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ACKNOWLEDGEMENTS. This research was supported by IPRB grant No. RF 92003#129 by the Rockefeller Foundation. We thank the Project Director Dr K. Krishnaiah, Directorate of Rice Research and Prof. E. A. Siddiq for their interest and support.

Received 20 August 2001; revised accepted 7 November 2001

Vegetation *vis-à-vis* climate and glacial fluctuations of the Gangotri Glacier since the last 2000 years

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Pollen analysis of a 1.25 m sediment profile from an outwash plain at Bhujbas (3800 m asl) near Gangotri Glacier has revealed the vegetational changes in relation to climatic and glacial fluctuations in the area during the past 2000 years. Around 2000 years BP, open *Juniperus–Betula* forest occupied the area vacated by the glacier, revealing comparatively cooler and moist climate than the one prevailing at present. Subsequent increase of local arboreal taxa (*Juniperus*, *Betula*, *Salix*) and extra local elements (mainly *Pinus*) around 1700 years BP, indicates further amelioration of climate, i.e. increase of both precipitation and temperature in this region. Around 850 years BP there is a shift in the vegetational pattern, with sharp increase in *Ephedra* and other steppe elements notably *Artemisia* and Asteraceae. This reflects a trend towards drier climatic conditions, which is also evidenced by a decrease in Ferns and *Potamogeton*. At the upper part of the diagram, i.e. during recent times, climate again reverted to warm and moist, and due to increase in temperature, resulting in the retreat of snout to higher elevations.

THE Himalayan glaciers are a storehouse of freshwater and almost all the major river systems in the Indo-Gangetic Plain owe their origin to them. The Gangotri Glacier situated in the Uttarkashi district of Uttranchal, Western Himalaya, is one of the largest valley glaciers of India (Figure 1). The glacier is around 30 km long, 0.5 to 2.5 km wide and covers an area of around 143 km^2 (ref. 1). It originates from the Chaukhamba group of peaks (700 m asl) and flows in the northwesterly direction forming the source of Bhagirathi river at Gaumukh (4000 m asl), snout of Gangotri Glacier. Birch (*Betula utilis*) forms the present-day tree-line at 3900 m asl about 3 km south of the snout (Figure 2), while the conifers (*Pinus wallichiana*) are present at a distance of 9 km from the snout, at an altitude of ca. 3700 m asl. In the vicinity of the glacier, the vegetation is characterized by alpine steppe, which is dominated by grass, *Artemisia, Juniperus*, *Ephedra*, *Salix* along with other taxa represented by the members of Asteraceae, Rosaceae, Brassicaceae, Ranunculaceae, Saxifragaceae and Polygonaceae.

The Gangotri Glacier, source of the holy Ganga, holds a special place amongst all the Himalayan glaciers, due to its economic, social and religious significance. Hence, the rapid retreat of the glacier in the recent past has generated much concern and debate. Since the initiation of systematic mapping of the snout position in 1935 (ref. 2), there have been several studies on snout monitoring

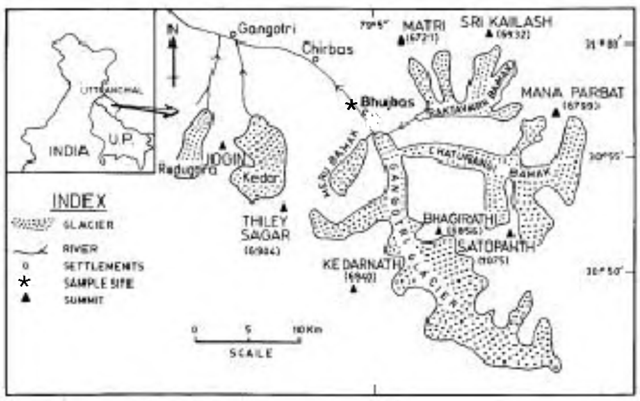

Figure 1. Map of Gangotri Glacier showing area of study (modified after Sharma and Owen[7]).

*For correspondence. (e-mail: amalava@yahoo.com) throughout the 1950s, 60s, 70s and 90s (refs 3–6). During the last decade, some groups other than the Geological Survey of India have also worked on the possible extent of the Gangotri Glacier during the Pliestocene glaciation and its sub-sequent retreat[7,8]. The Department of Science and Technology (Govt of India), has formed a core group for Gangotri Glacier in which a number of organizations are engaged in the study of various aspects of glaciology such as snow–melt–run-off modelling, mass balance studies, hydrometry, palaeoclimate, geomorphologic studies, etc. A small group at the Birbal Sahni Institute of Palaeobotany (BSIP), Lucknow under the leadership of one of us (A.B.) is engaged in the analyses of climatic changes vis-à-vis glacial fluctuations in the Gangotri Glacier based on pollen and tree-ring studies.

Climate obviously is the governing factor responsible for the advance and retreat of glaciers. The glaciers, therefore, are one of the best recorders of past climate changes. Over the years, palynology has proved to be an important tool for climatic reconstructions, especially for the Quaternary period. The changes in the vegetational pattern in response to climatic fluctuations are well preserved in pollen/spore record of fluvio-glacial and lacustrine sediments. In the present paper, an attempt has been made to unravel the vegetational changes and climatic history around the Gangotri Glacier during the past 2000 years.

The study is based on the pollen analysis of a 1.25-m deep sediment profile from an outwash plain at Bhujbas (3800 m asl), about 2.5–3 km aerial distance towards downstream from the snout (Figure 2). The top 40 cm of the profile mainly consists of humus and clay along with rootlets. The underlying sediments mostly constitute fine to coarse-grained sand with gravels. Occasional clay lenses and intercalations are found throughout the sandy sequence. At 1.25 m depth, large morainic boulders are encountered, below which it was not possible to dig (Figure 3). Clay/carbonaceous clay samples were collected at 10 cm intervals for pollen analysis. Two samples (about 500 g in weight) of carbonaceous clay, having rich organic matter, at a depth of 35 cm and 85 cm respectively, were separately collected for ^{14}C dating. These samples have been dated at the radiocarbon laboratory in BSIP. These dates are, 600 ± 90 years BP (BS-1750) and 1590 ± 250 years BP (BS-1788), respectively (Figure 3). The approximate rate of sedimentation for this small profile has been calculated on the basis of these two consecutive radiocarbon dates at different depths (Figure 4). The 50 cm thick sediments between these two depths, comprising clay, fine to coarse sand and gravels, seem to be deposited at the rate of 5 cm/100 years. For 85–125 cm interval, the age is extrapolated and assumed to be 2000 years BP at 125 cm, considering the fact that the rate of deposition was relatively faster as evidenced by the presence of coarse-grained sediments. To facilitate regional correlation, the above two ^{14}C dates have been changed to calendar years using the suggested method of calibration[9], which are 1357 AD and 433 AD, respectively. Pollen analysis was carried out using standard procedures such as treatment with 10% potassium hydroxide, hydrofluoric acid and a mixture of 1 : 9 conc. sulphuric acid and acetic anhydride (acetolytic mixture). Ten samples were macerated, of which eight were found productive. Sample between depths of 60–80 cm did not yield as it contains coarse sand, but the reason for the barren sample at the depth of 10–20 cm is not clear. The coarse sand to pebble-size sediments present from 100 to 120 cm were not analysed. These coarse sediments are not suitable for pollen analysis. For quantitative analysis, a number of

Figure 2. Outwash plain at Bhujbas. Tl, tree-line limit; Tm, terminal moraines; G, Gangotri Glacier; and SS, sampling site.

Figure 3. Sampling trench showing the lithological package (arrow indicate ^{14}C date).

slides were prepared and 200–400 pollen grains per sample were counted (Figure 5). Out of this total pollen count, the extra local elements like *Pinus*, *Cedrus*, *Picea*, *Abies*, *Carpinus*, *Alnus*, *Quercus*, *Juglans* and *Ulmus* (shown in box, in Figure 5), local aquatic element (*Potamogetan*) and fern spores are excluded, in calculating the percentage representation of each pollen/spore type in the pollen diagram. These taxa are plotted in the pollen diagram by their relative percentage in terms of total pollen count.

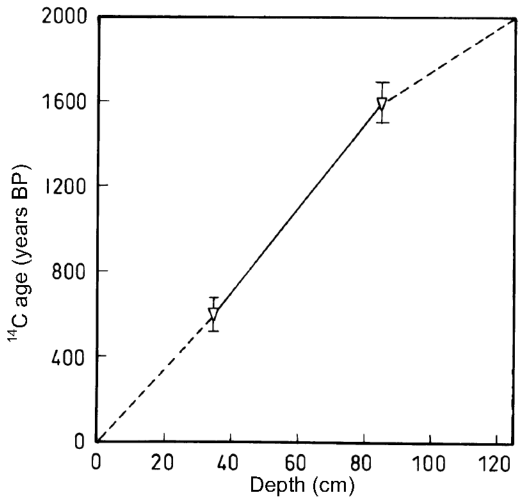

Figure 4. ^{14}C date vs depth plot.

The pollen sequence in the diagram has been divided into three distinct pollen zones, BJ-1, BJ-II and BJ-III, on the basis of changes in the frequency of important arboreal and non-arboreal taxa. The prefix 'BJ' is after the name of site of investigation, Bhujbas (Figure 5).

Pollen zone BJ-I (125–95 cm) covering a time span of 2000 to 1700 years BP is characterized by the overall dominance of non-arboreals (66–68%) over arboreals (34–32%). Amongst the local arboreal taxa, *Juniperus* (3–5%) and *Ephedra* (4–5%) show dominance over *Betula* (4%), *Salix* (2–3%) and *Myricaria* (1–2%). The extra local conifers are characterized by good percentage of *Pinus* (10%), followed by small amount (1–2%) of *Cedrus*, *Picea* and *Abies*. The broad-leaved elements, *Quercus* (2%), *Alnus* (2–3%) and *Ulmus* (1–2%) also mark their appearance. Amongst the non-arboreal taxa, Poaceae shows an increasing trend from 10% at the bottom to 25% at top of this zone, followed by *Artemisia* and Caryophyllaceae (9–11%), Brassicaceae and Ranunculaceae (7–8%), Saxifragaceae (5–6%). Rosaceae (1–2%) and Cheno/ Ams (1–3%) are low in frequencies, whereas Tubuliflorae (6–9%) and Liguliflorae (2–5%) show good representation. *Thalictrum* (4%) shows the presence at the bottom of the zone. Ferns and *Potamogeton* (aquatic) also represent good percentages between 6 and 17%, and 6 and 8%, respectively.

Pollen zone BJ-II (95–50 cm) covers a time span of 1700 to 850 years BP, and shows a decrease in non-arboreals (64–59%) and increase in arboreals (36–41%) than in the preceding zone. *Juniperus* (3%) and *Ephedra*

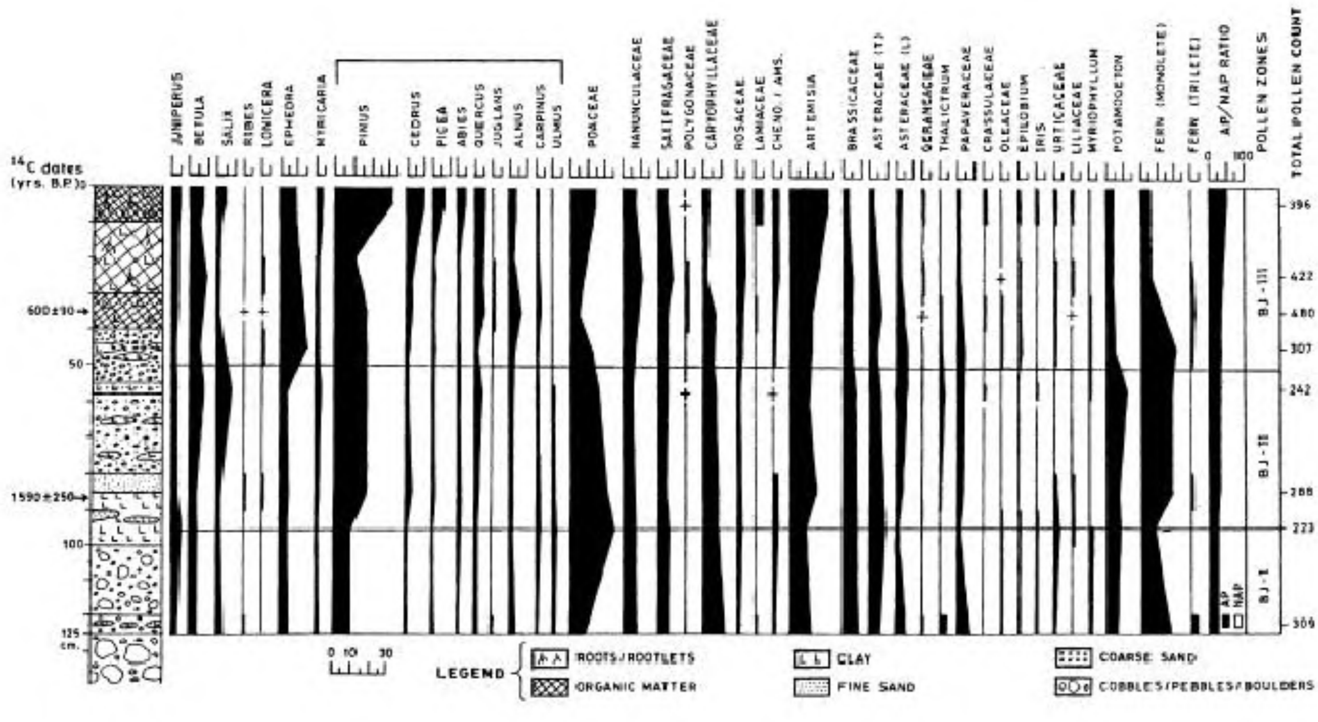

Figure 5. Pollen diagram from Bhujbas, Gangotri Glacier.

(3–5%) slightly decline, whereas *Salix* (2–8%) and *Betula* (3–7%) show increasing trends. *Myricaria* (1–3%) also shows slight increase with respect to the previous zone. *Pinus* increases sharply to 18% and maintains this throughout the zone. This is followed by the slight increase in *Cedrus* (1–3%) and *Quercus* (2–5%), whereas *Picea* (1–2%), *Abies* (1–2%), *Alnus* (2–3%) and *Ulmus* (1–2%) maintain the same trend. Non-arboreals are represented by a declining trend in Poaceae from bottom (20%) to top (14%) of this zone. *Artemisia* varies from 10 to 15%. Brassicaceae (6–7%), Caryophyllaceae (7–8%), Saxifragaceae (4–6%) and Ranunculaceae (5–7%) show a slight decline. Liguliflorae (4–7%) is marked by minor increase, whereas Tubuliflorae (6–9%) maintains the same trend. Rosaceae also remains at 2–5% throughout this zone. *Thalictrum* shows an increasing trend from 1 to 3%, but Cheno/Ams becomes sporadic. Ferns increase to 21% and maintain this trend through major parts of this zone. *Potamogeton* also shows gradual increase from 8 to 12%.

Pollen Zone BJ-III (50 cm–surface) covering a time span of 850 years BP to Recent is characterized by a change in the overall vegetational pattern. There is a sharp increase in the frequency of *Ephedra* to 15% at the base of this zone with gradual decline to 8% at the top, but overall maintaining higher frequency than the previous zones. *Betula* (5–9%) shows slight increase, but *Juniperus* (2–3%) and *Myricaria* (1–3%) maintain the same trend. *Salix* varies from 1% at the bottom to 3% at the top. *Pinus* (14–31%), *Cedrus* (2–10%), *Picea* (1–7%), *Abies* (1–4%) and *Quercus* (2–6%) show maximum values at the top of the zone. *Alnus* remains between 4 and 7%. Non-arboreals are characterized by sharp increase in *Artemisia* (13–22%) and sharp decrease in Poaceae (5–14%), representing their higher values at the top. Ranunculaceae (6–11%), Saxifragaceae (5–8%) and Rosaceae (3–5%) show an increase in percentage, whereas Caryophyllaceae (3–7%), Brassicaceae (3–5%) and Tubuliflorae (3–7%) show gradual decline towards the top. Liguliflorae also shows declining trend from 7% at the bottom to 3% at the top of this zone. Cheno/Ams (1–4%) again increases in number and shows maximum value at the top. This zone is also marked by a sharp decline in the percentage of ferns (21–3%) and *Potamogeton* (4%).

The interpretation of the pollen diagram (Figure 5) has revealed three short-term climatic phases in the Gangotri Glacier area during the late Holocene. Between 2000 and 1700 years BP, i.e. between 45 BC and 365 AD calendar year, the tree line was characterized by open *Juniperus–Betula* forest. Whereas Poaceae, *Artemisia*, Brassicaceae, Asteraceae and *Ephedra* mainly form the ground vegetation. Moisture-loving elements like ferns and *Potamogeton* are present in good amounts. This type of vegetation might have thrived under comparatively cooler and moist climate than the one prevailing at present.

Between 1700 and 850 years BP, i.e. 365 AD and 1195 AD calendar year, there is an increase in local arboreal taxa *Betula* and *Salix*, also accompanied with sharp increase in extra-local arboreals, especially *Pinus*. This indicates amelioration of climate, which might be due to comparatively warmer and moist climate than the earlier phase. This is also reflected in the increase in Ferns and *Potamogeton*.

From 850 years BP, i.e. 1195 AD calendar year, a major shift in the vegetational pattern has been noticed. There is a marked increase in the frequency of *Ephedra* along with other steppe elements like *Artemisia* and Asteraceae. This indicates that the climate became much cooler and drier than the earlier stage. This is also evidenced by a sharp decrease in ferns and *Potamogeton*. However, the increase of extra local elements *Pinus*, *Cedrus*, *Picea*, *Abies*, and other local tree elements *Betula*, *Salix*, *Juniperus* during upper part of this zone suggests that *Pine–Cedar* dry temperate forest might have ascended closer to the study site representing a modern situation. This suggested that climate reverted to warm–moist again.

A number of palynological studies have been carried out in the higher Western Himalayan region, related to palaeoclimatic aspects covering the last 2000 years or more[10–14]. However, many of them have not addressed directly the study of glacial advance and retreat. This study site lies at the level of present riverbed, which was once occupied by the main trunk glacier. Since the 1.25 m sedimentary sequence deposited over the morainic boulders is from an outwash plain (having fluvial influence), it is obvious that the glacier must have vacated the Bhujbas area (aerially 2.5 to 3 km from the present-day snout) prior to 2000 years BP. Around 2000 years BP, the glacier seems to have been stationary for a long time. This is evidenced by the formation of well-developed terminal moraines and a large outwash plain at Bhujbas (Figure 2). This outwash plain thereafter came under fluvial influence depositing the sedimentary sequence from which the samples for the present study were collected. Past studies on snout position reveal that the Gangotri Glacier has retreated about 1.25 km during the past 65 years[2,5,6,15]. Since 1971, it has retreated by approximately 850 m (ref. 8).

The aerial distance of Bhujbas to the present snout is 2.5–3 km and a retreat of 2 km has been calculated during the last 200 years[7]. Thus, prior to 200 years the retreat was very slow. This time span (200–300 years BP) broadly coincides with the 'Little Ice Age'[16], which is also recorded in other parts of the Himalayas[17,18]. It seems that retreat of the Gangotri Glacier ceased, possibly with some minor advancement, during this time. This is manifested in the formation of well-developed terminal moraines at a distance of about 2 km from the snout (Figure 2). These terminal moraines seem to be at least older than 200 years. Trees (*Betula utilis*) growing on them have been found to be 125–200 years in age, through tree-ring counting by one of us (A.B.).

Since the last three decades or so, the retreat is very rapid (approx. 25–28 m/yr)[6,8], which is quite alarming. This is probably due to rising temperature during the past several decades[19]. Tree-ring data also suggest that higher growth in *Pinus wallichiana* of this region since 1950 AD is related to the increasing trend of winter temperature. This higher temperature might have ascended dry temperate pine deodar forest close to Chirbas (9 km downstream from the snout) that is overtopped by open birch–willow–juniper forest at the vicinity of the site. Increased anthropogenic activities, mainly the cutting of forests all around the Gangotri region, might also be one of the important factors in the change of climate, particularly around Bhujbas. This site was well-forested by *B. utilis* (Bhojpatra) in the not-so-distant past. It is now surrounded by just a few patches of greenery. From the environmental point of view, restriction of human activities might be important, but would it stop the glacier from receding? Almost all the Himalayan glaciers, even those having no direct human interference are still reported to be in the receding stage. Thus the impact of global climatic changes towards warming seems to be a major factor responsible for the retreat of the Gangotri Glacier.

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ACKNOWLEDGEMENTS. We are indebted to Prof. Anshu K. Sinha, Director, BSIP for his constant encouragement and permission to publish this paper. A.B. is grateful to the Department of Science and Technology (Government of India) for financial assistance rendered vide project No. ES/91/018/97.

Received 14 May 2001; revised accepted 2 November 2001

Errata

New initiatives for science in India

[*Curr. Sci.*, 2002, **82**, 128–129]

The following title footnote was missing: 'This is the text of a document submitted by the Indian National Science Academy to the Government of India.'

Compressed natural gas: A problem or a solution

Sandhya Wakdikar
[*Curr. Sci.*, 2002, **82**, 25–29]

Page 26, column 2, line 4 should read: 'Higher octane rating . . ., reducing carbon emissions', instead of '. . . carbon dioxide emissions.'

Remembering Satish Dhawan

Amulya K. N. Reddy
[*Curr. Sci.*, 2002, **82**, 226]

The last sentence of the third paragraph in the third column on page 226 should read (the italicized sentences were inadvertently omitted in the original): 'But I cannot imagine him *donning army fatigues to please any government. From the deep impression that Andrei Sakharov's Memoirs made on him, my guess is that* Satish would have had many significant things to say had he written his memoirs.'

The omissions are regretted.