ARCTIC
VOL. 35, NO. 3 (SEPTEMBER 1982) P. 411-416

Earth Hummocks in the Sunshine Area of the Rocky Mountains, Alberta and British Columbia

GEORGE W. SCOTTER[1] and S.C. ZOLTAI[2]

ABSTRACT. Earth hummocks were found on the Continental Divide of the Rocky Mountains in a non-permafrost environment. Many hummocks show involutions of organic layers within 25 cm of the surface, suggesting that the hummocks are still active. The soil material is a non-plastic, silt-textured volcanic ash. During brief periods in the spring the upper soil horizons can become super-saturated with water; the soil then becomes liquid, resulting in involutions in the surface layers. This mechanism is generally erosional and it is unlikely that it contributed to the formation of earth hummocks. The hummocks are believed to be relict features that were formed under colder conditions, when permafrost was likely present in the ground.

Key words: Rocky Mountains, hummocks, permafrost, soil horizons

RÉSUMÉ. Des monticules de terre ont été trouvés le long de la ligne de partage des eaux des Rocheuses dans un milieu non affecté par le pergélisol. Nombre de ces collines présentent des involutions de couches organiques à aussi prés que 25 cm de la surface, ce qui suggère que les monticules sont toujours actifs. Le sol est formé de cendre volcanique vaseuse non plastique. Lors de courtes périodes au cours du printemps, les horizons supérieurs du sol peuvent devenir ultra-saturés d'eau; par conséquent, le sol se liquéfie, entraînant des involutions des couches de la surface. Ce mécanisme cause d'ordinaire une certaine érosion et ne semble pas avoir contribué à la formation de monticules de terre. Ces derniers sont peut-être des traits résiduels formés dans des conditions plus froides, lorsque le sol était probablement en proie au pergélisol.

Mots clés: Rocheuses, monticules, pergélisol, horizons du sol

Traduit pour le journal par Maurice Guibord.

INTRODUCTION

Earth hummocks are a particular type of nonsorted net or circle, characterized by a three-dimensional knob-like shape and a cover of vegetation (Washburn, 1980). As defined by Lundqvist (1969), earth hummocks consist of mineral soil, but involutions of organic and mineral soil are typical, indicating that the mineral soil has been forced upward into and through the humus cover.

Earth hummocks are a circumpolar phenomenon found in northern Europe (Lundqvist, 1969), Greenland (Raup, 1965), Iceland (Schunke, 1977), and in many permafrost regions of northern Canada such as the subarctic forest of the Mackenzie Valley, the Yukon, the western and central Arctic, and on the Arctic Islands (Tarnocai and Zoltai, 1978). In contrast, there have been few reports from alpine regions of North America (Sharp, 1942; Johnson and Billings, 1962; Knapik *et al.*, 1973; Knapik and Coen, 1974).

In the North American Arctic and Subarctic, earth hummocks are nearly always associated with permafrost (Tarnocai and Zoltai, 1978). The rare earth hummocks in non-permafrost soil are believed to be fossil forms, as indicated by well-developed soil horizons that are not disrupted or involuted (Zoltai and Tarnocai, 1974). However, in northern Europe earth hummocks are found in non-permafrost environments. Some of these are regarded as fossil forms (Aartolahti, 1969; Schunke, 1975), but others are active (Lundqvist, 1962; Schunke, 1977).

Earth hummocks having involuted soil horizons were found in the Sunshine area of the Rocky Mountains, Alberta and British Columbia, in a non-permafrost environment. In this paper the physical characteristics, soils, associated vegetation, climate, and possible mechanism of hummock formation are described.

STUDY AREA

The Sunshine area is located in the Canadian Rocky Mountains 16 km southwest of Banff townsite (51°04′N, 115°47′W) in Alberta and British Columbia. Sunshine is an extensive, undulating alpine area dotted with several shallow lakes along the Continental Divide, and has an average elevation of 2225 m AMSL. The area was glaciated during the Pleistocene period.

Several plant community types exist at Sunshine. The relationship of these communities to soil types was described by Knapik *et al.* (1973). Scattered clumps and individuals of *Larix lyallii* and *Abies lasiocarpa* occur above the timberline around 2240 m AMSL and the trees are stunted and twisted. Alpine vegetation is found from timberline to 2969 m AMSL on the summit of Lookout Mountain, which is the highest peak in the area.

The winters at Sunshine are long and cold; the summers are short and cool. Strong winds are common throughout the year. Precipitation is low in summer but high in winter; for eight to nine months each year the ground is covered with 1-4 m of snow, and depressions on some north- and east-facing slopes may remain snow-filled all year.

There are five locations at Sunshine where earth hummocks occur, all close to Rock Isle Lake at elevations between 2215 and 2280 m AMSL. Three of these areas, referred to as T-23, T-24 and T-25, were selected for detailed study. The hummocks occur on the flat floor of shallow, basin-like depressions 30-100 m in diameter.

[1]Canadian Wildlife Service, 1000, 9942 - 108 Street, Edmonton, Alberta, Canada T5K 2J5
[2]Northern Forest Research Centre, 5320 - 122 Street, Edmonton, Alberta, Canada T6H 3S5

METHODS

Fifty measurements of diameter and height were taken along randomly selected lines at two of the study sites. Means and standard deviations were calculated.

Soils were described and classified according to the Canadian System of Soil Classification (Canada Soil Survey Committee [CSSC], 1978). Soil samples of major horizons for each pedon were subjected to physical analyses. Analytical methods were those used by the Canada Soil Survey, as outlined by McKeague (1978). Soil samples of known volume were collected with a piston sampler, and moisture content was determined by comparing their weights before and after oven drying. Bulk samples were collected from involuted and near-surface Ah horizons and wet sieved with distilled water to eliminate live roots. The radiocarbon dates of the samples were determined by the Radiocarbon Laboratory, Brock University.

In order to analyze the cover and frequency of plants on the hummocks, we marked off 4 x 10-m areas with tape, subdivided the 10-m side into 20 rows and randomly selected eight rows for sampling. Four plots (0.2 x 0.5 m) spaced 0.5 m apart in each row were selected and analyzed. On even-numbered rows the first plot was next to the tape; on odd-numbered rows the first plot was placed 0.5 m from the tape.

RESULTS

The hummocks consist of closely spaced mounds of mineral earth that are covered with a continuous blanket of vegetation (Fig. 1). The height of the hummocks averages 15-19 cm; average diameter at the base is between 50 and 75 cm (Table 1). Hummocks in the center of the depressions are higher than those on the periphery. A few hummocks have bare or sunken tops.

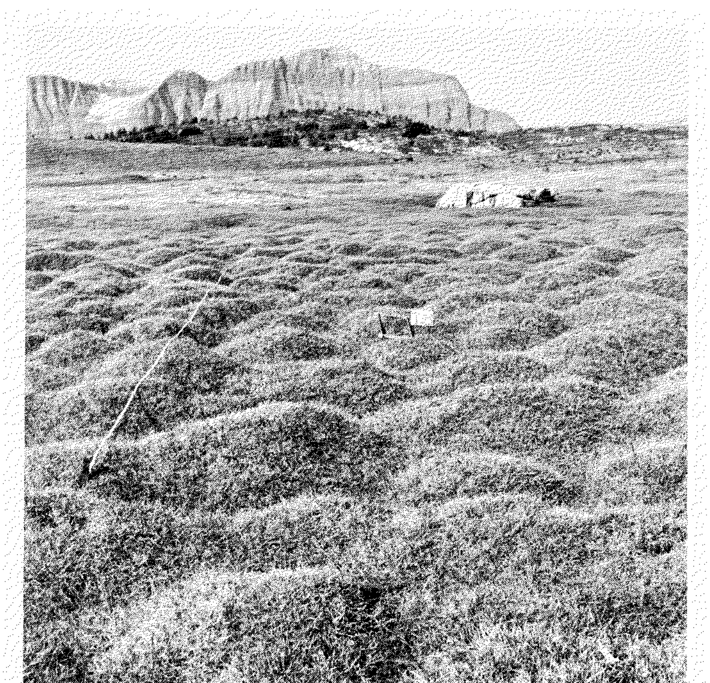

FIG. 1. A group of closely-spaced earth hummocks in a small basin (Area T-23).

TABLE 1. Description of hummocks and hummock areas in the Sunshine area

Characteristics	T-23	T-24	T-25
Elevation	2250 m AMSL	2215 m AMSL	2280 m AMSL
Topography	depression	depression	depression
Drainage Class	imperfectly drained	imperfectly drained	imperfectly drained
Vegetation	*Carex nigricans*	*Carex nigricans*	*Carex nigricans*
Hummock height (n = 50)			
Range	5-28 cm	10-33 cm	
Mean	15.4 cm	19.2 cm	
Standard deviation	6.6 cm	5.5 cm	
Hummock diameter (n = 50)			
Range	17-90 cm	30-130 cm	
Mean	51.4 cm	74.1 cm	
Standard deviation	19.3 cm	25.3 cm	

A lacustrine deposit 0.5 m thick lines the depressions in which the hummocks occur, covered by 0.5-1 m of aeolian volcanic ash. In the study area the volcanic ash is restricted to the hummocky depressions, as no perceptible amounts were found on nearby slopes. The ash consists mainly of silt-sized particles (Table 2). Faint horizontal bedding is apparent in the lower part of the ash deposit over the horizontally bedded lacustrine silt.

The soil horizons have developed within the volcanic ash layer, consisting of a sequence of Ah, Bm, and C horizons (Table 3). However, the Ah and upper Bm horizons of the hummocks have been described by Knapik *et al.* (1973) as contorted and discontinuous due to frost action (Figs. 2 and 3). According to the Canadian soil classification system, the soil is an Orthic Melanic Brunisol, turbic phase (CSSC, 1978). In the U.S. classification system, these soils would be classified as (Turbic) Dystric Cryandepts (Soil Survey Staff, 1975).

TABLE 2. Particle size of soils at T-25 in the Sunshine area[1]

Horizon	Textural class	Parent material	Particle size in mm 2-0.05	0.05-0.002	<0.002
Ah	Silt loam	Volcanic ash	16	79	5
Bmul	Silt	Volcanic ash	17	82	1
Bmu2	Silt loam	Volcanic ash	26	70	4
Bml	Silt	Volcanic ash	19	80	1
IICg2	Silt loam	Lacustrine	20	63	17

[1]Modified from Knapik, L.J. 1973. Alpine soils of the Sunshine area, Canadian Rocky Mountains. Unpublished M.Sc. thesis, Department of Agriculture, University of Alberta, Edmonton, Alberta. 231 p.

TABLE 3. Description of soil horizons at T-25 in the Sunshine area[1]

Horizon	Thickness	Description
Of	7-10 cm	Fibric peat
Ah	0-10 cm	Dark brown (10YR 3.5/3 m) silt loam, pH 6.2
Ahu	0-24 cm	Dark brown (10YR 3.5/3 m) silt loam
Bmul	0-14 cm	Reddish brown (5YR 4/4 m) silt loam, pH 6.0
Bmu2	0-22 cm	Yellowish brown (10YR 5/6 m) silt loam, pH 6.4
Bm	10-15 cm	Reddish brown (5YR 5/4 m) interband and strong brown (7.5YR 5/8 m) bands; silt; pH 5.9
C	8-10 cm	Pale brown (10YR 6/3 m) silt
IICgl	9 cm	Very dark grayish brown (2.5Y 3/2 m) silt loam
IICg2	10+ cm	Dark grayish brown (2.5Y 4/2 m) silt loam, pH 6.1

[1]Modified from Knapik, L.J. 1973. Alpine soils of the Sunshine area, Canadian Rocky Mountains. Unpublished M.Sc. thesis, Department of Agriculture, University of Alberta, Edmonton, Alberta. 231 p.

In spring and fall 1980, we measured soil moisture content at the apex, trough, and midpoint of a hummock. In the spring we encountered remnants of the seasonally frozen layer, chiefly under the hummocks, but thawing was already complete under most interhummock troughs. The moisture content of the upper soil layers varies considerably with the seasons. In the spring high moisture levels were found in the still frozen soil (68-78% by volume, 138-193% by weight), in contrast with the soil both above and below (Table 4). In the fall the moisture levels were considerably lower and uniform throughout the volcanic ash layer (Fig. 4). The high values of moisture by weight in the Ah horizons are caused by the low bulk density of the organic-rich horizons (Table 4); it is therefore more appropriate to use the volume basis.

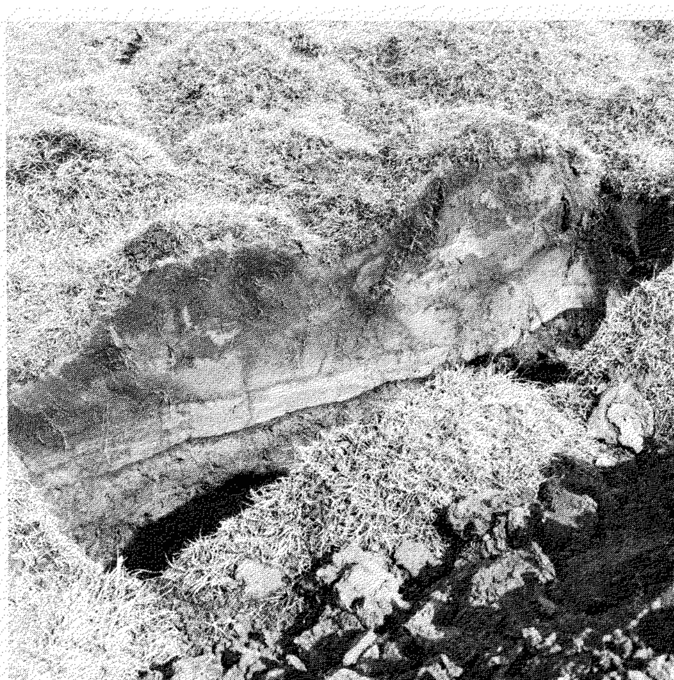

FIG. 2. Cross section of two hummocks. The convoluted upper horizons and the sharp, even boundary between volcanic ash and lacustrine sediments are evident (Area T-25).

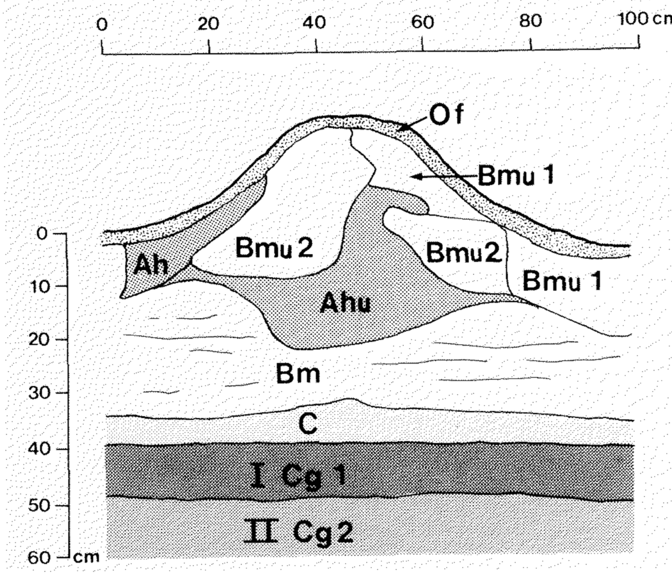

FIG. 3. Soil profile of an earth hummock at T-25 in the Sunshine area. The subscript 'u' indicates turbation.

The mechanical properties of the volcanic ash were examined by determining the Atterberg limits. The liquid limit was reached at 90% moisture content by weight. The soil is nonplastic, crumbling even at moisture content levels above 90%.

Samples for radiocarbon dating were collected from two hummocks in different areas. Two samples were taken from one hummock (Area T-25). Sample 1-1 was from an involution in the Ah horizon 17-23 cm below the surface of the apex and yielded a radiocarbon date of 3000±100 years B.P. (BGS-695). Another sample from an undisturbed Ah horizon 5-8 cm below the surface of the same hummock was dated at 1680±100 years B.P. (BGS-696). Sample 2-1, from a hummock some 0.5 km away in area T-23, was taken from an involuted Ah horizon at 14-20 cm below the surface of the apex; it yielded a date of 2600±100 years B.P. (BGS-697).

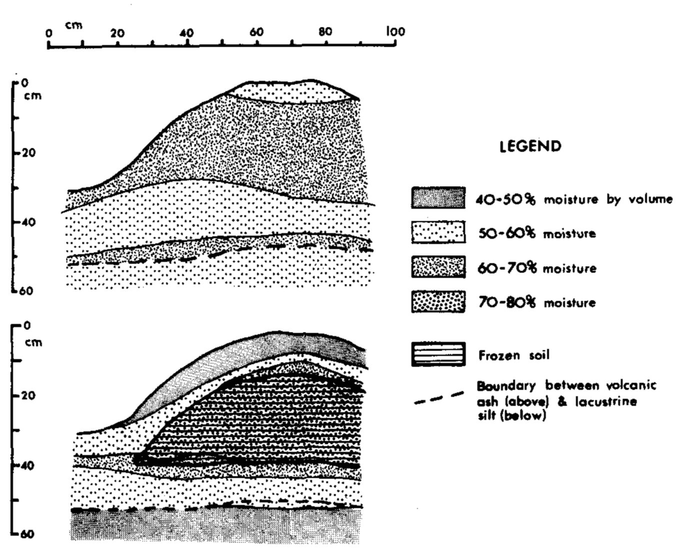

FIG. 4. Moisture content of a hummock in the fall (above) and in the spring (below), expressed as % moisture by volume.

TABLE 4. Moisture content of soil by volume and by weight under the apex of a hummock, 17 June 1980 (spring) and 8 October 1980 (fall)

Soil horizon	Depth (cm)	% moisture by volume		% moisture by weight	
		Spring	Fall	Spring	Fall
Ah	8-11	54.2	56.2	149.8	120.1
Ahu	13-15	*72.6	61.5	*192.9	120.5
Bmu2	20-23	*74.1	61.4	*166.0	113.9
Bm	30-34	*73.6	61.6	*158.2	123.8
Bm	36-39	63.4	60.5	119.6	112.0
IICgl	60-63	43.0	53.1	39.6	44.2

*Seasonally frozen when sampled.

A nearly complete mat of vegetation covers the hummocky depressions, dominated by *Carex nigricans* at all sites (Table 5). Plants are distributed evenly on the tops of the hummocks and in the interhummock areas, although bryophytes (*Dicranum fuscescens, Lescuraea incurvata, L. radicosa, Pogonatum alpinum,* and *Pohlia cruda*) are found most frequently in the depressions. Lichens such as *Cetraria islandica, Cladonia coccifera, C. ecmocyna, Lecidea granulosa,* and *Peltigera aphthosa* and a hepatic, *Anthelia juratzkana,* are occasionally present on the sides of hummocks.

Small bare patches occur on the tops of a few hummocks (Fig. 5), occasionally extending down the sides. In some cases the destruction of vegetation is attributable to burrowing by ground squirrels (*Spermophilus columbianus*). Needle ice was observed on bare areas as often as two to three times a week during the summer of 1969 and 1970.

In the hummock basins, the snow generally melts by early to mid-June, but late-melting snowbeds may persist for another two weeks along the basin margins. During the snowmelt the hummocky depressions usually become

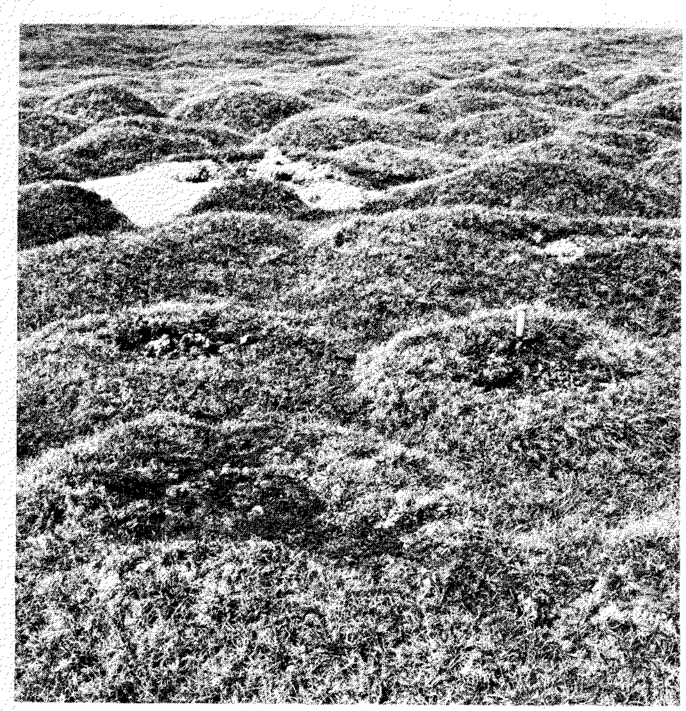

FIG. 5. Group of hummocks, with three hummocks in the foreground having bare, somewhat depressed tops. The mineral soil in the background is a soil pit (Area T-25).

TABLE 5. Percent cover and percent frequency of plants on earth hummocks in the Sunshine area

	T-23		T-24		T-25	
	Cover	Frequency	Cover	Frequency	Cover	Frequency
Grasses, sedges and rushes						
Phleum alpinum	0.3	25	0.8	34	2.9	69
Poa alpina	0.2	13	0.2	9	0.4	19
Poa paucispicula	*	3	0.1	9	—	—
Trisetum spicatum	0.1	3	0.3	6	—	—
Vahlodea atropurpurea ssp. *latifolia*	*	6	*	3	—	—
Carex attata var. *atrosquamosa*	0.2	3	—	—	5.8	19
Carex nigricans	90.9	100	92.8	100	89.7	100
Juncus drummondii	—	—	—	—	0.6	13
Forbs						
Antennaria alpina	*	13	—	—	0.2	3
Anemone drummondii	—	—	0.2	13	—	—
Anemone occidentalis	—	—	—	—	0.1	3
Epilobium alpinum	—	3	—	—	—	—
Erigeron sp.	—	—	—	—	—	3
Sibbaldia procumbens	6.8	91	*	3	—	—
Veronica alpina var. *unalaschensis*	*	3	—	—	0.2	6
Others						
Litter	2.7	38	6.3	75	0.9	16
Lichens	0.4	28	0.1	3	0.1	6
Bryophytes	3.8	94	0.8	88	4.6	100
Bare ground	0.3	9	0.8	13	0.2	6

* = trace, <0.1%

flooded with meltwater and only the top few cm of the hummocks remain above water.

There are many temperature fluctuations about 0°C along the Continental Divide (Fraser, 1959). During the period 16 July to 1 September 1970 (48 days) there were only eight days when temperatures did not drop to or below 0°C. The temperature dropped below 0°C twice on eight days, three times on three days and five times on one day. Freeze-thaw cycles can be divided according to their frequency and duration into short cycles (freeze-thaw several times in one day), daily cycles, several-day cycles, annual cycles, and several-year cycles (Rapp, 1970). Sunshine's could be described as a combination of short and daily cycles.

No evidence of permafrost was found within 2 m of the surface at any site, although permafrost occurs on a nearby ridge (Scotter, 1975). The seasonal frost penetrates no more and possibly less than 50 cm, as shown by the remnant of frost in June. However, temperature fluctuations above and below 0°C are common in the top 20 cm of the soil during snowmelt. Thorn (1979) found that in the Colorado Front Range 115 freeze-thaw cycles occurred in the soil during the two months before the melting of the snowpack, although only nine cycles exceeded the amplitude of 4°C. After the meltout up to 16 freeze-thaw cycles were recorded at a depth of 20 cm.

DISCUSSION

In the Sunshine area earth hummocks occur only in small depressions where 50+ cm of volcanic ash has accumulated. This volcanic ash was identified by J.A. Westgate (Knapik *et al.*, 1973) as Mazama ash, originating from an eruption of Mt. Mazama at Crater Lake, Oregon, about 6600 years ago (Westgate and Dreimanis, 1967).

Volcanic ash is found only in depressions, without discernible amounts in the soils on the surrounding slopes. In the basins, the volcanic ash is underlain by stonefree lacustrine silt of varying thickness over the till. This sequence suggests that the ash was concentrated in the basins of small ponds by erosion from the surrounding slopes.

In order to determine the possible mechanism of earth hummock formation, we must examine their internal morphology. All excavated hummocks show evidence of displaced soil horizons within the top 25 cm. These appear as convoluted organic- or iron-rich horizons, suggesting plastic flow of viscous mass. Their direction indicates a displacement from the sides toward the center. In some instances an upward movement at the center is suggested. Such convolutions and displacement patterns are typical of earth hummocks occurring in the permafrost regions of northern Canada where they are related to cryoturbation (Tarnocai and Zoltai, 1978). Below the convoluted layer, however, the volcanic ash shows faint horizontal bedding, suggesting deposition in a pond. The transition between the ash and the underlying lacustrine silt is sharp and not distorted, indicating that the lower parts of the soil remained stable.

FIG. 6. Cross-section of a hummock with a bare top. Convoluted organic streaks (dark) and parent material (light) suggest upward movement under the bare patch on the hummock (Area T-25).

The displacement of soil is neither frequent nor severe enough to prevent vegetation from covering the hummocks, although evidence points to a flow of liquefied soil from the occasional bare patches noted previously. In cross section, streaks of subsoil material extend to the surface under bare hummock apices (Fig. 6). These features indicate that, while the hummocks are not active enough to prevent vegetation from covering them, occasional eruptions of material do take place. Internally, the absence of continuous soil horizons under the bare patches also indicates some relatively recent activity.

The high levels of moisture in the seasonally frozen volcanic ash may be due to ice lensing. During the freeze-up process, moisture is drawn from the surrounding soil to the freezing front, where it freezes into ice lenses (Penner, 1963). Moisture continues to migrate to the freezing front as it advances, resulting in a seasonally frozen layer that is high in moisture. The moisture in the underlying unfrozen soil may be replenished from the groundwater table or from the sideslopes of the basin.

Any speculation on the genesis of these earth hummocks must take the preceding features into account. Current theories of earth hummock formation include the cryostatic and the equilibrium theories (Mackay, 1980), both of which require the presence of a permafrost table. The hydrostatic (Lundqvist, 1969) and the frost thrusting (Schunke, 1977) theories require only seasonal frost, but neither theory explains why earth hummocks do not occur in temperate North America where winter frost is present.

The earth hummocks in Iceland are largely restricted to medium-grained volcanic ash (Schunke, 1977) and bear a remarkable resemblance to the hummocks at Sunshine in both internal and external morphology. The earth hummocks in the lowlands are largely inactive and are regarded as fossil forms that developed during a colder climatic period (Schunke, 1975). In the highlands they are not related to permafrost, although in some cases permafrost has been found under the earth hummocks (Schunke, 1977) and it may have been present in the hummock fields a century ago (Thorarinsson, 1951). In Sweden, earth hummocks occur only rarely below the timber line (Lundqvist, 1962). In both regions, as at Sunshine, permafrost is only marginally absent. A slightly cooler climate in the past could have induced permafrost in all these areas.

Radiocarbon dates from Sunshine show the age of the surface and involuted humus, but not the date of involution development. The surface humus took 1680 years to accumulate. Assuming that the humus which was later involuted into the soil also required 1680 years to accumulate while still at the surface, the age of involution may be approximately dated by the difference between the ages of the involuted and surface humus. Thus at Area T-25 a date of 3000 − 1680 = 1320 years B.P., and at Area T-23 a date of 2600 − 1680 = 920 years B.P., are indicated as the approximate dates of involution development. Because of the assumptions involved in deriving these dates, the dates should be taken only as indications of orders of magnitude of time elapsed since the involutions were formed, and not as absolute values.

The near-surface involutions of relatively recent age can be explained by the temporary liquefaction flow of the supersaturated surface layer on the hummocks. Observations suggest the following sequence of events. As the ice-rich soils thaw in the spring, the soil becomes saturated with water, well beyond its liquid limit. The soil may become liquefied in response to changes in pressure during the frequent freeze-back periods. The liquefied soil either is displaced by gravity flow under the organic mat, or it can be extruded to the surface where the vegetation mat is disrupted by rodents or cracks created by frost heaving. The extruded soil will cover some of the vegetated mat, initiating more buried Ah horizons. This process is largely erosional, as material is displaced from the hummock apices and it is unlikely that it was responsible for the formation of the hummocks.

CONCLUSIONS

The hummocks at Sunshine were created by a set of special circumstances. Fine-grained volcanic ash was concentrated in small, local basins by erosion. The texture of the ash was suitable for intensive frost heaving and there was ample moisture in the soil within the basin for frost action. Earth hummocks were formed during a slightly cooler climate when permafrost was present in the moist depressions. The dense sedge vegetation helped to preserve their shape even after they were no longer active. Because the volcanic ash is nonplastic, sufficient moisture is released from the thawing seasonal frost to liquefy the upper soil layers, creating involutions of organic materials. The involutions may be recent, but the earth hummocks themselves are relict features.

REFERENCES

AARTOLAHTI, T. 1969. On patterned ground in southern Finland. Annales Academiae Scientiarum Fennicae, Series A, III. Geologica-Geographica No. 104. 30 p.

CANADA SOIL SURVEY COMMITTEE. 1978. The Canadian system of soil classification. Canada Department of Agriculture, Research Branch, Publication No. 1646. 164 p.

FRASER, J.K. 1959. Freeze-thaw frequencies and mechanical weathering in Canada. Arctic 12:40-53.

JOHNSON, P.L. and BILLINGS, W.D. 1962. The alpine vegetation of the Beartooth Plateau in relation to cryopedogenic processes and patterns. Ecological Monographs 23:105-135.

KNAPIK, L.J. and COEN, G.M. 1974. Detailed soil survey of the Mount Revelstoke summit area. Alberta Institute of Pedology Publication No. M-74-3. 118 p.

KNAPIK, L.J., SCOTTER, G.W. and PETTAPIECE, W.W. 1973. Alpine soil and plant community relationships of the Sunshine area, Banff National Park. Arctic and Alpine Research 5(3):A161-A170.

LUNDQVIST, J. 1962. Patterned ground and related frost phenomena in Sweden. Sveriges Geologiska Understöknig Ser. C. No. 583. 101 p.

______. 1969. Earth and ice mounds: a terminological discussion. In: Péwé, T.L. (ed.). The Periglacial Environment. Montreal:McGill-Queen's University Press. 203-215.

MACKAY, J.R. 1980. The origin of hummocks, western Arctic Coast, Canada. Canadian Journal of Earth Sciences 17:996-1006.

McKEAGUE, J.A. (ed.). 1978. Manual on soil sampling and methods of analysis. Canadian Society of Soil Science. 212 p.

PENNER, E. 1963. Frost-heaving in soils. In: Proceedings of the 1st Permafrost International Conference. National Academy of Sciences-National Research Council Publication No. 1287. 197-202.

RAPP, A. 1970. Some geomorphological processes in cold climates. In: Ecology of the Subarctic Regions (Helsinki Symposium). UNESCO, Ecology and Conservation No. 1. 105-114.

RAUP, H.M. 1965. The structure and development of turf hummocks in the Mesters Vig District, northeast Greenland. Meddelelser om Grønland, Bd. 160. 112 p.

SCHUNKE, E. 1975. Neue Beobachtungen zur Periglazialmorphologie Islands (Ein Forschungsbericht). Die Erde 106(1-2):47-56.

______. 1977. Zur Genese der Thufur Islands und Ost-Grönlands. Erdkunde 31:279-287.

SCOTTER, G.W. 1975. Permafrost profiles in the Continental Divide region of Alberta and British Columbia. Arctic and Alpine Research 7:93-95.

SHARP, R.P. 1942. Soil structures in the St. Elias Range, Yukon Territory. Journal of Geomorphology 5:274-301.

SOIL SURVEY STAFF. 1975. Soil taxonomy. U.S. Department of Agriculture, Soil Conservation Service, Agriculture Handbook No. 436. 754 p.

TARNOCAI, C. and ZOLTAI, S.C. 1978. Earth hummocks of the Canadian Arctic and Subarctic. Arctic and Alpine Research 10:581-594.

THORARINSSON, S. 1951. Notes on patterned ground in Iceland, with particular reference to the Icelandic "flas". Geografiska Annaler 33:144-156.

THORN, C.E. 1979. Ground temperatures and surficial transport in colluvium during snowpatch meltout; Colorado Front Range. Arctic and Alpine Research 11:41-52.

WASHBURN, A.L. 1980. Geocryology. New York: John Wiley and Sons. 406 p.

WESTGATE, J.A. and DREIMANIS, A. 1967. Volcanic ash layers of Recent age at Banff National Park, Alberta, Canada. Canadian Journal of Earth Sciences 4:155-161.

ZOLTAI, S.C. and TARNOCAI, C. 1974. Soil and vegetation of hummocky terrain. Environmental-Social Committee, Task Force on Northern Oil Pipeline Development. Report 74-3. 86 p.