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Style and timing of glaciation in the Lahul Himalaya, northern India: a framework for reconstructing late Quaternary palaeoclimatic change in the western Himalayas

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ABSTRACT: This paper presents a revised glacial chronology for the Lahul Himalaya and provides the most detailed reconstruction of former glacier extents in the western Himalayas published to date. On the basis of detailed geomorphological mapping, morphostratigraphy, and absolute and relative dating, three glaciations and two glacial advances are constrained. The oldest glaciation (Chandra glacial stage) is represented by glacially eroded benches and drumlins (the first to be described from the Himalaya) at altitudes of >4300 m and indicates glaciation on a landscape of broad valleys that had minimal fluvial incision. The second glaciation (Batal glacial stage) is represented by highly weathered and disssected lateral moraines and drumlins representing two phases of glaciation within the Batal glacial stage (Batal I and Batal II). The Batal stage was an extensive valley glaciation interrupted by a readvance that produced superimposed bedforms. Optically stimulated luminescence (OSL) dating, indicates that glaciers probably started to retreat between 43 400 ± 10 300 and 36 900 ± 8400 yr ago during the Batal stage. The Batal stage may be equivalent to marine Oxygen Isotope Stage 4 and early Oxygen Isotope Stage 3. The third glaciation (Kulti glacial stage), is represented by well-preserved moraines in the main tributary valleys that formed due to a less-extensive valley glaciation when ice advanced no more than 12 km from present ice margins. On the basis of an OSL age for deltaic sands and gravels that underlie tills of Kulti age, the Kulti glaciation is younger than 36 900 ± 8400 yr ago. The development of peat bogs, having a basal age of 9160 ± 70 ^{14}C yr BP possibly represents a phase of climatic amelioration coincident with post-Kulti deglaciation. The Kulti glaciation, therefore, is probably equivalent to all or parts of late Oxygen Isotope Stage 3, Stage 2 and early Stage 1. Two minor advances (Sonapani I and II) are represented by small sharp-crested moraines within a few kilometres of glacier termini. On the basis of relative weathering, the Sonapani advance is possibly of early mid-Holocene age, whereas the Sonapani II advance is historical. The change in style and extent of glaciation is attributed to topographic controls produced by fluvial incision and by increasing aridity during the Quaternary. © 1997 by John Wiley & Sons, Ltd.

KEYWORDS: Himalayas; glaciation; OSL dating; drumlins.

Introduction

Recent models of global climate change have stressed the significance of Late Cenozoic tectonic uplift of the Himalaya and Tibetan Plateau in the determination of climatic change in the Northern Hemisphere (Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992). However, there is much disagreement regarding the relationship between uplift and climate change, particularly with respect to the forcing mechanisms (Molnar and England, 1990), the timing of uplift (Shroder *et al.*, 1993; Coleman and Hodges, 1995; Owen *et al.*, 1996), and the nature and timing of environmental change (Zheng, 1989a and b; Derbyshire and Owen, in press). There is also

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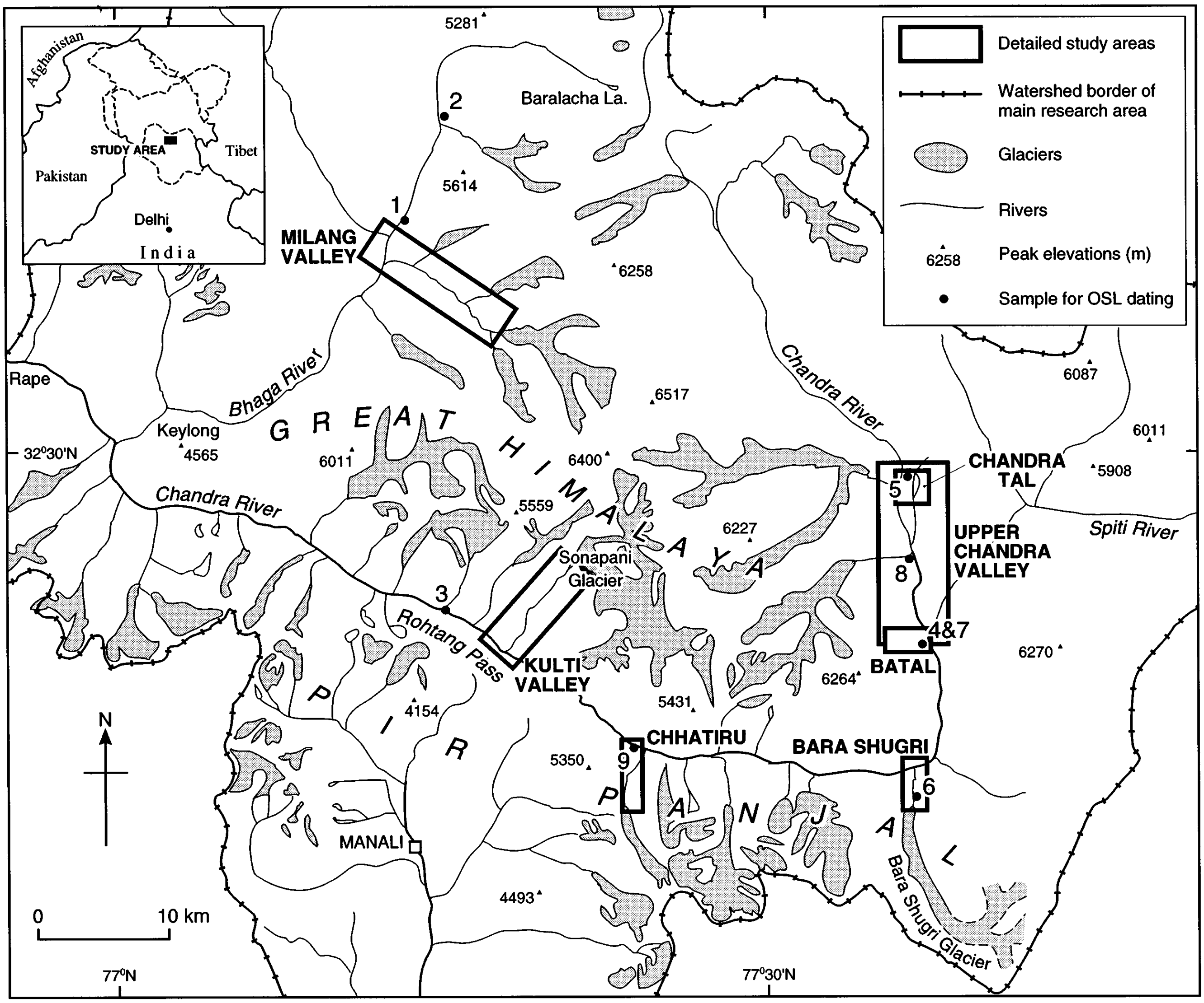

Figure 1 Map of the Lahul Himalaya showing the locations of detailed study areas: Kulti Nala valley; Milang valley; Batal (see Fig. 4 for detailed map); Chandra Tal (see Fig. 7a for detailed map); Bara Shugri (see Fig. 5 for detailed map); Chhatiru (see Fig. 6 for detailed map). Detailed maps of the Kulti, upper Beas and Milang valleys are presented in Owen *et al.* (1996).

a paucity of accurate reconstructions of former ice thickness and extent, and dating of glaciation from within the Himalayas and Tibet. This is surprising because mountain glaciers are very sensitive indicators of past climatic change and their deposits provide a palaeoclimatic record for high-altitude regions where biostratigraphic evidence is often fragmentary or absent (Clapperton, 1990; Gillespie and Molnar, 1995). Studies in the Karakoram Range (Derbyshire *et al.*, 1984; Shroder *et al.*, 1993), Swat Kohistan (Porter, 1970; Owen *et al.*, 1992), Lahul (Owen *et al.*, 1995, 1996), Garhwal (Sharma and Owen, 1996), central Nepal (Shiraiwa and Watanabe, 1991; Shiraiwa, 1993; Fort, 1996), north Everest (Burback and Cheng, 1991), and Zanskar (Osmaston, 1994) have delimited glacial sequences, yet there is often little or no dating control in these areas, which makes spatial and temporal correlation of the glaciations difficult.

This paper presents evidence from the Lahul Himalaya, Himachal Pradesh, northern India (Fig. 1), on former glacier extent, thickness and style, and timing of glaciation. It refines the initial chronology proposed by Owen *et al.* (1996) by using established absolute and relative dating criteria of sediments and landforms. This paper also provides the most detailed geomorphological mapping and reconstruction of former ice extents ever undertaken for any region within the western Himalayas and illustrates the usefulness and limitations of optically stimulated luminescence (OSL) dating in the Himalayas. Detailed reconstructions of former ice extents, such as those presented within this paper, are an essential data source for modelling regional palaeoclimates and global circulation patterns. This paper, therefore, provides a framework for reconstructing late Quaternary palaeoclimatic change in the western Himalayas.

Lahul is a particularly important region within the Himalaya because it marks the junction between the monsoon-influenced southern flank of the Pir Panjal (Lesser Himalaya) and the Great Himalaya, and is therefore sensitive to fluctuations in the south Asian monsoon through time. It is also an important area because it provides the best preservation of evidence of glaciation within the western Himalayas. Owen *et al.* (1996) highlighted its potential for palaeoclimatic studies by establishing the first glacial chronology in which they recognised three glaciations and at least two Holocene advances. This tripartite pattern of glaciation is recurrent within the western Himalaya and Karakoram Ranges, with each glaciation becoming progressively less extensive throughout late Pleistocene times (cf. Shroder *et al.*, 1993; Derbyshire and Owen, in press). Geological evidence has shown that the earlier glaciations were generally associated with broad valleys whereas later glacial advances were more topographically constrained, within the present valley system (Derbyshire *et al.*, 1984; Owen *et al.* 1996; Derbyshire and Owen, in press). The reasons for this remain unclear, but glaciation style may reflect terrain conditions, which are altered through time by erosional and depositional events during earlier glaciations (Shroder *et al.*, 1993; Owen *et al.*, 1996; Derbyshire and Owen, in press). This pattern may also be due to Pleistocene uplift of the Pir Panjal and the Lesser Himalaya relative to the northern ranges, which would have progressively shielded monsoonal precipitation, thereby controlling glacial style. In addition, this pattern may also reflect a weakening of the Indian monsoon during late Quaternary times. This paper provides evidence to show that the style of glaciation in the Lahul Himalaya was probably a consequence of increased aridity during late Quaternary times, probably due to a weakening of the Indian monsoon, and that the glaciers were topographically constrained. In the latter case, progressive incision of the landscape would have created narrower and deeper valleys down which glaciers would have flowed. The glaciers would have been confined within the valleys and could not have spread out to produce extensive ice-caps or ice-sheets.

The study area

The Lahul area lies just to the north of the Pir Panjal, which has been an area of active uplift during mid- to late Cenozoic times. The region of Lahul comprises two NW–SE trending mountain ranges, the Pir Panjal and the Great Himalaya, both of which include peaks higher than 6000 m in altitude and which are separated by the major valley of the Chandra River, having an average altitude in this area of 3500 m. The Bhaga River forms a major northern tributary within the Great Himalaya (Fig. 1). Climate varies both altitudinally and geographically, with a strong N–S precipitation gradient, varying from the monsoonal influenced southern slopes and passes of the Pir Panjal to arid valleys on the northern flank of the Great Himalaya. This is best seen in the distribution of vegetation, which ranges from mixed deciduous forest at lower altitudes on the southern slopes of the Pir Panjal, through coniferous forest to alpine vegetation at altitudes between 3550 and 4850 m, with little vegetation above 4850 m. North of the Pir Panjal, increasing aridity is indicated by the absence of trees. The dominant vegetation in this area is grassland, which decreases in cover northwards, such that much of the upper Chandra and Bhaga valleys are bare of vegetation.

Owen *et al.* (1995) showed that the present glacier system in the Lahul area is dominated by steep, high-activity glaciers that carry large amounts of supraglacial debris. Equilibrium line altitudes (ELAs) vary considerably, being dependent upon both geographical location, with respect to the N–S aridity gradient, and aspect, particularly with regard to the influence of blown snow and avalanche processes (cf. Holmes, 1993). The interpretation of present and past ELAs is difficult because of the poor quality of topographic maps and the inaccessibility of much of the region. In addition, variations in ELAs between valleys today are so large that ELA values have little significance. For example, based on the height of the termination of lateral moraines up-valley and the topography of the ice surface, Batal Glacier and an unnamed glacier 2 km to the north have ELAs of 4450 and 4740 m, respectively. This is just one of many anomalous glaciers in Lahul and hence any regional reconstructions of ELAs would have to allow for or neglect these glaciers. In addition, many of the glaciers are debris covered, further complicating any reconstruction of ELAs because little is known with regard to the role of supraglacial debris in reducing ablation and hence affecting the ELA. A variety of glacial and paraglacial landforms and sediments are present at a range of altitudes throughout the Lahul Himalaya (Owen *et al.*, 1995) and can be differentiated temporally on the basis of relative weathering criteria (Fig. 2).

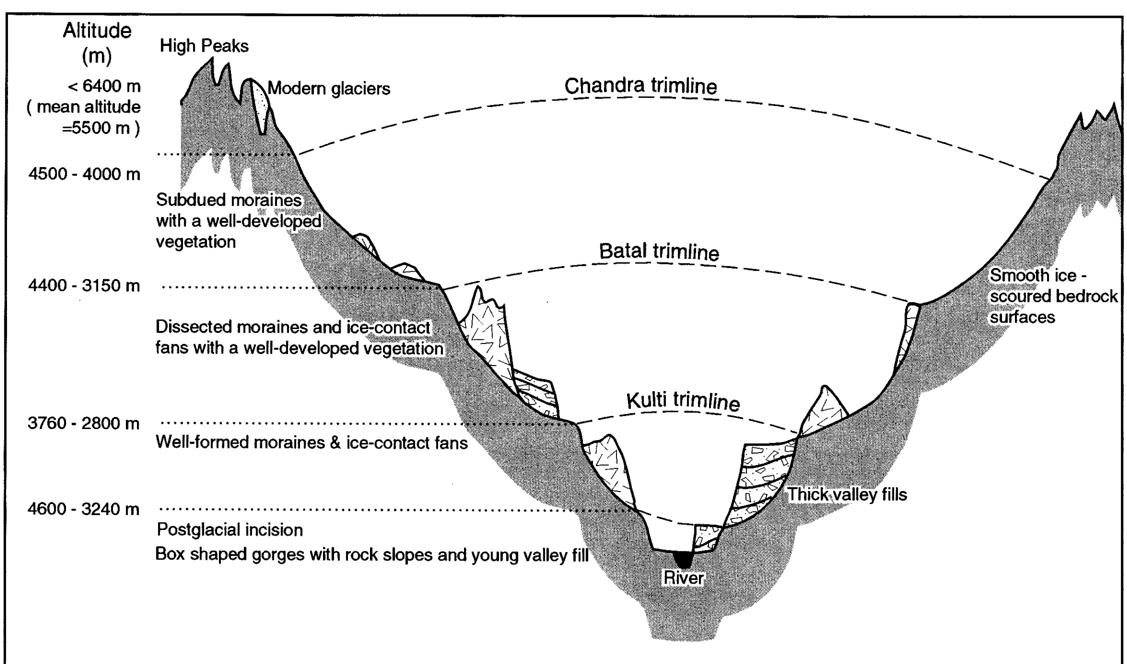

Figure 2 Schematic section showing the altitudinal zonation of landforms associated with the main valleys of Lahul.

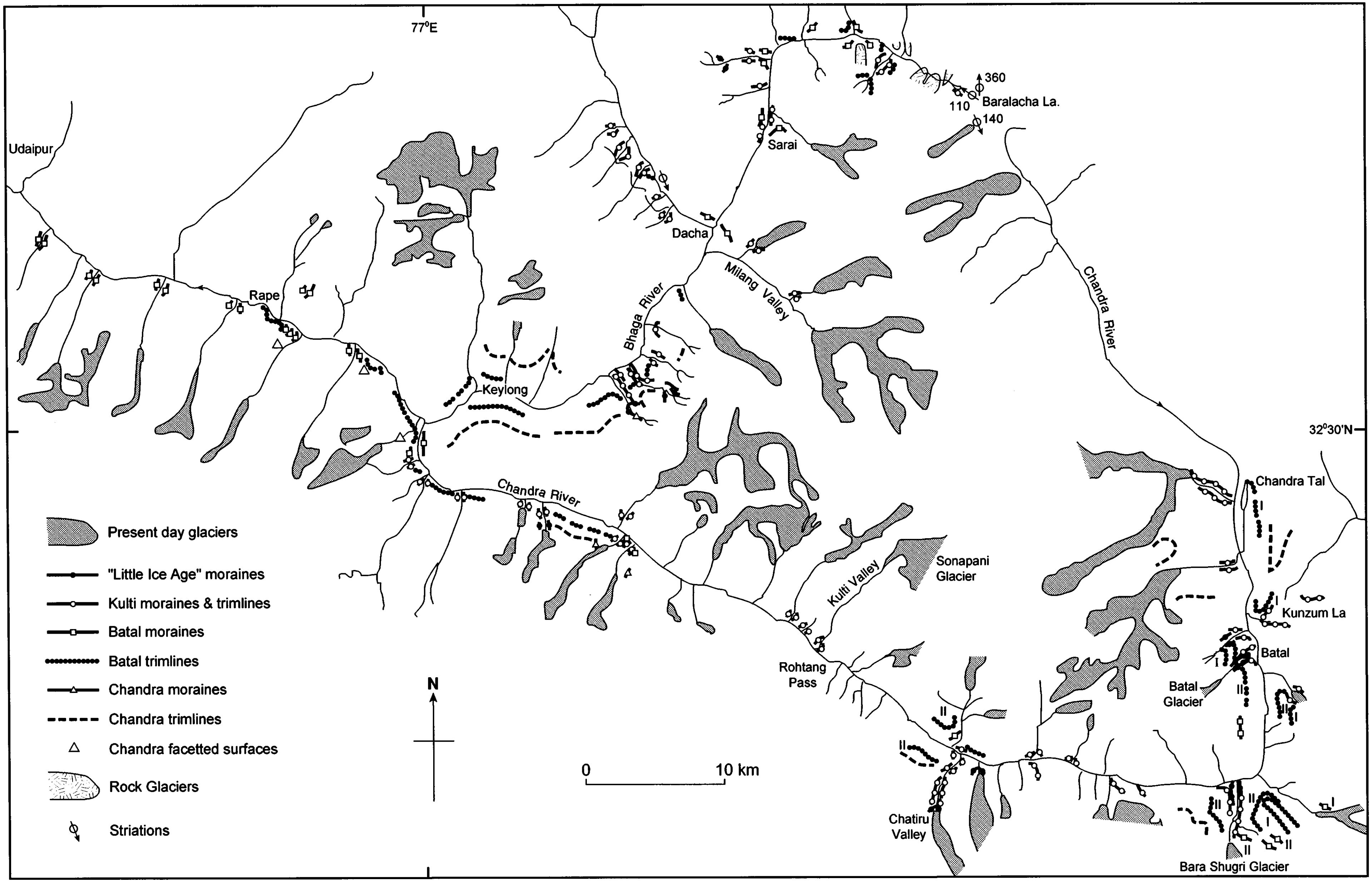

Figure 3 The main glacial landforms and the present ice distribution along the Chandra and Bhaga Valleys.

Methods

Geomorphology

Major glacial landforms were mapped along the Chandra and Bhaga valleys at a scale of 1:250 000 (U502 Series) as part of a reconnaissance survey of the valley systems (Fig. 3). This mapping allowed the selection of specific areas and side valleys for mapping at scales of 1:10 000 to 1:1000 (Figs 4–8) following established procedures using field survey techniques and a global positioning system to establish location, aided by barometric altimetry (Owen *et al.*, 1995, 1996). Previous mapping was undertaken in the Kulti valley, the upper Beas valley, the Milang valley and the upper Chandra valley. These maps are presented in Owen *et al.* (1996) (Fig. 1). Emphasis was on the identification of end moraines and on the interpretation of stratigraphy using sedimentological criteria to establish lithofacies following the examples of Derbyshire and Owen (1990) and Owen (1994).

Relative dating

A relative chronology has been established using techniques similar to those used by Burke and Birkeland (1979) in the Sierra Nevada and Burbank and Cheng (1991) for the Rongbuk Valley, Mount Everest (Table 1). Moraines are correlated initially on the basis of morphostratigraphy with the five major glacial events identified previously in Lahul (Owen *et al.*, 1996). Relative age measurements are then used as a check on this preliminary chronology.

Relative dating studies in the Chandra valley were made in the Batal area, and the Chhatiru and Bara Shugri tributary valleys (Figs 4–6, 9 and 10; Table 2). Contrasting microclimates in each of the study areas complicates regional correlations (e.g. Fig. 10) and great care must be taken when interpreting the results. Table 3 lists the degree to which each technique was successful in differentiating glacial events.

Owen *et al.* (1996) used lichometry in the Kulti valley as an aid in distinguishing moraines of different age. It was not possible, however, to use this technique throughout the region because of the lack of lichens in the higher and more arid regions.

Radiocarbon and OSL dating

Because of the lack of organic material within sediments and landforms throughout the region only one sample was collected for radiocarbon dating. At Chandra Tal, several peat bogs occupy depressions within moraines. A sample from the base of a 115-cm-deep pit in a peat bog at an altitude of 4325 m (Fig 7A) consisted of unhumified plant

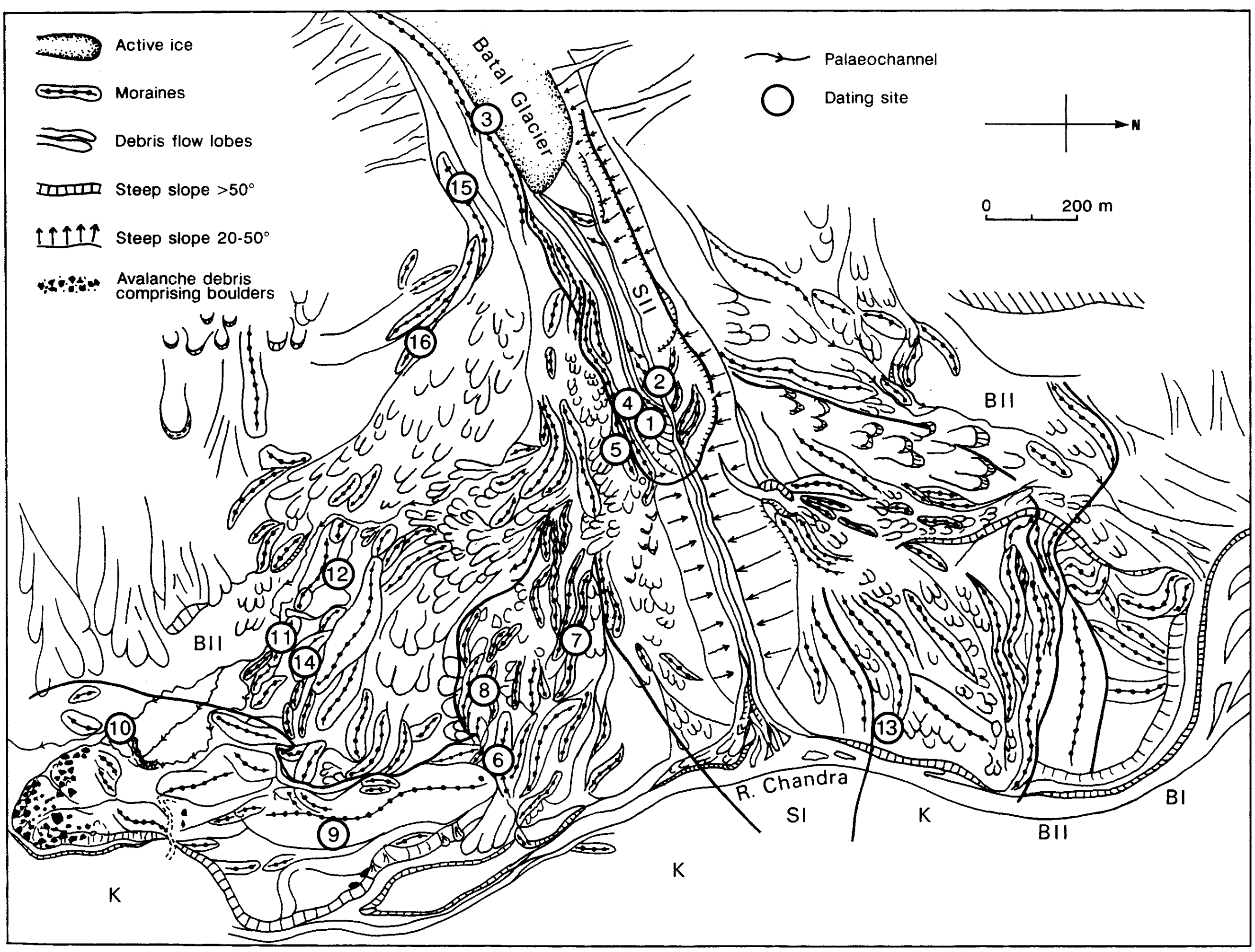

Figure 4 Geomorphological map of the Batal Glacier showing the positions of the relative dating sites (BI, Batal I Glacial moraines, BII, Batal II Glacial moraines; K, Kulti Glacial moraines; SI, Sonapani I moraines; and SII, Sonapani II moraines).

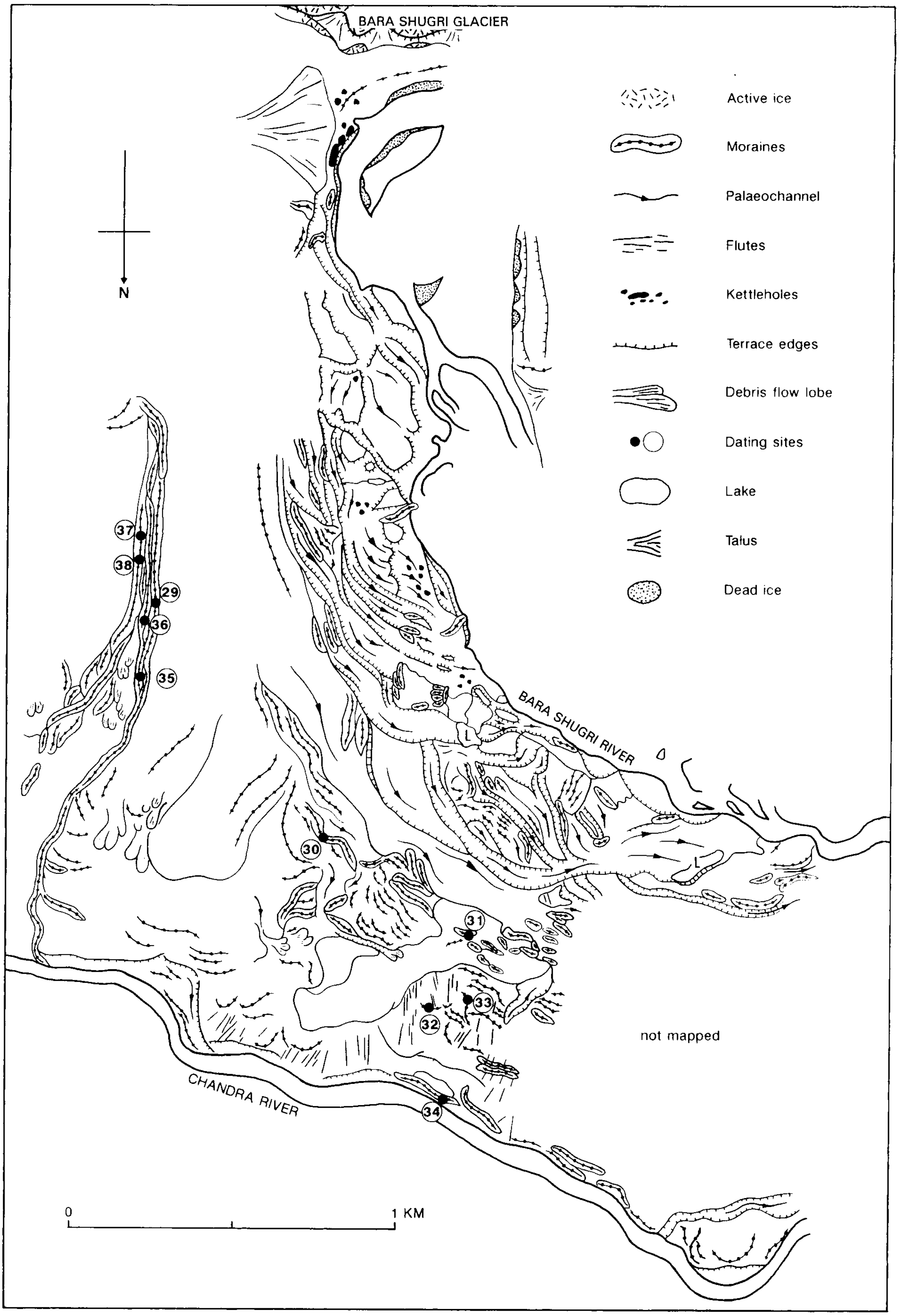

Figure 5 Geomorphological map of Bara Shugri.

fragments and algal mud. The detritus comprised comminuted plant fragments and the fine organic material was composed of algal mud. A ^{14}C AMS data of 9160 ± 70 ^{14}C yr BP was obtained (NERC Radiocarbon laboratory at East Kilbride in the UK). This is the first radiocarbon date from the Lahul Himalaya.

Nine samples were collected for optically stimulated luminescence (OSL) dating from nine different sites (Fig. 1 and Table 4). In the laboratory, under controlled lighting, the samples were dried (at 50°C) and sieved, isolating the 90–125 μm fraction. This material was subsequently treated with 40% hydrofluoric acid (HF), both to dissolve away the feldspar fraction and to etch off the outer alpha-irradiated layers of the quartz, and then washed in 10% hydrochloric acid and oven dried (at 50°C). The quartz fraction was floated off from the remainder of the sample using a sodium

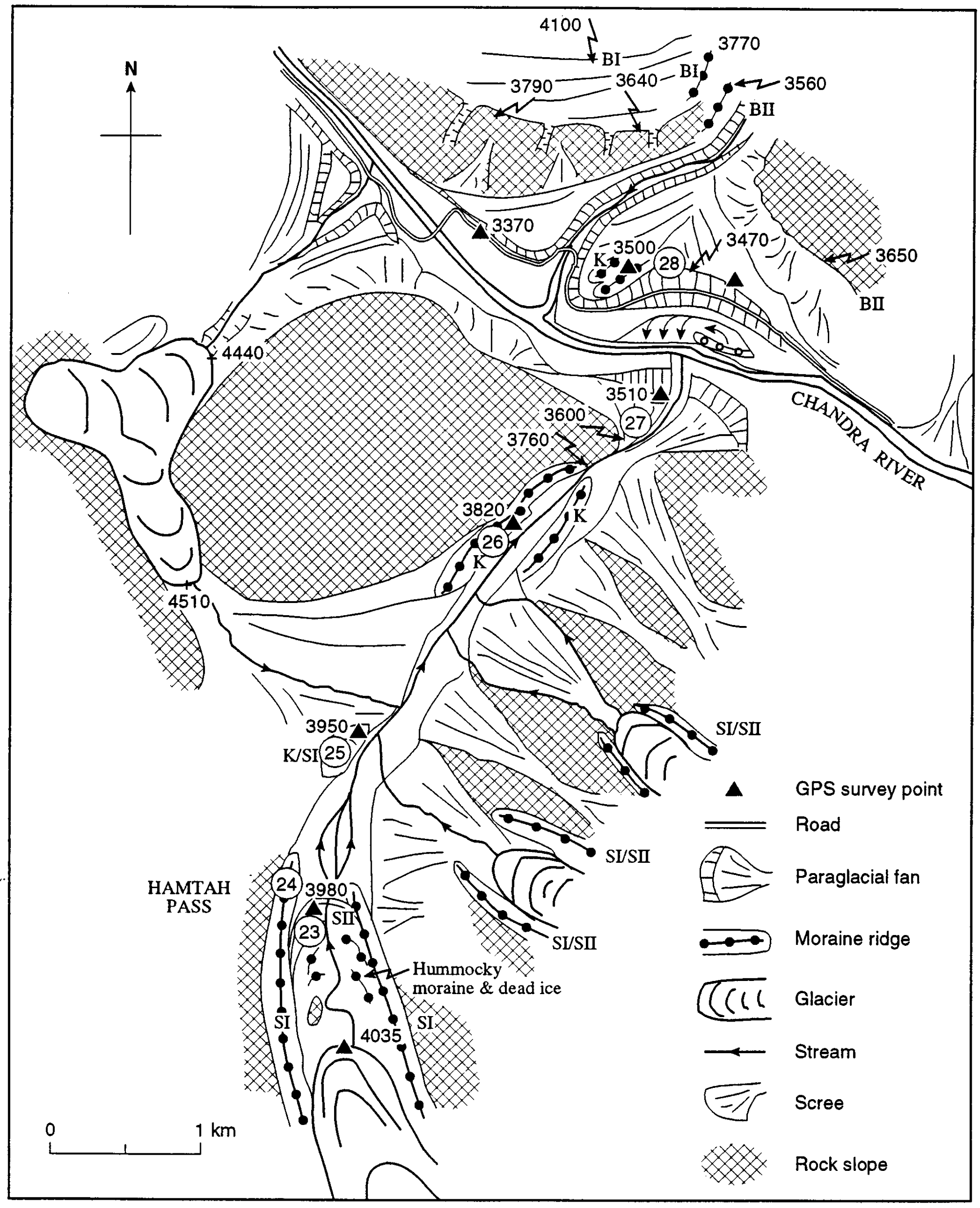

Figure 6 Geomorphological map of Chhatiru.

polytungstate solution of density 2.68 g cm^{-3}. After being dried and resieved, to retain the 90–125 μm size range, the samples were mounted on to 10 mm diameter aluminium discs using a silicone-based oil.

Seven samples (samples 1, 2, 3, 4, 6, 7 and 9) either completely dissolved away during the HF treatment (indicating that little or no quartz was present) or else had OSL signals dominated by feldspar inclusions within the quartz, preventing the separation of a pure quartz fraction. Very small concentrations of feldspar contributed significantly to the total signal owing to the low OSL sensitivity of the quartz in these samples. For this reason these samples are discussed no further, but mentioned here for the benefit of other workers who may collect samples from these locations.

Optically stimulated luminescence (OSL) measurements of the remaining two samples (5 and 8) were made on an automated Riso-set (TL-DA-12). During the OSL measurement, the samples were stimulated with green light from a filtered halogen lamp, at wavelengths between 420 and 560 nm (2.9–2.2 eV). Emissions were filtered with two U340 and one BG39 glass filters. The equivalent dose (ED) of each sample was obtained using the additive dose technique, applying a single saturating exponential fit to the naturally normalised total integral (from a 25 s OSL measurement) following a 5 minute 22°C preheat. To alleviate thermal transfer effects (Rhodes and Pownell, 1994), the signal measured following a subsequent bleaching and preheating treatment was subtracted from each aliquot.

The environmental dose rate calculations were based on the results of a neutron activation analysis of the sediments (measurements by Becquerel Laboratories, Lucas Heights, Australia). The moisture content of the sediment (as a percentage of the total weight) was estimated to be 3 ± 3%. The contribution to the environmental dose rate made by cosmic radiation was calculated according to Prescott & Stephan (1982) and was corrected for altitude.

Table 4 shows the results from the OSL measurements and other relevant information. The samples measured were found to have low OSL sensitivities, which combined with a considerable variation in behaviour between aliquots to give the relatively high degree of scatter observed in the

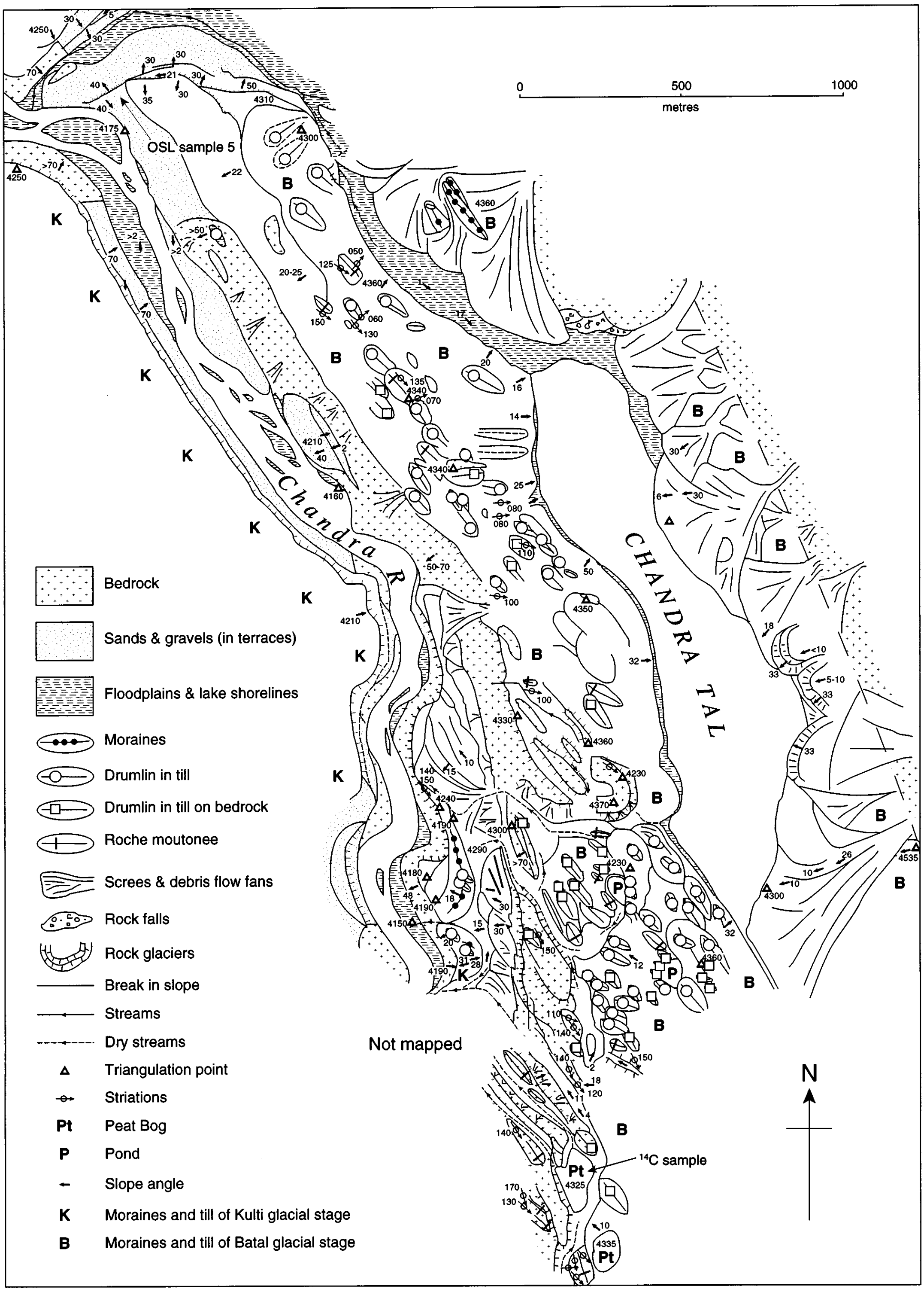

Figure 7 (a) Geomorphological map of the area around Chandral Tal.

results. The contribution to the total signal made by thermal transfer was small.

Styles of Glaciation

Previous work on the geomorphic features of Lahul (Owen *et al.*, 1995, 1996) has shown that many moraine ridges and trimlines can be allocated to specific glacial events (Fig. 3) and that progressively younger glacial landforms and sediments are inset into the older landscape, generally at lower altitudes (cf. Fig. 2). This initial interpretation was developed in 1993 and 1994 when a number of areas in both the Chandra and Bhaga valleys were mapped in detail. In this paper, the glacial landforms and sediments are first described within the framework already established (Owen *et al.*, 1996) allowing the use of this chronology to be tested by absolute and relative dating.

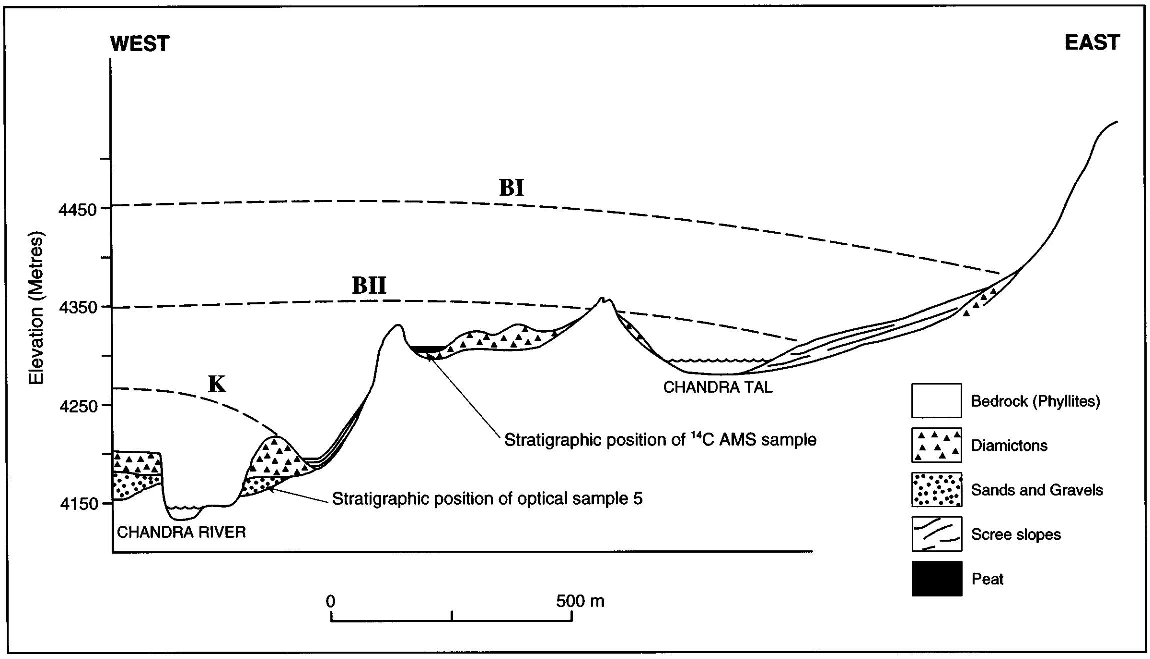

Figure 7 (b) Schematic cross-section showing former positions of ice across the Chandra Tal area.

Table 1 Details of the relative-weathering measurements (adapted from Burbank and Cheng, 1991)

Measurement	Number of measurements	Criteria for classification
Pitted (versus unpitted)	≥100 (phyllite boulders only)	Pits ≥3 mm depth covering more than 25% of the exposed surface of boulders ≥30 cm in diameter
Mean pit depth	10 (phyllite boulders only)	Average of measurements of the deepest pits found on boulders ≥30 cm in diameter; no more than two on any single boulder
Maximum pit depth	1 (phyllite boulders only)	Maximum pit depth found at site
Fresh-to-weathered	≥100 (phyllite boulders only)	Based on sound of repeated hammering of surfaces of boulders ≥30 cm in diameter; sharp "pings" defined as fresh; "thuds" defined as weathered
Surface boulder frequency	All boulders within an area of 30 m by 50 m	Number of boulders ≥30 cm in intermediate diameter
Boulder relief	≥100	Boulders ≥30 cm in diameter classified according to height (H) above ground surface versus intermediate diameter (ID) of widest cross-section. High relief: $H > 0.75\ ID$; intermediate relief: $0.75\ ID \geq H \geq 0.25\ ID$; low relief: $H < 0.25\ ID$
Maximum depth of solum	1	Maximum depth of solum at site
Mean percentage vegetation cover	5	The mean percentage vegetation cover for five 2 m quadrants at site
Vegetation diversity		The maximum number of different species of vascular plants at site

Chandra Glacial Stage

Evidence for this glaciation can be found along the Chandra and the lower Bhaga valleys, at altitudes between 3800 and 4500 m (Figs 3 and 11). It is represented by glacially eroded rock benches with abundant striations, whaleback and roche moutonnée forms, and subdued moraine ridge fragments that have well-developed vegetation, dependent to a degree on their altitude (Figs 12 and 13). Striations, such as those mapped north of the Kunzum La (the watershed of the Bhaga and Chandra Rivers) at altitudes >4600 m (Figs 8, 12 and 13) indicate a former ice flow direction to the southeast (140°). This interfluve area is composed of schist with a foliation dipping at high angles to the west. The outcrops are heavily striated and covered with a well-developed deep red-brown rock varnish. Scattered erratics of quartzite, sandstone and granite are found throughout this area to within 20 m of the interfluve ridge (Fig. 8). The former ice flow direction is oblique to the present trend of the Chandra valley, suggesting either that the ice was much thicker than the Chandra valley could accommodate or that this glaciation pre-dates the erosion of the Chandra valley. Small drumlins have been mapped at 4680 m in this same area and show a similar ice flow direction indicating ice moving southeast into the headwaters of the Spiti River.

A well-developed glacially eroded surface observed on

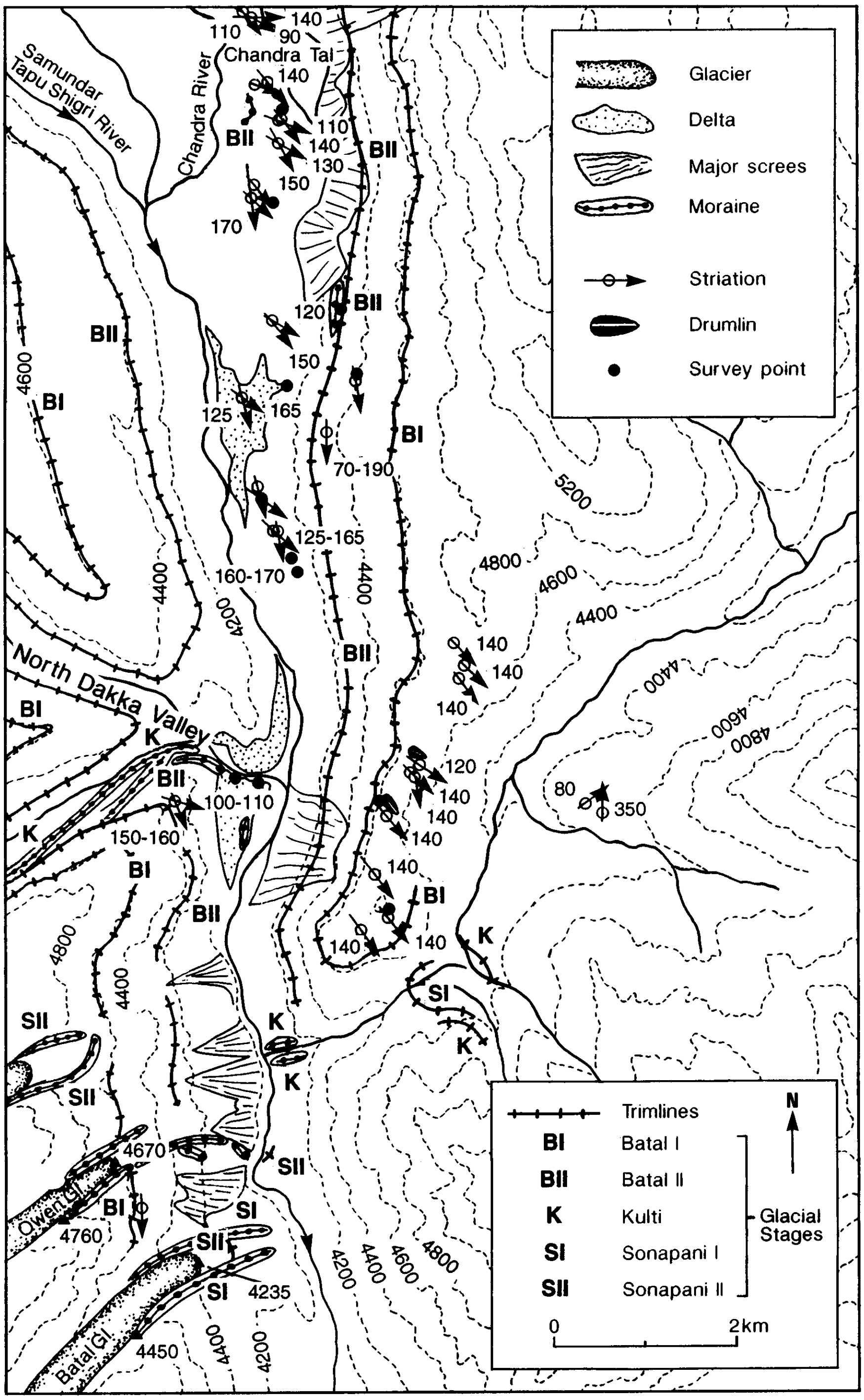

Figure 8 Geomorphology of the upper Chandra valley.

the western side of the Bara Shugri Glacier indicates a former ice flow northwards towards the Chandra valley at an elevation of ca. 4680 m. If this is correct, the ice had a source area in the Pir Panjal and those mountains were sufficiently high to allow glacier generation during the Chandra glacial stage. This suggests that uplift of the Pir Panjal during the Pleistocene was not significant in increasing the aridity of the Great Himalaya. Furthermore, ice flow direction is towards the main Chandra valley, which was therefore probably already in existence at this time.

In the lower Bhaga valley, around Keylong, a high-level erosion surface at 4000 m mapped on the eastern side of the valley is interpreted as being of Chandra Glacial age, owing to its position above a number of moraine ridges in the vicinity of the Chandra/Bhaga confluence that indicate later glacial events within these main valleys, at about Batal age. This point is exemplified at the confluence of the Shipting Nala with the Chandra River, where there are a number of terminal moraines from the tributary valley and lateral moraines from the main trunk of the Chandra valley at elevations 150–200 m above the present river level.

At the Baralacha La (Pass) at the head of the Bhaga valley, an indurated tillite of Chandra age was mapped at an altitude of 4900 m. This is interpreted as a product of an early period of glaciation to allow for lithification to occur (cf. Shroder *et al.*, 1993), although the degree of lithification may not necessarily be indicative of the age of the deposit. Striations in this area (Fig. 3), which relate to the same glacial event as the tillite, give ice flow both towards the north out of the Chandra catchment and towards the sou-

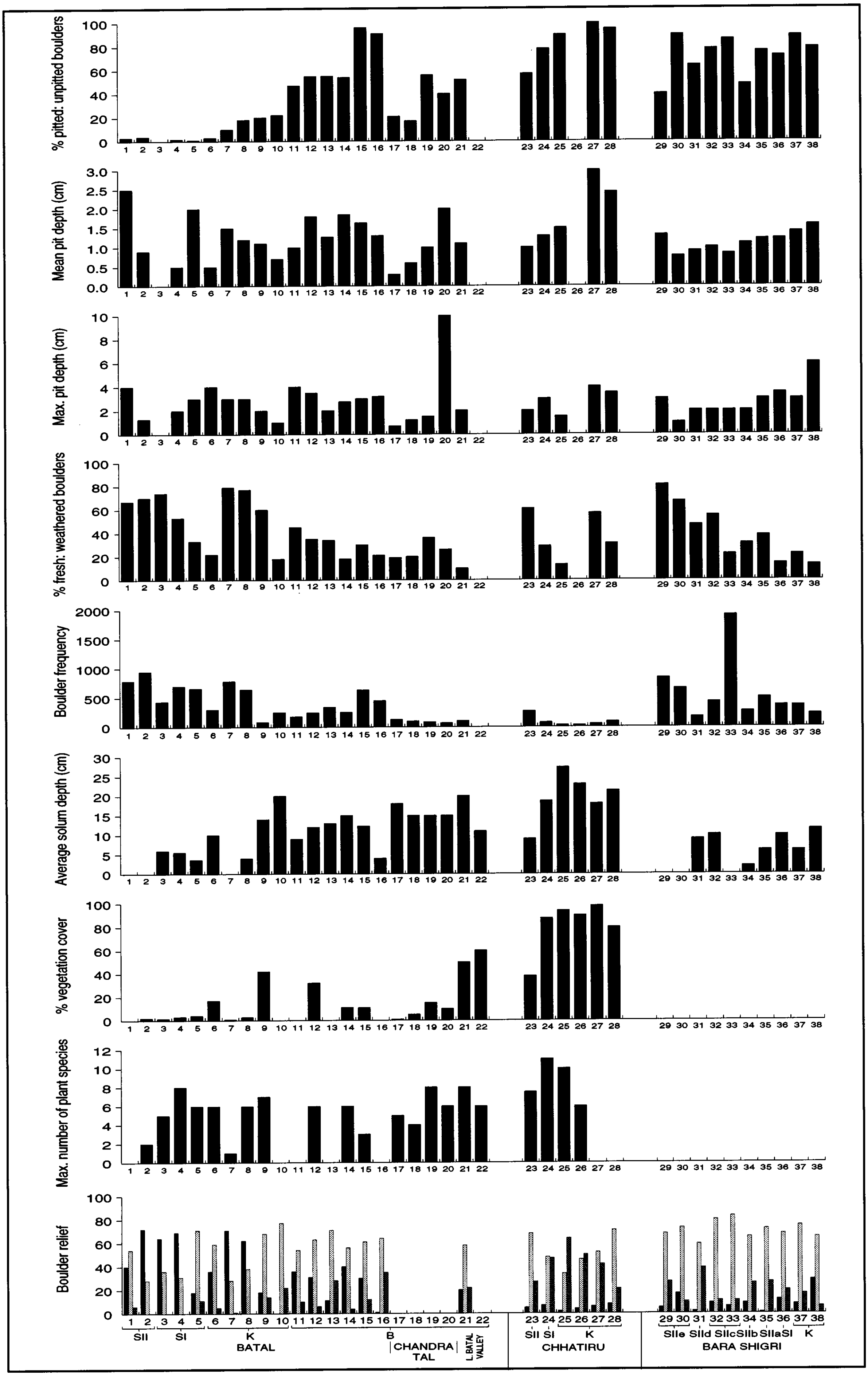

Figure 9 Histograms of relative dating criteria for the upper Chandra, Chhatiru and Bara Shugri valleys.

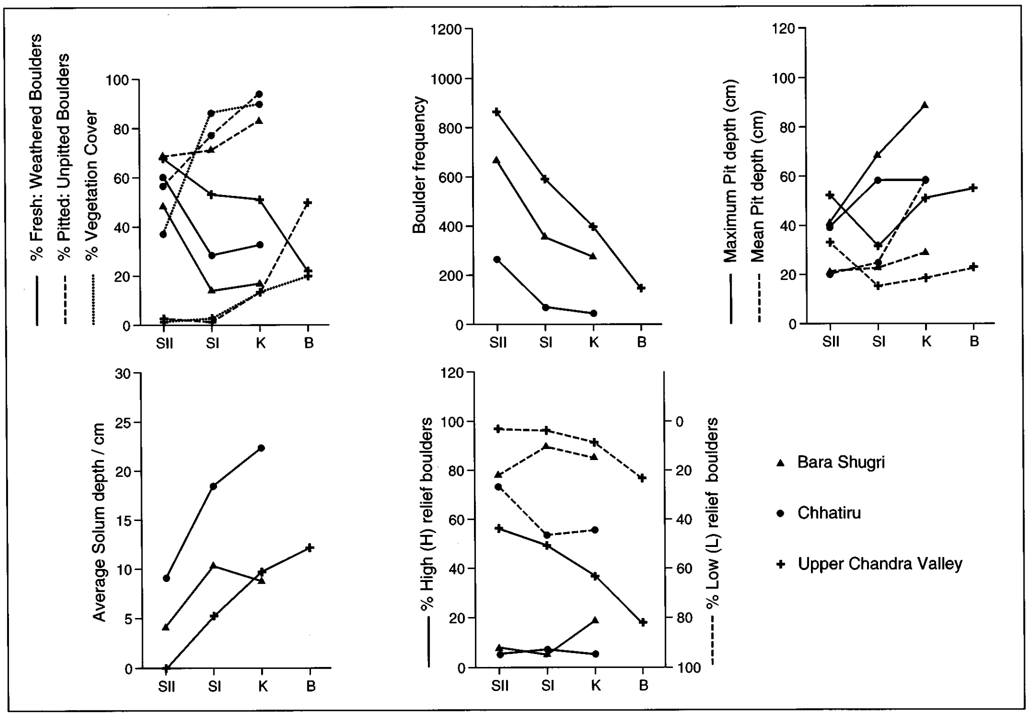

Figure 10 Summary graphs showing the relative dating characteristics for the upper Chandra, Chhatiru and Bara Shugri valleys. Each plot is the mean value for moraines of different ages in each of the regions.

theast, down the Chandra valley, suggesting that there was an ice divide near Baralacha La.

The Chandra glaciation was characterised by an extensive ice cover, sufficiently thick to allow flow across the interfluve areas. The wide area covered by ice probably reflects the substantially wider and shallower valleys of Chandra Glacial time, compared with those of the present-day valleys, deepened by later glacial and fluvial processes.

Batal I and II Glacial Stages

Owen *et al.* (1996) showed that this glaciation is represented by highly weathered and dissected lateral moraines and trimlines at high elevations in both the Chandra and Bhaga valleys, which are below features that can be ascribed to the Chandra glaciation. Figure 3 shows detailed mapping of these moraines and Figs 4 and 7 show the nature of Batal moraines and their associated paraglacial deposits. This stage can be divided into two parts on the basis of the altitudinal position of landforms, including superimposed drumlins in the area around Chandra Tal (Figs 7, 14 and 15). In the Chandra Tal area, the earlier substage, Batal I, is represented by drumlins approximately 50 m long (Fig. 7a) and streamlined bedrock that trends parallel to the valley axis. Batal I glaciers probably helped erode the depression that now forms Chandra Tal. A second event, Batal II, is represented by smaller drumlins, superimposed on the Batal I drumlins and streamlined bedrock. The younger drumlins indicate a former ice flow direction towards the east-southeast.

The main Batal trunk valley glacier advanced down to the Chandra and Bhaga valleys to approximately 5 km west of Rape village (Fig. 16). The terminal position was almost coincident with a major increase in stream gradient. Large end moraines are present west of Rape village, formed by tributary valley glaciers that extended into the main Chandra valley but which did not become confluent (Fig. 3).

At Batal, a complex sequence of moraine ridges has been mapped in more detail than the map presented in Owen *et al.* (1996) (Fig. 4). On the basis of morphostratigraphy, the outer moraines have been defined as of Batal age. They occur at ca. 4000 m altitude near the river and extend 4400 m further up slope. The outer moraines define the former extent of a glacier lobe that entered the main Chandra valley from the Batal tributary valley (Fig. 4). They are well vegetated, have few boulders, and are clearly distinguished from younger moraine ridges near the Batal Glacier. The younger moraines are poorly vegetated, have many surface boulders, and are thought to be of Kulti age or younger (Owen *et al.*, 1996). This indicates that at some stage during this glaciation, the main Chandra valley was no longer filled with ice but that the ice entered the main valley from tributary valleys.

After the Batal Stage glacier had retreated from the main Chandra valley, a lake developed that extended ca. 12 km up-valley. Large deltas extended into the lake (Fig. 17); their tops lie at approximately 4220 m. The deltaic sediments east of Chandra Tal are overlain by Kulti till. An optical date of ca. 43 400 ± 10 300 yr BP was obtained from sample 8 from the top of the southernmost delta at the confluence of the Dakka and Chandra valleys. Therefore, the main valley glacier of Batal age must have left the valley prior to the formation of this delta, and the Batal Glaciation must have terminated before 43 400 ± 10 300 yr BP, as the lake deposits probably formed during the final retreat stage of the Batal Glaciation because ice was still necessary to block the valley.

Kulti Glacial Stage

This glaciation is represented by numerous well-preserved lateral and end moraines that can be traced up to 12 km beyond the termini of modern glaciers (Figs 3, 4 and 18).

Table 2 Relative weathering data for individual sites that measured 30 m by 50 m (see Figs 4–6 for location of samples)

Location	Location number	Inferred age	Percentage pitted: unpitted	Mean pit depth (cm)	Maximum pit depth (cm)	Percentage fresh: weathered	Boulder frequency	Average solum depth (cm)	Percentage vegetation cover	Maximum number of plant species	Boulder relief		
											H	I	L
Batal	1	SII	3	2.5	4	67	789	0	0	0	40	54	6
	2	SII	4	0.9	1.3	70	948	0	2	2	72	28	0
		Mean SII	3.5	1.7	2.65	68.5	868.5	0	1	1	56	41	3
	3	SI	0	0	0	74	435	6	1.5	5	64	36	0
	4	SI	2	0.5	2	53	700	5.6	3	8	69	31	0
	5	SI	1	2	3	33	660	3.7	4	6	18	71	11
		Mean SI	1	0.8	1.6	53.3	598.3	5.1	2.83	6.3	50	46	3.7
	6	K	3	0.5	4	22	298	10	17	6	36	59	5
	7	K	10	1.5	3	79	786	0	0.8	1	71	28	1
	8	K	18	1.2	3	77	640	4	2.8	6	62	38	0
	9	K	20	1.1	2	60	85	14	42	7	18	68	14
	10	K	22	0.7	1	18	248	20			0	77	22
		Mean K	14.6	1	2.6	51.2	411.4	9.6	12.52	4	37	54	8.4
	11	BII	47	1	4	45	175	9			36	54	10
	12	BII	55	1.8	3.5	35	241	12	32	6	31	63	6
	13	BII	55	1.27	2	34	336	13			11	71	28
	14	BII	54	1.85	2.75	18	249	15	11	6	40	56	4
		Mean BII	52.75	1.48	3.06	33	250.25	12.25	10.75	3	30	61	12
	15	BI	96	1.63	3	30	631	4			1	64	35
	16	BI	91	1.3	3.2	21	447	10.9			23	59	16
		Mean BI	93.5	1.46	3.1	25.5	539	7.45	42	7	12	62	26
Chandra Tal	17	BII	21	0.3	0.7	81	126	18	1	5			
	18	BII	17	0.6	1.2	80	98	15	5	4			
	19	BII	56	1	1.5	64	82	15	15	8			
	20	BII	40	2	10	74	64	15	10	6			
		Mean BII	33.5	0.97	3.35	74.75	92.5	15.75	7.75	5.75			
L. Batal valley	21	BII	52	1.1	2	10	102	20	50	8	20	58	22
	22	BII						11	60	6			
		Mean BII	52	1.1	2	10	102	15.5	55	7	20	58	22
Chhatiru	23	SII	57	1	2	61	266	9	38	7.5	5	68	27
	24	SI	78	1.29	3	29	75	18.7	87.5	11	7	48	47
	25	K	90	1.5	1.5	13	30	27.3	94	10	2	34	64
	26	K					30	23	90	6	4	46	50
	27	K	100	3	4	57	50	18	98		6	52	42
	28	K	95	2.43	3.5	31	90	21.3	80		8	71	21
		Mean K	95	2.31	3	33.6	50	22.4	90.5	8	5	51	44
Bara Shugri	29	SIIe	40	1.32	3	81	838				5	68	27
	30	SIIe	90	0.77	1	67	656				17	73	10
	31	SIId	64	0.9	2	47	168	9			2	59	39
	32	SIIc	78	1	2	55	422	10.1			9	80	11
	33	SIIc	86	0.83	2	22	1910				6	83	11
	34	SIIb	48	1.1	2	31	263	2			9	65	26
	35	SIIa	76	1.21	3	38	501	6.1			1	72	27
		Mean SII	68.8	1.0	2.1	48.7	679.7	3.8	0	0	7	71	22
	36	SI	72	1.22	3.5	14	366	10			12	68	20
		Mean SI	72	1.22	3.5	14	183	10			6	34	10
	37	K	89	1.4	3	22	362	6.1			8	75	17
	38	K	79	1.58	6	13	219	11.5			29	65	6
		Mean K	84	1.4	4.5	17.5	290.5	8.8	0	0	19	70	12

The height of these moraines suggests that during this glaciation, ice was no more than 60 m thicker than at present. The Kulti may correlate with the Last Glacial Maximum of the Northern Hemisphere ice sheets ca. 18 000 yr BP (Owen *et al.*, 1996).

Where glaciers advanced into the main valleys, for example where the Sonapani Glacier advanced down the Kulti valley into the Chandra valley, the Koa Rong Chu glacier advanced into the Milang valley, and the Batal glacier advanced across the upper Chandra valley, the ice from the tributaries blocked the main valley drainage, diverting the main rivers and forming glacial lakes. Moraine ridges of the Kulti glaciation are characterised by being less vegetated, with thinner soil cover and more surface boulders than older glacial deposits, although vegetation has developed on Kulti moraines at lower altitudes. For example, the Kulti moraines at Kulti Nala, which extend into the main Chandra valley near the Rohtang Pass (Owen *et al.*, 1996), are more vegetated than the Kulti moraines at Batal, which is shielded from monsoonal influences by the Pir Panjal (Fig. 3). This contrast reflects notable microclimatic variations along the Chandra valley. Similarly, in the upper Bhaga valley, towards the summit of the Baralacha La, large unvegetated moraines thought to be of Kulti age extend into the valley floor just east of Zingzingbar Pass, separating Lahul from Spiti.

At Batal, the Kulti moraines form an inner group of ridges distinct from the earlier Batal moraines (Fig. 4). Most of these ridges are small and unvegetated, and do not extend on to

Table 3 The degree of success in correlating moraines on the basis of relative weathering criteria: (A) very good correlation with age; (B) moderate correlation with age; (C) very poor correlation with age; (–) data not collected

Relative dating method	Upper Chandra valley	Chhatiru	Bara Shugri
Percentage pitted:unpitted	A	A	A
Mean pit depth	C	A	A
Maximum pit depth	C	C	A
Percentage fresh:weathered	A	B	B
Boulder frequency	A	A	A
Average solum depth	A	A	B
Boulder relief	A	B	A
Percentage vegetation cover	A	B	–
Maximum number of plant species	C	B	–

the present floodplain. One moraine ridge extends to the present river, defining a lobe that dammed the Chandra valley (Fig. 4). The Samunder Tapu Shigri Glacier advanced and formed a small end moraine 600 to 700 m east of Chandra Tal. The ice overtopped deltaic sands and gravels deforming their upper surface and depositing drumlinised moraine. An underlying deposit of fluvial sands and gravels, approximately 100 m thick, is present in the Chandra Tal area. The sands and gravels comprise metre-thick cross-bedded polymictic gravels, planar laminated and rippled fine to coarse sands and silts. Optical sample 5, collected from half way down the succession (Fig. 7) has an age of approximately 36 900 ± 8400 yr BP. The Kulti Glaciation is therefore younger than 36 900 ± 8400 yr BP. This date also has implications for the timing of the Batal Glaciation, because ice must still have been present, although not as main trunk valley ice, to have blocked the Chandra valley to allow the lake to form and deltas to develop.

Sonapani I and II Glacial Advances

Two sets of sharp-crested moraines have been identified within 5 km of the present glacier termini, and these represent at least two glacial advances (Owen *et al.*, 1996) (Figs 4–6 and 19). They have sparse vegetation, small lichens (<10 mm diameter) and poorly developed rock varnishes, and can be differentiated on the basis of relative dating and lichenometry (Fig. 9). In the Kulti valley, the older moraines can be traced 4.3 km down-valley from the present terminus of the Sonapani Glacier, and are attributed to the Sonapani I glacial advance (Owen *et al.*, 1996). A younger group of moraines can be traced 2.75 km down-valley from the snout of the Sonapani Glacier and these are attributed to the Sonapani II glacial advance. On the basis of photographs published by Walker and Pascoe (1970), Owen *et al.*, (1996) showed that the Sonapani Glacier was only a few hundred metres up-valley from the lowest Sonapani II moraines in 1905. The Sonapani II moraines were, therefore, attributed to a late-nineteenth century advance, probably the culmination of the Little Ice Age (cf. Grove, 1988). The Sonapani I, therefore, may represent a Neoglacial (4500 yr BP to present) event. However, the terminology of the Little Ice Age and Neoglacial is interpreted in different ways in the literature (e.g. Osborn and Luckman, 1988; Shroder *et al.*, 1993), and without reliable dates it would be inappropriate to specify a time period for these moraines. Furthermore, the relative weathering data presented below suggests that the Sonapani I moraines may have formed during early to mid-Holocene times.

Analysis of related dating

Burbank and Cheng (1991) suggest that a 50% change in weathering characteristics between moraines indicates that the moraines formed during distinct glaciations and not during stadial events. On this basis, relative dating can distinguish between the Batal glacial stage, Kulti glacial stage and the Sonapani glacial advances that were defined by geomorphological mapping, although there are a number of problems. On the basis of the numerical dating, the Batal and Kulti glacial stages are clearly within the same glaciation. The Batal Glacial Stage is probably equivalent to oxygen isotopic stage 4 and early Oxygen Isotope Stage 3, whereas the Kulti glacial stage is probably equivalent to late Oxygen Isotope Stage 3, Oxygen Isotope Stage 2 or early Oxygen Isotopic Stage 1, or two or more of these stages. The Sonapani I advance is probably early or mid-Holocene in age, whereas the Sonapani II Advance is unequivocally historical.

Relative dating criteria can differentiate the Sonapani I Advance, which is probably of mid- to late Holocene age, and the Sonapani II Advance moraines, which are known to be historical (Owen *et al.*, 1996) (Fig. 10). The Kulti, Batal and Chandra stages are also differentiated from each other by some criteria but not others (Fig. 10). The assessment of correlation success (Table 3) can be used as a basis to evaluate the usefulness of certain dating criterion. These give a broad correlation, and using the mean data in Table 2, allow statements to be made regarding the ages of certain moraine ridges. For example, the data show a clear distinction between different sampling sites at Batal (Fig. 4), which allows the moraines to be ascribed to Kulti and Batal stages, even though the time difference between events may be relatively small. Batal is a critical site to evaluate this technique as it has a number of moraine ridges with distinctive physical differences in morphology, allowing them to be differentiated into different glacial periods, as justified by relative dating techniques. Relative dating criteria are not considered conclusive in every case, however, because a number of sites do not conform. For example, sites 11–16 are grouped subjectively as being of Batal age and sites 6–10 are defined as Kulti. On the basis of the mean values for percentage pitted/unpitted and boulder frequency, these are clearly of different ages. The division between Kulti and Sonapani moraines is less clear. This is, however, to be expected because moraines are dynamic landforms that alter shape through time, and boulders will be exposed on the surface of moraine ridges at different times as the ridge is exposed to weathering and surface erosion giving a range of relative weathering values (Hallet and Putkonen, 1994). This important point clearly shows the problems with relative dating and emphasises that the choice of sample site on

Table 4 Details of optical dating samples and OSL results

Sample number	Location	Sample position	Lithology	Age (ka)
1	Above rock bar west of the Bhaga River, ca. 3 km northeast of Dacha at an altitude of 3460 m	Approximately 8 m above the base of the 20-m-thick section of sands and gravels	Low-angled, cross-stratified, medium- to fine-grained fluvial sands	
2	100 m north of Patsia Resthouse, within moraine depressions	Approximately 10 cm from the base of an 80-cm-thick section. The section comprises, from the base up: 20 cm fluvial cross-stratified sands; 55 cm laminated lacustrine silts; and 15 cm aeolian silt	Fluvial cross-stratified fine sands	
3	Sand and gravel pit ca. 25–30 m above river level, north of the road at Khoshar Road Camp. The sediments are deposited behind Khoshar valley end moraine and can be traced for about 3 km along the valley	Sample collected at an altitude of 3170 m, from ca. 50 cm above the base of a 5-m-thick section which comprises coarse- to medium-grained sands with low-angled cross stratification within metre-thick sets. These onlap the moraine	Fluvial fine sands	
4	Glaciolacustrine fill within moraine ridges, ca. 600 m east-northeast of Batal bridge	Sample collected about 10 cm from the base of a 50-cm-thick deposit of galciolacustrine sediments	Glaciolacustrine clayey silts	
5	Thick sections east of the Chandra river ca. 2.5 km north-northwest of the northern end of Chandra Tal	Sample collected at an altitude of 4210 m, about half way up an 80-m-thick section comprising glaciofluvial/fluvial sands and gravels with lacustrine silts	Fluvial planar laminated fine sands	36.9 ± 8.4[a]
6	Small ablation valley between moraine ridge of Kulti age and the Batal moraines at an altitude of ca. 4120 m	Collected from a 1-m-deep excavation within ablation valley lacustrine sediments, ca. 20–30 cm from the base of the section	Ablation valley lacustrine silts	
7	Approximately 300-m west-southwest of Batal bridge within moraine ridges, just north of footpath to camping ground	Sample collected ca. 30 cm from the base of a 1.5-m-thick lacustrine/aeolian silt deposit	Colour laminated aeolian silts. Abundant roots present	
8	Delta top on the west side of the Chandara valley ca. 200 m west of the confluence of the South Dakka and the Chandra River	Sample collected ca. 20 cm below the delta top	Medium-grained sands of delta topsets	43.4 ± 10.3[b]
9	On top of a till inlier within the Chhatiru fan, ca. 3 km east-northeast of Chhatiru bridge	Sample collected ca. 30 cm from the base of a 1–2-m-thick deposit of aeolian sands	Fine- to medium-grained, cross-stratified aeolian sands and silts. Note abundant organic-rich clay	

[a]Dose rate = 3.3 ± 0.34 Gy ka^{-1}; equivalent dose (ED) = 121.62 ± 24.75 Gy
[b]Dose rate = 2.85 ± 0.33 Gy ka^{-1}; equivalent dose (ED) = 123.60 ± 25.71 Gy

moraine ridges is critical in determining the quality of the resultant data.

The difference between relative weathering for Sonapani II and Sonapani I advances is large for nearly every criterion, whereas the difference between Sonapani I and the Kulti is relatively small (Figs 9 and 10). This suggests that Sonapani I may represent an early Holocene or mid-Holocene event, and it is not strictly a Neoglacial advance. Until other dating

Figure 11 (a) View looking south from the eastern side of the forefield of the Bara Shugri Glacier at an altitude of 4120 m. The moraines in the centre foreground (K) were formed during the Kulti Glacial Stage, whereas the well-vegetated slopes (B), to the left of the plate, were formed during the Batal Glacial Stage. The glacially eroded slope (C), which is at an altitude of above 4600 m was carved during the Chandra Glacial Stage. The surface of the Bara Shugri Glacier can be seen in the centre right-hand side of the plate (G), which is at an altitude of 4000 m.

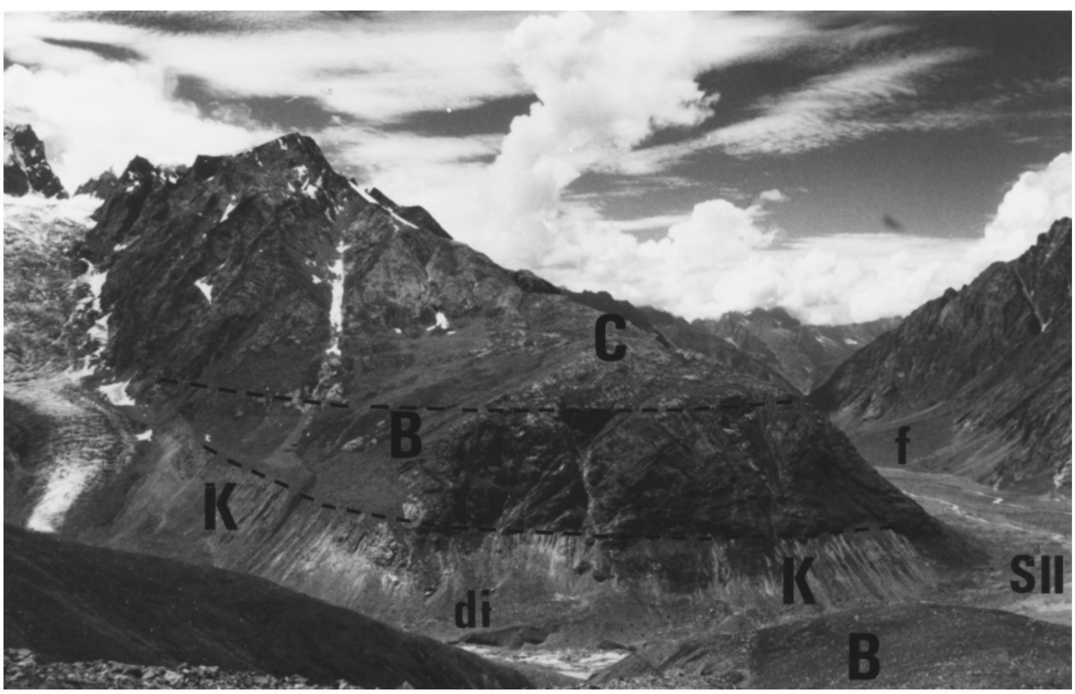

Figure 11 (b) View looking westwards across the Bara Shugri valley showing the Chandra Glacial surface (C) which rises to approximately 4680 m; the remnants of the Batal Glacial moraines (B) rise to approximately 4350 m; the Kulti Glacial moraine (K); and the Sonapani II moraines, which were deposited during the early part of this century. In the lower middle of the plate remnants of dead ice (di) can be seen, and in the distance paraglacial fans (f) are present along the Chandra valley.

techniques are applied, it will not be possible to resolve this problem. Nevertheless, the relative weathering criteria provide a quick and effective way to establish further correlations and chronologies within areas of similar geomorphological characteristics.

Discussion

On the basis of the glacial landforms, morphostratigraphy and relative weathering, reconstructions of the ice extent

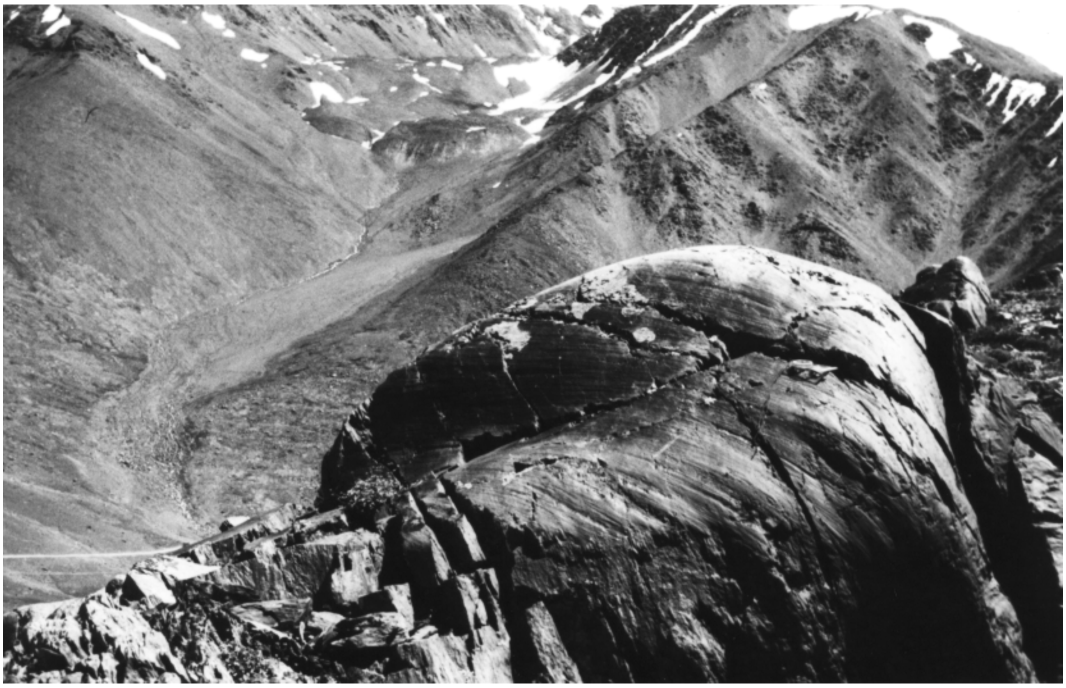

Figure 12 View looking southeast from above the Kumzum La at an altitude of approximately 4700 m at ice moulded bedrock. This was produced by a broad valley glacier during the Chandra Glacial Stage.

Figure 13 View looking northeast at the northern end of Chandra Tal. A large roche moutonnée (r) and a moraine (BI: partially buried under paraglacial fan debris) was produced during the Batal I Glacial Stage. To the left in the distance, a Kulti Glacial (k) end moraine is present.

during each glaciation were made (Fig. 20). It is clear from Figure 20 that styles of glaciation have changed through time. This substantiates the view of Owen *et al.* (1996) that glaciation has become progressively less extensive in Lahul throughout late Quaternary times.

Owen *et al.* (1996) suggested that this may be a result of several factors. First, it may be related to preservation, as less extensive older glaciations are less likely to be preserved. This is unlikely because the large relative relief in this area has helped preserve evidence which in other areas would have been destroyed. Secondly, this trend may be a consequence of uplift influencing local climate. Owen *et al.* (1996) suggested that the rapid uplift of the Pir Panjal to the south (Burbank, 1982; Burbank & Reynolds, 1984) could also have influenced climate during the Quaternary because it has uplifted approximately 2000 m since 0.8 Ma. This would have increased the storminess of the monsoon along the southern slopes of the Pir Panjal while progressively reducing

Figure 14 View looking north-northwest across Chandra Tal towards the Sumundar Tapu Shigri Glacier (far left) and the upper Chandra valley (far right). The middle ground comprises drumlinised moraine and ice moulded bedrock. These were formed during the Batal I Glacial and remodified during the Batal II Glacial to produce superimposed drumlins.

A

Figure 15 Views looking east at drumlins and ice moulded rocks on the east side of the upper Chandra valley at an altitude of 4600 m a.s.l. These were formed during the Batal II Glacial Stage. Ice movement direction is from left to right.

the supply of moisture to the northern slopes of the Pir Panjal and the Great Himalaya. The presence of moraines and glacial surfaces of Chandra Glacial age on the western side of the Bara Shugri Glacier indicates that the Pir Panjal was already high throughout the duration of the glacial stages examined in this study, suggesting that uplift was probably not an important factor in determining the style of glaciation.

Thirdly, this pattern may be due to global climatic conditions becoming progressively less favourable for the development of mountain glaciers during the late Quaternary. Support for this global climate model is provided by the fact that the pattern of glaciations in Lahul is similar to that in many montane areas elsewhere in the Western Himalayas and some other regions of the world (Gillespie and Molnar, 1995). Figure 21 summarises the chronological data for late Quaternary paleoclimatic change throughout the western end of the Himalayas so as to help examine regional climatic change. Parts a, b, c and d in Figure 21 summarise the attempt by Gupta *et al.* (1992) to model climate change for the Himalaya using $\delta^{18}O$ values from core SK-20-185 from the East Arabian Sea, core CD-17-30 off the coast of Oman

Figure 15 Continued.

Figure 16 View looking southeast from Rwaling towards Lot showing moraines produced during the Batal Glacial Stage. The moraine in the centre of the plate was a medial produced by the confluence of the main Chandra valley ice and tributary valley ice from the Lingar valley. Note the paraglacial fans which have infilled the valley between the moraines and the main valley wall (on the right of the photo). The fields and fully grown trees on the paraglacial fan provide a scale.

and from the Dunde Ice Cap in Tibet. Although the Dunde Ice Cap is on the northeastern margin of the Tibetan Plateau, and it may not have been greatly influenced by the monsoon, the data is important because it is the only set of oxygen isotopic data available for the Himalayan and Tibetan region. Figure 21 also presents data showing the abundance of *Juniperus* pollen from the Tsokar Lake in Ladakh. On the basis of these data, Gupta *et al.* (1992) suggested that the period between 20 000 and 16 000 yr BP was one in which glacial meltwaters originating in the Himalaya and Tibet increased in volume as a result of accelerated rates of melting of mountain glaciers. Gupta *et al.*'s (1992) data are compared with the glacial history for Swat (Porter, 1970; Owen *et al.* 1992), Garhwal (Sharma and Owen, 1996), the Hunza valley (Derbyshire *et al.*, 1984) and the revised chronology for Lahul. The estimated summer sea-surface temperatures from deep-sea core V23-82 provides a chronostratigraphical reference. Correlations such as these for the Himalaya of India and Pakistan are difficult because of the scarcity of dates and poor dating quality. Nevertheless, there are broad similarities between some regions, whereas others have sharp contrasts. Three glaciations have been recognised in Swat, Hunza and

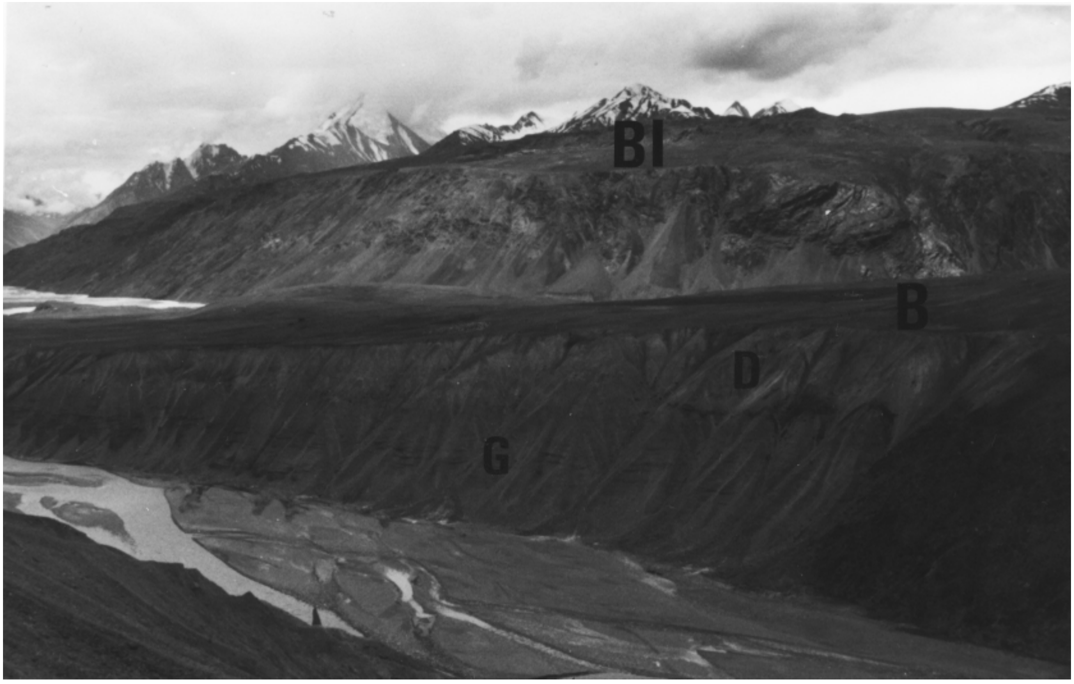

Figure 17 View looking west-southwest across the Chandra River and the Samundar Tapu Shigri valley. The valley section in the middle of the frame comprises fluvial sands and gravels (G) overlain by diamict (D) which constitutes the drumlinised surface (B) in the middle ground, formed during the Batal Glacial Stage. The streamlined surface (BI) in the distance was formed during the Batal I Glacial Stage.

Figure 18 View looking north up the Kulti valley at an end moraine produced during the Kulti Glacial Stage. The fan-like area to the east of the moraine comprises lacustrine sediments capped with fluvial and debris flow sediments. The lacustrine sediments were deposited in a lake that formed when the Chandra valley was blocked by glacial ice. The moraine is approximately 70 m high.

Lahul. It is difficult, however, to compare the timing of these glaciations. Most probably there were two major glaciations during the last glacial cycle, the earlier glaciation being more extensive. The dates on the older glaciation in the Hunza valley and Lahul suggest that this was probably equivalent to Oxygen Isotope Stage 4 or early Oxygen Isotope Stage 3, but the evidence for this is still equivocal and the Chandra glaciation may be much older, representing an earlier glacial cycle. It is tempting to correlate the later glaciation with Oxygen Isotope Stage 2, when the Northern Hemisphere ice sheets reached their maximum extent. Gupta *et al.* (1992), however, suggest that the period between approximately 20 000 and 15 000 yr BP may have been one of glacial melting. If this is correct, the later glaciation probably occurred after 15 000 yr BP, and it is not equivalent to Oxygen Isotope Stage 2, which extends to a time of about 12 000 yr BP. In Swat Kohistan, the last glaciation (Kalam Glacial Stage) must have occurred after at least 22 000 yr BP and terminated by about 6700 yr BP (Owen *et al.*, 1992), but for Hunza and Pakistan there are no dates

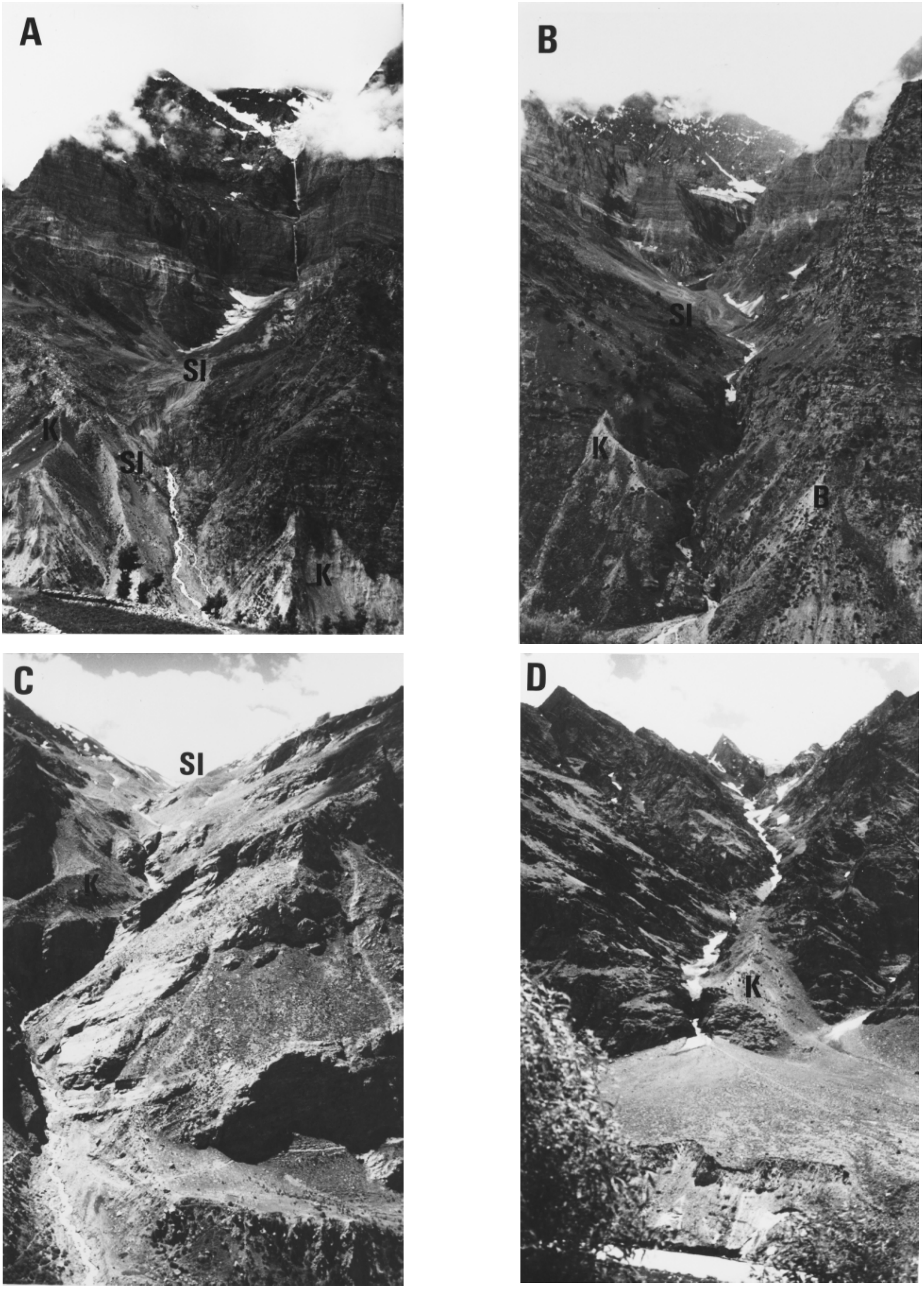

Figure 19 Characteristics of moraines throughout the Bhaga and Chandra valley. (A) View looking south at the Rawling Glacier, note the hanging and starved glacier. (B) View looking south up the Shuling valley. (C) View looking southeast from Kuaring valley at the first valley south of Tinnu. (D) View looking east from Gimmne up the third valley north of Tinnu. Note the paraglacial fan in the foreground of plates C and D (B, Batal Glacial moraines; K, Kulti Glacial moraines; SI, Sonapani moraines).

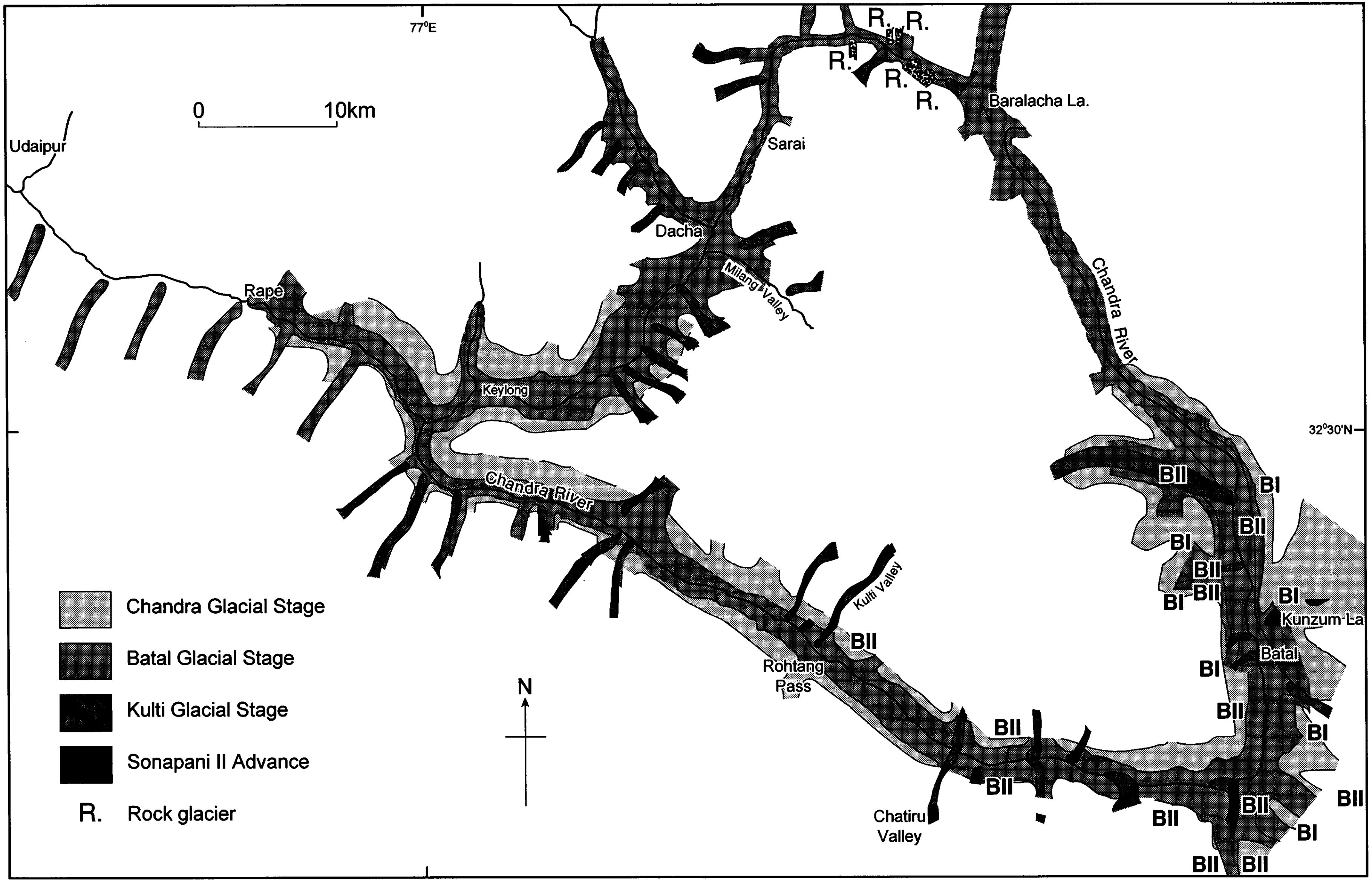

Figure 20 Reconstructions of former ice extents for the Chandra, Batal (BI, Batal I; BII, Batal II) and Kulti glacial stages, and the Sonapani advances.

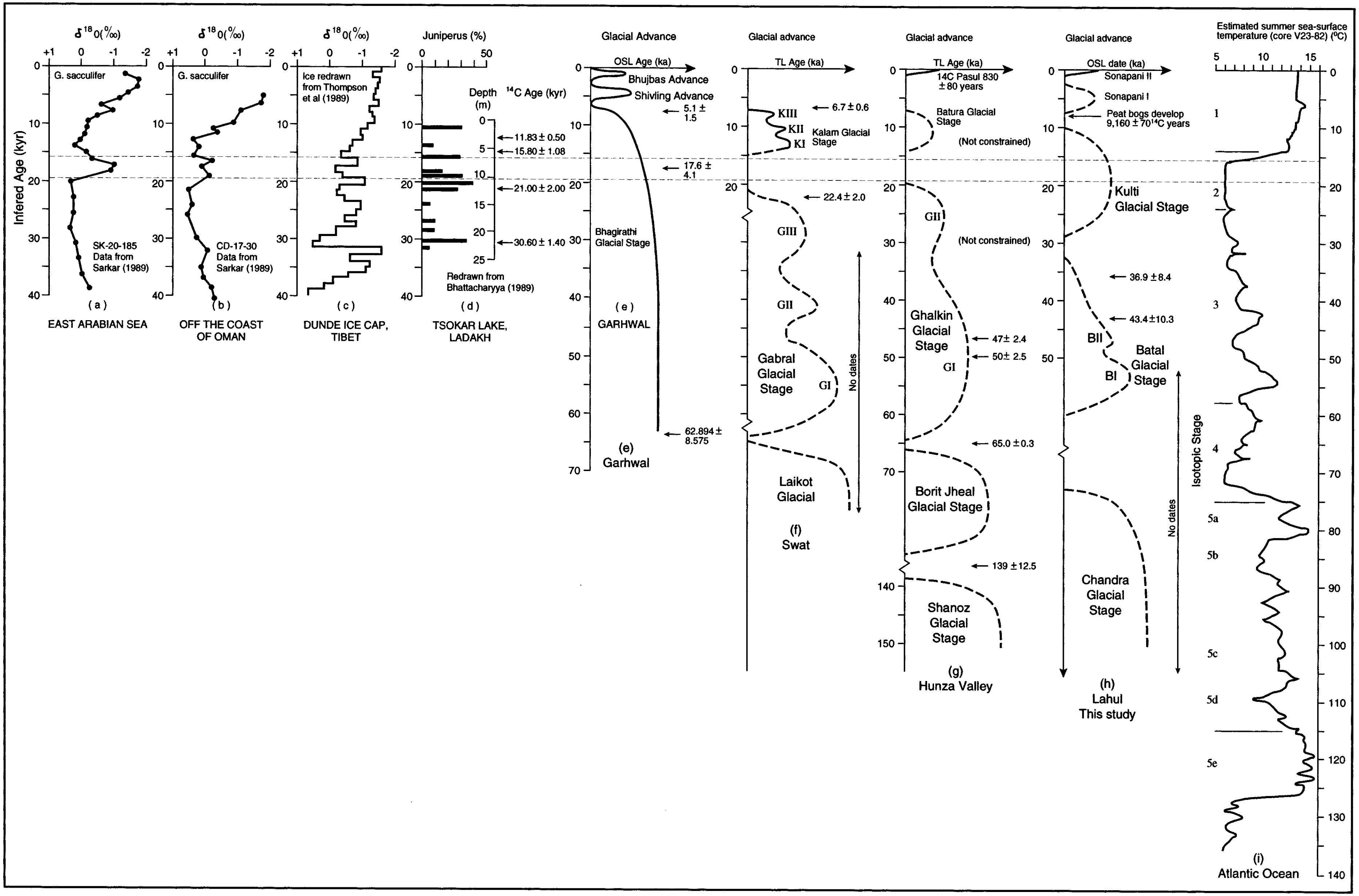

Figure 21 Comparison of the extent and timing of glaciation in selected areas of the Himalayas. $\delta^{18}O$ values from (a) *Globigerinoides sacculifer* from core SK-20-185 from the East Arabian Sea (Sarkar *et al.*, 1990) and (b) from core CD-17-30 off the coast of Oman (Sarkar *et al.*, 1990), (c) the Dunde Ice Cap core in Tibet (Thompson *et al.*, 1989), and (d) an increase in the abundance of *Juniperus* pollen from the Tsokar Lake in Ladakh (Bhattacharyya, 1989) are taken from Gupta *et al.* (1992). (e, f, g and h) Compare the timing and relative extents of glaciation for the Garhwal Himalaya (after Sharma and Owen, 1996), the Swat Himalaya (data from Owen *et al.*, 1992), and the Hunza valley (data from Derbyshire *et al.*, 1984) with the Lahul Himalaya. (i) Shows the estimated summer sea-surface temperatures for North Atlantic deep-sea core V23-82 and the oxygen isotope stages for reference (after Sancetta *et al.*, 1973).

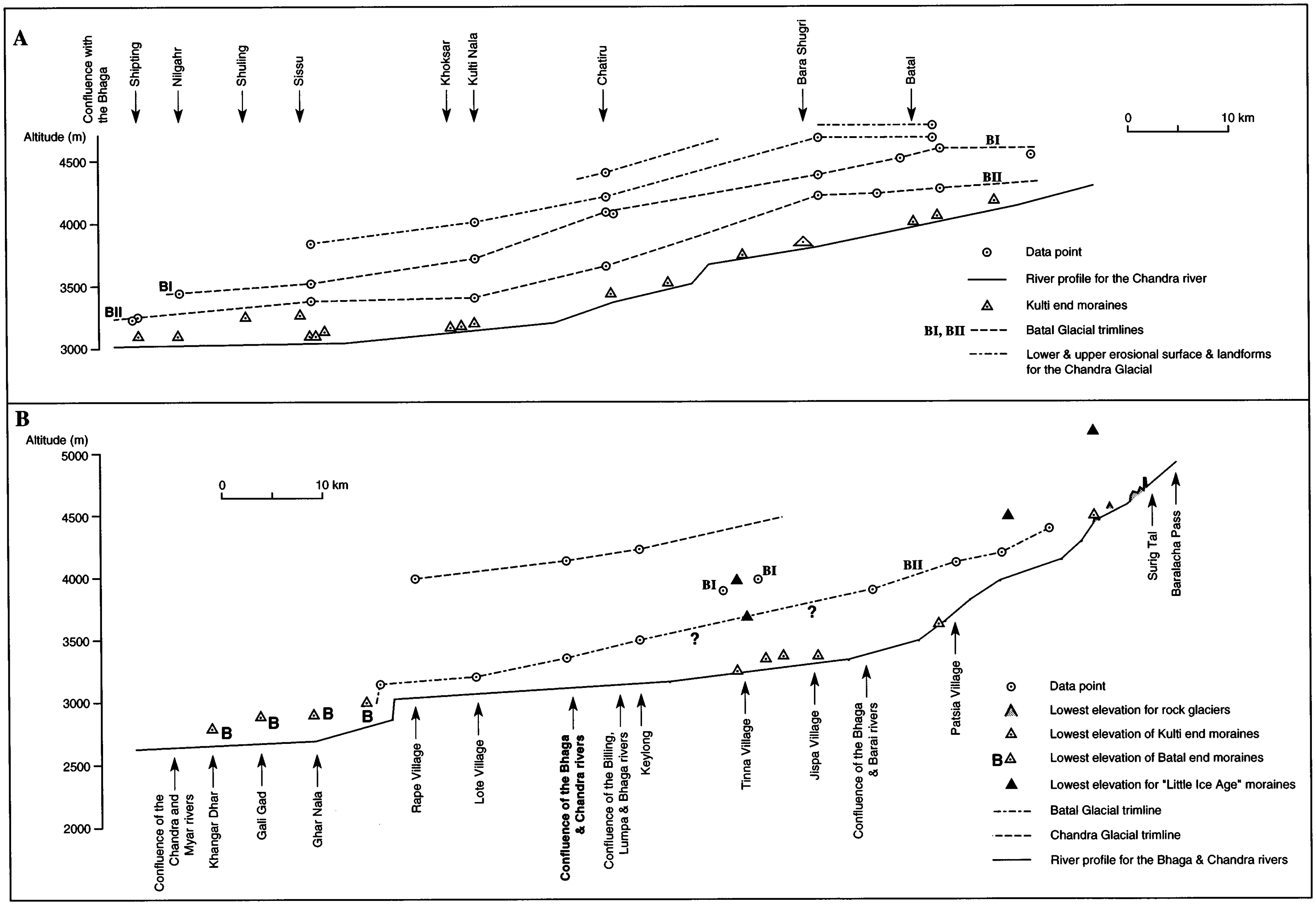

Figure 22 Profiles of the Bhaga and the middle Chandra valley (A) and the upper Chandra valley (B) showing the heights of glacial features and inferred trimlines for each glacial stage.

available. Therefore, the later glaciation in these areas could be attributed to Oxygen Isotope Stage 2 or early Oxygen Isotope Stage 1. Whereas in the Lahul Himalaya, the OSL dating strongly suggests that the Kulti Glaciation occurred after approximately 36 900 ± 8400 yr BP and it can therefore be attributed to late Oxygen Isotope Stage 3, Oxygen Isotope Stage 2 or early in Oxygen Isotope Stage 1. The Kulti Glaciation probably terminated before 9160 ± 70 ^{14}C yr BP when climatic amelioration was sufficient to allow peat bogs to develop at Chandra Tal. The dated peat bog, however, is not found directly on Kulti age deposits, rather it is on Batal moraines. Nevertheless, similar peat bogs are developed on Kulti age moraines east of the Tapu Shrigri River. Glaciation in the Garhwal Himalaya contrasts sharply with the other regions, with glaciers reaching their maximum extent at about 63 000 yr BP, and persisting in the valleys up to at least early Holocene times (Sharma and Owen, 1996). Sharma and Owen (1996) showed that glaciers in the Garhwal Himalaya may have begun to retreat at about 20 000 until 16 000 yr BP, after which their positions may have stabilised until at least 5000 yr BP, with no evidence for a readvance in Garhwal between 16 000 and 11 000 yr BP, as shown in the model of Gupta *et al.* (1992: Fig. 21). All these data suggest that the Indian monsoon may have been stronger during periods when the Northern Hemisphere ice sheets were at their greatest. This hypothesis needs to be tested within the framework presented in Fig. 21.

Following the detailed mapping in this study it has become apparent that one of the major controls on glacial style may be a consequence of the geomorphological character of the region. In particular fluvial incision has probably had a strong control on the styles of glaciation. The Chandra glaciation was extensive and of broad valley type, probably because it developed on a plateau surface which was not yet deeply incised. The glaciers incised and deepened the valleys to a moderate degree, aided by meltwater incision. Intense fluvial/glaciofluvial erosion probably helped produce valleys and it allowed later glaciers to exploit the valley as well as restricting the width and extent of the glaciers. This is illustrated best with the Batal glaciation, where the most deeply incised valley stretches are beyond the limit of the main trunk valley glacier. Figure 22 shows this clearly, where a knick point in the present valley profile is just slightly within the Batal limit, indicating progressive knick-point retreat since the Batal glaciation. In addition, moraines and valley fills associated with the Kulti glacial stage are perched on bedrock that has been incised up to 30 m. There is no evidence for the existence of glacial sediments within the incised bedrock gorges. This suggests that the incision occurred during post-glacial times. This fluvial incision has therefore controlled the distribution of glaciers and their deposits throughout this region. Although glacial style was influenced by fluvial incision, there is clearly a lower volume of ice with each progressive glaciation, the reasons for which have still not been resolved, although it seems likely that it is the combined effects of topographic controls resulting from fluvial incision, mountain uplift affecting local climate and the role of global climate change similar to the patterns suggested by Gillespie and Molnar (1995) for elsewhere in the world.

The presence of drumlins and streamlined bedforms during the Batal glaciation indicates that subglacial deposition was more dominant than during the succeeding Kulti glaciation, when supraglacial deposition was more dominant. This may be partially because the Kulti glaciers flowed in deep valleys, produced by post-Batal glaciofluvial incision. The longer and steeper slopes above the deep valleys creating greater volumes of supraglacial debris by mass wasting.

Fluctuations in the Holocene glacial record (Sonapani I and II Glacial Advances) may be attributed to perturbations in climate, resulting from variations in the intensity of the monsoon (Mayewski *et al.*, 1980). Overall the glaciers in Lahul have retreated during the last century, which is consistent with other regions in the Himalaya (Mayewski and Jeschke, 1979; Mayewski *et al.*, 1980) and elsewhere in the world (Houghton *et al.*, 1990).

Conclusions

Three glaciations and two minor Holocene glacier advances have been recognised in Lahul. These became less extensive with time and ranged from a broad-valley glaciation, the Chandra glacial stage, to valley glaciations, the Batal and Kulti glacial stages. On the basis of optically stimulated luminescence dating, glaciers probably had begun to retreat by between 43 400 ± 10 300 and 36 900 ± 8400 yr BP, during the Batal glacial stage. The Batal glacial stage is probably equivalent to Oxygen Isotope Stage 4 and early Oxygen Isotope Stage 3. The Kulti glaciation appears younger than 36 900 ± 8400 yr BP and may be equivalent to any or all of Oxygen Isotope Stages 3, 2 and early Stage 1. The development of peat bogs with a basal age of 9160 ± 70 ^{14}C yr BP possibly represents a phase of climatic amelioration that may be coincident with the end of the Kulti glaciation. On the basis of weathering characteristics the Sonapani glacial advance is probably of early to mid-Holocene age, whereas the Sonapani II glacial advance is historical. The age of the Chandra glaciation is unknown, but it probably is equivalent to the glaciation before the last interglacial.

These age constraints help rule out the possible tectonic control on the pattern of glaciation for this region, the period of uplift not being significantly long enough to result in sufficient elevation changes to reduce the amount of moisture reaching this region. The pattern may be attributed to topographic controls as each glacier is constrained by glacially and fluvially deepened valleys. Alternatively, tentative correlations and comparisons with other glaciated areas in northwest India and Pakistan show similar patterns which suggest that these changes in glacial style may be a reflection of regional climatic change, during which the region becomes progressively more arid during late Quaternary times. This pattern also supports the view that mountain glaciations in other regions of the world also may have been more extensive during Oxygen Isotope Stage 4 rather than Oxygen Isotope Stage 2. There is a need, however, for more precise dating in this and other regions of the Himalayas to evaluate the relative importance of global climate change and topography in controlling change in glacial style. Figure 21 provides a framework that should be vigorously tested by a variety of different dating techniques. There is also a need for accurate reconstructions of the former extent of glaciers in order to provide valuable data for palaeoenvironmental modelling.

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