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Investigating mountain permafrost distribution by ground temperature measurements in the Tateyama Mountains, the northern Japanese Alps, central Japan

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with 8 figures and 1 table

Summary. Field observations of ground temperatures and snow conditions were made in Kuranosuke Cirque and its surroundings in Tateyama Mountains, the northern Japanese Alps, which are snow covered (16 m in maximum thickness) for a large part of the year. Thermal parameters, the bottom temperature of snow and the mean annual ground surface temperature, as well as pit surveys, show that permafrost occurs on the north-facing slope of the cirque, where snow remains until late summer, while it is absent on the mountain crest, where snow disappears by early summer. Deep snow cover has generally been considered unfavorable for the development of permafrost. On the north-facing slope of the cirque, however, snow cover remaining until late summer prevents the percolation of warm rainwater that accelerates thawing of the frozen layer. Therefore, the deep snow cover plays a significant role in preserving permafrost in this environment.

1 *Introduction*

In Japan, mountain permafrost has been identified in three high mountain areas of Mt. Fuji (Higuchi & Fujii 1971), the Daisetsu Mountains, Hokkaido (Fukuda & Kinoshita 1974), and the Tateyama Mountains, the northern Japanese Alps (Fukui & Iwata 2000). Over the past two decades, a number of studies have examined permafrost in the Daisetsu Mountains. These studies concluded that snow cover is a major factor in determining the presence or absence of permafrost, and that permafrost is only present beneath wind-blown bare ground, where the winter frost can penetrate deeply (Sone et al. 1988, Ishikawa & Hirakawa 2000, Ishikawa & Sawagaki 2001). By contrast, there have been only a few studies of mountain permafrost in the northern Japanese Alps. Although mountain permafrost was found on an active protalus rampart, where much snow accumulates in winter (Fukui & Iwata 2000), little is known about the distribution and thermal regime of permafrost in this region.

The northern Japanese Alps have a unique climate. Northwesterly winds accompanying a winter monsoon cause a large amount of snow, which accumulates to depths of a few decameters on the leeside slopes of mountain crests, while the polar front causes a large amount

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of rain from June to mid-July (summer rainy season). Consequently, the distribution and thermal regime of permafrost in the northern Japanese Alps are likely to differ significantly from those in the Daisetsu Mountains and in other discontinuous and sporadic permafrost regions (e.g., SMITH 1975, KELLER & GUBLER 1993, HOELZLE et al. 1999, MITTAZ et al. 2000).

The aims of this study were (1) to find out the permafrost distribution by measuring the bottom temperature of snow (BTS), monitoring ground surface temperature, and by late autumn pit surveys, and (2) to clarify the near-surface ground thermal regime at a mountain crest, where the snow cover is thin, and at a protalus rampart, where much snow accumulates, by ground-temperature monitoring.

2 *Study area*

The Tateyama Mountains are located in the northern part of the northern Japanese Alps (Fig. 1). The highest peak is Mt. Onanji (3015 m ASL). Most of the cirques that were formed by Pleistocene glaciations (FUKAI 1974) are along the eastern side of the main Tateyama ridge. Field studies were undertaken in Kuranosuke Cirque (36°35′N, 137°37′E) and its surroundings (Fig. 1). The cirque floor terminates in a steep cliff at about 2500 m asl, which roughly corresponds to the forest limit, indicating the lower limit of the alpine zone. The cirque is divided into two lithological parts: the northern half consists of coarse-grained biotite granite, and the southern half of hornblende-biotite granodiorite and partly mylonitized tonalite (HARAYAMA et al. 2000). The cirque includes several periglacial landforms, such as an active protalus rampart (ONO & WATANABE 1986), a talus-derived rock glacier (the Kuranosuke rock glacier), and a perennial snow patch (Fig. 2). A fossil ice mass, which is 30 m in maximum thickness, was found in the lower part of the perennial snow patch (YAMAMOTO et al. 1986). Radiocarbon dating of plant remnants taken from dirty layers within the ice showed that the fossil ice was formed prior to 1700 years BP (YOSHIDA et al. 1990). The internal structure of the ice is similar to that of a cirque glacier.

Air temperature was monitored at Kuranosuke Hut (2786 m asl) from October 1997 until September 1998. The mean annual air temperature (MAAT) was –2.8°C (FUKUI & IWATA 2000). The Tateyama Mountains are characterized climatically by high snowfall and rainfall, and strong, predominantly westerly, winds during winter. Precipitation occurs mostly as snow between October and May. Snow accumulates to more than 16 m (WATANABE 1989) on the lee (eastern) side of the main Tateyama ridge as a result of snow-drift. By contrast, the snow is less than 1 m deep on the windward (western) slope. Summer precipitation (July–August) and snow depth (December–March) have been monitored at Murodo (2450 m asl), located on the windward side of the main Tateyama ridge (Fig. 1) by Tateyama-Kurobe Kanko Corporation. Total summer precipitation exceeds 1000 mm and maximum snow depth is 6–7 m in March or April. The water equivalent precipitation in winter exceeds 3000 mm.

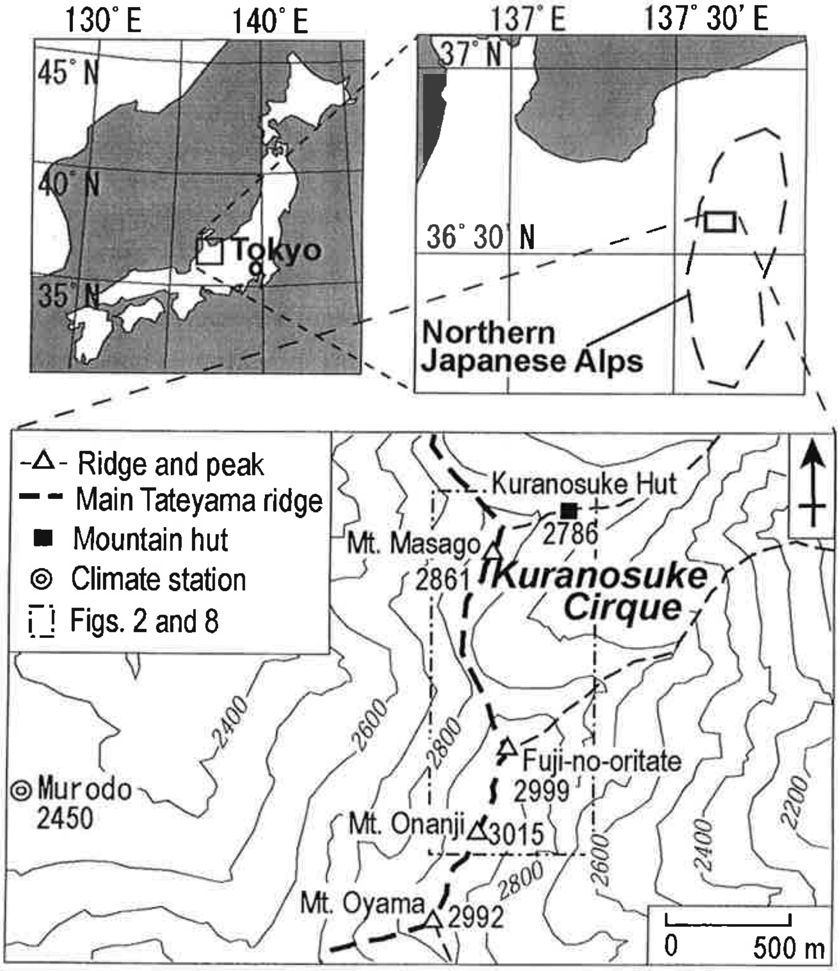

Fig. 1. Location of the study area.

3 *Methods*

3.1 *Ground temperature measurements*

BTS measurements allow us to map the distribution of permafrost in late winter or early spring (Haeberli 1973, Haeberli & Patzelt 1982, King 1986). If the snow thickness exceeds 80 cm and snowmelt has not started, the BTS is controlled mainly by the heat flux in the uppermost part of the ground. When permafrom is present, the BTS is less than –3 °C, but when permafrost is absent, the BTS exceeds –2°C (Haeberli 1973). Manual BTS measurements were made at 26 sites around the mountain crest between Kuranosuke Hut and Mt. Onanji on 28 April 2001 (Fig. 2a), using a thermocouple probe (ANRITSU Corp., HFT-50)

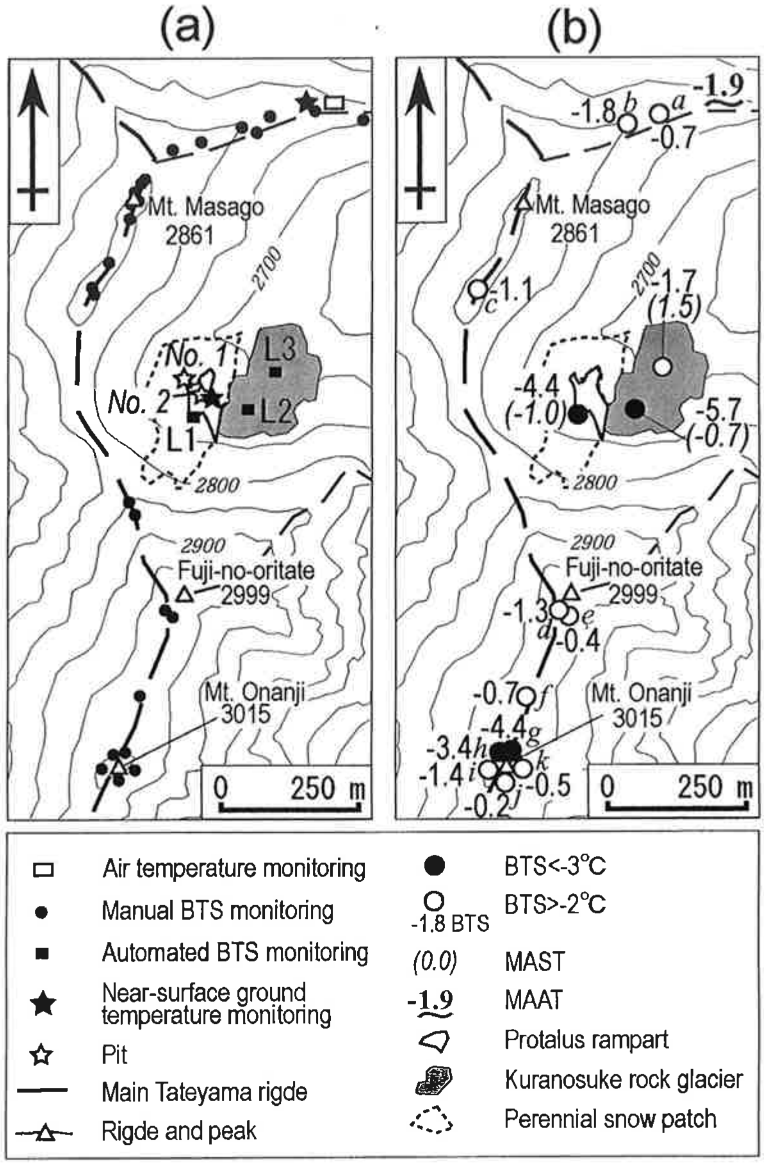

Fig. 2. Maps showing the spatial variation in BTS and MAST. (a) The locations of manual BTS measurements, miniature data loggers, and pits sites. (b) Spatial variation in BTS on 28 April 2001 and MAST. Air and ground temperatures were monitored with miniature data loggers from September 2000 to August 2001.

fixed to the bottom of a 4-m-long steel rod. The accuracy of the sensor was ±0.1°C. Wet and dry snows were distinguished by measuring snow temperatures at several depths in the hole made for the BTS measurement.

Three miniature data loggers (ONSET Corp., Optic-StowAway; accuracy ±0.3°C) recorded ground surface temperatures at 2-hour intervals in Kuranosuke Cirque from 4 September 2000 to 3 September 2001 (Fig. 2a). BTS and mean annual ground surface temperature (MAST) values were evaluated from the data.

Near-surface ground temperatures, soil water content, and precipitation were monitored from 4 June to 23 September 2001 on a mountain crest above Kuranosuke Cirque (Fig. 2a). Thermocouple sensors (accuracy ±0.1°C) were installed at depths of 0, 0.5, 0.8, 1.0, 1.5, and 1.8 m, and a TDR soil moisture sensor was installed at 0.2 m depth in the ground. A rain gauge was also installed near the monitoring site. All the sensors were connected to a data logger (Campbell Scientific Corp., CR-10X), which recorded data at 0.5-hour intervals.

Near-surface ground temperatures were also monitored from 1 June to 23 September 2001 at the protalus rampart. Thermistor sensors (accuracy ±0.1°C) were installed at depths of 0, 0.5, 1.0, 1.3, 1.6, and 2.2 m in pit no. 2 (Fig. 2a). All the sensors were connected to a data logger (KONA System Corp., KADEC US-6), which recorded temperatures at one-hour intervals.

3.2 *Additional measurements*

Pits were dug on 10 October 1999 (pit no. 1) and 6 October 2000 (pit no. 2) at the protalus rampart (Fig. 2a) to examine the internal structure and thermal conditions. The pits were 1.5 m and 2.2 m deep, respectively. Ground temperatures were measured with a platinum resistance thermometer (CUSTOM Corp., CT500P) at several depths in the pits just after the excavation. The accuracy of the thermometer was ±0.1°C.

Snow-covered and snow-free areas in Kuranosuke Cirque and its surroundings were mapped monthly from 28 April to 7 October 2001 by visual observations using the topographic maps at 1: 12500 and photography. Snow-covered periods at the protalus rampart and rock glacier were estimated using the miniature data logger data (Fig. 3) and changes in snow depth at Murodo (Fig. 4).

Air temperature was monitored at Kuranosuke Hut from 4 September 2000 to 3 September 2001 (Fig. 2a). A miniature data logger (ONSET Corp., StowAway; accuracy ±0.3°C) recorded air temperatures at 2-hour intervals.

4 *Results*

4.1 *Air and ground temperatures*

Snow depth at the manual BTS sites was 1.2–2.4 m (Table 1). Snow temperatures were negative (< 0°C) at 11 of 26 manual BTS measurement sites on 28 April 2001, which shows that the snowmelt had not yet started at these sites. Snow surface temperatures had already reached the melting point at the other sites. Most of the BTS values were above –2°C on the mountain crest (Fig. 2b). BTS below –3°C occurred at only two sites on the north-facing rock wall of Mt. Onanji.

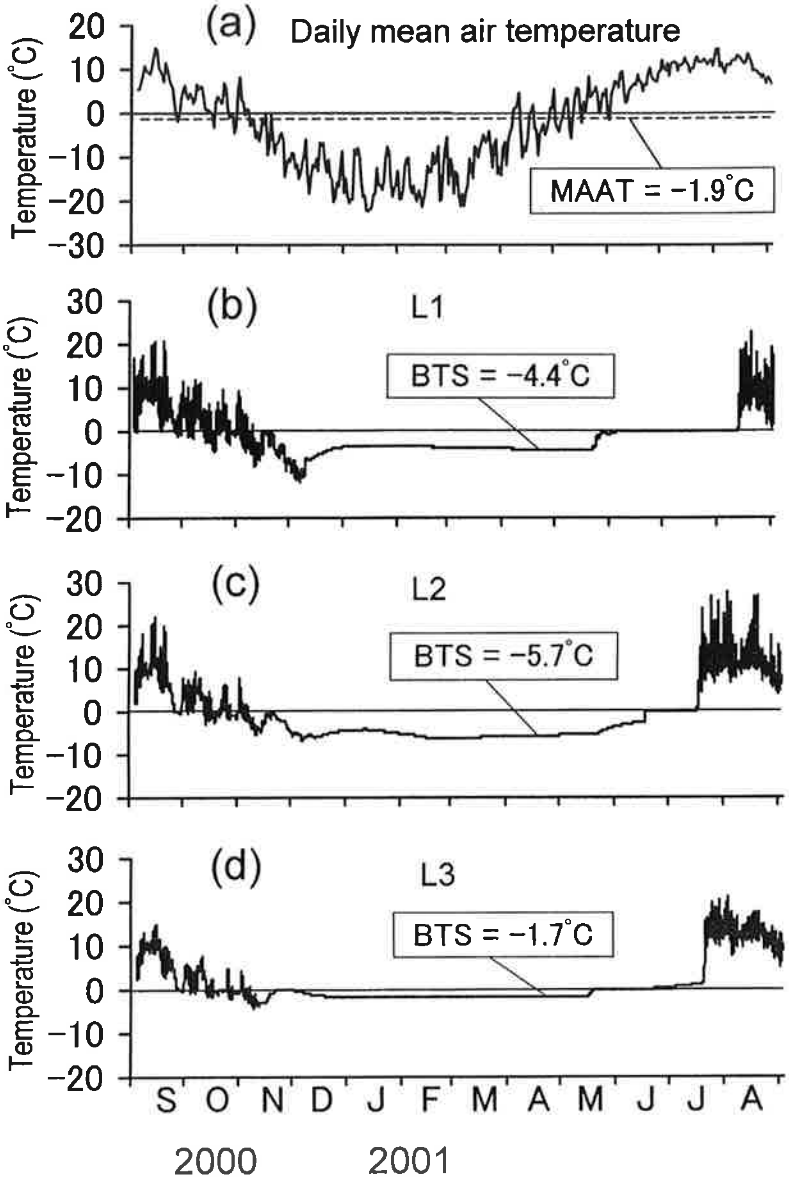

Fig. 3. Annual variations in air temperature (a) and ground surface temperature (b–d) from 4 September 2000 to 3 September 2001. Locations : (a) Kuranosuke Hut (2786 m asl); (b) Protalus rampart; (c) Upper part of the rock glacier; (d) Lower part of the rock glacier. See Fig. 2 for the locations.

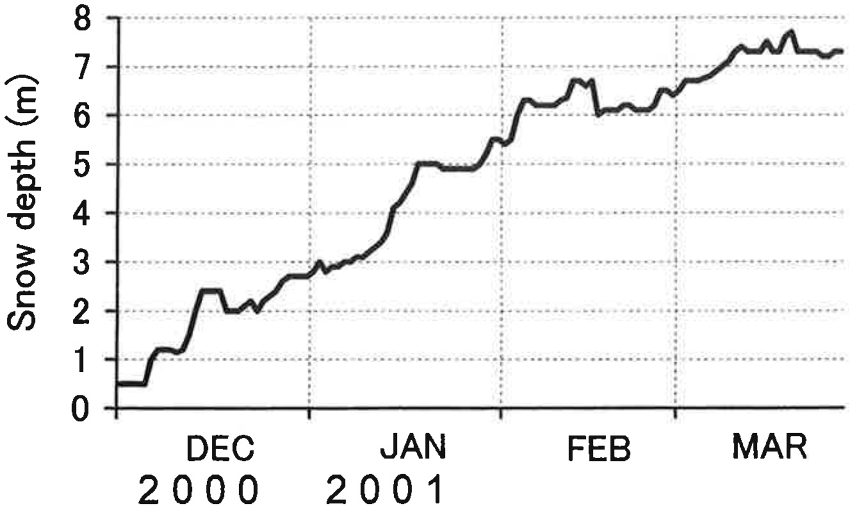

Fig. 4. Changes in snow depth from 1 December 2000 to 27 March 2001 at Murodo (2450 m asl). Observations were carried out by the Tateyama-Kurobe Corporation. See Fig. 1 for the location.

Table 1. Results of BTS measurements on 28 April 2001. See Fig. 2b for the locations.

Site	Slope aspect	Snow depth (m)	BTS value (°C)
a	NE	1.8	–0.7
b	NE	2.4	–1.8
c	–	1.2	–1.1
d	–	2.4	–1.3
e	–	2.1	–0.4
f	–	1.6	–0.7
g	N	1.2	–4.4
h	NW	1.4	–3.4
i	W	2.0	–1.4
j	S	1.5	–0.2
k	E	2.0	–0.5
L1	N	>3.0	–4.4
L2	N	>3.0	–5.7
L3	–	>3.0	–1.7

Data at L1–L3 sites derived from miniature data loggers.

The miniature data loggers indicated that seasonal freezing started at the protalus rampart and rock glacier at the end of September in response to dropping air temperatures (Fig. 3). The negligible diurnal temperature fluctuations suggested that seasonal snow cover was present during the period between early-December and mid-August on the protalus ram-

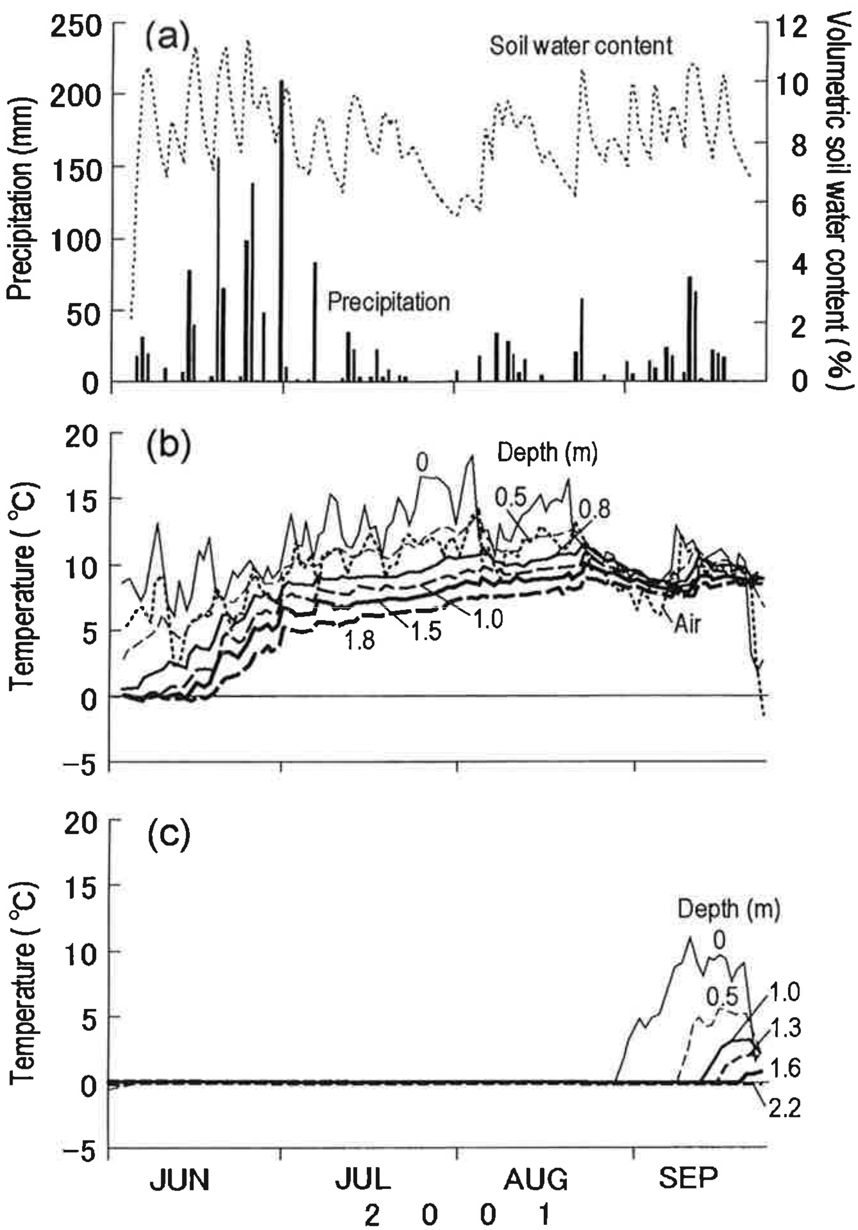

Fig. 5. Seasonal variations in air and ground temperatures, precipitation, and soil water content. (a) Daily precipitation and mean daily soil water content at the mountain crest. (b) Mean daily air and ground temperatures at the mountain crest. (c) Mean daily ground temperatures at the protalus rampart. See Fig. 2 for the locations.

part and between late-November and mid-July on the rock glacier (Fig. 3). This was supported by changes in snow depth, which rapidly increased after mid-December and reached 7.5 m in mid-March at Murodo (Fig. 4). On 28 April 2001, BTS values were below –3°C on the protalus rampart (Fig. 3b) and the upper part of Kuranosuke rock glacier (Fig. 3c), while they were above –2°C on the lower part of the rock glacier (Fig. 3d). MASTs were calculated to be –1.0, –0.7, and 1.5°C, respectively. MAAT at the Kuranosuke Hut was calculated to be –1.9°C (Figs. 2b & 3a).

Heavy rainfall (daily precipitation over 50 mm) occurred several times during the summer rainy season (Fig. 5a). The monthly precipitation in June was 930 mm. Ground temperatures at the mountain crest rose rapidly in response to increasing soil water content immediately after each rainfall event (Figs. 5a & 5b). Ground temperatures at the mountain crest rose most rapidly in June. At the protalus rampart, ground temperatures remained at about 0°C from June until the end of August (Figs. 3b & 5c).

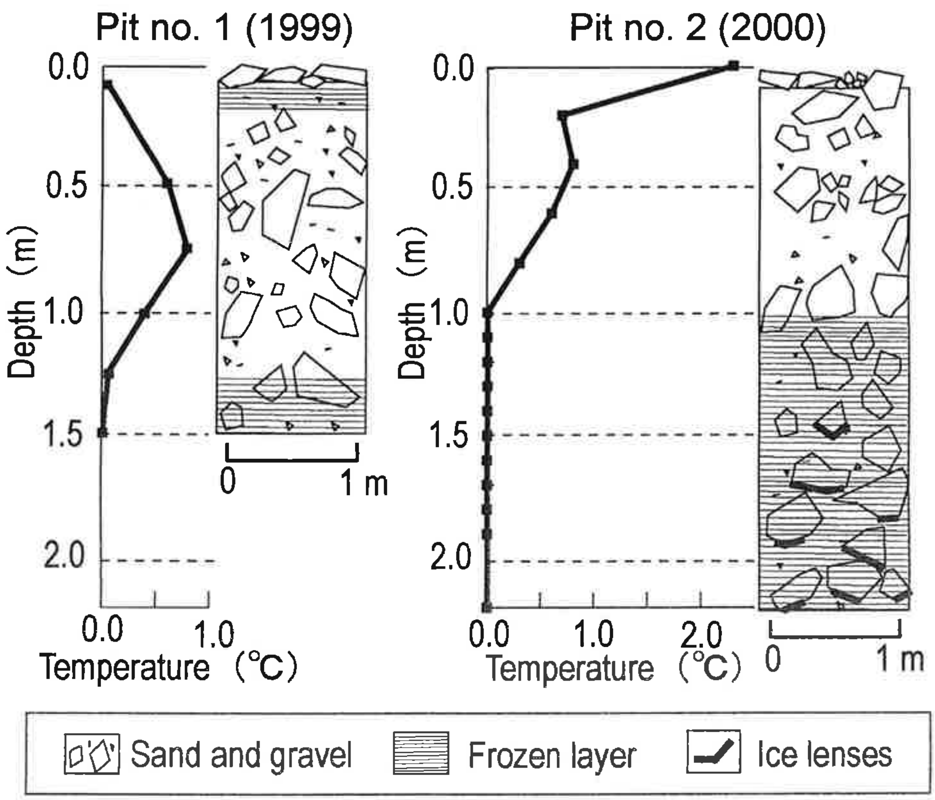

Fig. 6. Structures and late-autumn thermal conditions in the protalus rampart. See Fig. 2 for the locations. Pits no. 1 and no. 2 were excavated on 10 October 1999 and 6 October 2000, respectively.

4.2 *Ground frost and snow conditions*

The frost table was encountered at 1.3 m depth in pit no. 1 (1999) and at 1.0 m depth in pit no. 2 (2000) (Fig. 6). Thin ice lenses (< 1 cm) were observed under boulders between 1.5 and 2.2 m deep in pit no. 2. The ground temperature reached 0 °C at 1.5 m depth in pit no. 1 and at 1.0 m depth in pit no. 2.

Most of the study area was covered with snow on 28 April 2001, except for the windward (western) slopes of the main ridge (Figs. 7a & 8). By 3 June 2001, all of the manual BTS sites were exposed. The lower and upper parts of the rock glacier, and the protalus rampart were exposed by 1 July, 5 August, and 7 September 2001, respectively (Figs. 7 & 8). These observations were consistent with the miniature data logger data.

5 *Discussion*

5.1 *Permafrost distribution in relation to changes in snow-covered area*

BTS values lower than –3°C occurred on the protalus rampart, the upper part of the rock glacier, and the north-facing rock wall of Mt. Onanji. These values belong to the category "permafrost probable" (e.g., HAEBERLI 1973, KING et al. 1992). Moreover, MAST values were negative on the protalus rampart and the upper part of the rock glacier. These thermal parameters indicate that permafrost is present in the protalus rampart and upper part of the rock glacier, where snow cover remains until August or September. The low BTS values also indicate the presence of permafrost in the north-facing rockwall of Mt. Onanji. By contrast almost all the BTS values were above –2°C on the mountain crest, which belonged to the category "no permafrost". Therefore, permafrost is unlikely on the mountain crest, where snow disappears by June.

The excavations in early October showed a frozen layer beneath the protalus rampart. The year-round ground surface temperature measurements showed that seasonal freezing started at the end of September at the protalus rampart (Fig. 3b), suggesting that the observed frozen layer was unlikely to melt completely before the next year. Consequently, the frozen layer is regarded as permafrost. The active layer thickness is thought to have been about 1.3 m in pit no. 1 (1999) and 1.0 m in pit no. 2 (2000).

These observations suggest that the Tateyama Mountains are distinguished from other cold regions in terms of the controlling factors on permafrost distribution. Mountain permafrost in the Daisetsu Mountains is present mainly on wind-blown bare ground (SONE et al. 1988, ISHIKAWA & HIRAKAWA 2000, ISHIKAWA & SAWAGAKI 2001). Many studies of the mountain permafrost distribution in the Swiss Alps have shown that mountain permafrost is present under active and inactive rock glaciers, and on northeast- to west-facing slopes, hilltops, and wind blown crests (HAEBERLI 1978, HOELZLE 1992, KELLER 1992, HOELZLE et al. 1999, IMHOF et al. 2000). SMITH (1975) reported that snow cover is a permafrost-controlling factor in the Mackenzie Delta; where the accumulations are greatest, a talik forms due to the insulating effect of deep snow. In the Tateyama Mountains, by contrast, permafrost is distributed mainly in the lee slope, where much snow accumulates.

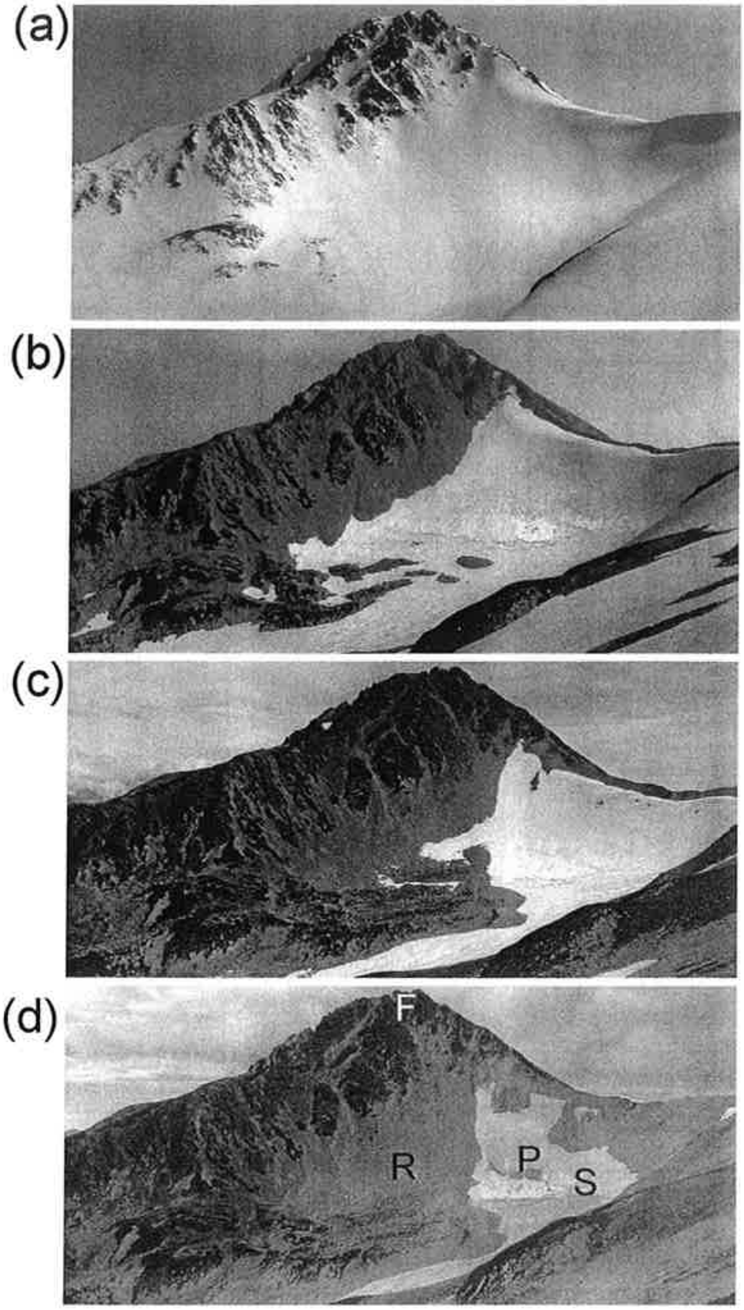

Fig. 7. Seasonal change in snow condition in Kuranosuke Cirque, seen from the north. (a) 28 April 2001. (b) 1 July 2001. (c) 5 August 2001. (d) 7 September 2001. R: Kuranosuke rock glacier; P: the protalus rampart; S: the perennial snow patch; F: Fuji-no-oritate.

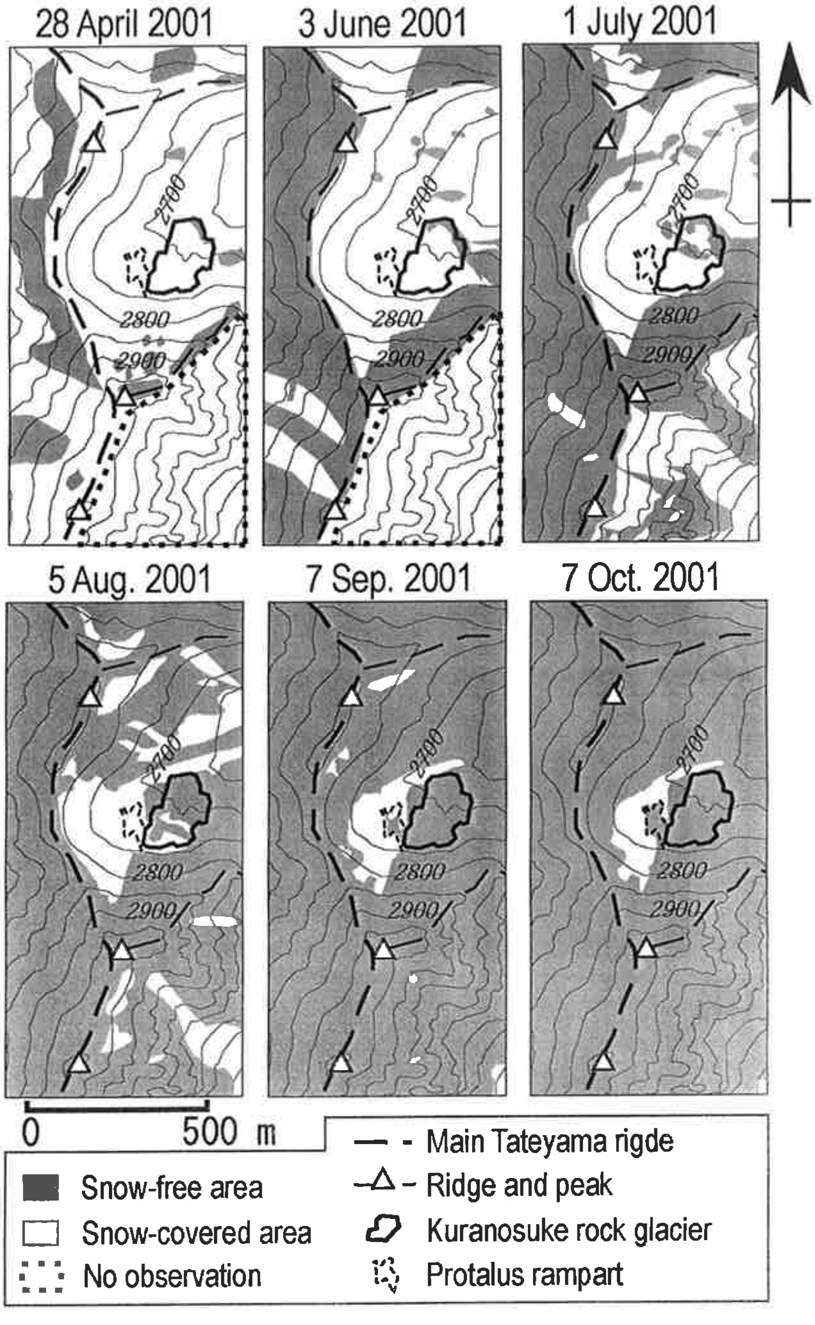

Fig. 8. Changes in snow-covered areas in Kuranosuke Cirque and its surroundings. Snow-covered areas were mapped by visual observations using the topographic maps at 1: 12500 and photography.

5.2 *Effects of deep snow cover and warm rain on the preservation of permafrost*

Deep snow cover in winter is generally considered to be unfavorable for the development of permafrost (e.g., SMITH 1975). However, GOODRICH (1982) and ZHANG et al. (2001) pointed out that the onset of late snow cover in winter is important for permafrost formation based on numerical simulations. For instance, at a site with MAST of 0°C and annual amplitude of 20°C, permafrost survives when snow cover starts after the middle of December, even when the maximum snow thickness exceeds 1.0 m (ZHANG et al. 2001). In the Tateyama Mountains, ground freezing started in late-September while seasonal snow cover was established in late-November or December. This time lag between the onset of seasonal freezing and snow cover probably favors permafrost formation.

GOODRICH (1982) pointed out that the effect of snow cover on summer thaw depth, although small, is not entirely negligible. In the Tateyama Mountains, the deep snow cover significantly affects ground thawing in summer. Snow cover disappeared on the mountain crest by early June. Ground temperatures at the mountain crest rose rapidly following heavy rainfall in the summer rainy season. HINKEL et al. (1993) suggested that heavy rainfall induces rapid saturation of the active layer, significantly increasing the enthalpy. Therefore, heat transport by the percolation of warm rainwater is one of the most important factors in melting of the frozen layer. Snow cover remained on the protalus rampart until the end of August. As a result, the ground temperature was maintained at about 0°C until the end of August. Thus, the snow cover protects the subsurface frozen layer from the percolation of warm rainwater, making the protalus rampart a favorable site for the preservation of permafrost.

6 *Conclusions*

1) BTS, MAST, and pit surveys showed that permafrost is present in the protalus rampart and upper part of the Kuranosuke rock glacier, where snow remains until August or September, while it is absent on the mountain crest, where snow disappears by June.
2) The onset of seasonal snow cover lags behind that of ground freezing for about two months, which allows deep freezing in winter. In addition, the snow cover remaining until late summer prevents the percolation of warm rainwater that otherwise accelerates melting of the frozen layer. Accordingly, deep snow cover favors the preservation of permafrost.

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