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QUATERNARY GLACIAL HISTORY OF NW GARHWAL, CENTRAL HIMALAYAS

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Abstract — A first account of the Quaternary glacial history is presented for northwest Garhwal, Central Himalaya. On the basis of sediments and landforms, one glacial stage has been recognised. This is called the **Bhagirathi Glacial Stage**, when extensive valley glaciers advanced down the Bhagirathi valley to Jhala, 40.5 km from the snout of Gangotri Glacier. The ELA depression during this stage was ca. 640 m. The Bhagirathi Glacial Stage is constrained by optically stimulated luminescence dates of ca. 63 ka and 5 ka BP, and this glaciation is considered equivalent to the Last Glaciation elsewhere in the world. The maximum extent of ice occurred ca. 63 ka BP. This, however, does not correlate with the Last Glacial Maximum for the northern hemisphere ice sheets (20–18 ka BP). A series of sharp-crested moraines are present between 1 to 3 km beyond the snouts of most of the present glaciers. These moraines formed during the mid Holocene (<5 ka BP), termed here the **Shivling Glacial Advance**. Small moraines are inset into these and are dated at about 200 to 300 BP (the **Bhujbas Glacial Advance**; ca. 300 to 200 BP) and considered equivalent to the Little Ice Age in other parts of the world. ELA depressions of between 40–100 m and 20–60 m occurred during the Shivling and Bhujbas Glacial Advances, respectively. Since the Bhujbas Glacial Advance, there has been progressive retreat of glaciers, initially by downwasting and retreat, and then by simple retreat. This retreat has accelerated during the last few decades. Impressive paraglacial fans are associated with deglaciation representing very rapid resedimentation during and soon after ice retreat. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The Bhagirathi River valley and its tributaries, north of Uttarkashi, provide a framework for a first glacial history for northwest Garhwal, Central Himalayas (Fig. 1). Previous work on the Quaternary glacial history of other regions of the trans-Himalayan mountains includes the Karakoram Mountains (Derbyshire *et al*., 1984; Shroder *et al*., 1993); the Nanga Parbat Himalaya (Shroder *et al*., 1989Shroder *et al*., 1993; Scott, 1992); the Swat Himalaya (Porter, 1970; Owen *et al*., 1992); Kashmir (Holmes and Street-Perrott, 1989); Ladakh (Burbank and Fort, 1985; Osmaston, 1994); the Nepal Himalaya (Fushimi, 1977; Iwata, 1984; Iwata *et al*., 1982; Fort, 1987, 1993, 1995; Shiraiwa and Watanabe, 1991); and the Lahul Himalaya (Owen *et al*., 1995a, 1996a) (Table 1). However, little work has been done in the upper catchments of the Ganges River system. The Garhwal Himalaya is a particularly important region because it has been, and still is, strongly influenced by the Indian monsoon. As such, it provides an opportunity to examine the variations in the palaeomonsoon and the influence of Milankovitch orbital forcing and/or the effects of recent mountain uplift on climate change in the Central Himalayas (cf. Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992; Valdiya, 1993). Also, this study provides a framework for interpreting Quaternary glacial chronologies and landforms elsewhere in the Himalayas.

GEOMORPHOLOGICAL SETTING

The study area is situated north of the Main Central Thrust (MCT) and comprises granites, garnet mica schist, quartz biotite schist, kyanite schist, augen gneiss and banded augen gneiss (Agarwal and Kumar, 1973; Metcalfe, 1993). It has a total area of ca. 2575 km^2 with altitudes ranging from 1500 m to 7075 m a.s.l. The climate is influenced by the south-west Indian monsoon with an average annual precipitation of 1550 mm (IMD, 1989). Both valley aspect and altitude have a marked effect on the microclimate. The main flora comprises *Quercus incana, Rhododenron arboreum, Pieris ovalifolia, Cednes deodara*, which are tolerant to long-lying snow cover, and *Artemisia marilima, Pinus excelsa, Pinus geradiana* and *Betula utelis* which occur as pioneers on scree, rock and steep slopes (Schweinfurth, 1968). The upper tree-line in Garhwal is represented by *Betula utelis* at an altitude of 4150 m a.s.l.

The aspect, length, snout altitude, and present and past equilibrium-line altitudes (ELAs) of glaciers within the study area are listed in Table 2. These glaciers are of high activity type (Andrews, 1975) and supraglacial debris transport pathways dominate the depositional environ-

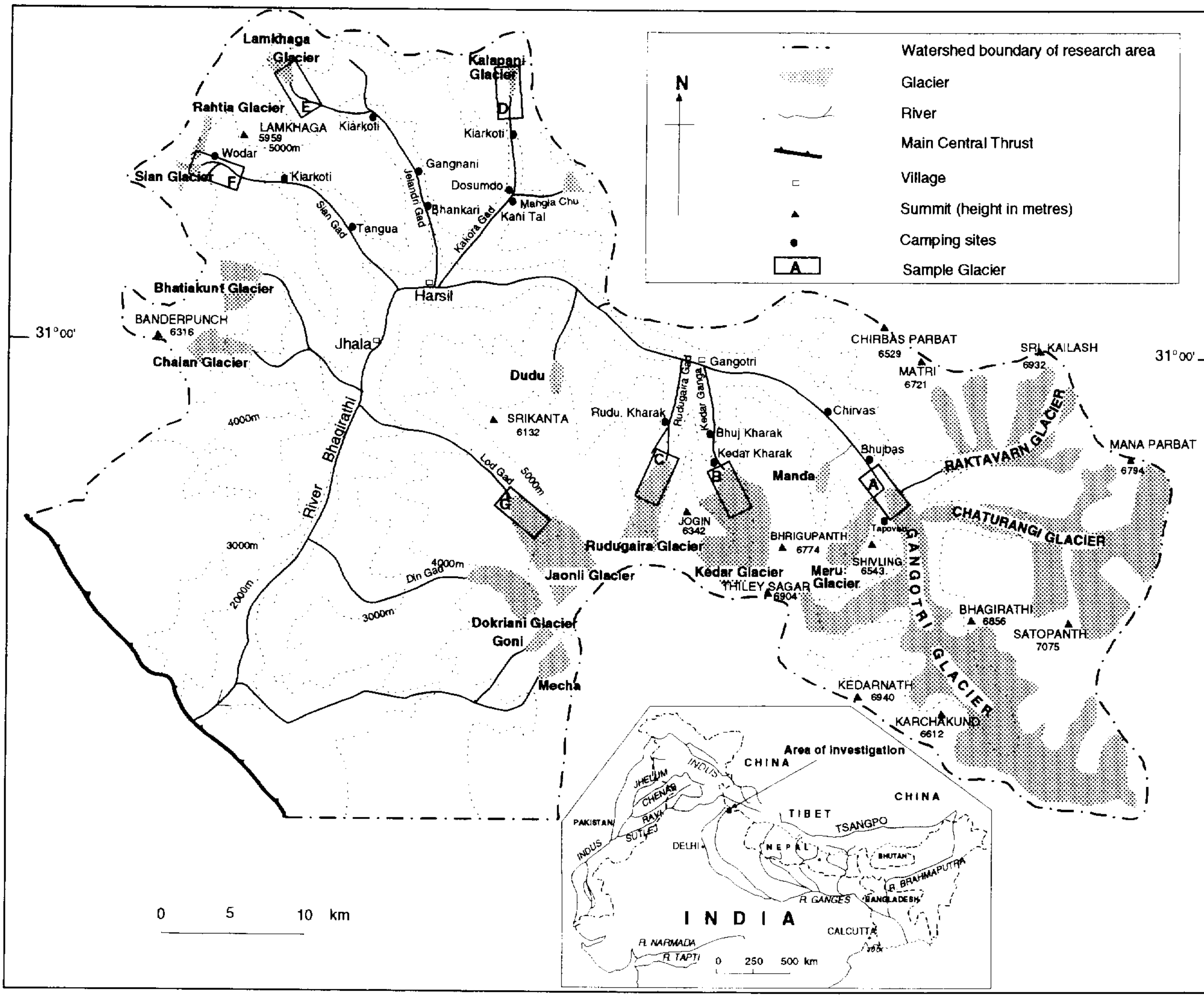


FIG. 1. The NW Garhwal Himalaya showing the main glaciers, rivers and peaks. The insets show main study area (A) Upper Bhagirathi; (B) Upper Kedar; (C) Upper Rudugaira; (D) Upper Kalapani; (E) Upper Lamkhaga; (F) Upper Sian; and (G) Upper Jaonli Valley.

TABLE 1. Tentative correlation of Quaternary Glaciations throughout the Himalayas. Note that there is little or no dating control on these chronologies and the dates which have been obtained are highly suscept, because of reworking of sediment by pedogenesis and resedimentation (cf. Owen *et al*., 1992)

GLACIAL NON-GLACIAL			Lahul	Middle Indus-Gilgit-Hunza Valleys			Upper Indus	Zanskar	Swat Kohistan	Garhwal	Tentative Dates
SERIES	STAGE	STADE	Owen *et al.* (1995)	Derbyshire *et al* (1984)	Shroder *et al.* (1993)	Zang & Shi (1980)	Cronin *et al.* (1989)	Osmaston (1994)	Porter (1970)	This study	Years
HOLOCENE			Sonapani II	Pasu II	Historical	Historical	Individual Moraines	Drang-drung Neoglacial	Neoglacial	Bhujbas	10^2
			Sonapini I	Pasu I	Little Ice Age	Little Ice Age					10^3
				Batura	Neoglacial	Neoglacial				Shivling	
PLEISTOCENE	LATE GLACIATION		Kulti	Ghulkin II	Darel-Shatial Moraine	Hunza Glaciation		Tepuk Glacial	Kalam Glaciation Late Stade	Bhagirathi	10^4
				Ghulkin I					Kalam Glaciation Intermed. Stade		
				Borit Jheel	Dainyor Moraine				Kalam Glaciation Early Stade		10^5
	M-L IG.		Batal II	Yunz	Valley Fill III	Yunz Glaciation	? Strong Erosion Alluviation	Thonde Glacial	Gabral Glaciation Late Stade		
	MIDDLE GLACIATION	Late Stade			M2 Tills		Satpura Till	Kilima Glacial			
					Valley Fill II		? Valley Fill				
		Early Stade	Batal I		M1 Tills		Bunthang Till		Gabral Glaciation Early Stade		
	E-M INTER G.		Chandra	Shanoz	Upper Jalipur Valley Fill I	Shanoz Glaciation					10^6
	EARLY G.				Lower Jalip. Till				Laikot Glaciation		

TABLE 2. Characteristics of glaciers *in the* Garhwal Himalayas and the present equilibrium-line altitudes determined by four different methods

Name of glacier	Aspect	Length (km)	Size (km^2)	Headwall altitude	Snout position	A-WM	AAR 0.6	AAR 1.3	THAR	Present mean ELA	Bhujbas	Shivling	Bhagirathi Stage
Gangotri	NW	30.7	87.08	6400	3900	5010	4850	4750	5150	4940	4920	4890	4300
Chaturangi	W	120.3	43.19	6300	4400	5460	5450	5350	5350	5390	*	*	*
Raktavarn	SW	12.3	25.62	6200	4500	5460	5300	5260	5350	5340			*
Meru	NE	6	4.9	5500	4465	4920	4750	4650	5065	4870			*
Bhrigpanthn	N	8.3	7.63	6000	4130	5000	4750	4650	5065	4870			*
Manda	NE	3.3	2.67	5000	4200	4550	4550	4450	4600	4540			*
Matri	SW	4.2	2.93	5600	4600	5200	5250	5150	5100	5180			*
Chirvas	SW	3.3	2.17	6100	4700	5370	5300	5200	5400	5320			*
Deogad	SW	3.3	1.24	5900	4500	5300	5300	5200	5200	5250			*
Kedar	N	9.3	16.28	5900	4400	5000	4900	4850	5150	4980	4960	4940	*
Rudugaira	N	6.3	14.61	5600	4540	5000	4800	4750	5070	4900	4880	4860	*
Dudu	N	6	3.73	5400	4100	4500	4450	4350	4750	4510			*
Jaonli	NW	9.8	10.84	6200	4310	4950	4900	4800	5255	4980	4930	?	?
Dokriani	NW	6.5	4.36	5500	3750	4860	4800	4700	4625	4750			DNA
Goni	SW	3.3	2.09	5400	4350	5025	4800	4700	4875	4850			DNA
Mecha	SW	4.5	3.2	5300	4150	4900	4850	4800	4725	4820			DNA
Kalapani	S	4.2	4.86	5200	4200	4725	4700	4600	4700	4680	4600	4500	*
Lamkhaga	S	5.1	4.28	5400	4380		4920	4800	4700	4890	4830	4740	4690
Rahtia	S	7.8	6.74	5700	4500	5120	5050	4950	5100	5060			
Sian	NE	5.4	7.4	5600	4400	4980	5000	4850	5000	4960	4890	4840	*
Bartiakhunt	NE	5.5	9.91	5600	4200	5050	5050	4900	4900	4980			DNA
Chaian	E	5.6	6.9	5700	4200	4700	5000	4900	4950	4890			DNA
Others			8										
Total Area			280.63										684.66

DNA = Data not available. * = Confluence wlth Gangotri Glacier. ? = Uncertain. Altitude in metres above sea level. Sample glacier in bold letters.

TABLE 3. Relative dating characteristics for moraines in the Garhwal Himalayas. The moraine numbers in the first column refer to the moraine ridges shown in Figs 3A and 9. See the text for a detailed discussion

GLACIER Moraine	GANGOTRI			KEDAR					RUDUGAIRA					KALAPANI					SIAN					JAONLI				
				% Boulder Relief					% Boulder Relief					% Boulder Relief					% Boulder Relief					% Boulder Relief				
No.	NOS	PVP	NOL	BF	FvW	H	M	L	BF	FwW	H	M	L	BF	FvW	H	M	L	BF	FvW	H	M	L	BF	FvW	H	M	L
1	47	60	7	31	0	35	19	46	18	0	72	16	12	–	–	–	–	–	73	8	44	32	24	25	8	48	32	20
2	43	60	7	56	66	50	36	14	–	–	–	–	–	75	16	24	32	44	103	26	32	48	20	108	34	56	20	24
3	38	38	7	63	78	42	30	28	–	–	–	–	–	78	30	36	30	34	103	76	32	52	16	123	62	24	48	28
4	31	34	7	110	78	56	24	20	7	0	28	14	58	61	24	20	56	24	120	68	20	64	16	107	86	26	36	38
5	–	–	–	77	84	54	32	14	26	0	23	46	31	94	72	42	32	26	91	76	24	30						
6	26	25	7	34	24	44	27	29	45	22	22	53	25	115	68	18	50	32										
7	23	33	7	41	14	24	46	30	67	24	24	60	16															
8	–	–	–						–	–	–	–	–															
9	–	–	–						113	36	18	70	12															
10	–	–	–																									
11	16	14	7																									
12	13	13	3																									
13	–	–	–																									
14	–	–	–																									
15	5	5	1																									

NOS = Number of plant species. BF = Boulder frequency %. M = Medium (0.5–1 m). PVP = Percent plant cover %. FvW = Fresh vs weathered %. L = Low (<0.5m).
NOL = Number of lichen types %. H = High (>1 m diameter).

ment. They are similar to Ghulkin-type glaciers described by Owen and Derbyshire (1989) in the Karakorarn Mountains. In the higher parts of the area, glacial meltwater dominates the fluvial system. Mass movement is common, and is initiated by heavy monsoon rains and active fluvial incision along the lower steep valley slopes (Owen *et al.*, 1995b, 1996b). Low frequency–high magnitude events such as earthquake induced mass movements are also important in the landscape evolution of this area. These are discussed in detail in Owen *et al.* (1995b, 1996b).

METHODS

Detailed geomorphological mapping of the upper Bhagirathi, upper Kedar Ganga, Rudugaira, Kalapani, Sian, Lamkhaga, and Jaonli valleys was undertaken using chain surveys and reconnaissance plane tabling (Fig. 1). Exposures were logged and sediment samples were collected for laboratory analysis. Glacial and non-glacial diamictons were distinguished using the criteria of Owen (1994).

Relative Dating

Morphostratigraphy and multiparameter relative dating methods were used to define and differentiate the complex assemblage of moraine ridges and associated landforms in the forefields of the present glaciers. In the forefield of Gangotri Glacier, these included the number of vascular plant species and the percentage plant cover (Birks, 1980; Wardle, 1980; Matthews, 1978; Matthews and Whittaker, 1987) and the number of lichen species and their diameter (Calkin and Ellis, 1980; Procter, 1983; Caseldine, 1985; Rodbell, 1992). The percentage plant cover and the number of species were calculated from transects of 30 m × 3 m, aligned consistently in a northwest–southeast direction in the Gangotri Glacier forefield. The Gangotri Glacier forefield is the only region where climatic conditions favour the growth of lichens and vascular plants. Therefore, relative dating techniques used in the other regions included boulder frequency, the ratio of fresh to weathered boulders and boulder relief. These were measured in transects of 15 m × 3 m using the techniques of Perrott and Goudie (1984), Burbank and Cheng (1991), Burke and Birkeland (1979), Carroll (1974) and Peck *et al.* (1990). The reliability of these techniques for differentiating the different ages of moraines was highly variable because of the differences in rates of exogenetic processes across the region due to microclimatic variations. However, the methods did allow broad contrasting characteristics to be used for correlation purposes. Table 3 shows the relative weathering results for moraines in the study areas and this will be referred to within the descriptions of each of the detailed study areas.

Optical Dating of Sediments

The optically stimulated luminescence (OSL) dating technique was used to determine the age of selected samples (Huntley *et al.*, 1985). The suitability of sediments for OSL dating was taken into consideration while collecting the samples for the present analysis (cf. Rhodes and Pownall, 1994). Table 4 and Fig. 2 show the characteristics and location of each sample. Samples were collected by hammering 15 × 3.8 cm plastic tubes into the sediment at locations at least 1 m below the crest of exposed sections in conditions of subdued light. These tubes were wrapped in X-ray proof Kodak photo-paper bags and processed at the Luminescence Laboratory in the Geography Department, Royal Holloway, University of London.

All samples were dried at 50°C before sieving. Size fractions with mean grain size of 90–125 and 125–180 μm were treated at room temperature with hydrochloric acid for 20 mins to eliminate calcium carbonate. Further treatment with concentrated hydrofluoric acid (40%) was carried out for 40 mins to remove the parts of grains that may have been affected by alpha radiation and to dissolve any feldspar that was present. The samples were then washed with hydrochloric acid and distilled water to remove fluorite precipitates produced during the HF treatment. Sodium polytungstate (density of 2.68 gcm^{-3}) was used for separating heavy minerals. The remaining quartz grains were dried at 50°C and sieved to remove any grains which were smaller than 90 or 125 μm, for two grain size categories for analysis.

Twenty four aluminium discs were prepared for each sample by mounting quartz grains as a monolayer using viscous silicone oil as an adherent Natural normalisation of 0.3 sec was followed by irradiation at the dose rates of 0, 400, 800, 1600, 3200 and 6400 sec. All discs were subjected to a preheat of 220°C and a 25 sec infrared stimulation prior to a 25 sec exposure to green light in a Riso set. Grün's (Grün, 1994) programme was employed in calculating the final age estimates.

Equilibrium-Line Altitude in the Garhwal Himalaya

Geographical position and aspect strongly control the mass balance of glaciers in the NW Garhwal. The areal extent of the glaciers and their ELAs were established using a 1:150,000 scale Swiss topographical map (Huber, 1985) of the Western Garhwal. Former glacier fronts and ELAs were estimated using moraines and glacial deposits. The ELAs were determined using Porter's (1970) accumulation area ratio of 0.6, Andrews' (1975) accumulation area ratio of 1.3, Sissons' (1974) area-weighted mean ($x = AihilAi$, where Ai is area in km^2, hi is mid-point altitude in contour interval) and Meirding's (1982) toe–headwall altitude ratios (THAR) of 0.4 and 0.5. The accumulation area ratio (AAR) assumes that the accumulation area comprises a certain fraction of the total glacier surface, whereas the area-weighted method is based on the assumption that the amount of ablation decreases linearly with height (Sissons, 1974). Likewise, toe–headwall ratio (THAR) represents the ELA lying at a certain fraction of the glacier's length (usually ~ 0.4).

TABLE 4. Optical dating characteristics and ages for samples in the Garhwal Himalaya, summarising the specifics of the sampling site and material, and the OSL characteristics

Sample ID No.	Location	Sample position and specification	Thorium ppm	Uranium ppm	Potassium %	Water %	ED (Gy)	Age (years)
MI 01	Excavation on terminal moraine Jhala, at 2300 m	~10 cm thick fluvial lens in diamict between path excavation. 1m from base and ~2m from top	13.0	9.8	1.052	1.43	279±35	62,894±8575
MI 02	On top of terrace at Rudugaira Kharak at 4200 m	~2 m thick aeolian silt overlying lateral moraine edge	16.0	4.0	2.877	6.0	23±5.8	4837±1209
MI 03	Above Bhuj Gaddi at 3995 m	~2 m thick aeolian silt above mts thick finely laminated and rippled lacustrine deposit on top of highest lateral moraine	19.0	19.4	0.952	5.6	34.1±10.2	5125±1544
MI 04	1 km west of Jangla bridge above road at 2700 m	Glaciofluvial deposit 5 m from top and 1m from base in stratified and deformed exposure	16.0	4.1	0.958	1.5	265±97	84,770±31,133
MI 0.5	1 km west of Gangotri road excavation	~20 cm lens in lateral moraine exposure, under boulder	17.0	10.2	0.96	1.5	82±19	17,559±4108

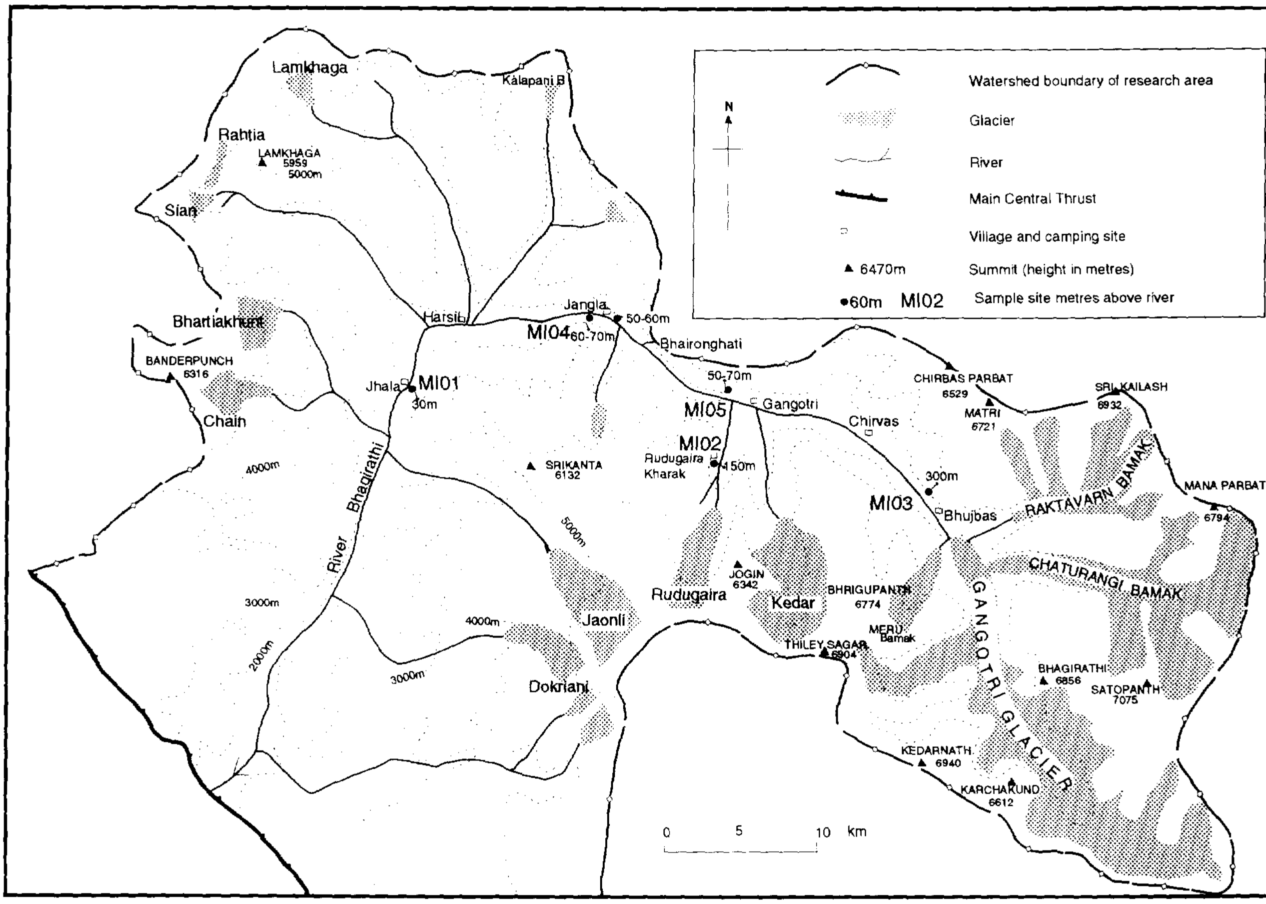


FIG. 2. Location of OSL samples collected for this study.

These four methods thus provide a test of the reliability of the different ELA techniques (Table 2). The THAR of 0.40 (cf. Meierding, 1982; Burbank and Fort, 1985) provided an unrealistic value in this study area compared with the results of the other methods. However, it did prove comparable with other methods when a ratio of 0.5 was used.

FIELD EVIDENCE

Large moraine ridges and smaller inset moraine ridges provide evidence for one major glaciation, here termed the Bhagirathi Glacial Stage, and two glacial advances called the Shivling Glacial Advance and the Bhujbas Glacial Advance (Table 1). Glacial retreat and the resedimentation of moraines has led to the formation of impressive river terraces and paraglacial fans. The geomorphological evidence for the nature and style of glaciation will be discussed for each of the study areas in turn.

Upper Bhagirathi Valley

The area extends from ca. 5 km west of the village of Gangotri to Gangotri Glacier, and includes the lower reaches of the Raktavarn, Chaturangi and Meru glaciers (Fig. 1). Gangotri Glacier is the largest glacier in the Garhwal Himalaya and is joined by the Maiandi and Swachand Glaciers from the northeast and the Ghanohim and Kirti Glaciers from the southwest. Prior to 1971, Chaturangi Glacier joined Gangotri Glacier (Vohra, 1988), but has since retreated by over 100 m. Figure 3 shows the area adjacent to the snout of Gangotri Glacier, between Bhujbas and Tapovan and Table 3 shows the weathering characteristics for each moraine ridge.

Impressive lateral moraines are present along the sides of the Bhagirathi valley. These extend to altitudes of above 4200 m, and can be traced from above Gangotri Glacier down the Bhagirathi valley to an altitude of ca. 3300 m (Figs 4–6). West of Gangotri village, the moraines are discontinuous, but they can be traced to Jhala, about 40.5 km from the present snout of Gangotri Glacier. A sharp crested end moraine dissected by the Bhagirathi River can be seen at Jhala (Fig. 7). Where tributary valley streams have incised down to the valley floors the moraines are deeply incised, revealing excellent sections. These moraines are well vegetated with abundant *Potentilla microphylla*. Open *Pinus* forest is present west of Bhujbas at an altitude of less than 3700 m, and becomes dense below Gangotri village. The surface of Gangotri Glacier is inset into these lateral moraines and has eroded steep slopes of loose debris that rise 120 m to the crest of the highest lateral moraine (Figs 5A and 6B, labelled BSM). These large lateral moraines form a series of discontinuous ablation valleys which are filled with scree, debris flow and lacustrine sediments. They are best developed at Tapovan where an extensive triangular plain is present at an altitude of ca. 4200 m a.s.l. (Fig. 5A). This

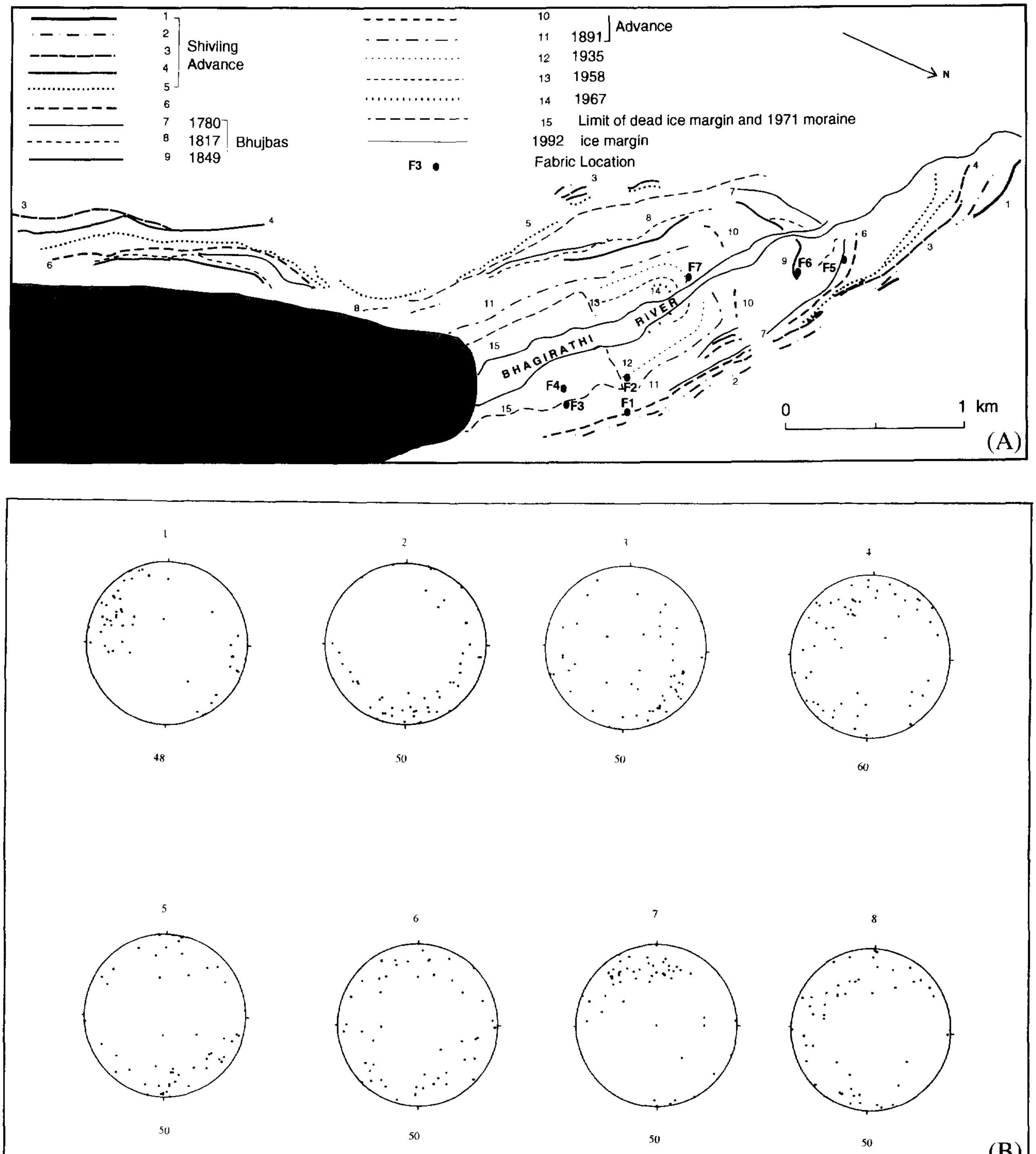


FIG. 3. (A) Relative ages of moraine ridges near Gangotri Glacier and location of pebble fabric measurements. The settlement of Bhujbas is situated just to the east of the figure. (B) Lower hemisphere stereonets for a-axis pebble fabrics from moraines near Gangotri Glacier. The small tick on the top of each circle refers to true north.

is delimited to the east by the western lateral moraines of Gangotri Glacier, to the west by the valley walls and to the north by the lateral moraines of Meru Glacier. This plain comprises lacustrine silts capped by ca. 0.5 to 1 m thick fluvial silts and sands. Historical documents contain descriptions of a large lake at Tapovan from the 7th Century A.D. (Law, 1968). Smaller lacustrine deposits and contemporary ponds are present between successive moraine ridges to the east of Tapovan. All these moraines are attributed to the Bhagirathi Glacial Stage.

West of Gangotri village an extensive striated rock surface that can be traced for several miles is present some 20 to 30 m above the present river level. The Bhagirathi River has incised a deep box-shaped gorge into this surface, to a depth of ca. 20–30 m. The rock surface is correlated with the Bhagirathi Glacial and extends for 10 to 12 km west of Gangotri village and it is then replaced by an extensive braidplain, which is best developed at Harsil.

A series of lateral moraines is inset into the Bhagirathi Glacial Stage lateral moraine (Figs 5A and 6A, labelled BSM) and can be traced down valley to Bhujbas (Fig. 3A).

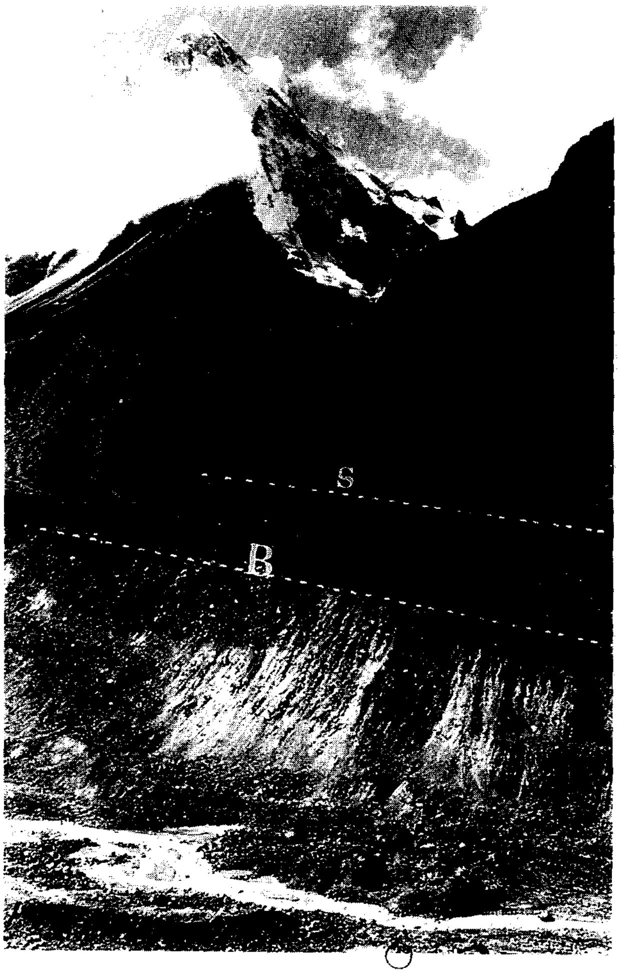


FIG. 4. View looking south towards Shivling peak and the Gangotri Glacier. The moraine labelled (S) is attributed to the Shivling Glacial Advance and (B) to the Bhujbas Advance. The circle encloses a tent for scale.

They can be correlated on the basis of morphostratigraphy, weathering criteria, vegetation and lichen characteristics and attributed to the Shivling and Bhujbas Glacial Advances (Figs 3A and 8, Table 3). In places the moraine ridges are buried beneath debris flows and fluvial sediments: elsewhere, the moraines have been eroded by tributary valley and migrating glaciofluvial streams, and by mass movement processes. Impressive palaeochannels have been preserved, allowing accurate reconstructions of former positions of the meltwater streams (Fig. 5A and B). At the mouth of the Raktavarn valley, three moraine ridges are present at heights of ca. 120 m above the present surface of Gangotri Glacier and 120 m below the highest lateral moraine level of the Bhagirathi Glacial Stage. These three moraine ridges, attributed to the Shivling Glacial Advance, curve westwards traversing the mouth of the Raktavarn valley and are deeply incised by the present Raktavarn stream which grades to the surface of Gangotri Glacier and then drains subglacially.

Within 1 km of the snout of Gangotri Glacier a chaotic assemblage of hummocky moraines and dead ice, with small ponds and lacustrine deposits are present (Figs 3 and 5B). These features have formed during rapid ice retreat since 1971. Pebble fabrics within the hummocks are very diffuse and have been reoriented by slumping (Fig. 3B). Spectacular paraglacial fans are present in the upper Bhagirathi valley (Fig. 6B). These comprise debris flow and fluvial sediments, the source of which is erosion of adjacent moraines. The former positions of Gangotri Glacier were reconstructed on the basis of these landforms (Fig. 8A and B).

Several small rock glaciers occur on the eastern side of Gangotri Glacier, southeast of the confluence with Chaturangi Glacier. Their snouts impinge on to the surface of Gangotri Glacier (Fig. 6A, labelled R). East of Tapovan, ca. 1 km southeast of the Meru glacier, rock glaciers have developed on the slopes. In addition, a small unnamed glacier has become separated from its backwall, and its lower reaches have been transformed into a rock glacier.

Upper Rudugaira Valley

The Upper Rudugaira valley contains two glaciers; Rudugaira Glacier and an unnamed steep hanging glacier (Fig. 9A). A medial ridge ca. 270 m long is capped with massive erratics in the middle part of the two glacial valleys (Fig. 10A). The surface of the hanging glacier is hummocky below the ice fall and eight clearly defined lateral moraines are present within 1875 m of the present snout (Fig. 9A, Fig. 10 and Table 3).

The highest lateral moraine of the hanging glacier is eroded and forms a terrace which is ca. 120 m wide and 1.5 km long (moraine 3 on Figs 9A and 10A). This can be traced along the western side of the valley at Rudugaira Kharak where it is overlain by a 2 m thick deposit of aeolian silt. On the basis of morphostratigraphy and relative weathering, this lateral moraine is attributed to the Bhagirathi Glacial Stage. Small stone stripes are present on the highest moraine ridge in the middle of these two glacial valleys (moraine 1 on Fig. 9A). A 60 m high lateral moraine descends steeply (>25°) from Rudugaira Glacier to an altitude of 4105 m (moraine 10 on Fig. 9A). A similar lateral moraine descends from the hanging glacier to an altitude of 4500 m a.s.l. (moraine 9 on Fig. 9A). A large lateral moraine (moraine 11 on Fig. 9A) can be traced for ca. 2 km from Rudugaira Glacier. This was probably formed during the Bhujbas Advance.

On the basis of these landforms, the former longitudinal profile of Rudugaira Glacier has been reconstructed (Fig. 11A).

Upper Kalapani Valley

In the Upper Kalapani valley, seven sets of lateral moraines are present within 2500 m of the present snout (Fig. 9B and Table 3). These dip down valley at 5° and enclose the present glacier. There is an abrupt break in slope at an altitude of 4215 m where three sets of lateral moraine ridges are present.

Extensive debris flow fans are the dominant landforms between Kalapani Glacier and Dosumdo (Fig. 1). The highest lateral moraine ridge is about 95 m higher than

(A)

(B)

FIG. 5. (A) A series of lateral moraines (centre), with Gangotri Glacier to the left and lacustrine valley fill of Tapovan to the right; (B) Hummocky moraines behind the 1935 end moraine, the circle encloses five tents to indicate scale; and (C) The 1891, 1935 and 1971 end moraines and palaeochannels near the snout of Gangotri Glacier.

(C)

FIG. 5. For caption see page 344.

the present valley floor and, although it is discontinuous, it can be traced to Harsil at an altitude of 2500 m a.s.l. East of Kakora Gad, the lateral moraine has been eroded to form a 300 m long terrace. Unsorted stone stripes have formed on the terrace at 3900 m a.s.l. A large, sharp-crested lateral moraine is present at ca. 145 m above the confluence of Kakora Gad and Mangla Chu which extends down to Harsil (Fig. 1). This is attributed to the Bhagirathi Glacial. A steep bedrock wall is present on the west side of Kakora Gad south of Dosumdo, below which there is an absence of superficial sediments. Figure 11B shows a cross valley profile in the Upper Kalapani valley and reconstructions of the former positions of Kalapani Glacier based on these landforms.

Lamkhaga Valley

Extensive debris flow fans are present along the upper Lamkhaga valley (Fig. 9C). A 500 m long lateral moraine rises 90 m above the present valley floor and is attributed to the Bhagirathi Glacial Stage. This encloses two sets of lateral moraines that formed during the Shivling and Bhujbas Glacial Advances. Six hanging glaciers between Kiarkoti and Lamkhaga Glacier supply large amounts of sediments to the valley which contribute material to the large debris fans. Figure 11C shows a reconstruction of the former ice positions for Lamkhaga Glacier.

Upper Kedar Valley

The Kedar valley contains Kedar Glacier and a small unnamed cirque glacier (Fig. 9D). The lateral moraines of Kedar Glacier and the cirque glacier converge to form a highly eroded and deeply weathered medial ridge that extends down valley for a distance of ca. 1500 m (Fig. 5B). A tabular terrace of dissected moraine is present at Kedar Kharak at an altitude of 4250 m a.s.l. This terrace is overlaid by a 2 m thick deposit of aeolian silt. In the lower 1 km of the valley, a striated bedrock surface is present up to 60 m from the valley floor, rising to an altitude of ca. 3800 m a.s.l. The river has eroded a 20 m deep box-shaped gorge into the bedrock surface. These landforms are attributed to the Bhagirathi Glacial Stage.

Relatively fresh lateral moraines descend to an altitude of 4250 m a.s.l. from Kedar Glacier (Table 3 and moraine 2 on Fig. 9D). The lateral moraine of Kedar Glacier has been eroded to form a terrace which stretches down to Bhuj Kharak at an altitude of 4000 m a.s.l. Stratigraphically equivalent landforms are present on the east side of the river. A set of intensely eroded and weathered lateral moraines can be traced, as a curving ridge, from the cirque glacier as far as Kedar Kharak. These are attributed to the Shivling Glacial Advance.

The Bhagirathi Glacial Advance lateral moraines of Kedar Glacier and the cirque glacier converge at an altitude of 4630 m a.s.l., to block the drainage of a small ablation valley stream. A lake has formed which stretches for ca. 1450 m and is ca. 300 m wide. Cross-valley profiles and a reconstructed longitudinal profile of former ice thickness are shown in Fig. 11D. The lateral moraines (moraine 1 on Fig. 11D) which enclose Kedar Glacier lie over older lateral moraines (moraine 2).

Glacigenic sediments are absent between Kadar Kharak and Gangotri village. However, a 10 to 15 m thick deposit of massive silty matrix-supported diamicton

(A)

(B)

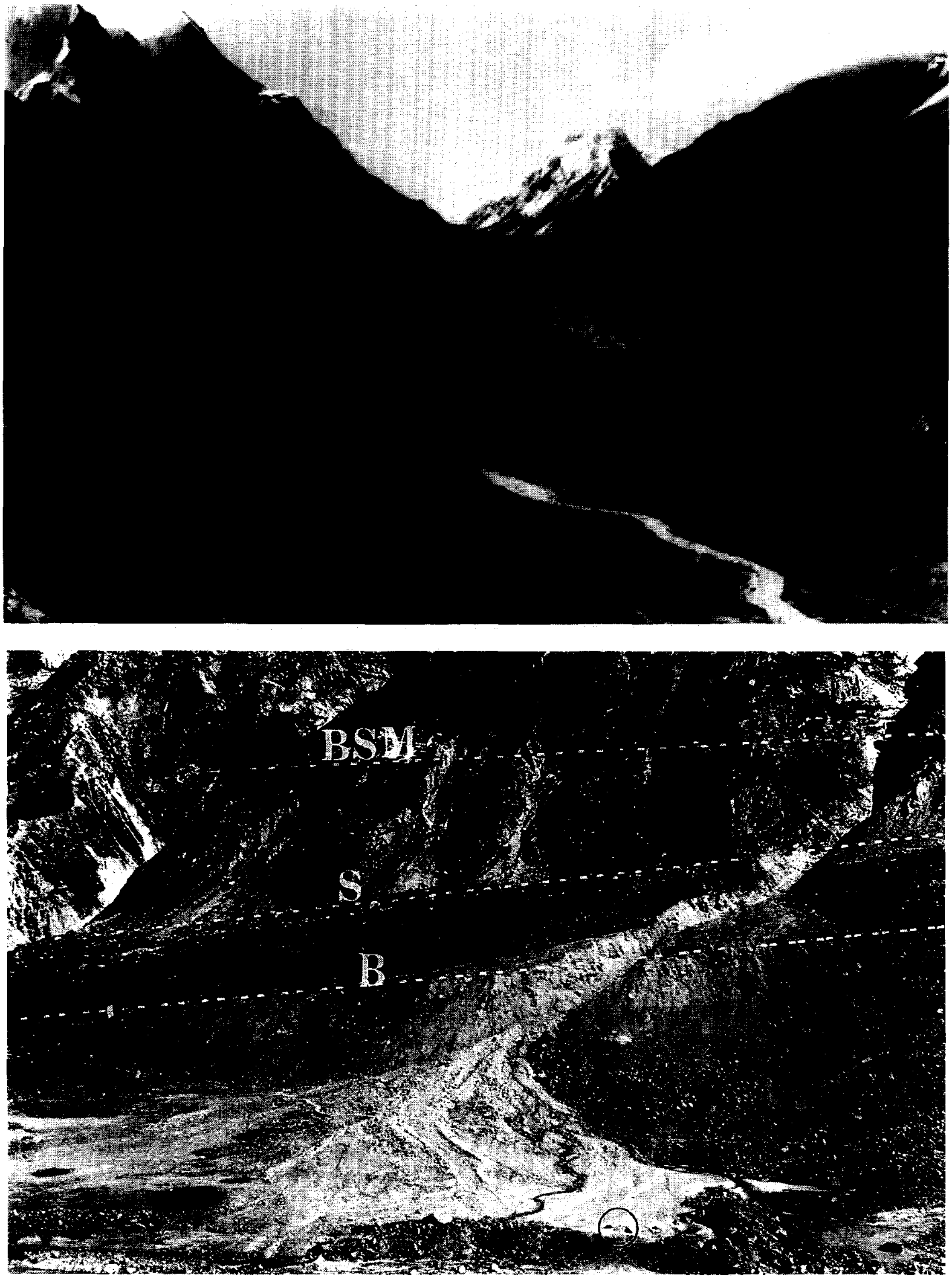


FIG. 6. (A) Rock glacier (R) along the eastern side of Gangotri Glacier; (B) View of a paraglacial fan adjacent to the large lateral moraine near the snout of Gangotri Glacier. The tents (circle) indicate the scale. Moraines of the various phases of advance are labelled BSM (Bhagirathi Stage Maximum); S (Shivling Advance) and B (Bhujbas Advance).

with boulders and cobbles, and metre thick beds dipping 10–15° down valley, is present at the confluence of the Kedar and Bhagirathi valleys forming an impressive gently-sloping (<10°) fan. These were probably deposited after the Bhagirathi Glacial when moraines were resedimented by paraglacial processes. Figure 11D shows cross valley moraines profiles and a reconstruction of the former Kedar Glacier.

Sian Valley

In the Sian valley, Rahtia Glacier and Sian Glacier have formed an 80 m high medial moraine (Fig. 9E and Table 3). Four sets of clearly defined lateral moraines are present in the upper part of the valley. The highest lateral moraine of Sian Glacier on the north of the river extends discontinuously down to an altitude

FIG. 7. View looking eastwards at the Bhagirathi Glacial Stage end moraine at Jhala at an altitude of ca. 2300 m. The ice flowed towards the right of the plate.

of <4320 m a.s.l. and is eroded to form a terrace on the north side of Sian Gad (moraine 1 on Fig. 9E). This terrace can be traced down valley to an altitude of ca. 3200 m a.s.l. A lateral moraine, ca. 2 km long, is present in a cirque basin and possibly corresponds to the highest lateral moraine of Sian Glacier. This descends to Sian Gad at an altitude of 4250 m a.s.l. The second lateral moraine of Sian Glacier is ca. 1950 m long and extends down to Wodar at an altitude of 4250 m a.s.l. (moraine 2 on Fig. 9E). All these are attributed to the Bhagirathi Glacial Stage.

Lateral moraines are well preserved on the northern side of the valley within 1750 m of the present snout of Sian Glacier (moraine 3 on Fig. 9E). On the south side of the valley, however, talus accumulation from steep bedrock walls has buried any evidence of moraines around Sian Gad. Another set of relatively fresh lateral moraines up-valley of Sian Gad extends to an altitude of 4320 m a.s.l. (moraines 4 and 5 on Fig. 9E). These are attributed to the Bhujbas Glacial Advance. Figure 11E shows the transverse and longitudinal profiles of former Sian Glacier based on these landforms.

Intense glaciofluvial activity and fluctuations in the position of Sian Glacier have produced five palaeochannels in the glacier foreland and a chaotic assemblage of moraine ridges, sandy hummocks and a glaciofluvial terrace. On either side of the river near Kiarkoti, extensive sediment fans have been formed by debris-flows (Fig. 1). A 10 m deep box-shaped gorge has been formed by meltwater from Sian Gad about 1 km above of the Bhagirathi River.

Jaonli Valley

Widespread debris flows and failures from steep bedrock walls have resulted in reworking of most of the glacial landforms on the northwest side of Lod Gad. An impressive lateral moraine is present near the snout of Jaonli Glacier (Fig. 9F and Table 3). Its crest is ca. 95 m higher than the present river bed and it has been eroded to form a 1100 m long terrace. This landform is attributed to the Bhagirathi Glacial Stage. Only one small lateral moraine ridge, ca. 80 m long, has been preserved as an inlier within the debris-flow fans (moraine 2 on Fig. 9F). This ridge is attributed to the Shivling Glacial Advance.

In front of Jaonli Glacier, a relatively fresh moraine is present and a set of small lateral moraine ridges, attributed to the Bhujbas Glacial Advance, extends down to an altitude of 4240 m (moraines 3, 4 and 5 on Fig. 9F). Another set of steeply sloping lateral moraines ca. 750 m in length, is inset within the highest lateral moraines. Recent retreat of Jaonli Glacier has produced a series of small lateral moraine ridges and a chaotic assemblage of hummocks in front of the present snout.

Two sets of strongly weathered and well-vegetated lateral moraine ridges descend from cirque basins to an altitude of about ca. 4000 m a.s.l. Numerous rotational landslides and associated 'run-out' deposits are also present along the valley at the altitude of ca. 4000 m. There is little surficial sediment on the steep bedrock wall that forms the northwest side of the valley. Extensive paraglacial fans and rock-avalanche deposits exist on the south side of Lod Gad at altitudes of between 3200 m and 3800 m

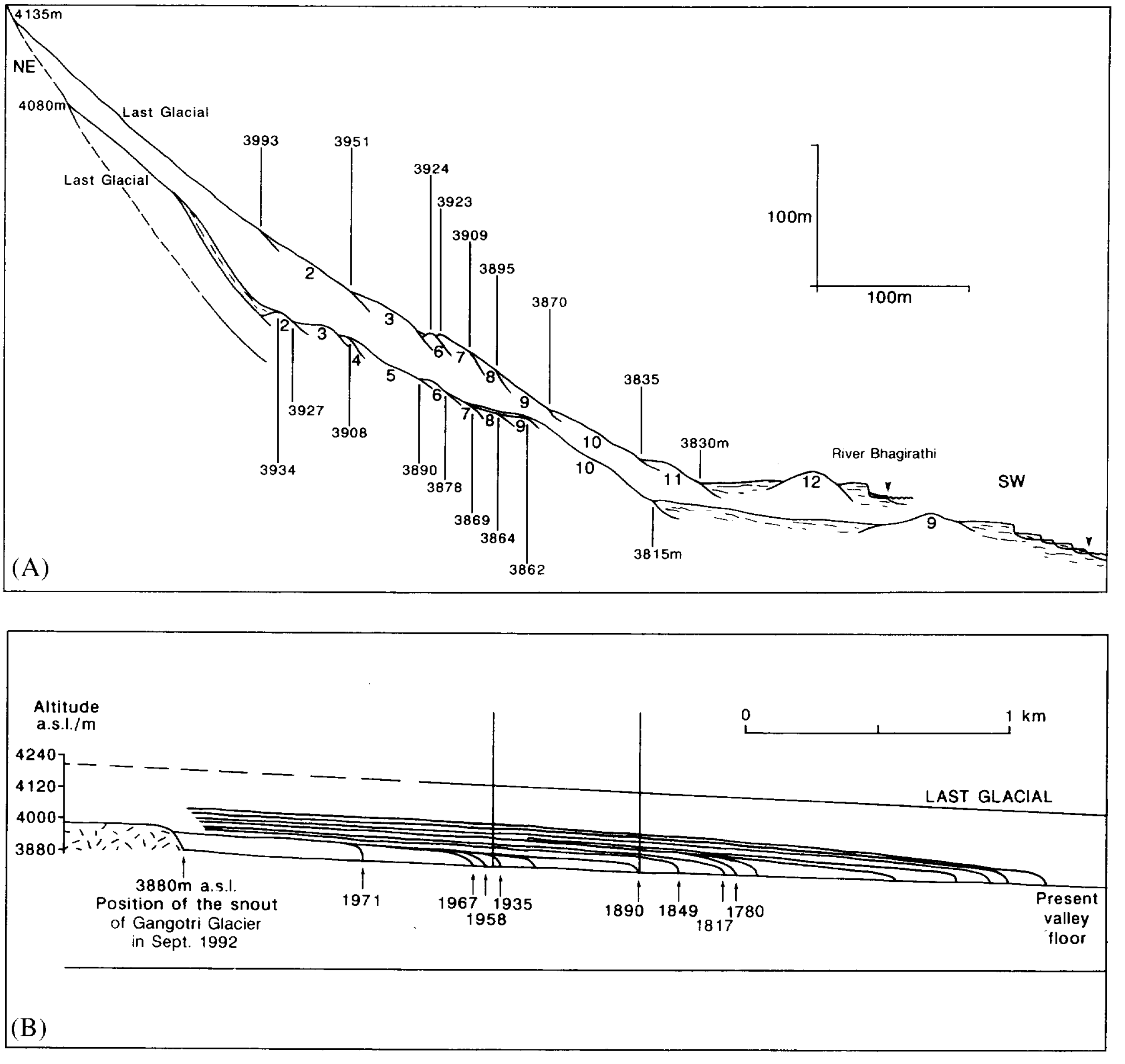


FIG. 8. (A) Relative heights of moraines along selected profiles on the north side of the Upper Bhagirathi Valley. The higher profile is located 1 km and the lower profile 2 km east of the snout of the Gangotri Glacier. Each moraine ridge is numbered as per the moraines in Fig. 3A; (B) Reconstruction of former ice positions for Gangotri Glacier. The vertical lines show the locations of the profiles in (A).

a.s.l. Figure 11F shows the cross-valley profile of the Jaonli valley and the former positions of Jaonli Glacier based on these landforms.

OPTICALLY STIMULATED LUMINESCENCE DATING RESULTS

The optically stimulated luminescence dating results are presented in Table 4. Sample MI 01 has a small confidence limit, whereas the other dates have greater confidence limits probably because of the high percentage of feldspar inclusions within the quartz. The age of sample MI 04 must be regarded with caution because of the large error bar values.

PRESENT DAY EQUILIBRIUM-LINE ALTITUDES

The present day ELAs for glaciers in the NW Garhwal are shown in Fig. 12 and Table 2. The four methods used to reconstruct former ELAs provide a wide range of values. The area-weighted method for reconstructing ELAs (Sissons, 1974) corresponds best to the average ELAs obtained by the other techniques, and is recommended for use in the Garhwal and other Himalayan regions. Meierding's (1982) method using a toe–headwall ratio (THAR) of 0.4 has been used elsewhere in the Himalaya's (Kulkarni, 1992; Burbank and Fort, 1985), but must be treated with caution because of the wide discrepancy between these results obtained by this, compared to other methods. Values of between 0.47 and

(A)

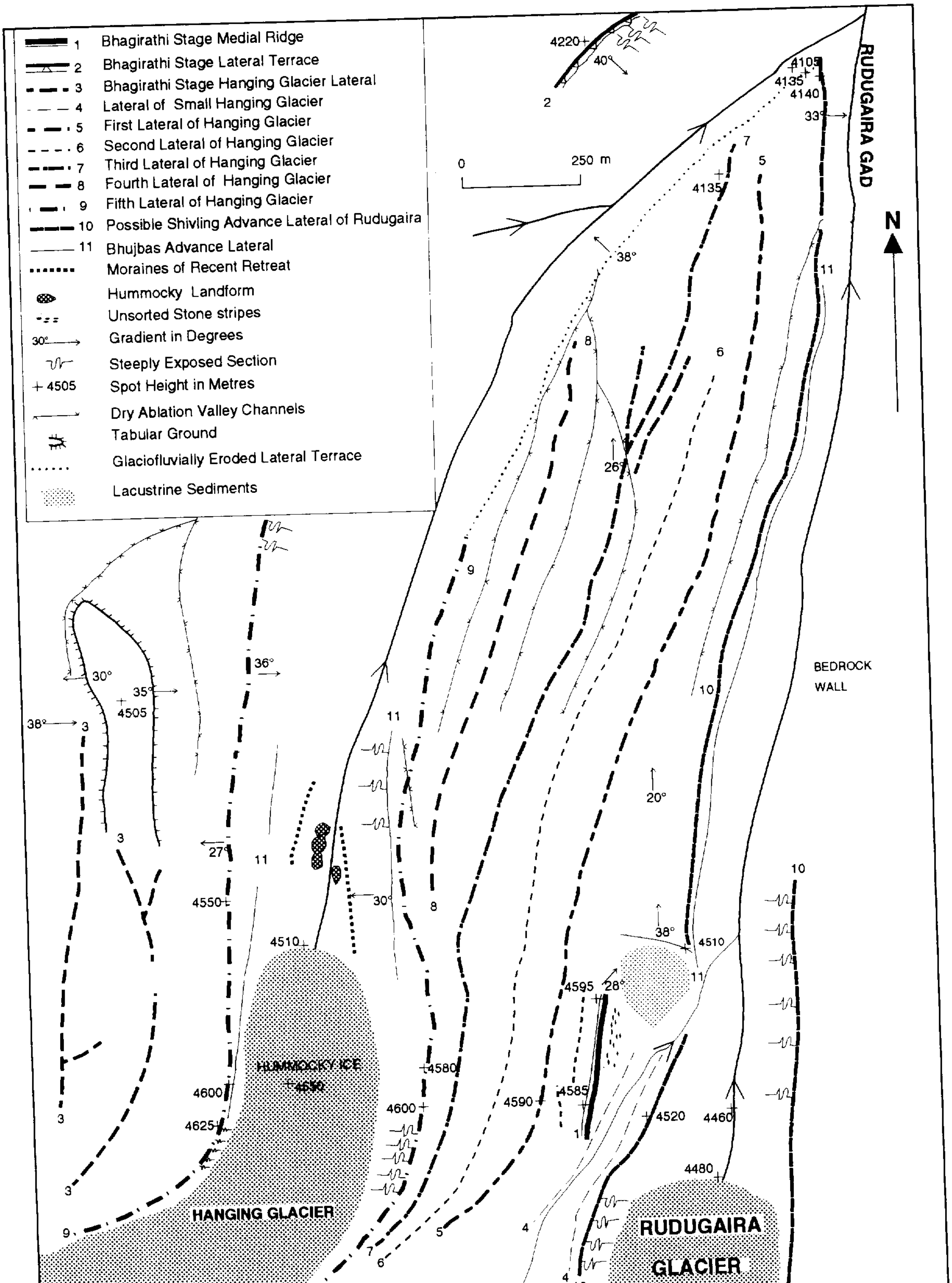


FIG. 9. Geomorphological map showing the main moraine ridges and associated landforms in the upper (A) Rudugaira; (B) Kalapani; (C) Lamkhaga; (D) Kedar; (E) Sian; and (F) Jaonli valley. Note that the moraine ridges are numbered independently within each study area but the names of glacial advances have been used to help correlate areas.

(B)

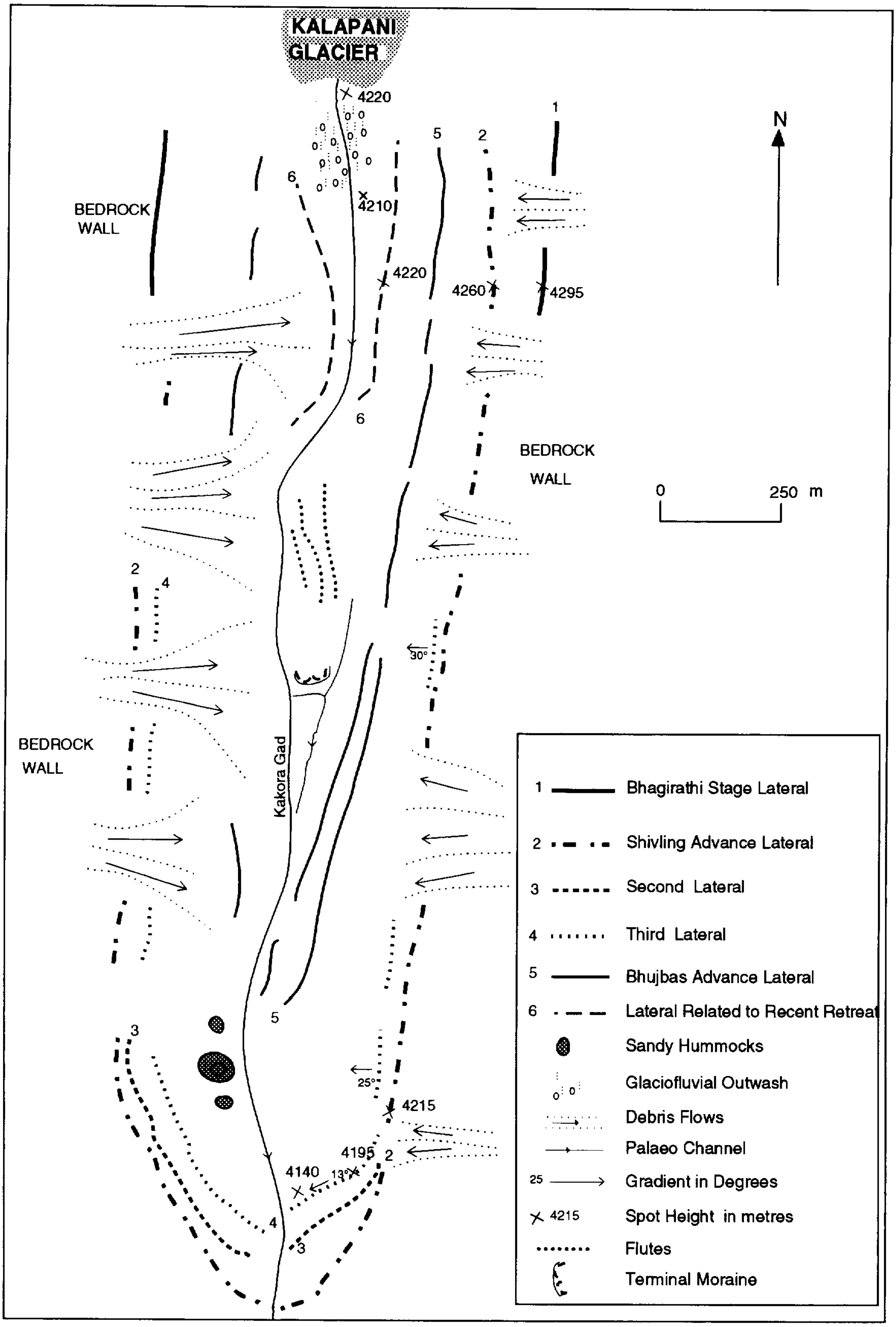


FIG. 9. For caption see page 349.

(C)

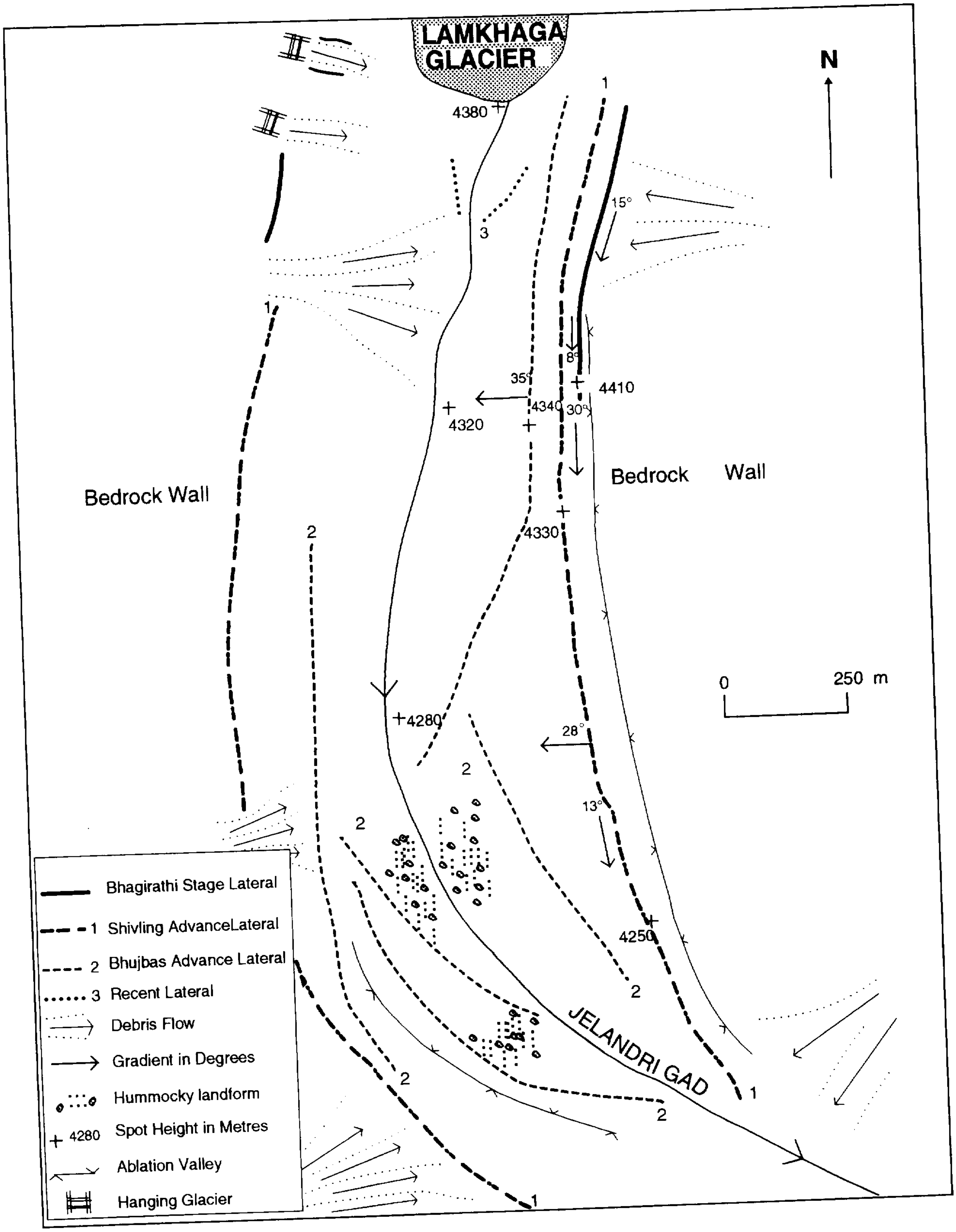


FIG. 9. For caption see page 349.

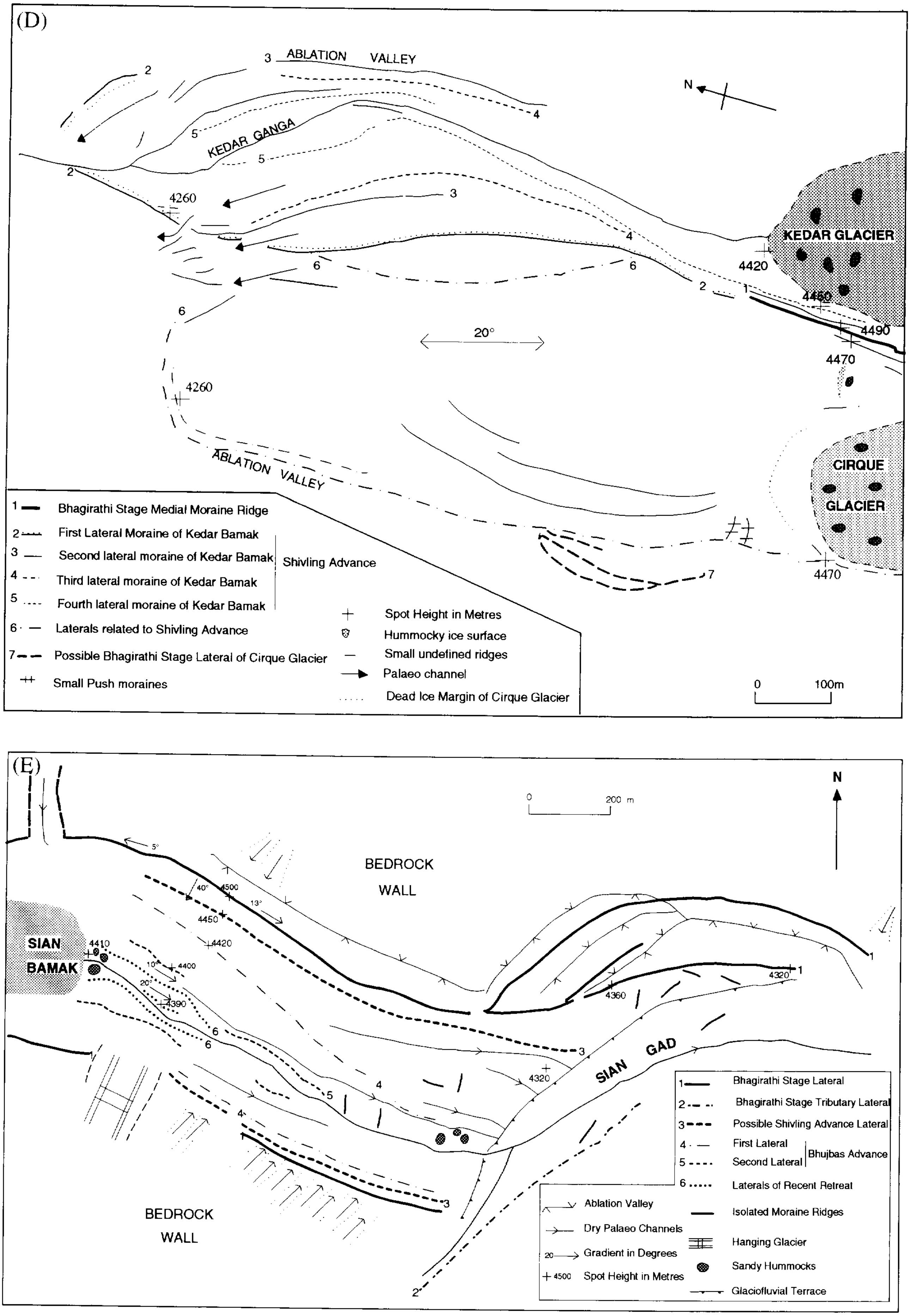


FIG. 9. For caption see page 349.

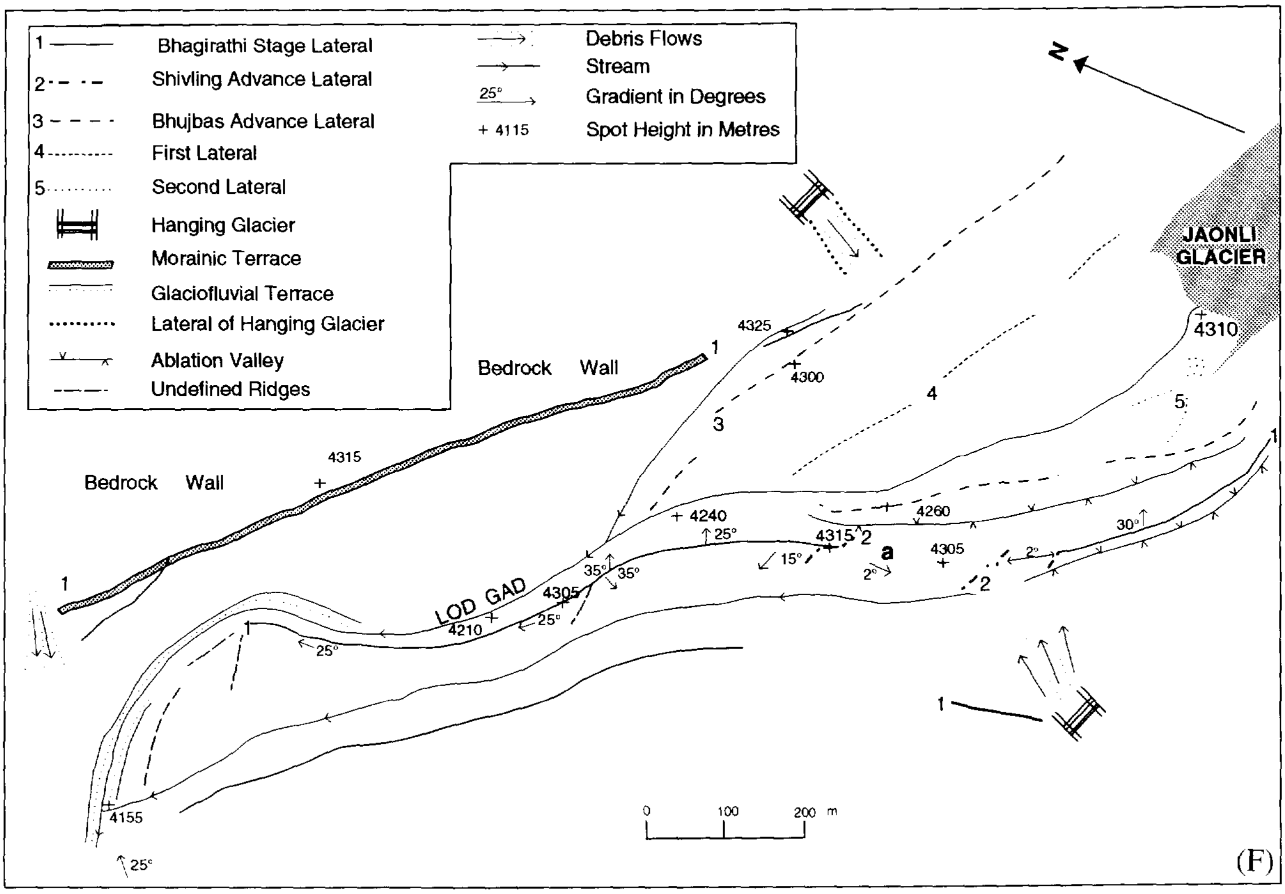


FIG. 9. For caption see page 349.

0.51, however, coincide more closely with the values derived from area-weighted and contour pattern methods. Unfortunately, each glacier probably requires independent THAR and AAR values.

The data presented in Table 2 show that Gangotri, Jaonli, Dokriani, Bhrigupanth, Kedar, Rudugaira and Dudu glaciers with northwestern and northern aspects have similar ELAs. A lower ELA for Dudu Glacier is explained by its areal coverage of only 3.73 km^2 and the fact that it is constrained within a small altitudinal range between 4100 and 5400 m a.s.l. Similarly, the small Manda Glacier, with a NE aspect and a length of only 3.3 km and an area of only 2.67 km^2, and has the lowest ELA of all these glaciers.

Of the three glaciers with southern aspects, the Kalapani and Lamkhaga, have relatively low ELA values of 4680 m and 4830 m, respectively. These two south-facing glaciers lie at the head of the S–N oriented Bhagirathi River valley and receive large falls of precipitation as winds are forced up the valley during the monsoon. In contrast, the third glacier in this group (Rahtia), has a higher average ELA of 5060 m, and is situated at the head of the Sian valley in the drier (northwestern) part of the region.

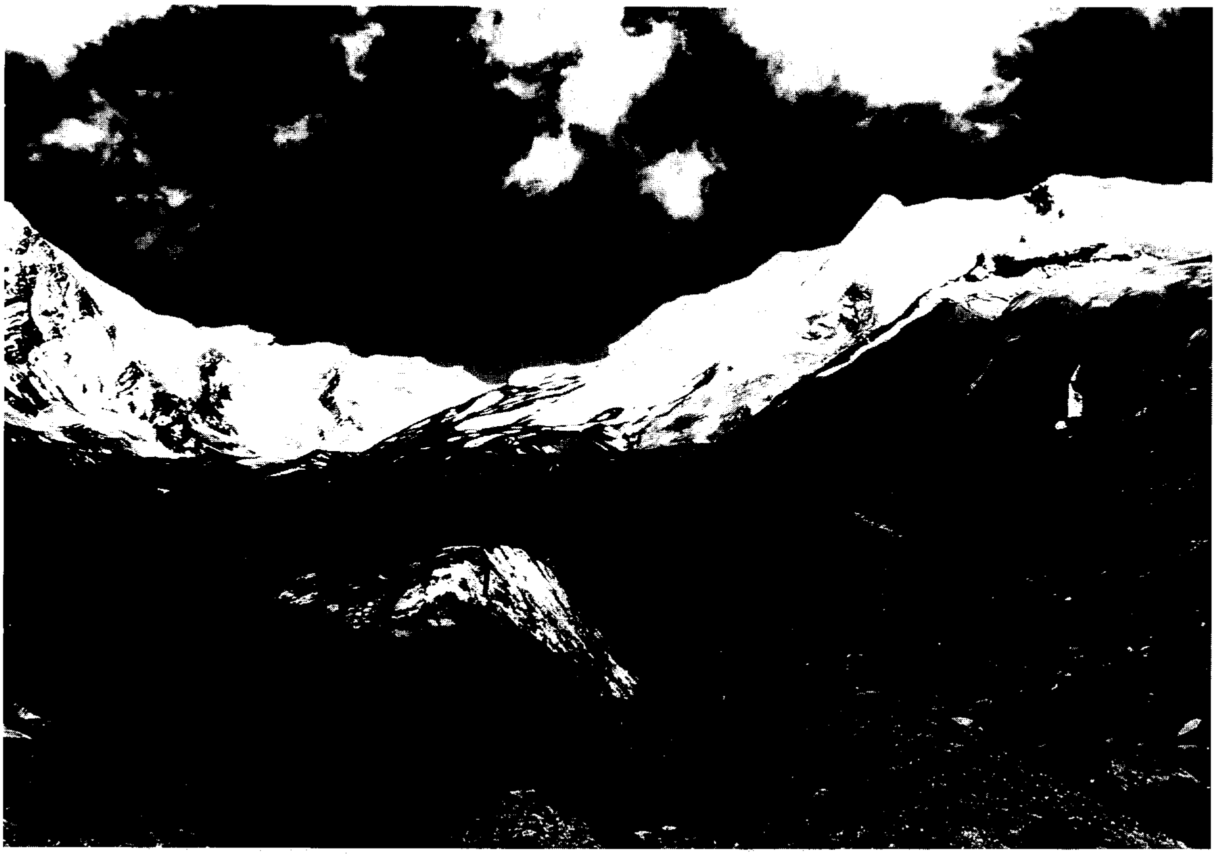
The majority of the glaciers with SW aspects, as well as Chaturangi Glacier which is the only glacier with a western aspect, have very high ELA values, of over 5180 m. Goni and Mecha Glacier with SW aspects, are located in the southern-most part of the study area and have low ELAs because they are in the wettest part of the region.

FORMER EQUILIBRIUM-LINE ALTITUDES

Comparisons between former and present day ELAs have yielded valuable information on the magnitude and extent of climatic change in mountains (Lowe and Walker, 1984; Bradley, 1985; Porter, 1977). Once the glacier limit is determined from the ice-marginal evidence in the form of terminal or lateral moraines and down-valley termination of hummocky moraines, ice surface contours may be estimated by analogy with the contour patterns of modern glaciers (Lowe and Walker, 1984). Furthermore, investigations into the mass balance of present glaciers has shown that ELAs provide a useful link between glaciers and climate (Sutherland, 1984).

Figure 11 shows some reconstructions of former ice positions in the NW Garhwal that were used to help calculate former ELAs. During the Bhujbas Glacial Advance, glaciers extended up to 2.2 km from the present snout positions. An increase in ice-thickness of between 40 and 130 m has been calculated from the seven study areas as a result of ELA depressions of between 20 and 60 m (Tables 1 and 5). An ELA depression of only 20 m for Gangotri Glacier produced an advance of ca. 2.2 km and a thickening of ca. 130 m. This shows that when glaciers occupy relatively gentle valley floors, a slight additional

(A)



(B)

FIG. 10. (A) View looking southwards across the supraglacial debris-laden surface of the Rudugaira Glacier; and (B) View south-southwestwards at the hanging glacier in the Rudugaira valley with six lateral moraines. These views typify the charactersitic of most of the glaciers in the Garhwal Himalaya. The moraine ridges are numbered in these plates correspond to the moraines numbered in Fig. 9A.

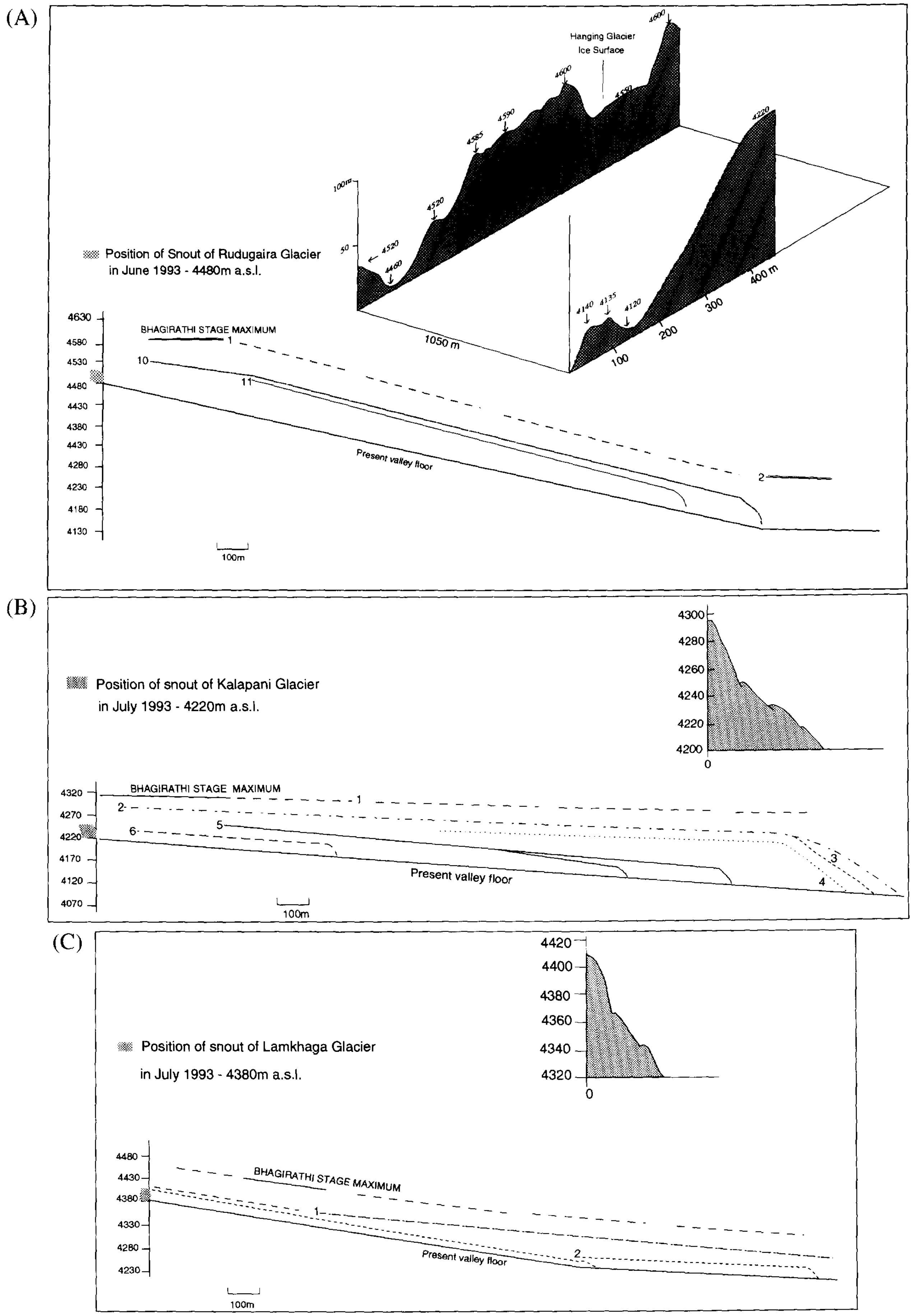


FIG. 11. Transverse and longitudinal valley profiles, and reconstruction of ice thickness and present position of glacier ice for (A) Rudugaira; (B) Kalapani; (C) Lamkhaga; (D) Kedar; (E) Sian; and (F) Jaonli valley.

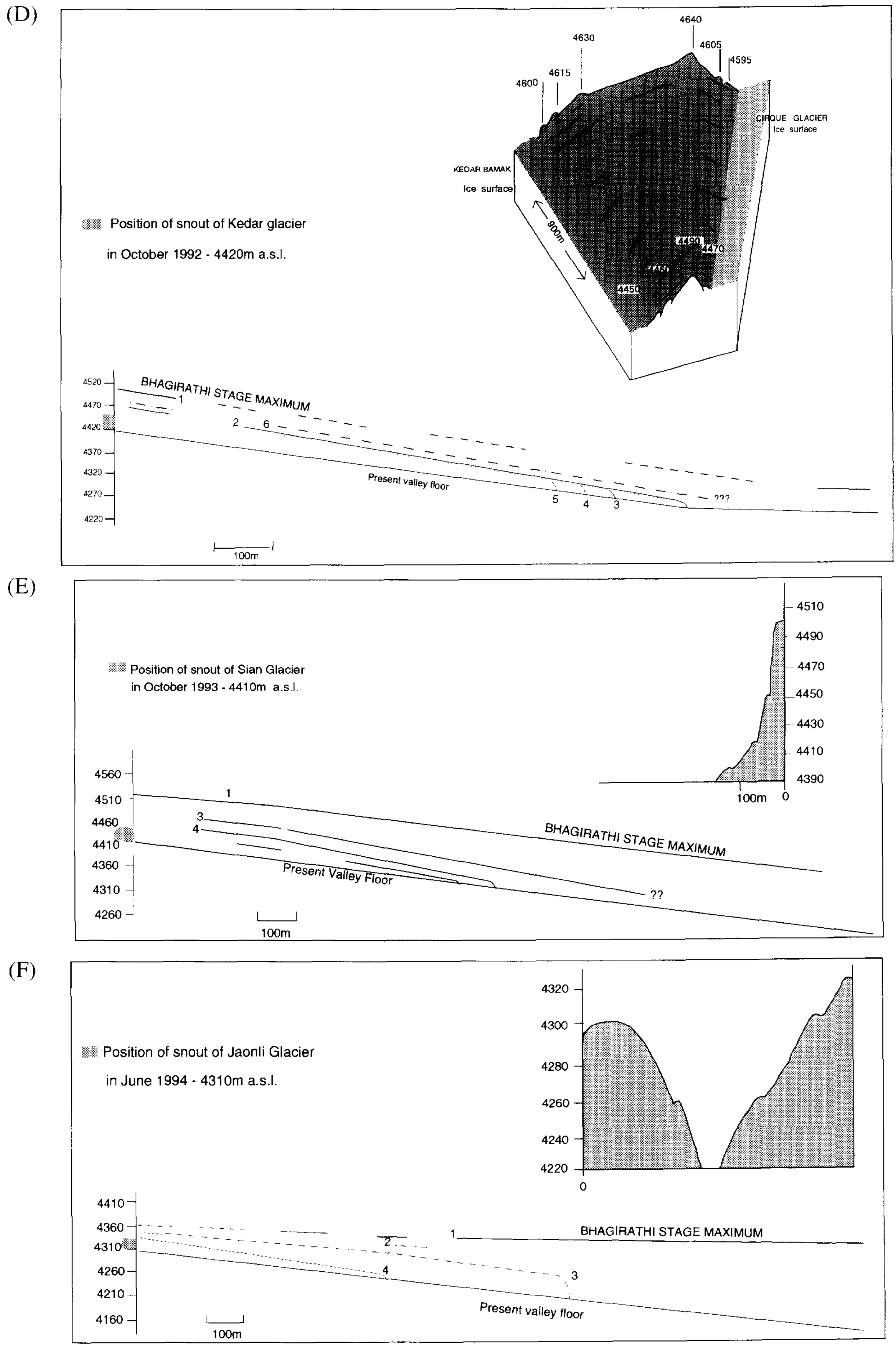


FIG. 11. For caption see page 355.

TABLE 5. Equilibrium-line altitudes for the Bhujbas Glacial and the Shivling Glacial Advance. (A-WM — Sissons' (1974) area-weighted mean; AAR0.6 — Porter's (1970) accumulation area ratio of 0.6; AAR1.3 — Andrews' (1975) accumulation area ratio of 1.3; THAR — Meireding's (1982) toe-headwall altitude ratio of 0.4)

GLACIER	Little Ice Age ELAs (Bhujbas Advance)		(Bhujbas Advance)				Holocene Advance ELAs (Shivling Advance)					
	A-WN	THAR	AAR0.60	AAR1.3	Average ELA	Depression	A-WM	THAR	AAR0.6	AAR1.3	Average ELA	Depression
Gangotri	4988	5050	4850	4800	4920	30	4968	5000	4850	4750	4890	60
Kedar	4981	5100	4900	4850	4960	20	4971	5050	4900	4850	4940	40
Rudugaira	4976	4850	4900	4800	4880	20	4957	4800	4900	4800	4860	40
Kalapani	4641	4600	4600	4550	4600	80	4622	4550	4550	4460	4540	140
Lamkhaga	4852	4750	4700	4650	4740	90	4799	4700	4650	4600	4690	140
Sian	4945	4800	5000	4800	4890	70	4926	4750	4950	4750	4840	120
Joanli	4636	5250	4800	4750	4930	50	?	?	?	?	?	?

All values in metres and rounded to the nearest ten.

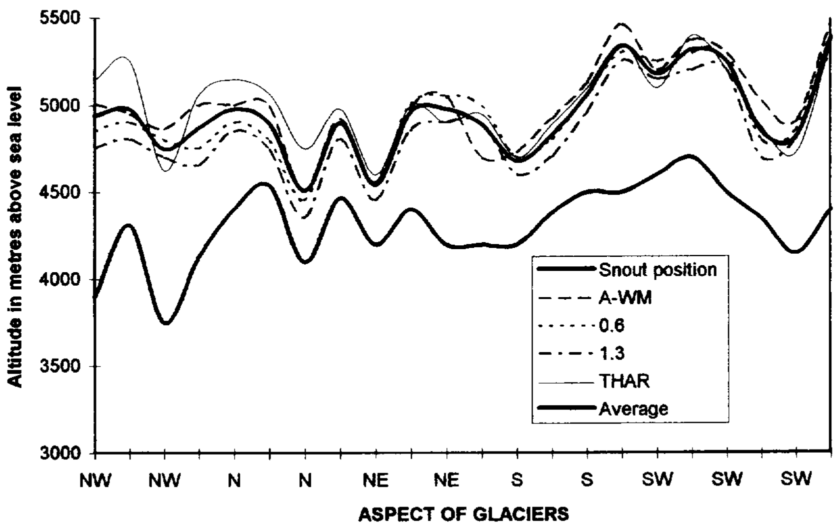


FIG. 12. Present ELAs in the Garhwal Himalaya for 22 glaciers determined by four different methods (A-WM — Sissons' (1974) area-weighted mean; 0.6 — Porter's (1970) accumulation area ratio of 0.6; 1.3 — Andrews' (1975) accumulation area ratio of 1.3; THAR — Meireding's (1982) toe–headwall altitude ratio of 0.4), and average of all four ELAs method, plotted against glacier aspect.

lowering of the ELAs brings about a significant increase in the glacier-covered area (cf. Porter, 1970). Similarly, Jaonli Glacier with its NW aspect experienced an ELA depression of ca. 50 m for the same period, resulting in an advance of ca. 800 m, while Kedar and Rudugaira Glaciers, in the drier eastern part of the region, experienced minor ELA depressions of 20 m which resulted in the glaciers advancing by ca. 950 m and 1900 m respectively. Sian Glacier, the only glacier with a NE aspect, descended to an altitude of ca. 4300 m a.s.l., an advance of about 850 m with an ELA lowering of about 60 m. Greater ELA lowering of between 80 m and 90 m occurred in the case of the Kalapani and Lamkhaga Glaciers. These have southerly aspects and the ice extended down-valley from the present snout for distances of ca. 1900 m and 2100 m. Both these glaciers are located at the head of the NS oriented Bhagirathi Valley, and are strongly influenced by high precipitation from orographically ascending air masses from the south. On the basis of historical data, moraine morphology, relative weathering and lichenometry, a late 19th century age is attributed to this glacial advance. It may correlate with the Little Ice Age advance as recorded elsewhere in the world, i.e. some 300–200 years ago (Groves, 1988).

Figure 11 also shows the Shivling Glacial Advance when glaciers extended between 1 and 5 km beyond their present limits. ELA values for the Shivling Advance are shown in Table 5. Because of the poor quality of the field evidence, the ELA depression for the Shivling Glacial Advance was not determined for the Jaonli valley. However, the Shivling Glacial Advance is similar in form and extent to the Bhujbas Glacial Advance in the NW Garhwal. ELA depressions in both cases are small and vary from 40 m to 140 m. For example, the Gangotri Glacier extended down-valley by ca. 3 km to an altitude of ca. 3600 m with an ELA depression of only 50 m. Ice thickness increased by ca. 150 m during this advance, which helped fill the Raktavam valley with ice to an altitude of ca. 4200 m. The ELA depression for Kedar and Rudugaira Glaciers, with their northerly aspects, was 40 m, the ice thickening approximating 50 m. These glaciers advanced to an altitude of ca. 4100 m a.s.l. Sian Glacier, with its easterly aspect, extended down to an altitude of ca. 4250 m asl, i.e. for a distance of ca. 1900 m beyond the present snout. Ice thickening was in the order of 70 m with an average ELA depression of 120 m. Kalapani and Lamkhaga Glaciers, with southerly aspects, had an average ELA depression of 140 m during the Shivling Advance and extended about 2500 m below the present ice front. Figure 13 shows the ELAs for the present ice positions and those considered to have prevailed during the Bhujbas and Shivling Glacial Advances.

The Bhagirathi Glacial Stage produced extensive ice which advanced to Jhala (Fig. 14). This resulted in the expansion of the glacierised area in the form of a long valley glacier system which covered a minimum area of ca. 685 km^2. The expansion in the area of the glacier involved the coalescence of all the tributary glaciers above Jhala (2300 m a.s.l.). An average ELA depression of 640 m (ELA of 4300 m) has been reconstructed using an accumulation area ratio of 0.6 (Porter, 1970) and a toe–headwall altitude ratio (Meierding, 1982) of 0.5. Contour maps for each of the glaciers, together with the extent of the Bhagirathi Glacial Stage, the Shivling Glacial Advance, the Bhujbas Glacial Advance, and the present position of ELAs are shown in Figs 13 and 14.

DISCUSSION

One major Pleistocene glaciation, the Bhagirathi Glacial Stage, and two Holocene glacial advances, the Shivling and the Bhujbas Glacial Advances, have been recognised in northwest Garhwal. The Bhagirathi Glacial Stage is represented by an extensive valley glaciation, when glaciers advanced and coalesced with the main Bhagirathi Valley Glacier to extend down-valley as far as Jhala (Fig. 14). Optical dating of lacustrine, aeolian and

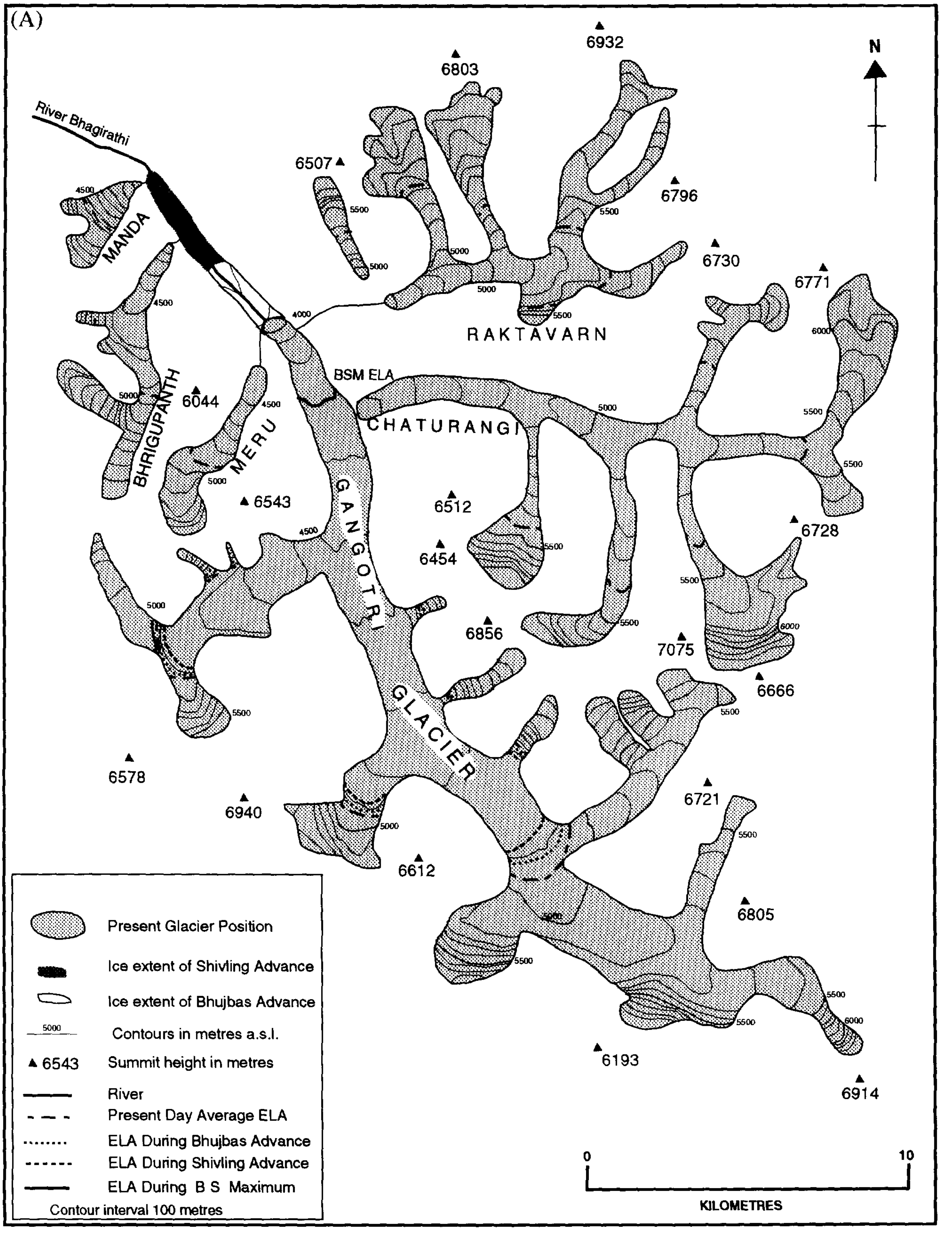


FIG. 13. Reconstruction of former ice extents for the Shivling and the Bhujbas Glacial Advances in (A) The catchment area of the Gangotri Glacier; (B) The central part of the study area; and (C) In the northwest part of the study area. Locations and altitudes of ELAs are also shown.

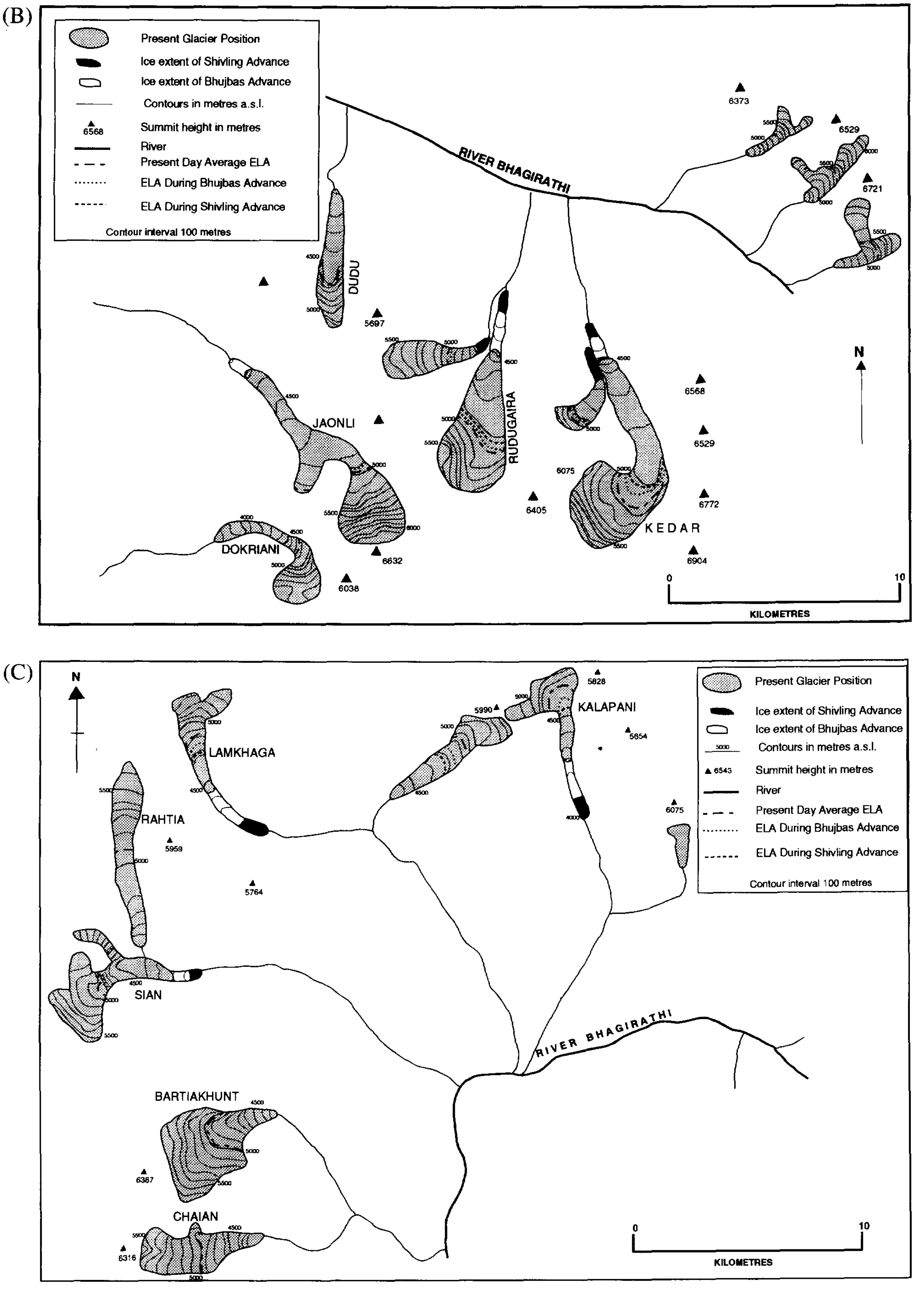


FIG. 13. For caption see page 359.

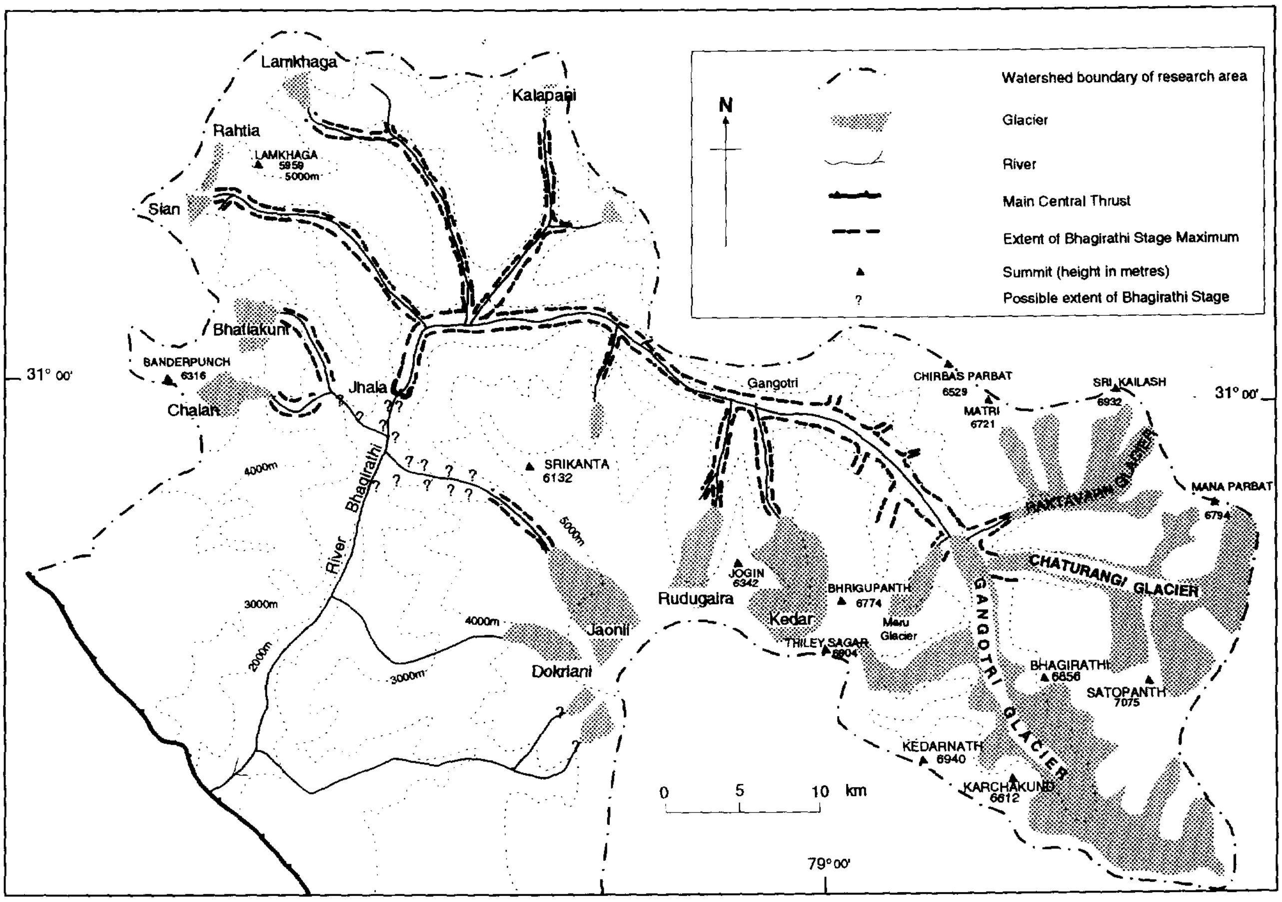


FIG. 14. Reconstructed ice extent in the Bhagirathi Glacial Stage.

glaciofluvial sediments within ablation valleys provide an age range for this glacial of between 62,894 ± 8575 and 5125 ± 1544 BP (Fig. 2; samples MI 01 and MI 03 in Table 4). The lateral moraines of the Bhagirathi Glacial Stage can be traced up valley from Jhala to Gangotri Glacier. They are diachronous (cf. Hewitt (1989) for discussion on the formation of lateral moraines), above Chirvas, they are less eroded and have a sparser forest cover than those down valley, suggesting that, above Chirvas, they are younger. This, in turn, suggests that ice retreat was probably sporadic, an initial retreat progressing as far as Gangotri where the ice then remained for a relatively long time. Erosion of the deeply incised gorges west of Gangotri may have begun during this stillstand. Thus, the date of ca. 63 ka BP at Jhala may represent the age of the maximum ice extent, while the dates of 17,559 ± 4108 BP (sample MI 05: 1 km west of Jangla) and 5125 ± 1544 BP (sample MI 03 at BhuJ Gaddi) suggests that these moraines date from a period of retreat during late Pleistocene and early Holocene times. These ages show that the glacial maximum in the Garhwal Himalaya does not correlate with the Last Glacial Maximum of ca. 18 ka BP for the northern hemisphere ice sheets. The evidence summarised by Gupta *et al.* (1992) provides some support for this view. They suggested that $\delta^{18}O$ values from core SK-20-185 from the East Arabian Sea (Sarkar *et al.*, 1990), core CD-17-30 off the coast of Oman (Sarkar *et al.*, 1990) and data from the Dunde Ice Cap cores in Tibet (Thompson *et al.*, 1989), as well as an increase in the abundance of *Juniperus* pollen from the Tsokar Lake in Ladakh (Bhattacharya, 1989) show that the period between 20 and 16 ka BP was one in which glacial meltwaters originating in the Himalayas and Tibet increased in volume, as a result of increased rates of melting of mountain glaciers. Fig. 15 compares the results of Gupta *et al.* (1992) with the glacial history of Garhwal proposed here. However, as the evidence presented here makes clear, the maximum ice extent of the Last Glacial Maximum in the Garhwal Himalaya occurred at about 63 ka BP, and substantial ice bodies probably persisted in the valley up to at least early Holocene times as indicated by the lateral moraines and ablation valley sedimentation at Bhuj Gaddi (ca. 5 ka BP). At the same time, it is important to note that there is no evidence for a readvance in Garhwal between 16 ka until 11 ka BP, as shown in the model of Gupta *et al.* (1992) (Fig. 15). Glaciers, in the Garhwal Himalaya may have begun to retreat at about 20 ka until 16 ka BP, after which their positions may have stabilised until at least 5 ka BP allowing the lateral moraines between Gangotri village and Gangotri Glacier to form.

Correlation with other glacial chronologies is extremely difficult but Derbyshire *et al.* (1984) provide TL dates for the Borit Jheel Glaciation in the Hunza valley, northern Pakistan, of 47,000 ± 2300 to 65,000 ± 3300 BP (Table 1). This may constitute an equivalent of the early Bhagirathi Glacial Stage. There is some uncertainty as to the reliability of these dates, because there is no

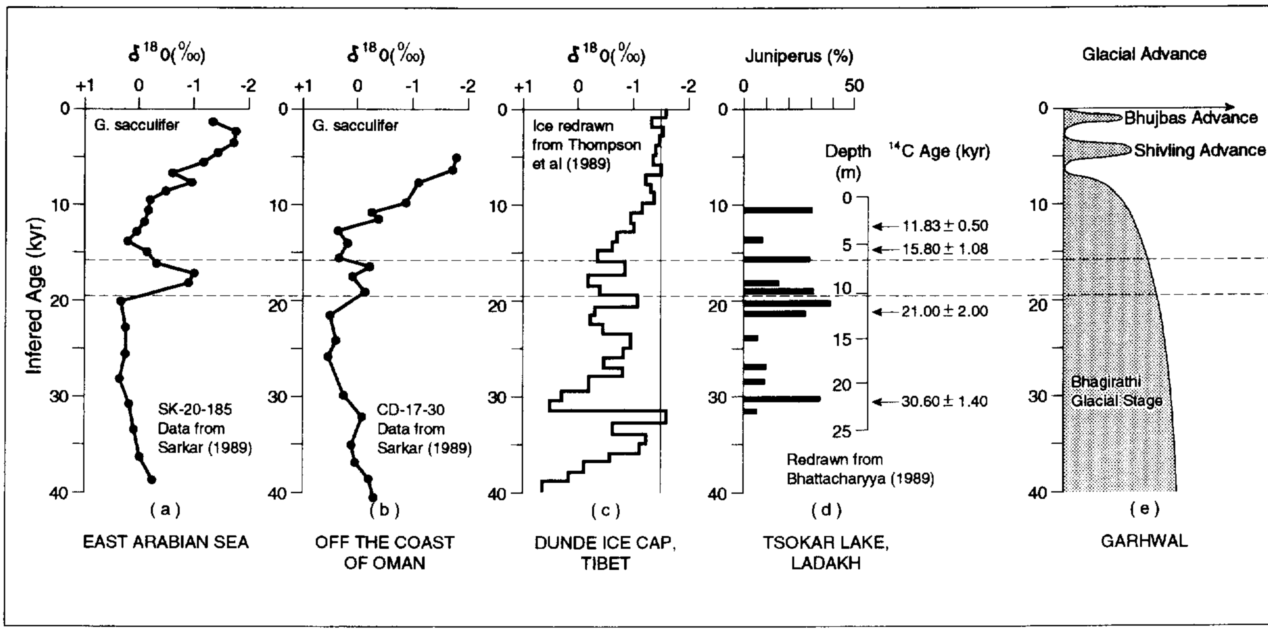
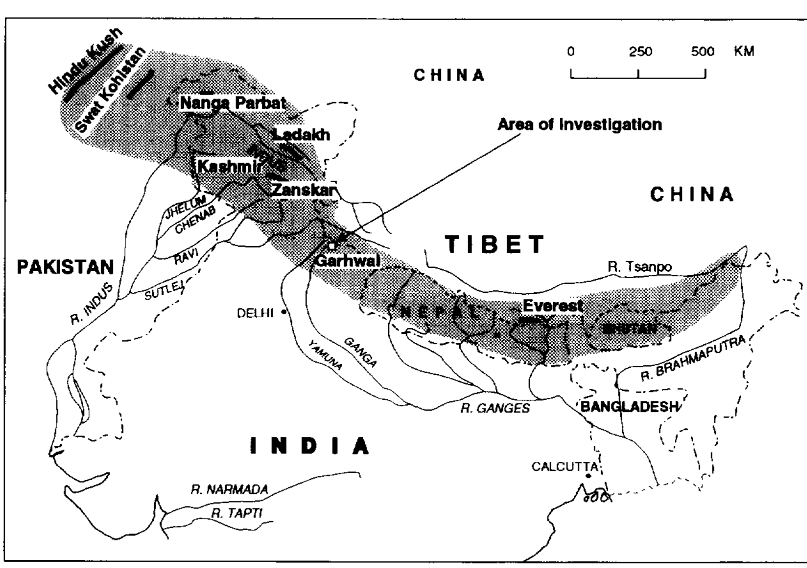


FIG. 15. Comparison of the extent and timing of glaciation in Garhwal according to the landforms and sediments preserved (e) with $\delta^{18}O$ values from (a) *G. sacculifer* from core SK-20-185 from the East Arabian Sea (Sarkar *et al.*, 1990); (b) from core CD-17-30 off the coast of Oman (Sarkar *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 (Bhattacharya, 1989). (Adapted from Gupta *et al.*, 1992.)

description of the laboratory proceedures used in determining their ages. In addition, Owen *et al.* (1992) published TL dates of between 6.7 and 2.85 ka for the late stage of the Kalam Glacial of Porter (1970), and this may coincide with the last phases of the Bhagirathi Glacial Stage or the Shivling Glacial Advance.

The Shivling Glacial Advance must have occurred after 5 ka BP i.e. after the Bhagirathi Glacial Stage moraines had formed at Bhuj Gaddi. Accordingly, it is proposed that the Shivling Advance is of mid to late Holocene age. Steep sharp-crested lateral moraines of this advance are well preserved in all glacial forefields, indicating an advance of between 1.5 and 3 km and an ice thickening of between 50 and 150 m.

During the Bhujbas Glacial Advance glaciers reached positions between 1 and 2.2 km beyond the present snouts. This advance occurred ca. 200 to 300 years ago (Hodgson, 1822; Griesbach, 1891; Auden, 1937; Vohra, 1988) and broadly correlates with the Little Ice Age as found elsewhere in the Himalaya (Derbyshire *et al.*, 1984; Fort, 1987; Röthlisberger and Geyh, 1985) and in other parts of the world (e.g. Groves, 1988). Since then, there has been progressive glacial retreat, leaving successive moraine ridges. In addition, reconstruction of ice thickness shows that, prior to 1890, there had been progressive retreat and downwasting of Gangotri and Kedar Glaciers. Since then, however, downwasting has been relatively insignificant and frontal retreat has dominated. In the



PRESENT EQUILIBRIUM LINE ALTITUDES ACROSS TRANS-HIMALAYAS	
HINDU KUSH	4300m (a.s.l.)
SWAT KOHISTAN	4250m
NANGA PARBAT	4475m
KASHMIR	4100m
LADAKH	5300m
ZANSKAR	5300m
WEST GARHWAL	4950m
SOUTH EVEREST	5200m
NORTH EVEREST	5800m
TIBETAN PLATEAU	5900m

FIG. 16. The present day ELAs for selected areas in the Trans-Himalayas.

TABLE 6. Present and Last Glacial maximum ELAs for the Trans-Himalayan region

Region	Present ELA (m)	Last Glacial Maximum	ELA depression (m)	Source
Hindu Kush	4000–4600	3000–3600	1000	Porter, 1970
Swat Kohistan	4100–4400	3000–3200	~1000	Porter, 1970
Nanga Parbat	3750–5200	3000–3700	600–1200	Scott, 1992
Kashmir	3900–4300	3200–3500	700–800	Holmes and Street-Perrott, 1989
Ladakh	5200–5400	4300	1000	Burbank and Fort, 1985
Zanskar	5200–5400	4700	600	Burbank and Fort, 1985
N. Everest	5800	5500	300	Williams, 1983
S. Everest	5200	4300	900	Williams, 1983
Tibetan Plateau	5900	4700	1200	Kuhle, 1987
Tibetan Plateau	****	****	450	Burbank and Cheng, 1991
NW Garhwal	4500–5400	4300	650	Present study

**** = Not mentioned.

forefield of Gangotri Glacier, moraines formed prior to 1971 are well developed with sharp-crested ridges and tills with strongly orientated fabrics. In contrast, moraines formed after 1971 are hummocky and have weak fabric strengths (Fig. 3B). Over the last 20 years Gangotri Glacier has retreated ca. 750 m, compared to ca. 2 km over the last 200 years (Fig. 8). This suggests that retreat was much slower before compared to after the year 1971, and that the glacier must have been stationary or in a seasonally advancing condition for long enough to produce the well defined moraines with their strong fabrics (Fig. 3A and B). Thus the well-formed moraines within Garhwal probably indicate formation during glacial advances, in contrast to the hummocky moraines associated with ice retreat. Future detailed work on the location and age of these moraines may yield further detailed proxy evidence for climate change.

The ELAs of contemporary glaciers show significant variations arising from micro-climatic and topographic controls on the mass balance. All the glaciers with SW aspect have relatively higher ELA values than those with other aspects. A south–north climatic gradient, with greater precipitation in the southern parts of the region, is reflected in the southernmost glaciers with their lower ELAs.

Figure 16 and Table 6 show present and former ELAs for the Last Glacial Maximum in selected areas of the Himalayas. Porter (1970) applied an accumulation area ratio (AAR) of 0.6 to determine ELAs in Swat Kohistan and estimated a Pleistocene depression during three episodes of extensive glaciation in this region of the order of ca. 800 to 1000 m, and in the adjoining Hindu Kush mountains ca. 1000 m. In the Nanga Parbat Himalaya, Scott (1992) determined an ELA depression of between 600 to 1200 m, while in the Kashmir Himalaya, ELA depressions of 700 to 800 m were calculated for two periods of glaciation by Holmes and Street-Perrott (1989). In Ladakh and Zanskar, a Pleistocene ELA depression of between 1000 m and 600 m has been proposed (Burbank and Fort, 1985). Williams (1983) showed that ELAs on the south-facing Himalayan slopes of the Everest region were depressed by ca. 1000 m, compared to values on the northern side (Tibetan Plateau) of ca. 400 m. Similarly, Burbank and Cheng (1991) suggested that the ELA depression was 450 m on the Tibetan Plateau. An average ELA depression of 640 m during the Bhagirathi Glacial Stage for the Garhwal Himalaya is therefore similar, although generally a little less than in most other regions of the Himalayas. This is somewhat surprising since the Garhwal Himalaya is wetter than most of the other study regions.

Kuhle (1987) suggests that an ELA depression of over 1000 m would have created an ice sheet on the Tibetan Plateau during the Pleistocene. Our calculated ELA depression value of 640 m conflicts with this hypothesis, being inconsistent with an ELA depression of ca. 1000 m in the more arid interior of the Tibetan Plateau.

CONCLUSION

This study provides a first glacial chronology and preliminary optically stimulated luminescence dates for northwest Garhwal. There is unequivocal evidence for a major glaciation, the Bhagirathi Glacial Stage, which reached its maximum at ca. 63 ka BP. During this glaciation Gangotri Glacier advanced ca. 40 km beyond its present limits, reaching Jhala at an altitude of ca. 2300 m, with an ELA depression of ca. 640 m. Many tributary glaciers coalesced with Gangotri Glacier to form a huge valley glacier system covering a minimum area of ca. 685 km^2, as compared to the present glaciated surface of 280 km^2. The Bhagirathi Glacial Maximum (ca. 63 ka BP) does not coincide with the Last Glacial Maximum of the northern hemisphere ice sheets (ca. 18 ka BP). This may provide some support for the conclusions of Gupta *et al.* (1992), who suggest that there was substantial melting of Himalayan glaciers between about 20 ka and 16 ka BP.

During mid to late Holocene times (<5 ka), the Shivling Glacial Advance caused glaciers to advance ca. 1.5 to 3 km beyond present ice fronts, with an ELA depression of between 40 and 100 m. The Bhujbas Glacial Advance caused glaciers to advance between 1 and 2 km with an ELA depression of between 20 and 60 m. This correlates with the Little Ice Age in the Himalayas and elsewhere in the world, i.e. about 200 to 300 BP. There appears to have been little difference in ice thickness of the Shivling and Bhujbas Glacial Advances. Aspect and geographical position play a significant role in determining the micro-climate of this region, as is evident from the range of ELA values for contemporary and former glaciers.

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