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Permafrost and surface movement of an active protalus rampart in the Kuranosuke Cirque, the Northern Japanese Alps

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ABSTRACT: A pit survey, near-surface ground temperature monitoring, DC resistivity tomography and an eighteen-year interval survey elucidate the internal structure and the recent movement of an active protalus rampart in the Kuranosuke Cirque, the northern Japanese Alps. Permafrost was found beneath the lower part of the protalus rampart using ground temperature monitoring and DC resistivity tomography. Results of DC resistivity tomography suggest that the materials of the protalus rampart are at least 15 m in thickness. Displacements of four targets for triangulation surveys on the lower part of the protalus rampart gave mean horizontal rates of 0.24–0.7 cm a^{-1} between 1983 and 2001. These displacements probably occurred by permafrost creep and/or deformation in the lower part of the active layer.

1 INTRODUCTION

A protalus rampart is a ridge or ramp of debris that develops along the lower margin of a perennial snow patch. Early studies of protalus ramparts assumed that they were formed simply through the accumulation of rock-fall debris rolling and sliding on the surface of a perennial snow patch (Bryan 1934, French 1976, Washburn 1979). Recently, Shakesby (1997) has noted that there are two opposing views on protalus rampart formation. One view suggests that protalus ramparts are part of a linear developmental continuum of rock glaciers. Thus, formation of a protalus rampart is thought to be due to permafrost creep (Haeberli 1985, Ballantyne & Benn 1994, Barsh 1996). The other view envisages a protalus rampart as part of a non-developmental morphological continuum of rock glaciers (White 1981, Shakesby et al. 1987).

There is an active protalus rampart in the Kuranosuke Cirque, in the northern Japanese Alps. Ono & Watanabe (1986) concluded that debris flows, of the order of $10^3 m^3$, and a landslide were the likely origins of the protalus rampart. This concslusion is derived from the latter view. However, Fukui & Iwata (2000) identified permafrost beneath the lower margin of the protalus rampart. This implies that protalus rampart formation is related to permafrost creep.

The objective of this paper was to clarify the movement and permafrost distribution of the protalus rampart in the Kuranosuke Cirque in order to discuss the process of protalus rampart formation. A pit survey, near-surface ground-temperature monitoring, DC-resistivity tomography and an eighteen-year geodetic survey were carried out.

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). Kuranosuke Cirque (36°35′N, 137°37′E) is located on the eastern side of main Tateyama ridge (Fig. 1). The cirque was formed by Pleistocene glaciations (Fukai 1974). The cirque floor terminates in a steep cliff at about 2500 m

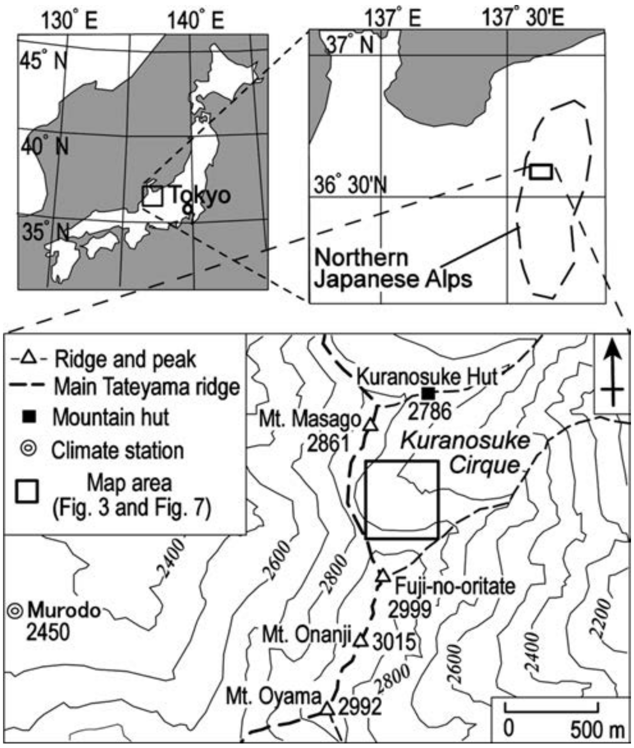

Figure 1. Study area.

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 tonalite, which is partly mylonitized (Harayama et al. 2000). The cirque includes several periglacial landforms, including 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 firn 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 at least 1700 BP (Yoshida et al. 1990). The internal structure of the ice is similar to that of a cirque glacier (Yamamoto & Yoshida 1987). The protalus rampart is located in the central part of the perennial snow patch. The protalus rampart is about 50 m wide and 100 m long and stretches from South to North. The surface layer of the protalus rampart consists of openwork clasts, while subsurface layer consists of clasts with much fine sandy matrix. The ground surface is completely vegetation free.

The 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 climatically characterised 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 Corp. Summer precipitation exceeds 1000 mm and maximum snow height is 6–7 m in March or April. Winter precipitation calculated from the water equivalent of snow exceeds 3000 mm.

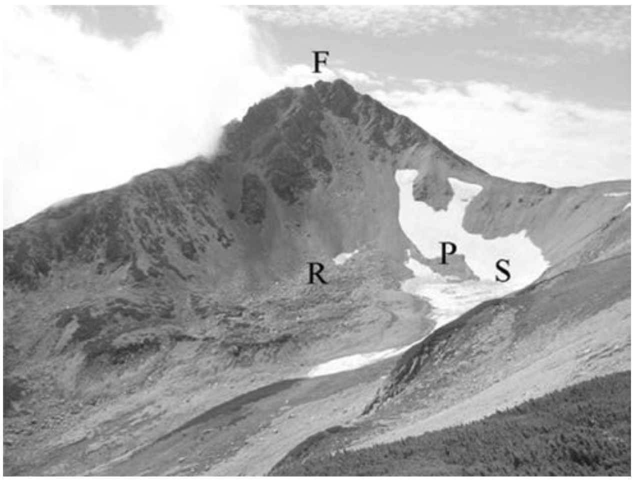

Figure 2. Kuranosuke Cirque looking from the north on 15 September 2002. R: Kuranosuke rock glacier; P: the protalus rampart; S: the perennial snow patch; F: Fuji-no-oritate (2999 m).

3 METHODS

A pit was dug in the central part of the protalus rampart (Fig. 3) on 6 October 2000, in order to examine its internal structure and thermal conditions. The pit was 2.2 m deep. Ground temperatures were measured at several depths in the pits, just after excavation, with a platinum resistance thermometer (CUSTOM Corp., CT500P). The accuracy of the thermometer was ±0.1°C. Grain size was measured at depths of 1.0, 1.3, 1.6, and 1.9 m.

Near-surface ground temperatures at the pit were monitored from 7 October 2000 to 5 October 2001. Thermistor sensors (accuracy ±0.1°C) were installed at depths of 0, 0.5, 1.0, 1.3, 1.6, and 2.2 m. All sensors were connected to a data-logger (KONA System Corp.,

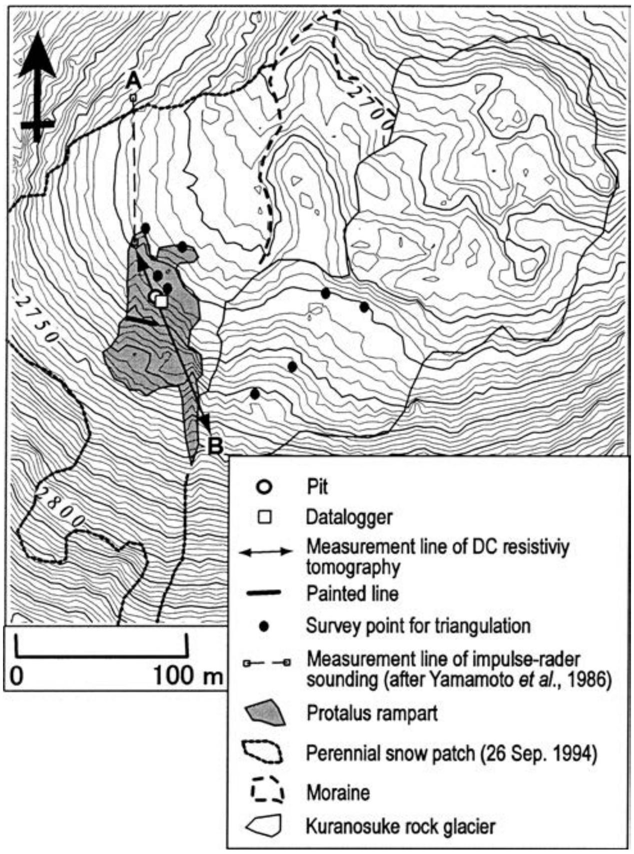

Figure 3. Landforms and locations of the different research techniques used in the study. The contour interval is 2 m.

KADEC US-6) that recorded temperatures at one-hour intervals.

DC-resistivity tomography was carried out at the protalus rampart in early October 2000 (Fig. 3). Thirty electrodes were set up, with 3 m spacing. A Wenner-Schlumberger configuration was used for the electrode layout. SYSCAL JUNIOR (manufactured by IRIS Crop.), multi-core cables, and a remote control multiplexer were used. A two-dimensional model interpretation was performed using RES2DINV (version 3.4) software (Loke & Barker 1996).

The positions of 4 survey points on the protalus rampart, and 4 survey points on the upper part of the Kuranosuke rock glacier, were established by triangulation with a Wild T2 theodolite in September 1983.

Boulders with an *a*-axis ranging from 1 m to over 2 m were marked with paint to serve as survey points. Repeated surveys were performed in October 2001 with a TM20HS (Sokkisha Corp.) theodolite. The estimated residual error in this survey is in the range of a few centimeters, at most.

4 RESULTS

The surface layer (up to 10 cm in depth) consisted of openwork angular cobbles and pebbles, while the subsurface layer consisted of non-sorted angular cobbles and pebbles with considerable sandy matrix (Fig. 4a). The grains of the subsurface layer contained 85. sand and 15. silt and clay (Fig. 4b). This indicates that the subsurface layer had low frost-susceptibility. The frost table was encountered at 1.0 m, and the ground temperature reached 0°C at a depth of 1.0 m in the pit (Fig. 4a). Thin ice lenses ($<$1 cm) were observed under boulders in the pit, at a depth of between 1.5 and 2.2 m. However, ice content seemed to be very low in the frozen layer.

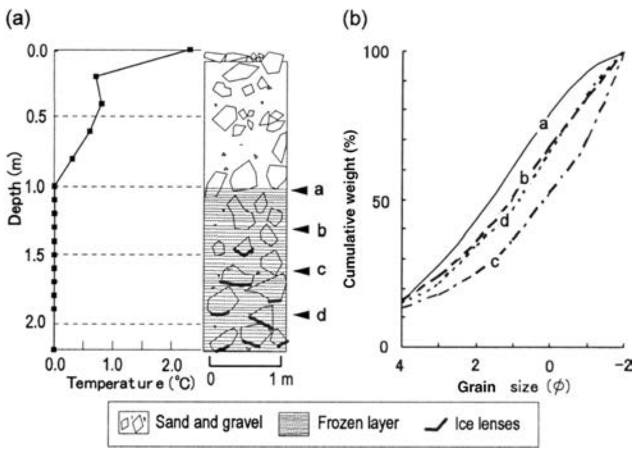

Figure 4. Stratigraphy, ground temperature and grain size distribution in the pit on 6 October 2000. Refer to Figure 3 for location.

The data-logger indicated that at a depth of 2.2 m, ground temperatures were below 0°C over the observation period (Fig. 5b).

Seasonal freezing, which started at the ground surface on 4 November 2000, exceeded 1.6 m in depth on 9 November 2000 (Fig. 5b). Seasonal snow-cover was indicated by negligible diurnal temperature fluctuations at the ground surface during the period between mid-November 2000 and late-August 2001 (Fig. 5a). Ground temperatures at all depths had dropped gradually from late-December to late-May. In late-May 2001, temperatures at the ground surface and at a depth of 2.2 m were -2.1°C and -0.4°C, respectively. Ground thawing began at the ground surface in late August 2001, and reached 1.6 m in depth by mid-September 2001.

Figure 6 shows the inverted resistivity tomogram across the protalus rampart. A high-resistivity zone

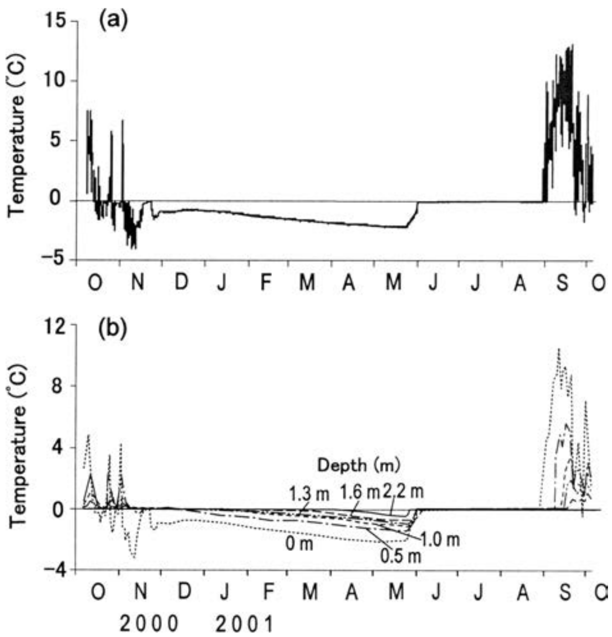

Figure 5. Seasonal changes in ground temperatures from October 2000 to October 2001 at the pit. (a) Daily range in ground surface temperature. (b) Mean daily ground temperatures.

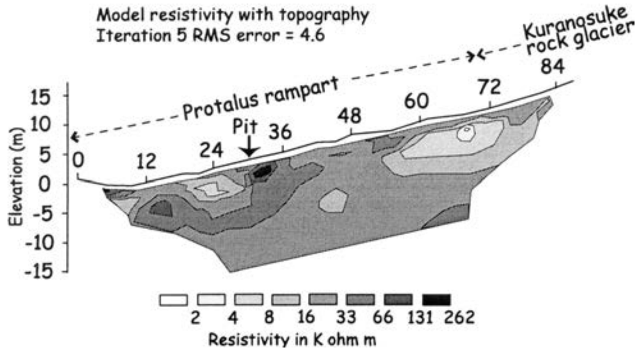

Figure 6. DC resistivity pseudosection across the protalus rampart. Refer to Figure 3 for location.

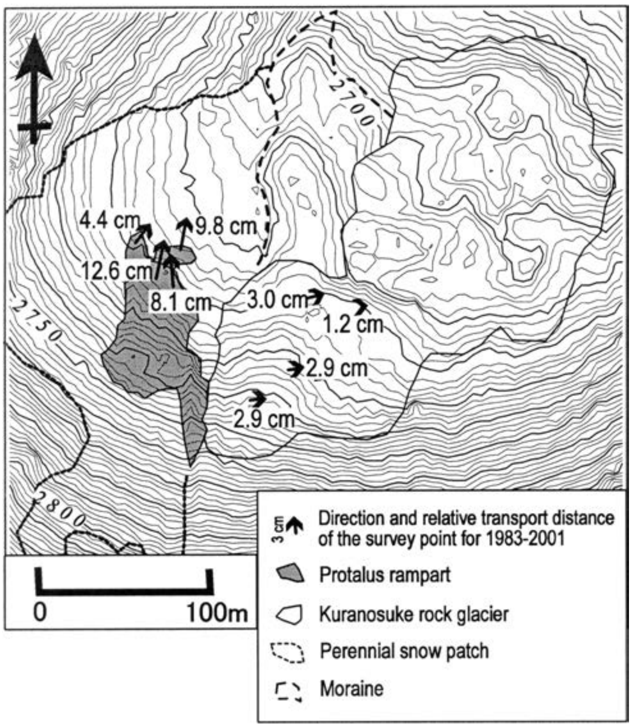

Figure 7. Direction and relative transport distance of the survey points, between 1983 and 2001.

(33–262 K Ωm) was found beneath the lower part of the protalus rampart. This zone reached about 10 m in thickness just beneath the pit. By contrast, a low-resistivity zone (below 8K Ωm) was found in the boundary region between the protalus rampart and Kuranosuke rock glacier.

Boulders on the surface of the protalus rampart showed marked movement to the north over the observation period (1983–2001) (Fig. 7). The direction of movement approximately followed the down-slope trend of the protalus rampart. Total horizontal vector displacements for survey points on the protalus rampart ranged between 4.4 and 12.6 cm (0.24–0.7 cm a^{-1}). By contrast, boulders on the surface of the rock glacier showed negligible movement over the observation period. Total horizontal displacement for survey points ranged between only 1.2–3 cm.

5 DISCUSSION

The excavation on 6 October 2000 revealed a frozen layer beneath the protalus rampart. The near-surface ground-temperature measurements showed that the frozen layer did not melt completely from one year to the next. Consequently, the frozen layer is regarded as permafrost. The thickness of the active layer is thought to have been 1.6–2.2 m.

A zone of high resistivity (over 33K Ωm) was found beneath the lower part of the protalus rampart. In

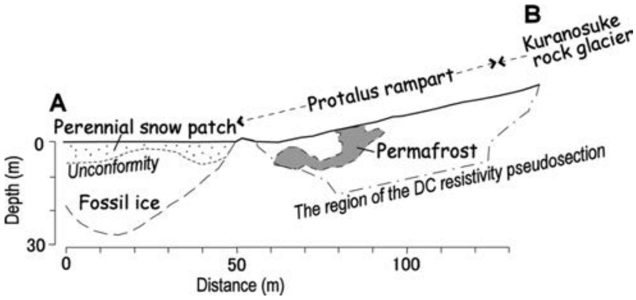

Figure 8. Schematic section of the protalus rampart and the perennial snow patch, based on the DC resistivity pseudosection and the results of impulse-radar soundings (Yamamoto et al. 1986). Refer to Figure 3 for location.

general, resistivity values for frozen materials are considerably higher than those of unfrozen materials (Hoekstra & McNeill, 1973). The range in DC resistivity of perennial frozen sand and silt is 10–100K Ωm (Haeberli & Vonder Mühll 1996). Moreover, a high-resistivity zone was identified beneath the pit site. Judging from this evidence, the high-resistivity zone was regarded as permafrost. The thickness of the permafrost was estimated about 10 m. The bottom of the protalus rampart was not found out in this DC resistivity pseudosection.

Between 1983 and 2001, horizontal displacement of the survey points ranged from 0.24 to 0.7 cm a^{-1}. Two alternative hypotheses may explain the displacement. One is that displacement was due to frost creep in the lower part of the active layer; however, this is unlikely, because the active layer was composed mainly of materials of low frost-susceptibility. The second hypothesis is that the displacement was due to permafrost creep. Savigny & Morgenstern (1986) investigated the creep of perennially frozen sand and silt in the Canadian Arctic through investigations of borehole deformation, using a borehole inclinometer system. In their investigation, permafrost creep was observed from just beneath the active layer (a few decimetres in depth) to the bottom of the borehole (20–40 m in depth). Creep velocity ranged from 0.2 to 0.3 cm a^{-1}. In this study, the estimated thickness of permafrost in the protalus rampart, based on the DC-resistivity pseudosection, was up to 10 m. The thickness of this permafrost is sufficient for permafrost creep to occur. Therefore, there is a high probability that the displacement of survey points was due to permafrost creep.

Figure 8 shows a schematic section of the protalus rampart and the perennial snow patch, based on the DC-resistivity pseudosection in this study and the results of impulse-radar soundings (Yamamoto et al. 1986). The thickness of the protalus rampart is over 15 m. The total volume of the protalus rampart is calculated as at least 75000 m^3. Judging from this, the primary origin of the protalus rampart was probably catastrophic landslide, since the present debris supply to the protalus rampart was very limited (Watanabe 1985) and there is a landslide scar on the cirque wall (Ono & Watanabe 1986). It is believed, therefore, that the protalus rampart was formed from catastrophic landslide and then modified by permafrost creep.

6 CONCLUSIONS

1. The results of the pit survey in autumn, year-round near-surface ground-temperature monitoring, and DC-resistivity tomography show that permafrost is present beneath the lower part of the protalus rampart. The permafrost just beneath the pit was 10 m thick.
2. Between 1983 and 2001, horizontal displacement of the survey points on the protalus rampart ranged from 0.24–0.7 $cm\,a^{-1}$. Since the estimated permafrost thickness, based on DC-resistivity tomography, is sufficient to cause permafrost creep, displacement of the survey points was probably due to permafrost creep and/or deformation of the active layer.
3. The total volume of the protalus rampart is calculated as at least 75000 m^3. Judging from this, the primary origin of the protalus rampart was probably catastrophic landslide, since the present debris supply to the protalus rampart was very limited and there is a landslide scar on the cirque wall. It is likely that the protalus rampart was formed from catastrophic landslide and then modified by permafrost creep.

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