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The Permafrost Environment of the Daisetsu Mountains, Central Hokkaido, Northern Japan

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Abstract

In the course of writing this paper the physical environment of the Daisetsu Mountains, that is related to the development of alpine permafrost and periglacial landforms, is described. The climatic environment of the Daisetsu Mountains is elucidated on the basis of long-term meteorological observations from 1985 to 1986. Taking the air temperature condition and the pattern of the winter snow distribution into consideration, the distribution of permafrost in the Daisetsu Mountains is discussed. Then, the characteristics of the permafrost environment and the possibility of occurrence of periglacial landforms in the Daisetsu Mountains are discussed in relation to freezing and thawing indexes. Consequently, the active existence of permafrost and periglacial landforms such as palsas and frost crack polygons can be explained by the present climatic environment of the Daisetsu Mountains.

Key Words: alpine permafrost, periglacial landforms, freezing and thawing indexes, the Daisetsu Mountains,

I Introduction

I－1 Significance and Purpose of the Study

Permafrost is defined as the thermal condition of the ground which remains at or below 0 ℃ for at least two years (Washburn, 1979). The author defines the permafrost environment as the climatic and physical environment in which both permafrost and typical periglacial processes occur.

Present permafrost regions in the middle latitude are restricted to alpine permafrost regions. In Japan, the existence of alpine permafrost was reported only in Mt. Fuji and the Daisetsu Mountains (Higuchi and Fujii, 1971 ; Fukuda and Kinoshita, 1974). However, only a few investigations were attempted as for the permafrost environment in the Daisetsu Mountains. Therefore, the relationship between the present climate and the occurrence of permafrost and related periglacial processes, were not elucidated, and the distribution of the alpine permafrost in the Daisetsu Mountains was also not studied.

It is considered that permafrost occurred in northeastern Hokkaido during the Last Glacial Age (Koaze et al., 1974 ; Nogami et al., 1980 ; Ono, 1980 ; Ono et al., 1982). The present permafrost environment of the Daisetsu Mountains will provide better understandings of the former permafrost environment on the lowlands in Hokkaido.

The purposes of this study are 1) to describe the alpine permafrost environment in the Daisetsu Mountains ; and 2) to compare it with other recorded permafrost environments in the northern hemisphere.

For these purposes, the author summarizes first the previous studies on the alpine permafrost in Japan. The Second and Third Chapters describe the topographical and geological settings and vegetation (Chapter Two), and the periglacial landforms (Chapter Three) in the Daisetsu Mountains. The Fourth Chapter treats of the climatic environment of the Daisetsu Mountains on the basis of long term meteorological observations. In the Fifth Chapter the author discusses the permafrost distribution and the characteristics of permafrost environment of the Daisetsu Mountains.

II−2 Previous Studies on the Alpine Permafrost in Japan

Although the permafrost in the arctic or subarctic regions has been well investigated, there are not so many studies on the alpine permafrost in the world. Investigations of the alpine permafrost have been conducted in the Canadian Rocky Mountains (Harris and Brown, 1978), the Colorado Rocky Mountains (Ives, 1978 ; Ives and Fahey, 1971 ; Greenstein, 1983), the Alps (Barsch, 1978 ; Haeberli, 1983), Scandinavia (King, 1986), Tien Shan and Pamir-Alai (Gorbunov, 1978), Nepal Himalayas (Fujii and Higuchi, 1976 ; Fujii, 1980a), Mouna Kea in Hawaii (Woodcock, 1974) and so on. Péwé (1983) and Harris (1986) discussed the distribution and zonation of the alpine permafrost in the North America, and Fujii and Higuchi (1978) and Fujii (1980b) discussed in the northern hemisphere.

In Japan, the alpine permafrost was first reported at the summit of Mt. Fuji in 1971 (Higuchi and Fujii, 1971). The existence of permafrost was confirmed in the whole area of the crater rim of the summit (Fujii and Higuchi, 1972). The lower limit of permafrost was estimated as 3,040 m a.s.l. with the annual mean temperature of −2.0 or −1.6 ℃ on the southern slope, and 2,950 m a.s.l. with that of −2.6 or −2.2 ℃ on the northern slope (Fujii, 1980b).

On the other hand, in the Daisetsu Mountains, the permafrost was found at the flat summit with the altitude of 2,150 m a.s.l. between Mt. Koizumi-dake and Mt. Hakuun-dake by boring tests and other physical investigations (Fukuda and Kinoshita, 1974). The maximum depth of the active layer was nearly 2 m, and the depth of permafrost base was estimated as 15 m or more (Fukuda and Kinoshita, 1974). In Hokkai−daira plateau at the altitude of 2,075 m a.s.l. about 0.5km northward from the summit of Mt. Hakuundake, ground temperature measurements were conducted several times in fall when the ground temperature could become maximum in a year, and the depth of permafrost table was estimated as 100 to 120cm from the ground surface (Koaze et al., 1975 ; Fukuda et al., 1976 ; Ono et al., 1982). A continuous monitoring of the ground temperature was carried out first in 1985, and revealed the permafrost occurrence under present climatic environment (Sone et al., 1988). Palsas in the mire south of Mt. Hiraga-take at the altitude of 1,710 m were discovered first in Japan (Takahashi and Sone,1988). The existence of palsas indicates geomorphologically the presence of permafrost in the Daisetsu Mountains. This proves that the permafrost occurred at least around 1,700 m a.s.l., which is 300 m lower than the previously known altitude of the permafrost distribution (Kaizuka et al., 1986).

Mt. Fuji is a strato volcano, where the permafrost spread on the mountain slopes, consisting of coarse superficial deposits. As a result, active layer contains little water, and periglacial processes are hardly observed. On the contrary, the Daisetsu Mountains are gentle lava plateaus which are favorable for retaining high water content in the active layer. This condition offers the Daisetsu Mountains a good development of periglacial landforms which the author describes in Chapter Three.

II Regional Settings of Study Area

II−1 Topography and Geology

The Daisetsu Mountains are located in central Hokkaido, northern Japan (Figure 1). They compose a part of the Daisetsuzan National Park, the largest one in Japan which occupies an area of about 230,000 ha. The study area covers the main part of the Daisetsu Mountains, and it stretches about 26 km from north to south and about 20 km from east to west. The volcanic landforms of the Daisetsu Mountains consist of the following five elements: (a) wide and flat lava plateaus ranging from 1,400 to 1,800 m a.s.l., (b) dome-shaped volcanic cones whose summits are around 2,000 m a.s.l., (c) Ohachi-daira crater of about 2 km in diameter, (d) Mt.Asahi-dake strato-volcano (2,290 m a.s.l.), and (e) large-scale landslides (Takahashi, 1990).

The history of the formation of the Daisetsu Mountains is grouped into the following four stages (Konoya et al., 1966; 1968):

I : stage of the formation of the basement of the Daisetsu volcanic group; Plio-Pleistcene.

II : stage of the formation of the Older Daisetsu Volcano; the detailed age is not known.

III: stage of the formation of the Younger Daisetsu Volcano, including the formation of Ohachidaira; the detailed age is unknown.

IV: stage of the formation of Mt. Asahi-dake Volcano; Holocene.

Major lava plateaus are called Takane-gahara, Goshiki-gahara, Numano-hara and Kogane-gahara. They are located in the central, the southeastern, the southeastern, and the southwestern part of the Daisetsu Mountains respectively. Major dome-shaped volcanos are Mt. Hokuchin-dake (2,244 m a.s.l.), Mt. Kuro-dake (1,984 m a.s.l.), and Mt. Hakuun-dake (2,230 m a.s.l.) in the northern part, and Mt. Tomuraushi-yama (2,141 m a.s.l.) in the southern part. They are composed of the ejecta in Stages II and III.

Ohachi-daira is located in the northern part, and is the largest crater in the Daisetsu Mountains. It was formed about 30,000 y.B.P. (Katsui and Ito, 1975). The bottom of the crater is covered with about 60 m-thick lake deposit (Kawachi et al., 1988).

Mt. Asahi-dake is a strato-volcano, composed of the ejecta of stage IV. It stretches a gentle slope on its northwestern to southern sides.

A number of landslides fringe the flat lava plateaus and gentle slopes. For example, large-scale landslides of more than 100 ha are located on the east of Takane-gahara, and on the north and the south of Goshiki-gahara. They consist of long and steep scarps,

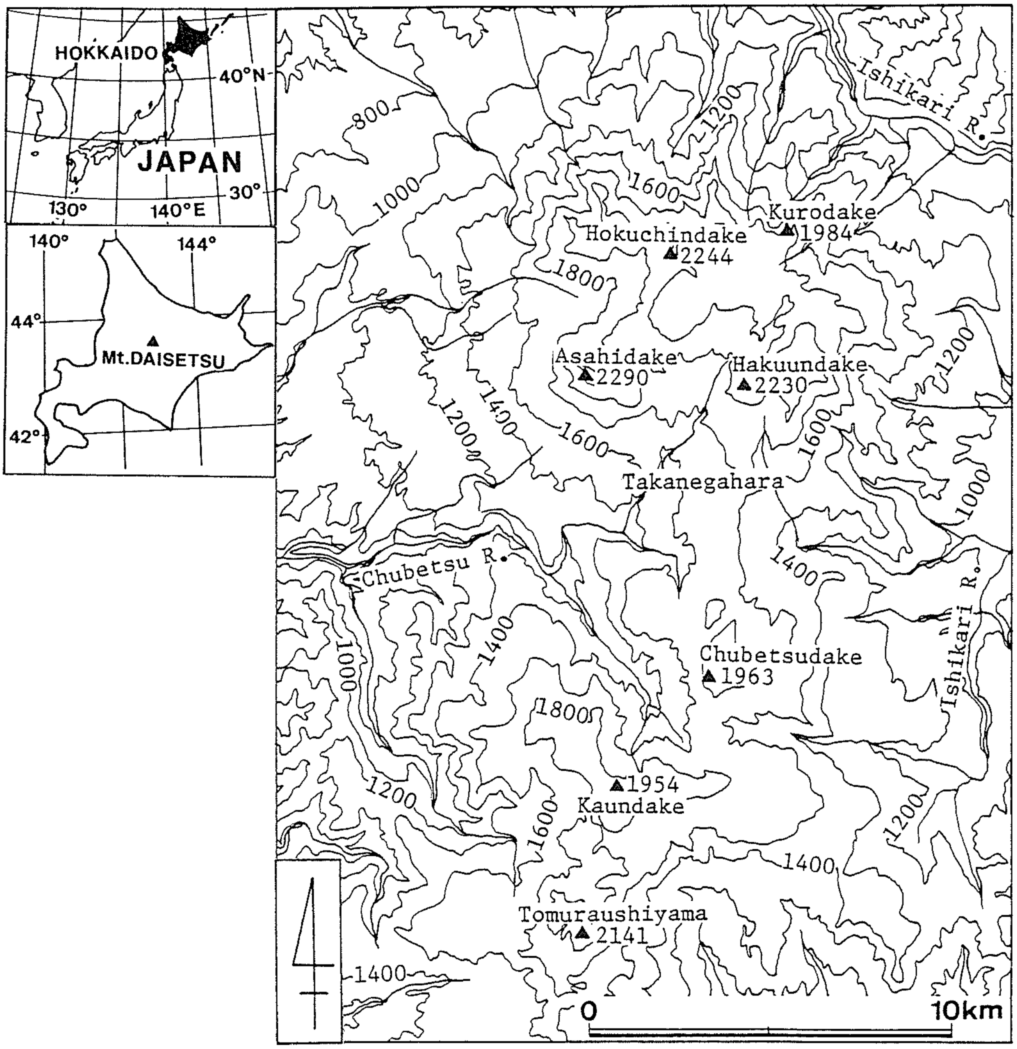

Figure 1 Location map of study area.

landslide blocks and depressions. The ages of ash layers and peats covering the landslide depressions indicate that the landslides occurred frequently during Holocene (Takahashi, 1983; 1990).

II−2 Vegetation

According to Ito and Sato (1981), the natural vegetation of the Daisetsu Mountains is divided into alpine, subalpine, montane vegetations and others. The montane forest occupies a comparatively narrow area below 600−800 m a.s.l. Pioneer herbaceous communities occupy the western slope of Mt. Asahi-dake. The subalpine vegetation stretches around and below the timber line, and consists of *Sasa kurilensis* and *Alnus maximowiczii* communities, *Betula ermanii* forest, upper mixed forest and coniferous forest from the higher to the lower. According to Takahashi (1990), the timber line rises to about 1,700–1,800 m on the eastern side of the mountains, and descends to about 1,300–1,400 m on the western side. The reason why the timber line is higher on the eastern slope than on the western one is attributed to the difference between the snow depth on both slopes.

The area above the timber line is about 15,860 ha. Above the timber line, the "alpine snow-hostile scrub community" (mainly *Pinus pumila*) and the "alpine snow-bed community" occupy a large area except the summit area.

The windward bare ground which is covered sparsely with the "alpine wind-blown dwarf scrub community", and the "alpine wind-blown rocky gravel herbaceous community" are distributed mainly on the surface of the summit areas.

The "alpine wind-blown rocky gravel dwarf scrub herbaceous community" spreads only around the summit of Mt. Koizumi-dake, because the occurrence of permafrost provide a shallow water table (Koizumi, 1983; Koizumi and Shinsho, 1983). However, the permafrost occurrence is not always related to this community.

III Periglacial Landforms in the Daisetsu Mountains

III–1 Distribution of Periglacial Landforms

Many kinds of periglacial landforms have been reported in the Daisetsu Mountains. They are palsas, block streams and slopes, and patterned grounds such as sorted polygons, circles, stripes, steps, frost crack polygons and earth hummocks (Koaze, 1965; Konoya et al., 1968 etc.). Figures 2 and 3 indicate the distribution of periglacial landforms in the Daisetsu Mountains.

(1) Patterned grounds

Typical sorted polygons with diameters of 1–2 m cover a depression about 2 km north from Mt. Tomuraushi-yama (Sako et al, 1958; Kaneko and Ueno, 1983). Debris islands with diameters of 3–6 m were reported in the depression with a snow patch near Chubetsu moor, about 1.5 km north from Mt. Chubetsu-dake (Takakura, 1972a). The sorted polygons and circles with diameter less than 1 m widely spread on the bare ground in the Daisetsu Mountains (Fujiki, 1975; Koaze, 1965; Konoya et al., 1968; Omoto, 1973; Suzuki and Fukuda, 1971; Wako, 1958).

The sorted stripes of several tens centimeters in width and steps are observed on the gentle slopes. The turf-banked terraces of 20–50 cm in height and 40–100 cm in width mainly cover the windward bare ground, while the stone-banked terraces cover the snowy bare ground.

The earth hummocks mainly occupy the wet sites such as the bottom of the volcanic craters and nivation hollows (Ellenberg, 1976; Takakura, 1972b).

Frost cracks are formed by the thermal contraction in the ground. Typical frost crack polygons with 15 to 30 m long rectangular pattern are observed on Hokkai-daira plateau (Koaze, 1974; Fukuda et al., 1976). They are similar in shape and size to the tundra polygons which are generally observed in continuous permafrost regions with formations of ice wedges. Though, the frost cracks at Hokkai-daira plateau cannot be classifed as ice wedges, because the depth of the crack is about 60 cm (Fukuda et al., 1976), and is not

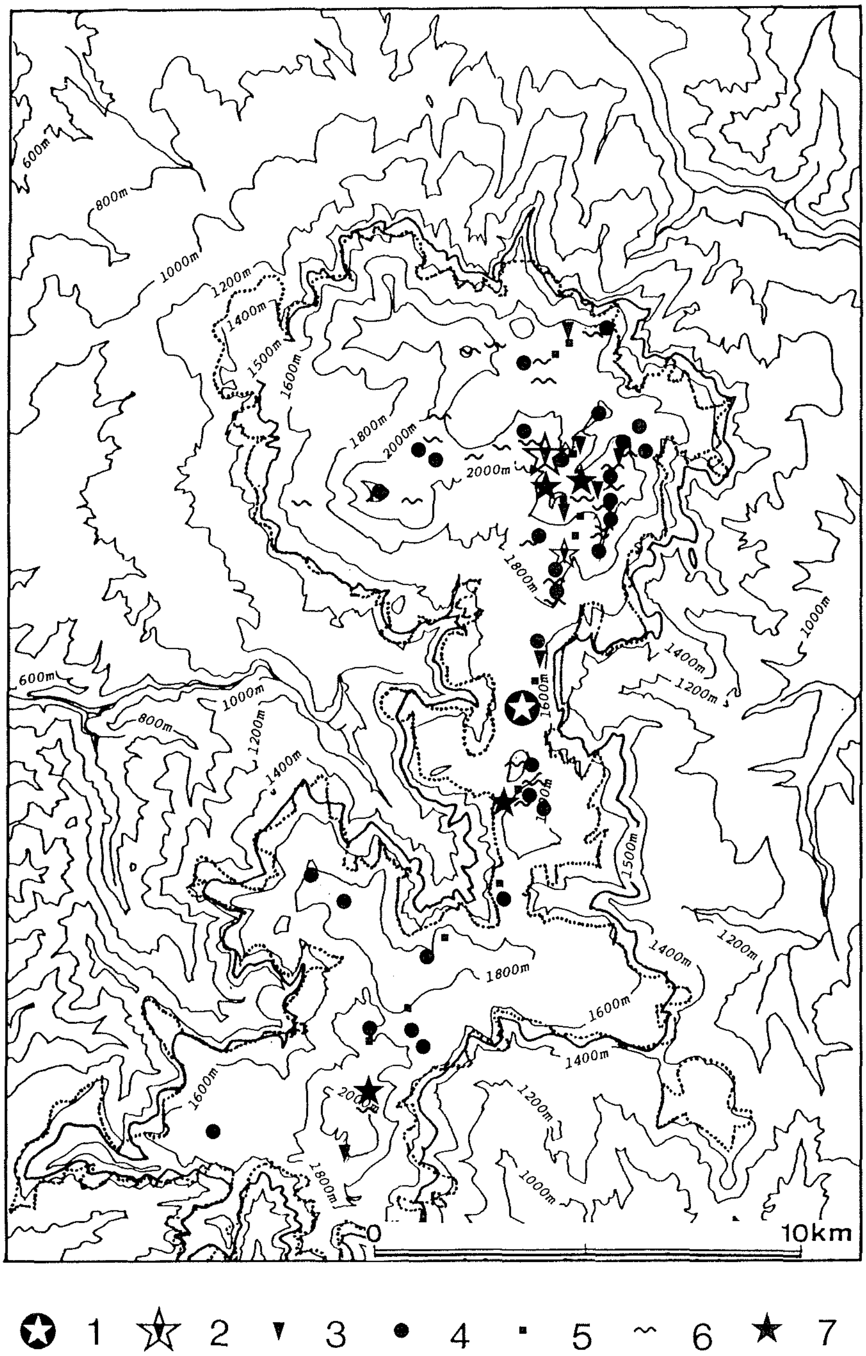

Figure 2 Distribution of periglacial landforms in the Daisetsu Mountains.
1: palsas, 2: frost crack polygons, 3: frost cracks, 4: sorted patterned grounds, 5: earth hummocks, 6: turf-banked terraces, 7: block streams and slopes. dotted line: timber line (after Takahashi, 1990)

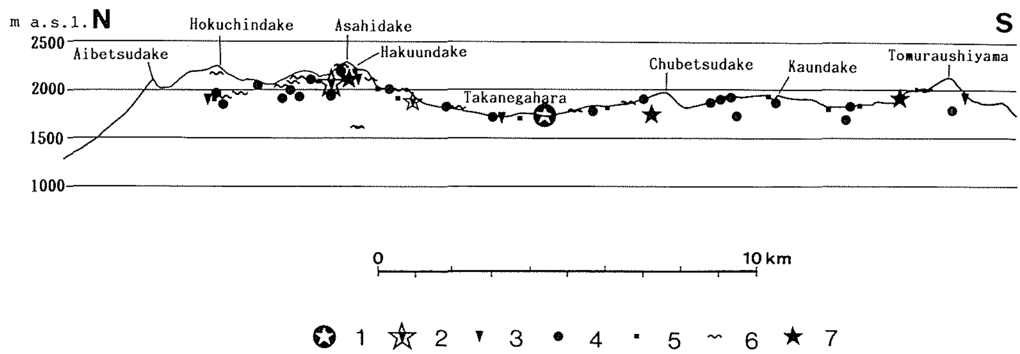

Figure 3 Vertical distribution of periglacial landforms in the Daisetsu Mountains. Legend is shown in Figure 2.

deeper than that of the active layer. However, the result of winter observation indicates that the frost cracking process on this site is active (Sone and Takahashi, 1986).

Polygonal patterns of frost cracks are also investigated at the altitude of 1,875 m on Takane-gahara plateau. Frost cracks are observed on Mt. Aka-dake, Mt. Tomuraushi-yama, Mt. Hakuun-dake etc. Their lower limit is, at least, at the altitude of 1,710 m a.s.l. in Takane-gahara plateau. Frost cracks are located on the windward bare ground.

According to Koaze (1965), more than 80 % of the patterned grounds develop on the windward crest slopes, about 15 % in depressions such as craters, nivation hollows and others, and less than 5 % on flat surfaces.

(2) Palsas

Palsas are peaty permafrost mounds (Washburn, 1983a). In the Daisetsu Mountains, palsas are observed only in the mire at the altitude of 1,720 m a.s.l. on the south of Mt. Hiraga-take. According to Takahashi and Sone (1988), palsas in the Daisetsu Mountains are summarized as follows:

There exist about 20 palsas of different stages of development. Their sizes range from 4 to 80m in diameter and from 0.2 to 1 m in height. Their plain figure is generally circular or elliptic. Most of them are peat plateaus in morphological classification, and are characterized by flat upper surfaces and relatively steep side slopes, accompanied with ponds just around them. Most of them are mineral-cored palsas in structural classification.

The palsa named palsa B is 80 cm high and 15 m long, elongating from north to south direction. It is composed of a peat layer of 60 to 110 cm thick which is underlain by silty sand and gravel layer. The permafrost table lay almost around 70cm deep and was nearly parallel to the palsa surface in late september 1986. And it almost coincided with the boundary between the peat and the silty sand and gravel layers.

Severe westerly wind in winter sweeps away the snow deposit on the ground surface, and the snow depth on the mire is less than 1 m. The top of palsas is often exposed partly during a whole winter season. The thickness of the snow cover was measured as much as 40−60cm deep in the east and west sides of palsa B on 29th December, 1986. However, the snow was less than 40cm deep on the top of palsa B, and some parts of palsa B were exposed.

Comparisons of air-photographs taken in 1955 and 1982 revealed that some palsas grew during this period while the total area of palsas in the mire was reduced by about 36%.

(3) Block streams and block slopes

Block streams and block slopes consist of moderate-sized or large blocks of rock with openwork textures. The block stream in the valley on the west slope of Mt. Chubetsu-dake was first suggested to be a rock glacier (Fujiki, 1976), however it was considered as a rock-slide avalanche deposit (Takahashi, 1985). Block slopes stretch around Mt. Hakuun-dake (Koaze, 1986) and Mt. Tomuranshi-yama (Sawaguchi and Nakahara, 1986).

III−2 Vertical Zonation of Periglacial Landforms

Iwata (1986), who studied the vertical zonation of periglacial landforms in the Daisetsu Mountains, classified the following three zones for periglacial landforms:

(1) Zone 1 : above the forest limit; the zone with patchy distribution of non-sorted patterned ground. This zone almost coincides with the *Pinus pumila* shrub zone.

(2) Zone 2 : above the upper limit of the *Pinus pumila* shrub zone; the zone of both turf-banked terraces and sorted patterned ground.

(3) Zone 3 : Typical sorted patterned ground occurs only in limited areas on the top portion of crests. This fact means that the zone of continuous sorted patterned ground occurs as a summit phenomenon related to the strong wind.

The boundary between the zones 1 and 2 is located at 1,850 m a.s.l.

IV Climatic Conditions in the Daisetsu Mountains

Climatic conditions are the most important factors for the occurrence of permafrost. Although the air temperature was measured in the thawing seasons in the alpine zone of the Daisetsu Mountains (Fukuda, 1976; Ito and Nishikawa, 1976; Sakai and Otsuka, 1970; Sakurai,1964 etc.), it was hardly measured in winter. Yamada et al. (1978) observed air temperature, wind direction and speed at the altitude of 1,595 m a.s.l., above the timber line on the western slope of Mt. Asahi-dake in 1977−78 snow season. Akitaya (1978) also attempted to measure air temperatures on Takane-gahara plateau in winter, but the data was not published. A whole-year air temperature was measured first in 1968 at the altitude of around 1,300 m on the northern slope of Mt. Kuro-dake (Sakai and Otsuka, 1970). However, a year-round record of air temperature was not obtained in the alpine zone of the Daisetsu Mountains before 1985.

Fukuda and Kinoshita (1974) estimated the mean annual air temperature at the altitude of 2,150 m as −3.0 °C by extrapolation from the nearest weather station. And Ono et al. (1982) estimated the mean annual air temperature at the altitude of 2,000 m as −2.5 °C.

The author carried out first a long-term observation of air temperature and the observations of wind direction and speed in winter at the altitude of 2,000 m a.s.l. in the Daisetsu Mountains (Sone and Takahashi, 1988).

IV−1 Air temperature condition

The meteorological observations were carried out at Hakuun hut located at the altitude of 2,000 m a.s.l. about 0.5 km southward from the summit of Mt. Hakuun-dake (2, 230 m), in central part of the Daisetsu Mountains (Figure 4).

The temperature sensors (Cu-Co thermo-junction and Pt 100Ω) were installed at the height of 2.0 m above the ground surface. The author used an automatic recorder of C-MOS RAM type with a battery power supply for data collection.

Air temperature data were collected at every one-hour intervals from January 1985 to September 1986. They give the daily mean, maximum and minimum air temperatures. Monthly mean, maximum and minimum air temperatures were calculated from these data as in Tables 1 and 2.

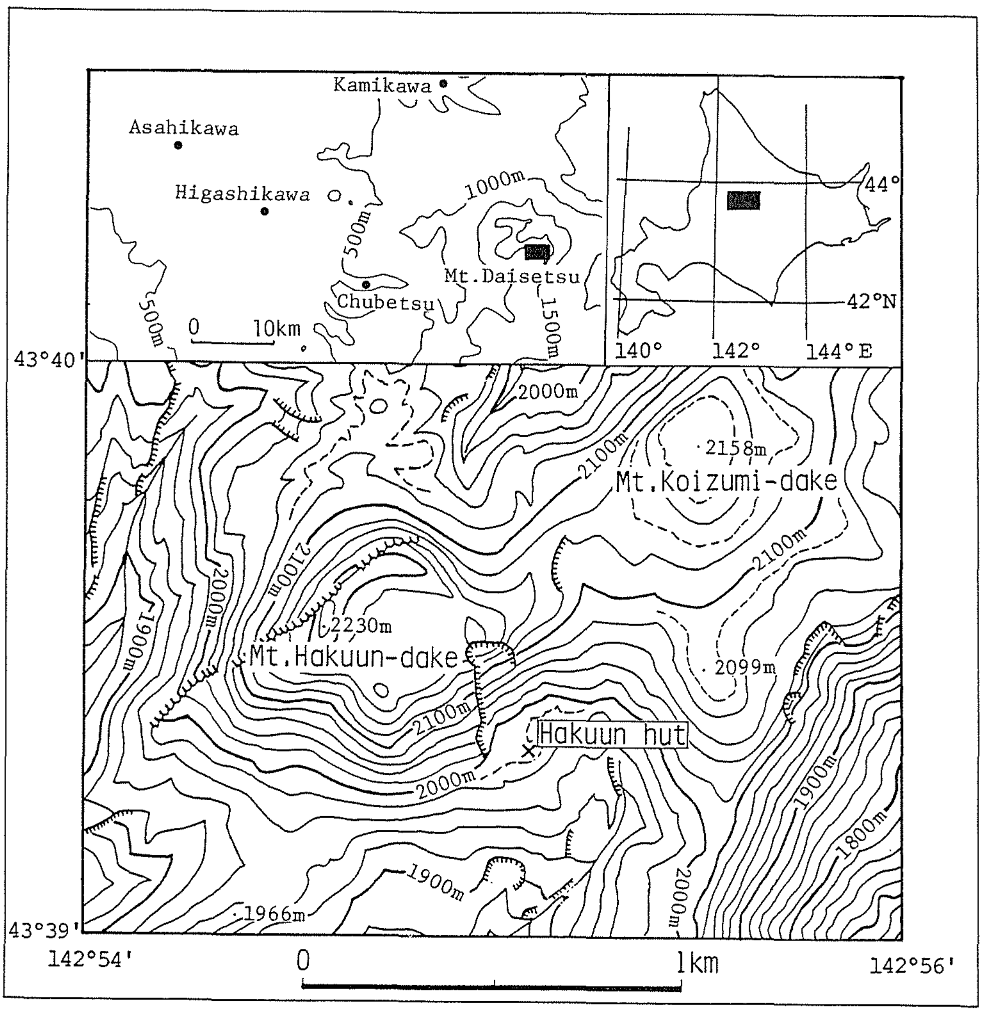

Figure 4 Location of Hakuun hut.

Mean annual air temperature in 1985 was −3.8 ℃. It is slightly lower than the previously estimated values. August is the warmest month with mean monthly temperature of 13.9 ℃, and January is the coldest month with a mean monthly temperature of −21.3 ℃. The climate of the Daisetsu Mountains is characterized by inland climate, with an annual range of air temperature of 35.2 ℃. The calculated freezing index amounts to 2,600 ℃ days, and thawing index about 1,200 ℃ days in 1985. The freezing index is the total of the mean daily temperatures below freezing point in a year, while the thawing is the total of mean daily temperatures above freezing point in a year. The warmth index is 15.5. The number of freeze-thaw days in Hakuun hut totals 72 days and is similar to that in lowland of Hokkaido (Suzuki, 1966). The minimum air temperature in 1985 is − 27.4 ℃, while that in Etanbetsu, west of Asahikawa, is −37.1 ℃. The minimum temperature is not always colder than that of lowland, because an inversion of temperature often occurs in lowland in winter.

Table 1. Monthly air temperature data at Hakuun hut, the Daisetsu Mountains in 1985. (after Sone and Takahashi, 1988)

month		Jun.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	year
monthly mean air temperature (°C)		-21.3	-15.9	-13.2	-3.2	0.6	5.5	11.1	13.9	4.5	-1.9	-9.2	-17.6	-3.8
monthly mean daily maximum air temp.		-18.6	-12.6	-9.2	1.2	4.0	10.0	14.9	16.7	7.6	1.1	-6.4	-14.9	-0.4
monthly mean daily minimum air temp.		-23.7	-18.6	-16.6	-7.0	-2.6	2.1	8.2	11.5	1.8	-4.9	-11.5	-20.2	-6.7
monthly maximum air temp.		-10.7	-7.6	-2.5	6.7	16.1	18.1	23.2	24.0	14.3	10.1	2.7	-5.6	24.0
monthly minimum air temp.		-27.4	-24.5	-22.5	-15.6	-9.9	-4.8	2.9	7.8	-4.7	-12.4	-21.2	-26.8	-27.4
number of days														
daily mean temp.	over 10°C	0	0	0	0	1	3	23	29	4	0	0	0	60
	under 0°C	31	28	31	26	16	1	0	0	5	18	27	31	214
	-10°C and under -10°C	31	28	24	1	0	0	0	0	0	0	15	30	129
	-20°C and under -20°C	21	2	2	0	0	0	0	0	0	0	0	7	32
daily maximum temp.	over 10°C	0	0	0	0	5	13	30	31	10	1	0	0	90
	under 0°C	31	28	31	10	7	0	0	0	1	12	25	31	176
	-10°C and under -10°C	31	22	13	0	0	0	0	0	0	0	7	26	99
	-20°C and under -20°C	16	2	0	0	0	0	0	0	0	0	0	3	21
daily minimum temp.	over 10°C	0	0	0	0	0	0	7	22	0	0	0	0	29
	under 0°C	31	28	31	30	2	6	0	0	12	26	30	31	274
	-10°C and under -10°C	31	28	29	5	0	0	0	0	0	9	19	31	152
	-20°C and under -20°C	29	8	7	0	0	0	0	0	0	0	4	15	63
freezing index (°C·days)		659.4	443.8	410.1	99.2	43.7	0.8	0	0	5.8	101.6	278.4	545.1	2587.9
thawing index (°C·days)		0	0	0	3.8	62.5	164.6	344.4	429.4	139.9	43.4	2.9	0	1190.8
warmth index		–	–	–	–	–	0.5	6.1	8.9	–	–	–	–	15.5
number of freeze-thaw days		0	0	0	20	15	6	0	0	11	14	5	0	71

Table 2. Monthly air temperature data at Hakuun hut, the Daisetsu Mountains in 1986.

month	Jun.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	year
monthly mean air temperature (°C)	-19.4	-19.1	-12.7	-6.2	-0.2	6.3	8.4	11.6	5.1				
monthly mean daily maximum air temp.	-16.5	-15.9	-8.4	-2.5	3.7	10.6	12.0	15.3	8.5				
monthly mean daily minimum air temp.	-22.2	-21.5	-16.2	-9.6	-3.4	2.9	5.8	8.8	2.3				
monthly maximum air temp.	-5.3	-7.7	-2.2	9.9	11.1	18.2	18.0	20.1	15.6				
monthly minimum air temp.	-27.1	-26.6	-27.2	-17.7	-10.8	-4.1	2.2	3.8	-2.3				
number of days													
daily mean temp. over 10°C	0	0	0	0	0	5	6	26	2				
under 0°C	31	28	31	28	18	2	0	0	2				
-10°C and under -10°C	30	28	24	10	0	0	0	0	0				
-20°C and under -20°C	14	11	2	0	0	0	0	0	0				
daily maximum temp. over 10°C	0	0	0	0	1	17	22	29	9				
under 0°C	31	28	29	19	7	1	0	0	0				
-10°C and under -10°C	28	25	11	2	0	0	0	0	0				
-20°C and under -20°C	10	5	0	0	0	0	0	0	0				
daily minimum temp. over 10°C	0	0	0	0	0	0	2	9	1				
under 0°C	31	28	31	30	26	5	0	0	6				
-10°C and under -10°C	31	28	30	13	2	0	0	0	0				
-20°C and under -20°C	20	19	2	0	0	0	0	0	0				
freezing index (°C·days)	601.7	535.0	393.3	191.1	45.1	2.2	0	0	0.4				
thawing index (°C·days)	0	0	0	5.7	39.7	191.5	261.6	359.4	154.6				
warmth index	-	-	-	-	-	1.3	3.4	6.6	0.1	-	-	-	11.4
number of freeze-thaw days	0	0	2	11	19	4	0	0	6				

IV−2 Wind and snow accumulation in winter

The mean monthly wind speed at Hakuun hut with the altitude of 2,000 m was 8.6 m/s (Sone and Takahashi, 1988), while it was 7.1 m/s at the western mid-slope of Mt. Asahi-dake with the altitude of 1,595 m (Yamada et al., 1978). The critical wind speed causing the blowing off of snow is about 4−7 m/s (Ohmura et al., 1967; Yamada, 1974). The wind record at 1,595 m a.s.l. showed that, in snow season, the frequency of occurrence of wind stronger than 7 m/s was more than 50 % (Yamada, 1982). The wind record at Hakuun hut in January 1985 showed that the frequency of occurrence of wind stronger than 4 m/s and 7 m/s was 80.4 % and 56.7 % respectively, and that the wind direction of strong wind was almost westerly (Sone and Takahashi, 1988). As a result, the pattern of the snow accumulation in winter is probably invariable.

Snow accumulation on the ground surface is another important factor for the occurrence of permafrost. The author visited to Hakuun hut at least once a month in 1984−85 winter season to observe the distribution of snow in the alpine zone. The observation revealed that the windward bare ground such as part of Hokkai-daira and Takane-gahara plateaus was barely covered with snow. In Hokkai-daira plateau, the maximum snow cover was only 16 cm thick on 18th February, 1985. But this snow cover was blown off from the ground surface by strong westerly wind on 20th February.

Snow accumulated on leeward eastern-side slopes, and formed snow patchs. Some of them are perennial. The pattern of the snow accumulation at the east-west cross section of Takane-gahara plateau is illustrated as in Figure 5. While the depth of snow increases with altitude below the timber line, it decreases with altitude above the timber line toward the summit area.

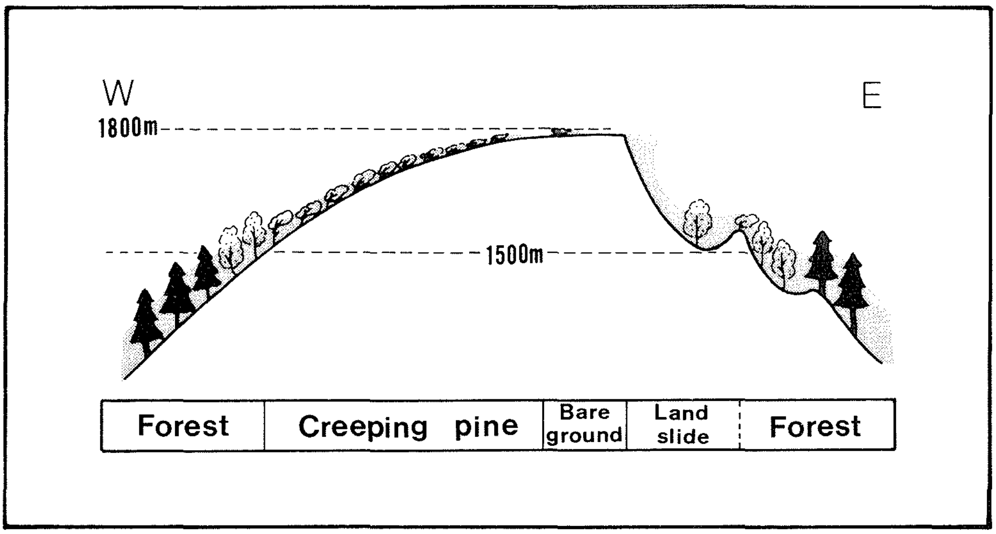

Figure 5 Scheme of the winter snow distribution on Takane-gahara plateau.

On the eastern slope of Takane—gahara plateau, the maximum snow depth reached 25—30 m (Wakahama et al., 1968; 1969). According to Yamada (1982), on the western slope of Mt. Asahi-dake below the timber line, the depth of snow increased with altitude. The maximum snow depth at the altitude of 1,070 m a.s.l. was 270 cm in 1978, but that at 1,620 m in the alpine zone was 150 cm and ranged from 50 to 150 cm during the snowy season, from December, 1978 to March, 1979 (Yamada, 1982).

Most of precipitations between October and May are snow. But the winter precipitation has never been measured because of the strong wind and extremely localized snow accumulation stated above.

IV—3 Correlation of air temperature between Hakuun hut and other locations

Table 3 shows the correlation coefficients between daily mean air temperature at Hakuun hut in 1985 and that in other meteorological observatories. By simple regression, the air temperatures at 800 mb surface above Sapporo has the highest correlation coefficients. By multiple regression, correlation coefficients are high using the air temperatures at 800 mb surface above Sapporo and those in lowland weather stations around the Daisetsu Mountains. Therefore, the mean daily air temperature at Hakuun hut can be estimated by multiple regression analysis with a high reliability. Kikuchi et al. (1978) also estimated the mean daily air temperatures in winter at the altitudes of 1,595 m and 1,070 m in the western slope of Mt. Asahi-dake by multiple regression analysis. They used the values at 850 mb surfaces above Sapporo and Higashikawa AMeDAS station.

Table 3. Correlation coefficient and standard error between air temperature at Hakuun hut and that of other meteorological stations.

		SIMPLE REGRESSION		MULTIPLE REGRESSION	
STATION	(ALTITUDE)		SAPPORO 850mb	SAPPORO 800mb	SAPPORO 700mb
ASAHIKAWA	112m	0.981 (6.52)	0.992 (2.30)	0.994 (1.68)	0.991 (2.51)
HIGASIKAWA	215m	0.975 (6.86)	0.991 (2.40)	0.994 (1.79)	0.990 (2.68)
KAMIKAWA	350m	0.976 (5.20)	0.992 (2.22)	0.994 (1.62)	0.992 (2.28)
CHUBETSU	370m	0.981 (5.20)	0.992 (2.29)	0.994 (1.65)	0.992 (2.30)
SAPPORO 850mb SURFACE		0.990 (2.83)			
SAPPORO 800mb SURFACE		0.991 (2.48)			
SAPPORO 700mb SURFACE		0.983 (4.64)			

In addition to the values at 800 mb surface above Sapporo, the mean daily temperatures in Asahikawa where meteorological observations were conducted continuously for long years were used for the estimation in this study. The mean daily air temperature at Hakuun hut can be estimated by the formula,

$$T(H)=A\times T(A)+B\times T(S)+C \qquad \text{[Eq.(1)]}$$

where T(H) is the daily mean air temperature at Hakuun hut, T(A) is the daily mean air temperature in Asahikawa, T(S) is the daily mean air temperature at 800 mb surface above Sapporo, A, B and C are coefficients. Table 4 shows the values of the coefficients A, B, C and multiple correlation coefficients during the entire period of the observation.

Table 4. Values of coefficient A, B, C, multiple correlation coefficient, and standard error between measured air temperatures at Hakuun hut, and estimated ones by using the data at Asahikawa meteorological station, and 800 mb surface above Sapporo.

	SPRING	SUMMER	FALL	WINTER		ENTIRE PERIOD
A	0.279	0.310	0.345	0.165		0.268
B	0.667	0.657	0.689	0.840		0.747
C	−4.29	−3.25	−4.54	−3.02		−3.679
CORRELATION COEFFICIENT	0.974	0.947	0.987	0.960	0.994	0.993
STANDARD ERROR	2.35	1.74	1.40	1.25	1.70	1.89

The year-to-year variation of the air temperature at Hakuun hut is estimated by using Eq.(1) (Figure 6). Mean annual air temperatures, freezing, thawing and warmth indexes, at Hakuun hut in normal years (1951−1980) are obtained as −3.6 ℃, 2485.3 ℃ days, 1168.0 ℃ days and 14.2 ℃ respectively.

The mean annual air temperature at Hakuun hut is similar to that in Fairbanks, Alaska, located in the discontinuous permafrost zone, though the climate in Fairbanks is more continental than that in the Daisetsu Mountains.

The year-to-year variation of two freezing indexes is also shown in Figure 6. The freezing index in a calendar year is naturally different from that in a freezing season from the fall to the spring. The latter is more important for the activity of frost actions in a freezing season than the former.

Mean lapse rate of air temperature between Hakuun hut and nearby lowland meteoro-

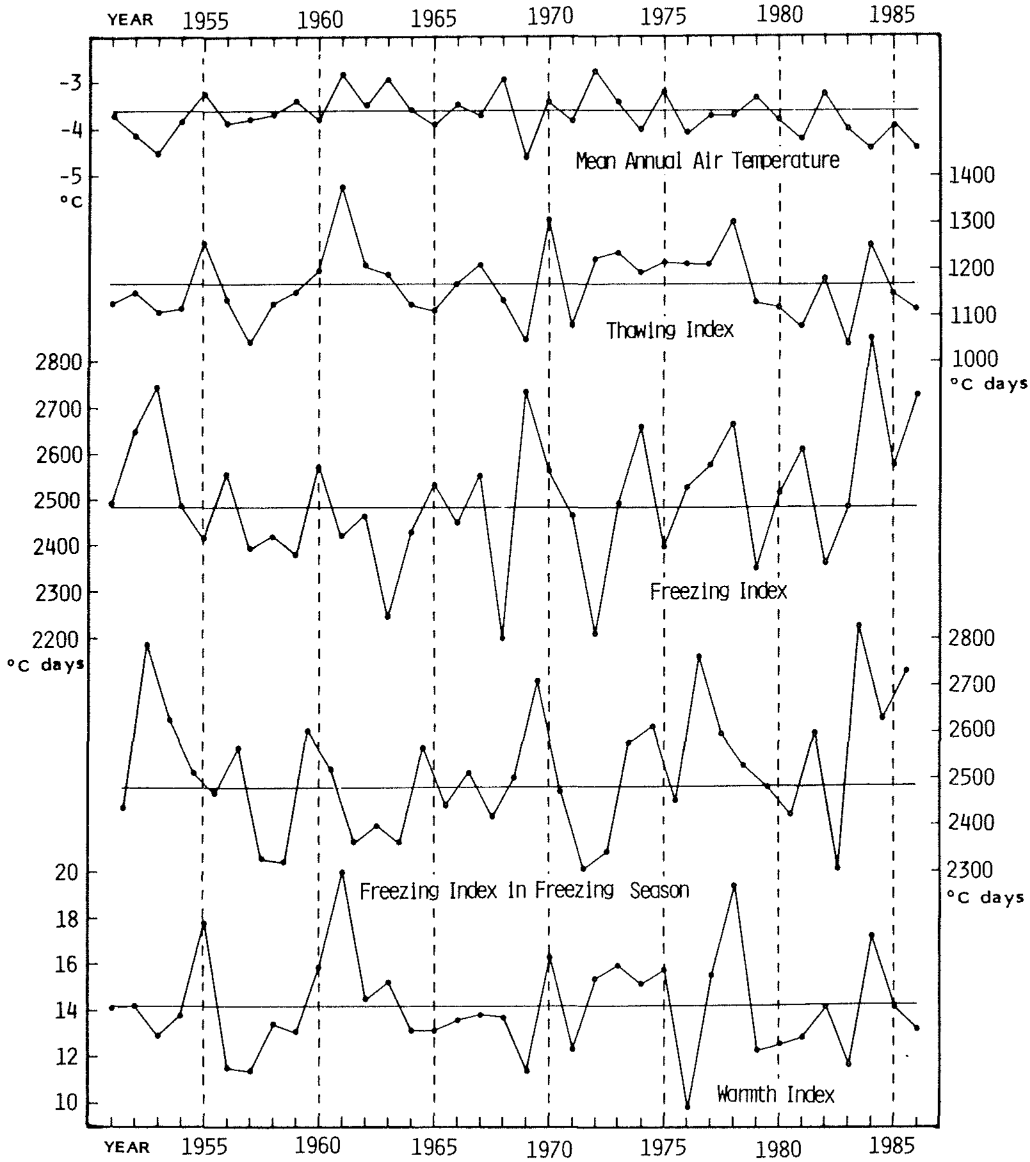

Figure 6 Year-to-year variations of air temperature and warmth, freezing and thawing indexes at Hakuun hut.

logical observatories during the period of the observation is estimated as 5.3 ℃/km. Using this value, the mean annual air temperatures and freezing and thawing indexes at altitudes ranging from 1,300 m to 2,300 m a.s.l. in the Daisetsu Mountains are estimated (Figure 7).

According to Okitsu and Ito (1984), the forest limit does not coincide with the warmth index 15 in Hokkaido. In the Daisetsu Mountains, the warmth index at the forest limit varies from 28.8 (1,300 m a.s.l.) to 18.2 (1,800 m a.s.l.). Therefore, the forest limit is independent of the warmth index 15, also in the Daisetsu Mountains.

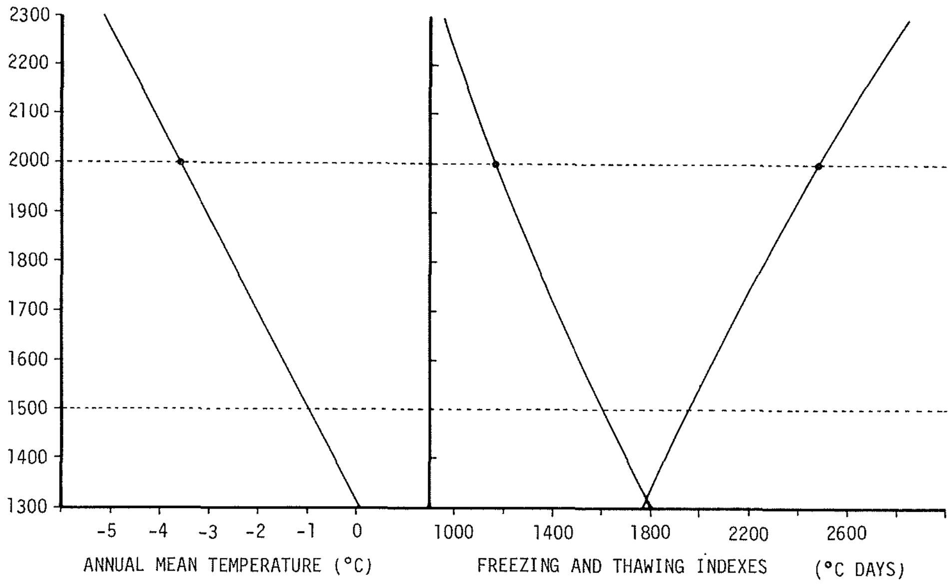

Figure 7 Estimated mean annual air temperatures, freezing and thaw indexes in the Daisetsu Mountains.

V Discussion

V−1 Distribution of Permafrost in the Daisetsu Mountains

The insulating effect of snow cover on ground surface is well known. The snow cover is often a critical factor in determining the presence or absence of permafrost (Gill, 1973; Nicholson and Thom, 1973). For example, in Scheffervill, northern Quebec, where the mean annual air temperature is −4.5 ℃, a winter snow depth of 65−70 cm is sufficient to prevent the development of permafrost (Nicholson and Granberg, 1973).

In the mire at the south of Mt. Hiraga-take, the depth of snow was measured as much as 40−60 cm, and less than 40 cm around and on the top of palsa B respectively. The thickness of the snow cover around palsas was generally more than 50 cm. In this mire, the permafrost occurs only where palsas exist. Therefore, the snow cover of 50 cm thickness is likely critical for the permafrost occurrence in this mire. Harris and Brown (1978) also stated that the sites where the snow covers the ground surface for more than 50 cm in winter, are insulated from the coldness, and tend to show abnormally higher temperature than in the air.

Creeping pines grow where the ground surface is covered with snow ranging from 30 to 300 cm thick in winter; namely, the depth of snow is nearly equal to their height (Okitsu and Ito, 1983). It appears that the permafrost does not generally occur in the area covered with creeping pines, because most of creeping pines are usually taller than 50 cm. The shrubs of creeping pine stretch patchy and their height is smaller than 50 cm, even if they are distributed on the windward bare ground where the permafrost can occur.

Though the snow cover is almost blown off from the ground surface on windward bare ground, however, even a thin snow cover has a thermal insulation effect on such areas. The author examined this effect on the bare ground near Hakuun hut.

The ground surface temperature of this bare ground was measured at the same time as air temperature was measured at Hakuun hut during the period from 10 th October, 1985 to 20th May, 1986. While the calculated freezing index of air temperature at Hakuun hut was 2690.5 ℃ days, that of the ground surface temperature of the bare ground was 2341. 3 ℃ days during this period. Therefore, about 90 % of freezing index of air temperature was conducted to the bare ground surface.

If the ground surface is devoid of snow, the depth of winter freezing (Df) can be simply estimated by Stefan's equation (Washburn, 1979),

$$Df = a\sqrt{FI} \qquad [Eq.(2)]$$

where Df is the depth of freezing, a is a parameter, FI is a freezing index.

The depth of summer thawing (Dt) can also be estimated by Stefan's equation (Washburn, 1979),

$$Dt = b\sqrt{TI} \qquad [Eq.(3)]$$

where Dt is the depth of thawing, b is a parameter, TI is a thawing index.

Permafrost can develop where the seasonal depth of freezing (Df) is larger than that of thawing (Dt). The value of the parameters "a" and "b" varies according to the soil properties. On the basis of the ground temperature measurement, the value of "a" is 3.14 in Hokkai-daira plateau, while that of "b" is estimated as 3.0 to 3.5 (Kinoshita et al., 1978). Freezing and thawing indexes were already obtained in Chapter Four. Taking the snow cover effect in the windward bare ground into consideration, the 90 % value of FI is used instead of the total FI. Using the value of 3.0 for the parameter "b", the altitude where the depth of freezing (Df) is larger than that of thawing (Dt) is estimated as around 1,500 m a.s.l. (Figure 8). This value shows the lower limit of permafrost in the windward bare grounds in the Daisetsu Mountains. The annual mean air temperature of this altitude is estimated as −1.0 ℃. In Canada, the southern limit of discontinuous permafrost also coincides roughly with the −1 ℃ annual mean air isotherm (Brown and Péwe, 1973).

Figure 9 shows the distribution of the windward bare ground in the Daisetsu Moun-

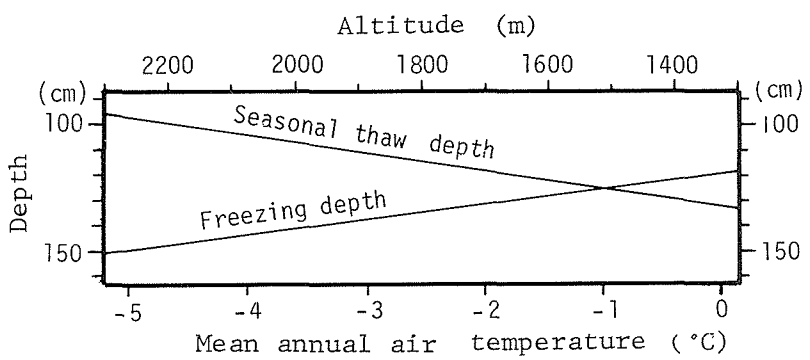

Figure 8 Potential depth of seasonal freezing and thawing versus altitude in the Daisetsu Mountains.

tains. It stretches above 1,650 m a.s.l. Therefore, the lowest limit of the permafrost is 1, 650 m in the Daisetsu Mountains under the present climatic conditions.

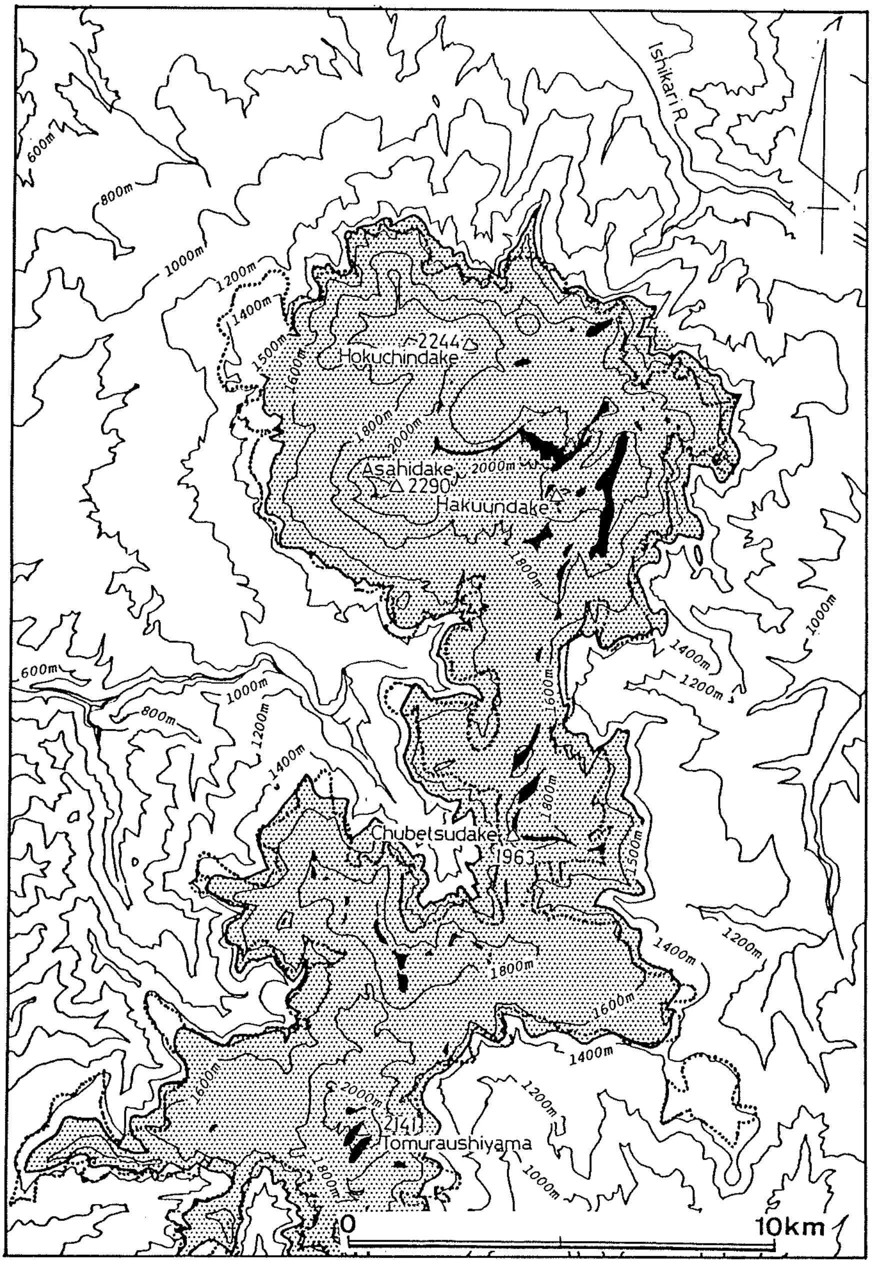

Figure 9 Inferred distribution of permafrost in the Daisetsu Mountains.
shaded part: the area above 1,500 m a.s.l.
dotted line: timber line (after Takahashi, 1990)

In addition to the area with the snow cover less than 50 cm, the permafrost probably exists in some snow-patch bare ground where the snow does not completely thaw until the end of thawing season. In such snow-patch bare ground, the ground surface is exposed to the coldness till the beginning of snow accumulation season and is protected from summer heat by snow cover.

On the basis of the distribution of snow accumulation in spring, the area with the snow cover less than 50 cm in winter surrounds the windward bare ground, but the former area is not likely to be so large. Therefore, the permafrost in the Daisetsu Mountains spreads mainly in the windward bare ground (Figure 9), although more data are required for the detailed mapping of the permafrost.

The altitude of the lower limit of the alpine permafrost generally decreases with latitude. The lower limit of permafrost is estimated as 2,950 m in Mt. Fuji (Fujii, 1980b). Then the latitudinal gradient between Mt. Fuji and the Daisetsu Mountains is estimated to be 160 m/degree. It is very close to that of air temperature (158 m/degree). However, the latitudinal gradient of lower limit of permafrost is 300 m/degree in North America (Harris, 1986).

V−2 Characteristics of the Permafrost Environment of the Daisetsu Mountains

Harris (1981a, b, 1982) studied the relation between the freezing and thawing indexes and the distribution of zonal permafrost landforms in areas with snow cover less than 50 cm thick in winter: the limits of distribution for continuous, discontinuous and sporadic permafrost zones are determined in relation to the freezing and thawing indexes as indicated in Figure 10-a (Harris, 1981a).

Freezing and thawing indexes calculated at each altitude between 1,300 m and 2,300 m a.s.l. with the range of ±1 ℃ in mean annual air temperature in the Daisetsu Mountains are plotted on the diagram of Harris (1981a), together with those for Alps, Canada, Mongolia and Norway (Figure 10-b). This figure illustrates that the areas above 2,025 m, 1,350 m and 655 m a.s.l. in the Daisetsu Mountains are included in the continuous, discontinuous and sporadic permafrost zones respectively, if the snow hardly covers the ground surface in winter. However, as the snow covers the ground surface in winter by more than 50 cm thickness widely in the Daisetsu Mountains, they are included in the discontinuous or sporadic permafrost zones, where the permafrost spreads mainly on the windward bare ground.

Figure 10-b shows that the permafrost environment of the Daisetsu Mountains is more continental than the Alps, but much less continental than Mongolia.

Harris (1981a; 1982) also illustrated the limits of the distributions of periglacial landforms such as ice wedge polygons, frost cracks, palsas, pingos, etc. They are also indicated on the diagram with freezing and thawing indexes. The plots of freezing and thawing indexes of the Daisetsu Mountains on these diagrams (Figures 11, 12, 13 and 14) illustrate the possibility of the occurrence of these periglacial landforms in the study area.

From a climatic point of view, ice wedges in mineral soils and peat can be formed at the sites where the mean annual air temperatures are below −4.9 ℃ (above 2,250 m a.s.l.), and between −2.7 ℃ (above 1,825 m a.s.l.) and −3.7 ℃ (below 2,025 m a.s.l.) respectively

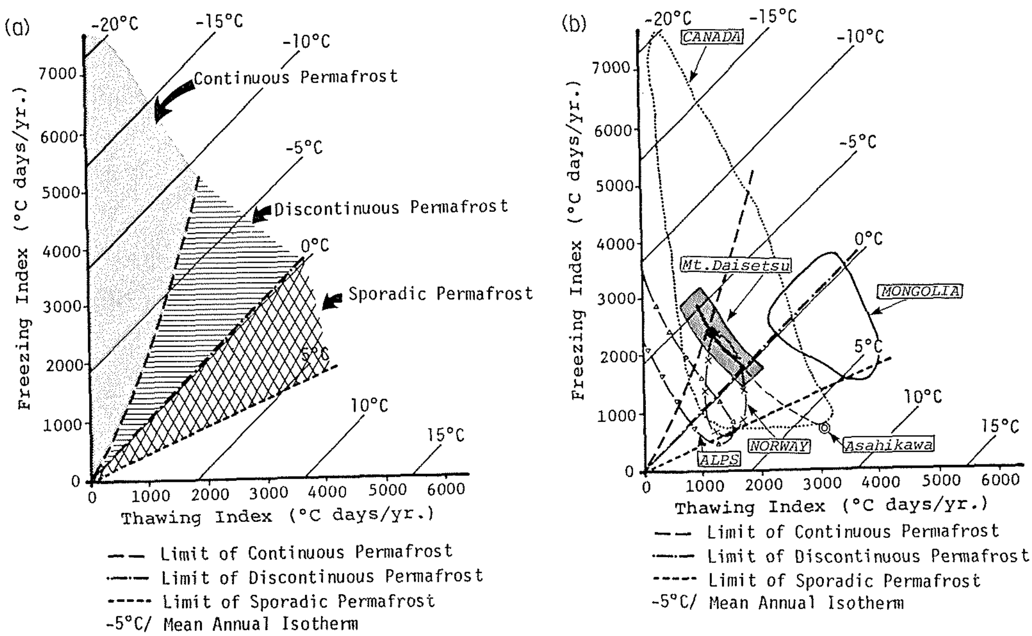

Figure 10 a) Relationship between permafrost zones and freezing and thawing indexes (after Harris, 1981a).
b) Range of freezing and thawing indexes of the Daisetsu Mountains plotted on the diagram of Harris (1981a) with the data for Canada, Mongolia, Norway, and the Alps.

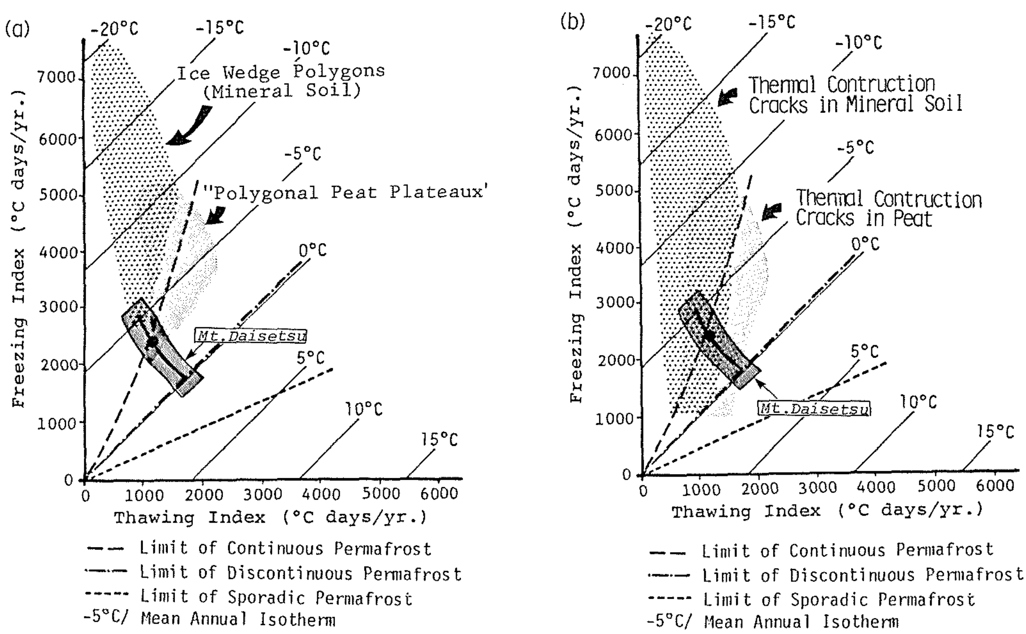

Figure 11 Possibility of the occurrence for ice wedges (a) and frost cracks (b) in the Daisetsu Mountains in relation to freezing and thawing indexes (after Harris, 1982).

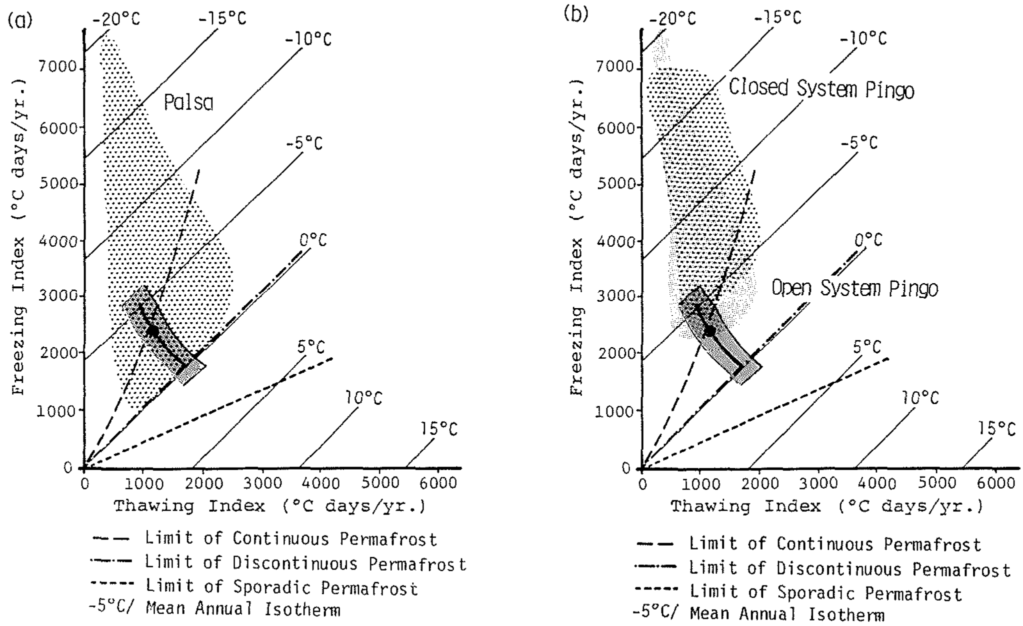

Figure 12 Possibility of the occurrence for palsas (a) and pingos (b) in the Daisetsu Mountains in relation to freezing and thawing indexes (after Harris, 1982).

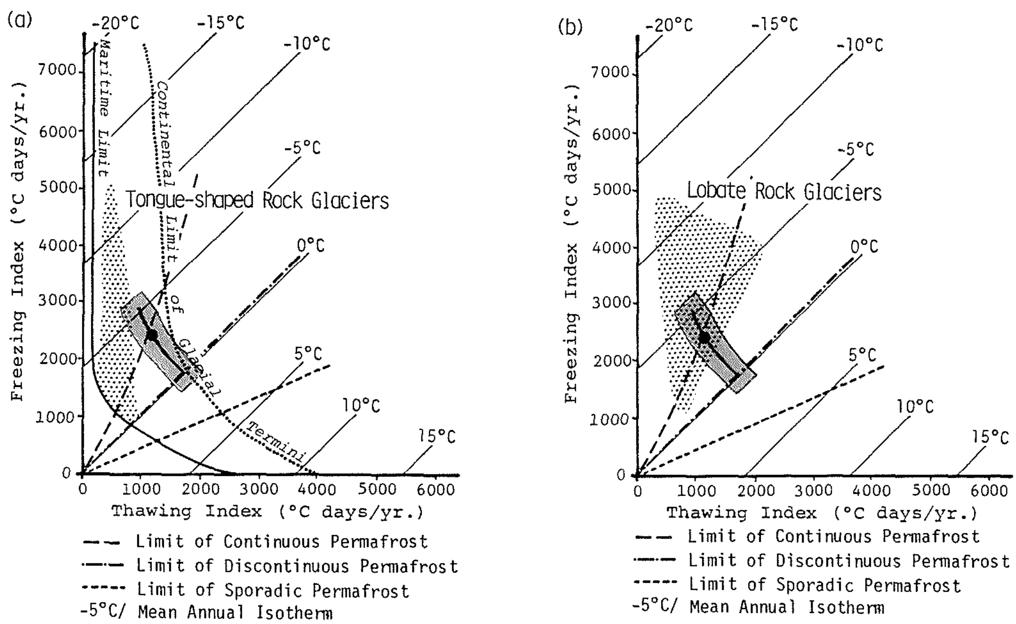

Figure 13 Possibility of the occurrence for tongue-shaped rock glaciers (a) and lobate rock glaciers (b) in the Daisetsu Mountains in relation to freezing and thawing indexes (after Harris, 1981a).

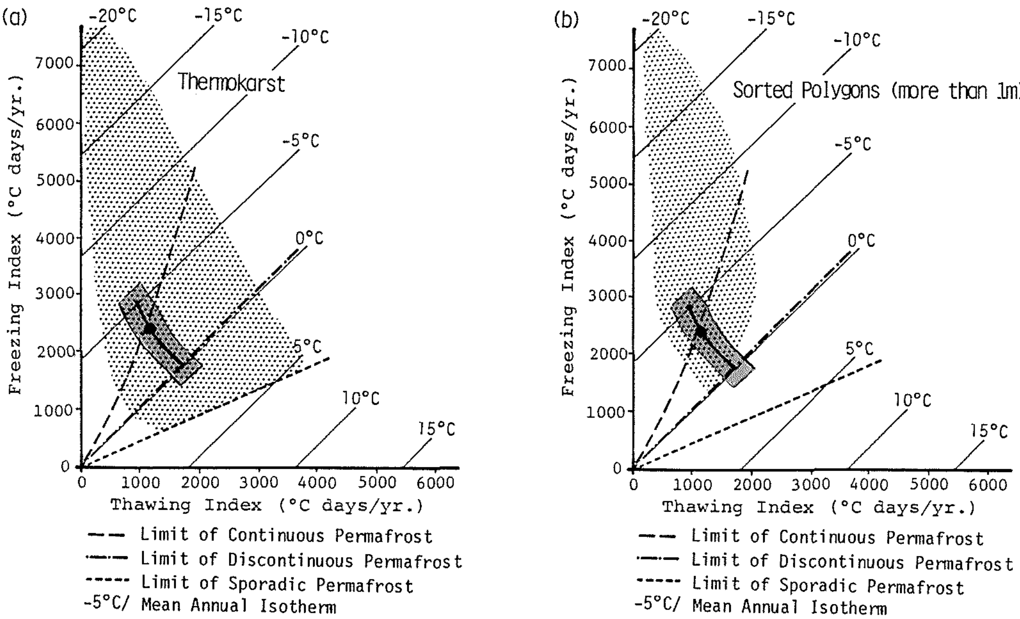

Figure 14 Possibility of the occurrence for thermokarst features (a) and sorted polygons (b) in the Daisetsu Mountains in relation to freezing and thawing indexes (after Harris, 1982).

(Figure 11a). However, there is no flat ground surface above 2,250 m a.s.l. which may allow the growth of ice wedge, and there is no permafrost in the peat bogs above 1,800 m a.s.l. Therefore the ice wedges can hardly develop under the present climatic conditions in the Daisetsu Mountains.

On the basis of Figure 11b, frost cracks in mineral soils and peat can be formed at the sites where the mean annual air temperatures are below −2.1 ℃ (above 1,710 m a.s.l.) and − 0.2 ℃ (above 1,350 m a.s.l.) respectively. The windward bare ground spreads above 1,650 m a.s.l. in the Daisetsu Mountains, so that the frost cracks can develop. As already mentioned in Chapter Three, frost cracks in mineral soils are observed above 1,710 m a.s.l.

Many peat mires occur above 1,350 m a.s.l. in the Daisetsu Mountains, but there is only one mire that is located in the windward side. Frost cracks in peat can occur in this peat mire with the altitude of 1,720 m a.s.l. at the south of Mt. Hiraga-take. However, further observations are necessary to ascertain this idea.

On the basis of Figures 12 a and b, palsas, closed and open system pingos can develop at the sites where the mean annual air temperatures are below −0.2 ℃ (above 1,350 m a.s.l.), −4.7 ℃ (above 2,200 m a.s.l.) and −2.8 ℃ (above 1,850 m a.s.l.) respectively. As mentioned above, there is only one mire located at the site with thin snow cover in the Daisetsu Mountains. Therefore, palsas are observed only in this mire in the Daisetsu Mountains. There are no flat ground surfaces above 2,200 m a.s.l. which would for allows for the development of the closed system pingo, so that it can hardly be expected to develop in the Daisetsu Mountains. On the contrary, open system pingo can develop above 1,850 m a.s.l., on the windward bare ground that is distributed above 1,650 m a.s.l. But it has not been found yet in the Daisetsu Mountains.

On the basis of Figures 13 a and b, lobate rock glaciers can be formed at the sites where the mean annual air temperature is below −0.2 ℃ (above 1,775 m a.s.l.), while tongue-shaped rock glaciers are almost impossible to develop in the Daisetsu Mountains. It is possible that lobate rock glaciers occur at the site with thin snow cover above 1,775 m a.s.l. However, no rock glaciers have been identified yet in the Daisetsu Mountains, though block streams and slopes are observed above 1,700 m a.s.l.

On the basis of Figures 14 a and b, thermokarst and sorted polygons of more than 1 m in diameter can occur at the sites where the mean annual air temperatures are below 3.5 ℃ (above 655 m a.s.l.) and −0.7 ℃ (above 1,450 m a.s.l.) respectively in the Daisetsu Mountains. Thermokarst features are observed only in the palsa mire at the south of Mt. Hiraga-take with the altitude of 1,720 m a.s.l. In other sites, no typical thermokarst features were found, probably because the permafrost possibly contains only limited excess ice.

Large scale sorted polygons will seldom occur in the windward bare ground, while they generally appear to develop in the wet sites such as shallow lake bottoms or depressions

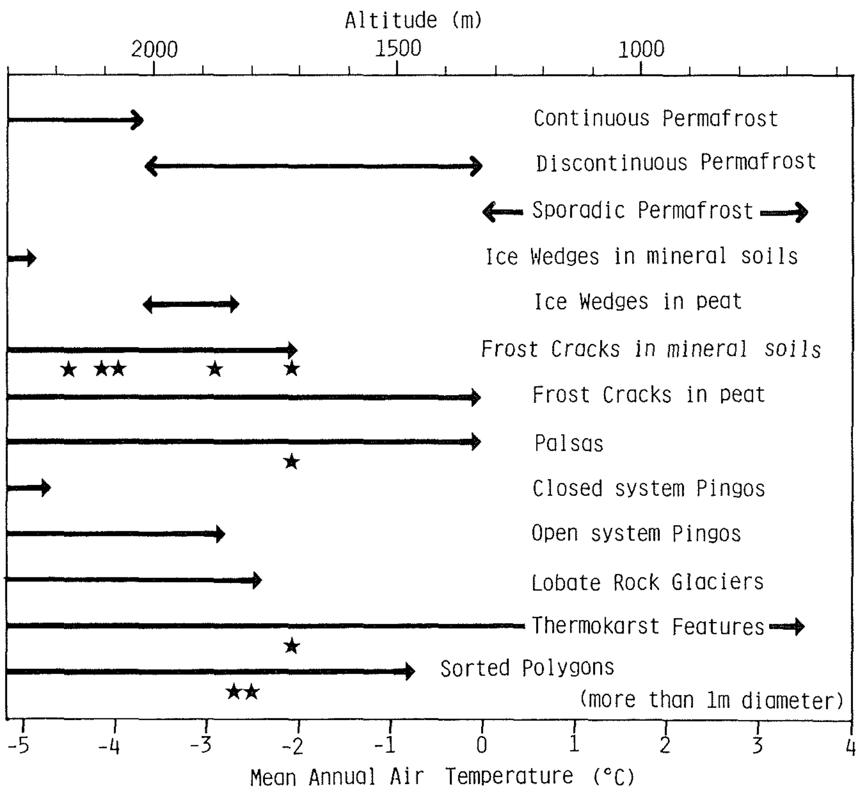

Figure 15 Possibility of the occurrence for permafrost zones and periglacial landforms, and the actual distribution of periglacial landforms (star) in the Daisetsu Mountains.

(Ray et al., 1983). Sorted polygons with more than 1 m in diameter are observed in the depressions with the altitude of 1,790 m and 1,825 m a.s.l. in the Daisetsu Mountains.

The possibility of the occurrence of periglacial landforms and their actual distribution are summarized in Figure 15. As mentioned in Chapter Three, the periglacial processes such as palsa formation and frost cracking occur under the present climatic conditions in the Daisetsu Mountains. Lobate rock glaciers and open system pingos may be discovered in the Daisetsu Mountains in the future.

According to the results of pollen analysis, the climate became coolest around 2,000 y. B.P. during the last 7,500 years, and the cool climatic condition was maintained after 2, 000 y.B.P. (Igarashi and Takahashi, 1985; Takahashi and Igarashi, 1986). Palsas in the Daisetsu Mountains were initiated also ca. 2,000 y.B.P.(Takahashi and Sone, 1988). This suggests that the permafrost environment has continued at least for 2,000 years. Fukuda and Kinoshita (1974) concluded that the permafrost in the Daisetsu Mountains was formed in the Last Glacial Age, and then gradually became smaller through Holocene. According to Figure 8, permafrost existed above 1,875 m a.s.l. in the Daisetsu Mountains, even if the mean annual air temperature was higher by 2 ℃ than at present. Therefore, if the windward bare ground stretched as far as at present, the permafrost probably survived above 1,875 m a.s.l. during the Atlantic time. However, further investigations including boring tests, electric-resistivity measurements, and pollen analysis are required for the reconstruction of the paleo-permafrost environment of the Daisetsu Mountains.

VI Conclusion

The permafrost spreads mainly in the windward bare ground, and does not generally occur in the area covered with creeping pines under the present climatic conditions, since a snow cover of around 50 cm is likely critical for the presence of permafrost in the Daisetsu Mountains.

The lower limit of permafrost in the windward bare ground in the Daisetsu Mountains is estimated to be around 1,500 m a.s.l. However, the windward bare ground stretches above 1,650 m a.s.l. Therefore, the lowest limit of the permafrost is 1,650 m in the Daisetsu Mountains under the present climatic conditions.

According to the diagram of Harris (1981a, 1982) using freezing and thawing indexes, the areas above 2,025 m, 1,350 m and 655 m a.s.l. in the Daisetsu Mountains are included in the continuous, discontinuous and sporadic permafrost zones respectively, if the snow hardly covers the ground surface in winter. However, as the snow covers the ground surface in winter by more than 50 cm thick widely in the Daisetsu Mountains, they are included in the discontinuous or sporadic permafrost zones, where the permafrost spreads mainly on the windward bare ground.

The actual occurrence of some periglacial processes such as palsa formation and frost cracking under the present climatic conditions in the Daisetsu Mountains is explained by the diagram. Additionally, the diagram indicates the possibility of the occurrence of other periglacial landforms such as lobate rock glaciers and open system pingos, of which their actual distribution has not been discovered, The permafrost probably survived above 1,875 m a.s.l. during the Atlantic time when the mean annual air temperature was higher by 2 ℃ than at the present, if the windward bare ground stretched out as it does at present.

However, further investigations are required for detailed mapping of the permafrost and periglacial landforms, and the reconstruction of the paleo-permafrost environment of the Daisetsu Mountains.

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