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Freeze-Thaw Activities and Rock Breakdown in the Langtang Valley, Nepal Himalaya

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Abstract

Measurement of rock breakdown from outcropping cliffs and observation of air and rock surface temperatures gave preliminary insight into the altitudinal variation in magnitude of frost shattering in the Langtang Valley, Nepal Himalaya. Rock breakdown occurred in 9 painted quadrangles among the 22 quadrangles established at 5 measurement sites, and the maximum shattering rate was found at the altitudes between 4100 m and 4700 m. The rock surface temperature on the south-facing slope at 5110 m a.s.l. fluctuated between −2 ℃ and 2 ℃, i.e., the effective freeze-thaw cycle (EFTC), at least 190 times in 1989, but only 62 times on the north-facing slope (5090 m a.s.l.). The altitudinal variation in magnitude of the estimated annual number of EFTC events, computed from the temperature data obtained at two meteorological sites, suggests that the frost shattering should be most active at 5600 m on the south-facing slope and 6200 m on the north-facing slope. The inconsistency between measurement and estimation of the altitude of maximum frost shattering may be attributed to various properties of the rocks in the study area.

Key words : Freeze-thaw activity, Rock surface temperature, Periglacial, Frost-shattering, Field measurement, Himalaya.

1. INTRODUCTION

Rock detritus on ablation areas of glaciers influences significantly the ablation processes of glaciers in the Himalaya (Inoue and Yoshida, 1980). This debris originates from both rockfall and subglacial erosional processes. Fushimi (1980) suggested that the debris supplied onto the glaciers increased with increasing area of free-faces since the deglaciation of recent times, based on his experience on the Khumbu Glacier in East Nepal (Fushimi *et al.*, 1980). It is, therefore, an important task for Himalayan glaciologists to clarify both the mechanism and the volume of fracturing rocks as a controlling factor of the glaciation in the Himalaya.

Matsuoka (1984) estimated that the altitudinal belt between approximately 5000 and 5500 m currently suffers the most active frost-shattering in the Great Himalaya on the basis of both air temperature and precipitation, although the data used were limited to those from a lower altitude (4420 m). While Whalley *et al.* (1984) suggested the significance of chemical weathering in the Karakoram Range by observing both rock surface temperature and weathering condition. However, no quantitative measurement of rock breakdown has been done in the Himalayan regions due to their remote location.

Rock surface temperature has been occasionally monitored as a possible controlling factor for rock breakdown in the Himalaya (Hewitt, 1968; Dronia, 1978; Kuhle, 1986, 1988; Francou, 1989), however, a long-term monitoring of it has not yet been carried out in this remote area.

This study firstly attempts to estimate the altitudinal belt currently suffering the most active frost shattering in the Himalayan region from the observation of air and rock surface temperatures, and from the field measurements of rock breakdown at several elevations.

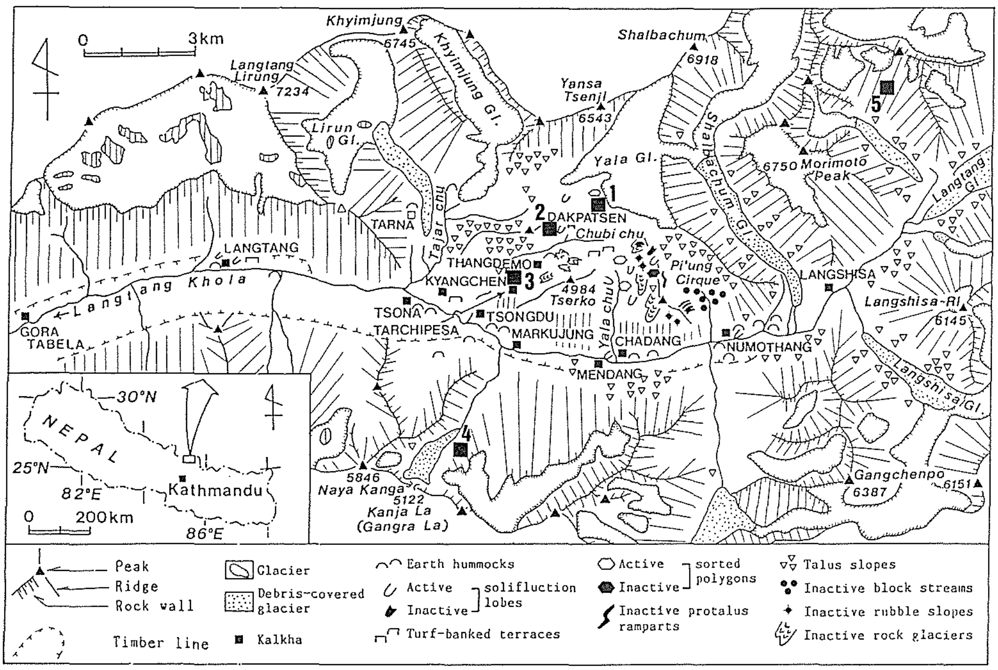

Figure 1 Locations of the meteorological observation sites and the sites for the measurement of the rock breakdown. The distribution of the major periglacial phenomena is also indicated (after Watanabe *et al.*, 1989). 1 : Glacier Camp, 2 : Dakpatsen site, 3 : Tarchipesa site, 4 : Gangja La site, and 5 : Pemdang site.

2. STUDY AREA

The study was carried out in the Langtang Valley, Nepal Himalaya. It is located approximately 60 km north of Kathmandu, the capital of Nepal (Figure 1, Watanabe *et al.*, 1989). This location makes continuous observation easy as compared to other regions of the Himalaya which are protected by difficult accessibility. The valley is surrounded by high mountains and ranges, in altitude from 1400 m at the mouth of the valley (Shabru Benshi, not shown in Figure 1) to 7239 m at the highest summit (Mt. Langtang Lirung).

Extensive distribution of periglacial landforms above 4000 m indicates that the valley lies in an active periglacial environment. The area below 4000 m is considered to contribute less to the rock breakdown because a large part of the area is covered with vegetation.

The geology of the study area is characterized by a granite of fine-grained facies on the right bank of the main river and an augen gneiss of medium- to coarse-grained facies on the left bank. The rock mass on the right bank is more fractured than that on the left bank.

The monsoon climate prevails in this valley, and supplied 78 % of annual precipitation during the summer five months, June to October in 1985−86 (Takahashi *et al.*, 1987). The mean annual air temperature at an altitude of 5090 m on the south-facing slope was −3.8 ℃ in 1988, and the freezing and thawing indices were 1703 ℃・days/yr and 311 ℃・days/yr, respectively. Although empirical studies by Harris (1981) suggest that freezing and thawing indices of 1703 and 311 ℃・days/yr should be sufficient for maintaining permafrost in this area, thick snow cover is believed to inhibit permafrost development at this south-facing site (Watanabe *et al.*, 1989).

3. STUDY METHOD

3.1. ROCK BREAKDOWN

The procedure for the field measurement of rock breakdown followed Matsuoka (1990a). Quadrangles of 50×50 cm were initially painted in red on the free faces, and percentage of the shattered area within the painted part was quantified by photographs taken after several time intervals. Joint spacings, which are determined by average distances between the joints, for each quadrangle were also measured in the field. The measurement sites were established at the Gangja La (Ga-1 to 3, 5090 m), Dakpatsen (Da-1 to 6, 4692 m to 4714 m), Tarchipesa (Ta-1 to 8, 4070 m to 4318 m), Glacier Camp (GC-1 to 3, 5090 m) and Pemdang (Pe-1 and 2, 5160 m) sites (Figure 1). Most of the quadrangles were defined in May 1988, and photographs were made during May 1989, December 1989 and June 1990.

3.2. AIR AND ROCK SURFACE TEMPERATURES

Air and rock surface temperatures were observed in order to estimate the freeze-thaw activities in the valley. The observation sites and the details on the data acquisition systems are shown in Figure 1 and Table 1, respectively. The Glacier Camp site represents the south-facing slope, while the Gangja La site represents the north-facing slope. Both sites are located in flat morainic fields in front of the glaciers. The sites are located in wind-blown places, although the surroundings are generally covered with deep snow from January to mid-April.

The air temperature at 180 cm above the ground was measured using a thermistor shaded with a white pipe. Artificial ventilation of the pipes was not considered. The thermistors were connected to automatic data-loggers (KADEC-U of KONA System Co.) in which the data were stored every hour.

The rock surface temperature was observed on outcropping rock cliffs near the sites

Table 1 Meteorological data acquisition systems at the Glacier Camp and Gangja La sites. T_a :air temperature. T_r : rock surface temperature.

	Glacier Camp	Gangja La Site
Aspect of slope	South facing	North facing
Altitude	5090 m (T_a) 5110 m (T_r)	5090 m
Aspect of rock surface	S25°W, 17°S ('88Apr.−'89May) S28°W, 90°S ('89May.−'90May)	N52°W, 60°N
Heighf of sensor	1.8 m (T_a) −1.5cm (T_r)	1.6 m (T_a) −1.5cm (T_r)
Sensor	Thermistor accuracy ±0.5 ℃	Thermistor accuracy ±0.5 ℃
Data Logger	KADEC-U (KONA system)	KADEC-U (KONA system)
Interval	60 min.	60 min.

of the air temperature observations. Thermistors were installed in drilled pits of 1.5 cm depth below the rock surfaces, and the pits were fixed with silicone rubber mixed with granules. The data were recorded hourly in the automatic data loggers mentioned above.

The observation has been continuous from June 1988 to May 1990. The data for the Gangja La site, however, were limited to June 1989 to May 1990 because of unexpected damage to the instruments. Hereafter, the data from June 1988 to May 1989 are referred to as 1988's data, and those from June 1989 to May 1990 as 1989's data.

4. RESULTS

4.1. ROCK BREAKDOWN

Table 2 shows the cumulative shattered area (%) during each interval, and the monthly shattering rate during the whole observational period. Rock breakdown was most obvious in the Dakpatsen site where all quadrangles experienced breakage from 0.4 % to 6.5 % /month. The breakdown of Da-4 was the highest among the quadrangles, and amounted 155 % in total over 2 years. The Tarchipesa site also suffered rock breakdown, but the rates were generally small, with exception of Ta-1 which was 86.5 % broken over 2 years. The quadrangles in the Gangja La, Glacier Camp and Pemdang sites have not changed at all, although slight change was found at GC-1 (7.6 %/2 years). This indicates that the active frost shattering occurred at lower altitudes within the study area.

A major rock breakdown is generally succeeded by a small one as shown in sites Da -2, 4, 5, 6, and Ta-1, although the intervals of the measurement were not uniform. This may suggest that the mechanical weathering of rock requires a certain threshold time period for re-fracturing after a major breakage.

Table 2 Characteristics of the painted rockwalls and the shattering rate.
Ga : Gangja La, Da : Dakpatsen, Ta : Tarchipesa, GC : GlacierCamp, and Pe : Pemdang. Gr : Granite, Gn : Gneiss, nd : data not available, s : spring, and f : fall or autumn.

Location number	Rock type	Aspect	Altitude (m)	Joint spacjng (cm)	Cumulative shattered area (%) '88s-'89s	'89s-'89f	'89f-'90s	Monthly shattering rate (%/month) [duration]
Ga-1	Gr	S 34 °W	5090	> 100.0	0.0	nd	0.0	0.0 [24 months]
Ga-2	Gr	S 26 °W	5078	50.0	0.0	nd	0.0	0.0 [24 months]
Ga-3	Gn	S 26 °W	5070	8.7	0.0	nd	0.0	0.0 [24 months]
Da-1	Gr	N 10 °E	4700	4.4	4.9	8.3	1.2	0.6 [24 months]
Da-2	Gr	E	4692	4.2	44.5	31.8	1.4	3.2 [24 months]
Da-3	Gr	N 80 °W	4692	6.7	6.1	16.2	0.0	0.9 [24 months]
Da-4	Gr	S 40 °E	4712	< 4.0	87.5	41.0	26.5	6.5 [24 months]
Da-5	Gr	S 30 °W	4712	6.1	nd	8.0	1.1	0.8 [24 months]
Da-6	Gr	S 15 °E	4714	9.5	nd	4.2	0.5	0.4 [24 months]
Ta-1	Gr	N 12 °W	4162	10.5	86.1	0.0	0.4	3.6 [24 months]
Ta-2	Gr	N 39 °W	4152	8.7	0.0	0.0	0.0	0.0 [24 months]
Ta-3	Gr	S 47 °W	4070	12.5	nd	nd	0.0	0.0 [6 months]
Ta-4	Gr	N 25 °E	4080	6.9	nd	nd	0.0	0.0 [6 months]
Ta-5	Gr	N 40 °E	4100	12.5	nd	nd	0.0	0.0 [6 months]
Ta-6	Gr	S 63 °W	4310	< 3.4	nd	nd	0.0	0.0 [6 months]
Ta-7	Gr	S 22 °E	4317	6.1	nd	nd	11.5	1.9 [6 months]
Ta-8	Gr	N 82 °E	4318	6.9	nd	nd	0.0	0.0 [6 months]
GC-1	Gr	S 77 °W	5095	6.3	0.0	1.2	6.1	0.3 [24 months]
GC-2	Gr	W	5095	6.1	nd	0.0	0.0	0.0 [12 months]
GC-3	Gr	S 80 °W	5093	8.0	nd	nd	0.0	0.0 [6 months]
Pe-1	Gr	N 70 °W	5162	10.5	nd	0.0	0.0	0.0 [13 months]
Pe-2	Gr	E	5162	10.5	nd	0.0	0.0	0.0 [13 months]

The joint spacings are generally smaller in the quadrangles which suffered greater rock breakdown than those of the unchanged ones (Figure 2). This indicates that the joint spacing is closely related to the rock breakdown.

4.2. AIR TEMPERATURE

Using freeze-thaw cycle data derived from air temperature, Matsuoka (1984) speculated that freeze-thaw activity was occurring during the monsoon season between 5000 and 5500 m in the Khumbu region, approximately 100 km east of the Langtang Valley.

In this study, the freeze-thaw cycle of air temperature occurred mainly in spring and autumn. Figure 3 shows the diurnal ranges of the air temperature at the Glacier Camp (A) and Gangja La (B) sites through the observational periods. The measurement of air temperature at these sites revealed no significant difference between north- and south-facing slopes. The average air temperature is above 0 °C during the three summer months ; July through September. Conversely, it is below 0 °C during the five winter months, November through March, although intermittent warm periods sometimes enable the air temperature to fluctuate around 0 °C on both sites. These results are inconsistent with those of Matsuoka (1984).

The diurnal ranges are generally small during the summer from July to September because the thick monsoon clouds shade the whole area in the afternoon when the daily air temperature usually attains its maximum. Those of the anti-monsoon season, however, are characterized by larger diurnal ranges of air temperature.

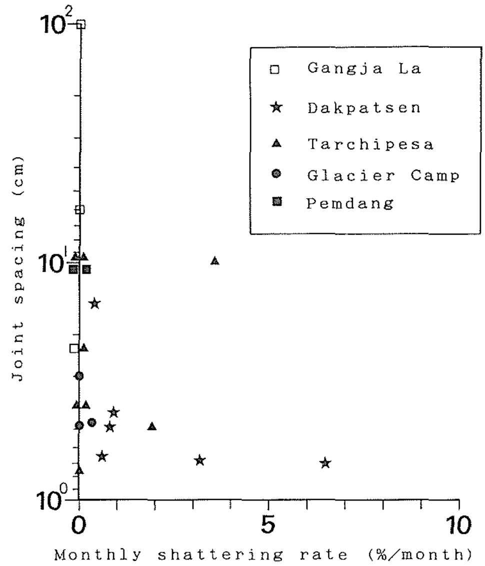

Figure 2 Monthly shattering rate (%/month) as a function of joint spacings (cm).

4.3. ROCK SURFACE TEMPERATURE

The diurnal ranges of the rock surface temperature are shown in Figure 4. The annual fluctuation of rock surface temperature is generally similar to that of air temperature. The rock surface temperature, however, has larger diurnal ranges than those of air temperature. This may be attributed to short wave radiation absorbed by the rocks with low albedo. As a result, the rock surface temperature often oscillated around 0 ℃ in the winter season. In this context, a significant contrast is seen in the

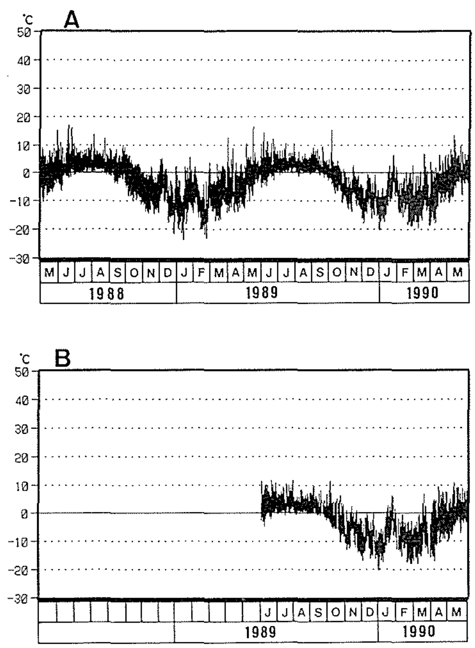

Figure 3 Diurnal ranges of air temperature. (A) Glacier Camp (5090 m), (B) Gangja La (5090 m).

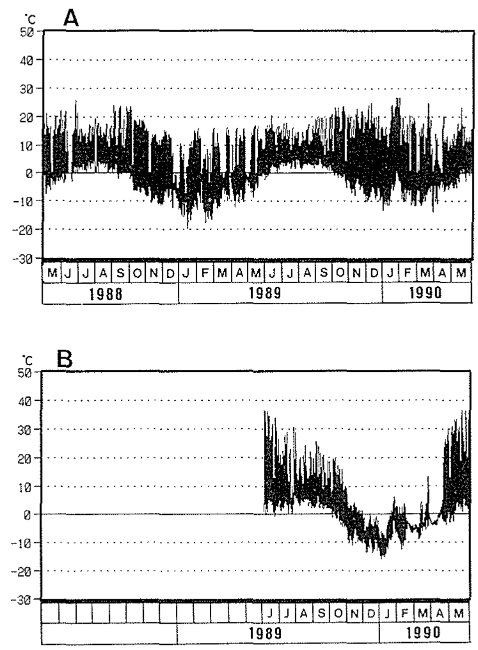

Figure 4 Diurnal ranges of rock surface temperature. (A) Glacier Camp (5110 m), (B) Gangja La (5090 m).

magnitude of the diurnal range of the rock surface temperature during the winter season between the south- and north-facing slopes. The temperature frequently fluctuated around 0 °C at the Glacier Camp site, while at the Gangja La site it was constantly below 0 °C. This is explained by the seasonal difference in the solar elevation, which is high enough to provide effective short wave radiation on both slopes only during the summer, i.e., the lower solar elevation during winter is less effective for heating the north-facing slope. As a result, frequent freeze-thaw cycle events were encountered only on the south-facing slope during the winter.

Here, the freeze-thaw cycle is defined as the effective freeze-thaw cycle (EFTC) which is a temperature-fall below −2 °C followed by a rise above +2 °C (Matsuoka, 1990 a), because several experiments have clarified that a rock temperature fall below 0 °C followed by a rise above 0 °C is not sufficient to cause frost shattering (e.g., Matsuoka, 1990b). The annual numbers of EFTC totaled 188 events in 1988 and 190 events in 1989 at the Glacier Camp site, and 62 events in 1989 at the Gangja La site (Table 3).

Table 3 Numbers of EFTC events at the Glacier Camp and Gangja La sites during the observational periods. nd : Data not available.

Location	1988								1989												1990				
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Glacier Camp	22	6	0	0	1	27	27	19	27	20	17	22	15	0	0	0	0	12	30	31	27	22	27	26	9
Gangja La Site	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	0	0	0	18	11	0	12	5	8	7	1

5. DISCUSSION

5.1. ALTITUDINAL DISTRIBUTION OF NUMBERS OF THE EFTC

Rates of frost shattering are controlled, in broad terms, by three factors: temperature, moisture, and rock properties (Matsuoka, 1990 a). Only the altitudinal distribution of numbers of the EFTC, however, is discussed here as the parameter controlling the frost shattering, because only the thermal factors were measured in this study. The EFTC number is however, considered to be an important factor influencing frost shattering in a moist environment.

A linear regression analysis was performed in order to define the relationship between the rock surface temperature and the air temperature (Figure 5). The regression equations were calculated for daily maximum rock surface temperature [T_r(max)] against daily maximum air temperature [T_a(max)] (Figure 5a and d), daily minimum rock surface temperature [T_r(min)] against daily minimum air temperature [T_a(min)] (b and e), and T_r(min) against daily average air temperature [T_a(avg)] (c and f), for the two sites; i.e., Glacier Camp and Gangja La sites. The most significant relation was found on the T_r(min)$-$$T_a$(min) at the Glacier Camp site (r=0.92, Figure 5b), while the least significant was on the T_r(max)$-$$T_a$(max) at the Glacier Camp (r=0.37, Figure 5a). The T_r(max) was much closer to the T_a(max) on the north-facing slope (r=0.80, Figure 5d).

The rock surface temperature at different altitudes was estimated by the following procedures. At first, the air temperature at each altitude was calculated for every 100 m in elevation using the temperature lapse rate of −0.6 °C/100 m through the year; the value is based on the earlier observations in this valley (Takahashi *et al.*, 1987). The calculated air temperature was then converted to the rock surface temperature using the regression equations mentioned above, assuming that the regression equations are constant at every altitude. The maximum rock surface temperature on the south-facing slope was,

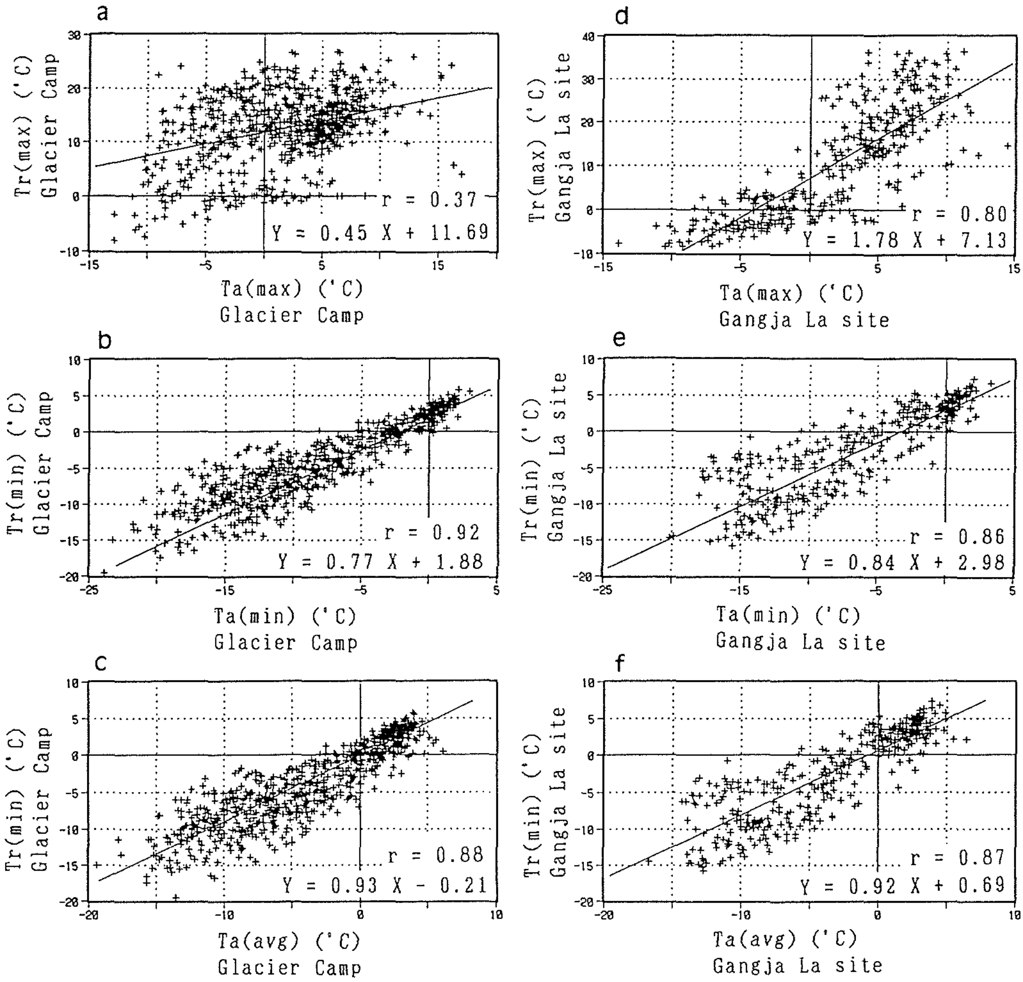

Figure 5 A linear regression analysis between the air temperature and the rock surface temperature. T_a: air temperature, T_r: rock surface temperature, (max): daily maximum, and (min): daily minimum. (a) and (d): T_r(max) -T_a(max), (b) and (e): T_r(min)-T_a(min), and (c) and (f): T_r(min)-T_a(avg). (a), (b) and (c) are the relations at the Glacier Camp site, while (d), (e) and (f) are the relations at the Gangja La site.

however, extrapolated from the rock surface temperature at the Glacier Camp site using the lapse rate of −1.51 ℃/100 m (Kuhle, 1986, 1988) because the correlation coefficient of the equation obtained here was very low (r=0.37). The lapse rate of −1.51 ℃/100 m, obtained by the direct measurement of the rock surface temperature using passive infra-red detectors, seems to be high considering the fact that the short wave radiation increases with increasing altitude. No reliable data on the lapse rate of rock surface temperature, except the results of Kuhle (1986, 1988), lead to the application of this value.

Figure 6 shows the results of the computation in the form of altitudinal distribution of EFTC numbers on the south- (A) and north-facing (B) slopes. The highest annual EFTC

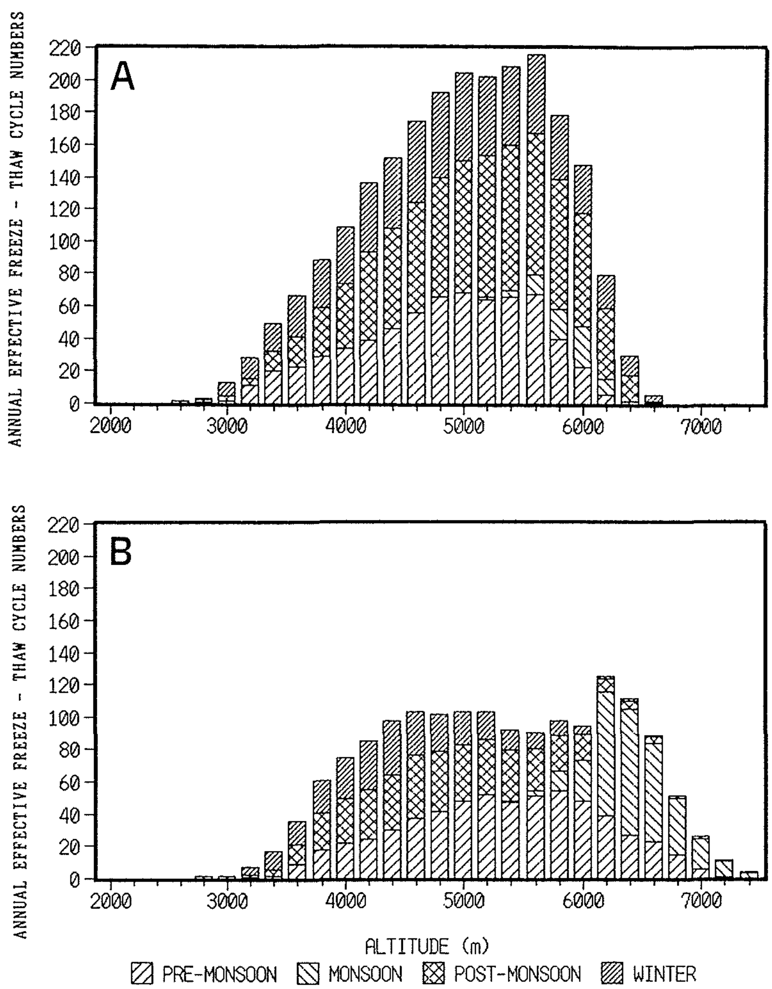

Figure 6 Computed altitudinal distribution of annual numbers of effective freeze-thaw cycle (EFTC) events in the south - (A) and the north-facing (B) slopes. Note that the seasonal distribution of EFTC events at each altitude is considerably different.

numbers appear at the altitude of 5600 m (216 times) and 6200 m (125 times), for south- and north-facing slopes, respectively. The EFTC disappears above the altitude of 6600 m (south) and 7400 m (north), and below 2600 m (south) and 2800 m (north). The result obtained here seems to be somewhat unrealistic because the south-facing slope receives more incoming solar radiation than the north-facing one; hence, in the high altitude, the EFTC should occur more frequently on the south-facing slope than the north. The reason is attributed to the application of Kuhle's (1986, 1988) lapse rate of -1.51 ℃/100 m. If we apply a lower value for the lapse rate, the south-facing slope will receive more frequent EFTC at higher altitudes; the lack of data, however, prevents us from estimating actual condition of the EFTC at high altitudes on the south-facing slope.

5.2. SEASONAL EFFECTIVENESS OF EFTC ON THE FROST SHATTERING

The EFTC during the wet season may contribute greatly to the frost shattering as Matsuoka (1984) noted. The seasonal moisture condition in the Langtang Valley is discussed here in relation to the magnitude of frost shattering.

The climate of the Langtang Valley can generally be divided into four seasons: the monsoon, post-monsoon, winter, and pre-monsoon seasons. The monsoon season, from June to September, is characterized by continuous but weak precipitation, while the post-monsoon season, from October to December, is the driest season throughout the year. The winter, January and February, is rather dry although intermittent snowfall covers the ground. The joints of the rock masses are generally filled with snow. In the pre-monsoon season, i.e., March to May, both the ground and the cliffs are wet because both melt-water and intermittent precipitation occur.

As a result, the EFTC occurring in the monsoon and the pre-monsoon seasons are most likely to contribute to the frost shattering in the area. The number of EFTC events during the monsoon and pre-monsoon seasons varies from 1 (2800 m) to 79 (5600 m) on the south-facing slope, and from 1 (3200 m) to 115 (6200 m) on the north-facing slope, as shown in Figure 6. The frost-shattering may thus be most active around the altitudes of approximately 5600 and 6200 m, for the south- and north-facing slopes respectively.

The number of EFTC events during the wetter season is, however, less variable between 4000 m and 5200 m, where all measurement sites are located. Therefore, the field measurement which showed that the rock breakdown culminated at the lower sites (Dakpatsen and Tarchipesa) rather than at the higher sites (Glacier Camp, Gangja La, and Pemdang) suggests that numbers of EFTC can not be regarded as the dominant factor that affected the strength of the frost shattering in this study. The difference in the rate of rock breakdown may be attributed to the difference in the properties of the rock within the sites as shown by the joint spacing listed in Table 2.

6. CONCLUSIONS

Measurements of the rock breakdown from the outcropping cliffs were performed in the Langtang Valley, Nepal Himalaya. Both air and rock surface temperatures were simultaneously measured on south- and north-facing slopes, and subsequently the numbers of effective freeze-thaw cycle (EFTC) events were calculated. In the results, the following points are revealed.

1. Active rock breakdown occurred between 4100 m and 4700 m in elevation, and the frost shattering rate amounted to 0.0 to 6.5 %/month, while the higher measurement sites were not shattered during the study periods.

2. The annual numbers of EFTC amounted to 190 and 62 times on the south- and north-facing slopes, respectively, at an altitude of approximately 5100 m.

3. The estimated peaks of the numbers of EFTC events are located at the altitudes of 5600 m and 6200 m, for the south- and north-facing slopes respectively.

4. The smaller variability of estimated EFTC events within the measurement sites suggests that differences in rock properties might control the magnitude of the frost shattering in this study area.

This study firstly attempted to quantify the rock breakdown in the Himalaya, however, it is still difficult to extend the results to the whole Himalayan region due to the regional variety of parameters controlling the rock breakdown. Studies on the moisture condition and the rock properties are particularly needed to provide further understanding of the altitudinal distribution of the frost shattering strength in the Himalaya.

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REFERENCES

1. Dronia, A. (1978). Gesteinstemperaturmessungen im Himalaya mit einem Infrarot-Thermometer. *Zeitschrift für Geomorphologie N.F.*, **22**, 101–114.
2. Francou, B. (1989). Températures de parois rocheuses mesurées en hiver dans l'Himalaya du Khumbu vers 6000 m. *Inter-Nord*, **19**.
3. Fushimi, H. (1980). Glaciers in the Interior Asia : on their regionality and history (Nairiku Ajia no hyogagun : hyoga gensho no chiikisei to rekisisei ni tuite). *The Earth Monthly* (Gekkan chikyu), **2**, 3, 201–210 (in Japanese).
4. Fushimi, H., Yoshida, M., Watanabe, O. and Upadhyay, B.P. (1980). Distributions and grain sizes of supraglacial debris in the Khumbu Glacier, Khumbu region, east Nepal. *Seppyo*, **41**, Special Issue, 18–25.
5. Harris, S.A.(1981). Distribution of active glaciers and rock glaciers compared to the distribution of permafrost landforms, based on the freezing and thawing indices. *Canadian Journal of Earth Sciences*, **18**, 376–381.

6. Hewitt, K. (1968). The freeze-thaw environment of Karakoram (Himalaya). *Canadian Geographer*, **12**, 85–98.
7. Inoue, J. and Yoshida, M.(1980). Ablation and heat exchange over the Khumbu Glacier. *Seppyo*, **41**, Special Issue, 26–33.
8. Kuhle, M. (1986). The upper limit of glaciation in the Himalayas. *GeoJournal*, **13**, 331–346.
9. Kuhle, M. (1988). On the geoecology of Southern Tibet : measurements of climatic parameters including surface-and soil-temperatures in debris, rock, snow, firn, and ice during the South Tibet- and Mt. Everest Expedition in 1984. *GeoJournal*, **17**, 597–613.
10. Matsuoka, N.(1984). Frost shattering of bedrocks in the periglacial regions of the Nepal Himalaya. *Seppyo*, **46**, 19–25 (in Japanese with English abstract).
11. Matsuoka, N. (1990 a). The rate of bedrock weathering by frost action: field measurements and a predictive model. *Earth Surface Processes and Landforms*, **15**, 73–90.
12. Matsuoka, N. (1990 b). Mechanisms of rock breakdown by frost action: an experimental approach. *Cold Regions Science and Technology*, **17**, 253–270.
13. Takahashi, S., Motoyama, H., Kawashima, K., Morinaga, Y., Seko, K., Iida, H., Kubota, H. and Turadahr, N.R.(1987). Meteorological features in Langtang Valley, Nepal Himalayas, 1985–1986. *Bulletin of Glacier Research*, **5**, 35–40.
15. Watanabe, T., Shiraiwa, T. and Ono, Y. (1989). Distribution of periglacial landforms in the Langtang Valley, Nepal Himalaya. *Bulletin of Glacier Research*, **7**, 209–220.
15. Whalley, W.B., McGreevy, J.P. and Ferguson, R.I.(1984). Rock temperature observations and chemical weathering in the Hunza region, Karakoram: Preliminary data. In Miller, K.J. (*ed.*), *International Karakoram Project.* **Vol.2**, Cambridge : Cambridge University Press, 616–633.