Proc. NIPR Symp. Antarct. Geosci., 4, 55–66, 1990

# GROUND TEMPERATURE REGIMES AND THEIR RELATION TO PERIGLACIAL PROCESSES IN THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA

Norikazu MATSUOKA[1], Kiichi MORIWAKI[2], Shuji IWATA[3] and Kazuomi HIRAKAWA[4]

[1]*Institute of Geoscience, University of Tsukuba, 1-1, Tennodai 1-chome, Tsukuba 305*
[2]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[3]*Department of Geography, Faculty of Humanities and Social Sciences, Mie University, Kamihama-cho, Tsu 514*
[4]*Department of Geography, Tokyo Metropolitan University, 1-1, Fukazawa 2-chome, Setagaya-ku, Tokyo 158*

***Abstract:*** Rock and soil temperatures were observed on some nunataks in the Sør Rondane Mountains during 1985–1989. Three different types of automatic recorders made it possible to collect the temperature data at 1- to 4-h intervals throughout the year. Multiple freeze-thaw events were recorded on many bedrock surfaces and in soil surface layers during the summer season, whereas the ground was completely frozen during the remaining periods. The number of freeze-thaw cycles is comparable to those in mid-latitude alpine environments where the frost action, including frost weathering, heave and creep, is regarded as prevailing geomorphic process. Geomorphic change by the frost action, however, is believed to be insignificant in the most part of the Sør Rondane Mountains, because the water content of the ground is generally too low. The frost action may be effective only on the ground with a fairly high moisture content due to snow spray as well as with frequent freeze-thaw cycles.

## 1. Introduction

Antarctic nunataks belong to the coldest periglacial environment in the world. Air temperature does not rise above 0°C throughout the year. Strong insolation in summer, however, often raises the ground surface temperature above 0°C, and consequently, the frost action may cause geomorphic change in the nunataks.

Since 1985, the geomorphological research group of the Japanese Antarctic Research Expedition has observed the present-day geomorphic processes in the Sør Rondane Mountains. Items of the field measurements include rates of processes such as frost heave (MATSUOKA *et al.*, 1988), frost creep, rockfall, ice-wedge cracking and wind erosion; and their controlling factors as the temperature, moisture and material properties of the ground, and the direction and speed of wind. This article deals with temperature regimes on the surface of nunataks, and their relation to the frost action, *i.e.*, frost weathering and periglacial mass movements.

## 2. Study Area

The Sør Rondane Mountains, lying about 200 km from the nearest coast, consist of a number of nunataks exposed on the ice sheet. Four sites are selected for observation of the ground temperature (Fig. 1). One (Site 27–1) is located in Selungen, an isolated small nunatak close to the Asuka Station; the other three (Sites 26–1, 27–2 and 27–3) in the northern parts of Brattnipene, one of the largest nunatak in the Mountains. Meteorological data at the Asuka Station indicate that the annual mean, maximum and minimum air temperatures in 1987 were −18.5, −2.9 and −48.7°C, respectively; and that the katabatic wind from ESE-direction prevails throughout the year with the mean and maximum velocities of 12.8 and 45.2 m/s, respectively (YAMANOUCHI *et al.*, 1988; AYUKAWA, 1989).

These measurement sites are different in climatic conditions. The isolated position of Site 27–1 makes it the coldest among the four sites despite of its lowest altitude; snow supplied by the katabatic wind also prevents a temperature rise. Facing NW and hence lying leeward, Site 26–1 is in the warmest environment (Photo 1). Site 27–2 lies on a moraine field surrounded by high mountains except on the north (Photo 2); the katabatic wind is thus blocked by these mountains despite of a dry-strong wind often blowing down from Mt. Tekubi (2361 m a.s.l.), the highest peak in Brattnipene. Climatic condition changes locally within Site 27–3 according to the aspect of ground surface (Fig. 2; Photo 3). The northern part of the east-facing slope is subject to constant strong wind and hence to snow spray even in summer. By con-

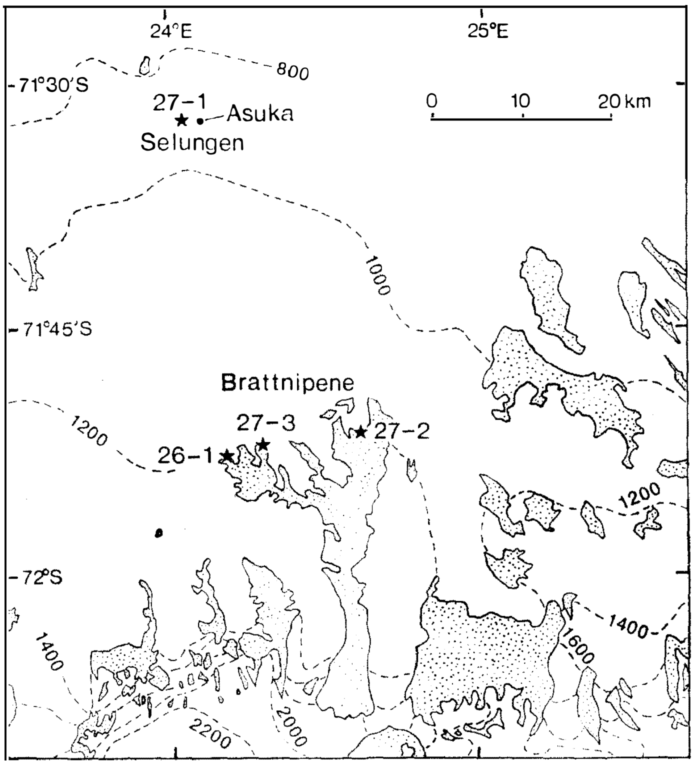


*Fig. 1. Location of measurement sites.*

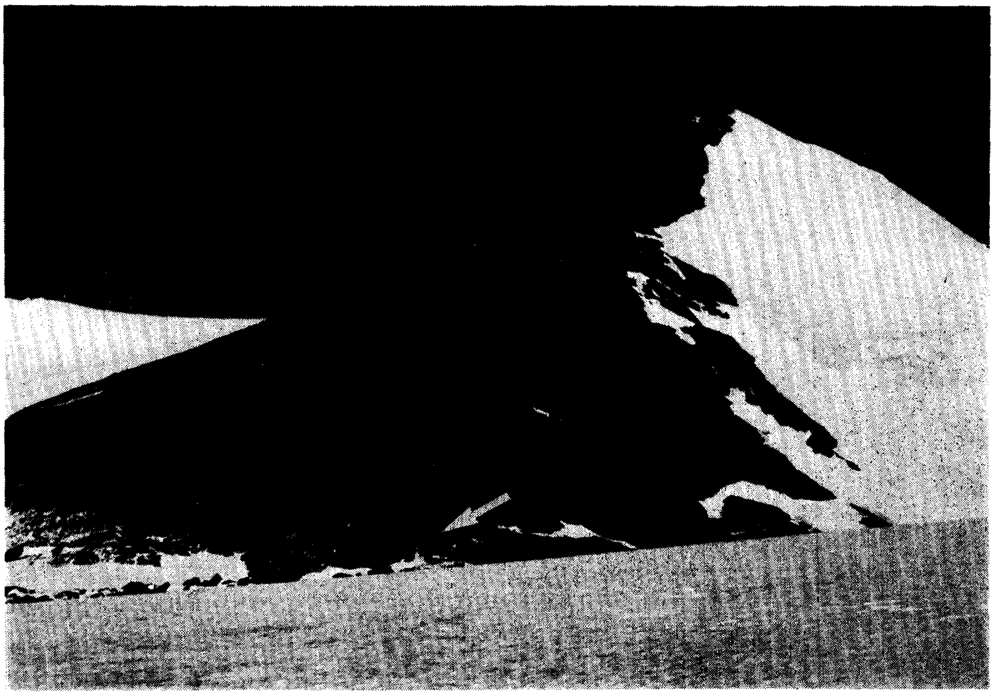

*Photo 1. View of Site 26–1 from the north. The arrow shows the location of the temperature sensor installed into the rockwall. The nunatak stands 350 m above the ice sheet.*

*Photo 2. View toward south at Site 27–2, a wide moraine field located at the northern foot of Mt. Tekubi (behind). The arrow shows the location of temperature sensors installed at various depths in the ground.*

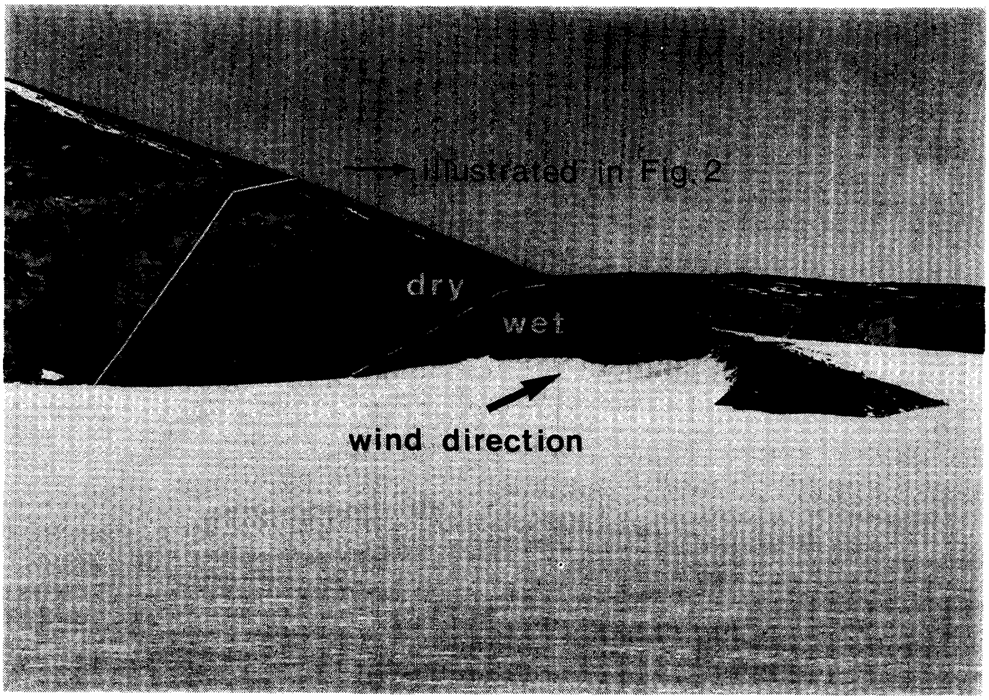


*Photo 3. View of Site 27–3 from the east. Snow-bearing wind often blows up the debris slope from the southeast.*

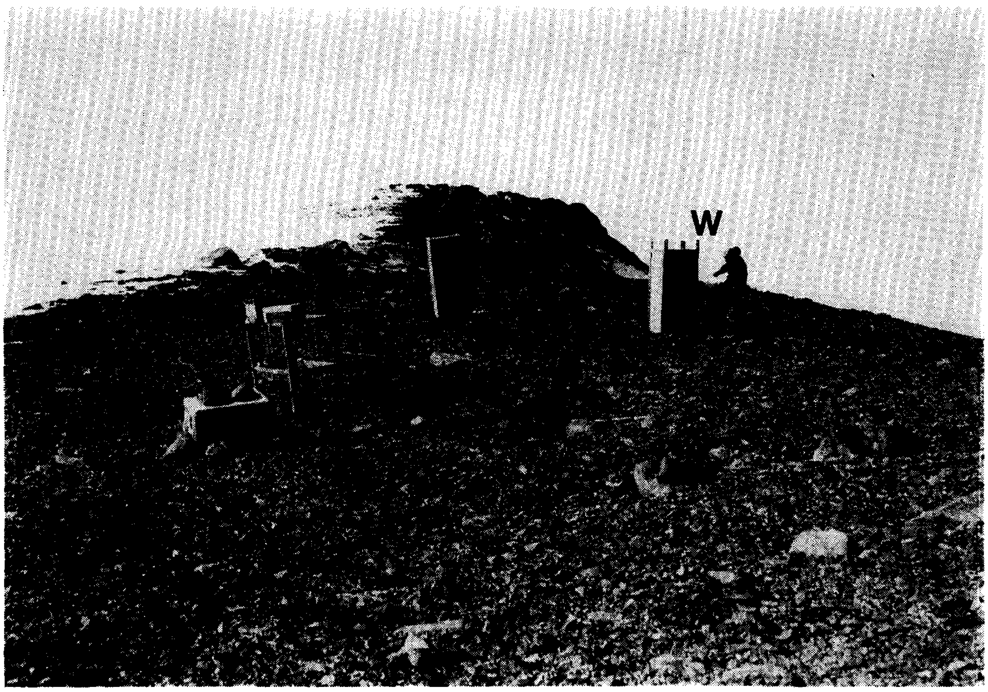


*Photo 4. View of Site 27–3 from the north, indicating the location of temperature sensors installed into the ground (the arrow), the temperature recorder (T), the frost-heave frame (F), and the box for measurement of wind erosion (W).*

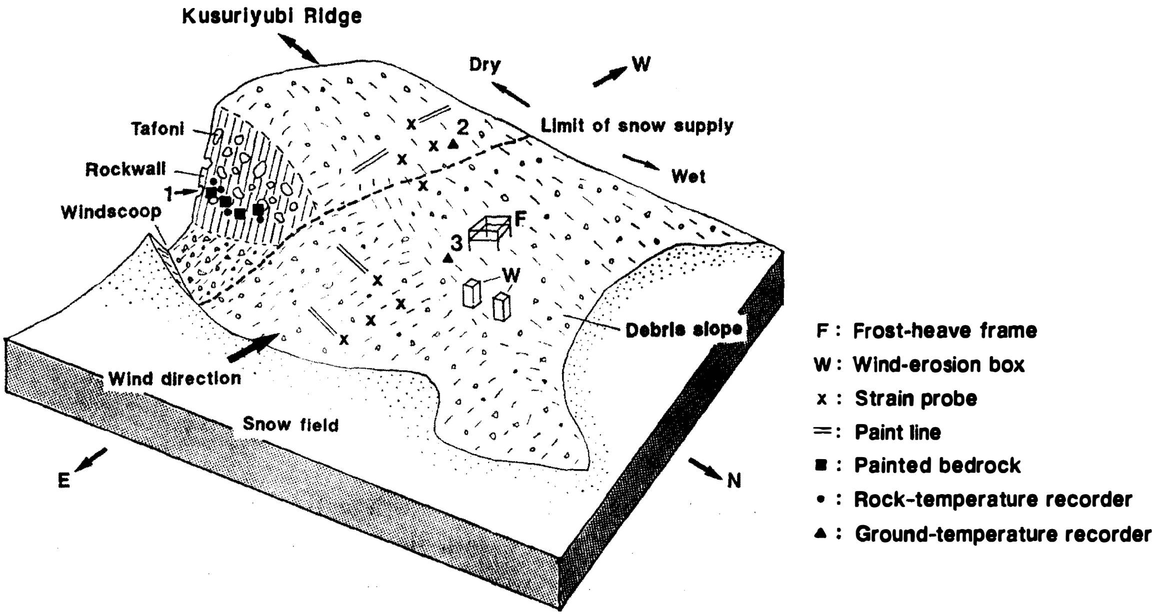


*Fig. 2. Schematic diagram of Site 27–3, showing the location of the experimental plots. The point numbers indicate the temperature recorders described in the text.*

trast, the southern rockwall part of the east-facing slope and the upper part of the north-facing slope are subject to neither strong wind nor snow spray at least in summer. Such snow spray at the former site keeps the ground in wet condition.

These sites are composed mainly of biotite gneiss and granite of late Proterozoic or early Paleozoic ages (KOJIMA and SHIRAISHI, 1986). Ground surface features of these sites are classified into the following three categories: rockwalls, debris slopes (referred to as debris-mantled rectilinear slopes in IWATA, 1987) and moraine fields. Sediments of the debris slopes (Sites 27–1, 27–3) are derived from *in-situ* weathered material from the bedrock. Those of moraine fields (Sites 26–1, 27–2) are derived from other nunataks as glacial drift. Grain size of these sediments ranges from silt to gravel, but silt fraction is usually less than 10% in weight.

## 3. Instrumentation

Rock and soil temperatures were automatically measured using three different types of recorders (Table 1). Recorders A and B plot data on a chart and run con-

*Table 1. Temperature recorders.*

| Type of recorder | Sensor | Channel | Range (°C) | Recording interval (h) |
|---|---|---|---|---|
| A. Takara: Seven-corder | Thermistor | 1 | −30∼+30<br>or −30∼+20 | 3 |
| B. Grant: Miniature chart recorder | Thermocouple or thermistor | 4 | −50∼+50<br>or −30∼+20 | 4 |
| C. Grant: Squirrel meter logger | Thermistor | 4 | −25∼+25 | 1 |

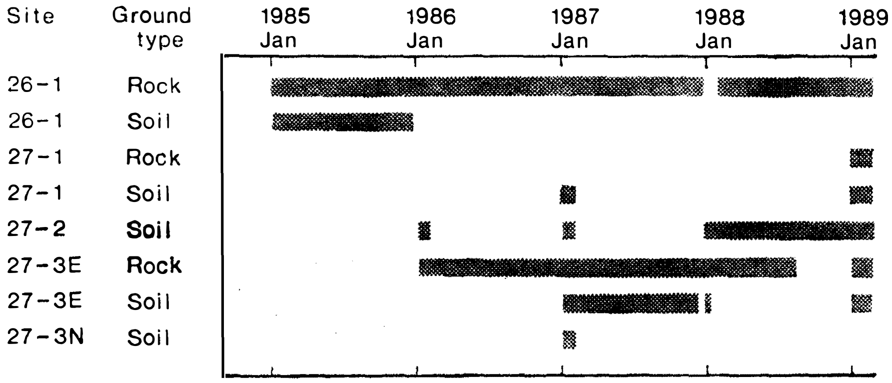


*Fig. 3. Periods of rock and soil temperatures on record, shown by bars.*

tinuously more than a year with the help of a lead storage battery (DC 6 or 12 V). Recorder C, a C-MOS-type logger which stores data in memory IC, was used only in summer. Two types of temperature sensors were used, which are a thermistor and a thermocouple of copper-constantan.

A probe was inserted in a 1.5 cm-deep hole drilled into rockwall, connected to recorder A or B (Table 1), and thereby rock surface temperature was monitored at 3 or 4-h intervals. Four probes, inserted at various soil depths and connected to recorder B or C (Table 1), made it possible to determine a temperature profile at every sampled time (1 or 4-h intervals). Rock surface temperature was observed on rockwalls at Sites 26–1, 27–1 and 27–3. Soil temperature was done on debris slopes and moraine fields at all measurement sites. Although mechanical troubles sometimes interrupted the data collection, we got available data at maximum for four years (Fig. 3).

## 4. Bedrock Temperature Regimes

The solar insolation heats rock surface during summer days, often raising the surface temperature above 20°C (Fig. 4). Diurnal ranges of rock surface temperature are usually between 20 and 30°C during fine summer days, while they are quite small in winter. Freeze-thaw cycles, defined as temperature oscillation above and below 0°C, occur frequently from October to March.

Difference in the aspect of ground surface produces a time lag in temperature curves (Fig. 5). Being subject to insolation in the morning, the northeast face (Site 27–3; point 1 in Fig. 2) attains the daily maxima earlier than the northwest face (Site 26–1) does. Aspects influence also daily ranges: the windward northeast face shows somewhat smaller ranges than the leeward northwest face does, probably because the wind carrying snow particles prevents a temperature rise. In addition to the aspect effect, irregular rock surface also produces local variation in temperature. Cavernous weathering features, so-called "tafoni" (*e.g.* SELBY, 1982), develop on the rockwall at Site 27–3. Daily temperature ranges inside of a tafone (about 50 cm in diameter) are about half those outside of the tafone (Fig. 5). This indicates that insolation weathering which results from alternate warming and cooling is not responsible for the tafoni development. The spatial variation in daily ranges is virtually produced by the daily

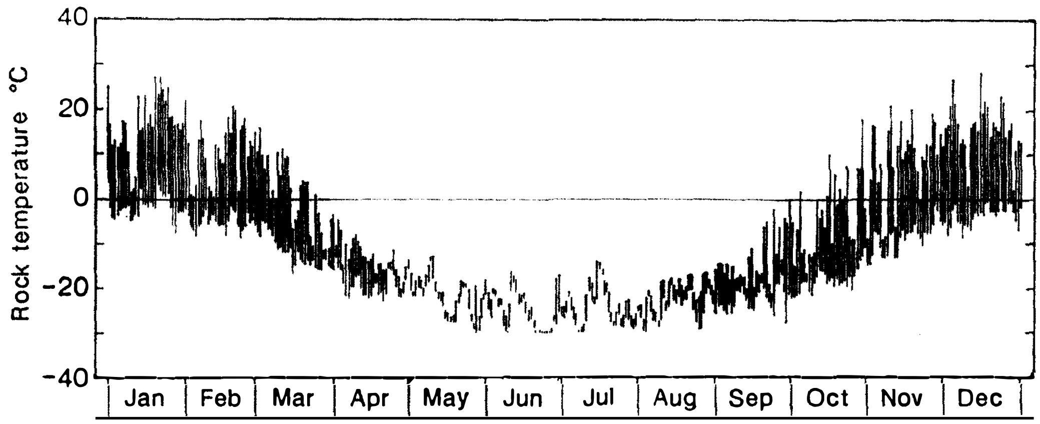


*Fig. 4. Annual fluctuation in rock surface (1.5 cm depth) temperature at Site 26-1 (the northwest-facing rockwall) in 1986. Daily ranges are shown with solid lines. Note that records are limited within ±30°C.*

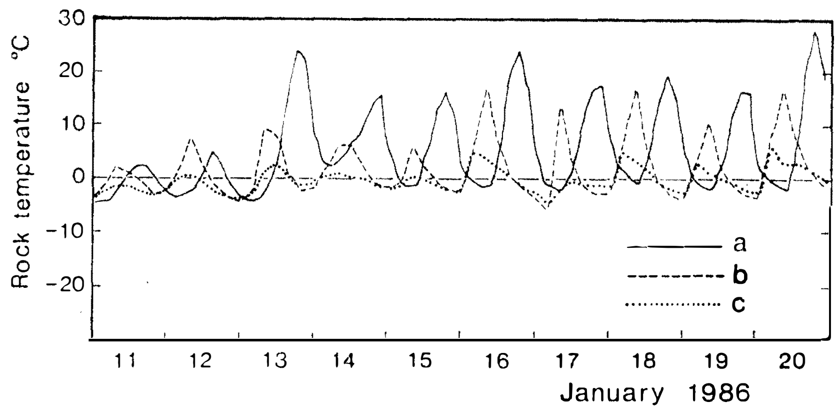


*Fig. 5. Fluctuations in rock surface (1.5 cm depth) temperature during summer days, recorded on the smooth rockwall at Site 26-1 (a), on the rim (b) and on the inner surface of a tafone at Site 27-3 (c).*

maxima rather than the minima. In other words, the solar insolation is the most important control on daily temperature variation.

Figure 6 shows a comparison of monthly freeze-thaw frequencies among the three sites corresponding to those in Fig. 5. An effective freeze-thaw cycle is defined as a fall below −2°C on the rock surface followed by a rise above +2°C (MATSUOKA, 1990a). A number of effective freeze-thaw cycles occurred on these rockwalls, particularly from October to March. These frequencies are comparable to those in such mid-latitude alpine environments as Colorado Front Range (THORN, 1979), French Alps (COUTARD and FRANCOU, 1989) and Japanese Alps (MATSUOKA, 1990a), where freeze-thaw action is regarded as the predominant agent for rock breakdown. Nonetheless, our observation provided little evidence for intense frost weathering in the Sør Rondane Mountains. Rock fragments little accumulate under rockwalls, and little breakage of painted bedrock occurred during four years. Such inactivity in frost weathering can be explained in terms of low moisture content of the bedrock. Labo-

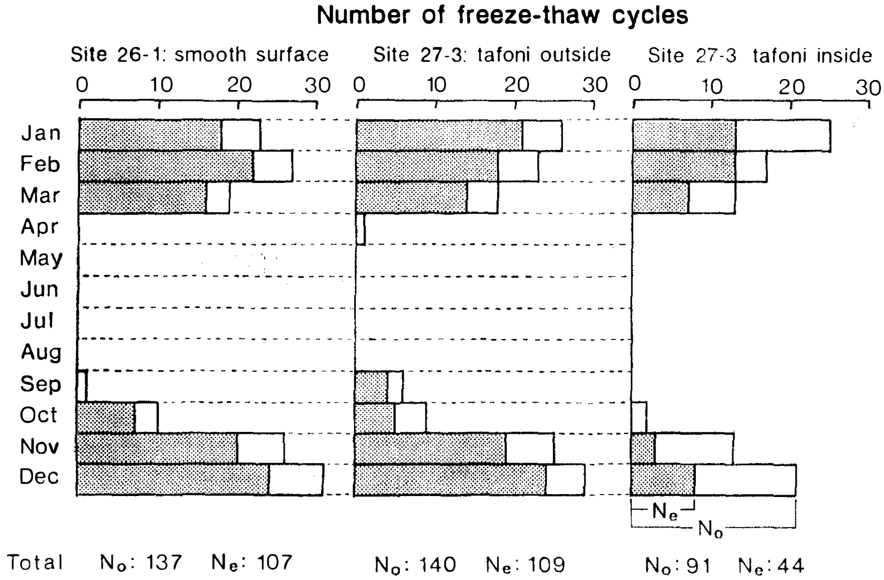


*Fig. 6. Monthly freeze-thaw frequency recorded on rock surfaces in 1986: $N_0$ is the number of cycles oscillating above and below 0°C; $N_e$ is the number of the effective freeze-thaw cycles defined in the text.*

*Table 2. Average moisture contents of rock samples collected from rockwalls.*

| Site | Aspect | Degree of saturation (%) | |
|---|---|---|---|
| | | January 1986 | January 1987 |
| 26–1 | NW | nd* | 37.2 (5**) |
| 27–1 | W | 32.7 (4) | 32.4 (6) |
| 27–3 | NE | 32.2 (6) | 37.2 (6) |

* No data.
** The number of samples.

ratory experiments showed that frost weathering becomes active when the degree of saturation in the rock is more than 75–80% (*e.g.* MATSUOKA, 1990b). A field measurement in Japan also revealed that high moisture content is responsible for intense frost weathering (MATSUOKA, 1990a). Bedrock moisture contents in the Sør Rondane Mountains, however, are quite low, usually less than 75% in the degree of saturation (Table 2). Frost weathering is regarded as inactive in this region unless both blowing snow and subsequent its melting provide high moisture to the rockwall.

## 5. Soil Temperature Regimes

Temperature profiles in soil layers on the east-facing debris slope at Site 27–3 (Fig. 7) exhibit similar annual variation to the rock surface temperature (see Fig. 4), *i.e.*, wide ranges and frequent freeze-thaw oscillation during the summer season. Diurnal freeze-thaw layers are often formed in December through February, whereas the soil is completely frozen during the remaining seasons (Table 3).

The active layer features, evaluated from temperature profiles in soil layers, however, are quite different among the sites (Fig. 8). Diurnal thaw depths are very shallow at Site 27-1 where snow provided by the strong katabatic wind prevents the ground from thaw penetration. The maximum thickness of the active layer is only 8 cm during the period of observation (Table 4). The number of freeze-thaw cycles is also very small at this site.

At Sites 27-2 and 27-3, by contrast, active layers appeared frequently, although their depths are quite different among the sites. The active layer is always deeper at Sites 27-2 and 27-3N (the north-facing slope at 27-3; point 2 in Fig. 2) than at Site 27-3E (the top of the east-facing slope at 27-3; point 3 in Fig. 2). The moisture content of active layers seems to control their depths: higher moisture content at Site 27-3E results in shallower active layers (Table 4). Frozen ground with high ice content, on thawing from the surface, releases a large amount of the latent heat. Active layers at Site 27-3E thus penetrate slowly into the frozen ground, usually exceeding not more than 20 cm in depth; whereas those at Sites 27-2 and 27-3N, containing little moisture (Table 4), penetrate more quickly and sometimes reach 30 cm in depth. Because many debris slopes and moraine fields in the Sør Rondane Mountains are in

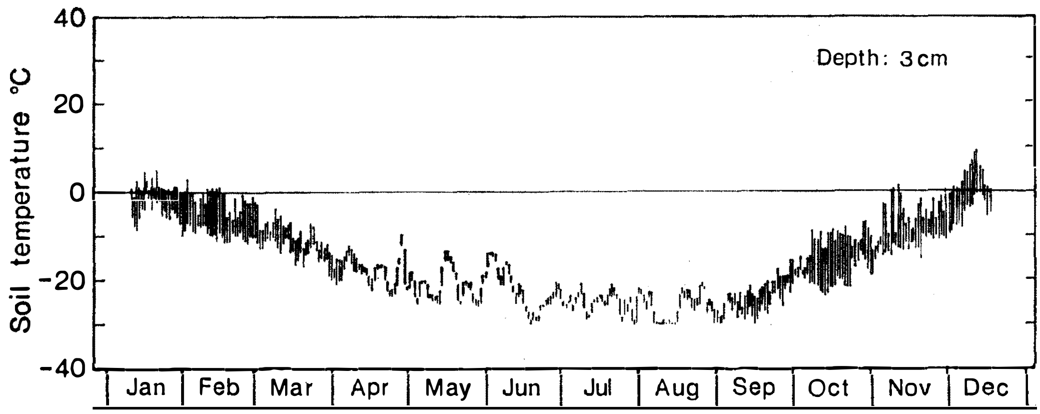


*Fig. 7. Annual fluctuation in soil temperature at Site 27-3E (the east-facing debris slope) in 1987. Daily ranges are shown with solid lines. Note that records are limited from +20 to −30°C.*

*Table 3. Monthly freeze-thaw frequencies observed at various depths in east-facing debris slope, Site 27-3E.*

| Depth (cm) | 1987 Jan. | Feb. | From Mar. to Oct. | Nov. | Dec. | Annual total |
|---|---|---|---|---|---|---|
| 3 | 19 | 12 | completely frozen | 3 | 16 | ≥50 |
| 8 | 13 | 1 | completely frozen | 0 | 8 | ≥22 |
| 15 | 1 | 0 | completely frozen | 0 | 3 | ≥4 |
| 30 | 0 | 0 | completely frozen | 0 | 0 | ≥0 |
| Days without data | 11 | 0 | 0 | 0 | 12 | 23 |

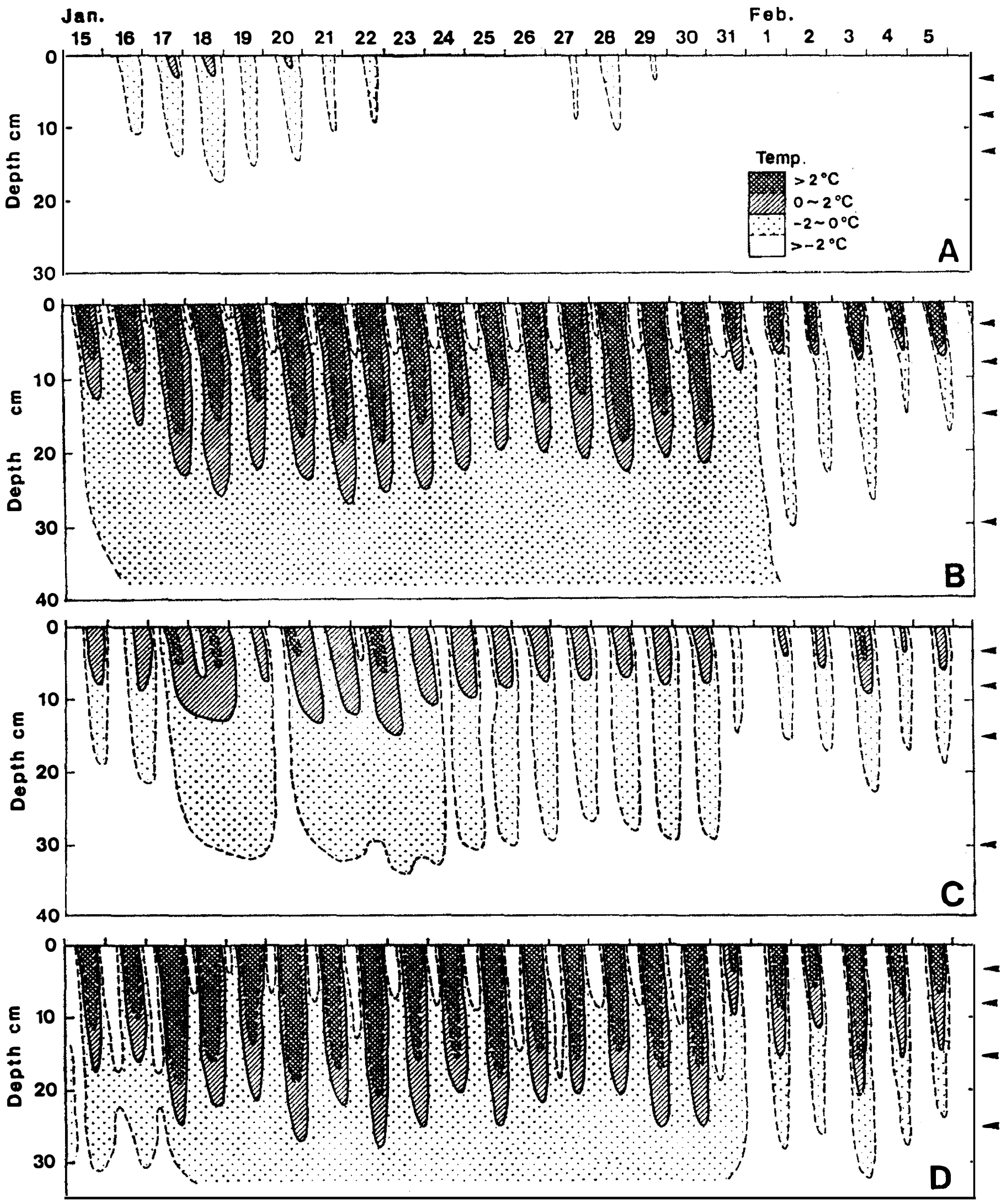


*Fig. 8. Subsurface isotherms during the midsummer of 1987. A: Site 27-1 (the east-facing debris slope), B: Site 27-2 (the flat moraine field), C: Site 27-3E (the east-facing debris slope), and D: Site 27-3N (the north-facing debris slope). The marks on the right margin indicate the positions of temperature probes.*

*Table 4. Active layer conditions.*

| Measurement site | Aspect | Annual maximum thaw depth (cm) | Water content (%) |
|---|---|---|---|
| 27-1 | E | 3-8 | nd* |
| 27-2 | flat | 25-30 | 1.7- 2.4 |
| 27-3 | E | 15-22 | 8.0-10.4 |
| 27-3 | N | 25-30 | 1.2- 1.8 |

* No data.

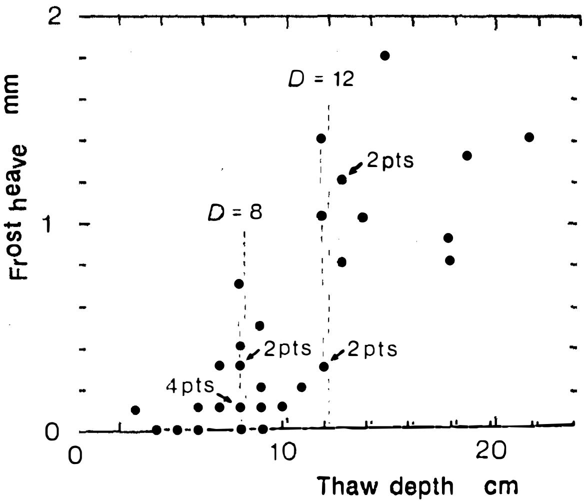


*Fig. 9. The amount of diurnal frost heave as a function of diurnal thaw depth D. The data were obtained from Site 27-3E during 15 January-6 February, 9-19 December 1987 and 1-9 January 1988.*

dry condition like the latter sites, 30 cm is likely the common value as the maximum depth of active layers.

The thaw depth, *D*, is an important control of frost action working on debris slopes with high moisture content. For example, MATSUOKA *et al.* (1988) showed that the value of *D* influences the amount of succeeding frost heave. Visible heave (more than 0.2 mm in height) occurs when *D* exceeds 8 cm; large heave (more than 1.0 mm) occurring when *D* exceeds 12 cm. Such frost heave activity was observed on the slope at Site 27–3E (see Fig. 2 and Photo 4) where *D* exceeeds 8 cm frequently during the summer season (Fig. 9). By contrast, frost heave is not likely to occur at Site 27–1 where the thaw depth never excceeds 8 cm. In spite of deep active layers, frost heave is probably inactive at Sites 27–2 and 27–3 either. This is due to low moisture contents in the active layers. The refreezing of such dry active layers must not be accompanied with ice segregation: hence, the ground is never heaved.

The thaw settlement of frost-heaved soil grains on a slope results in the downslope movement of these grains, referred to as frost creep (*e.g.* WASHBURN, 1979). This process may also occur on slopes with both high moisture and a deep active layer like Site 27–3E, although such places seem rather uncommon in the Sør Rondane Mountains. Frost action is hence believed to be the major geomorphic process only where both the moisture and the depth of active layer exceed certain critical values.

## 6. Summary

The number of freeze-thaw cycles during the summer season was estimated based on the spot measurements of rock surface temperature, and it is suggested that frost weathering is the major agent in the Sør Rondane Mountains. No distinctive rock breakdown, however, occurs under low water content in the bedrock. Frost weathering may hence work only on the rockwall being subject to abundant water supply through snow spray caused by wind.

Diurnal freeze-thaw layers up to 30 cm in depth are frequently formed on soil surfaces during the summer season. Frost heave and possibly frost creep occur on some windward slopes where snow spray and subsequent melting of the snow lead to high moisture content in the active layer. The amount of frost heave increases with the depth of active layer. Despite of thick active layers, however, low water content of the leeward slopes may result in minor activity of frost heave and creep. In the Sør Rondane Mountains, the activities of frost weathering and periglacial mass movements are therefore believed to be limited to the places where the moisture content and depth of active layer exceed certain critical values.

## Acknowledgments

We are indebted to Drs. M. ANIYA and M. HAYASHI and the other members of the Sør Rondane field parties of JARE-26 to -30, for their assistance and cooperation in the construction of measurement sites and the data collection.

### References

AYUKAWA, M. (1989): Dai-28-ji Nankyoku Chiiki Kansokutai Asuka Kansoku Kyoten ettô hôkoku 1987 (Activities of the First Wintering Party at Asuka Station by the 28th Japanese Antarctic Research Expedition in 1987). Nankyoku Shiryô (Antarct. Rec.), **33**, 234–268.

COUTARD, J. P. and FRANCOU, B. (1989): Rock temperature measurements in two alpine environments; Implications for frost shattering. Arct. Alp. Res., **21**, 399–416.

IWATA, S. (1987): Debris-mantled rectilinear slopes in the western Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 178–192.

KOJIMA, S. and SHIRAISHI, K. (1986): Note on the geology of the western part of the Sør Rondanc Mountains, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 116–131.

MATSUOKA, N. (1990a): The rate of bedrock weathering by frost action; Field measurements and a predictive model. Earth Surf. Processes Landforms, **15**, 73–90.

MATSUOKA, N. (1990b): Mechanisms of rock breakdown by frost action; An experimental approach. Cold Reg. Sci. Tech., **17**, 253–270.

MATSUOKA, N., MORIWAKI, K. and HIRAKAWA, K. (1988): Diurnal frost-heave activity in the Sør-Rondane Mountains, Antarctica. Arct. Alp. Res., **20**, 422–428.

SELBY, M. J. (1982): Hillslope Materials and Processes. Oxford, Oxford University Press, 264 p.

THORN, C. E. (1979): Bedrock freeze-thaw weathering regime in an alpine environment, Colorado Front Range. Earth Surf. Processes, **4**, 211–228.

WASHBURN, A. L. (1979): Geocryology; A Survey of Periglacial Processes and Environments. London, Edward Arnold, 406 p.

YAMANOUCHI, T., SHIBUYA, K. and SAKAI, R. (1988): Meteorological data at Asuka Camp, Antarctica in 1987. JARE Data Rep., **140** (Meteorology 21), 104 p.

*(Received March 6, 1990; Revised manuscript received April 20, 1990)*