Palynological study of glacio-geomorphic features and its relevance to Quaternary palaeoclimate and glacial history

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Palynological studies have provided a good overview of the palaeovegetational and palaeoclimatic scenario of the Indian subcontinent. However, little has been explored in this regard from the glaciated sites of the Himalayan region. In recent years, some palynological data have been generated from a few glaciated sites of Western Himalaya and it has been found that other than palaeoclimatic reconstruction, spores–pollen can be used as an important parameter to know the possible extent of the glaciers during Late Quaternary. Glacier dynamics plays an important role in carving and consequent modification of the various geomorphic features, which are the characteristic of various stages of glacial fluctuations. Because the distribution of spores–pollen of the type vegetation is ubiquitous, collection of subsurface sediments from the depositional geomorphic features, for palynological study as well as dating, is important to get the chronological history of various glacial stages.

Keywords: Chronological dating, glacial geomorphology, palynology, palaeoclimate, tree-line shift.

CLIMATE change is a dynamic process and the governing factor for the advance or retreat of glaciers as well as periodic vegetational shifts in a particular region. The Quaternary is well known for its repeated climatic changes, having glacial and interglacial phases. The Late Quaternary or Holocene climate has been even more variable[1,2]. These climatic changes have been large enough to have manifested in various glacial processes. For a clear understanding of such climatic changes, a scientific study of climate controlled natural agents like glaciers, rivers, lakes, etc. is required. In this regard, a good number of palynology-based palaeoclimatic reconstructions have been done from various regions in the higher Himalayas[3–7], but the glaciated sites, i.e. above the tree-line limit or close to the glacier snout have been little explored and explained in terms of palaeoclimate and glacial fluctuations[8–14]. However, some studies have been initiated in the recent past, which discuss the extent of glaciation in some glaciated valleys of the Himalaya during Late Quaternary, based on geomorphological features and absolute dates[15–20]. This article is an attempt to generalize the importance of palynological studies of various glacial geomorphic features, supported by absolute dates, in inferring the palaeoclimate vis-à-vis glacial fluctuations. A brief review of previous palynological studies carried out from various glaciated Himalayan sites (Figure 1 and Table 1) has also been discussed.

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Palynology and climatic reconstruction

Palynology, i.e. the study of spores and pollen, has been accepted as an indispensable tool for the palaeoclimatic reconstructions during the Quaternary. This is so because the spores and pollen recovered from the Quaternary sediments can be attributed to a particular living plant group. Spores and pollen are produced in large quantities by the plants, and are dispersed and deposited along with the sediments over large areas by various dispersal agencies, of which wind plays an important role followed by water, insects, birds and other animals. Spores and pollen are produced in such large quantities that even a small amount of sediment may yield hundreds of palynofossils representing diverse plant groups. Because of the distinct morphology of an individual spore or pollen grain, due to the different sculpture and ornamental pattern of its outer layer (exine), each spore and pollen can be identified and correlated to a particular plant family or even up to species level. As different plant communities grow under specific environmental and climatic conditions, the population of spores and pollen in a sedimentary layer is the optimum representation of contemporaneous flora, and thus reflects the climate during that point of time.

In the field, the sediment samples for palynological studies are collected from a sedimentary profile (either core or trench) at regular intervals (generally 5 cm). For the extraction of spores and pollen from the sediments, the standard maceration procedure (acetolysis) is followed. Samples are treated with 10% aqueous KOH solution to

Table 1. Vegetational shifts vis-à-vis climatic phases during Holocene from some glacial valleys of Western Himalaya

Study area	Geomorphological set-up (sampling site)	Age range in yrs BP (^{14}C)	Vegetational shift as evidenced by pollen/spores	Climatic phase
Gangotri Glacier, Uttarakhand	Outwash plain	Recent	Increase in conifers and temperate broadleaved arboreal taxa	Warm–moist
		~ 850 to ~ 200	Marked increase in the frequency of steppe elements; sharp decrease of ferns and other aquatic elements	Cold–dry
		~ 1700 to ~ 850	Increase in alpine scrubs, conifers, fern spores and other moist taxa	Warm–moist
		~ 2000 to ~ 1700	Open alpine scrub forest, moisture-loving elements present in good amount	Cool–moist
	Kame deposits	~ 1000	Decline in alpine scrubs and conifers, as well as arboreal pollen/non-arboreal pollen ratio	Cold–dry
		~ 7100 to ~ 6000	Increase of arboreal taxa and decline of steppe elements	Warm–moist
		~ 8300 to ~ 7100	Decline in broadleaved taxa and conifers, but abundance of ferns and moist elements	Cool–moist
		~ 9000 to ~ 8300	Fair number of alpine scrubs, conifers and other broadleaved elements	Warm–moist
	Tapoban palaeolake	~ 9000	Fair number of conifers and other broadleaved elements	Warm–moist
Chaurabari Glacier, Uttarakhand	Outwash plain	Recent	Increase of arboreals, ferns and aquatic taxa	Warm–moist
		Dates not available	Decrease of arboreals, ferns and aquatic taxa; increase of steppe elements	Dry phase
		~ 2360 to ~ 1160	Dominance of arboreal taxa, abundance of ferns and aquatic elements	Warm–moist
Baspa Valley, Himachal Pradesh	Alpine meadow	~ 1800 to Recent	Increase in conifers and temperate broadleaved arboreal taxa	Warm–moist
		~ 4310 to ~ 1800	Barren with charcoal pieces	Dry phase
		~ 10,450 to ~ 4310	Poor steppe elements; good number of fern spores, marshy/aquatic and arboreal pollen	Warm–moist

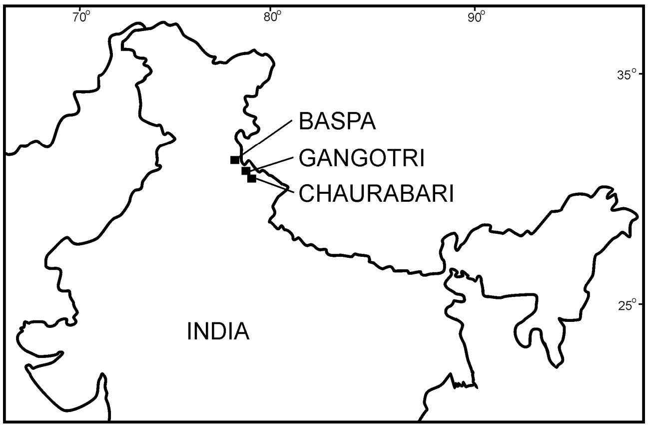

Figure 1. Map of India showing the locations of Gangotri, Chaurabari and Baspa valleys.

deflocculate the pollen/spores and then with 40% hydrofluoric acid to dissolve the silica content of the sediments. Thereafter, the samples are treated with acetolysing mixture (9 : 1 acetic anhydride and concentrated sulphuric acid respectively). The macerated samples are observed under high-power microscope for the identification (qualitative) and counting (quantitative) of different spores–pollen taxa, and frequency 'pollen diagrams' are prepared for the past vegetational and climatic interpretations. The variation in the qualitative and quantitative representation of spores–pollen taxa within the sedimentary layers, as reflected in the pollen diagram, can therefore be applied to infer the past vegetational vis-à-vis climatic changes. However, certain limitations of palynological studies cannot be ruled out. The foremost among these are that the preservation of the spores and pollen is restricted only to the fine-grained sediments and therefore, the presence of coarser sediments within the sedimentary sequence can affect the palynological profile. Also, care has to be taken against the contamination of samples during maceration, which may affect the interpretation of results.

Glacial geomorphology vis-à-vis palynology

Glaciated valleys within the Himalayan region are characterized by the presence of various glacial and fluvioglacial deposits of the Quaternary, the sediments of which are good archives for palynological studies. The

Quaternary experienced four major glacial episodes, when most of the Himalayan region was under snow/ice cover. These glacial episodes were intervened by warm interglacial phases that resulted in the melting of glacial ice and carving of the region, giving rise to various erosional and depositional landforms. However, the geomorphic features of each glacial/interglacial phase have been obliterated or modified to some extent by the next glacial/interglacial episode. Thus, glacier dynamics plays an important role in the carving and consequent modification of various geomorphic features, of which depositional features, such as lateral moraines, end moraines, outwash plain deposits, kettle plains, kame-terraces, ablation valley fills, extant and extinct glacial lakes, etc. are more important, as each and every feature is related to a certain glacier stage and thus preserves the signatures of glacial history. On the other hand, these features are also good sites for the deposition and preservation of spores and pollen of the vegetation existing during that particular time-period.

Since the Last Glacial Maximum, i.e. around 20 k yrs BP, all the Himalayan glaciers are on continuous retreat, longitudinally as well as laterally. This recession is taking place at varying rates, which is related to short-term climatic fluctuations within that time-frame. During retreat, the glaciers have deposited most of the above-mentioned features at various altitudes within their respective valleys. Contemporaneous to this, vegetation has also responded by growing successively on these geomorphic features at different altitudes within the area vacated by the glaciers. In this vegetational succession, arboreal taxa or trees hold more importance as they form the tree-line limit, below the altitude of glacier snout, within the glaciated valleys. In general, the onset of warm and moist conditions results in the retreat of glaciers. Consequently, the arboreal taxa or tree-line, along with other vegetation, move to higher altitudes; whereas, arid and colder climate results in the stagnation or advancement of the glaciers, thus suppressing the vegetational growth and resulting in the movement of tree-line towards lower altitudes. Since the pollen of these arboreal taxa, along with the spores–pollen of other lower plants, is continuously being deposited in various geomorphic regimes, fluctuation of the tree-line during the past can be recorded by the quantitative representation of pollen in the sediments collected from these depositional features. The changes in the vegetational pattern in response to climatic fluctuations can thus be well recorded in the spores–pollen record of glaciogenic sediments. These data can then be applied to study the advance or retreat of glaciers during particular climatic phases.

Glacial geomorphology vis-à-vis chronological dating

Absolute dating of the different glacial deposits is important so as to have a chronological control for the vegetational shifts and climatic oscillations vis-à-vis glacial fluctuations. For Quaternary deposits, the absolute dating methods used are radiocarbon dating (conventional ^{14}C technique or Accelerated Mass Spectrometry (AMS)) and Optically Stimulated Luminescence (OSL). The radiocarbon dating technique is based on the principle of half-life of ^{14}C isotopes present in the organic carbon (5730 yrs). After the death of any organism, the amount of ^{14}C starts declining and a proportional count of the decaying ^{14}C atoms is done, which gives an indication of the time elapsed since the organism lived. In AMS dating, an accelerator-based mass spectrometer is used to count all the ^{14}C atoms, rather than just those atoms which are decaying. Compared to conventional ^{14}C dating, which requires between 1 and 10 g of carbon, AMS can use as little as 1–2 mg. The radiocarbon dating techniques can date samples up to 40 k yrs BP. OSL dating is a method of determining how long ago minerals were last exposed to the daylight, and thereby provides information about the time when the sediments were deposited. Luminescence dating uses minerals such as quartz and feldspar that commonly occur in sediments. As the glacial deposits are often poor or devoid of organic carbon, the OSL technique is useful for the dating of such sediments[19]. However, care should be taken while sampling so that the sediments are not exposed to light. Through OSL dating, ages can be determined from a few years to several thousand years, or even up to million years in some cases[21].

The various geomorphic features deposited by the glacial processes during different time spans provide the material required for developing the climatic history that can be extended back to several thousand years. The sediments of the outwash plains (Figure 2) are the most important in this regard as they represent the trunk valley, which was occupied by the main trunk glacier. Once the glacier retreats, the fluvial processes become active and deposit the sediments in front of the snout. If the glacier continues its retreat, such fluvio-glacial deposits gradually develop into an outwash plain. The finer sediments on the top would represent the depositional history of the time when the glacier had vacated that area; and the underlying big morainic boulders at the bottom would represent the time span when the glacier was present and deposited such unsorted material (till). The sequence of outwash sediments can be dated either by the radiocarbon method, if rich in carbonaceous material, or by the OSL technique, if the sediments are devoid of organic carbon. Thus, the dating of outwash plain deposits would provide a clear indication of the time when the glacier had started its retreat from the area.

Every valley glacier is bounded by the lateral moraines which form kame-terraces (Figures 2 *c* and 3 *a*). The kame-terraces are also important geomorphic features, which depict the history of a particular glacier. Different levels of the kame-terraces represent the past levels of the lateral extent of the glacier, as well as episodes of the

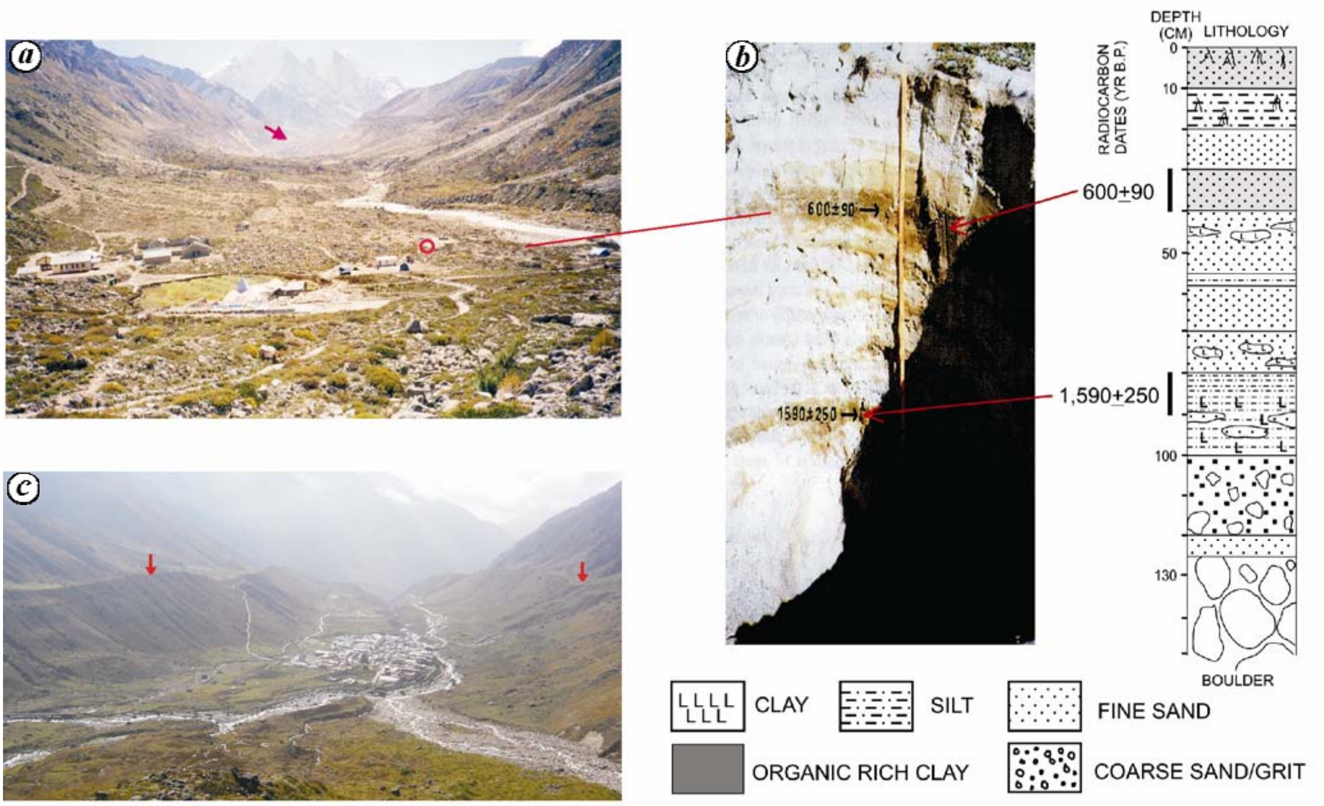

Figure 2. ***a***, Bhojbasa outwash plain, 4 km downstream of Gangotri Glacier snout (red arrow); ***b***, Photograph and litholog of sedimentary profile from outwash plain at Bhojbasa; ***c***, Downstream view of outwash plain of Chaurabari Glacier and Kame-terraces on lateral moraines (red arrows).

glacial retreat. Thus, the higher terrace would represent an older phase, whereas the lower terraces a younger phase of glacial history. The dates of the sediments from these terraces at different levels can provide the chronology of glacial episodes and also the rate of advance or retreat. Moreover, many of the terraces are sites in which ponding conditions had developed and contain the sediments suitable for both palynological analysis and radiocarbon dating. Other non-carbonaceous kame-deposits may be dated using OSL methods.

Other features within glacial sites which yield materials having good potential for pollen studies and dating are the ablation valleys, dead ice-filled basins, proglacial and periglacial lakes, etc. Ablation valleys develop at the marginal contact of a tributary glacier with the trunk glacier and get filled with sediments under fluvio-glacial and lacustrine conditions (Figure 4 *a*). Such valleys make good flat grounds or palaeolakes, one of the best archives for developing the past vegetational and climatic scenario of a glaciated region. Dead ice is the mass of ice detached from the main glacier after its retreat and forms the less well-ordered small lake system. Proglacial lakes (Figure 5 *a*) are small lakes formed at the mouth of the glacier within the end moraines after the retreat of the glacier. The radiocarbon or OSL dating of the sediments from these sites can provide a near approximation of the glacial retreat from these points. There are many extant and extinct periglacial lakes at lower altitudes within the Himalayan region, which were formed due to the daming of glacial melt water in a large area within the valley. The exposures of thick deposits of some extinct lakes and/or varve deposits provide good evidence of near-homogenous deposition (Figure 5 *b*). The palynology and dating of such deposits at close intervals can give a good picture about the vegetational shifts and climatic oscillations within a chronological framework.

Case studies

In the last few years, palynological studies of some geomorphic features have been carried out from the Gangotri[8–10], Baspa[11–13] and Chaurabari[14] glaciated valleys of the Western Himalayan region (Figure 1). Along with the vegetational change and palaeoclimate of the area, the studies, supported by ^{14}C dates, also provided an approximation of the glacial history during the Holocene of the Quaternary (Table 1). Within the Gangotri Glacier valley, studies were carried out from three geomorphic features, viz. outwash plain deposits at Bhojbasa[9], at an altitude of 3800 m amsl; kame-terrace deposits at an altitude of 4000 m amsl above the right lateral moraines at

Bhojbasa[8], and Tapoban palaeolake at an altitude of 4300 m amsl above the glacier snout level[10].

The subsurface sediments collected from Bhojbasa kame-terrace and Tapoban palaeolake were ^{14}C dated as 8730 yrs BP and 9000 yrs BP respectively, at the base of both the sedimentary profiles, thus covering almost the entire Holocene (Figures 3 *b* and 4 *b*). Palynological analyses of both the profiles show the presence of spores–pollen of local terrestrial herbaceous taxa as well as marshy taxa, along with those of temperate tree taxa transported from lower altitudes in good amount during Early Holocene. This indicates that during Early Holocene, i.e. around 9000 yrs BP, the sites were free from glacial ice, thus giving open ground for the growth of local herbaceous taxa. This can be possible only if lateral levels of the Gangotri Glacier were below the altitude of these sites. This suggests that during Early Holocene, though the snout of the glacier would have been at a much lower altitude than the present day (4100 m amsl), the lateral levels of the Gangotri Glacier must have been below the altitude of these study sites. Also, the glacier was retreating under warm–moist climate, which is evident by the presence of local marshy taxa and temperate tree taxa in good amount.

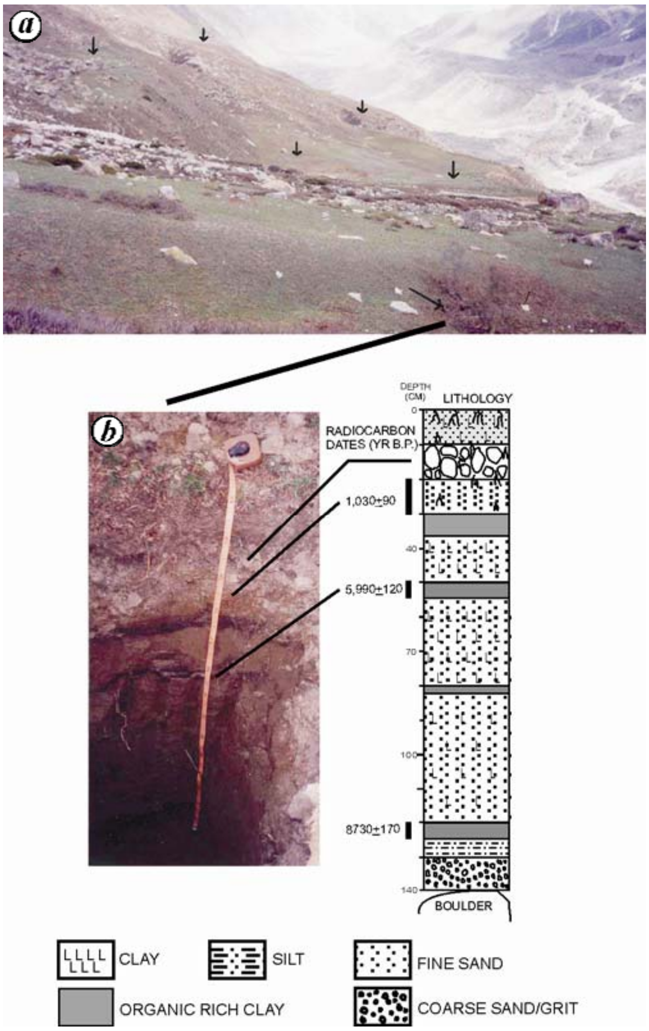

Figure 3. ***a***, Kame deposits on right lateral moraines at Bhojbasa (arrows show locations of various subsurface profiles collected); ***b***, Photograph and litholog of one of the sedimentary profiles analysed from the kame deposits.

The Late Holocene record of the Gangotri Glacier can be discussed through the study of sedimentary sequence of the Bhojbasa outwash plain deposits (Figure 2 *a*). The 1 m thick sediments, deposited under fluvial conditions over the morainic boulders, have provided the ^{14}C date of 1590 yrs BP near the base of the sedimentary profile, which was extrapolated to 2000 yrs BP further down (Figure 2 *b*). This shows that the Gangotri Glacier must have vacated the Bhojbasa area prior to 2000 yrs BP (ref. 9). At present, the distance between the snout position and the Bhojbasa is around 4 km, which suggests that since 2000 yrs BP till present, the resultant retreat of the glacier is 4 km. Further, the palynological study of this sedimentary profile indicates cool climate since 800 yrs BP till the time span coinciding with Little Ice Age when the Gangotri Glacier might have been stagnant or shown some advancement[9]. Similarly, a ^{14}C date of 2358 yrs BP at the base of 160 cm thick sediments from the outwash plain of Chaurabari Glacier, also indicates a time-frame about the retreat of the glacier within the valley and provides evidence about the antiquity of the Kedarnath Temple, which is located on the outwash plain.

Another palynological study was carried out on the 1.2 m thick palaeolake deposits at an altitude of 3100 m amsl from Rukti valley, a left tributary of Baspa valley, Kinnaur, Himachal Pradesh[12,13]. The study supported by three ^{14}C dates – 10,450, 4310 and 1800 yrs BP respectively, at the base, middle and near the surface of profile, have revealed that during Early to Middle Holocene, the pollen frequency of tree-line forming taxa, viz. *Betula* and *Juniperus* was higher than that during Late Holocene. This shows that during Early to Middle Holocene, the tree-line formed by *Betula* and *Juniperus* was as low as around the altitude of the study site (3100 m amsl) compared to the present-day level between 3800 and 3900 m amsl within the valley. Also, the fair number of conifers along with low pollen concentration of temperate, broadleaved taxa during Early to Middle Holocene indicates that conifer–broadleaved temperate forest was located further downstream than its present-day altitude and its pollen must have been transported by the wind to the study site. During Late Holocene, the decrease in pollen frequency of *Betula* and *Juniperus*, and increase in the pollen values of conifer–broadleaved temperate taxa indicate that these elements might have shifted to higher elevations with the retreat of the glacier under warm conditions. This means that during Early to Middle Holocene, the glacier snouts within the Baspa valley also might have been at lower levels in comparison to the present level of 4300 m amsl (ref. 13).

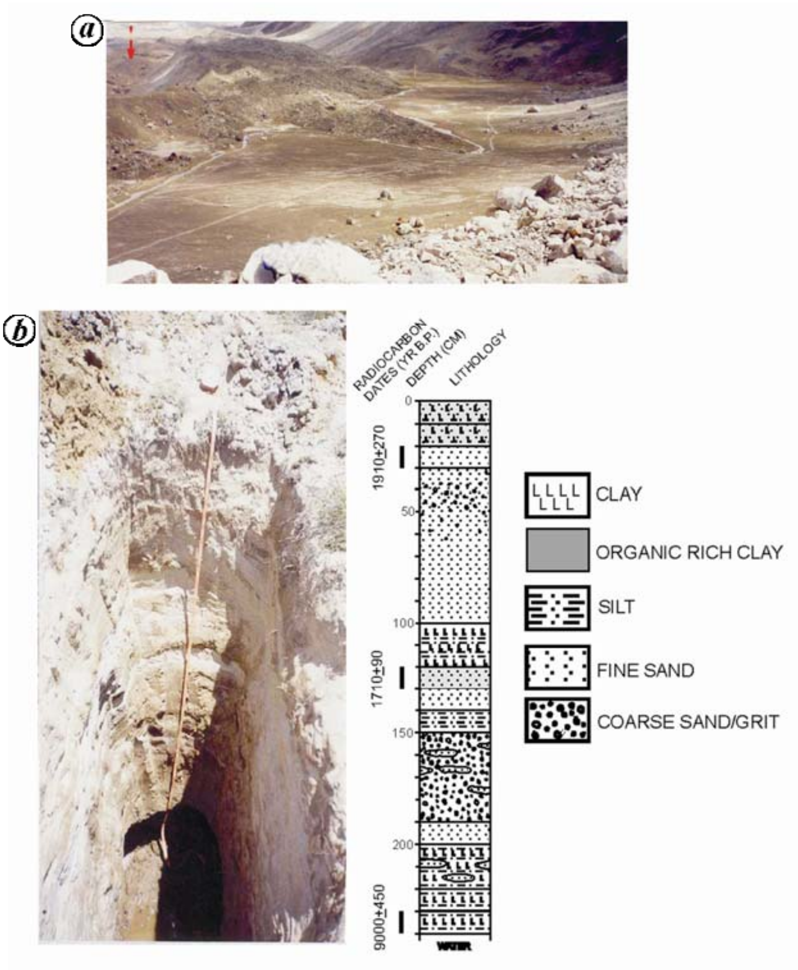

Figure 4. ***a***, Tapoban palaeolake above the Gangotri Glacier. Red arrow shows glacier body; ***b***, Photograph and litholog of the sedimentary profile from Tapoban palaeolake deposits at Bhojbasa.

Figure 5. ***a***, Proglacial lake formed by Meru Glacier, a left tributary of Gangotri Glacier; ***b***, Exposures of varve deposits at Sangla within Baspa valley.

Concluding remarks

It is evident from the present study that apart from palaeoclimatic reconstructions, palynology, supported by absolute dates, can be used as a valuable tool in glaciological studies for analysing the glacial history during the Quaternary. However, to build the past extent of the Himalayan glaciers and to analyse the natural and anthropogenic effects on vegetation, climate, tree-line shift and related glacial movements in a more precise manner, the study also requires qualitative as well as quantitative approach for the development of modern pollen–tree line and tree line–glacier relationships. These relationships may vary for different glaciated valleys within different Himalayan regions due to variations in local climatic and ecological conditions, as well as orientation and gradient of the glaciated valley.

1. Houghton, J. T., Jenkins, G. J. and Ephraums, J. J., *Climate Change. The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1990.
2. Mayewski, P. A. *et al.*, Holocene climate variability. *Quaternary Res.*, 2004, **62**, 243–255.
3. Bhattacharyya, A. and Chauhan, M. S., Vegetational and climatic changes during recent past around Tipra Bank Glacier, Garhwal Himalaya. *Curr. Sci.*, 1997, **72**, 408–412.
4. Chauhan, M. S., Sharma, C. and Rajagopalan, G., Vegetation and climate during Late Holocene in Garhwal Himalaya. *Palaeobotany*, 1997, **46**, 211–216.
5. Chauhan, M. S., Mazari, R. K. and Rajagopalan, G., Vegetation and climate in upper Spiti region, Himachal Pradesh during late Holocene. *Curr. Sci.*, 2000, **79**, 373–377.
6. Phadtare, N. R., Sharp decrease in summer monsoon strength 4000–3500 cal yrs BP in the central higher Himalayas of India based on pollen evidences from alpine peat. *Quaternary Res.*, 2000, **53**, 122–129.
7. Bhattacharyya, A., Vegetation and climate during post-glacial period in the vicinity of Rohtang Pass, Great Himalayan Range. *Pollen Spores*, 1988, **30**, 417–427.
8. Ranhotra, P. S., Bhattacharyya, A., Kar, R. and Sekar, B., Vegetation and climatic changes around Gangotri glacier during Holocene. *Geol. Surv. India Spec. Publ.*, 2001, **65**, 67–71.
9. Kar, R., Ranhotra, P. S., Bhattacharyya, A. and Sekar, B., Vegetation vis-à-vis climate and glacial fluctuations of the Gangotri Glacier since the last 2000 years. *Curr. Sci.*, 2002, **82**, 347–351.
10. Ranhotra, P. S. and Bhattacharyya, A., Vegetation, climate and lake history of Tapoban, Gangotri Glacier, Garhwal Himalaya. *Geol. Surv. India Spec. Publ.*, 2004, **80**, 215–221.
11. Bhattacharyya, A., Ranhotra, P. S., Ganjoo, R. K. and Koul, M. N., The early Holocene vegetation and climate in Naradu Glacier Valley of Kinnaur District, Himachal Pradesh. *Palaeobotany*, 2006, **55**, 89–96.
12. Chakraborty, S., Bhattacharyya, S. K., Ranhotra, P. S., Bhattacharyya, A. and Bhushan, R., Palaeoclimatic scenario during Holocene around Sangla valley, Kinnaur, northwest Himalaya based on multi proxy records. *Curr. Sci.*, 2006, **91**, 777–782.
13. Ranhotra, P. S. and Bhattacharyya, A., Holocene palaeoclimate and glacier fluctuations within Baspa Valley, Kinnaur, Himachal Pradesh. *J. Geol. Soc. India*, 2010, **75**, 527–532.
14. Kar, R., Palynological studies and geomorphological observation around Chaurabari Glacier (Kedarnath): Interpretation of climatic changes and glacial fluctuations during Holocene (Abstract publication). In National Seminar on Glacial Geomorphology and Palaeoglaciation in Himalaya, Lucknow, 2008, pp. 95–97.
15. Sharma, M. and Owen, L. A., Quaternary glacial history of the Garhwal Himalayas, India. *Quaternary Sci. Rev.*, 1996, **15**, 335–365.
16. Owen, L. A., Derbyshire, E. and Fort, M., The Quaternary glacial history of the Himalaya. *Quaternary Proc.*, 1998, **6**, 91–120.
17. Naithani, A. K., Nainwal, H. C., Sati, K. K. and Prasad, C., Geomorphological evidences of retreat of the Gangotri glacier and its characteristics. *Curr. Sci.*, 2001, **80**, 87–94.
18. Singh, D. S. and Mishra, A., Role of tributary glaciers on landscape modification in the Gangotri Glacier area, Garhwal Himalaya, India. *Curr. Sci.*, 2002, **82**, 567–571.
19. Nainwal, H. C., Chaudhary, M., Rana, N., Negi, B. D. S., Negi, R. S., Juyal, N. and Singhvi, A. K., Chronology of the Late Quaternary glaciation around Badrinath (Upper Alaknanda Basin): Preliminary observations. *Curr. Sci.*, 2007, **93**, 90–96.
20. Chaujar, R. K., Climate change and its impact on the Himalayan glaciers – a case study on the Chorabari glacier, Garhwal Himalaya, India. *Curr. Sci.*, 2009, **96**, 703–708.
21. Singhvi, A. K. and Kale, V. S., *Palaeoclimate Studies in India: Last Ice Age to the Present*, IGBP–WCRP–SCOPE Report Series: 4, Indian National Science Academy, New Delhi, 2008, pp. 7–8.

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