INFLUENCE OF ORGANIC (O_f) LAYER THICKNESS ON ACTIVE-LAYER THICKNESS AT TWO SITES IN THE WESTERN CANADIAN ARCTIC AND SUBARCTIC

With 5 figures and 5 tables

STUART A. HARRIS

Zusammenfassung: Einfluß der Dicke des organischen Horizontes (O_f) auf die Mächtigkeit des Auftaubodens an zwei Standorten in der Westkanadischen Arktis und Subarktis

In zwei Gebieten Westkanadas mit kontinuierlichem Permafrost beeinflußt der organische Horizont (O_f) mit einer Mächtigkeit oberhalb des Schwellenwertes von 2,5 cm die Wärmeaustauschprozesse derart, daß der natürliche Logarithmus der Mächtigkeit des Auftaubodens mit wachsender Dicke der organischen Auflage zunehmend geringer wird. Der Steigungswert dieser Beziehung ist klimaabhängig, er wird in höheren Breiten steiler. Oberhalb einer bestimmten O_f-Mächtigkeit (16 cm bei Inuvik) wird die Auftaubodenmächtigkeit relativ konstant. Hangneigung, Bodentextur, Auslage, Vegetationsdecke und Entwässerungsbedingungen rufen kleinere Abwandlungen hervor. Wird die O_f-Lage dünner als 2,5 cm, üben die anderen Geländefaktoren den Haupteinfluß auf die Mächtigkeit des Auftaubodens aus.

In Hochgebirgen wie den St. Elias Mountains führen Unterschiede in der Mächtigkeit des organischen Horizontes zu augenfälligen Änderungen der Auftaubodenmächtigkeit mit der Höhe, so daß wenig oberhalb der Baumgrenze der Auftauboden tiefgründer ausgebildet sein kann als 200 m unterhalb der Baumgrenze. Die Beziehung zwischen der Mächtigkeit der organischen Auflage und der Auftaubodenmächtigkeit ist gebietsspezifisch; ist sie jedoch einmal bekannt, so hat sie erhebliche Bedeutung für die Bestimmung der Mächtigkeit organischer Mulchauflagen (z. B. von Torf, Holzspänen usw.), die zur Stabilisierung des Auftaubodens in Bereichen mit anthropogenen Störungen benötigt werden. Der Wandel klimatischer Faktoren (Temperatur und Schneedecke) muß gesondert berücksichtigt werden.

Angaben über die Auftaubodenmächtigkeit, welche nicht die Variabilität an bzw. zwischen den Standorten berücksichtigen, sollten mit Vorsicht behandelt werden. Gute Beispiele für die Variabilität liefern die Daten aus den St. Elias Mountains und von Inuvik (Tab. 2 u. 4). Angesichts dieser Variabilität liegt auf der Hand, daß eine sinnvolle Kartierung von Frostböden nahe der Südgrenze des Permafrostes auf Schwierigkeiten stößt.

Introduction

The thickness of the active layer is probably one of the most important parameters in the successful design of foundations in permafrost areas, but there have been few systematic studies of its variability under natural conditions. BROWN (1973, 1978) showed that some of the variations at a series of stations in Northern Canada could be correlated with certain climatic and terrain factors, but other variations defied explanation.

Table 1 shows the data fom BROWN (1978) arranged to show the amount of variation at eleven sites between 1974 and 1976. The year in which maximum thaw depth occurred varied from site to site at a given location, while actual differences between maximum and minimum depths ranged up to 71 cm. These variations represent a variability of up to $\pm$ 42.9% of the mean active-layer thickness, and give an area of the difficulty of accurate prediction.

BROWN and PÉWÉ (1973) summarized the main controlling climatic and terrain factors, but omitted the effects of Man (HARRIS 1986a). The effects of the climatic factors such as freezing and thawing indices and snow depth are relatively well documented (BROWN 1966b; MACKAY 1978; NICHOLSON 1978; HARRIS a. BROWN 1978; HARRIS 1981), while ROUSE (1983) has examined the energy exchange during part of the year in wet and dry tundra at Churchill.

JAHN (1946; 1985, 22–24) has shown that the surface of the active layer in Greenland thaws rapidly in the spring, but the rate of thickening decreases with the square root of the time in days from the commencement of thawing. Thus in the northern hemisphere, the rate of thickening is small in August and September. This is in accordance with the general equation for conductive heat transfer in freezing and thawing ground published by TERZAGHI (1952). In actual practice, local variations in persistence of snow cover, and differing moisture regimes and textures resulting in different thermal conductivities of the soil materials mask this relationship in wet, well vegetated areas (Fig. 1), while the type of vegetation also affects the results (JAHN, 1985, Fig. 2–5).

Since the climate usually becomes colder at higher elevations, the active layer is normally expected to become thinner with altitude. Field measurements support this conclusion, GORBUNOV (1978, 1980) reporting a decrease in active-layer thickness of 20 cm

Table 1: Variation in active-layer thickness between 1974 and 1976 at a series of sites in Northern Canada (modified from Brown *1978, 18)*

Schwankungen in der Auftaubodenmächtigkeit zwischen 1974 und 1976 für eine Reihe von Lokalitäten im Norden Kanadas (verändert nach Brown 1978, 18)

Location		Active layer thickness (cm) 1974	1975	1976	Mean active layer tickness (cm)	Range (cm)	% of Mean
Churchill							
	1	739	768	777	761.3	38	5.0
	2	61	94	76	77.0	33	42.9
	3	46	52	52	50.0	6	12.0
Rankin Inlet							
	1	329	344	326	333.0	18	5.4
	2	143	155	152	150.0	12	8.0
	3	113	131	107	117.0	24	20.5
	4	116	128	128	124.0	12	9.7
Heninga Lake							
	1	290	341	341	324.0	51	15.7
	2	216	287	259	254.0	71	28.0
	3	158	174	182	171.3	24	14.0
	4	104	146	140	130.0	42	32.3

for each 100 m increase in altitude between 3100 m and 4100 m in the Northern Tien Shan, and its absence above 4500 m. On the west side of the Andes at latitude 33 °S, Marangunic (1976) reported a 5 m thick active layer at 3700 m, while Lliboutry (1961) reported a thickness of only 30 cm at 5300 m elevation. On the east side at the same latitude, Corte et al. (1984) and Corte (1985) report active-layer thicknesses of 1–2 m at 3200m, 70 cm at 3700m,

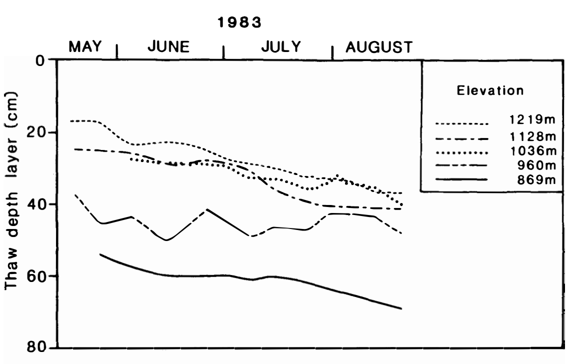

Fig. 1: Variations in mean thickness of the active layer at sites at different elevations along the vertical transect from May to August, 1983. Each data point is based on the mean of 10 measurements

Unterschiede in der mittleren Auftaubodenmächtigkeit an Standorten verschiedener Höhenlage entlang des Vertikalprofils vom Mai bis August 1983. Jeder Datenpunkt stützt sich auf ein Mittel von 10 Messungen

30 cm at 4100 m and 0 cm at 5300 m. However, these authors did not discuss its variability at these sites. Harris and Brown (1978, Fig. 7) provided evidence that both the active-layer thickness and its variability decrease with elevation on the alpine-tundra at Plateau Mountain, southwestern Alberta.

Jahn (1985, Fig. 2–7) has demonstrated that slope angle modifies the thickness of the active layer on bare tundra in the High Arctic at a given elevation, with the nearly horizontal surfaces having thicker active layers. No explanation of this was given.

In another study of the effects of slope and aspect in a vegetated area in Central Alaska, Dingman and Koutz (1974) used the Lee method which estimates insolation for a horizontal surface at "equivalent latitude". They concluded that the effects of the vegetation and related soil factors were at least as important. One of these is the effect of the organic surface layer (Brown 1966a), which acts as an insulator. In interior Alaska, the thickness of the active layer has been reported to depend on vegetation cover, slope position and organic-layer thickness (Dyrness a. Grigal 1979). In the permafrost areas in northwestern Canada, the surface organic layer is usually an O_f layer (*Canada Soil Survey Committee* 1978), consisting largely of fibric materials, readily identifiable as to botanic origin (usually moss).

This paper explores the effects of varying thicknesses of O_f horizon on the thickness of the active layer on both alpine and polar permafrost, by examining data from two sites, one near Kluane Lake, St. Elias Mountains, Yukon Territory and one at Inuvik, Northwest Territories.

The study area

In southwestern Alberta, the alpine permafrost is relatively arid (HARRIS 1986a,b), but it becomes more moist northwards. Around Jasper, peaty soils appear in depressions, while in northern British Columbia, the alpine tundra is characterized by lichens and mosses on the more gentle slopes above treeline. In this area, and in the western Arctic, the permafrost areas are wet, and the surface organic horizons play a significant role in heat exchange processes.

The primary study area is along a vertical transect from the eastern shore of Kluane Lake (Yukon Territory) to the shrub tundra above tree line in the zone of continuous permafrost (HARRIS 1983). It lies along a trail which starts opposite the service station at Mile 1055 on the Alaska Highway and proceeds up the northwest-facing slope of the outermost range of the St. Elias Mountains on the south side of the Shakwak trench. The main slopes are covered in a *Picea glauca/Hypnum* moss association (BLOOD a. Associates 1975) with varying amounts of aspen *(Populus tremuloides)*, balsam poplar *(Popular balsamifera)*, willow (*Salix* spp.) and birch *(Betula glandulosa)*. Above about 1200 m elevation, birch and willow become widespread, with treeline being reached at 1250 m. At higher elevations, the shrubs decrease in heigth and this shrup-tundra zone finally gives way to arctic-alpine tundra above about 1400 m elevation. This sequence will be described in detail elsewhere.

Above 920 m elevation, the soils on the slope are developed in thick till deposits with icy permafrost beneath them. There is a thin covering of Holocene loess which has been incorporated into the soil profile. At lower elevations, the loess overlies mudflow deposits on a former active mudflow fan. Above 1300 m elevation, the loess cover becomes very thin an the stony till lies close to or at the surface.

Soil formation commenced after deglaciation, about 12 500 years B. P. (DENTON a STUIVER 1966), with the resulting soil profiles including examples of all four subdivisions of cryosols (*Canada Soil Survey Committee* 1978)

The secondary study area consists of a north-south transect across the Boot Creek valley, 2 km east of Inuvik, Northwest Territories, in the region burned in 1968 (MACKAY 1970, 1977b; HEGINBOTTOM 1971, 1973, 1974) and in a nearby unburned transect, together with a third transect at the southern end of the Caribou Hills escarpment. The work was a byproduct of a study of permafrost, fire, and the regeneration of white spruce *(Picea glauca)* at arctic treeline (GREENE 1983a, 1983b). While gathering data to determine the conditions favouring and limiting the regeneration of spruce, valuable information was compiled on active-layer thickness and the thickness of the O_f horizon.

Sufficient time (13 years) had elapsed since the burn for the active layer to adjust to the new conditions. The data were obtained from sandy loam soils in the Caribou Hills transect, and silty loam soils in the Boot Creek traverses. A variety of different aspects, slopes and vegetation covers were studied. The soils were classified as Regosolic Static Cryosols, Orthic Static Cryosols and Organic Cryosols *(Canada Soil Survey Committee* 1978). Only one site (BC 2) showed signs of cryoturbation.

Methods used

In early August 1981, a reconnaissance study of the thickness of the thawed layer along the vertical tansect showed some rather startling results. Instead of simply decreasing in thickness with altitude, it doubled in thickness above tree-line. Air temperature data for the summer of 1981 (ALLEN 1982) could not explain the differences, nor could they be explained by movements of suprapermafrost water. The vegetation cover did not correlate with the changes (cf. DINGMAN a. KOUTZ, 1974), nor did slope angle (cf. JAHN 1985, Fig. 2-7).

During 1983, W. BLUMSTENGL repeatedly measured the depth of thaw at five sites at different elevations by using a steel rod of 0.5 cm diameter. As noted by MACKAY (1977a), the use of a steel rod to measure the depth of the penetrable layer may slightly overestimate the active-layer thickness, especially at the wetter sites, since the mineral soil had sandy loam to silt loam textures, but this error should be reasonably consistent for a given moisture content. Ten randomly chosen measurements were made at each site and the results were averaged to give the depth estimate for a given visit.

The data showed that the thickness of the thawed layer was becoming reasonably stable and showing relatively small increases with time by early August, so a detailed study of the altitudinal variations in apparent active-layer thickness was carried out on 2

August 1983. Where possible, measurements were made along the trail corresponding to a vertical interval of 30 m elevation, commencing at the Alaska Highway. The measurements at 883 m were omitted since they fell on the bouldery bed of a stream. At each site, a 5 m × 6 m plot was identified, and within it, thirty probings were made to measure the thickness of the apparent active layer in a rectangular pattern, modified only to avoid tree trunks. If a stone appeared to be encountered, a second probing measurement was located about 10 cm to one side to confirm the depth of the permafrost table. Negligible problems were encountered except on the stream bed and above 1211 m elevation. At the latter sites, the loessic cover was very thin and stones were becoming quite a problem. Above this elevation, the stony till precluded the use of probing to identify the permafrost table. Examinations of the results showed that there were indeed substantial variations in the apparent thickness of the active layer which had not been expected.

Meanwhile the results of the study by D. F. GREENE at Inuvik became available. GREENE had dug pits at each of his sites on his transects in August and had recorded both depth to the permafrost table and thickness of the organic O_f layer. Examination of the results suggested that the thickness of the O_f layer might be very important in determining active-layer thickness in wet soils (GREENE 1983 a).

In 1984, the author returned to the vertical transect and measured the thickness of the O_f layer at 30 points in a 5 × 6 m grid pattern at approximately the same sites as those used for the measurement of the apparent active-layer thickness. Unfortunately, the site at 914 m elevation had been disturbed and could not be used. For both data sets at each site, the mean of the thirty observations was calculated, together with the standard deviation (unbiased, i. e. using n = 1).

Results

Figure 1 shows the changes in mean thickness of the thawed layer at five sites representing different elevations on the vertical transect during the summer of 1983. In late May, the higher sites show only shallow thawing, whereas the lowest site exhibited deeper thaw. As the summer progressed, the higher sites developed deeper thaw zones, although at varying rates. This was probably partly due to changes in thermal conductivity with time as the thawed surface layers lost moisture at different rates, and partly to later wetting of the snow pack at higher elevations. Weather fluctuations also resulted in varying downward heat flow. Obviously in forested areas, the rate of thawing of the soil is more complicated than the case studied by JAHN (1946) in Greenland. However, the general pattern of gradually decreasing rates of thaw penetration applied, and by August, further thawing added little to the total thickness of the thawed zone. It was therefore con-

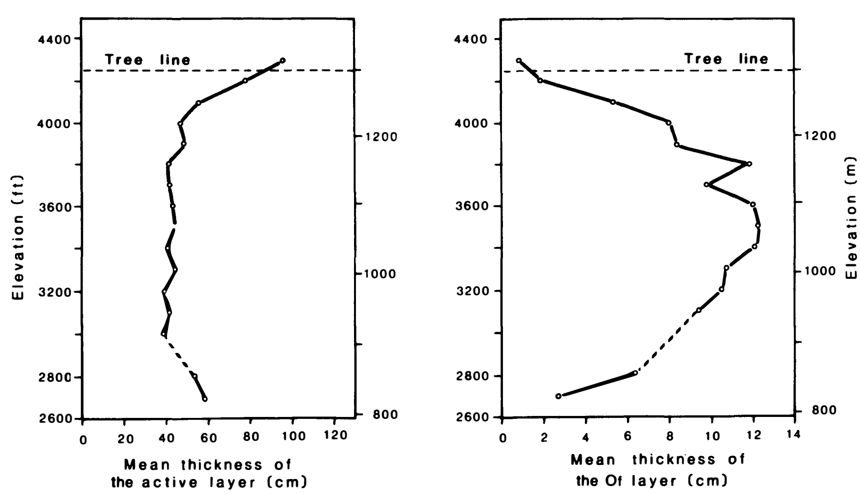

Fig. 2: Variations in mean thickness of the active layer on August 2nd, 1983, and mean thickness of the O_f layer with elevation along the vertical transect at Kluane Lake

Unterschiede in der mittleren Auftaubodenmächtigkeit am 2. August 1983 und der mittleren Dicke des O_f-Horizontes mit der Höhenlage entlang des Vertikalprofils Kluane Lake

Table 2: Thickness of the active layer (cm) at various elevations along the vertical transect, Kluane, on August 2, 1983
Auftaubodenmächtigkeit (in cm) in verschiedenen Höhen entlang des Vertikalprofils Kluane am 2. August 1983

Observation No.	Elevation (m) a.s.l. 823	853	914	945	975	1006	1036	1067	1097	1128	1189	1158	1219	1250	1280	1311
1	54	40	39	35	46	45	35	51	60	43	50	58	45	43	48	81
2	49	60	60	35	46	40	34	45	51	42	33	40	39	52	53	76
3	52	35	39	40	44	40	33	39	52	54	39	48	40	53	50	90
4	49	30	34	54	44	36	30	34	37	45	37	49	56	59	50	>120
5	45	40	34	41	43	33	47	46	30	48	34	43	37	54	59	100
6	53	82	37	41	40	40	31	38	46	48	53	44	33	45	71	80
7	80	34	40	40	39	53	40	31	35	47	46	60	37	50	75	84
8	89	39	33	47	45	63	28	29	30	42	49	64	39	63	83	>120
9	71	54	37	40	40	60	43	40	38	48	30	54	45	54	83	95
10	32	28	38	39	35	48	50	50	32	41	31	47	50	48	89	85
11	90	34	32	42	50	47	46	40	53	31	39	40	54	50	112	90
12	35	58	43	39	50	55	49	45	42	41	29	59	47	45	83	95
13	38	50	37	40	42	43	51	53	35	34	48	49	60	47	62	99
14	38	54	40	40	36	52	39	35	36	35	44	43	51	43	69	91
15	71	41	35	37	33	50	39	31	40	42	38	43	49	46	101	110
16	50	57	36	50	36	49	36	54	38	48	53	35	46	41	80	103
17	49	55	44	41	40	41	41	47	38	31	39	46	50	54	71	95
18	52	50	41	49	36	50	42	47	50	41	40	42	47	53	79	>120
19	31	51	40	45	31	43	44	33	36	39	31	42	50	53	87	>120
20	56	66	42	50	42	38	30	43	39	51	31	41	58	48	85	91
21	56	62	50	47	40	38	34	48	57	31	41	54	54	61	83	86
22	89	92	41	45	33	39	29	40	58	30	61	50	55	60	87	75
23	95	55	35	38	40	38	38	48	37	40	51	60	44	74	101	90
24	60	101	41	38	35	48	45	40	51	39	36	50	47	71	88	93
25	61	101	37	33	31	38	60	42	59	35	41	47	34	61	54	96
26	70	80	42	33	30	47	43	54	45	42	38	43	41	81	48	78
27	61	36	38	32	31	43	48	53	43	53	45	51	48	67	98	98
28	57	45	35	35	41	46	41	58	52	41	34	46	63	72	88	83
29	85	43	40	39	38	48	42	60	45	40	34	62	61	67	97	110
30	50	52	35	65	51	33	35	52	41	40	41	63	46	57	86	102
Max.	95	101	60	54	51	63	60	60	60	54	61	64	63	81	112	>120
Min.	31	28	32	32	30	33	28	29	30	30	29	35	33	41	48	75
Mean	58.9	54.2	39.2	41.0	39.6	44.8	40.1	44.2	43.5	41.4	40.5	49.0	47.5	55.7	77.3	> 95.2
Standard Deviation (unbiased)	18.0	19.8	5.45	5.52	5.89	7.35	7.56	8.33	8.86	6.48	8.04	7.88	7.93	10.23	17.65	>13.3

sidered reasonable to measure the depth of thaw at a larger number of sites at different elevations along the transect, to obtain a reasonable comparative estimate of the variation in thickness of the active layer with elevation.

Table 2 shows the thickness of the apparent active layer at the various sites along the vertical transect, measured on 2 August 1983. The first striking feature is the tremendous variability of the results at each site. The surface of the ground was gently undulating, but this was far too small to explain the results. The standard deviations and ranges for a given site increased with increasing mean active-layer thickness.

The mean depths of thaw for the sites showed the thinnest active layers between 914 m and 1158 m elevation (see Fig. 2). At lower elevations close to the lake, the active layer was rather thicker, which would be expected in the better drained, coarser-textured fan deposits on more gentle slopes. However, above 1158 m elevation, the apparent active layer increased in thickness, reaching almost 1 m at 1311 m elevation. This is the reverse of what is normally found when

Table 3: Thickness of the O_f layer (cm) at various elevations along the vertical transect, Kluane, 1984

Mächtigkeit des O_f-Horizontes (in cm) in verschiedenen Höhen entlang des Vertikalprofils Kluane 1984

Observation	Elevation (m) a.s.l.														
No.	823	853	945	975	1006	1036	1067	1097	1128	1158	1189	1219	1250	1280	1311
1	3	7	6	2	12	20	10	5	10	12	11	14	3	1	1
2	4	5	5	12	8	14	22	2	4	5	12	12	5	3	0
3	3	7	2	6	10	14	22	11	3	4	4	4	4	1	3
4	5	5	10	15	10	10	5	8	6	15	5	5	2	2	2
5	2	7	11	10	13	6	12	10	10	12	9	8	3	1.5	1
6	4	9	5	16	13	10	12	10	15	16	10	7	4	2	1
7	10	3	9	4	13	7	17	12	12	16	4	5	3	1.5	3.5
8	5	9	12	9	7	10	10	19	12	7	13	9	6	3	0.5
9	2	4	6	10	9	10	15	10	8	13	13	8	5	1.5	0
10	2	2	15	12	18	12	3	15	15	4	8	6	2	1	0
11	5	8	10	19	21	18	10	24	7	16	12	11	2	1	0.5
12	4	4	4	14	10	24	14	18	6	7	2	9	2	1.5	0.5
13	1	2	7	12	16	7	30	9	4	0	3	4	3	2	1
14	1	3	4	19	10	6	4	9	10	12	13	12	3.5	3	0.5
15	1	6	7	14	9	8	5	16	12	10	3	14	4	3.5	0.5
16	1	15	7	3	4	6	3	19	8	24	17	11	7	4	0.5
17	3	2	14	11	13	14	7	21	9	7	17	10	6	4.5	0.5
18	2	3	7	19	6	10	17	8	15	16	4	10	5	1	1
19	4	4	15	10	10	4	28	7	6	9	2	5	14	1.5	0.5
20	5	2	10	10	6	5	8	14	16	10	4	6	12	2	0.5
21	1	7	13	12	4	12	9	17	6	8	12	4	13	3	0.5
22	1	4	10	12	12	16	15	20	20	5	11	2	12	1	1.5
23	1	12	12	5	6	22	8	10	16	18	9	6	3	0.5	1
24	3	7	13	4	8	25	10	8	7	10	14	9	3	3	0.5
25	2	4	20	6	10	20	10	5	11	5	9	10	4	2.5	1.5
26	4	18	8	12	7	8	24	18	9	8	7	7	3	2	0.5
27	1	12	28	12	13	8	21	4	10	11	5	11	10	1.5	0.5
28	1	5	16	4	10	18	11	7	6	10	6	7	10	1	0.5
29	1	7	14	18	7	9	4	10	8	16	4	8	2	1	0.5
30	1	5	9	10	19	8	8	14	12	6	3	6	1	0.5	0.5
Max.	10	18	28	19	21	25	30	24	20	24	17	14	14	4.5	3.5
Min.	1	2	2	3	4	4	3	2	3	4	2	2	1	0.5	0
Mean	2.67	6.27	10.87	10.87	10.47	12.03	12.47	12.00	9.76	11.73	8.20	8.00	5.22	1.92	0.85
Standard Deviation (unbiased)	2.01	3.89	5.50	5.69	4.52	5.89	7.36	5.62	4.13	4.81	4.53	3.09	3.68	1.04	0.79

crossing tree-line (see for example, HARRIS a. BROWN 1978; GORBUNOV 1978, 1980).

Table 3 shows the data for the thickness of the organic O_f horizon at each site along the vertical transect, measured in 1984. Once again, there is appreciable variability in the results obtaines from within each plot. This is partly due to the growth of *Hypnum* moss carpeting much of the ground between 945 m and 1158 m elevation and forming lobate masses of varying thickness.

The variation in mean thickness of the O_f layer with elevation forms a partial mirror image of the pattern for the mean thickness of the apparent active layer (Fig. 2), the active layer tending to be thinner where the O_f layer thickens. The match is not perfect, largely due to the presence of springs of intrapermafrost and suprapermafrost water between 1158 m and 1250 m elevation.

When the mean thickness of the active layer is plotted against the mean thickness of the O_f layer for

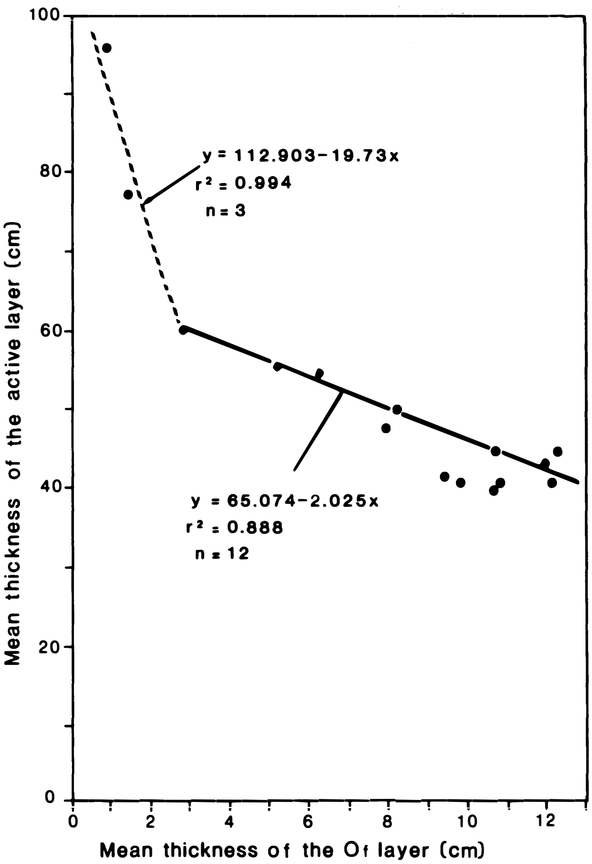

Fig. 3: Plot of the mean thickness of the active layer against the mean thickness of the O_f horizon for the data from vertical transect, Kluane Lake. Each data point is the mean of 30 observations

Diagramm der mittleren Auftaubodenmächtigkeit im Verhältnis zur mittleren Dicke des O_f-Horizontes aufgrund der Daten des Vertikalprofils Kluane Lake. Jeder Datenpunkt stützt sich auf ein Mittel von 30 Beobachtungen

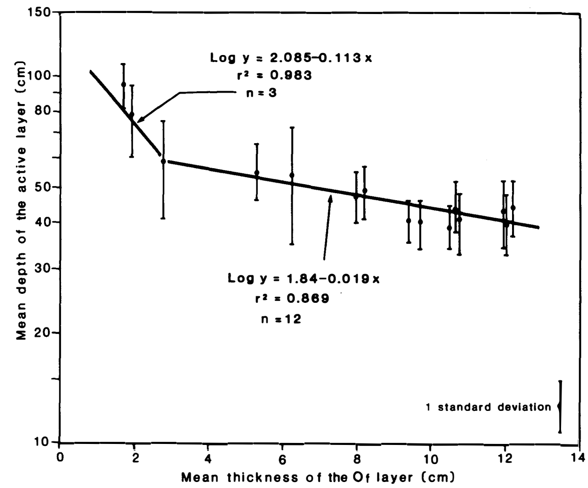

Fig. 4: Plot of the log of mean active-layer thickness against the mean thickness of the O_f horizon for the data from the vertical transect, Kluane Lake. Each data point is the mean of 30 observations.

Diagramm des Logarithmus der mittleren Auftaubodenmächtigkeit im Verhältnis zur mittleren Dicke des O_f-Horizontes aufgrund der Daten des Vertikalprofils Kluane Lake. Jeder Datenpunkt stützt sich auf ein Mittel von 30 Beobachtungen

each site on the transect, the data plot along two lines of different slope meeting at a dog-legged junction (Fig. 3), suggesting the presence of a threshold. The same result is obtained when the data are plotted on semilogarithmic paper (Fig. 4), all the data falling within one standard deviation from the line of best fit. At Kluane, it appears that when the mean thickness of the O_f layer exceeds 2.5 cm, there is a predictable relationship between the active layer depth and the thickness of the O_f layer. Thus the organic layer is the major factor causing the variability in active-layer thickness along the vertical transect, with increasing thickness of O_f layer resulting in a systematic decrease in the thickness of the active layer. However, when the O_f layer thickness decreases below 2.5 cm, the slope changes abruptly and the standard deviation increases to approach the value of the mean. This suggests that other factors become the dominant controls on active-layer thickness, but whether the "critical value" of the threshold is consistent from year to year is unknown.

The question arises as to what happens in soils with really thick organic (O_f) horizons. Table 4 shows the data obtained by GREENE (1983 a) from the pits with over 2.5 cm of organic horizon (O_f layer) present along his three traverses near Inuvik. They include data from burned and unburned sites, from north and south facing slopes, from well drained to poorly drained sites, and from at least two different textures of mineral soil beneath the surface organic horizons.

When the thickness of the O_f layer is plotted against the thickness of the active layer using a semilogarithmic scale (Fig. 5), a dog-legged relationship is found. For the thinner O_f horizons, there is a rapid decrease in thickness of the active layer with increasing O_f thickness. However, when the O_f layer exceeds about 16 cm, active-layer thickness abruptly becomes almost constant at approximately 32 to 36 cm, as indicated by the r^2 value of 0.089. Other factors then cause the local variations. There is no noticeable correlation between texture of the mineral horizons, slope angle, aspect, drainage condition, or vegetation cover and the results (see Table 4 and

Table 4: Relationship of active-layer thickness in 1982 to texture, aspect, slope, and vegetation cover for sites with O_f layers thicker than 2.5 cm at Inuvik (after GREENE *1983a)*

Verhältnis der Auftaubodenmächtigkeit im Jahr 1982 zu Textur, Auslage, Hangneigung und Vegetationsdecke für Standorte mit O_f-Horizonten von über 2,5 cm Dicke bei Inuvik (nach GREENE 1983a)

Transect	Stand	O_f Thickness (cm)	Slope (°)	Active layer thickness (cm)	Texture	Aspect
Caribou Hills	3	6.5	30	77	SL	South
	4	12.5	14	67	SL	South
	5	23	5	40	SL	South
	6	32	1	36	SL	South
	7	21	3	39	SL	North
	8	12.5	14	42	SL	North
	9	12.6	19	39	SL	North
	10	11.5	29	52	SL	North
	11	9	19	53	SL	North
Boot Creek (unburned)	1	7	0	50	SiL	Creek-side
	2	24	0	24	SiL	South
	3	17	1	24	SiL	South
	4	17	1	28	SiL	South
	5	15	1	34	SiL	South
	6	30	2	30	SiL	South
	7	23	3	34	SiL	South
	8	26	8	29	SiL	South
	9	26	9	33	SiL	South
	10	18	10	33	SiL	South
	11	14	15	53	SiL	South
	12	10	21	64	SiL	South
Boot Creek (burned)	2	30	2	52	SiL	South
	3	30	5	30	SiL	South
	4	5	6	62	SiL	South
	7	3	12	140	SiL	South
	10	3	7	117	SiL	South
	11	5	10	102	SiL	South
	13	25	3	40	SiL	Tableland

Fig. 5). Data for sites at Inuvik where the O_f layer is thinner than 2.5 cm show much higher variability in active-layer thickness (Table 5), suggesting that a similar lower threshold of effectiveness of the O_f layer as a control also applies in this case. It would therefore appear to be necessary to establish the slope of the relationship for a given area, but once this is known, the curve could be used for estimating the probable thickness of the active layer under natural conditions based on the thickness of the overlying O_f horizon, provided the latter exceeds a critical value such as 2.5 cm. When it is thinner, other variables such as texture (MACKAY 1970, 1975), moisture content, and the texture and moisture content of the underlying soils will be the dominant determinants of active-layer thickness, as is indicated in Table 5. Under those conditions, fine texture, high moisture content, and poor drainage correlate with minimum thickness of active layer, while the data agree with previous studies, indicating that destruction of the vegetation cover by fire substantially increases the thickness of the active layer (see MACKAY 1977b). However, all such between-site variations that can be ascribed to terrain factors will be subject to fluctuations from year to year due to variations in the climate, and these must also be allowed for.

Use of the results in prediction of active-layer thickness

The results imply that the effects of terrain factors in controlling active-layer thickness in a given area

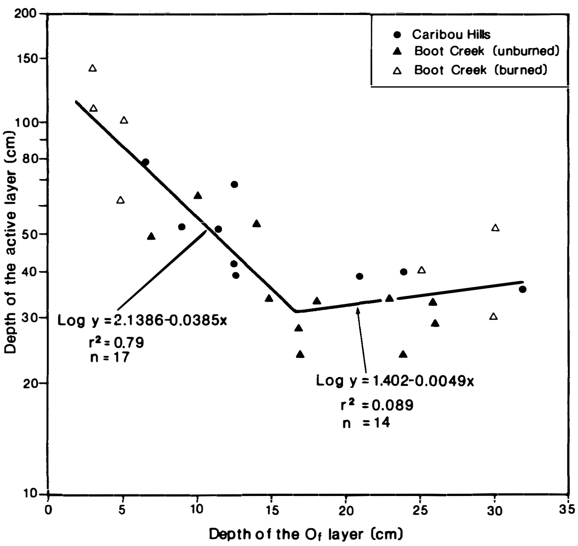

Fig. 5: The relationship between thickness of the O_f layer and depth of the active layer on August 3–6th, 1982, for data from the three transects near Inuvik, Northwest Territories. Points where the O_f layer is less than 2.5 cm thick have been omitted (see Table 5, modified from Greene, 1983 a).

Beziehung zwischen der Dicke des O_f-Horizontes und der Auftaubodenmächtigkeit am 3.–6. August 1982 aufgrund der Daten der drei Profile bei Inuvik, Northwest Territories. Punkte mit einer Mächtigkeit der O_f-Lage von unter 2,5 cm wurden weggelassen (vgl. Tab. 5, verändert nach Greene 1983 a)

of poorly drained continuous permafrost can be established fairly quickly. Thickness of O_f horizons and type of vegetation cover will be key determinants for most situations, while active-layer thickness in areas with less than 2.5 cm of O_f horizon will depend more on other factors such as aspect and texture. Variations in moisture content may modify the results where springs or seepage occur.

There will still be substantial variation in active-layer thickness from year to year (see Table 1) due to variations in the climatic factors. The effect of temperature changes may be estimated by using freezing and thawing indices (Harris 1981, 1982), but there will also be variations caused by differences in snowfall amount and distribution. These probably account for considerable local variation from year to year, and this variability will only be predictable if adequate measurements of snow depth are available. Unfortunately, this is currently one of the weakest links in the available climatological data. The variation will be most pronounced in areas of tundra, in undulating areas, or on slopes. Generally, the snow cover tends to undergo less drifting in forest. Modification of the vegetation or addition of man-made objects will often drastically alter the snow distribution (Mackay 1978; Nicholson 1978).

The data also suggest that if peaty layers can be placed over a disturbed area, then the increase in thickness of the active layer will be minimized. The use of wood chips as a mulch on problem slopes along the pipeline from Norman Wells (Northwest Territories) to Zama Lake (Alberta) serves the same purpose. The exact depth of a given mulch that is required would have to be determined by experiments, to allow for possible thermal changes due to fermentation (H. Baker 1986, personal communication), but curves such as that in Figure 5, based on field observations, should allow a reasonably reliable prediction of the thickness required. Although simple analytical solutions have been proposed (e. g. Harlan a. Nixon, 1978, p. 144), these do not allow for fer-

Table 5: Relationship of active-layer thickness in 1982 to texture, aspect, slope, and vegetation cover for sites with O_f layers thinner than 2.5 cm at Inuvik (after Greene 1983a)

Verhältnis der Auftaubodenmächtigkeit im Jahr 1982 zu Textur, Auslage, Hangneigung und Vegetationsdecke für Stellen mit O_f-Horizonten von unter 2,5 cm Dicke bei Inuvik (nach Greene 1983 a)

Transect	Stand	O_f Thickness (cm)	Slope (°)	Active layer thickness (cm)	Texture	Drainage	Aspect
Caribou Hills	1	2	8	120	SL	V. Good	Ridge Top
	2	2.5	28	81	SL	Good	South
	12	0.2	2	105	SL	V. Good	Ridge Top
Boot Creek (burned)	1	1	1	51	SiL	Poor	Creek-side
	8	1	8	144	SiL	Good	South
	9	2	7	135	SiL	Good	South
	12	2	7	135	SiL	Good	South

mentation effects, and they require detailed measurements of radiation and heat flow. They are therefore more difficult to use and more expensive.

Classification of cryosols

The identification of cryosols (*Canada Soil Survey Committee* 1978) depends on reliably determining the maximum thickness of the active layer. Tables 1, 2 and 4 show how difficult this can be in practice. Variations in climate from year to year will also undoubtedly alter the position of the boundary of cryosols, since the latter are defined by active-layer thickness. Indeed, reliable mapping will be extremely difficult since it is only in August–October when that thickness can be determined. Obviously the maps purporting to show the outer limits of cryosols should be treated with caution.

Conclusions

In areas of continuous permafrost, the organic (O_f) layer acts as a significant modifier of the heat-exchange processes wherever it is thicker than about 2.5 cm. There is a systematic reduction in the natural logarithm of active-layer thickness with increasing thickness of the O_f layer until a critical value is exceeded (see Fig. 5). At Inuvik, this is about 16 cm of O_f layer. Thereafter, there is little change. Slope, texture, aspect, vegetation cover and drainage cause minor variations but these are overshadowed by the effects of the O_f layer. When the O_f layer is thinner than about 2.5 cm, the other terrain factors become dominant.

In mountainous terrain such as the St. Elias Mountains, the variations in O_f layer thickness produce spectacular changes in active-layer thickness with elevation (Fig. 2). The active layer may be far thicker just above tree-line than 200 m below it.

The exact effect of the O_f layer varies from area to area and must be established by making suitable measurements. Once these are available, it should be fairly easy to determine the thickness of natural mulches required to minimize changes in the active layer resulting from earthworks. These will only minimize changes due to the terrain factors affecting active-layer thickness. Changes related to climatic factors (particularly temperature or snow cover) must also be incorporated into any design.

Finally, caution should be used when interpreting data on active-layer thickness that do not discuss variability at and between sites. Tables 1, 2 and 4 provide examples of the problem of arriving at a representative value for a given site. Obviously maps of the distribution of cryosols in lower latitudes should be treated with caution since the boundaries undoubtedly vary from year to year with normal yearly variations in the climate.

Acknowledgements

The field work was carried out using funds from NSERC Grant A-7843, which are gratefully acknowledged. The author is also indebted to W. Blumstengel for his help in 1983 at Kluane, and to Nigel Waters for his help with fitting the regression lines.

References

Allen, H. D.: Dendrochronological Studies in the Slims River Valley, Yukon Territory. Unpublished M. Sc. thesis, Department of Geography, University of Calgary 1982.

Blood, D. A. a. Associates: The Soil, Vegetation, and Wildlife Resources of Five Potential Transportation Corridors in Kluane National Park, Yukon. Report to Prairie Region, Parks Canada, Winnipeg 1975.

Brown, R. J. E.: Influence of Vegetation on Permafrost. In: Proceed. 1st International Permafrost Conference, Lafayette, Indiana. National Academy of Sciences Publication 1287, Washington, D. C., 1966a, 20–25.

– : The Relationship Between Mean Annual Air and Ground Temperatures in the Permafrost Regions of Canada. In: Proceed. 1st International Permafrost Conference, Lafayette, Indiana. National Academy of Sciences Publication 1287, Washington, D. C., 1966b, 241–246.

– : Influence of Climatic and Terrain Factors on Ground Temperature at Three Locations in the Permafrost Region of Canada. In: North American Contribution, Permafrost 2nd International Conference, Yakutsk, USSR. National Academy of Sciences, Washington, D. C., 1973, 27–34.

– : Influence of Climate and Terrain on Ground Temperatures in the Continuous Permafrost Zone of Northern Manitoba and the Keewatin District, Canada. In: Proceed. 3rd International Conference on Permafrost, Edmonton, Alberta, Vol. I, 1978, 15–21.

Brown, R. J. E. a. Péwé, T. L.: Distribution of Permafrost in North America and its Relationship to the Environment: A Review, 1963-1973. In: North American Contribution, Permafrost 2nd International Conference, Yakutsk, USSR. National Academy of Sciences, Washington, D. C., 1973, 71–100. National Research Council, Division of Building Research, Ottawa, Technical Paper No. 441.

Canada Soil Survey Committee: Canadian System of Soil Classification. Research Branch, Canadian Department of Agriculture, Publication No. 1646, 1978.

CORTE, A. E.: Comparative Study of Ceogryogenic (Periglacial) Conditions, Features and Processes in the Andes and Himalayas. In: The Andes. Union Geografica Internacional, Primera Reunion Latinoaméricana sobre la importancia de los fenomenos periglares. Tercera Reunion Grupo Periglacial Argentino, 1985, 35-48.

CORTE, A. E. a. BUK, E. M.: El marco criogénico para la hidrología cordillerano; aspectos hidrológicos del detrito cordilleranos Jornadas de hidrología de nieves. Hielos en América del Sur, Santiago de Chile 1984.

DENTON, G. H. a. STUIVER, M.: Neoglacial Chronology, Northeastern St. Elias Mountains, Canada. In: American Journal of Science 264, 1966, 577-599.

DINGMAN, S. L. a. KOUTZ, F. R.: Relations Among Vegetation, Permafrost, and Potential Insolation in Central Alaska. In: Arctic and Alpine Research 6, 1974, 37-42.

DYRNESS, C.T. a. GRIGAL, D.F.: Vegetation-Soil Relationships Along a Spruce Forest Transect in Interior Alaska. In: Canadian Journal of Botany 57, 1979, 2646-2656.

GORBUNOV, A. P.: Permafrost in the Mountains of Asia [In Russian]. In: Proceed. 3rd International Conference on Permafrost, Edmonton, Alberta. National Research Council, Ottawa. Vol. 1, 1978, 372-377.

- : Permafrost in the Mountains of Central Asia. In: 3rd International Conference on Permafrost, Edmonton. English translations, Part 1. National Research Council, Ottawa 1980, 357-369.

GREENE, D. F.: Permafrost, Fire and the Regeneration of White Spruce at Tree-line Near Inuvik, Northwest Territories, Canada. Unpublished M. Sc. Thesis, Department of Geography, University of Calgary 1983 a.

- : Permafrost, Fire, and the Regeneration of White Spruce at Tree-line Near Inuvik, Northwest Territories, Canada. In: Permafrost: Proceed. 4th International Conference, Washington, D. C., 1983 b, 374-379.

HARLAN, R. L. a. NIXON, J. F.: Ground Thermal Regime. In: ANDERSLAND, O. B. a. ANDERSON, D. M. (Eds.): Geotechnical Engineering for Cold Regions. New York 1978, 103-163.

HARRIS, S. A.: Climatic Relationships of Permafrost Zones in Areas of Low Winter Snow-cover. In: Arctic 34, 1981, 66-70.

- : Identification of Permafrost Zones Using Selected Periglacial Landforms. In: FRENCH, H. M. (Ed.): Proceed. 4th Canadian Permafrost Conference, Roger J. E. Brown Memorial Volume. National Research Council, Ottawa 1982, 49-58.

- : Comparison of the Climatic and Geomorphic Methods of Predicting Permafrost Distribution in Western Yukon Territory. In: Permafrost: Proceed. 4th International Conference, Washington, D. C., 1983, 450-455.

- : The Permafrost Environment. Croom Helm, Beckenham, Kent, 1986 a.

- : Permafrost Distribution, Zonation, and Stability Along the Eastern Ranges of the Cordillera of North America. In: Arctic 39, 1986 b, 29-38.

HARRIS, S. A. a. BROWN, R. J. E.: Plateau Mountain: A Case Study of Alpine Permafrost in the Canadian Rocky Mountains. In: Proceed. 3rd International Conference on Permafrost, Edmonton, Alberta. National Research Council, Ottawa. Vol. I, 1978, 385-391.

HEGINBOTTOM, J. A.: Some Effects of a Forest Fire on the Permafrost Active Layer at Inuvik, N.W.T. In: National Research Council of Canada, Associate Committee on Geotechnical Research, Technical Memorandum No. 103, 1971, 31-36.

- : Some Effects of Surface Disturbances on the Permafrost Active Layer at Inuvik, N. W.T. Environmental-Social Committee on Northern Pipelines, Report No. 73-16, 1973.

- : The Effects of Surface Disturbance on Ground Ice Content and Distribution. Geological Survey of Canada, Paper 74-1A, 1974.

JAHN, A.: Badania nad struktura i temperatura gleb w Zachodniej Grenlandii. In: Rozprawy Wydz. Mat.-Przyr. Akademii Umiejetnosci, Krakow 72, 1946, 1-122.

- : Experimental Observations of Periglacial Processes in the Arctic. In: CHURCH, M. a. SLAYMAKER, O. (Eds.): Field and Theory: Lectures in Geocryology. Vancouver 1985, 17-35.

LLIBOUTRY, L.: Phénomènes cryonivaux dans les Andes de Santiago (Chili). In: Biuletyn Peryglacjalny 10, 1961, 209-224.

MACKAY, J. R.: Disturbances to the Tundra and Forest Tundra Environment in the Western Arctic. In: Canadian Geotechnical Journal 7, 1970, 420-432.

- : The Stability of Permafrost and Recent Climatic Change in the Mackenzie Valley. N.W.T. In: Geological Survey of Canada. Report of Activities. Part B. Paper 75-1B, 1975, 173-176.

- : Probing for the Bottom of the Active Layer. In: Geological Survey of Canada, Paper 77-1A, 1977a, 327-328.

- : Changes in the Active Layer from 1968 to 1976 as a Result of the Inuvik Fire. In: Geological Survey of Canada, Paper 77-1B, 1977b, 273-275.

- : The Use of Snow Fences to Reduce Ice-wedge Cracking, Garry Island, Northwest Territories. In: Geological Survey of Canada, Paper 78-1A, 1978, 523-524.

MARANGUNIC, C.: El glaciar de roca Pedregoso, Río Colorado V Región. In: Primer Cong. Geol. Chileno 1976, 71-80.

NICHOLSON, F. H.: Permafrost Modification by Changing the Natural Energy Budget. In: Proceed. 3rd International Conference on Permafrost, Edmonton, Alberta. National Research Council, Ottawa. Vol. 1, 1978, 61-67.

ROUSE, W. R.: Active Layer Energy Exchange in Wet and Dry Tundra of the Hudson Bay Lowlands. In: Permafrost: Proceed. 4th International Conference Washington, D. C., 1983, 1089-1094.

TERZAGHI, K.: Permafrost. In: Boston Society of Civil Engineers, Journal, Vol. 39, 1952, 319-368.