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SOIL PROPERTIES DEVELOPED ON THE COMPLEX TUNDRA RELIEF OF NORTHERN ALASKA

Abstract

A five-year investigation of the Coastal Plain tundra in the vicinity of Barrow, Alaska, provides the basis for evaluating the variations in soils, surface relief, and near-surface lithology in a region underlain by continuous, perennially frozen ground. Analyses of 80, one-meter long soil cores showed no statistical correlation between microrelief and thaw or microrelief and moisture. A significant negative correlation was established between thaw depth and total moisture contained in the seasonally thawed soil. Seasonal thaw at the 80 points during 1962 to 1966 averaged 43, 41, 33, 36, and 37 cm for each of these years respectively. Morphological examination indicated a maximum thaw of approximately 52 cm based upon depth to ice wedges and high-ice soil. Correlation of the 5-year measured than with climatic data indicated that wet-warm summers such as 1951 and 1954 could produce the observed thaw of 52 cm.

Chemical analyses of the soil and near-surface sediments demonstrate the freshened character of the thawed soil. A vertical depression of the chemical concentrations beneath part of the 1.5-km study transect to a depth exceeding 3 meters suggests the previous occurrence of thaw features such as a lake. Buried organic matter at the base of the active layer and in the perennially frozen ground yields radiocarbon ages of less than 2,500 to 10,500 years. The younger peat occurs over ice wedges and demonstrates a recent burial cycle associated with wedge growth. The wide range in ages of buried peat and the general lack of textural unconformities support the theory of cryopedologic burial of the peat.

INTRODUCTION

The climate of northern Alaska produces great thicknesses of perennially frozen ground, actively growing contraction crack polygons and ice wedges, and a thin layer of seasonally thawed soil. The complex tundra landscape of the Coastal Plain is one of subdued regional topography with a high degree of variation in microrelief due to two types of frost features: (1) hummocks and frost scars and (2) polygonal ground. Considerable areal and

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seasonal variations exist in soil properties associated with these types of microrelief. The principal objectives of this investigation were to determine the variation in such soil properties as depth of thaw, morphology, moisture content and chemical and textural compositions, and to evaluate the causes of these variations (Brown and Johnson, 1965). It is the purpose of this report to summarize the major findings to date of a 5-year research program at Barrow, Alaska.

LOCATION, EXPERIMENTAL DESIGN, AND DESCRIPTION OF STUDY AREA

The study area is located at the northern extremity of the Arctic Coastal Plain (71°19′N, 156°35′W). Geomorphologically the region is flat, dominated by ice-wedge polygons, covered with shallow oriented lakes and drained lake basins, and underlain by perennially frozen ground to depths in excess of 300 meters. The near-surface sediments consist of Pleistocene marine and non--marine deposits (Gubik Formation). The seasonally thawed soils are predominantly fine-grained, generally close to water-saturated, and usually contain abundant quantities of surface and buried organic matter. These soils have been referred to as Upland Tundra, Meadow Tundra and Bog soils in order of increasing wetness and amounts of organic matter (Tedrow, *et al.*, 1958). The vegetation is predominantly wet tundra with an abundance of sedges, grasses, herbs, a few dwarf shrub species and lichens, and no cottongrass tussocks. The mean annual air temperature at Barrow is —12.4°C with average annual precipitation of 116 mm. The duration of the thaw season [1] is approximately 88 days with a thaw degree-day accumulation of 294 (C) and a thaw season precipitation of 57 mm (averages based on 45-year record).

In order to sample soils and terrain characteristic of the Barrow landscape, a 200-meter wide, 2.1 kilometer transect was established in 1962. This has been described and illustrated in detail (Brown and Johnson, 1965). The results discussed here are from a 100-meter wide, 1.5-km long portion of this transect which was subdivided into 10 geomorphic units based largely upon slope and surface microrelief. Two randomly distributed 10×10 meter plots

[1] The thaw season is defined as the period during which positive-degree days (0°C base) accumulate consistently, even though frequent frosts may occur.

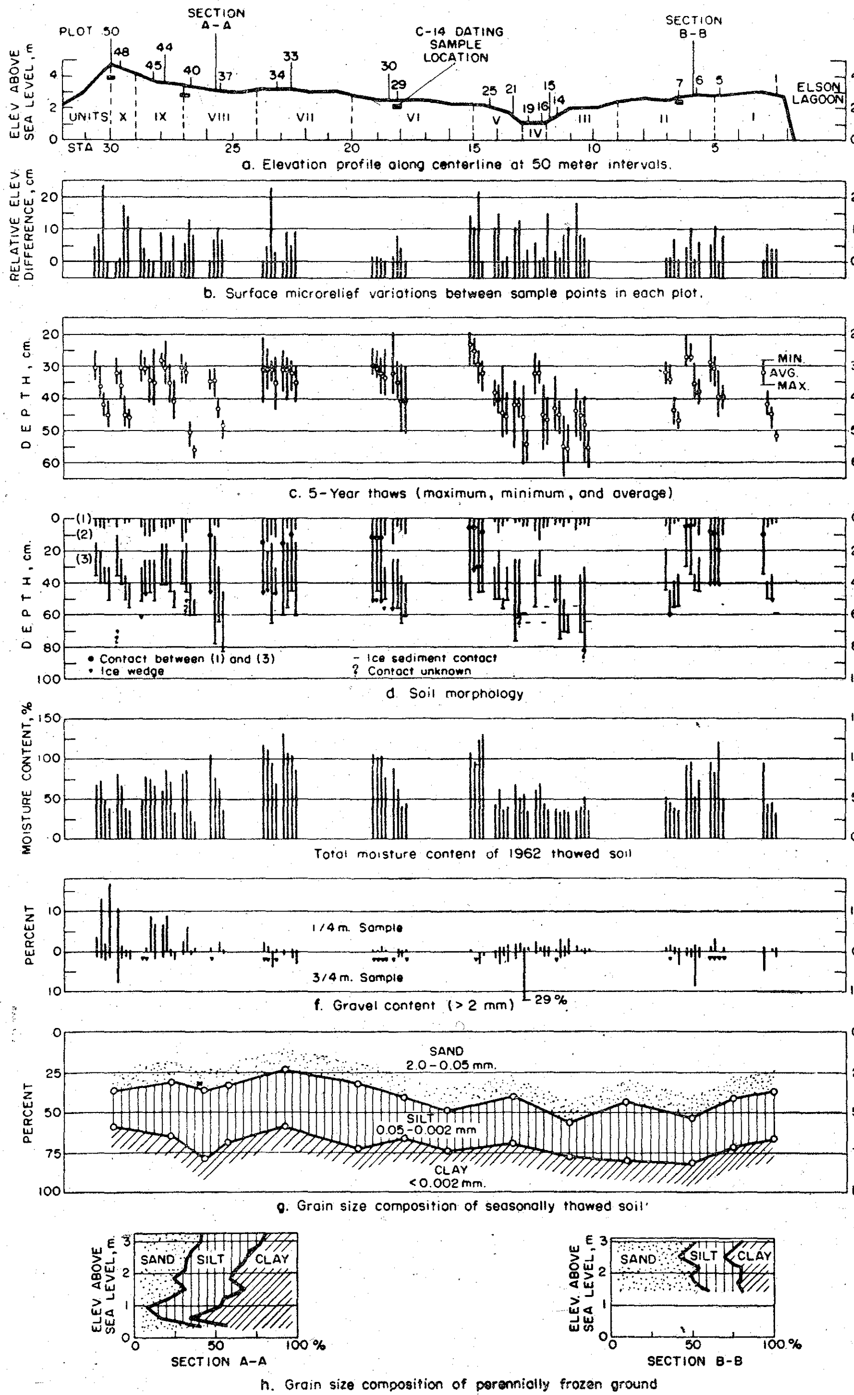

Fig. 1. Cross-section of study transect, graphically presenting microrelief, 5-year thaw, morphological, moisture and gravel data for 80 cores and grain size composition of soils and sediments

were established in each unit. The resulting 20 plots were each divided into a 2×2 meter grid providing a total of 36 points per plot for observations. Figure 1 (section a) indicates the positions of the plots and units along the transect. Plate 1 is a low altitude aerial oblique photograph across the transect in the vicinity of Units X to VIII. It illustrates the hummocky and moundy relief associated with the top and back slope of the beach ridge (X) and the well-developed, ice-wedge polygons and mineral frost scars situated below the subdued ridge (VIII and IX).

METHODS

Depth of thaw penetration was measured periodically throughout the thaw season on the peripheral 20 points of each plot and on all 36 points at the time of maximum thaw. These measurements were made by probing the soil to the point of refusal with a pointed, 1-cm diameter steel rod. Readings were to the nearest centimeter. Elevations on all 36 points were determined and 5-cm contour maps prepared for each plot. A comprehensive soil sampling program was conducted to (1) determine the variability in soil-chemical and -physical properties as related to depth and type of area and (2) correlate soil and frozen ground morphology with measured depths of thaw and climatic data.

The comprehensive sampling of all 20 plots was accomplished in the spring of 1963 and consisted of four 1-meter long cores per plot. The sample sites were restricted to the inner 16 points of the plots and represented two minimum and two maximum values of the preceding year's thaw. The 6.5-cm diameter cores were completely frozen at time of sampling. Each of the 80 cores was photographed, cut into 5-cm increments and moisture content determined on each segment (oven dried at 105°C). Water was extracted under vaccuum filtration from two samples per core for chemical analyses: (1) from a 5-cm increment at approximately the center of the 1962 thawed zone (referred to as the $^1/_4$-m sample); and (2) from a segment 50 cm below this sample in the perennially frozen ground (referred to as the $^3/_4$-m sample). The electrical conductivity of the water extract was determined, this value converted to meq./l., and based upon moisture content of the sample, the concentration was calculated as meq./100 gm oven-dried soil (O'Sullivan, 1966). Loss-on-ignition (500°C) and saturation moisture were determined on most of these two increments. Grain size analyses were performed on selected samples. Deeper samples were obtained in 1964 along the transect and similar determinations conducted.

RESULTS AND DISCUSSION

SOIL MORPHOLOGY

Soil morphological studies are based largely upon the 80 cores, although supplemental excavations and observations were made, particularly in the frost scar area. The major properties observed directly in the frozen cores or in the photo logs and graphically illustrated in Figure 1 (section d) are: (1) thickness of surface peat, (2) thickness of mineral soil (indicated by the blank vertical space), (3) depths to buried organic matter, and (4) depth to high-ice sediment or ice wedge. The cores for each plot are arranged in order of increasing thaw based upon the 5-year average (section c). The occurrence of buried organic matter is not always obvious by visual observations. Its presence is estimated when an abrupt increase in moisture content (oven-dried basis) occurs without visible ice lensing. The increased moisture holding capacity coincides with an increased organic content (loss-on-ignition of more than 10%). The contact to high ice is generally sharp and easily discernible as thick horizontal ice lenses or peds of soil suspended in ice. Ice-wedge ice is massive with predominant vertical foliation. Both the upper contacts to high-ice soil and ice-wedge ice are considered the maximum depth of observed thaw.

Soils in the vicinities of plots 25, 30, 33, and 34 are primarily organic with thick surface peat merging into mineral soil containing considerable buried organic matter (wet Meadow Tundra and Half Bog soils). Plots 1, 7, 14, 15, 16, 19, 21, 29, and 48 generally have thin peat cover and reasonably thick zones of organic-free soil (Upland Tundra soils). Ice wedges were clearly encountered in 20 of the 80 cores. Plots 5 and 30 had ice-wedge ice under all four sample locations and plot 34 in three out of four locations. The buried organic matter, generally beneath a thin zone of mineral soil, is characteristic of all mineral tundra soils (Douglas and Tedrow, 1960). It generally occurs at the base of the seasonally thawed soil and usually extends into the perennially frozen ground for at least one meter.

GRAIN SIZE COMPOSITION

Grain size analyses from selected portions of the thawed soils along the transect indicate a more sandy composition in Units II, IV, V, VI and particularly III (Fig. 1, section g). Sampling in the perennially frozen ground substantiates this sandy trend with depth (Fig. 1, Unit II, B—B, section h). In contrast, Unit VIII is apparently underlain by increasingly more clayey sediments with depth, a condition that would favor increased migration of "unfrozen water" associated with the clays. A comparison of the gravel contents in the $^1/_4$-m and $^3/_4$-m samples of each core serves as an index for comparing textures between the thawed soil and the frozen sediments (Fig. 1, section f). The influence of the gravelly beach ridge (Unit X) is observed in the gravel contents of the soils in Units VIII, IX, and X. A number of $^1/_4$-m samples contain considerably more gravel than the underlying $^3/_4$-m samples. There are at least two explanations for these increases: (1) gravel was concentrated in the thawed soil as a result of deflation or (2) particle migration within the thawed soil as a result of the convergence of the upper and lower freezing fronts concentrated gravel disproportionately in the mid-section of these cores (Corte, 1963). Based upon the grain size analyses there seems to be no gross unconformity between the thawed soils and the underlying perennially frozen ground. The gravel content of deeper permafrost in Units V to IX is generally less than 1%. Unit X is underlain by a core of well-sorted, pea-size gravel.

THAW CHARACTERISTICS

Table I contains the thaw-season climatic chronology and measured thaw for the 5-year period of record. Maximum thaw occurred in the warm-wet summer of 1962 and minimum thaw occurred in 1964, a dry and cool summer. The dryness resulted in an early desiccation of the surface peats which provided a good insulation to limit further thaw. Figure 1 (section c) demonstrates that the 5-year extremes for the entire traverse lie essentially within two limits; a minimum thaw of approximately 20 cm and a maximum thaw of approximately 80 cm. The deep thaws in Unit III, IV and V are associated with the drier more sandy soils. Other deep thaws are associated with the bare frost scars in Plots 37 and 40. The shallower thaws occur in the wetter and more peaty

Table I

Thaw season and depth of thaw, Barrow, Alaska

Year	Thaw season	Thawing index (DD*) C-degree days	Thaw season precipitation (mm)	Final ave. 80 pt*	Depths of thaw (T)	
					400 pt	720 pt
1962	9 June — 5 Sept	389	84	43	43	43
1963	4 June — 3 Sept	196	115	41	40	40
1964	6—13 June — 9 Sept	160	22	33	32	32
1965	24 June — 27 Aug	247	47	36	37	36
1966	11 June — 28 Aug	202	73	37	38	37

* Regression analysis for 5 year's data, $T = 30.3 + 0.032 \cdot DD$, $r = 0.72$, $p < 0.2$

soils. A significant characteristic of the thaw season is that 50% of the total thaw usually occurs within less than 3 weeks of the onset of the thaw season. In some summers 100% of the thaw is attained by the first two weeks of August.

Morphological examination of the 80 soil cores revealed a maximum average depth of thaw of 52 cm. The criteria for these determinations were the depths to which ice-wedge ice was first encountered or the upper limit of the high-ice soil. Table II contains a summary of these morphological observations according to reliability of observations and ice morphology types. The discrepancy between the 5-year measured thaw (43 cm maximum) and the morphologically observed thaw (52 cm) can be explained by examination of the 20-year climatic record from Barrow. The most favorable thaw conditions occur during a warm and wet summer. The data for the summers of 1951 and 1954 suggested an adequate thawing potential to produce this estimated 52-cm thaw penetration. In order to establish this a simple linear regression analysis was conducted on the maximum seasonal thaw observations (T) and thaw degree days (DD) for the 5-year record (Table I), $T = 30.3 + 0.032\ DD$. If this line is extrapolated to 500 C degree days, the regression line yields 47 cm. The maximum observed thaw of 52 cm falls within the 95% confidence interval at this point.

Table II

Morphologically observed * and maximum measured thaw (cm) **

Number of cores		Depth (cm)
39	Maximum ave. observed thaw with sharp high-ice contact Maximum ave. measured field thaw	= 51 cm = 42 cm
21	Maximum ave. observed thaw with questionable contact Maximum ave. measured field thaw	= 59 cm = 49 cm
20	Depth to top of ice wedges Maximum ave. measured field thaw over ice wedges	= 47 cm = 39 cm
80	Maximum ave. depth of observed thaw Maximum ave. depth of measured thaw	= 52 cm = 43 cm

* Estimated to nearest 5-cm interval from core photo.

** Measured to nearest 1-cm, but averages same if rounded off to closest 5-cm interval (5-year period).

The set of data from the 80 cores provided the opportunity to evaluate the relationships between differences in elevations, moisture, soil morphology and thaw. No correlation exists between microrelief and thaw, or microrelief and moisture for any of the 8 cores per geomorphic unit or for all 80 cores taken together. The lack of correlation between microrelief and thaw was further substantiated by regression analyses of the 36 pairs of thaw and microrelief measurements in each plot. This is important since one might anticipate that microrelief highs would be drier and thaw more deeply than depressions which should be wetter and have shallower thaw.

The significant correlations are between total moisture content of the thawed soil and the depth of thaw penetration. Table III contains the correlation coefficients for the various combinations of thaw vs moisture. The highest correlation (negative) was between the total moisture content in the 1962 volume of thawed soil and the 5-year average thaw at these 80 points (Table III). Correlation was significant in 8 out of the 10 units at the < 0.05 level ($n = 8$) and significant at the < 0.001 level ($n = 80$) for all 80 points. Less significant relationships existed between moisture and 1962 thaw, the minimum thaw and maximum thaw. This negative correlation of moisture content with thaw is simply explained by the volumetric heat capacity of the thawing soil. The wetter or more ice-rich soils (more organic) have a high volumetric heat capacity, thereby requiring more energy to thaw a similar depth of soil than the drier, more sandy soils. The total moisture content of the thawed soil is a convenient index value for correlation purposes. The moisture content or index reflects the complex composition of the soil. Higher moisture contents are associated with soils containing thick surface peats, large amounts of buried peat and more silts and clays. Lower moisture contents reflect less organic matter and more sandy soils. The fact that the best correlation of the moisture data (1962) with thaw was for the 5-year period increased the validity of using the 1962 moisture data as index values for other correlations regardless of season or year of sampling.

The correlation of percent field moisture (W) with percent loss-on-ignition (I, a measure of soil organic matter) of the $1/4$-m sample produced the equation $I = 1.01 + 0.290\ W$, $r^* = 0.84$ ($n = 80$). These samples, collected in the frozen state, were partially de-

* Significant at < 0.001.

Table III

Correlation coefficients for total moisture contents vs depths of thaw

Unit	% moisture (W) vs ave. 5-yr thaw (T)	% moisture vs min. 5-yr thaw	% moisture vs 1962 thaw	% moisture vs max. 5-yr thaw
I	—0.81*	—0.86*	—0.70	—0.70
II	—0.80*	—0.80*	—0.80*	—0.80*
III	—0.27	—0.37	—0.08	+0.10
IV	—0.80*	—0.82*	—0.78*	—0.55
V	—0 86*	—0.73*	—0.84*	—0.85*
VI	—0.97*	—0.65	—0.93*	—0.93*
VII	—0.82*	—0.56	—0.46	—0.45
VIII	—0.95*	—0.95*	—0.96*	- 0.97*
IX	—0.56	—0.60	—0.38	—0.38
X	—0.95*	—0.95*	—0.96*	—0.95*
Total 80 cores	—0.83**	—0.80**	—0.77**	—0.75**

* Significant at $<$ 0.05 level, n = 6.

** Significant at $<$ 0.001 level with $T = 101 - 15.4 \ln W$, for T = 5-yr ave.

hydrated since water migrates away from the mid-zone during freeze-up. Saturation moisture percent (W′) was determined on samples of low organic contents and correlation with loss-on-ignition produced the equation $I = -7.63 + 0.438\,W'$, $r^* = 0.77$ ($n = 67$). These relationships indicate the influence of soil organic matter upon the moisture holding capacity of the soil, which in turn is reflected in the thaw penetration. These relations can be observed graphically in Figure 1 (sections c, d, e) among thaw, morphology and total moisture contents.

CHEMICAL PROPERTIES OF SOILS AND NEAR-SURFACE LITHOLOGY

The average value for the chemical composition of the $^1/_4$-m soil sample based upon the water extract technique was 0.23 meq/100 gm dried soil and for the $^3/_4$-m sample was 5.6 meq/100 gm. This increase of 24-fold in the salt content downward between the two groups of samples clearly indicates a removal of ions from the seasonally thawed soil. Although there was considerable chemical variation between cores, plots, and units, a distinct freshened zone was noted in the $^3/_4$-meter samples in Units VII

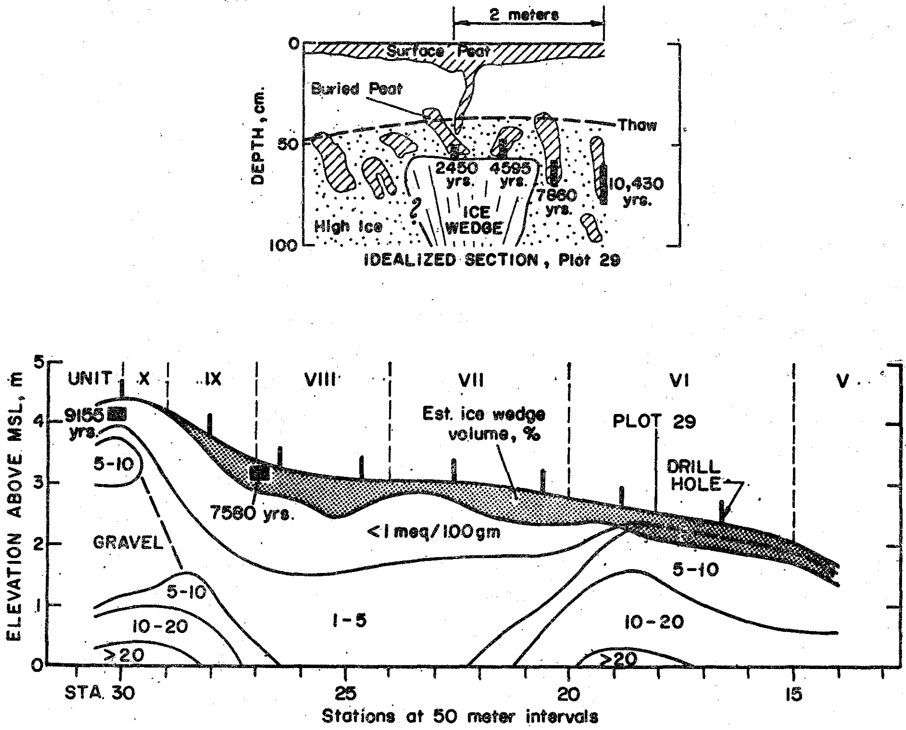

Fig. 2. Chemical profile along centerline of study area showing depressed zone in Units VII and VIII

Estimated ice wedge volumes above sea level are based upon measured trough dimensions and assumed vertical dimensions of wedges (see B r o w n, 1966, for details). Insert presents idealized section in Plot 29 for radiocarbon dating sites

and VIII. In order to more conclusively establish this trend, which also coincided with the frost scar area, a deeper coring program was undertaken along the transect in 1964. Frozen cores were taken to sea level (3—5 meters) at approximately 100-meter intervals and supplemented with data from several auger holes obtained earlier (O'S u l l i v a n, 1966). The results of these chemical investigations are shown in Figure 2. The depression of the chemical concentrations noted in the 1-m core sampling was verified and extended downward by the deeper coring (B r o w n, 1966). From this it was concluded that the depression of the chemical gradient was associated with the freshening effect of a pre-existing lake. Similar freshened zones are found under recently drained lake basins. In the present case, no surfical expression of a lake basin is observed. The association of active frost scar in these units may be associated with the freshened sediments, but no relationship is obvious at this time.

AGE AND ORIGIN OF BURIED PEAT

The origins and ages of buried organic matter in tundra soils throughout the arctic and particularly northern Alaska have been discussed by a number of workers. In general, it is likely that the majority of the pedogenic peats were buried by cryopedologic processes (Douglas and Tedrow, 1960) rather than by conventional sedimentary agents such as wind or water alone. In the present study, dating of near-surface buried peat was conducted to determine the range in ages of peat associated with the study transect and the different geomorphic units (Table IV).

Table IV

Radiocarbon ages of buried peats along transect

Unit	Plot	Core	Depth (cm)	Sample No.	Yrs. B.P.	B.C.
X	—	—	90	I—1183	9155 ± 300	7205
VIII	40	8	60—85	I—2050	7580 ± 140	5630
VI	29	29	50—57	I—2123	2450 ± 120	500
	29	21—1	45—60	I—2600*	4595 ± 110	2645
	29	22—1	58—70	I—2601	7860 ± 120	5910
	29	22	55—80	I—2049	10,430 ± 320	8480
	7	21	55—75	I—2048	6690 ± 130	4740

* Mean of two dates (4390±110 on volatiles and 4800±115 on residue).

The age of buried peat in Unit X was reported earlier (9155 ± 300 yrs) and was in close agreement with other buried organic matter overlying clean gravel on the same beach ridge (8715±250 yrs; Brown, 1965). Samples from Plots 7, 29 and 40 were dated to determine if the buried peats found throughout the soils and frozen ground of the transect were similar in age and therefore origin to the peat buried on the beach ridge. In addition, peat overlying an ice wedge in Plot 29 was dated to determine if a relatively young age would be obtained to correspond with other peats overlying ice wedges (1775±120 yrs; Brown, 1965). Subsequent sampling in this plot produced two more dates.

Plots 7 and 40 both yielded buried peats of younger age than the beach ridge dates (Table IV). The non-ice wedge sample in

Plot 29 produced an age of 10,430 years. However, within two meters distance and overlying the ice wedge, the buried peat was only 2450 years. Two samples between these two points and at similar depths were dated at 4595 and 7860 years (see insert Fig. 2). This range in ages within a distance of two meters provides the basis for explaining variations in radiocarbon ages of buried peats along the transect and elsewhere. The youngest peats overlie the actively growing ice wedge and are therefore apparently associated with current wedge growth. Two other wedge tops in the Barrow area, including one from along Elson Lagoon (I-2602, unpublished, 2200 ± 105 yrs) contained peat of similarly young age. The older, adjacent peats are either associated with previous wedge growth cycles or have a non-ice wedge origin. The 10,430-year age represent the oldest traces of *in-situ* soil development along the transect and corresponds to the beach ridge peats. Similar ages have been associated with peats buried to the depth of 3 meters (Brown, 1965). At least three generations of buried peat seem to be present along the transect: (1) the oldest 9155 to 10,430 age, (2) the intermediate 6690 to 7860 age, and (3) the youngest 2450 to 4595 age.

The wide range in the radiocarbon ages and the relatively coarse and nonuniform mantle of mineral soil overlying the buried peats make it unlikely that burial occurred by a single event such as wind deposition. Burial by water deposition over this large area of diverse topographic relief and long period is also considered unlikely. Burial along much of the transect is apparently a continuous process and is in part associated with cycles of ice wedge formation. Some peat apparently moves downward through the contraction cracks. Douglas and Tedrow (1960) showed the fingering of the surface peat into the soil and its occurrence over ice wedges and adjacent to them. The oldest peats (10,430 yrs) may be relict of a more continuous soil cover, particularly on the topographic highs. The relatively old age of the buried soil peat in Unit VIII which occurs in the postulated thaw depression, suggests a considerable age for both the basin and the perennially frozen ground.

SUMMARY AND CONCLUSIONS

Soil properties along a typical tundra landscape of northern Alaska show considerable areal, seasonal, and perennial variations.

Extremes range between deeply thawed, sandy soils to shallowly thawed, organic rich soils. Average thaws for a 5-year period at 80 locations range between 33 and 43 cm. Thaw differences are correlated with differences in total moisture content of the thawed soil which in turn corresponds to the amount of organic matter in the soil. Differences between morphologically observed thaws and actual measured thaw can be accounted for by year to year seasonal differences in summer climate. No significant correlations were established between microrelief and thaw or microrelief and moisture for 80 cored points. Thawed soils are considerably more depleted chemically as a result of sustained leaching. A chemically depleted zone of perennially frozen ground is related to the freshening of sediment beneath an inferred ancient lake. Differences in radiocarbon ages of buried peat at the seasonally thawed soil-perennially frozen ground interface of between 2500 and 10,500 years can in part be related to ice wedges; the youngest peats are found over actively growing wedges and oldest peats adjacent to wedges or in the absence of wedges. The wide range in ages of buried peat reduces the likelihood of water or windborne burial and supports the theory of cryopedologic origin for the burial of the peats.

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Pl. 1. Aerial oblique of transect in the vicinity of the beach ridge and frost scar area (Units VIII to X)