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Altitude Trends in Permafrost Active Layer Thickness, Kluane Lake, Yukon Territory

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ABSTRACT. On the northwest-facing slopes of Outpost Mountain, Kluane Lake, the permafrost active layer shows an anomalous relationship with altitude, being thinner (typically 40 cm) between 823 and 910 m altitude than above or below this belt. Maximum thicknesses (about 90 cm) are encountered in the shrub tundra at 1310 m elevation. These thicknesses do not correlate with soil types or suprapermafrost drainage, but they do correlate well with the thickness of the organic mat (0_f layer) where this exceeds 2.5 cm thickness. The mat apparently acts as a natural insulator.

Key words: 0_f thickness, active layer thickness, alpine permafrost, altitudinal variations, alpine and subalpine vegetation

RÉSUMÉ. Sur les pentes nord-ouest de la montagne Outpost au lac Kluane, la couche active du pergélisol montre une anomalie avec l'altitude, étant plus mince (40 cm en général) entre 823 et 910 m d'altitude, qu'au-dessus ou en dessous de ce niveau. Les épaisseurs maximales (90 cm environ) se trouvent dans les arbustes de la toundra à une altitude de 1310 m. Ces épaisseurs ne présentent pas de corrélation avec les types de sol ou le drainage du suprapergélisol, mais elles en présentent une très nette avec l'épaisseur du tapis de matériau organique (la couche O_f) là où il dépasse 2,5 cm d'épaisseur. Ce tapis semble agir comme un isolant naturel.

Mots clés: épaisseur O_f, épaisseur de la couche active, pergélisol alpin, variations avec l'altitude, végétation alpine et subalpine

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INTRODUCTION

Since the mean annual air temperature usually becomes colder at higher elevations, the permafrost active layer is typically thinner with increased altitude in mountains, as shown by field measurements in Northern Tien Shan (Gorbunov, 1978, 1980), the Andes (Lliboutry, 1961; Marangunic, 1976; Corte and Buk, 1984; Corte, 1985) and the Rocky Mountains of Alberta (Harris and Brown, 1978).

Systematic studies of the ecosystem near the Kluane Lake Research Station of the Arctic Institute of North America, however, showed that the thickness of the active layer in that region failed to conform to this model.

STUDY AREA

The vertical transect used began from the southeastern shore of Kluane Lake, Yukon Territory (Fig. 1), commencing at mile 1055. It extended from 823 m elevation at the Alaska Highway up to about 1311 m in the shrub-tundra above tree line. The transect was on the northwest-facing slope of Outpost Mountain on the south side of the Shakwak Trench and lay in the zone of continuous permafrost (Harris, 1983).

The vegetation consisted of a *Picea glauca/Hypnum* moss association (Blood and Associates, 1975) with varying amounts of aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), willow (*Salix* spp.) and birch (*Betula glandulosa*). Above about 1200 m, birch and willow became widespread, with the last spruce tree occurring at 1250 m. At higher elevations, the shrubs decreased rapidly in height, and this shrub-tundra zone changed to arctic-alpine tundra above 1400 m.

Between 920 and 1300 m elevation, the soils on the slope were developed in thick till deposits with icy permafrost beneath them. There was a covering of Holocene loess incorporated into the soil profile. At lower elevations, the loess overlay mudflow deposits on a former active mudflow fan. Above 1300 m elevation, the loess cover became very thin and the stony till lay close to or at the surface.

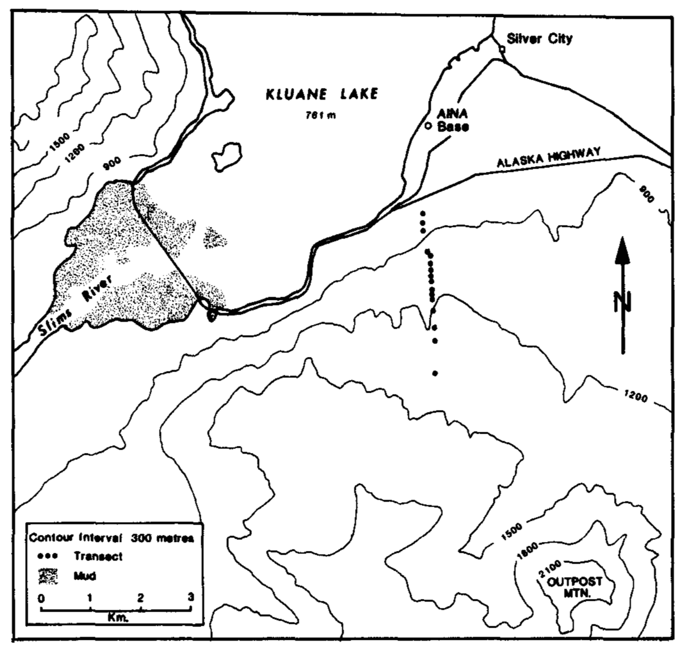

FIG. 1. Location of the altitudinal transect on the north slope of Outpost Mountain, Kluane.

Soil formation commenced after deglaciation, about 12 500 years B.P. (Denton and Stuiver, 1966), with the resulting soil profiles including examples of all four subdivisions of Cryosols (Canada Soil Survey Committee, 1978).

METHODS USED

In early August 1981, a reconnaissance study of the depth of the thawed layer along the transect showed some unexpected 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,

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nor could movements of suprapermafrost water. The vegetation cover did not appear to correlate with the differences (*cf.* Dingman and Koutz, 1974), nor did slope angle (*cf.* Jahn, 1985:Figs. 2-7).

In 1983 the depth of the thawed layer was measured at regular intervals at five sites at different altitudes by using a steel rod of 0.5 cm diameter. As noted by Mackay (1977), the use of a steel rod to measure the depth of the penetrable layer may give over-estimates of the active layer thickness, especially at the wetter sites, since the mineral soil had sandy loam to silt loam textures. This error should have been 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 location.

The data showed that the thickness of the thawed layer became reasonably stable and with relatively small increases over time by early August. Accordingly, a detailed study of the altitudinal variations in the 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, 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 6 × 5 m plot was identified, and within it 30 probings were made in a rectangular pattern to measure the thickness of the apparent active layer, modified only to avoid tree trunks. If a stone was encountered, a second probing measurement was located about 10 cm to one side. 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 became a serious problem. Above this altitude, the stony till precluded the use of the probing method.

In 1984, the thickness of the organic mat (0_f layer) was measured at 30 points in a 6 × 5 m grid pattern at approximately the same sites as those used for the earlier measurement of the apparent active-layer thickness. Unfortunately, the site at 914 m elevation had been disturbed and could not be used again. For each data set at each site, the means of the 30 observations were calculated together with the standard deviation (unbiased, i.e., using n = 1).

RESULTS

Figure 2 shows the changes in mean depth of the thawed layer at five sites representing increasing elevations along the Carlos Trail during the summer of 1983. In late May, the higher sites showed only shallow thawing, whereas the lowest site exhibited deeper thaw. As the summer progressed, the higher sites developed deeper surface thawing. This variation was probably partly due to differences in thermal conductivity with time as the thawed surface layers lost moisture at different rates and partly to later melting 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. The rate of deepening of the thawed zone decreases as the summer passes, so that by August the residual deepening represented a relatively small proportion of the total thickness of the thawed zone. It was therefore possible to examine the variations in thickness of the active layer with elevation along the transect.

Table 1 shows the depths of the active layer at the various sites along the altitudinal transect measured on 2 August 1983.

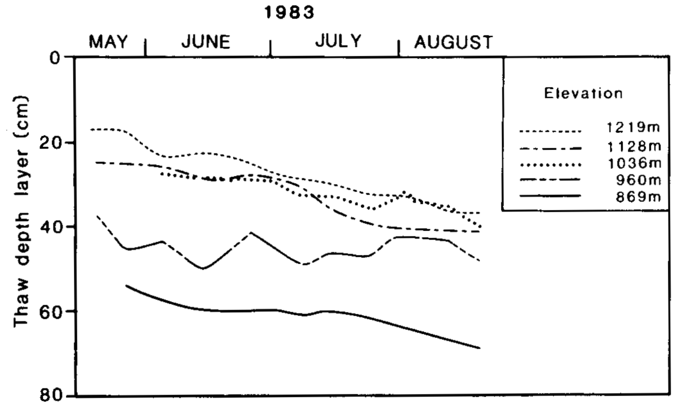

FIG. 2. Mean depth of the thaw depth as a function of elevation along the vertical transect May-August 1983. Each data point is the mean of 10 measurements.

The first feature is the 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 depth of the active layer for the sites showed the thinnest active layers between 914 and 1158 m elevation (see Fig. 3). At lower elevations close to the lake, the active layer was rather thicker, as would be expected in the better drained, coarser textured fan deposits on more gentle slopes. However, above 1158 m elevation, the active layer increased in thickness until it reached a thickness of almost 1 m at 1311 m elevation. This is the reverse of the normal pattern across tree lines (Harris and Brown, 1978; Gorbunov, 1978, 1980). No obvious relationship exists between the active layer thickness and the structure of the vegetation.

Table 2 shows the data for the thickness of the organic (O_f) horizon at each site along the altitudinal transect along the Carlos Trail measured in 1984. Again there was appreciable variability within each plot. This was partly due to the uneven growth of the *Hypnum* moss, which carpeted much of the ground between 945 and 1158 m elevation and formed lobate masses of varying thickness.

The variation in mean thickness of the organic mat layer with elevation forms a partial mirror image of the pattern for the mean depth of the apparent active layer (Fig. 3), 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 suprapermafrost water between 1158 and 1250 m elevation.

When the mean thickness of the active layer is plotted against the mean thickness of the organic layer for each site on the transect, the data plot along two lines meet at a dog-legged junction (Fig. 4), suggesting the presence of a threshold at 2.5 cm. All data overlap the line of best fit within one standard deviation. On northwest-facing slopes at Kluane, a predictable relationship between the active layer depth and the thickness of the organic layer occurred when the mean thickness of the organic layer exceeded 2.5 cm. Thus the organic layer appeared to be the major factor controlling the depth of the active layer along the transect, with increasing thicknesses of organic layer resulting in a systematic decrease in the thickness of the active layer. However, when the organic layer thickness decreased below 2.5 cm, the slope of the relationship changed abruptly and the standard deviation increased to approach the value of the

TABLE 1. Depth of the active layer (cm) at various altitudes along the Carlos Trail, Kluane, 2 August 1983

	Altitude (m)															
Observation #	823	853	914	945	975	1006	1036	1067	1097	1128	1158	1189	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
Maximum	95	101	60	54	51	63	60	60	60	54	61	64	63	81	112	>120
Minimum	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	5.42	5.89	7.35	7.56	8.33	8.86	6.48	8.04	7.88	7.93	10.23	17.65	>13.3

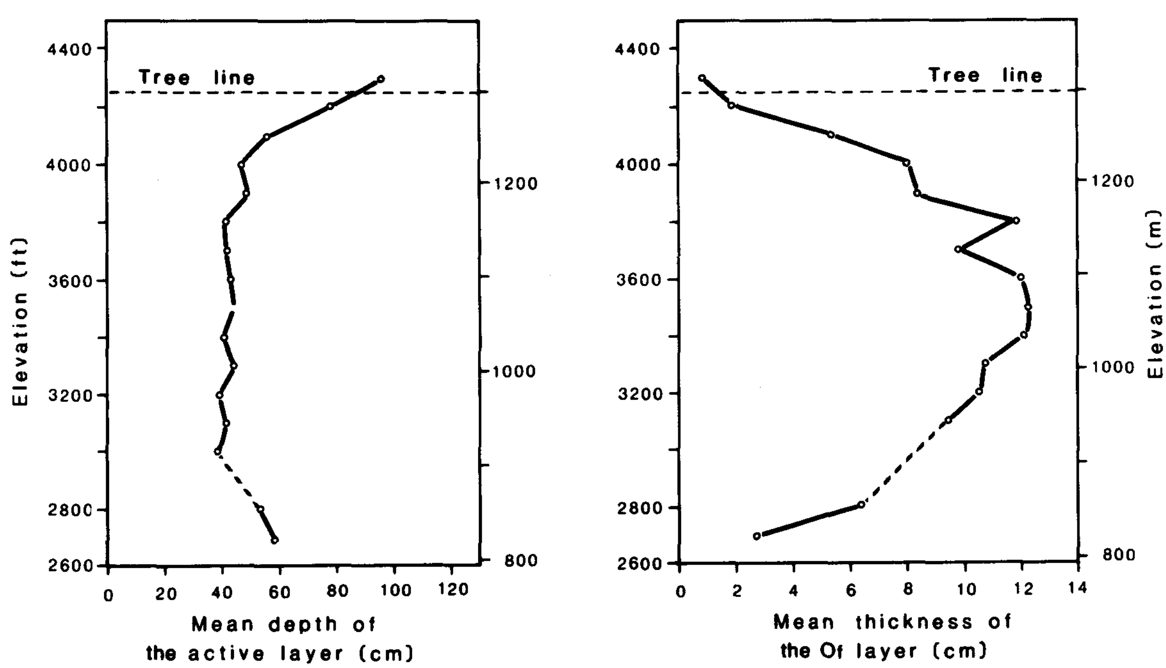

FIG. 3. Mean depth of the active layer on 2 August 1983, and mean thickness of the organic (O_f) layer as functions of altitude along the Kluane Lake transect.

TABLE 2. Thickness of the O_f layer (cm) at various altitudes along the Carlos Trail, Kluane, 1984

	Altitude (m)														
Observation #	823	853	945	975	1006	1036	1067	1097	1128	1158	1189	1219	1250	1280	1311
1	3	7	2	6	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
Maximum	10	18	28	19	21	25	30	24	20	24	17	14	14	4.5	3.5
Minimum	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	4.69	4.52	5.89	7.36	5.62	4.13	4.81	4.53	3.09	3.68	1.04	0.79

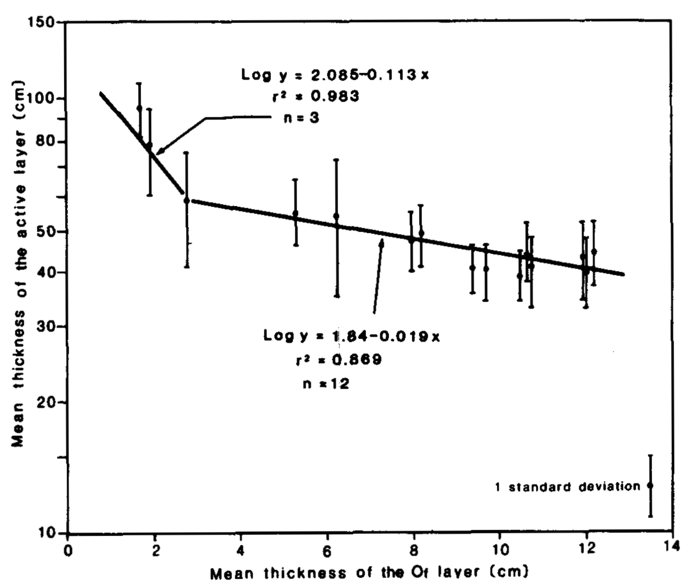

FIG. 4. Semilogarithmic plot of the mean depth of the active layer against the mean thickness of the organic (O_f) horizon for the data from the altitudinal transect, Kluane Lake. Each data point is the mean of 30 observations.

mean. This suggests that in this case other factors dominate the thickness of the active layer. Whether the threshold value is consistent from year to year is unknown.

CONCLUSIONS

It appears that the organic mat (the O_f layer) acts as an insulating cover when thicker than 2.5 cm and is the dominant factor in controlling the thickness of the active layer along the vertical transect above Kluane Lake, especially in the sub-alpine forest.

Variations in the thickness of the active layer do not correlate with soils, suprapermafrost drainage or vegetation cover. However, they do correlate with the thickness of the organic mat (the O_f layer).

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