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RELICT LATE QUATERNARY PERMAFROST ON A FORMER NUNATAK AT PLATEAU MOUNTAIN, S. W. ALBERTA, CANADA

ABSTRACT

On Plateau Mountain in southwest Alberta is an example of relict alpine permafrost left from the Late Wisconsin glaciation. The flat mountain top was not glaciated during the Pleistocene and the relict permafrost on its summit is not yet in equilibrium with the present-day climate. The near-surface ground temperature becomes colder with depth and heat is moving slowly into the ground. This heat flow is accomplished by heat conduction and groundwater movement, but this is partly counteracted by air moving through block fields or cracks in the bedrock. Ground water and air movement produce large but localized ground temperature effects which may change location over time.

The surface shows inactive sorted patterned ground and thermokarst resulting from melting of ice wedges formed beneath the stony borders during a colder climate. At the north end of the mountain, an ice cave occurs in the surface of the relict permafrost. The alpine vegetation includes disjunct species from the floras of the Arctic from around the Atlantic Ocean, from eastern Siberia, and also from the west coast of the contiguous United States south to California. These distributions imply a migration of alpine floras during past cold events. Some local speciation has also occurred.

INTRODUCTION

Relict permafrost is fairly common at lowland sites in the unglaciated portions of the Yukon Territory, Canada (Mackay *et al.*, 1972) and Alaska (Péwé, 1966), and is widespread in Siberia, but has rarely been found in alpine locations in formerly glaciated areas. An exception is Plateau Mountain in the Rocky Mountains of southwest Alberta, Canada. This paper describes the results of an ongoing study of air and ground temperatures and related features on Plateau Mountain that commenced in 1974. Preliminary descriptions were given in Harris and Brown (1978, 1982).

Plateau Mountain is a flat-topped mountain lying approximately 80 km southwest of Calgary (Fig. 1) with a summit elevation of 2519 m. The mountain is formed from the core of an anticline which is tilted gently downwards to the north and west. The cap rock consists of Upper Carboniferous siliceous dolomite of the Spray Lakes Group, overlying limestones,

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dolomites, soft sandstones and shales of the Etherington and Mount Head formations (DOUGLAS, 1958; NORRIS, 1993a, b). The flat top occupies some 13 km^2.

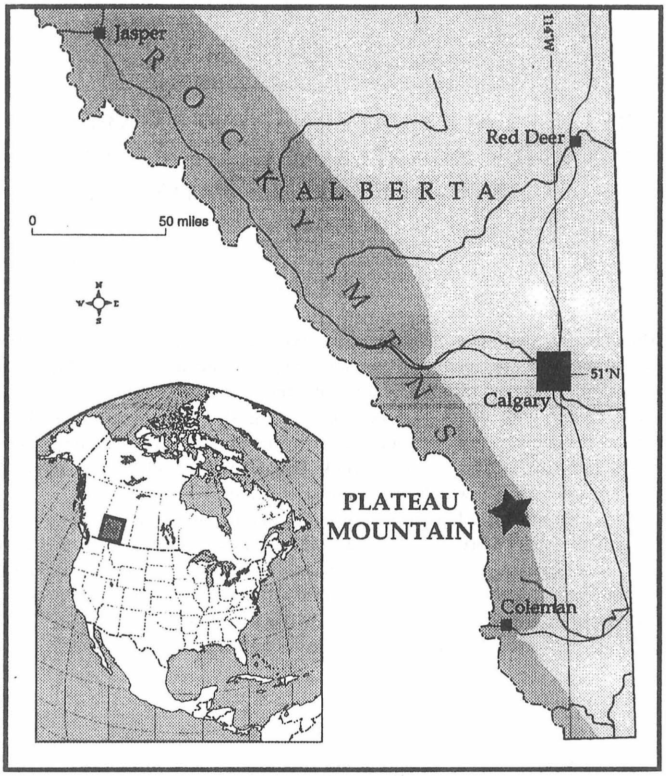

Fig. 1. Location of Plateau Mountain in southwest Alberta, Canada

Rys. 1. Położenie Plateau Mountain w SW Alberta, Kanada

Tree-line varies in height, depending on aspect (Fig. 2), but averages 2290 m elevation on the west side (BRYANT, SCHEINBERG, 1970). Typically this timberline is not sharp but includes krummholtz and glades of willow and grass among the trees, extending downward in a vertical zone to about 180 m below this elevation. Above tree-line, the lower part of the alpine zone is dominated by a grassy alpine meadow consisting of a *Carex-Cetraria* association grading upwards into lichen-covered rocks with *Salix nivalis* on the alpine tundra on the summit. The upper part of the sub-alpine forest is dominated by Engelmann spruce and alpine larch, with lesser amounts of whitebark pine, lodgepole pine and douglas fir.

The area lies in the rainshadow east of the Continental Divide. As such, the top of the mountain lies well below the glaciation limit (ØSTREM, 1966), and the top of the mountain was not glaciated during the Wisconsin

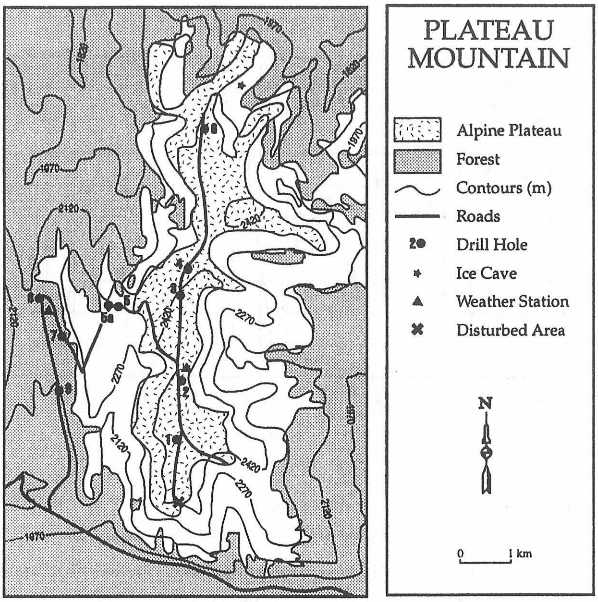

Fig. 2. Location of the ground temperature cables and alpine zone on Plateau Mountain (modified from HARRIS & BROWN, 1978)

Rys. 2. Rozmieszczenie czujników do pomiarów temperatur gruntu i strefy alpejskiej na Plateau Mountain (w/g HARRIS'A i BROWN'A, 1978; zmodyfikowane)

glaciations. The limited snowfall blows off the top to accumulate in the back of cirques on the south and east sides of the mountain (Fig. 2). Mean annual air temperature (MAAT) at 2500 m for the period 1974–1995 is –2.22°C, although the MAAT has been far more variable since 1985 (Fig. 3). During the period of study (21 years), there has been a cooling in MAAT of approximately 1.62°C.

METHODS USED

In 1974, a drilling program was commenced to determine whether permafrost was present. Over the next four years, ten boreholes (Fig. 2) were drilled and instrumented, including one to 150 m (HARRIS, BROWN, 1978, 1982). Air temperature and snow cover have been recorded at five stations since 1974, and relative humidity has been recorded since 1995 at 2500 m. Monthly measurements of the ground temperatures have been made in order to determine the presence or absence of permafrost, while the continuous record at key sites provides a check on climatic changes and changes in ground temperatures. In addition, measurements have been

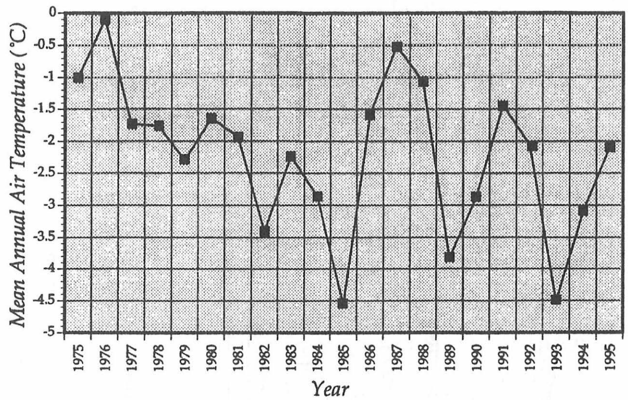

Fig. 3. Variation in mean annual air temperature at 2500 m (PM 2) on Plateau Mountain between 1974 and 1995

Rys. 3. Zmienność średnich rocznych temperatur na wysokości 2500 m n.p.m. (PM nr 2) na Plateau Mountain między 1974 i 1995

made of the temperatures in an ice cave at the north end of the mountain (Harris, 1979).

Additional studies on the mountain include the distribution of plants (e.g. Bryant, Scheinberg, 1970) and the nature of the felsenmeer and patterned ground (e.g. Woods, 1977), and these studies are continuing. The plant collections are determined in Calgary, while detailed studies of the origin of xeric alpine non-sorted circles are being carried out using neutron probes, ground temperature cables, and nests of telescoping hollow tubes of different lengths. Data loggers are being employed to examine the heat exchange characteristics of mineral soils and adjacent blockfields. Dr. Angélique Prick is examining the susceptibility of the bedrock to physical weathering by both freeze-thaw and wetting and drying cycles, using facilities at the C.N.R.S. at Caen and the Universities of Liège and Calgary.

RESULTS

Characteristics of the Permafrost

Permafrost underlies all of the alpine zone at depth. In winter, snow blows off the top of the mountain into the adjacent cirques on the east and south sides of the mountain, so that the ground is not usually insulated by snow. Average winter snow cover is 12 cm, in contrast to about 95 cm in the adjacent forest. Where the mean winter snow cover is over 50 cm,

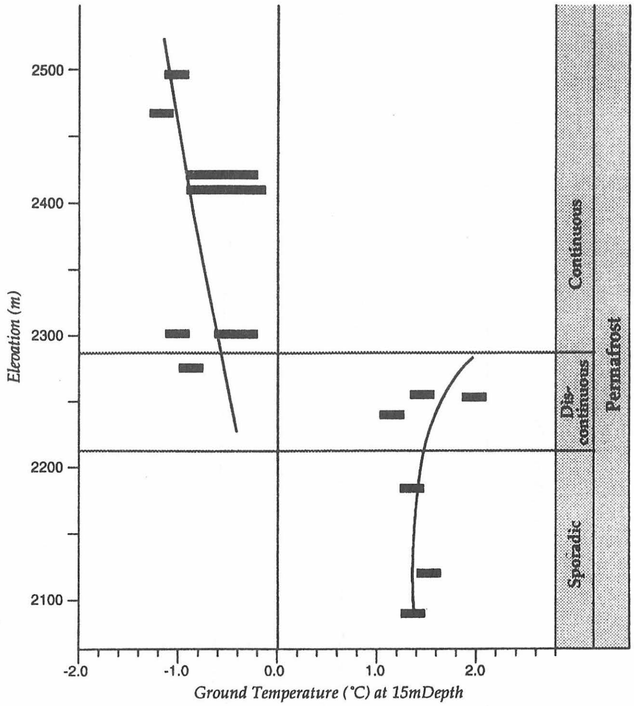

Fig. 4. Variation in ground temperature at 15 m depth as a function of altitude and vegetation cover, Plateau Mountain

Rys. 4. Zmienność temperatury gruntu na 15 m głębokości jako funkcja wysokości i pokrywy roślinnej, Plateau Mountain

permafrost is absent (Figs. 4, 5). Active layer thicknesses vary from about 5 m to 15 m (Fig. 6), and this relationship suggests that the active layer is strongly related to the present-day climate.

The 150 m borehole shows three peaks of cold temperatures at 9 m, 60 m, and 130 m depth (Fig. 7). It does not show the effects of the climatic changes apparently produced in the last 120 years that have been reported from the north slope of the Brooks Range, Alaska (see GOLD, MARSHALL, 1969; GOLD, LACHENBRUCH, 1973). The peaks of cold at about 60 m and 130 m depth probably represent relict cold from the late Wisconsin glaciation, since the Late Wisconsin glaciers only reached to about 2130 m elevation just on the west side of the mountain. To the east and south only small cirque glaciation occurred on the mountain slopes.

Figure 8 shows the ground temperatures measured at Plateau Mountain 2 by the thermistors between 1976 and 1989 (after HARRIS, 1990, Fig. 2). The air temperature and the ground temperatures between 75 cm and 6 m remained fairly constant, indicating a limited change in input of solar energy from the surface, but the temperatures at 9 m showed a decline from 1977 to about 1982, and then became constant. Since the thermistors

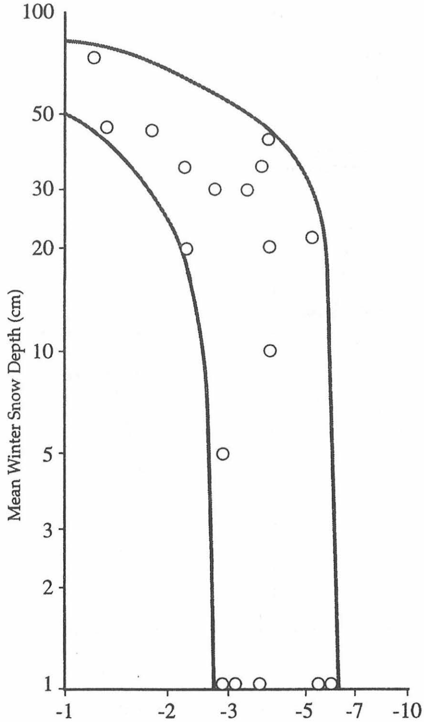

Fig. 5. Winter soil temperature at 150 cm under different mean winter snow covers, alpine zone, Plateau Mountain (modified from HARRIS & BROWN, 1978)

Rys. 5. Zimowa temperatura na 150 cm pod różną średnią zimową pokrywą śnieżną, strefa alpejska, Plateau Mountain (w/g HARRIS'A i BROWN'A, 1978, zmodyfikowane)

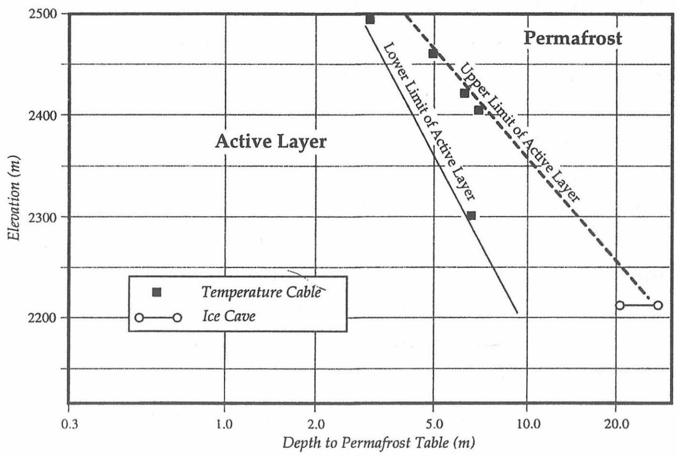

Fig. 6. Variation in thickness of the active layer with elevation, Plateau Mountain

Rys. 6. Zmienność miąższości warstwy czynnej wraz z wysokością, Plateau Mountain

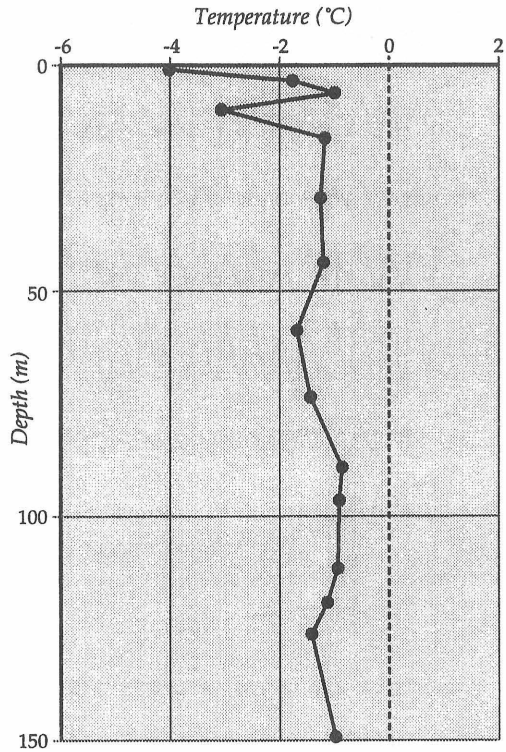

Fig. 7. Ground temperatures recorded in the 150 m borehole (PM 2A) at Plateau Mountain in 1979 (from HARRIS, 1990)

Rys. 7. Temperatury gruntu zanotowane w 150 m głębokim otworze wiertniczym (PM nr 2A) na Plateau Mountain w 1979 roku (HARRIS, 1990)

in other boreholes show no signs of a change in geothermal heat flux, this decline at 9 m appears to have been caused by moisture moving through the ground and altering the heat budget. In 1984, the thermistor at 16 m showed the beginnings of a similar decline, probably due to the same cause.

Figure 9 shows the ground temperature envelope for Plateau Mountain 1. It will be seen that the ground temperatures actually decrease with increasing depth, showing that the permafrost is still adjusting to the warmer present-day climate.

PLATEAU MOUNTAIN ICE CAVE

One of the intriguing features of Plateau Mountain is the ice cave located on the northeast slopes of the mountain (Fig. 2) at an elevation of

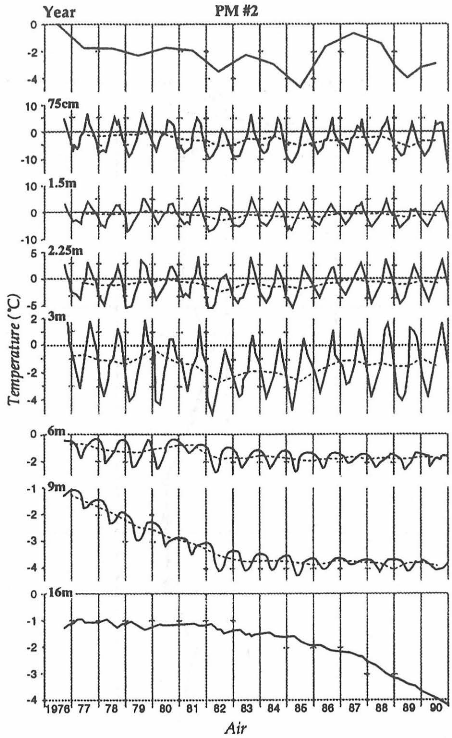

Fig. 8. Ground temperatures measured at various depths at Plateau Mountain 2 adjacent to PM 2A between 1976 and 1989, together with the mean annual air temperature. Six-month running means have been used to smooth some of the curves

Rys. 8. Temperatury gruntu pomierzone na różnych głębokościach na Plateau Mountain nr 2 obok PM nr 2A między 1976 i 1989, wraz z średnią roczną temperaturą powietrza

2225 m. The perennial ice is confined to the deepest parts of the cave (Fig. 10) and the ice includes large dendritic and hexagonal plate-like crystals up to 25 cm in diameter (Wigley, Brown, 1976) that grow at temperatures close to 0°C. Repeated measurements of the temperatures in the ice cave have shown that they remain remarkably constant and never drop lower than –0.25°C. There is no air movement within the cave and the perennial ice is slowly retreating downwards as the ground temperatures rise. This melting is aided by ground water draining downwards through joints into the roof of the cave due to melting of the ice which used to seal the fractures in the enclosing limestone. The depth to the perennial ice appears to conform to the general active layer-altitude relationship, as suggested from borehole-temperature measurements elsewhere on the mountain (Fig. 6); the temperatures in the ice also seem to conform to this relationship (Fig. 4). Retreat of the ice is most marked during summers with significant rainfall, and undoubtedly the impact of heating by groundwater is the major factor in causing melting of the upper margin of the permafrost.

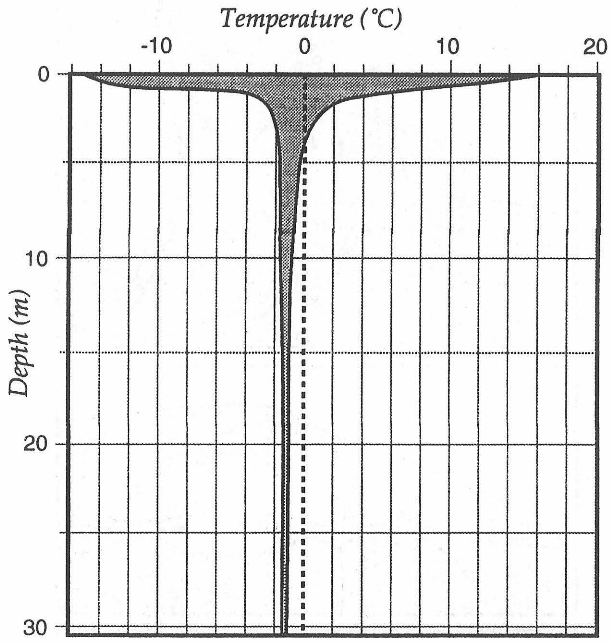

Fig. 9. Ground temperature envelope for PM 1 at 2519 m

Rys. 9. Przebieg temperatury gruntu na PM nr 1 na wysokości 2519 m

PATTERNED GROUND

Relict sorted patterned ground is widespread on the gently sloping mountain top. It ranges from sorted circles via sorted nets to sorted stripes (Woods, 1977). This is developed in a blocky mixture of sand and silt (Fig. 11) which may represent either a deposit on an old erosion surface on the summit of the mountain, or weathered siliceous limestone. This deposit is quite different in grain size from aeolian loess and is up to 40 m thick at Plateau Mountain 2A.

The stones and blocks in the margins of the sorted patterns have a marked cover of lichens on their upper surface and are bare on the underside. This suggests that the sorting occurred a long time ago and has now ceased. The variety of lichens on the calcareous substrate is exceptional (Bryant, Scheinberg, 1970), supporting this idea. Locally on top of the mountain, hollows up to 70 cm deep occur in the stony borders, suggesting that former ice wedges beneath the borders have thawed, causing substantial subsidence. Since ice wedges and sorted patterned ground are not forming in the disturbed areas today, these features must have been formed during a previous glaciation.

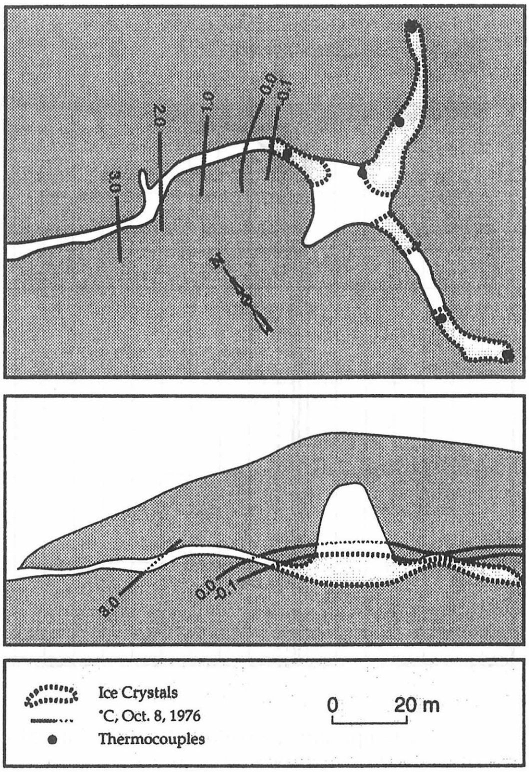

Fig. 10. Location of the perennial ice in Plateau Mountain ice cave (after HARRIS, 1979)

Rys. 10. Położenie przetrwałego lodu w jaskini lodowej na Plateau Mountain (w/g HARRIS'A, 1979)

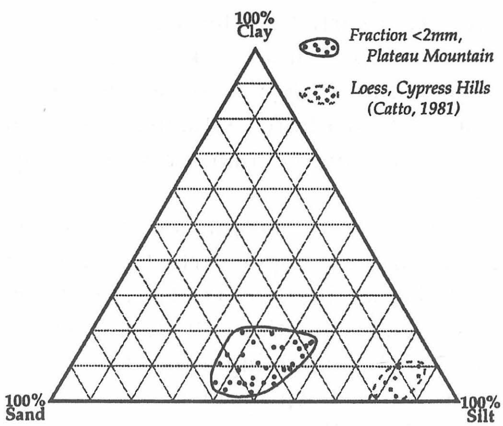

Fig. 11. Grain size distribution of the fine fraction in the sorted patterned ground, Plateau Mountain, compared with aeolian loess from the Cypress Hills (CATTO, 1981)

Rys. 11. Granulometria drobnej frakcji z gruntów strukturalnych z segregacja i lessu eolicznego z Cypress Hill (CATTO, 1981)

VEGETATION

The vegetation of North America shows many interesting features resulting from migrations (WEBER, 1965), but the nature and direction of these migrations has been disputed. Did the old Tertiary flora move north to form the pan-Arctic tundra vegetation (TOLMACHEV, 1959; HULTEN, 1962, p. 4), or did the Arctic tundra flora move south in cold periods and become stranded on mountain tops when the climate warmed (HOOKER, GRAY, 1880; DARWIN, 1883; WALLACE, 1900)? PACKER, VITT (1974) reviewed the literature on refugia in Canada and provided evidence for the presence of refugia on the unglaciated peaks in the Front Ranges of the Rocky Mountains of Alberta. Plateau Mountain lies in this zone.

At least 488 species of vascular plants have been collected on Plateau Mountain, of which 212 (43%) occur in the alpine zone. The latter show exceptional diversity of geographic distribution (Fig. 12). Some, such as *Poa pattersonii* and *Epilobium clavatum* are normally found in the mountains of southwestern U.S.A. At least 10 are pan-Arctic (e.g., *Campanula uniflora*), Beringian (e.g., *Myosotis alpestris* ssp. *asiatica*), or amphi--Atlantic (e.g., *Pedicularis flammea*) and disjunct southwards on Plateau Mountain, suggesting that HOOKER and GRAY, DARWIN and WALLACE were right in these cases. Others are only found in the range of the Rocky Mountains between Jasper and Waterton Park (Fig. 1), and indicate local speciation (e.g. *Haplopappus lyallii*). Yet others such as *Erigeron aureus* are also found in the alpine zones of the mountain tops in southeastern British Columbia across to Washington State, U.S.A.

Plateau Mountain lies in the transition zone between the Boreal forest to the north and the Montane forest to the south. However, to have conditions where alpine plants could migrate across the deserts and forests from California or down past the present boreal forest from the Arctic, there must have been a cold event when the current vegetation was replaced by tundra and the glaciers did not provide a barrier to plant migration. This probably occurred in the early and middle Wisconsin (see HARRIS, 1994). This would also provide the opportunity for those species evolved locally and relatively recently to extend their range along the Rocky Mountains in this vicinity.

HEAT FLOW INTO THE RELICT PERMAFROST

Table I shows the resultant downward heat flow based on the measured temperature decrease in specific layers in Plateau Mountain 1, 18 months after drilling. The downward ground heat flow decreases with depth. When the ground heat flows are compared for the same depth in the five

Table I

Donward heat flow in the first five boreholes in permafrost in the alpine zone on top of Plateau Mountain 1 1/2 years after drilling, based on measured thermal conductivity values and ground temperatures (modified from HARRIS & BROWN, 1978)

Site	Depth of layer m	Temperature decrease with depth for layer °C	Thermal conductivity[a] W/mk	Ground heat flow through layer[b] W/m^2	Elevation m
1	4.6–6.1	0.04	5.18	0.136	2519
1	6.1–7.6	0.04	5.18	0.136	
1	7.6–12.2	0.08	5.18	0.093	
1	12.2–15.2	0.04	5.18	0.065	
1	15.2–18.2	0.04	5.18	0.063	
1	18.2–30.5	0.12	5.18	0.053	
2	12.1–15.2	0.05	5.18**	0.085	2484
3	12.2–15.2	0.03	5.18**	0.051	2438
4	12.2–15.2	0.05	4.82	0.081	2426
5	12.2–15.2	0.05	6.10	0.120	2319

* Average of monthly observations over 1 to 2 year period and represents differences in temperatures between two levels on same instrument at same time. Thus they are relative, not absolute values.

* Values inferred from similar rock type at Site 1.

a Determinations by A. S. JUDGE, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa.

b Calculations by L. E. GOODRICH, Division of Building Research, National Research Council, Ottawa, Canada.

boreholes on the top of the mountain, they are found to tend to increase with decreasing altitude.

This heat flow confirms the idea that the permafrost is relict and still not in equilibrium with the present-day climate. However, the ground temperatures on the mountain top are the result of at least four processes acting on different parts of the mountain. The most obvious is conduction of heat, and this is assumed in the calculations used in table I. However, the effect of water percolating downwards in the soil (Fig. 8) and through cracks in the rock in the ice cave will be to increase the thawing of the upper layers of the permafrost. Thus, the difference in temperature between 6 m and 9 m in Plateau Mountain 2 in 1984 was 1.9°C, which corresponds to almost 400 times the normal heat flow calculated in table I. In the felsenmeer, this process was only encountered in one borehole out of five, while in bedrock, water can only flow along the joints. Thus it would not affect more than 10% of the felsenmeer and 3% of the bedrock, but it is still a very important factor. Its actual location will change with time as the size of the permafrost body decreases.

Once the ice has gone from the cracks in the bedrock, air can flow through the cracks at any season of the year (WIGLEY and BROWN, 1971).

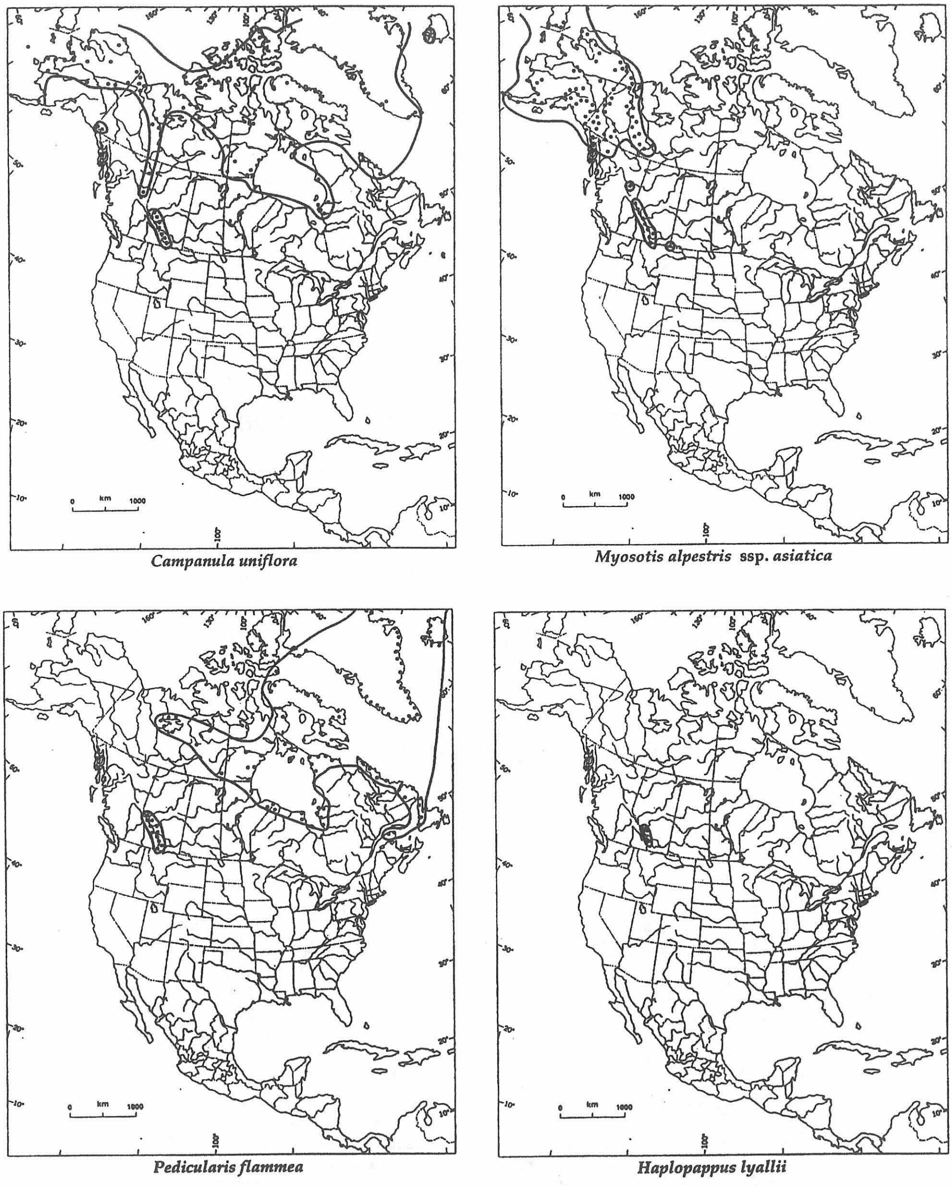

Fig. 12. Contrasting distributions in North America of four species of vascular plants found in the Alpine zone of Plateau Mountain. *Campanula uniflora* (Pan-Arctic); *Myosotis alpestris* spp. *asiatica* (Beringian); *Pedicularis flammea* (amphi-Atlantic); *Haplopappus lyallii* (local endemic)

Rys. 12. Rozmieszczenie w Ameryce Północnej 4 gatunków roślin naczyniowych występujących w alpejskiej strefie na Plateau Mountain. *Campanula uniflora* (pan–Arktyka); *Myosotis alpestris* ssp. *asiatica* (rejon M. Beringa); *Pedicularis flammmea* (wodno-lądowe północnego pobrzeża Atlantyku); *Haplopappus lyallii* (lokany endemit)

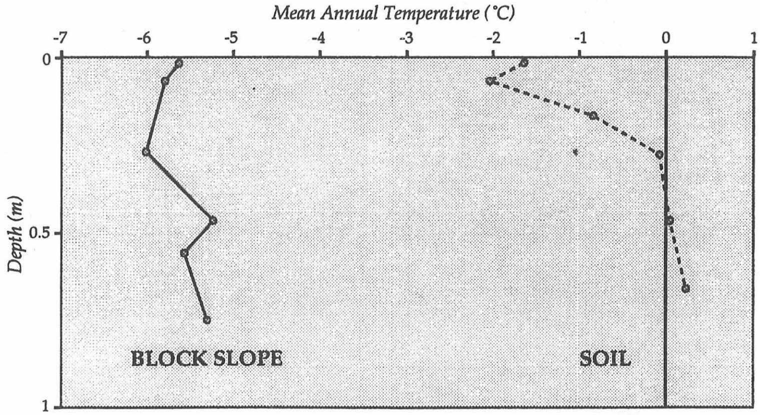

Fig. 13. Main annual ground temperature under soil and blocks, 10 m apart on a north-facing slope at Plateau Mountain in 1995

Rys. 13. Średnia roczna temperatura gruntu pod glebą i blokami 10 m od stoku z ekspozycją północną na Plateau Mountain w 1995 r.

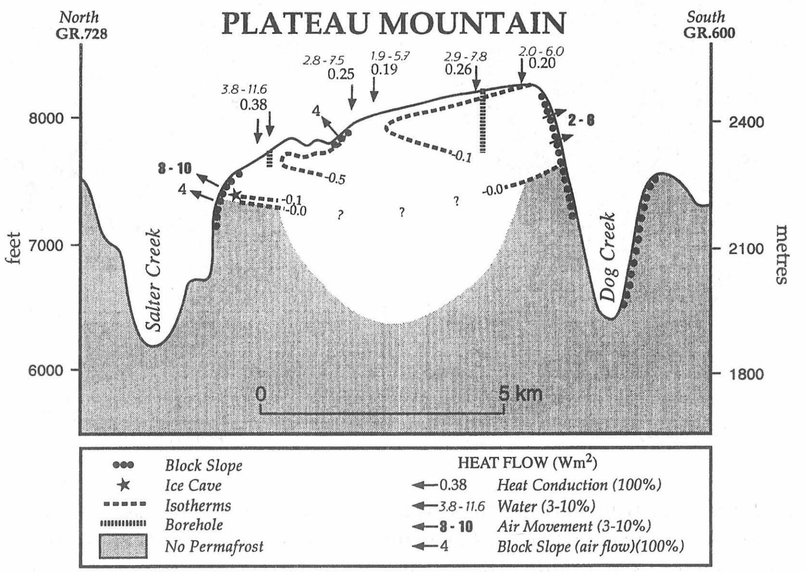

Fig. 14. Summary of the measured heat flows into and out from the permafrost body at Plateau Mountain

Rys. 14. Zestawienie pomierzonych strumieni ciepła do i ze zmarzliny na Plateau Mountain

This will occur where the bedrock outcrops at the surface on cliffs at the margins of the Plateau, and it is usual to find multiple locations with air moving through the rock. e.g. at Canyon Creek Ice Cave (HARRIS, 1979). Since there are seven months with mean air temperatures below 0°C and five months with mean air temperatures above 0°C, the net effect is to cool the rock adjacent to the cracks. Any groundwater passing through the cooled zone may form ice which acts as a reservoir of cold. Thus this will tend to counteract the effects of warming, although it will, again, only affect 3% of the rock.

The final factor modifying heat flow is the presence of block fields and coarse felsenmeer on the slopes and part of the top of the mountain. Mean ground temperatures beneath a blocky layer can be up to 7°C colder than in the adjacent soils in the Kunlun Shan (HARRIS, 1996) and similar results are being obtained from the slopes of Plateau Mountain (Fig. 13). Thus the presence of block slopes around the mountain probably serves to reduce the rate of warming of the relict permafrost in the main mass of the mountain by heat loss from its sides.

Figure 14 summarizes these heat flows as they are currently known. It will be seen that the heat conduction based on ground temperatures is only a part of the total heat fluxes. In mountains, water and air moving through the rock, together with surface materials such as blocks (kurums) can greatly modify rates of attainment of equilibrium ground temperatures locally after a climatic change. Air movement and blocky surfaces cool the underlying rocks. Thus prediction of the thermal effects of a climatic change in ground temperatures on the mountain is far more difficult than is usually assumed in models based on simple heat flow models, and the rate of change is probably nonlinear.

CONCLUSIONS

Plateau Mountain has relict permafrost on its summit that is not yet in equilibrium with the present-day climate. The near-surface ground temperature become colder with depth and heat is moving slowly into the ground. Heat flow into the ground is the result of heat conduction and groundwater movement, but this is partially counteracted by air moving through block fields or cracks in the bedrock. Groundwater and air movement produce large but localized ground temperature effects that may change location with time.

The surface shows inactive sorted patterned ground and thermokarst resulting from melting of ice wedges formed beneath the stony borders under a colder climate. The alpine vegetation includes disjunct species from the floras of the Arctic and from the west coast of the United States south to California, which can only be explained by migration of alpine floras during past cold events. Some local speciation has also occurred.

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