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# Style and timing of glacial and paraglacial sedimentation in a monsoon-influenced high Himalayan environment, the upper Bhagirathi Valley, Garhwal Himalaya

Patrick L. Barnard[a,b,*], Lewis A. Owen[a,1], Robert C. Finkel[a,b]

[a] *Department of Earth Sciences, University of California, Riverside, CA 92521, USA*
[b] *Lawrence Livermore National Laboratory, 7000 East Ave, MS L202, Livermore, CA 94550, USA*

**Abstract**

The Gangotri Glacier, at the source of the Ganges River, has fluctuated greatly throughout the late Quaternary in response to climatic oscillations. This has resulted in impressive moraines, paraglacial debris flow fans and terraces along the upper stretches of the Bhagirathi Valley. Cosmogenic radionuclide (CRN) dating of glacial and paraglacial landforms shows that fans, terraces and associated moraines formed approximately synchronously as the landscape readjusted to changing environmental conditions. This synchronicity suggests that fan and terrace formation is intimately related to glaciation, and that fluctuations in glacial and associated environments during times of climatic instability cause rapid sediment transfer and resedimentation of glacial landforms. The CRN dates show that all existing glacial and paraglacial landforms in the upper Bhagirathi Valley formed during the late Pleistocene and Holocene. This demonstrates that, in this high mountain environment, paraglacial and glacial landforms are eroded and resedimented within about 20,000 years. Furthermore, this testifies to the dynamic nature of glacial environments in monsoon-influenced high mountain regions.


*Keywords:* Paraglaciation; Cosmogenic radionuclide dating; Himalaya; Climate; Gangotri glacier

## 1. Introduction

The term 'paraglacial' was coined by Ryder (1971a,b), and later, Church and Ryder (1972) used this term to describe nonglacial processes that are directly conditioned by glaciation. They also used the term to describe the processes that operate and the landforms that are produced during deglaciation as the landscape readjusts to new climatic and environmental conditions. 'Paraglacial time' refers to the period when paraglacial processes are dominant.

The dominant paraglacial processes are mass movements and fluvial erosion. These are particularly important in the resedimentation and transfer of glacial and proglacial sediments within and beyond the high-mountain landscapes, thus helping to contribute to the net denudation of high mountains (Ballantyne, 1995, 2002, 2004). Furthermore, mountain glaciers are very sensitive to climatic oscillations and have fluctuated repeatedly, particularly on millennial time-

* Corresponding author. U.S. Geological Survey, Pacific Science Center, 400 Natural Bridge Drive, Santa Cruz, CA 95060, USA.
*E-mail address:* pbarnard@usgs.gov (P.L. Barnard).
[1] Department of Geology, University of Cincinnati, P.O. Box 0013, Cincinnati OH 45221-0013.

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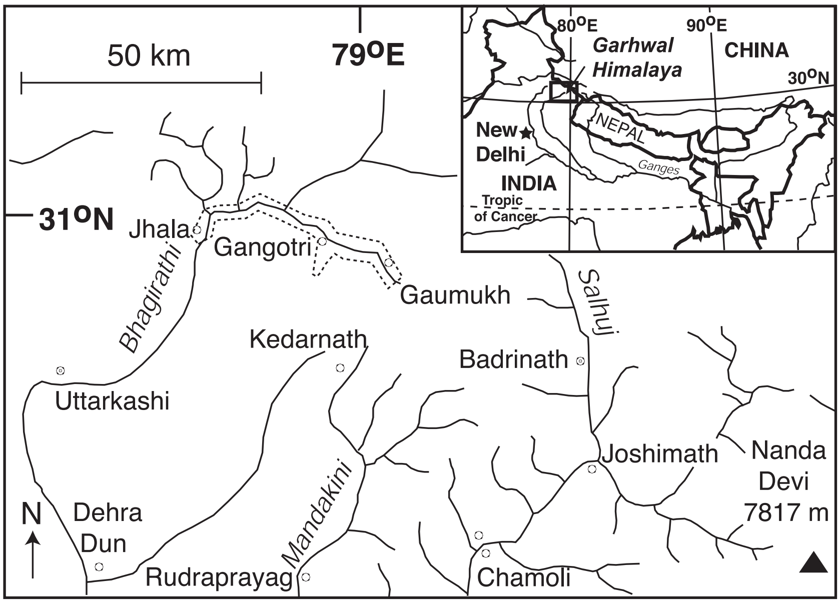



Fig. 1. Location of the study area.

scales, throughout the late Quaternary. The landscapes in glaciated mountain regions have therefore been continuously readjusting to changing climatic and environmental conditions. Paraglaciation in such a regime is particularly evident and important. In this paper, we aim to test the relationship between glaciation and fan and terrace formation in one of the world's most glaciated and highest mountain regions, the Garhwal Himalaya of northern India. This region was chosen because it is one of the few areas of the Himalaya where a framework for the glacial history already exists and where paraglacial debris flow fans[1] have been described (Sharma and Owen, 1996; Owen and Sharma, 1998). The previous studies, however, were able to take only a limited advantage of numerical dating. Therefore, we concentrated on developing the chronological framework by applying cosmogenic radionuclide (CRN) $^{10}$Be dating of surfaces to define the ages of glacial and paraglacial landforms, and to provide an indication of the timing of landscape evolution in the region.

[1] For simplicity, we use the genetic term "debris flow fan" to describe fan-shaped landforms that comprise dominantly diamict units. Some sedimentary units within these landforms may not have formed by debris flow processes senso stricto but may have been deposited by hyperconcentrated flows and/or fluvial processes.

In addition, geomorphic and paleoclimatic studies in the Garhwal Himalaya provide important information on the dynamics of the main climatic system, the southwest Indian summer monsoon, which influences this region. The Ganges River, fueled by the monsoonal climate and glacial outwash, originates in this region and forms one of the main drainages across the Himalaya and Indo–Gangetic Plain. This river system supports several hundred million people that live on its floodplain; therefore, changes in its hydrology have important socio–economic and political implications. Improved knowledge of the landscape evolution in this part of the Himalaya should provide a better understanding of the nature of climate change in this region and its influence on surface processes and landscape development. Our study also provides a framework for understanding the nature of denudation and sediment transfer within a continental–continental collision zone.

## 2. Research area

The upper Bhagirathi Valley is located in the Garhwal Himalaya of northern India (Fig. 1). The altitude within the research area ranges from 2500 m asl at Jhala to 6772 m asl at Bhrigupanth (Fig. 2). The southwest Indian summer monsoon provides most of the 1550 mm annual precipitation (Indian Meteorological Department, 1989). Numerous microclimates exist within the Bhagirathi Valley controlled by valley aspect, proximity to glaciers and altitude (Sharma and Owen, 1996). The region is north of the Main Central Thrust and is seismically active experiencing rapid uplift that has exposed phyllites, quartzites, granites and augen gneiss (Agarwal and Kumar, 1973; Metcalfe, 1993; Owen et al., 1995, 1996).

Mass movements are common throughout the study area and are initiated by fluvial incision, heavy monsoon rains and earthquakes (Owen et al., 1996; Barnard et al., 2001). The glaciers in the area are of high-activity type and have retreated during the last two centuries resulting in the formation of paraglacial debris flow fans and glaciofluvial outwash fans and terraces in the glacier forelands (Owen and Sharma, 1998). The glaciers have source areas at high altitudes and equilibrium line altitudes ranging from 4510 to 5390 m asl (ibid). The Gangotri Glacier is the main valley glacier of the upper Bhagirathi River catchment. It is a debris-mantled glacier that retreated over 1 km during the latter part of the 20th century to its present altitude of 3960 m asl (Figs. 2 and 3; ibid). Outwash from several important tributary glaciers, including the Kedar Glacier and Rudugaira Glacier, feed into the main valley from the south near Gangotri Village.

Using geomorphic mapping, relative dating techniques, historical documentation and optically stimulated luminescence (OSL) dating, Sharma and Owen (1996) developed a framework for the Quaternary glacial history of NW Garhwal. They dated the oldest stage, the Bhagirathi Glacial Stage, to between 63 and

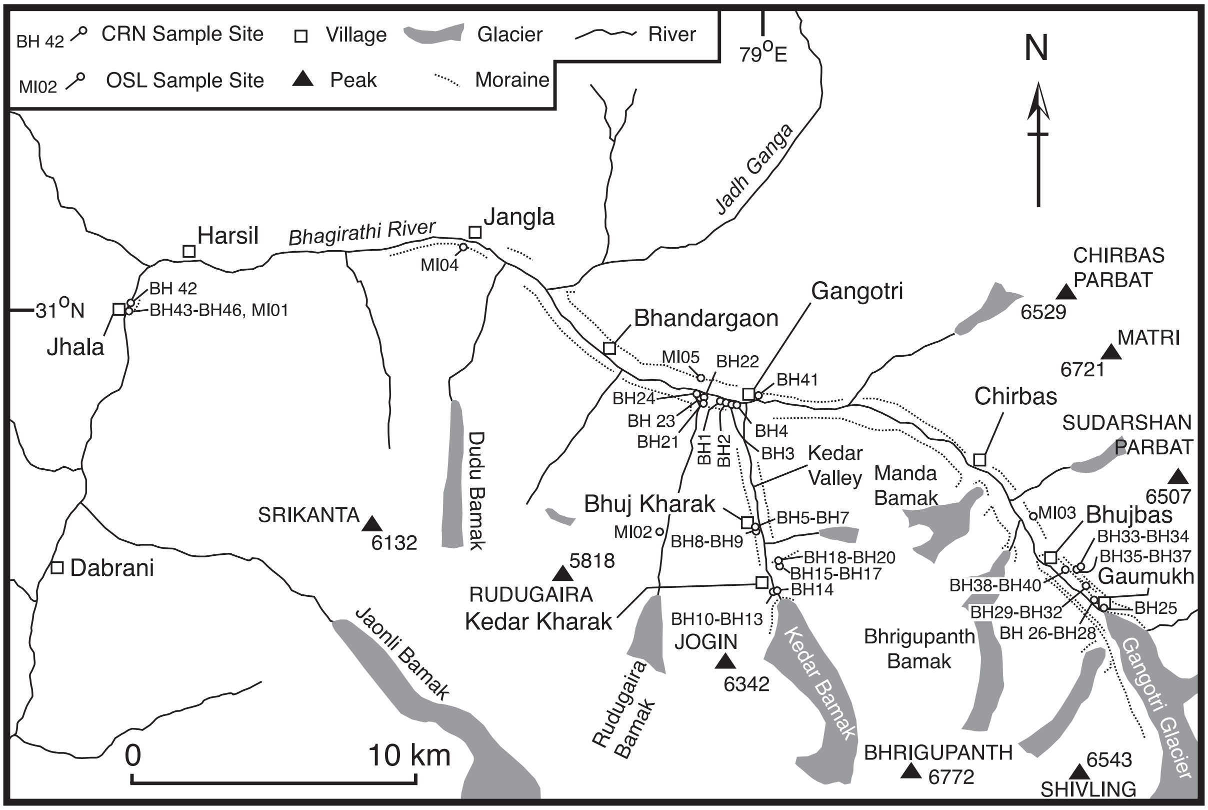



Fig. 2. The upper Bhagirathi Valley showing the sample sites for CRN dating and the location of Sharma and Owen's (1996) sites for OSL dating.

Fig. 3. View of the Gangotri Glacier showing the debris-mantled surface from above Bhujbas in October 2000. The snout is $\sim$ 75 m high. Note the lack of development of any terminal moraine.

5 ka and suggested that, during this stage, an extensive valley glacier reached 41 km down valley from the present Gangotri Glacier to an end moraine at Jhala (Fig. 2). The second glacial stage, the Shivling Glacial Advance, was dated to the Neoglacial (<5 ka), and they believed it represented a limited advance of $\sim$1–3 km. Sharma and Owen (1996) suggested that sharp-crested moraines within 1 km of the present glacier represented a Little Ice Age advance that they called the Bhujbas Glacial Advance and dated it to 200–300 years BP. During the last 200 years, the Gangotri Glacier has been retreating rapidly, particularly in the past several decades.

Using geomorphic evidence and historical documentation, Owen and Sharma (1998) showed that paraglacial debris flow fans in the foreland of the Gangotri Glacier near Gaumukh formed $\sim$200–300 years ago. Within $\sim$100 years of the initial retreat of the Gangotri Glacier, the fans stopped forming and were further modified only by small-debris flows. They argued that this showed that paraglacial reworking is extremely rapid initially but becomes less important as the landscape readjusts to new environmental conditions. In the glaciated landscape of Norway, Ballantyne (1995) also came to similar conclusions regarding the rapid rates of paraglacial reworking and determined that paraglacial features form and become inactive within 100–200 years of deglaciation. If paraglaciation is this rapid, it suggests that glacial and associated paraglacial landforms that are thousands of years old will be indistinguishable in age when applying dating techniques, such as CRN surface-exposure and OSL dating, which have errors commonly exceeding 10% of the age. Ballantyne and Benn (1994) and Curry and Ballantyne (1999) showed that, in Norwegian glacial environments, the principal process of glacial reworking is by debris flow. They describe a cycle of alternating glacial and paraglacial deposits in which glacial and nonglacial (i.e., paraglacial) sediments have similar characteristics but can be distinguished by structural characteristics and clast orientation. This illustrates the close association and reworking of sediments in a setting with geomorphic characteristics similar to Garhwal, albeit at somewhat lower altitudes.

## 3. Methods

Three primary study areas were chosen around the settlements of Jhala, Gangotri and Gaumukh (Fig. 2). These areas contain good examples of

Table 1
Cosmogenic radionuclide dates for samples collected from the upper Bhagirathi Valley

| Sample # | Location | Landform | Latitude ($^\circ \pm 0.01^\circ$) | Longitude ($^\circ \pm 0.01^\circ$) | Altitude (m) | Shielding factor[a] | Be-10[b] ($10^6$ atoms/g) | Exposure age (ka) Be-10[b] | Geomag. corr.[c] (ka) Be-10[b] |
|---|---|---|---|---|---|---|---|---|---|
| BH1[d] | Gangotri | Strath | 31.00 N | 78.93 E | 3028 | 0.93 | $0.710 \pm 0.100$ | $3.19 \pm 0.45$ | $3.57 \pm 0.50$ |
| BH2 | Gangotri | Strath | 31.00 N | 78.93 E | 3015 | 0.93 | $0.109 \pm 0.004$ | $2.94 \pm 0.12$ | $3.34 \pm 0.13$ |
| BH3 | Gangotri | Strath | 31.00 N | 78.93 E | 3021 | 0.93 | $0.143 \pm 0.005$ | $3.86 \pm 0.14$ | $4.38 \pm 0.16$ |
| BH6 | Bhuj Kharak | Terrace | 30.96 N | 78.95 E | 3810 | 0.91 | $0.173 \pm 0.011$ | $3.00 \pm 0.19$ | $3.42 \pm 0.21$ |
| BH7 | Bhuj Kharak | Terrace | 30.96 N | 78.94 E | 3878 | 0.91 | $0.096 \pm 0.007$ | $1.61 \pm 0.12$ | $1.70 \pm 0.13$ |
| BH9 | Bhuj Kharak | Fan | 30.96 N | 78.94 E | 3896 | 0.93 | $0.103 \pm 0.014$ | $1.71 \pm 0.23$ | $1.84 \pm 0.24$ |
| BH14 | Kedar Kharak | Terrace | 30.94 N | 78.95 E | 4396 | 0.97 | $0.460 \pm 0.011$ | $5.96 \pm 0.14$ | $6.60 \pm 0.16$ |
| BH16 | Kedar Kharak | Fan | 30.94 N | 78.95 E | 4314 | 0.97 | $0.445 \pm 0.011$ | $6.00 \pm 0.14$ | $6.64 \pm 0.16$ |
| BH19 | Kedar Kharak | Moraine | 30.94 N | 78.95 E | 4323 | 0.97 | $0.493 \pm 0.012$ | $6.61 \pm 0.16$ | $7.22 \pm 0.17$ |
| BH20 | Kedar Kharak | Moraine | 30.94 N | 78.95 E | 4242 | 0.97 | $0.438 \pm 0.010$ | $6.12 \pm 0.15$ | $6.75 \pm 0.16$ |
| BH21 | Rudugaira | Fan | 31.00 N | 78.92 E | 3015 | 0.95 | $0.172 \pm 0.006$ | $4.64 \pm 0.15$ | $5.22 \pm 0.17$ |
| BH24 | Rudugaira | Strath | 31.00 N | 78.92 E | 3040 | 0.95 | $0.159 \pm 0.007$ | $4.23 \pm 0.19$ | $4.80 \pm 0.21$ |
| BH25 | Gaumukh | Inheritance | 30.93 N | 79.08 E | 3960 | 0.99 | $0.039 \pm 0.005$ | $0.63 \pm 0.08$ | $0.63 \pm 0.08$ |
| BH26 | Gaumukh | Moraine | 30.94 N | 79.06 E | 3917 | 0.97 | $0.058 \pm 0.003$ | $0.96 \pm 0.05$ | $1.00 \pm 0.06$ |
| BH27 | Gaumukh | Moraine | 30.94 N | 79.06 E | 3918 | 0.97 | $0.102 \pm 0.004$ | $1.67 \pm 0.06$ | $1.82 \pm 0.07$ |
| BH29 | Gaumukh | Moraine | 30.94 N | 79.06 E | 3973 | 0.97 | $0.033 \pm 0.009$ | $0.52 \pm 0.14$ | $0.49 \pm 0.13$ |
| BH30 | Gaumukh | Moraine | 30.94 N | 79.06 E | 3956 | 0.97 | $0.016 \pm 0.007$ | $0.26 \pm 0.11$ | $0.24 \pm 0.10$ |
| BH31 | Gaumukh | Moraine | 30.94 N | 79.06 E | 3973 | 0.97 | $0.012 \pm 0.007$ | $0.19 \pm 0.12$ | $0.17 \pm 0.10$ |
| BH32 | Gaumukh | Moraine | 30.94 N | 79.06 E | 3956 | 0.97 | $0.046 \pm 0.007$ | $0.74 \pm 0.12$ | $0.74 \pm 0.12$ |
| BH33 | Gaumukh | Fan | 30.95 N | 79.06 E | 4140 | 0.97 | $0.214 \pm 0.009$ | $3.14 \pm 0.13$ | $3.70 \pm 0.16$ |
| BH34 | Gaumukh | Fan | 30.95 N | 79.06 E | 4145 | 0.97 | $0.115 \pm 0.008$ | $1.68 \pm 0.12$ | $1.85 \pm 0.13$ |
| BH35B | Gaumukh | Moraine | 30.95 N | 79.06 E | 4093 | 0.97 | $0.940 \pm 0.028$ | $14.53 \pm 0.43$ | $15.32 \pm 0.46$ |
| BH36 | Gaumukh | Moraine | 30.95 N | 79.06 E | 4112 | 0.97 | $0.695 \pm 0.019$ | $10.36 \pm 0.28$ | $11.13 \pm 0.31$ |
| BH37 | Gaumukh | Moraine | 30.95 N | 79.06 E | 4098 | 0.97 | $0.513 \pm 0.015$ | $7.70 \pm 0.22$ | $8.23 \pm 0.24$ |
| BH38 | Gaumukh | Fan | 30.95 N | 79.06 E | 3857 | 0.97 | $0.040 \pm 0.008$ | $0.67 \pm 0.14$ | $0.67 \pm 0.14$ |
| BH39 | Gaumukh | Fan | 30.95 N | 79.06 E | 3863 | 0.97 | $0.051 \pm 0.008$ | $0.86 \pm 0.14$ | $0.89 \pm 0.14$ |
| BH41 | Jhala | Inheritance | 30.99 N | 78.94 E | 3063 | 0.99 | $0.014 \pm 0.010$ | $0.37 \pm 0.27$ | $0.35 \pm 0.25$ |
| BH43 | Jhala | Moraine | 31.01 N | 78.71 E | 2510 | 0.95 | $0.006 \pm 0.013$ | $0.21 \pm 0.49$ | $0.19 \pm 0.44$ |
| BH44 | Jhala | Moraine | 31.01 N | 78.71 E | 2499 | 0.95 | $0.035 \pm 0.011$ | $1.28 \pm 0.42$ | $1.36 \pm 0.44$ |
| BH45 | Jhala | Moraine | 31.01 N | 78.71 E | 2490 | 0.95 | $0.012 \pm 0.011$ | $0.46 \pm 0.41$ | $0.42 \pm 0.37$ |
| BH46 | Jhala | Moraine | 31.01 N | 78.71 E | 2495 | 0.95 | $0.027 \pm 0.011$ | $0.99 \pm 0.39$ | $1.02 \pm 0.41$ |

Sample sites can be located on Fig. 2.
These ages were calculated with a sea-level high-latitude production of $^{10}Be = 5.16$ atoms/g/quartz using the scaling factors of Lal (1991) as modified by Stone (2000).

[a] The topographic shielding factor was determined using the methods of Nishiizumi et al. (1989).

[b] Uncertainty includes only uncertainty in AMS measurement.

[c] Corrected for time varying geomagnetic field as described in text. The uncertainty is carried over from that in the exposure age. No additional uncertainty was assigned arising from correction for geomagnetic field change.

[d] Used Al data for sample BH1 only.

glacial and paraglacial landforms that can clearly be morphostratigraphically correlated and were described as critical stratigraphic sites by Sharma and Owen (1996).

The Jhala study area is thought to be the glacial limit for the local Last Glacial Maximum in the Bhagirathi Valley (Sharma and Owen, 1996). At Jhala, the valley morphology changes from a broad

Table 2
OSL dates of Sharma and Owen (1996)

| Sample # | Location | Age (ka) |
|---|---|---|
| MI01 | Jhala | $62.89 \pm 8.58$ |
| MI02 | Rudugaira Kharak | $4.84 \pm 1.21$ |
| MI03 | Bhujbas | $5.13 \pm 1.54$ |
| MI04 | Jangla | $84.77 \pm 31.13$ |
| MI05 | Gangotri | $17.56 \pm 4.11$ |

U-shape to a narrow, deep river gorge. A large end moraine coincides with the change in valley form.

The Gangotri study area is important because it is situated at the confluence of the Bhagirathi and two glaciated tributary valleys, the Kedar and Rudugaira. As a consequence, large well-preserved fans, an impressive strath terrace and moraine fragments are present.

The Gaumukh study area, in the foreland of the Gangotri Glacier, contains a succession of well-preserved moraines that represent both the oldest and youngest glaciations in this region. The study area also contains the youngest paraglacial debris flow fans that are no longer aggrading. Owen and Sharma (1998) highlighted the importance of this region for studying contemporary paraglaciation because of the recent rapid retreat of the Gangotri Glacier over the last few centuries.

In each of the three study areas, the morphostratigraphic relationships of landforms were examined,

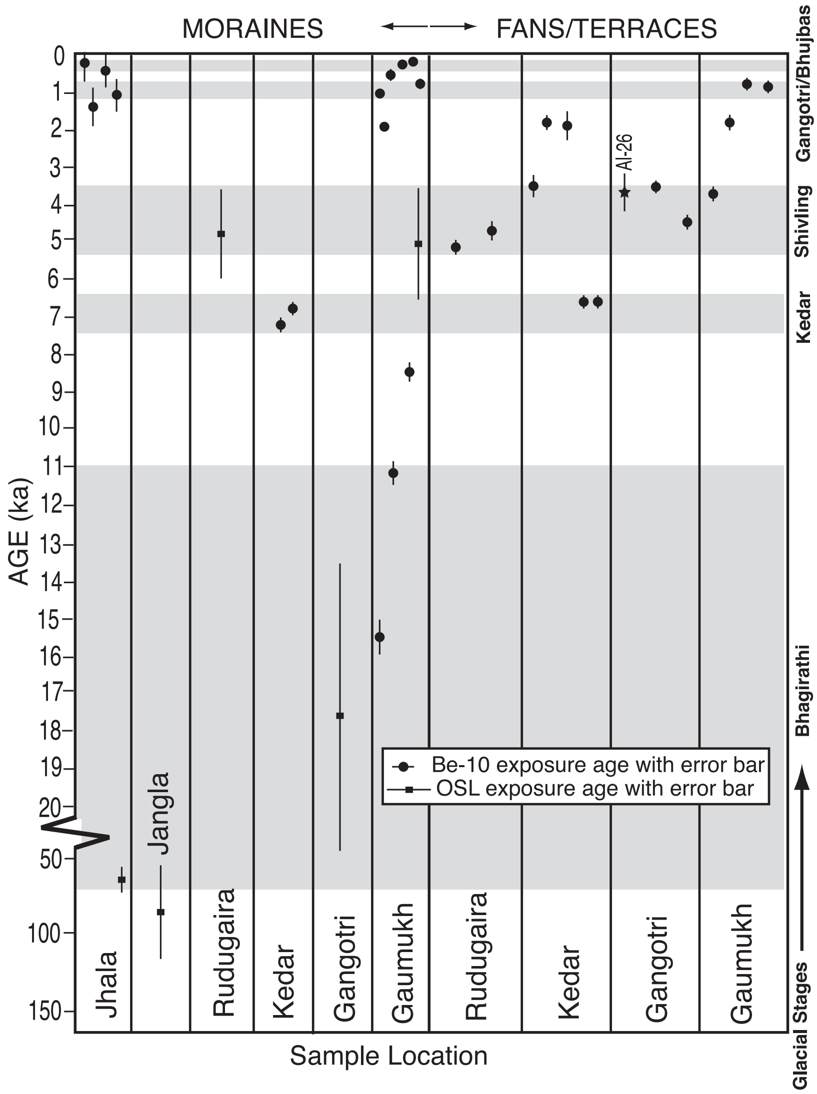



Fig. 4. Numerical dates from landforms in the upper Bhagirathi Valley: CRN-dated moraine ridges from this study and OSL dates from Sharma and Owen (1996) (left half) and CRN-dated fans, terraces, and strath terraces from this study (right half). The glacial stages are shaded.

and geomorphic maps were constructed using and modifying Sharma and Owen's (1996) study. Sample locations for CRN dating were chosen on the basis of Sharma and Owen's (1996) framework and an inspection of the morphostratigraphic relationships. Sampling sites were selected that were located along narrow moraine ridges and the distal edges of fans/terraces where the chances of erosion and exhumation of surface boulders is low. This minimizes the effects of overburden shielding that can produce erroneously young ages. The samples were located on the geomorphic maps aided by the use of a handheld global positioning system (Fig. 2).

The samples for CRN dating were processed at Lawrence Livermore National Laboratory (LLNL) by measuring $^{10}$Be ($t_{1/2}$=1.5 Myr) that had been produced by cosmic rays in the quartz crystals as a consequence of nuclear reactions resulting from the bombardment of cosmic rays with rock surfaces (Kohl and Nishiizumi, 1992). The samples were crushed and sieved to a uniform size of 250–500 μm. Approximately 90 g of this fraction was then extracted and chemically leached to isolate the quartz as per the methods of Kohl and Nishiizumi (1992), using HCl and HF:$HNO_3$ baths. A Be carrier of 0.5 mg was added to the clean quartz separates, and the sample was dissolved in 3:1 HF:$HNO_3$. Be was separated in ion exchange columns. The processed samples were then loaded into the accelerator mass spectrometer to determine the ratio of the radionuclide to the stable $^{9}$Be (Repka et al., 1997). Age determinations were based on the equations and production rates in Lal (1991) as modified by Stone (2000). A correction for variation in the geomagnetic field was applied to determine the final age of each sample as described in Nishiizumi et al. (1989) using the SINT800 geomagnetic intensity assessment (Valet, private communication). Full details of the methodology use in the age determination are described in Owen et al. (2002b).

Care must be taken when interpreting the CRN dates because of the high fluvial incision rates (5 mm/year—Barnard et al., 2001) and denudation rates in this region that are due to intense monsoon rains, paraglacial activity, rapid mechanical and chemical weathering, and slope instability. All these processes enhance the likelihood of a boulder disintegrating, being exhumed or toppling. This may produce younger ages than the surface that is being dated. However, multiple sampling was employed on each landform surface to help test the reliability of the dates because weathering and exhumation processes should be stochastic and produce a wide range of ages. Similar ages on a given landform provide confidence in the dating.

## 4. Dating results

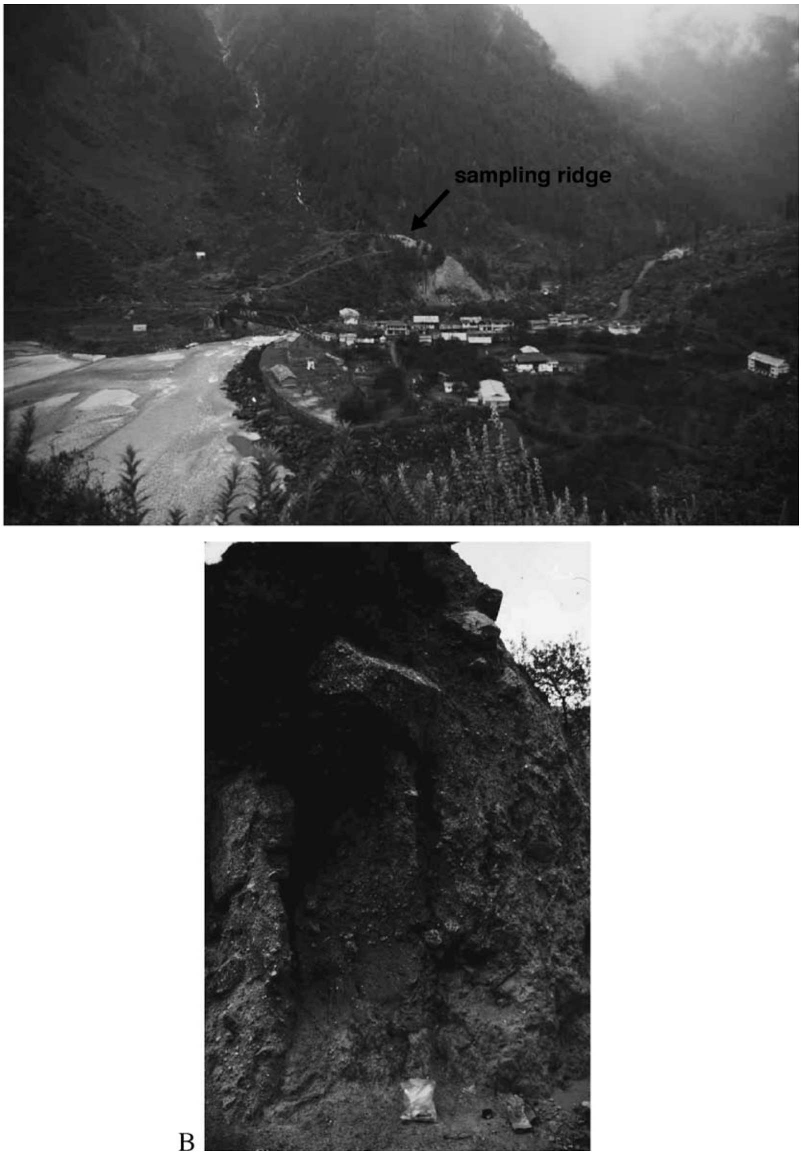
The CRN dating results and Sharma and Owen's (1996) OSL dates are presented in Tables 1 and 2, respectively. The CRN dating results are summarized and are grouped by location and landform in Fig. 4. The CRN dates on the moraines date the time when the glacier deposited the boulders and is likely to represent the time when the glacier began to retreat. However, because glaciers fluctuate on millennial time scales, the CRN dates may be essentially coincident with the time of a glacial advance (Zreda and Phillips, 1995).

## 5. Glacial chronology

Our CRN dating results and field observations question several aspects of Sharma and Owen's (1996) glacial chronology. Before discussing the relationship of glaciation to fan development, it is therefore important and pertinent to review and revise the glacial chronology. In the three primary study areas, each glacial stage is discussed mainly on the basis of new field observations and the CRN dating.

### *5.1. Bhagirathi stage*

Sharma and Owen (1996) believed that the maximum extent of ice during this stage was to Jhala because of the change in valley form and the existence of a sharp-ridged end moraine at this location (Fig. 5). CRN dating of boulders on the crest of the end moraine produced an age of ~1 ka (samples BH43–BH46). This contrasts sharply with Sharma and Owen's (1996) age of ~63 ka that was determined by OSL dating of glaciogenic sediments within the end moraine (sample MI01). There are several possible reasons that may




A

B

Fig. 5. The Jhala end moraine. (A) View looking down valley of moraine ridge at Jhala at ~2500 m asl. Jhala village, across the valley, is situated on the flood terrace. (B) Section from which OSL sample MI01 was derived by Sharma and Owen (1996). The CRN sites were directly above this site on the moraine ridge.

explain the different ages that were produced by OSL and CRN methods:

(i) The OSL dates might considerably overestimate the age of the sediment. This may occur if the sediment was poorly bleached before deposition and/or the dating analysis was erroneous (Richards et al., 2000). We believe this is not the case as bleaching tests were undertaken on the samples (Sharma, personal communication).
(ii) The boulders fell onto the surface of the landform ~1000 years ago. This is unlikely because there is a substantial depression between the crest of this landform, and the valley sides and any rock falls

and/or avalanches would have been more likely to have fallen into the depression rather than onto the crest of the landform. Furthermore, the CRN surface exposure ages of the four sampled boulders are remarkably similar, indicating that they all have comparable exposure histories. Such consistent ages would be unlikely on boulders that were deposited by rock fall processes because they would likely have different exposure histories prior to their failure, and thus different amounts of inherited CRN. Furthermore, they would have likely fallen at different times. These factors would produce markedly different CRN ages.

(iii) The landform is not an end moraine but a mass movement deposit. However, the section comprises a massive matrix-supported diamict that contains striated and edge-rounded clasts with a strong up-valley fabric (Fig. 5B). Decimeter- and meter-size beds and channel fills of poorly sorted sands are present within the diamict probably representing englacial or supraglacial channels. These are all characteristics consistent with the sediment having a glacial origin. Furthermore, the asymmetric cross-valley ridge form is characteristic of end moraines. However, contrary to most end moraines, the steeper face of the ridge faces down valley. If this landform was a mass movement deposit, it would be likely that the diamicts would have a cross-valley fabric and morphology consistent with movement across the valley and an associated scarp on the valley side from where the failed material originated (cf. Owen, 1994).

(iv) The landform represents several glacial events with its initial formation being defined by the OSL dating, and the latest glacial being represented by the CRN dates. Richards et al. (2000) showed that end moraines can continue to develop over substantial durations in the Khumbu Himalaya where they dated complexes that started to form during the early Holocene and continued to ~1 ka. However, it is highly improbable that any glacier could have extended down to 2500 m asl during the late Holocene, as the CRN dates might suggest, because this would infer a considerable climatic change that is inconsistent with proxy data from any other part of the Himalaya and the world.

(v) The boulders that were dated by CRN methods may have been exhumed recently in the history of the landform. Up stream of the Jhala end moraine, remnants of finely laminated lacustrine silts are present along the banks of the Bhagirathi River. This suggests that a lake formed behind the moraine, likely a result of a landslide damming the valley from the west. A very wide braided stream system lies immediately up valley from the end moraine (Fig. 5A) which stands in stark contrast to the high-energy deep river gorge below. The village of Jhala is built on an impressive bouldery terrace that we believe represents the landslide deposit that was reworked into a flood terrace as the landslide-dammed lake was breached, resulting in a catastrophic flood. These features are similar to the landforms associated with the Batal flood described by Coxon et al. (1996) in the Lahul Himalaya. A late Holocene flood could have eroded away all other landforms that were present along the valley floor near Jhala, leaving only a streamlined end moraine fragment, the flood terrace and a wide braided stream system channel up valley. The CRN dates may, therefore, be dating the age of the flood event that occurred ~1000 years ago and not the original surface of the glacial landform. This would explain the presence of such a prominent ridge on top of an end moraine believed to be 63 ka old. The damming/flooding event may be linked to deglaciation following a glacial advance at ~1 ka documented further up valley at Gaumukh (samples BH29–BH32; see Discussion).

The geomorphic and sedimentary evidence thus suggests that both OSL and CRN dates may be valid; the former dating the maximum extent of ice in the Bhagirathi Valley at ~63 ka, and the latter dating a flooding event that may have resulted from glacial outwash following a glacial advance at ~1 ka. Further evidence of the validity of the 63 ka OSL date comes from a glaciofluvial deposit (Table 2, OSL sample MI04) dated by Sharma and Owen (1996) at ~85 ka from just up valley at Jangla, 2700 m asl, in an exposure comprising deformed stratified sands and gravels. This sample has an extremely large error (±31.1 ka) but lends credence to the potential validity of the end moraine's timing and origin.


A

B

C


Fig. 7. View of the Kedar Valley showing the moraine (M) that was sampled on the east side of the Kedar Valley with its associated fan (F).

Sharma and Owen (1996) suggest that an OSL date of 17.6 ka (sample MI05) on lateral moraines near Gangotri Village (Fig. 2) shows that this glacial stage continued to this point. This moraine, which is discontinuous but can be traced down to Jhala, was attributed to the Bhagirathi Stage by Sharma and Owen (1996). A very prominent lateral moraine above Gaumukh, 2.5 km from the present mouth of the Gangotri Glacier at an elevation of 4100 m asl, was morphostratigraphically correlated with Sharma and Owen's (1996) Bhagirathi Stage lateral moraine and was dated using CRN methods (Fig. 6). Samples BH35 and BH36 were collected from the highest local point on the moraine, while BH37 was acquired from ~0.5 km down valley on a more hummocky portion of the moraine. This lateral moraine is ~150 m above the present elevation of the Gangotri Glacier. Traces of its matching lateral moraine can be seen across the valley (Fig. 6C). The moraine is heavily vegetated with very few exposed boulders. These moraines are almost 200 m above the closest contemporary moraines in this part of the valley and 250 m above the local valley bottom. This suggests a significant change in base level and/or ice thinning from the Bhagirathi Stage to the present.

The CRN dates on this moraine range between 15.3 and 8.2 ka (samples BH35B, BH36–BH37). The youngest date is likely the result of recent exhumation. Given the possibility that the youngest date is an underestimation, the moraine at this location probably formed between 15 and 11 ka during the Late Glacial. If these data and the OSL dates are correct, it is likely that an extensive valley glacier existed in the Bhagirathi Valley for much of the latter part of the last glacial. These CRN dates show that an extensive glacier, possibly a few tens of kilometers long, existed through the end of the global Last Glacial Maximum at ~15 ka and possibly until the Late Glacial at ~11 ka.

### 5.2. Kedar stage

A well-defined moraine in the Kedar Valley (Fig. 2) was studied in detail and is shown in Fig. 7. The moraine can be traced to a cirque glacier at the eastern end of the valley. The moraine crest is broad and is densely vegetated with only a scattering of surficial boulders. Several of these boulders were sampled for

Fig. 6. Views of the landforms at Gaumukh. (A) Down-valley view of Bhagirathi Stage moraine (BSM) and Gangotri Stage moraine (GSM) from Gaumukh. (B) The sampling site for BH35B located on the ridge of the Bhagirathi Stage Moraine, ~4090 m asl; a gneiss boulder 3 m in diameter and 1 m of relief. (C) Trace of Bhagirathi Stage moraine on the south side of the Bhagirathi Valley, directly across from the moraine ridge sample sites of BH35B and BH36.

CRN dating at an altitude of ~4340 m asl (samples BH19 and BH20). The CRN ages indicate that this moraine formed between 6.8 and 7.2 ka, and we assign this to a new glacial stage, the Kedar Stage. There are no paraglacial deposits in the main valley to suggest that the Gangotri Glacier had retreated before this time. Massive reworking during successive stages may have limited the evidence for this stage to the tributary valleys.

### 5.3. Shivling advance

Using OSL methods, Sharma and Owen (1996) defined a glacial advance, the Shivling Advance, in the Bhagirathi Valley and one of its tributary valleys which terminated before 5 ka (samples MI02 and MI03). Their OSL dates were determined for aeolian silt that caps lateral moraines in the upper Rudugaira Valley and above Bhujbas near Gaumukh (Fig. 2). They believed that the aeolian caps that indicate glacial sedimentation had ceased before aeolian sedimentation began. Based on this assumption, it is possible that this moraine formed during the Kedar Stage identified by CRN dating in the Kedar Valley at ~7 ka. However, a prominent paraglacial debris flow fan and terrace in the Kedar Valley dated at ~6.6 ka, which formed almost concurrently with the Kedar Stage at ~7 ka, indicates that there was substantial glacial retreat at ~6.6 ka resulting in fan and terrace formation. Furthermore, a large paraglacial debris flow fan and terrace in the lower Kedar Valley, consisting of reworked glacial moraine material at Bhuj Kharak (see Debris flow fan sedimentology and chronology), is younger (<5 ka) than the paraglacial debris flow fan deposits related to the Kedar Glacial Stage that are present further up the valley. We believe that these younger paraglacial deposits result from glacial retreat following the Shivling Advance. This illustrates that there were two distinct and separate phases of glacial and associated paraglacial sedimentation, thus distinguishing the Kedar Glacial Stage from the Shivling Advance.

### 5.4. Gangotri stage

Sharp-crested lateral moraines are present near Gaumukh at an elevation of 3965 m asl and ~2.5 km down valley from the snout of the Gangotri Glacier. These are ~200 m below the base of an impressive Bhagirathi Stage lateral moraine (see Fig. 6A). Multiple low (<10 m relative relief) but prominent ridges constitute this complex set of moraines (Fig. 8). The surfaces of the moraines are armored with boulders that exceed 4 m in diameter. Sharma and Owen (1996)

Fig. 8. Looking toward the valley bottom along a Gangotri Stage moraine, ~3970 m asl. Sample BH31 is shown in the foreground and comprises a gneiss boulder ~5 m in diameter with 3 m of relief.

assigned these moraines to the Shivling Advance. CRN dating of this moraine, however, shows that it formed <1000 years ago (samples BH29–BH32). We therefore assign this moraine to a new glacial stage, the Gangotri Stage.

### 5.5. Bhujbas stage

A glacial advance, the Bhujbas Stage, occurred during the mid-18th century and is confirmed by historical maps and dendrochronology (Sharma and Owen, 1996). In the foreland of the Gangotri Glacier, numerous small moraines represent this advance. These have been modified to varying degrees by paraglacial debris flow fans and glacial outwash. The moraines are small ( ~ 10 m high) and extremely hummocky, containing large boulders that commonly exceed 8 m in diameter. The moraine surfaces are almost completely devoid of vegetation and soil development (Fig. 9). The moraine ridge that was sampled is ~ 2 km down valley from the snout of the Gangotri Glacier and is on the edge of an eroded riverbank along the Bhagirathi River. Several samples were taken for CRN dating (BH26–27) to test the potential of dating very young landforms of known age and as a test for the inheritance of CRN due to prior exposure on the glacier surface and/or mountain sides. Samples BH26 and BH27 yielded dates of 1.00 and 1.82 ka, respectively. These are much older than CRN dates determined for contemporary glaciofluvial and fluvial sand samples that were collected from the mouth of the Gangotri Glacier (BH25=0.63 ka) and at Jhala (BH41=0.35 ka). These samples provide a test of the inheritance of CRNs and show that inheritance is only a minor problem, accounting for an overestimation of age by about several hundred years. The older ages on the moraine may be due to the moraine being positioned in a highly dynamic environment, where landform reworking and prior exposure is most common.

## 6. Debris flow fan sedimentology and chronology

The sedimentology within all the fans in the study areas is remarkably similar (Fig. 10). They comprise meter-thick massive beds of matrix-supported diamict. The diamicts generally consist of chaotically oriented, isotropic clast fabrics with an occasional weak imbrication and a slight preference for down-valley clast orientation. The clasts are


Fig. 9. A moraine in the upper the Bhagirathi Valley with an unvegetated, very coarse debris fan in the foreground. The moraine formed during the Bhujbas Stage and was sampled for CRN dating.

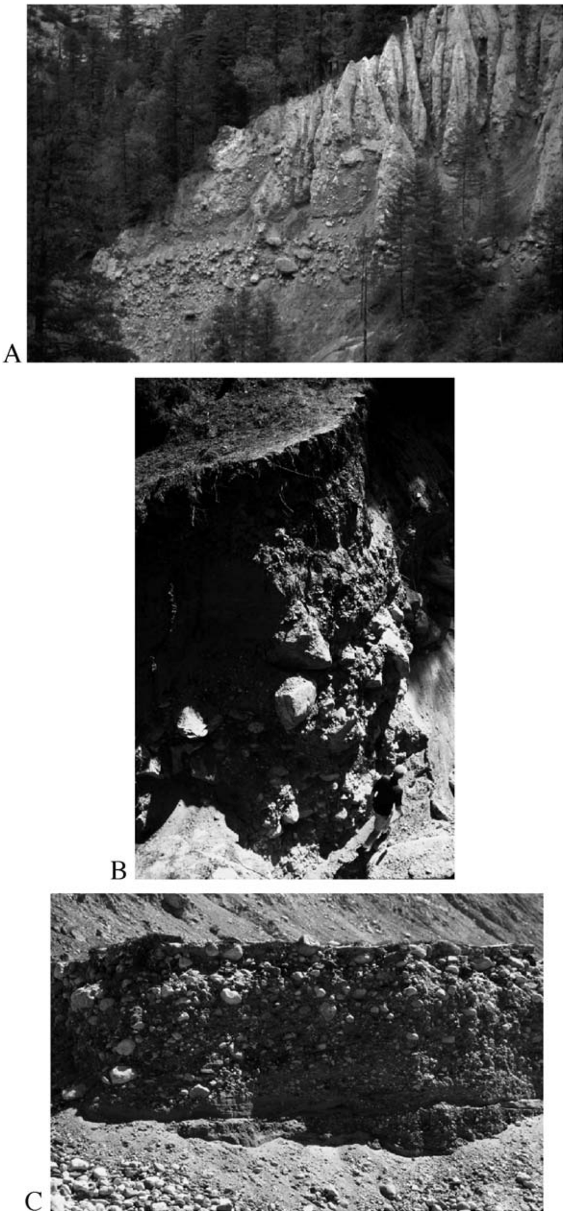



Fig. 10. Typical sections within fans in the study areas. (A) Fan sediments at the mouth of the Kedar Valley underlying till. The section is 30 m thick. (B) Massively bedded fan section (10 m thick) at the mouth of the Rudugaira Valley. (C) Fan section (5 m thick) at Gaumukh. Note the greater rounding of the clasts as compared to the other sections.

generally subangular, edge-rounded and occasionally striated. Clasts in the Bhagirathi valley, however, tend to be more rounded than in the Kedar Valley due to the greater transport distances and continuous reworking and resedimentation in the foreland of the Gangotri Glacier. Fan sections commonly exceed 20 m in thickness, exposing several sedimentary units and representing just a few depositional events. This shows the infrequent yet catastrophic nature of deposition of these fans and suggests that this may be climatically driven, possibly during deglaciation. The sedimentary characteristics of most of the deposits suggest that they were deposited by hyperconcentrated debris flows (Beverage and Culbertson, 1964; Costa, 1988). The fan deposits commonly underlie or overlie tills (Fig. 10A).

### 6.1. Gangotri village/Kedar valley

A tabular terrace that comprises reworked moraine is situated just below a large-moraine complex at Kedar Kharak at 4250 m asl in the upper Kedar Valley (Fig. 11A). This vast, grass-covered terrace contains few boulders but several exceed 7 m in diameter. A series of interrelated fans and moraines that originated from an unnamed cirque glacier are present several kilometers down valley on the eastern side (Fig. 11B). These paraglacial debris flow fans are very steep ($\sim 17^{\circ}$) and bouldery, containing numerous large (diameter >5 m) boulders. The CRN ages on the fan and terrace (samples BH14, BH16) are virtually indiscernible from their associated moraines (samples BH19–BH20), $\sim 6.6$ and $\sim 7.0$ ka, respectively. The age, geomorphic relationship and sedimentology all indicate a close relationship between glacial retreat and rapid paraglaciation. The upper Kedar Valley contains the oldest known paraglacial deposits in the entire study area.

Striated bedrock near Bhuj Kharak (Fig. 12A) on the east side of the Kedar Valley and sections consisting of interbedded moraine and paraglacial debris flow fan sediments provide clear evidence that the Kedar Glacier extended into and beyond this area. A series of very steep ($\sim 20^{\circ}$) coalescing fans which flatten toward the valley center where they are being actively eroded by slope processes are present on the west side of the valley in the vicinity of Bhuj Kharak at 3875 m asl (Fig. 12B).

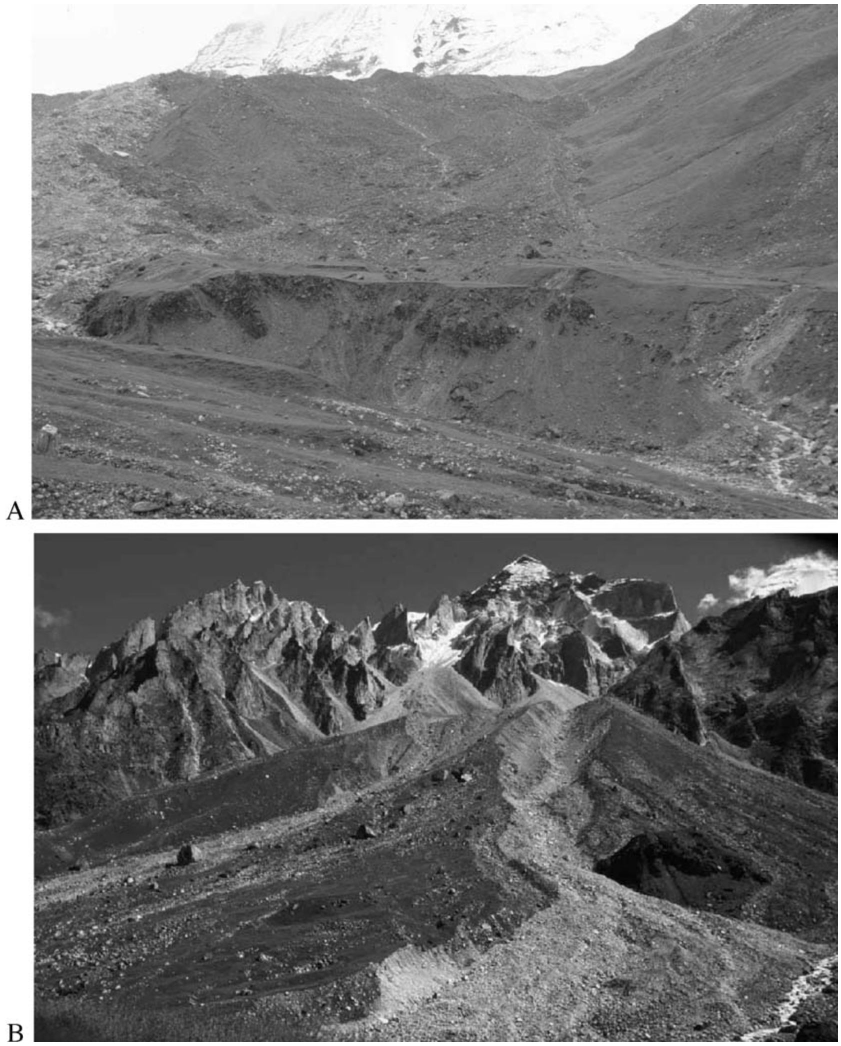


Fig. 11. Views of the upper Kedar Valley. (A) Terrace that was dated in this study (BH14) and its associated moraine above. (B) Cross-valley view of fan sampled near Kedar Kharak (BH16). See also Fig. 7.

These fans are covered with grasses, shrubs and trees. Meter-size (≤3 m in diameter) deeply weathered and moss-covered schist, quartzite and phyllite boulders are scattered across the surface. The fan comprises massive, poorly sorted, matrix-supported diamict dominated by subangular and slightly edge-rounded boulders that are 0.2 to 0.5 m in diameter (Fig. 12C). There is a weak down-valley clast fabric. These characteristics suggest that the sediment represents paraglacial debris flow deposits resedimented from tills.

A large fan radiates out into the Bhagirathi Valley from the mouth of the Rudugaira Valley at 3015 m asl. This fan slopes at about 12° and contains subrounded clasts up to 1 m in diameter. There is a clear down-valley fabric in the massive matrix-supported diamict that comprises the 10-m-thick exposed section, with some of the clasts imbricated (Fig. 10B). These features are characteristic of catastrophic debris flow deposits (Smith, 1986; Todd, 1989). Large boulders (>10 m in diameter) are present on the forested surface of the fan (Fig. 13),

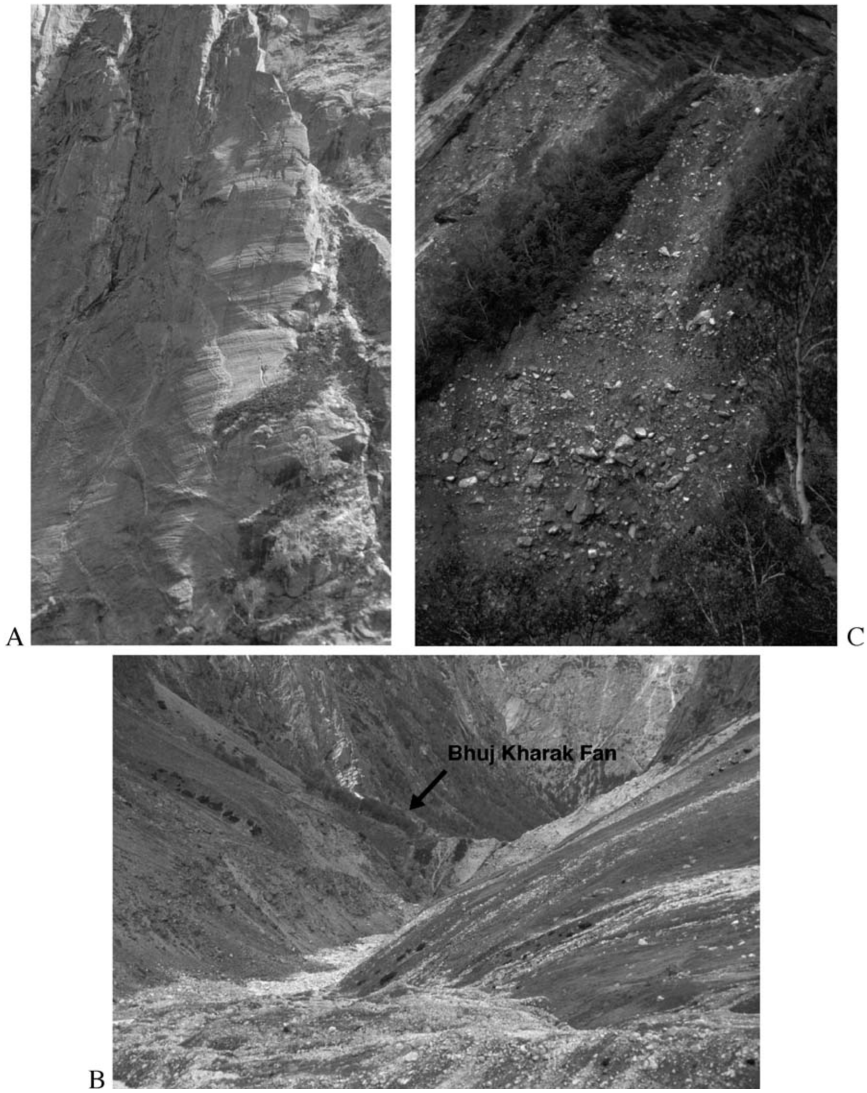



Fig. 12. The Kedar Valley showing (A) striations in bedrock on the east side of the valley below Bhuj Kharak (B) down-valley view of the main fan that was sampled at Bhuj Kharak. This illustrates the steepness of the valley sides and short-transport distance. (C) A 25-m-thick section of debris flow fan at Bhuj Kharak containing resedimented glacial sediments comprising massive matrix-supported diamict with edge-rounded clasts up to 1.5 m in diameter.

but the numbers have been reduced because of quarrying for building stone.

The area between Gangotri Village and just below the mouth of the Rudugaira Valley (Fig. 2) is dominated by a wide ($\sim 250$ m) granite strath terrace that is incised by the Bhagirathi River to form a 50-m-deep box-shaped canyon (Fig. 14). The Gangotri strath terrace is inset into the Rudugaira debris flow fan and thus post dates fan formation. However, the truncation of the Rudugaira debris flow fan is minor, indicating that the cutting of the strath terrace occurred shortly after fan sedimentation ceased when the local base level had not dropped significantly.

CRN dating was undertaken on the debris flow fan and terrace at Bhuj Kharak at 3875 m asl

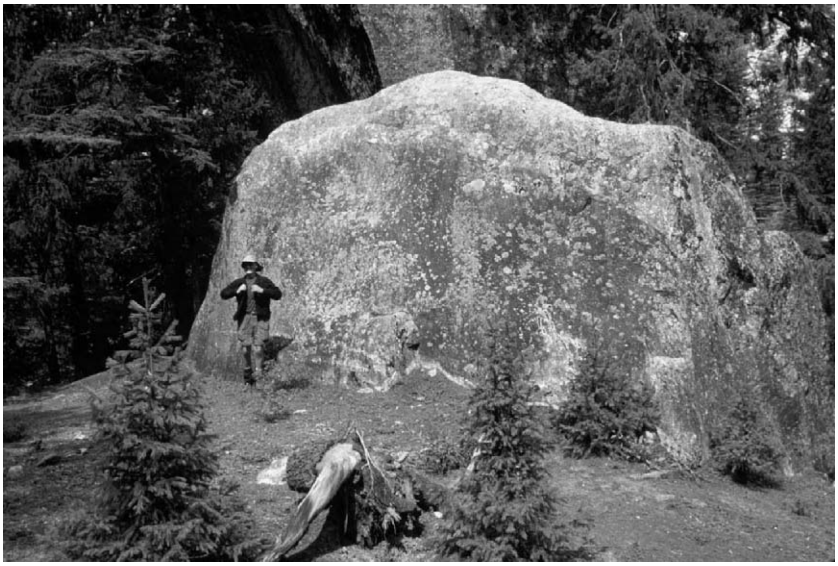


Fig. 13. Sample BH21 on the surface of the Rudugaira fan where it enters the Bhagirathi Valley at ~ 3015 m asl. This sample comprises a gneiss boulder ~ 6 m in diameter with 5 m of relief. A section through this fan is shown in Fig. 10B.

(samples BH6–7, BH9), on the debris flow fan at the mouth of the Rudugaira Valley at ~3025 m asl (sample BH21) and the strath terrace below Gangotri village at ~3020 m asl (samples BH1–3, BH24). The CRN dates on the paraglacial debris flow fans define their formation to between ~5.2 and 3.4 ka, while the strath terrace formed between ~4.8 and 3.3 ka. A debris flow fan dated above

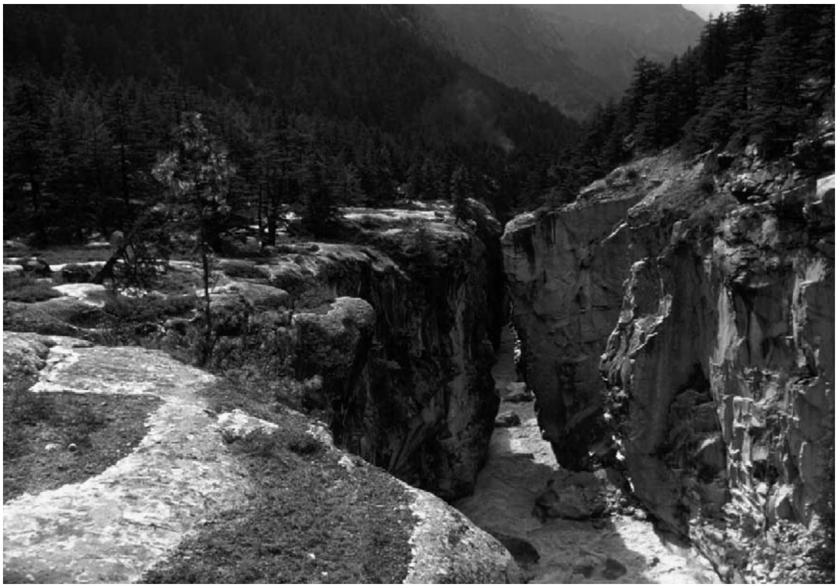


Fig. 14. Down-valley view of the strath terrace near Gangotri village illustrating the extensive flat surface of fluvially polished granite bedrock and the 50-m-deep box canyon cut into the strath terrace.

Bhujbas (elevation: 4140 m asl) in the Gaumukh area is also related to this period of paraglacial activity having an age of ~3.7 ka (sample BH33).

Several of the samples (BH7, BH9, BH34) that were CRN dated from these landforms have younger ages, ~1.8 ka. The strong clustering of older ages (~4.8 to 3.3 ka) derived from the strath terrace and its position stratigraphically higher than the paraglacial debris flow fans suggest that it is likely that these younger ages are invalid, and that the true age is between ~5.2 to 3.3 ka. There are several possible explanations for these younger ages:

(i) The boulders toppled perhaps during a single event such as an earthquake. This is an unlikely scenario because the boulders sampled are

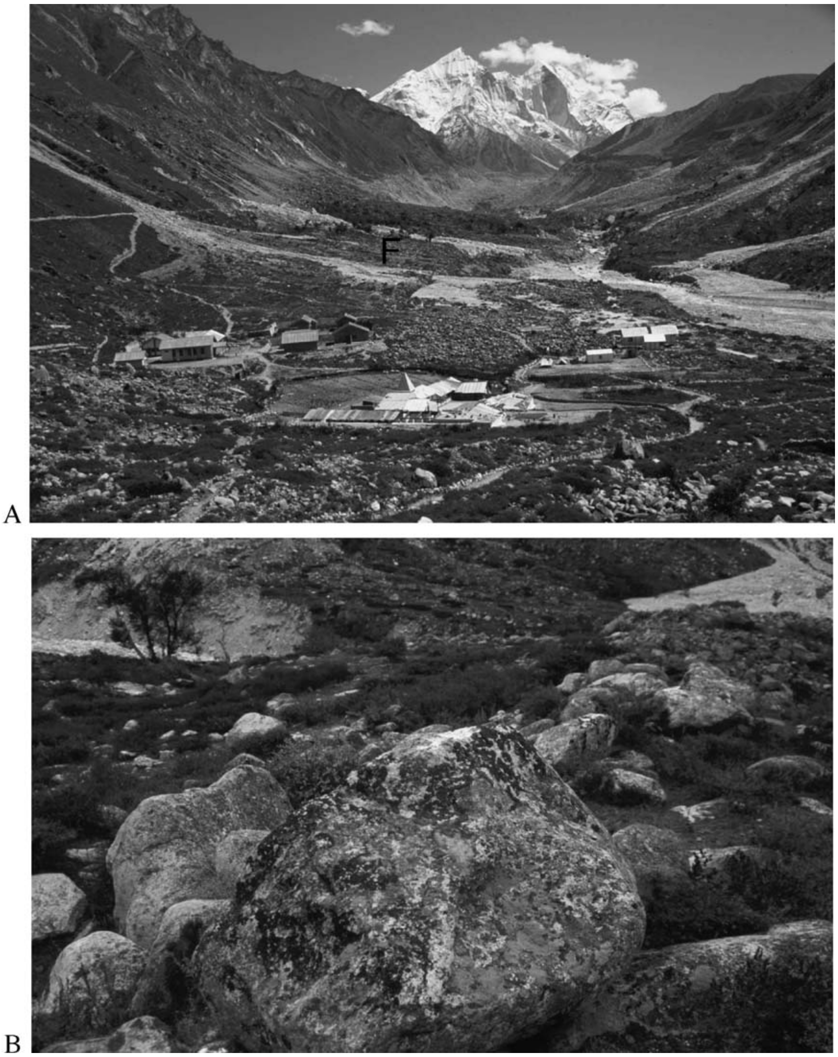



Fig. 15. View of the paraglacial debris flow fans that built out following the Gangotri Stage. (A) Up-valley view from Bhujbas (foreground) toward the Gangotri Glacier showing the impressive paraglacial debris flow fans that have built out during the last millennium and the fan (F) where samples BH38 and BH39 were derived. (B) Down-valley view along the fan associated with the Gangotri Stage moraine. Note the coarseness and mild vegetative cover.

situated along the relatively flat distal fan edges far removed from areas that are subjected to topple and rock falls.

(ii) The boulders yielding older ages were previously exposed, and thus, the younger boulders actually give the true age of deposition. This is unlikely because four CRN dates (samples BH1–3, BH24) from the strath terrace tightly cluster and are contemporaneous with CRN dates on the older fans. Furthermore, sample BH21 from the Rudugaira fan (Fig. 13) is an ideal sample because it is extremely large (6 m diameter, 5 m relief), firmly in place on the fan surface, and, therefore, it is highly unlikely that it has moved or been exhumed since initial fan development. It produced a CRN age of ~5.2 ka.

(iii) The fans could have been reworked during undetected paraglacial events around ~1.8 ka and deposited the smaller, less exposed boulders on the existing fan surfaces. However, the sediments comprise conformable massive beds with no apparent evidence of an erosional event.

(iv) The boulders may have been exhumed by postdepositional erosion. This is very likely given the intensity of monsoonal rainfall events in this region and the associated high rates of erosion (Barnard et al., 2001).

### 6.2. Gaumukh

A fan above Gaumukh at an altitude of ~4145 m asl and >250 m above the present valley floor, grades into a depression below a moraine that formed during the Bhagirathi Glacial Stage. The fan surface is covered with grasses and low shrubs, and numerous small boulders (<2 m in diameter). The debris flow fan was CRN-dated (samples BH33–34) to between 3.7 and 1.9 ka. The youngest sample is probably the result of exhumation because the majority of CRN dates on other morphostratigraphically similar terraces and fans cluster at ~4–5 ka (see previous section: samples BH1–3, BH6, BH21, BH24). This is the oldest documented paraglacial deposit near the Gangotri Glacier.

The entire valley floor between Bhujbas and Gaumukh, in the foreland of the Gangotri Glacier (Figs. 2 and 3), has been extensively reworked and resedimented by glacial and paraglacial activity. A large, bouldery and mildly vegetated debris flow fan (Fig. 15), ~3.25 km from the present mouth of the Gangotri Glacier and directly down valley of the Gangotri Stage moraines, dates to ~0.8 ka (samples BH38–39). This age is essentially identical to CRN dates of the Gangotri Stage moraines (samples BH29–BH32; see Fig. 8). Furthermore, the vegetation, soil development, boulder size and frequency, lichen growth and the lithoclast assemblage are similar on the paraglacial debris flow fan and moraine.

Historical accounts document that the last 200 years or so have been marked by rapid retreat of the Gangotri Glacier (>2 km), much of which (>1 km) occurred during the later part of the 20th century (Owen and Sharma, 1998). The area within 2 km of the mouth of the Gangotri Glacier is a complex assemblage of

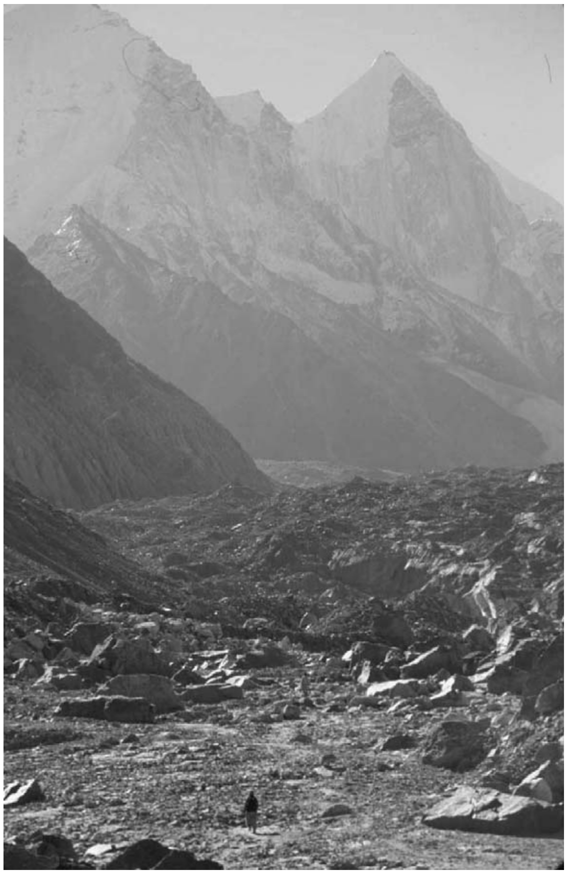


Fig. 16. Up-valley view toward the mouth of the Gangotri Glacier, showing the vast field of debris. Note the person in the foreground for scale.

boulder-dominated debris flow fans and moraines that are unvegetated with little or no soil development (Fig. 16). The fan sediments comprise poorly sorted, massive, matrix-supported diamicts containing subrounded, poorly imbricated pebbles, cobbles and boulders. This suggests extensive reworking of the sediment by repeated cycles of glacial and paraglacial activity. Owen and Sharma (1998) used geomorphic mapping, historical documentation and sedimentology to show that these young fans were the result of the rapid resedimentation of moraines by paraglacial debris flow fans that occurred immediately upon glacial retreat and were quickly abandoned. Major sedimentation ceased on all fans in the study area soon after deglaciation was complete.

## 7. Discussion

The CRN dating undertaken in this study and Sharma and Owen's (1996) OSL dates show a complex glacial and paraglacial depositional history for this region. The revised glacial chronology is shown in Table 3. Glacial chronologies based on or refined by CRN dating have been presented in other areas of the Himalaya (summarized in Owen et al., 2002a). Owen et al. (2001) showed that in Lahul, northwest Himalaya, glacial events did not coincide with global ice volume extension but were related to increases in monsoon activity. They hypothesized that a strong monsoon can cause heavy snowfall at higher elevations and thus contribute to a positive mass balance, even if temperatures are warmer, such as during the Late Glacial Interstadial. This theory is supported by our work in Gangotri which shows a glacial advance during the Late Glacial at between 11 and 15 ka. The termination of this glacial stage may be tentatively correlated with Heinrich Event 1 (H1) at 14.3 $^{14}$C ka BP; however, it may be also be coincident with the Late Glacial Interstadial and/or the Younger Dryas Stade. Nevertheless, recent work is increasingly indicating that glaciers and ice sheets in other regions of the world maintained their maximum extent until ~H1, after which, they underwent significant retreat (Licciardi et al., 2001; Clague and James, 2002; Dyke et al., 2002), and we suggest that the glaciers maintained until this time. In contrast, Owen et al. (2001) provide evidence for extensive glaciers during the Late Glacial Interstadial in the Lahul Himalaya to the NW of Garhwal, and, therefore, it is possible that the glaciers were also extensive in this region during the Late Glacial Interstadial.

Table 3
Revised glacial chronology of the Garhwal Himalaya

| Glacial stage | Characteristics | Age | Climatostratigraphic stage |
|---|---|---|---|
| Bhagirathi Stage | Extensive valley glaciation | ~ 63–11 ka | MIS4/MIS3 to Late Glacial Interstadial |
| Kedar Stage | Moraines and fans in tributary valley | ~ 7 ka | Probably early Holocene, related to the ~ 8.5 ka cold event? |
| Shivling Advance | Moraines in all valleys followed by extensive paraglaciation | ~ 5 ka | Early Neoglacial |
| Gangotri Stage | Moraines and fans in upper main valley flood at Jhala | ~ 1 ka | Medieval Warm Period/Little Climatic Optimum |
| Bhujbas Stage | Moraines and fans near present glacial snout | ~ 200–300 years BP | Little Ice Age |

Elsewhere in the Himalaya, glaciation was restricted to within 10 km of the present glacier terminus (Owen et al., 2002a). In the Khumbu Himal of Nepal, Richards et al. (2000) showed that glaciers were restricted in extent during the global Last Glacial Maximum, and they recognized an advance coincident with the early Holocene insolation maxima.

It is tempting to correlate the Kedar Stage (~7.0 ka) with the ~8.5 ka cooling event that is evident in the Greenland ice cores (Alley et al., 1997) caused by the catastrophic drainage of the Laurentide lakes into the North Atlantic at 8.47 ka (Barber et al., 1999). In support of this, Phillips et al. (2000) believe that they recognize a glacial advance in the Nanga Parbat Himalaya at this time. Although, our CRN dates are significantly younger, the difference in timing might be attributed to an underestimation in CRN ages due to erosion or a significant lag time between glacial response in the Himalaya and the North Atlantic. The latter view is unlikely because no lag time was evident from the Nanga Parbat data of Phillips et al. (2000).

No paraglacial evidence is preserved in the main Bhagirathi Valley that predates the Shivling Advance (~5 ka). At the end of this glacial advance, the area near Gangotri Village, including the mouth of the Kedar and Rudugaira Valley, was the site of intense paraglacial activity during the start of the Neoglacial (~5 ka). Abundant glacial sediment available upon the termination of the Shivling Advance was resedimented to form paraglacial debris flow fans, and the high meltwater discharges and high sediment loads associated with glacial retreat were responsible for cutting the strath terrace at ~4–5 ka. This was later incised to form the contemporary box-shaped gorge. These landforms are virtually identical in age to OSL samples (~5 ka) derived from aeolian material overlying moraine material. These dates combined with exposed sections consisting of till directly overlain by massive fan deposits suggest their close relationship. Ballantyne and Benn (1994) and Curry and Ballantyne (1999) describe similar stratigraphy in the glaciated landscapes of Norway.

On the basis of OSL dating, Richards et al. (2000) recognized a similar age advance to the Gangotri stage (~1 ka) in the Khumbu Himal, which they assigned to the Lobuche Glacial Stage, coincident with the Little Climatic Optimum. The subsequent advance, the Bhujbas Stage (~200–300 years), is equivalent to the Little Ice Age (Grove, 1988).

The last 1000 years has been marked by several smaller cycles of glacial and paraglacial activity within ~3.5 km of the present Gangotri Glacier, culminating with the recent rapid glacier retreat. It is likely that there were numerous similar glacial fluctuations on centennial time scales during other paraglacial times in the middle and early Holocene. The repeated cycles of glacial and paraglacial reworking may have eliminated the evidence of the smaller scale fluctuations.

CRN and OSL dating, geomorphological relationships, dendrochronology, sedimentology, stratigraphy and historical documentation illustrate that fan and terrace sedimentation coincided with or immediately followed the glacial stages. The deposits are indicative of catastrophic paraglacial debris flow fans consisting of massively bedded diamicts, containing edge-rounded clasts, often striated, with isotropic clast fabrics that show slight down-valley preference. In section, the sediments are occasionally found directly overlying and/or underlying glaciogenic sediments. The depositional history of each fan is rarely represented by more than one or two events in sections commonly exceeding 20 m in thickness, indicating that fan sedimentation is extremely rapid and catastrophic. The paraglacial debris flow fan deposits in Garhwal are similar to those studied in Langtang Himal (Watanabe et al., 1998) as well as those studied by Ballantyne and Benn (1994) and Curry and Ballantyne (1999) in Norway.

The absence of Pleistocene fans, terraces and moraines can be attributed to the high denudation and resedimentation rates associated with rapid sediment transfer in the glaciated upper Bhagirathi valley. CRN dating indicates that complete resedimentation of landforms occurs on a time scale of less than ~20,000 years for moraines (oldest BH35B, ~15.3 ka) and is less than ~10,000 years for paraglacial debris flow fans and terraces (oldest BH14, BH16, ~6.6 ka). The preservation of paraglacial debris flow fans and terraces is more tenuous than the moraines because they are commonly situated in the foreland of fluctuating glaciers. The existence of high-runoff rates and sediment loads is evidenced by the broad strath terrace that formed below Gangotri Village at ~4–5 ka.

## 8. Conclusions

The upper Bhagirathi Valley is a highly dynamic environment with rapid sediment transfer responding to oscillations between periods of glacial advance and retreat. On the basis of our CRN dating, it is apparent that the formation of fans is intimately related to deglaciation, and that fan ages are indiscernible from those of adjacent moraines. Furthermore, the sedimentology and stratigraphy of the exposed fan sections support the view that they formed by resedimentation of tills. These sections generally consist of massively bedded, matrix-supported diamicts with edge-rounded, isotropic clast fabrics but with occasional down-valley preference. These sedimentary features taken together with the thick sections commonly containing only one or two events are indicative of a depositional history dominated by catastrophic paraglacial debris flow fans. The rapid glacial retreat during the last several decades suggests that glaciers are highly sensitive to climate fluctuations, and that the Himalaya may be an ideal location to document the effects of human–induced global warming. The CRN dates on moraines in this study have helped to refine the glacial chronology for the Garhwal Himalaya summarized in Table 3. These data suggest that glaciers are likely to advance during insolation maxima and are likely asynchronous with the maximum advances of the Northern Hemisphere ice sheets. There exists compelling evidence that significant glacial advances coincided not with global increases in ice volume but rather with peak monsoon periods. This conclusion supports the work in Lahul (Owen et al., 2001) and Karakoram Mountains (Owen et al., 2002b) which suggest that, despite warmer temperatures, the increased snowfall at higher elevations during increased monsoon activity may cause glaciers to advance. This may explain how certain glaciers in the Himalayas are presently advancing (Owen et al., 1998) despite the current warming trend. Furthermore, it implies that the mass balance of some Himalayan glaciers may become more positive in the future if warming trends are coupled with increased monsoon activity.

## Acknowledgements

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