C. J. Stevenson

Canada

GEOGRAPHICAL PAPER No. 18

A Subsurface Organic Layer Associated with Permafrost in the Western Arctic

J. Ross Mackay

GEOGRAPHICAL BRANCH
Department of Mines and Technical Surveys, Ottawa

Price: 50 cents

Canada

GEOGRAPHICAL PAPER No. 18

A Subsurface Organic Layer Associated with Permafrost in the Western Arctic

J. Ross Mackay

GEOGRAPHICAL BRANCH
Department of Mines and Technical Surveys, Ottawa

Price: 50 cents

61825—1

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1958

PREFACE

The Geographical Branch has been investigating permafrost and associated phenomena over the past ten years in connection with its studies of terrain conditions in northern Canada. This paper deals with the organic layer associated with the permafrost surface and suggests an origin for this layer.

It is hoped that this report will be of assistance to those who are concerned with the application of northern terrain characteristics to problems of construction and transportation.

N. L. Nicholson,
Director,
Geographical Branch.

THE ORIGIN OF A SUBSURFACE ORGANIC LAYER ASSOCIATED WITH THE PERMAFROST SURFACE IN THE WESTERN ARCTIC OF CANADA

J. Ross Mackay

A discontinuous subsurface organic layer, ranging in thickness from less than an inch to several feet, lies close to the permafrost surface throughout extensive areas of the Western Arctic of Canada. Although the organic layers are found in a variety of materials and on gentle to steep slopes, they are best developed in silty to clayey soils on slopes of less than 10^{o}. Plant microfossils from some organic layers indicate that past climates differed from the present; carbon 14 dating suggests a considerable age for some organic layers; organic material has been found beneath a marine clay; and archaeological complexes have been discovered associated with organic layers (Hopkins and Giddings, 1953; Lowther, personal communication; MacNeish, 1956). The study of the organic layer is, therefore, of broad interest, because it involves problems of pedology, geomorphology, stratigraphy, climatology, biogeography, and archaeology. It is the purpose of this paper to suggest an origin for the organic layer.

FIELD WORK AND ACKNOWLEDGEMENTS

During the course of field work in the Western Arctic in the summers of 1955, 1956, and 1957, numerous observations were made on organic layers. Field work in 1955 and 1957 was carried out for the Geographical Branch, federal Department of Mines and Technical Surveys. In 1956, W.H. Mathews and the writer spent several weeks, supported by a research grant from the Arctic Institute of North America, at the Engigstciak archaeological site (Firth River, Yukon Territory) under excavation by R.S. MacNeish. Organic layers were examined at the site. J. Fyles, A. Leahey, and W.H. Mathews have made helpful suggestions on the paper; G. Lowther and R.S. MacNeish have made available some unpublished data.

DISTRIBUTION OF THE ORGANIC LAYER

Organic layers are present in many tundra regions of the world, although their widespread occurrence has apparently escaped recognition, probably because of the paucity of studies of tundra soils. In the Western Arctic of Canada, organic layers were observed in the coastal region between Firth River (Yukon Territory) and West Channel of Mackenzie River, and near the headwaters of Blow River (Yukon Territory). Leahey (1947, p. 460) has described the soil profile for a knoll between West Channel of Mackenzie River and Richardson Mountains. At a depth of 10 to 20 inches, where the frost table was 20 inches below the surface, there were streaks of organic matter up to one inch in thickness. To quote Leahey: "No explanation can be given for the presence of organic streaks in the lower part of the subsoil other than that they may have resulted from the activities of burrowing animals". Organic layers have been found in several areas near the Porcupine and Old Crow rivers of Yukon Territory (Lowther, personal communication). The layers lie at, or near to, the permafrost surface and may be associated with archaeological complexes. Organic layers occur near Point Atkinson and in the Cape Bathurst-Harrowby Bay area, District of Mackenzie.

Organic layers are probably present in the Eastern Arctic, but the writer has no record of them. The apparent absence of reports may be due to the fact that fine grained soils, such as Pleistocene silts and muds, in which organic layers best develop, are more widespread in the Western than in the Eastern Arctic. Feustel, Dutilly, and Anderson (1939) made no mention of any organic layers in their survey of soils from Churchill to Ellesmere Island, although the soils were analyzed for organic content. Most of the soils, which were of sand, gravel till, and weathered bedrock, were shallow in depth and sparsely covered with vegetation, these being factors not conducive to organic layer development.

In a study of Alaskan soils, Kellogg and Nygard (1951, pp. 34-40) reported tundra soil profiles containing organic material at the base of the active layer or in permafrost, but no explanation as to origin was given. Hopkins and Sigafoos (1951) have described stringers of peat beneath the soil centres of tussock rings and attribute the distribution of the decomposed fragments of peat to a convective circulation of material within individual polygons.

Studies of arctic brown soils in Alaska show that "A dark stain is sometimes present on top of the permafrost table, indicating that small quantities of humus finally work their way to lower depths in the profile" (Tedrow and Hill, 1955, p. 271). Tedrow, Drew, Hill, and Douglas (1958) have recently described an idealized profile of a tundra soil in northern Alaska. They recognize three master horizons: (1) the active layer; (2) the upper portion of the permanently frozen layer containing considerable organic staining and pieces of orgahic matter; and (3) the permanently frozen parent material without organic staining. They state that the processes by which the organic matter is dispersed through the ice in the upper part of the permafrost is unknown. The one typical and identical tundra profile from the U.S.S.R. given in the well known soil books by Robinson (1949), pp. 352-353) and Glinka (1940, pp. 117-118) had dark spots, apparently of organic matter, just above the permafrost table. It is quite possible that organic layers are described fully in Soviet publications, but the writer has been unable to find any such discussion. Organic layers have also been seen in Manchuria (Sugaya, 1956) and Norway (P.J. Williams, personal communication).

CHARACTERISTICS OF THE ORGANIC LAYER

Composition

Most of the organic material is partly decomposed and dark gray in colour, but there may also be nearly fresh greenish-yellow sphagnum moss, greenish willow leaves, twigs, etc., intermixed with the partly decomposed material. On moist gentle slopes with many sedgy tussocks and associated vegetation, thick chocolate brown peaty layers of sphagnum moss, sedges, etc., with much included ice, are common.

The organic layers vary from nearly pure vegetation in various stages of decomposition to streaks of organic material in a matrix of soil or ice. Most of the organic material contains sand to silt sized particles, locally in discontinuous thin laminae. If the mineral soil in the area has pebbles, a concentration is often observed at the ground surface and close to, or within, the organic layer.

If the organic layer thaws in summer, it tends to be saturated and ooze where exposed by digging. Frozen organic material, whether in the active layer or in permafrost, has a high ice content which often exceeds 50 per cent by volume. Such frozen material, which resembles a hard wax in consistency, can be whittled with a knife.

Thickness and continuity vary inversely with slope. On gentle slopes where there may be soil creep from nearby steeper slopes, the organic layers may be several feet thick. Such organic material is composed largely of chocolate brown sphagnum moss, sedges, etc., with much interstitial ice. As the development of ground ice segregations is usually extensive in such areas, the organic material may overlie thick, tabular, horizontal ice sheets and be contorted where cut by vertical ice wedges of ice-wedge polygons. On the steeper slopes of about 3^{o} to 10^{o}, the organic layer is typically only several inches thick. With gradually increasing slope, the organic layer becomes thinner and more patchy until it is no longer present.

The upper contact of the organic material with mineral soil may be transitional, but the lower contact tends to be distinct and sharp.

Relationship to the permafrost table

The most strikingly uniform, diagnostic, and characteristic feature of the organic layer is its position either at the bottom of the active layer, at the top of the permafrost zone, or in both. This is certainly true of the organic layers in the Western Arctic of Canada and those of Alaska (Tedrow, Drew, Hill, and Douglas, 1958). In one place the organic layer may lie at the base of the active layer, whereas two feet away it may be in both the active and permafrost zones, or even entirely within the latter (Figure 4). For this reason, a pit dug into the ground in June or July will usually reach frozen ground before any organic layer that is present is encountered. It was found by the writer that if a pit is dug to the frost table in late summer (when thawing has normally reached its maximum depth) without encountering an organic layer, the excavation should be extended at least one foot into frozen ground in order to be reasonably certain that no organic layer is present.

Age

Data from pollen spectra and carbon 14 dating show that some organic layers are many thousands of years old. Dr. R.S. MacNeish, in studying the archaeology of the Engigstciak site by the Firth River (Yukon Territory) collected specimens from the organic layer. Analyses of microfossils (by Dr. J. Terasmae, Geological Survey of Canada) have shown that one assemblage indicates more temperate climatic conditions than the present, chiefly because of the abundance of spruce and the presence of pine and tree-birch pollen. A carbon 14 dating for woody material from one organic layer gave an age of 1,560 years, although it is possible that the specimen may have been contaminated (MacNeish, personal communication). Carbon 14 dates for two organic layers in tundra soils of Alaska range from 5,300 to 10,900 years in age (Tedrow and Douglas, 1958). Although information on the composition of the organic layer is limited, pollen spectra and carbon 14 dating both indicate that some organic material may be of considerable antiquity.

ORIGIN OF THE ORGANIC LAYER

There is no doubt that many organic layers have formed in different ways. For example, organic material may be buried by mudflows, landslides, advancing solifluction lobes, windblown sediments, and by the lateral growth of ice wedges which have contorted the ground to cause overturning of surface accumulated humus. Alternatively, organic material might "grow" in situ by: the transfer of vegetation downwards in suspension or in a colloidal state; the lateral spread of roots above the thermal hardpan of the permafrost surface; and the carrying of nesting material to depths by burrowing animals. Overridden and buried humic material (the A_0 soil horizon) can be distinguished from the type of organic layer under discussion not only by geomorphic criteria (e.g. relation to landslides, solifluction lobes, slope, type of overlying material, etc.) but by the nature of the buried organic layer. A buried undisturbed A_0 horizon usually has downward penetrating roots beneath it, a transitional contact between A and B horizons, and a position at depth that is not regionally associated with the present permafrost surface. The alternative explanation of organic layers growing in situ is also unsatisfactory, because it cannot explain the presence of fibrous, woody, and fresh material often found in such layers.

Theory of Marine Burial

In parts of the Western Arctic, organic layers lie beneath marine clays (Prest, 1957). Despite the probability of local marine burial of old soil profiles, the organic layer is probably not a buried soil profile both in the areas where the organic layer lies beneath a marine clay, and also where it does not, for the following reasons. (1) The organic layer shows no evidence of being a buried A_0 soil horizon. Sections through the organic layer into the underlying mineral soil, where present (i.e. the organic layer is frequently underlain by ground ice) expose no traces of soil development. There are no visible weathered or leached horizons. No roots extend downwards from the organic layer as might be expected if it were a buried soil profile. No "fingers" of organic matter penetrate into the mineral soil beneath in a manner corresponding to that of organic material occupying the cracks and fissures of the hummocky ground in the present tundra and nearby forested areas. The contact between the organic and underlying inorganic material, such as sand or silt, is often so sharp that the two can be separated by a gentle pull or by sliding a knife blade between them. The organic layer may rest upon different materials within a lateral distance of a few feet; for example, a continuous organic layer has been observed to lie on top of both a marine clay and frost shattered shaley bedrock within a horizontal distance of 10 feet, and yet show no change in its features. (2) Even if it is granted that the A_0 horizon of a soil could be buried by only one to two feet of marine sediments over an extensive area, transgression and regression of marine waters across a tundra surface would likely erode, destroy, and rework the surficial material rather than to preserve it intact; furthermore, soil creep operating over the thousands of years since emergence would be expected to modify the stratigraphic distribution of any material in the active layer. (3) The close correspondence of the subsurface organic layer with the permafrost surface for an east-west distance of 300 miles from Firth River to Cape Bathurst, and from sea level to over 600 feet in altitude, could not result from a marine burial, as such uniformity in deposition would be impossible over such distances. If areas beyond the Western Arctic of Canada (e.g. Alaska) are considered, the position of the subsurface organic layer in relation to the permafrost surface adds strength to the argument against marine burial. (4) As seemingly identical organic layers occur both above and below the highest known marine limit, lie a theory of marine burial would require the existence of at least two types of organic layers.

Organic layers, representing turf buried by windblown sands and silts, are present along some rivers and wave cut cliffs, but these layers are easily recognizable and do not have the characteristics of the extensive organic layers under discussion. Some muck silt deposits of Alaska are of this category (Taber, 1958). The organic materials of the tundra in Alaska are probably not buried profiles (Tedrow and Douglas, 1958).

Convective Circulation Theory

Hopkins and Sigafoos (1951) have described the distribution of decomposed fragments of peat in the mineral soil of tussock-birch-heath polygons along the base of the annually thawed layer. They suggest that material is moved from the peat ridges at the margins of the polygons along the frost table to the centres, and from the frost table toward the surface in a convective circulation pattern. The theory may explain the partial transfer of organic material downwards and laterally, but it does not seem to explain the widespread occurrence of organic layers in the Western Arctic of Canada because: (1) Many of the areas with organic layers lack the tussock-birch-heath polygon development described by Hopkins and Sigafoos. (2) Although peaty material may be moved along the frost table to the centres of polygons, according to the convective circulation theory, there is very little field evidence in the Western Arctic for a continuous upward "convective" movement from the frost table to the surface. The tendency is for the peaty material to remain close to, or become a part of, the permafrost zone once it is moved downwards to the permafrost surface. (3) If the convective circulation process has operated through the active layer over thousands of years, organic and inorganic material should be thoroughly mixed. This is not the general case. Although the inorganic material may ;e streaked with organic matter, the amount is quite small in relation to that present in the organic layer. (4) The disruption of the surface layer and the formation of the convective circulation process has been thought (Hopkins and Sigafoos, 1951, pp. 83-92) to occur in a period as short as 10 years with new frost scars forming as old ones become stabilized. Such rapidity in formation of frost scars should result in intensive churning and mixing of organic with inorganic material but, as discussed above, this is not so.

Progressive Burial Theory

In contrast to the foregoing theories, the writer proposes a progressive burial theory, according to which, organic material that has accumulated in interhummock depressions of the tundra surface is progressively rolled under and smeared along the base of the active layer and on top of the permafrost surface. Progressive burial is believed to be a continuing process that has operated for some thousands of years. The theory seems to explain satisfactorily the known features of the organic layer.

In the field study of a total length of several miles of organic layers exposed in wave cut cliffs, and over 200 pits dug to frozen ground, there were numerous examples of organic matter in surface depressions that could be traced underground as an unbroken sheet until it became a subsurface organic layer. The organic layers seem, therefore, to be portions of surface accumulated organic material buried by a rolling-under and sliding-over process. The continuity of surface and subsurface organic material is the strongest evidence for the progressive burial theory.

The method of progressive burial can perhaps be best explained by discussing the microrelief of the vegetated tundra with an organic layer on a moderate slope of cohesive soil. With very few exceptions, tundra terrain that supports a fairly continuous growth of vegetation, such as that present along the coastal zone in the Western

Arctic, is hummocky. The hummocks range from one to several feet across and from a few inches to two feet in height above the depressions in between them (Figure 2). The hummocks are flat to convex on top. The depressions between the hummocks usually have a thick accumulation of living and dead organic material composed of mosses, lichens, sedges, grasses, willows, etc. (Figures 1 and 4). The hummock "centres" tend to have a thin accumulation of organic material; indeed, only the bare mineral soil of the familiar "mud boils" of Arctic regions may be present. The thickness of the A_0 horizon, is, as a rule, greater in silts and silty clays than in sands. In the latter, the sparse vegetation - often of avens - contributes relatively little humus to the soil either on the hummocks, or in the depressions.

The mechanism of the rolling-under and sliding-over process can only be inferred, at present. It involves the gradual movement of hummocks over partially decomposed vegetation occupying the basal portions of the interhummock depressions.

Figure 1. Vegetation types, King Point, Yukon

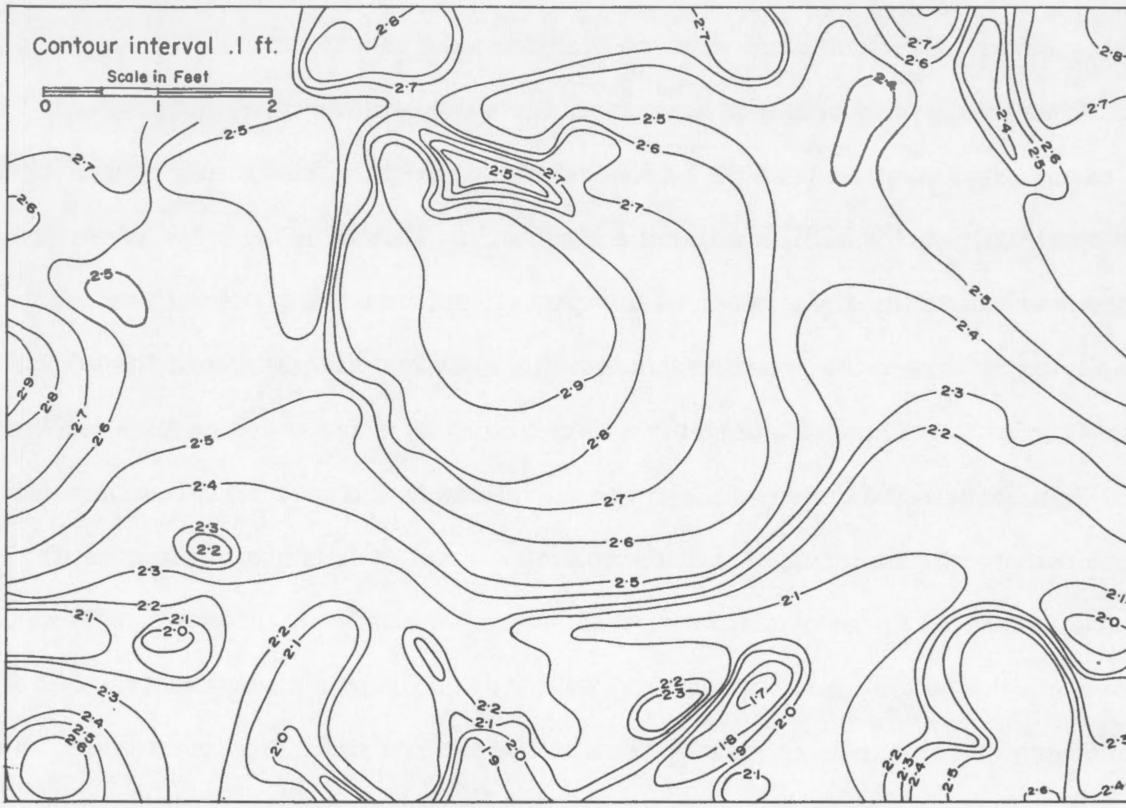

Figure 2. Surface contours above datum, King Point, Yukon

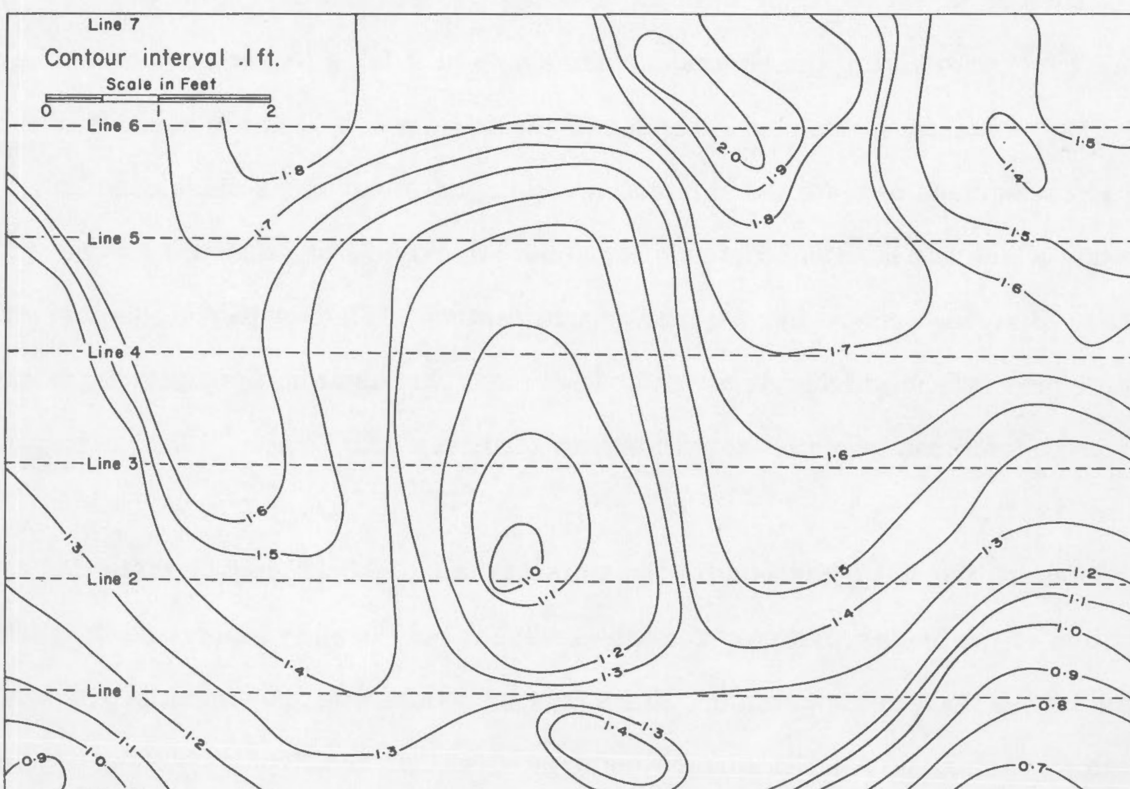

Figure 3. Frost table contours above datum, King Point, Yukon

Probably several different processes contribute to the movement.

When the ground begins to thaw from the surface downwards in summer, a point of any given altitude beneath a depression may remain frozen longer than a point at the same altitude beneath an adjoining hummock. This is because the permafrost surface does not follow the contour of the ground, but forms a crude mirror image of it, being lowest where the ground surface is highest, and highest where the ground is lowest (Figure 3). Thus, the permafrost surface is usually deeper beneath the hummocks than beneath the depressions. The elevations in the permafrost surface lie beneath the organic material of the depressions, possibly because of the greater insulating qualities of the organic material in comparison to the predominantly mineral soil beneath the hummocks. In addition, evaporation of the abundant moisture in the organic material may help to maintain low temperatures and a high frost table (Benninghoff, 1952, pp. 38-39).

If there is any tendency towards downslope movement during the period of thaw, the inorganic material of the hummocks can share in it for a longer period of time than the organic material in the depressions. It should be noted, that the position of the permafrost surface beneath the hummocks and depressions under discussion is different from that which has been encountered for some other types of patterned ground. Where garlands of stones occupy depressions around centres of finer material, isotherms in summer may indicate higher temperatures at any given depth in the active layer beneath the depressions than beneath the hummocks (Cailleux and Taylor, 1954, p. 58; cf. Taylor, 1957).

During the fall freeze-back, the soils of the hummocks may be distended by the formation of ice lenses, not only near the surface, but possibly also at depth. When the ice lenses thaw in the summer, there may be differential movement in a downslope direction, particularly in the surface material (Sigafoos and Hopkins, 1952, p. 178).

Movement might also be aided by excess water from melting of the ice layers and a reduction of shear strength following disturbance due to ice layer formation (Williams, 1957). The role of pore water pressure is unknown, but it may be important.

The net result of the many factors contributing to movement may be that each hummock tends to override the organic material in the depressions immediately downslope from it (Figures 5 and 6). This may often be observed where bands of organic material in the depressions dip upslope.

Once organic material is overridden, it generally remains at the base of the active layer. An examination of many sections shows little upward "convective" movement. Indeed, as organic material is progressively rolled under, the permafrost table may rise until part, at least, of the organic material is incorporated into the permafrost zone.

Overriding is believed to be a slow process with an average yearly movement of only a minute fraction of an inch. The process is so slow that fresh organic material accumulates in depressions and partially decomposes, before being rolled under. In an area where hummocks are two to three feet across, a hummock movement of 10 feet downslope in a few thousand years would result in several hummocks overriding any given point beneath the ground. It would require only a portion of the organic material between the hummocks to be overridden in order to produce an organic layer. There might also be some squeezing of organic material from the depressions towards the centres of the hummocks, but without an upward convective circulation as suggested by Hopkins and Sigafoos (1951).

It should be pointed out that overriding is dependent upon hummocks maintaining some semblance of individual identity for hundreds, if not thousands, of years. This is probably the case. Dwarf willows, ground birch, and lapland rhododendrons growing on hummocks or on the sides of depressions may be many tens if not a hundred years old.

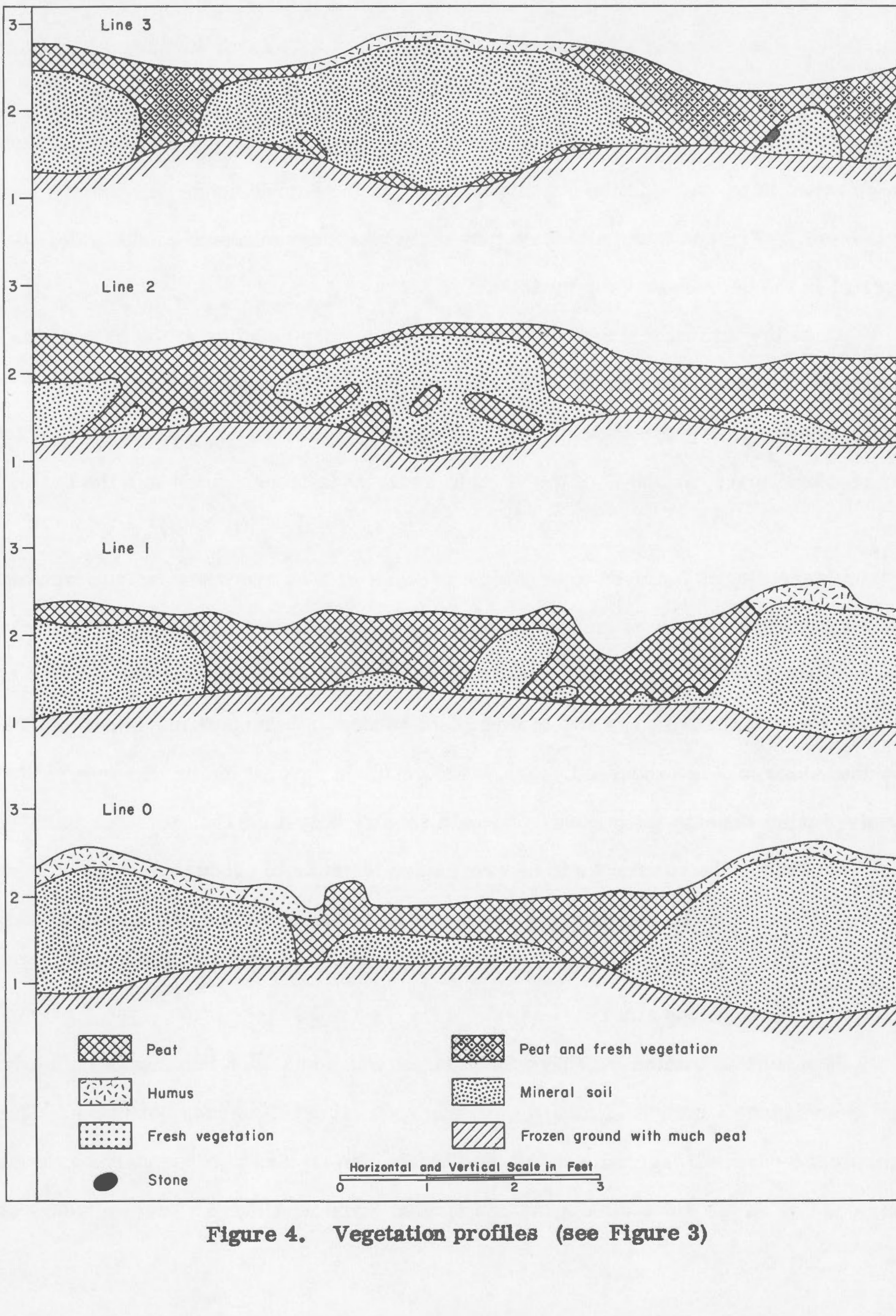

Figure 4. Vegetation profiles (see Figure 3)

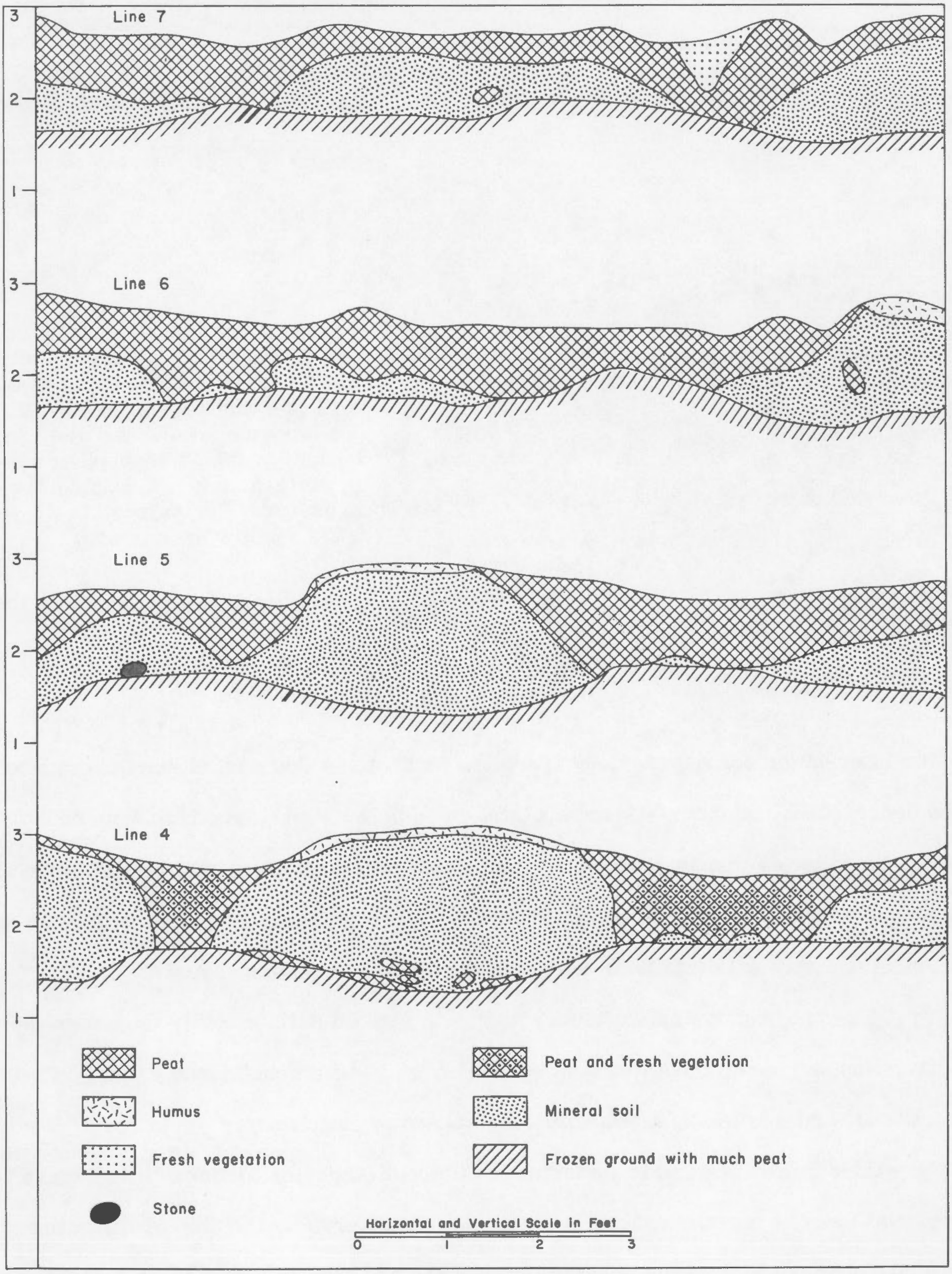

Figure 4 continuation

At the Engigstciak archaeological site on the Yukon coast, artifacts and refuse of complexes, possibly ancestral to the Eskimo of the Yukon Arctic coast, occur in surface materials and humus (MacNeish, 1956). Numerous excavations show that

Figure 5. The white string marks the boundary between mineral soil and organic material. An ice-wedge shows up as white in the bottom of the photograph. Note how organic material occupies the depression. Permafrost is 12 to 18 inches below the surface.

some inter-hummock depressions are filled with refuse that was either thrown into the depressions, or naturally accumulated in such low spots. As archaeological evidence suggests that the complexes associated with the refuse may be well over a thousand years old, there is good archaeological evidence to show that hummocks and depressions may maintain their individuality for over a thousand years.

The progressive burial theory seems to explain satisfactorily the known characteristics and peculiarities of the organic layer. The discontinuous extent, varying thickness, and mixture of fresh with decomposed organic matter would result from progressive burial of organic material in different stages of decomposition; fresh material can fall into the cracks or be pushed downwards by the step of a passing animal. The position of the organic layer at the base of the active layer and in permafrost logically results from the theory. The smearing of the organic layer over mineral soil accounts for the absence of underlying soil profiles, root systems, and downward penetrating organic tongues. Stones found at or near the organic layer may

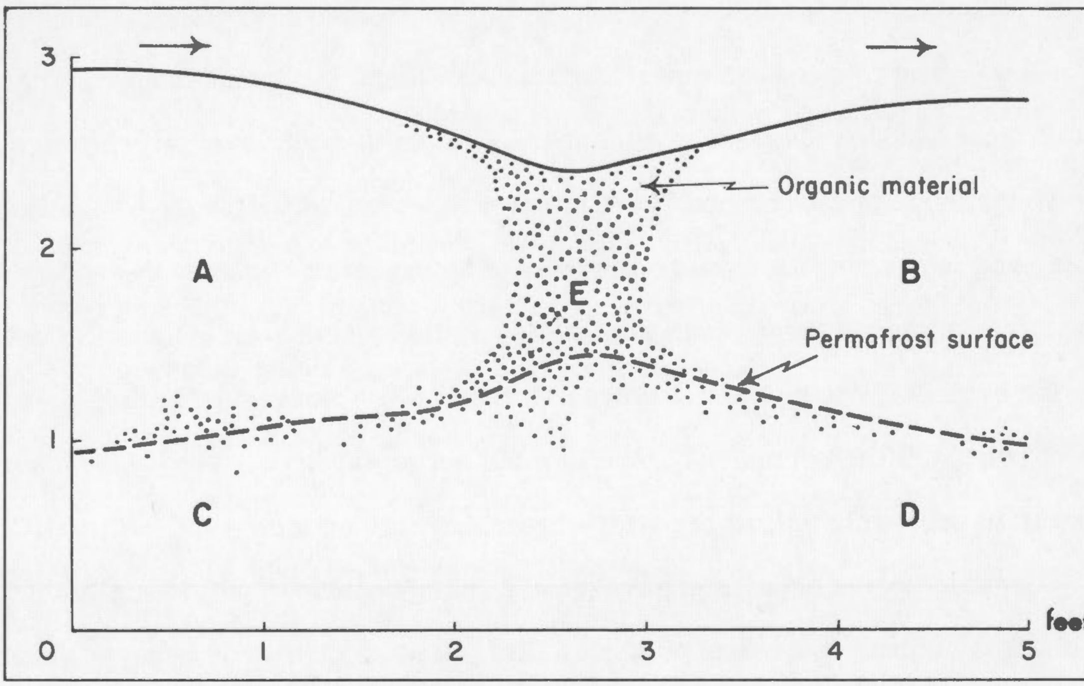

Figure 6. Hummocks A and B move downslope so that A moves to position B. The organic material in the depression at E is smeared along the permafrost surface.

have been frost-heaved to the surface and then moved laterally by frost heaving and gravity into the organic material of the depressions. The sandy and silty material in some organic layers may have been washed from the bare spots of the hummocks and screened through the filter of organic material in the depressions. Water oozing out from organic layers when they are sectioned shows that they act as ready aquifers for the filtering of ground water.

There is no doubt that climatic oscillations have taken place in the Western Arctic, as elsewhere, during the past few thousand years. At times of warmer climates, the active zone would have been thicker, and the organic layer may have formed at greater depth. On the other hand, the gradual downslope movement of the active layer may locally cause a slight retrogression of the permafrost surface. However, in several areas where the active layer was slowly sliding off the hilltops like frosting off a cake, plugs of inorganic material had punched from below the permafrost surface through the organic layer into the active layer. The plugs were from a few inches to a foot or more in diameter. Some had punched upwards at least 18 inches. Such plugs were common where the organic layer overlay fine cohesive material that remained "plastic" even when the temperature was below freezing and ice segregations were present. The pressure required to squeeze the fine material upwards through the organic layer might have been supplied in several ways; for example, by the lateral growth of vertical ice wedges. The injection of plugs of soil from the permafrost zone into the active layer may be one means of renewing the inorganic soil of the active layer as it slides slowly off a hilltop.

Organic layers occur more frequently under cohesive soils like silts and silty clays than under noncohesive sands. This is to be expected, because vegetation is more abundant in hummocks composed of fines; the organic tongues extend to greater depths and permafrost is shallower. As a rule of thumb, permafrost in sand will be roughly 30 to 50 per cent deeper than in silty clays so that sparse organic material has a much smaller chance of being frozen at depth and rolled under. In sandy areas, humic streaks seem to be the counterpart of the organic layers of fine soils.

CONCLUSIONS

Organic layers are not local phenomena, but appear to have a wide distribution in the tundra regions of the world. They have not formed as a part of tundra soil development, in the pedologic sense, but have resulted from progressive burial of the organic tongues that extend downward in the depressions between hummocks. The organic layers develop slowly, probably over a period of thousands of years. A record of former climates may be obtained, in part, by a study of plant microfossils. The use of carbon 14 determinations for the age of the organic layers should be treated with reserve, because organic materials of greatly differing age may be intermixed. In areas which have been inhabited by man, ashes, refuse, and artifacts have tended to accumulate in the natural pockets formed by the inter-hummock depressions. These evidences of human occupation may be rolled under, along with the organic material, to give organic layers with artifacts, bones, charcoal, ashes, etc., with the oldest at the greatest depth, the youngest nearest the top, although inversions occur.

BIBLIOGRAPHY

Benninghoff, W.S.
1952 : Interaction of Vegetation and Soil Frost Phenomena. Arctic, vol 5, pp. 34-44.

Cailleux, A., and Taylor, G.
1954 : Cryopédologie: Etude des Sols Gelés. Paris: Expéditions Polaires Françaises, vol. 4, 218 p.

Feustel, I.C., Dutilly, A., and Anderson, M.S.
1939 : Properties of Soils from N. American Arctic Regions. Soil Science, vol. 48, pp. 183-199.

Glinka, K.D.
1940 : The Great Soil Groups of the World and their Development. Trans. by C.F. Marbut. Edwards Bros., Inc., Ann Arbor, Michigan. 150 p.

Hopkins, D.M., and Giddings, Jr., J.L.
1953 : Geological Background of the Iyatayet Archaeological Site, Cape Denbigh, Alaska. Smithsonian Misc. Colls., vol. 121, 33 p.

Hopkins, D.M., and Sigafoos, R.S.
1951 : Frost Action and Vegetation Patterns on Seward Peninsula, Alaska. United States Geol. Surv. Bull., 974-C, 101 p.

Kellogg, C.E., and Nygard, I.J.
1951 : Exploratory Study of the Principal Soil Groups of Alaska. Agricultural Monograph No. 7, United States Department of Agriculture, 138 p.

Leahey, A.
1947 : Characteristics of Soils Adjacent to the Mackenzie River in the Northwest Territories of Canada. Proc. Amer. Soil Science Soc., vol. 12, pp. 458-461.

MacNeish, R.S.
1956 : The Engigstciak Site on the Yukon Arctic Coast. Anthropological Papers of the University of Alaska, vol. 4, pp. 91-111.

Prest, V.K.
1957 : Pleistocene Geology and Surficial Deposits. pp. 443-495 IN C.H. Stockwell (ed.): Geology and Economic Minerals of Canada (4th. ed.), Econ. Geol. Ser. No. 1, Geol. Surv. Canada, 517 p.

Robinson, G.W.
1949 : Soils: Their Origin, Constitution, and Classification. Thomas Murby & Co., London, 3rd. ed., 473 p.

Sigafoos, R.S., and Hopkins, D.M.
1952 : Soil Instability on Slopes in Regions of Permanently Frozen Ground. Frost Action in Soils: A Symposium. Highway Research Board, Washington, D.C., pp. 176-192.

Sugaya, J.
1956 : Congelation-structure and Frost Heaving Ratio at Assan, Manchuria. Trans. from unpublished ms. by E.R. Hope; Defence Research Board, Ottawa, 18 p.

Taber, S.
1958 : Complex Origin of Silts in the Vicinity of Fairbanks, Alaska. Bull. Geol. Soc. Amer., vol. 69, pp. 131-136.

Taylor, R.S.
1957 : Physical Characteristics and Mechanics of Certain Depressed-Center Stone Rings in Northwestern Greenland, (abstract), Bull. Geol. Soc. Amer., vol. 68, p. 1804.

Tedrow, J.C.F., et al.
1958 : Major Genetic Soils of the Arctic Slope of Alaska. Soil Science, vol. 8 (in press).

Tedrow, J.C.F., and Douglas, L.A.
1958 : Carbon 14 Dating of Some Arctic Soils. Mimeographed Note; Department of Soils, Rutgers University, January, 1958, 6 p.

Tedrow, J.C.F., and Hill, D.E.
1955 : Arctic Brown Soil. Soil Science, vol. 80, pp. 265-275.

Williams, P.J.
1957 : Some Investigations into Solifluction Features in Norway. Geographical Journal, vol. 123, pp. 42-58.

GEOGRAPHICAL PAPERS

Papers Nos. 1 to 6 are out of print.

No. 7. Extracts relating to the Navigability of Canadian Inland Waterways. By W. A. Black, Ottawa, 1956. 55 p., offset. *Price 50 cents.*

No. 8. Notes on Potential Building Sites in the Bathurst Inlet Area, N.W.T. By J. B. Bird and M. B. Bird, Ottawa, 1956. 15 p., map, offset. *Price 25 cents.*

No. 9. A Report on Sea Ice Conditions in the Eastern Arctic, Summer 1956. By W. A. Black, Ottawa, 1956. 32 p., maps, illus., offset. *Price 50 cents.*

No. 10. A Preliminary Report on Ice Conditions at Cacouna Island, Quebec. (Bilingual). By B. Robitaille, Ottawa, 1957. 24 p., maps, illus., offset. *Price 50 cents.*

No. 11. An Illustrated Glossary of Ice Types in the Gulf of St. Lawrence. By W. A. Black, Ottawa, 1957. 50 p., map, illus., offset. *Price 75 cents.*

No. 12. Gulf of St. Lawrence Ice Survey, Winter 1956. By W. A. Black and C. N. Forward, Ottawa, 1957. 23 p., maps, offset. *Price 25 cents.*

No. 13. Notes on Small Boat Harbours, N.W.T. By J. Ross Mackay, Ottawa, 1957. 12 p., illus., offset. *Price 25 cents.*

No. 14. Gulf of St. Lawrence Ice Survey, Winter 1957. By W. A. Black, Ottawa, 1957. 29 p., maps, illus., offset. *Price 75 cents.*

No. 15. A Report on Sea Ice Conditions in the Eastern Arctic, Summer 1957. By W. A. Black, Ottawa, 1958. 32 p., maps, illus., offset. *Price 50 cents.*

No. 16. Ice Conditions in the Gulf of St. Lawrence during the Spring Seasons 1953-1957. By C. N. Forward, Ottawa, 1958. 13 p., maps, offset. *Price 25 cents.*

No. 17. Etude du Port de Québec. By P. Camu, Ottawa, 1958. 79 p., maps, illus., offset. (*in press*).

Price: 50 cents Cat. No. M-67-18

Available from the Queen's Printer, Ottawa, Canada