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Past and recent glacier fluctuations in Kanchenjunga Himal, Nepal

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ABSTRACT

Kanchenjunga Himal, which lies in the easternmost part of the Nepal Himalaya, is a typical area under strong summer monsoon environment. Studies on glacial variations of Kanchenjunga Himal can reveal climate changes particularly monsoon fluctuations since the Last Glaciation and those in the recent time.

The aerial photo interpretation and field observation identified changing valley morphology from an ambiguous U-shaped to a V-shaped along the Ghunsa Khola at an altitude of approximately 2,800 m. This clear morphological change may indicate the former maximum extent of the glaciers. Geographical positions of glacial landforms and relative dating data led to the classification of the glacial activities into at least five stages. From the younger to older order, they are historical stage (around the early part of the Twentieth Century), the Little Ice Age, the Holocene, and the late and early substages of the Last Glaciation. The two substages could be correlated with the Last Glacial Maximum (LGM) and Marine Isotope Stage 3 or 4. The extent of the glaciers in the LGM was not generally so large as compared with that of the existing glaciers. Relatively small glacier expansion can probably suggest weaker summer monsoon and less precipitation in the LGM period.

A comparison of the 1992 glaciers with those of 1958 in the Ghunsa Khola drainage, the main drainage of Kanchenjunga Himal, revealed that out of examined 57 glaciers, 50% of them had retreated in the period from 1958 to 1992. Also, 38% of the glaciers were under stationary conditions, and 12% were advancing. Consequently, the general tendency should be regarded as "mostly retreating". The distribution and magnitude of the glacier variations suggest that general rising of air temperature possibly caused the recent glacier retreats, and that the stationary or advancing conditions were likely to be related to the local increase and variations of precipitation.

INTRODUCTION

The Kanchenjunga Himalayan Range, which includes peaks higher than 8,000 m, lies in the easternmost part of the Nepal Himalaya. Generally, the existing glaciers lie above 5,000 m and occupy an area of about 400 km^2. Well-developed moraines and tills in the entire region provide extensive evidences for the past glaciations. The Ghunsa Valley originating from the peak of Kanchenjunga has well-developed landforms related to the past glaciation. Kuhle (1990) and Meiners (1999) mentioned such landforms, but their idea is based on the story of the Tibetan Ice Sheet. They proposed a drastic and large glacial extension during the Last Ice Age in the Ghunsa Khola drainage basin: the glacier originated at the outlet of the Tibetan Ice Sheet reached an altitude of 890 m.

Monsoon precipitation plays an important role in glacier accumulation and fluctuation. The glaciers in the eastern Nepal Himalaya are maintained mostly by monsoon rainfall in summer. Therefore, a study on the changes of palaeoclimate of the glaciers or glaciated areas will shed light on the relative importance of monsoon. Considering the fact that dry–wet variations on the Qinghai–Tibetan Plateau cause the monsoon fluctuations, the glacial changes in the eastern Nepal Himalaya can improve our knowledge of meteorology of the Asian continent. Kanchenjunga Himal is a typical area influenced strongly by the summer monsoon.

The changes in the position of glacier snouts reflect the mass balance conditions of the past years, and a general tendency of short-term glacier variations indicates a corresponding climate changes. Hence, studies on glacial variations of Kanchenjunga Himal can reveal climate changes (particularly, monsoon fluctuations) since the Last Glaciation and those in the recent period.

This study aims at revealing the long- and short-term climate changes in Kanchenjunga Himal by reconstructing the past and recent glacier fluctuations.

METHODOLOGY

For studying the long-term glacier variations, the glacial landforms were grouped into several stages based on aerial photo interpretation. Then, the past glacier extent was confirmed by field observations, chronology of the glacier extent was examined by relative dating methods, climatological conditions during the glaciations were estimated, and the changes in the palaeoclimate since the Last Glaciation were reconstructed by integrating all types of above information.

The methodology for short-term glacier variations was based on the comparison of the results of the present glacier inventory with the earlier topographical maps of the Ghunsa Khola drainage basin, a main drainage basin of

Kanchenjunga Himal. This comparison revealed the glacier variation during 1958 and 1992. Characteristics of the geographical distribution and the magnitude of the variation patterns (retreating, stationary, or advancing) of the glaciers suggest recent climate changes.

GLACIAL LANDFORMS

Glacial landforms were investigated using 1:50,000 scale vertical aerial photographs, taken by the Survey Department, His Majesty's Government of Nepal in 1992. A series of moraines and trough edges are distributed along the Ghunsa Khola above the Gyabla Village at an altitude of 2,800 m (Fig. 1). The study of landform characteristics and their relative dating (based on weathering criteria) were carried out during the field study. The moraine complexes were initially divided into four groups based on their geographical positions. The field survey together with aerial photograph interpretation confirmed that the four groups belonged to different stages.

Kuhle (1990) and Meiners (1999) believe the existence of the glacial landforms in the lower reaches below Gyabla, such as lateral moraines, roches moutonnées, and subglacial potholes. However, we were not able to find in the field any such landforms but only fluvial terraces and deposits, except potholes (at 1,400 m). These potholes are located on the past undercut slope near the present riverbed, showing that they were formed just by a surface stream but not by subglacial processes. The cross-section of the Ghunsa Khola is V-shaped below the village of Gyabla, whereas it shows a typical U-shaped valley upstream of it. Hence, the past glacial extent was most likely limited to the region above the village.

RELATIVE DATING METHODS

A relative chronology was established by the techniques similar to those used by Burbank and Cheng (1991) for Mount Everest, Shiraiwa and Watanabe (1991) for the Langtang Valley, and Owen et al. (1996) for Lahul Himalaya. The following methods were applied at 23 sites on the moraine complexes: Schmidt hammer rebound value of the boulder surface, percentage of the clasts with oxidation stain, maximum height of the mafic mineral projection, maximum height of the weathering pit, thickness of the weathering rind on the clast surface, maximum size of lichen of *Rhizocarpon geographicum*, and soil development. Data from the surface debris on the existing glaciers are indicators of a reset of weathering values. Adopted methods to boulders or clasts were based on the weathering criteria. There were 23 sampling sites. The boulders at the sampling sites were classified into granite and gneiss. At least 50 boulders were examined at each site, and their maximum value (the second maximum number must be larger than 80% of the maximum value) or mean value was adopted. The Schmidt hammer rebound values shown in Table 1 were obtained by taking the mean value of three measurements for each of 50 boulders.

The relative dating values clearly suggested at least four past glacial advances except the newest stage of the present glaciers (Table 1). Especially, the Schmidt hammer rebound

Table 1: Relative dating values adopted on glacial landforms in the Ghunsa Khola drainage, Kanchenjunga Himal. The locations are shown in Fig. 1. Stages of the moraine complexes were divided into four by means of the geographical locations of the glaciers. The Schmidt hammer rebound value is mean value with standard deviation of 95% confidential interval. Soil development lithology was observed on the surface of test pit on the top of the moraine crest.

S. N.	Location	Moraine complex		Schmidt hammer rebound value (Schmidt hammer unit)		Ratio of oxidised to unox. rocks	Max. lichen	Max. mafic mineral	Max. weathering pit	Weathering rind	Soil development
		Stage	*Alt.*	***Granite***	***Gneiss***	(%)	(mm)	(mm)	(mm)	(mean)	
1	Jannu Gl. Surface	Existing Gl.	4190	46.36±3.94	47.78±3.71	14	32	0	0	0	-
2	Kanchenjunga Gl.	Existing Gl.	4660	47.79±3.59	47.06±2.85	10	-	13	-	0	-
3	Pangpema	I	5560		45.57±2.84	24	-	10	18	0	Cox/Cu
4	Nup Chu	I	5070	43.85±3.49		28	75	18	22	0	Cox/Cu
5	Pangpema	I	5490	44.56±2.48		32	25	24	47	0	-
6	Ramtang (inner)		4570	43.31±2.89		44	46	21	49	0	-
7	Jannu Gl. (R)	I	4130	42.84±3.86		48	48	8		0	B/Cox/cu
8	Jannu Gl. (L)	I	4180	44.12±2.65		44	42	11	52	0	-
9	Nup Chu Pokhari	I	5080		44.44±3.84	35	46	14	16	0	B/Cox/Cu
10	Yamatari Gl.		4300		43.74±2.33	46	47	29	21	0	-
11	Nup Chu	II	4940	41.78±3.46		76	66	24	32	0	A/B/Cox
12	Lhonak		4740	41.10±3.02	41.49±2.71	72	43	42	109	0	Bt/Cu
13	Ramtang (termin.)		4520		43.31±2.89	72	94	48	94	0	A/Cox
14	Rampuku (R)		3940	43.32±5.75		96	47	32	62	0.4	A/Cox
15	Rampuku (L)		3960	42.01±2.36		96	-	13	39	0	A/B/2Ab/3Bw/4Cox
16	Kambachen	III	4230	42.75±6.17		88	90	24		0	A/B/Cox
17	Kambachen	III	4240	41 07±4.33		88	70	21	57	0	A/Cox/Cu
18	Ramtang (outer)		4585		41.03±2.14	80	60	38	63	0	A/Cox
19	Yamatari-Tal	III	3600	38.74±7.31		92	-	37	133	0	A/Cox
20	Phale	III	3920		38.17±3.11	100	-	26	74	0	A/Cox
21	Gyabla (inner)	IV	2740		32.88±3.33	100	-	41	81	0.5	A/Bt/2Bt
22	Gyabla (innermost)	IV	2730		32.14±3.44	100	-	32	67	0	
23	Kambachen	IV	4190	39.74±4.09		96	58	19	130	0	A/B/Cox

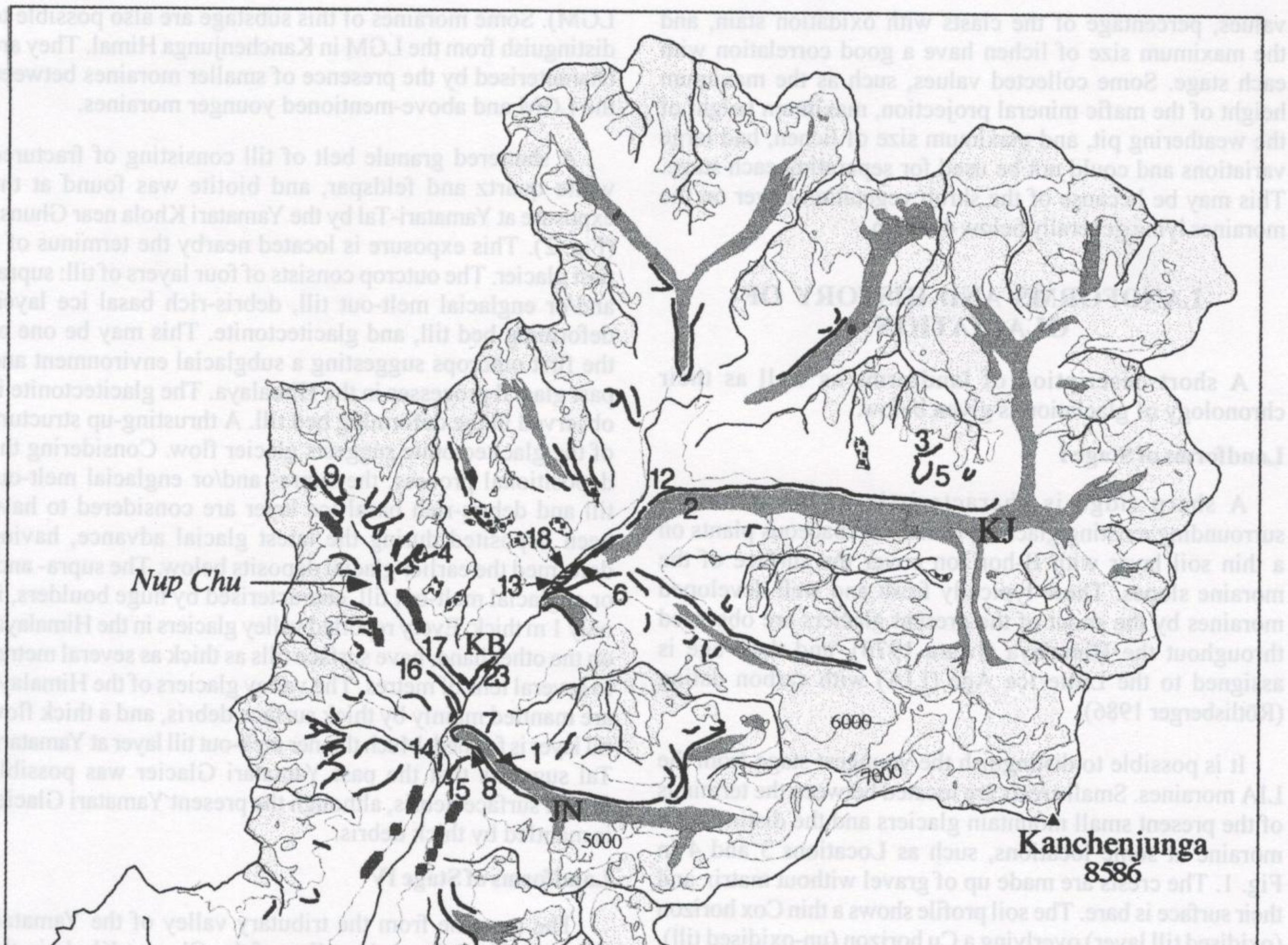

Fig. 1: Distribution of glacial landforms and existing glaciers in the Ghunsa Khola drainage, Kanchenjunga Himal. KB: Kambachen, KJ: Kanchenjunga Glacier, JN: Jannu Glacier, and YT: Yamatari Glacier and the Yamatari Khola (valley). Loc. 1 to 23: Sampling sites of relative dating

values, percentage of the clasts with oxidation stain, and the maximum size of lichen have a good correlation with each stage. Some collected values, such as the maximum height of the mafic mineral projection, maximum height of the weathering pit, and maximum size of lichen, had large variations and could not be used for separating each stage. This may be because of the shrub vegetation cover on the moraines lying generally below 4,000 m.

LANDFORMS AND HISTORY OF GLACIATION

A short description of landforms as well as their chronology of glaciation is given below.

Landforms of Stage I

A sharp ridge is characteristic of the moraines surrounding existing glaciers. Mainly herbaceous plants on a thin soil layer with B-horizon cover the surface of the moraine slopes. These typically fresh and well-developed moraines by the snout of the present glaciers are observed throughout the Himalaya (Iwata 1976), and their age is assigned to the Little Ice Age (LIA) with carbon dating (Rötlisberger 1986).

It is possible to distinguish the youngest stage from the LIA moraines. Small crests are located between the terminus of the present small mountain glaciers and the distinct LIA moraine at some locations, such as Locations 3 and 4 in Fig. 1. The crests are made up of gravel without matrix and their surface is bare. The soil profile shows a thin Cox horizon (oxidised till layer) overlying a Cu horizon (un-oxidised till), but neither A- nor B-horizon is developed (Table 1). The age of these moraines should be younger than the LIA.

Landforms of Stage II

A continuous ridge from the Stage I moraine is typically developed near the small mountain glaciers in the valley of the Nup Chu (a tributary west of Kambachen). A fossil rock glacier overlies the moraine terrace. A slightly degraded moraine complex lies at the foot of the LIA moraines of the large valley glaciers. Soil development of A-horizon and the higher ratio of oxidised rocks clearly separate the Stage II moraines from the Stage I moraines. The Stage II moraines could have been formed during the Holocene (Neoglacial) advance.

Landforms of Stage III

Terrace-shaped dissected moraines are well developed below the Stage I moraine complex, and those at the confluence of the Ghunsa Khola and its tributary at Kambachen and Ghunsa are typical examples. The moraines are covered by dense shrub or grass growing on soil layer and loess. The relative height of the moraine ridge and the present riverbed is less than 100 m. Such moraines with the same geographical situation are spread in the entire Nepal Himalaya, and are regarded as the ones formed in the late substage of the Last Glaciation (the Last Glacial Maximum, LGM). Some moraines of this substage are also possible to distinguish from the LGM in Kanchenjunga Himal. They are characterised by the presence of smaller moraines between the LGM and above-mentioned younger moraines.

A shattered granule belt of till consisting of fractured white quartz and feldspar, and biotite was found at the exposure at Yamatari-Tal by the Yamatari Khola near Ghunsa (Fig. 2). This exposure is located nearby the terminus of a past glacier. The outcrop consists of four layers of till: supra- and/or englacial melt-out till, debris-rich basal ice layer, deforming bed till, and glacitectonite. This may be one of the first outcrops suggesting a subglacial environment and past glacial processes in the Himalaya. The glacitectonite is observed in the deforming bed till. A thrusting-up structure of the glacitectonite suggests glacier flow. Considering the depositional process, the supra- and/or englacial melt-out till and debris-rich basal ice layer are considered to have been deposited during the latest glacial advance, having deformed the earlier glacial deposits below. The supra- and/or englacial melt-out till, characterised by huge boulders, is only 1 m thick. Every reported valley glaciers in the Himalaya, on the other hand, have surface tills as thick as several metres to several tens of metres. The valley glaciers of the Himalaya are mantled mainly by thick surface debris, and a thick flow till layer is formed. Much thinner melt-out till layer at Yamatari-Tal suggests that the past Yamatari Glacier was possibly free of surface debris, although the present Yamatari Glacier is mantled by thick debris.

Landforms of Stage IV

The moraine from the tributary valley of the Yamatari Khola reached the main valley of the Ghunsa Khola in the LGM, as described above. This means that glaciers have not filled up the major part of the Ghunsa Khola since the LGM, in spite of the fact that the Ghunsa Khola Valley shows a typical U-shaped configuration (Fig. 1).

The lateral moraine on the right bank of the Ghunsa Khola, which is composed of weathered boulders and oxidised till, is developed near and above Kambachen (Location 23 in Fig. 1). This lateral moraine was eroded by the past glacier from Nup Chu (former "Nup Chu Glacier"), which is demonstrated by the relationship of these lateral moraines in the field. The former "Nup Chu Glacier" formed the terminal moraine at a short distance from the confluence at Kambachen. A trough edge of U-shaped valley, however, perched along the Ghunsa Khola continuously from upstream.

The trough edge is observed at places as low as Gyabla. Four crests of the lateral moraines converge concentrically on the Gyabla terrace downstream, which suggests the terminus position at that stage. Changing valley morphology from an ambiguous U-shaped to a V-shaped along the Ghunsa Khola at an altitude of approximately 2,800 m indicates the former maximum extent of the glaciers.

The relative dating values shown in Table 1 do not have a great difference between Stage IV and Stage III, except for the soil development of B-horizon. However, Stage IV and

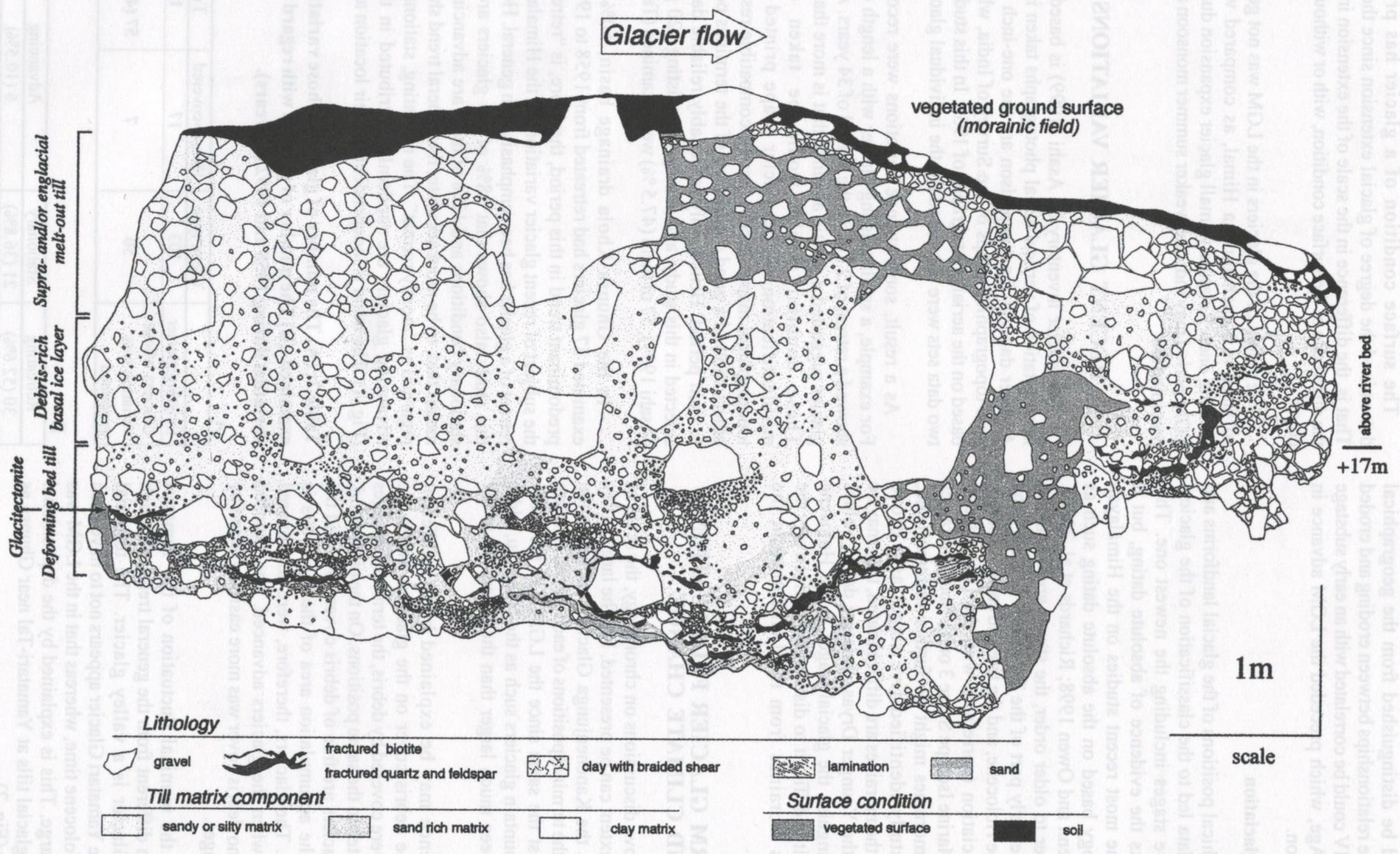

Fig. 2: Exposure of glacial till consisting of supra and/or englacial melt-out till, debris-rich basal ice layer, deformation bed till, and glacitectonite at Yamatari-Tal, in the vicinity of Ghunsa. Its location is shown in Fig. 1. This outcrop is located just under the morainic field. Terminology after Hart (1998) and Benn and Evans (1998).

Stage III should be distinguished from the geographical positions, and the relationships between eroding and eroded moraines. Stage IV could be correlated with an early substage of the Last Ice Age, which preceded the LGM advance in the Last Glaciation.

Chronology of glaciation

The geographical positions of the glacial landforms and relative dating data led to the classification of the glaciers into at least five stages including the newest one. This chronology lacks the evidence of absolute dating, but it matches with the most recent studies on the Himalayan glacial chronology based on the absolute dating such as OSL and TL (Benn and Owen 1998; Richards et al. 2000). From the younger to older order, the stages are: historical stage (around the early part of the Twentieth Century), the Little Ice Age, the Holocene, and the late and early substages of the Last Glaciation (correlated with the Last Glacial Maximum and Marine Isotope Stage 3 or 4). Some moraines near the LGM moraines might be further differentiated, although this study identified five stages as a broad classification. If the moraines are differentiated, they may be correlated with the Younger Dryas. Relative dating values can clearly distinguish the glacial stages in the Holocene time. However, it is difficult to discriminate effectively the Younger Dryas moraines from the LGM ones in the Pleistocene time.

LONG-TERM GLACIER FLUCTUATIONS AND CLIMATE CHANGE

From the above discussions on chronology, the scale of the past glacial extent can be presented. For the large valley glaciers such as the Kanchenjunga Glacier and the Jannu Glacier (Fig. 3), the terminal positions of each glacial advance have been almost the same since the LGM. On the other hand, for the mountain glaciers such as the Nup Chu, older extension had been much larger than the extension at the younger stage.

This difference may be explained by the different conditions in the debris cover on the glaciers. When the valley glaciers were covered by debris, the terminus changes were almost limited to the same positions. On the other hand, the mountain glaciers are free of debris cover now, and the topography of the accumulation area of these glaciers is generally gentle. The glaciers, therefore, were not covered by debris even when the glaciers advanced. The exposed glacier ice with no debris cover was more easily affected by the climate changes.

Meanwhile, the terminal fluctuation of the Yamatari Glacier has been different from the general trend, although the Yamatari Glacier is a valley glacier. The terminal fluctuation of the Yamatari Glacier appears not to have been so large in the Holocene time, whereas that in the LGM was comparatively large. This is explained by the depositional structure of the glacial tills at Yamatari-Tal near Ghunsa as described above (Fig. 2).

The surface condition of a glacier has probably determined the degree of glacial extension since the LGM. That is, the difference in the scale of the extension indicates the difference of the surface condition, with or without debris cover.

The extent of the glaciers in the LGM was not generally so large in Kanchenjunga Himal, as compared with the existing ones. Relatively small glacier expansion during the LGM period may indicate weaker summer monsoon and less precipitation.

RECENT GLACIER VARIATIONS

The glacier inventory by Asahi (1999) is based on the interpretation of vertical aerial photographs taken in 1992. Another data set for comparison are the one-inch to one-mile topographical maps of the Survey of India, which are based on the aerial photographs of 1958. In this study, these two data sets were compared for the individual glaciers.

As a result, some strange variations were recognised. For example, a small existing glacier with a length of 1 km showed a retreat of 2 km for the period of 34 years. Another glacier suggested a drastic advance that is more than 1 km. These doubtful results would be taken as the misidentification of the glacier shape printed on the topographical maps. Except these incompatible results, all others showed a good correlation of the terminus positions in each period. Hence, only reasonably reliable data were selected in this study, and among the existing 120 glaciers (Asahi 1999), 57 of them (47.5 %) were examined (Table 2).

In the Ghunsa Khola drainage basin, 50% of the examined 57 glaciers had retreated from 1958 to 1992. The predominant trend in this period, therefore, is "retreat." On the subject of recent glacier variations in the Himalayas, the retreat of a glacier has been emphasised in general. However, this study also shows that 38% of the glaciers are under stationary conditions and 12% of them are advancing. This means that, to be more accurate, the general trend should be regarded as "mostly retreat". The retreating, stationary, and advancing glaciers are randomly distributed in the area (Fig. 4). The trend is independent of their location and size.

Table 2: (A) The number of glaciers whose variation was examined. (B) The number of glaciers with regard to their variation during 1958 and 1992 (34 years).

A

	Clean type	Debris-covered	**Total**
Existing glacier	103	17	**120**
Glaciers whose variation was examined	50	7	**57 (47.5%)**

B

Retreating	Stationary	Advancing
30 (52.6%)	21 (36.8%)	6 (10.5%)

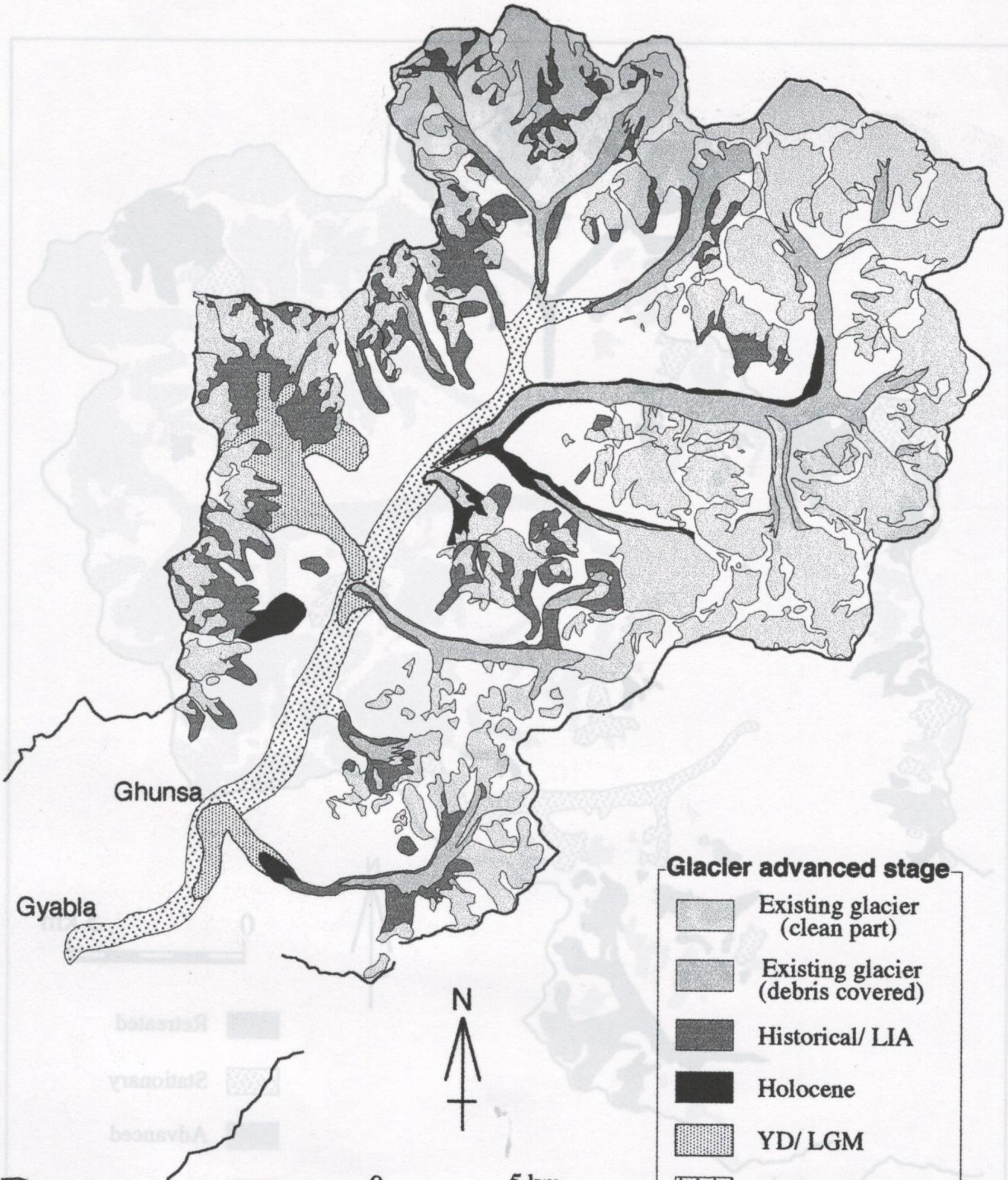

Fig. 3: Glacier extension in each advancing stage in the Ghunsa Khola drainage, Kanchenjunga Himal. LIA: Little Ice Age, YD: Younger Dryas, LGM: Last Glacial Maximum, and MIS4: Marine Isotope Stage 3 or 4.

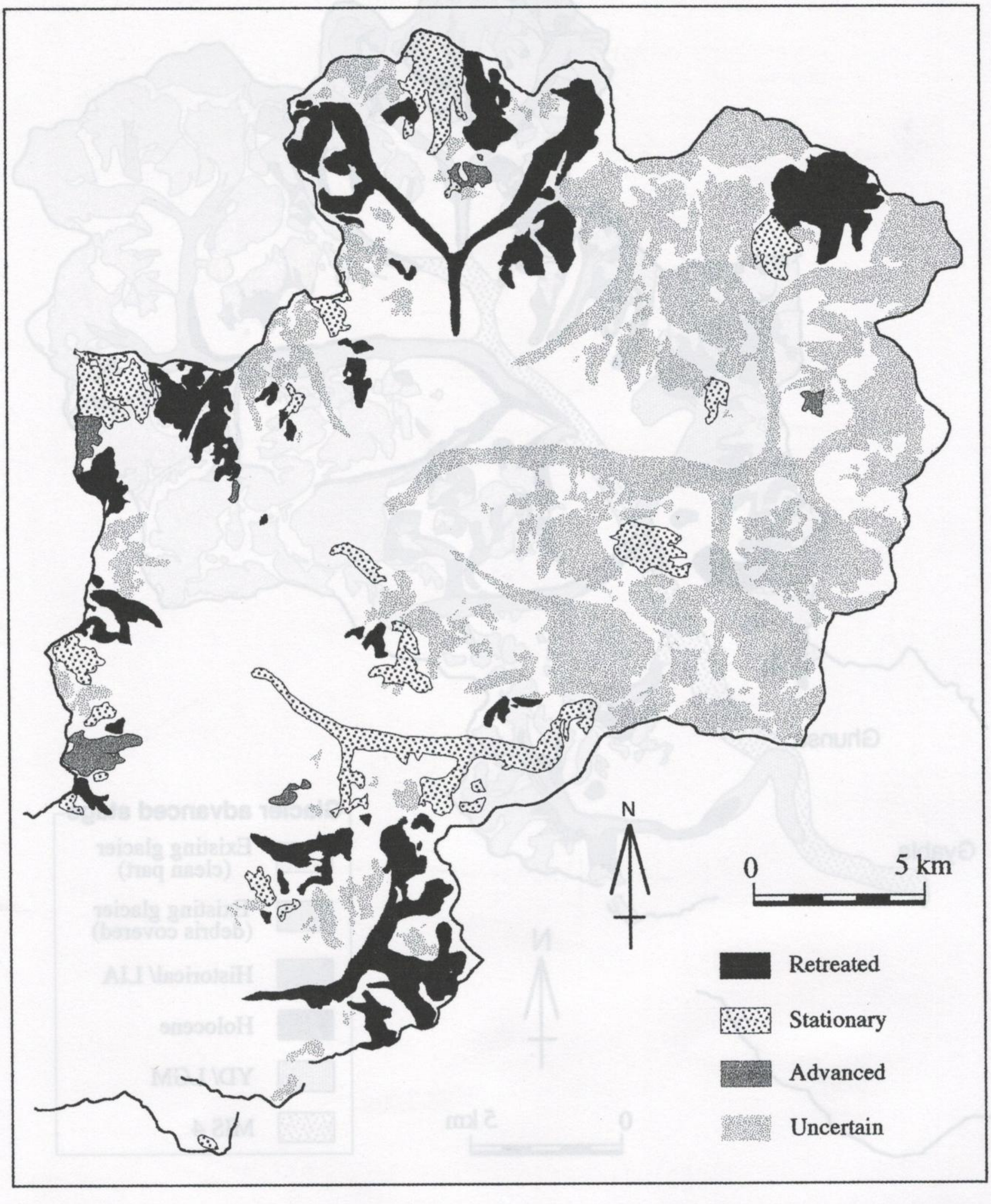

Fig. 4: Distribution of the glacier changes (retreating, stationary, or advancing) by means of the variation type during 1958 and 1992

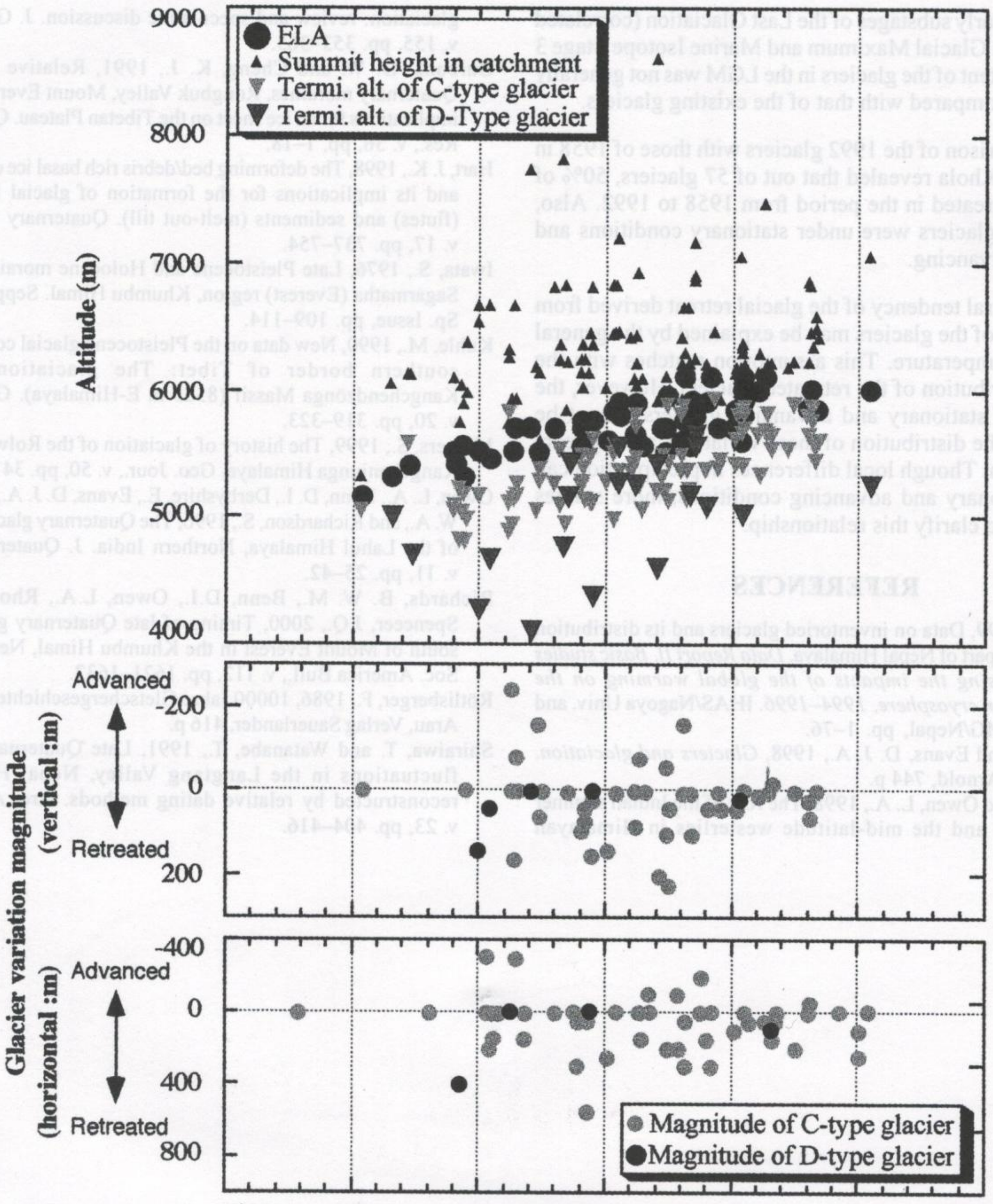

Fig. 5: Latitudinal tendency of glaciers and glacier variation magnitude in the Ghunsa Khola Watershed, Kanchenjunga Himal. ELA: Equilibrium-line altitude. C-type and D-type represent bare ice glacier and debris-mantled glacier, respectively.

This study defines the magnitude of the glacier variation in terms of two elements: vertical and horizontal extents (Fig. 5). The range of the magnitude varied practically independently when the magnitude was plotted on the latitudinal profile. The magnitude is also independent of the highest and lowest altitudes of the glacial ice body, and the glacial equilibrium-line altitude (ELA).

CONCLUSIONS

The geographical positions of the glacial landforms and relative dating data led to the classification of the glaciers at least into five stages. From the younger to older order, the stages are: historical stage (around the early part of the Twentieth Century), the Little Ice Age, the Holocene, and the late and early substages of the Last Glaciation (correlated with the Last Glacial Maximum and Marine Isotope Stage 3 or 4). The extent of the glaciers in the LGM was not generally so large as compared with that of the existing glaciers.

A comparison of the 1992 glaciers with those of 1958 in the Ghunsa Khola revealed that out of 57 glaciers, 50% of them had retreated in the period from 1958 to 1992. Also, 38% of the glaciers were under stationary conditions and 12% were advancing.

The general tendency of the glacial retreat derived from the majority of the glaciers may be explained by the general rise in air temperature. This assumption matches with the random distribution of the retreated glaciers. However, the existence of stationary and advancing glaciers cannot be neglected. The distribution of these variations also appears to be random. Though local differences in precipitation can induce stationary and advancing conditions, more studies are needed to clarify this relationship.

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