long enough, to produce the well-defined moraines with their strong fabric. Thus the well-formed moraines probably indicate their formation during glacial advances, in contrast to the hummocky moraines associated with ice retreat.

The recession of the snout is common to most of the glaciers in the Himalayan region, but such retreat is rather irregular in amount, rate and time of occurrence[25]. This may partly be attributed to the large annual fluctuations in the rates of snowfall. The topography of this area shows that this area receives little precipitation. As precipitation was dropped, glaciers and ice mass, snow and ice cover began to retreat, as the frozen ground began to absorb more solar radiation. An unusually long terminal retreat in a glacier due to the ice being rather thin in the zone of ablation, especially at the snout of the Gangotri glacier, is only 40 m and consequently variations in the thickness of the ice in the ablation zone have a pronounced effect on the position of the snout. Data for 61 years (1936–96) show that the total recession of Gangotri glacier is 1147 m, with the average rate of 19 m per year[26]. During the month of May and June in 1999, the snout changed its shape everyday because huge blocks of ice got detached from the main body everyday. Since we have been monitoring the snout since 1996, we never saw this type of situation before. From May 1996 to October 1999 the snout has receded by 76 m.

This is presumably a natural phenomenon, but we cannot neglect the interference of human activities particularly to this glacier. We are always surprised to see that the Government permits saints to construct their huts not only near Gaumukh but also over the glacier (Tapoban). Every year thousands of tourists, pilgrims, mountaineers and trekkers visit this area, and have left huge amounts of waste material there. Thus there is an immediate task to prevent any type of human activity, except scientific research work to preserve this holy place Bhagirathi, and to maintain its aesthetic beauty.

1. *Inventory of Himalayan Glaciers*, Geological Survey of India, 1999.
2. Metcalfe, R. P., *Geol. Soc. London*, 1993, **74**, 495–509.
3. *Climate of Uttar Pradesh*, Indian Meteorological Department, 1989, pp. 372–375.
4. Owen, L. A., Sharma, M. C. and Bigwood, R., in *Geomorphology and Land Management in a Changing Environment* (eds McGregor, D. F. M. and Thompson, D. A.), John Wiley, 1995, pp. 69–88.
5. Vohra, C. P., in *The Himalayas: Aspects of Change* (eds Lall, J. S. and Moddie, A. D.), Oxford University Press, New Delhi, 1981, pp 138–151.
6. Doornkamp, J. C. and King, C. A. M., *Numerical Analysis in Geomorphology*, Edward Arnold, 1971, p. 181.
7. Prasad, C., in Proc. of I Convention of Indian Institute of Geomorphologist, Allahabad, 1987.
8. Bloom, A. L., *Geomorphology, A Systematic Analysis of Late Cenozoic Landforms*, Prentice Hall, New Jersey, 1991, p. 532.
9. Auden, J. B., *Rec. Geol. Surv. India*, 1937, **73**, 135–141.
10. Thakur, V. C., Virdi, N. S., Gergan, J. T., Mazari, R. K., Chaujar, S. K. and Philip, G., Scientific Report submitted to DST, New Delhi, 1991.
11. Vohra, C. P., *Indian Mountaineer*, Indian Mountaineering Foundation, 1988, pp. 1–8.
12. Tiwari, A. P., *Geol. Surv. India Misc. Publ.*, 1972, **15**, 69–74.
13. Tiwari, A. P., *Rec. Geol. Surv. India*, 1972, **106**, 248–256.
14. Sharma, M. C. and Owen, L. A., *J. Quat. Sci. Rev.*, 1996, **15**, 335–365.
15. Owen, L. A. and Derbyshire, E., *Z. Geomorphol. Suppl. Bd*, 1989, **76**, 33–73.
16. Hewitt, K., *Z. Geomorphol. Suppl. Bd.*, 1989, **76**, 9–32.
17. Law, B. C., in *Mountains and Rivers of India* (ed. Law, B. C.), 1968, pp. 187–210.
18. Holmes, A., *Principles of Physical Geology* (Revised ed. Holmes, D. L.), Thomas Nelson and Sons Ltd, 1981, p. 417.
19. Hodgson, J. A., *Asiatic Res.*, 1822, **14**, 60–152.
20. Griesbach, C. L., *Geol. Surv. India Memoirs*, 1891, **23**, 27.
21. Derbyshire, E., Li, J., Perrott, F. A., Xu, S. and Waters, R. S., in *International Karakoram Project* (ed. Miller, K.), 1984, pp 456–495.
22. Fort, M., *J. Nepal Geol. Soc.*, 1995, **11**, 257–272.
23. Rothlisberger, F. and Geyh, M. A., *Z. Gletscherkol.*, 1985, **21**, 237–249.
24. Groves, J. M., *The Little Ice Age*, Methuen, London, 1988, p. 498.
25. Bhadur, J. and Naithani, A. K., *Down to Earth*, 30 April 1999, 27–34.
26. Shankar, R. and Srivastava, D., Invited papers, Symp. Snow, Ice and Glaciers: A Himalayan Perspective, GSI, Lucknow, 9–11 March 1999, pp. 1–7.

ACKNOWLEDGEMENT. Financial assistance from the Department of Science and Technology, Govt of India, New Delhi, is acknowledged.

Received 6 March 2000; revised accepted 18 September 2000