TUNDRA RELIEF FEATURES NEAR POINT BARROW, ALASKA

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ABSTRACT. The distribution of minor tundra relief patterns shows that topography plays a leading part in their development. In extensive areas of very low relief, local expression may well exceed the regional range. Aside from the initial relief, the greatest deviations from a flat surface in the Barrow area are related to the growth or thaw of ground ice. This leads to such features as high- and low-centred polygons, ice-wedge troughs, ice-cored mounds and thaw basins of all sizes. The genesis of most of these features has been determined. However, it has been questioned that the basins could have been formed by thaw. Specimens of the frozen ground were collected and analyzed to determine their relative ice content. The values were extrapolated, and it was found that even the largest basins can be true thermokarst features.

RÉSUMÉ. *Traits de relief de la toundra près de Point Barrow, Alaska.* La distribution des traits mineurs du relief de la toundra démontre que la topographie joue un rôle majeur dans leur développement. Dans de grandes zones de relief très faible, l'expression locale dépasse souvent la portée régionale. Abstraction faite du relief initial, les plus grandes déviations de la surface plane dans la région de Barrow sont liées à la croissance ou à la fonte de la glace dans le sol. Ce qui donne des traits comme les polygones à centre soulevé ou en creux, les fentes de coins de glace, les monticules à noyau de glace et des cuvettes de fonte de toutes dimensions. On a pu déterminer la genèse de la plupart de ces traits. Cependant, on a mis en doute la formation des cuvettes par la fonte. La cueillette et l'analyse de spécimens de sol gelé ont permis de déterminer leur teneur relative en glace. Ces valeurs extrapolées ont démontré que même les plus grandes cuvettes peuvent être d'origine thermokarstique.

REZI͡UME. *Osobennosti rel'efa tundry vblizi Mysa Barrou, Ali͡aska.* Rasprostranenie tipov malogo rel'efa tundry pokazyvaet chto topografii͡a igraet znachitel'nui͡u rol' v ikh obrazovanii. Na obshirnykh uchastkakh ochen' nizkogo rel'efa lokal'nye cherty mogut prevyshat' raĭonnyĭ kharakter. Krome pervonachal'nogo rel'efa naibolee znachitel'nye otklonenii͡a ot ploskoĭ poverkhnosti v raĭone Barrou svi͡azany s rostom ili tai͡aniem podzemnogo l'da. Ėto privodit k formirovanii͡u vysoko i nizko kont͡sentrirovannykh poligonov, ledi͡anykh klin'evprogibov, ledi͡anykh bugrov i vpadin tai͡anii͡a raznogo razmera. Genesis bol'shinstva ėtikh chert ustanovlen. Nesmotri͡a na ėto schitaetsi͡a somnitel'nym chto vpadiny obrazovalis' tai͡aniem. Obraztsy merzlykh gruntov byli sobrany i proanalizirovany s t͡sel'i͡u opredelit' otnositel'noe soderzhanie l'da. Dannye byli ėkstrapolirovany i bylo ustanovleno, chto dazhe samye bol'shie vpadiny mogli imet' podlinnye cherty termokarsta.

Introduction

MANY of the landform features characteristic of the Arctic Coastal Plain are well developed in the area immediately south of Barrow, Alaska (Fig. 1). Among the more predominant are the polygonal ground and the numerous oriented lake basins. These features have been described in considerable detail by several investigators, including Black (1950, 1954), Black and Barksdale (1949), Rex (1958), Britton (1958), Carlson (1957), Rosenfeld and Hussey (1958), O'Sullivan and Hussey (1957), Carson and Hussey (1960, 1962), Lachenbruch (1962a). Other localized frost-related features include the hummocks, mounds, and stripes.

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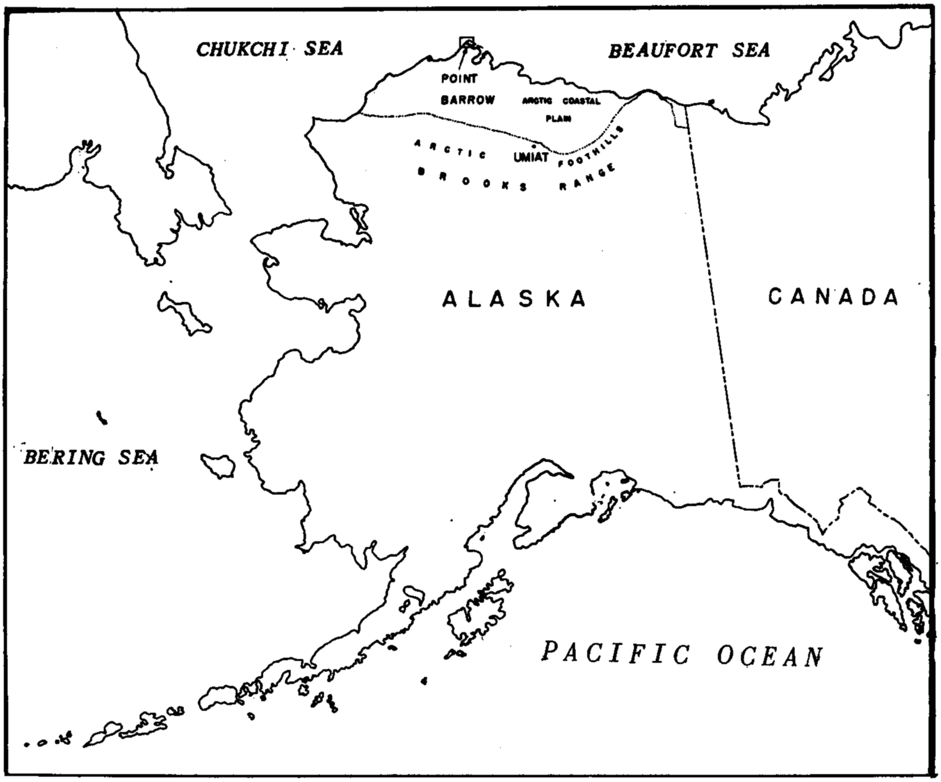


Fig. 1. Map of Alaska showing the Arctic Coastal Plain and Point Barrow.

In this report, major relief features are considered to be extensive areas such as: thaw lake basins, initial surface residuals, residual slope features and more prominent drainage features; local areas such as troughs and ridges associated with the ice-wedge polygons, hummocks, mounds and stripes, are referred to as minor relief features.

Statement of the Problem

The distribution of many of the minor relief features, especially those that make up the variety of ground patterns, indicates that each tends to be associated with a particular major relief feature. This suggests that the topographic position may be a critical factor in the development of minor relief features through the passive control it exercises on the active processes.

It is important to the problem that a description be presented of some of the minor relief features and their topographic setting to establish their relationship to the geomorphic processes; that the evolution of the present topography, as it is determined by the subsurface ground ice conditions, be analyzed; and, in the light of the above, that the cyclic generation of the thaw lake basins be discussed.

The relationship between the minor relief features and their topographic positions can be determined from a study of aerial photographs of the area.

The association has been attributed to one or more factors. These include relative degree of surface and sub-surface drainage, spatial and quantitative distribution of ground ice, angle of slope, and particle size distribution of sediments. Field observations and measurements indicate that all of these factors do exert an influence on the development of minor relief features in general, and that one of them is usually dominant in any specific area.

Inasmuch as most of the geomorphic processes in the Barrow area are associated with the presence and the behaviour of ground ice, a knowledge of its spatial and quantitative distribution is essential to an understanding of the evolution of the landforms characteristic of the area. The landscape is typical of thermokarst regions, the topography of which, according to Muller (1947), is produced by "settling or caving of the ground due to melting of ground ice." This process is probably responsible for the formation of most lake basins in the Barrow area. However, to establish the validity of the assumption, it must be shown that the ground ice is, or was, sufficiently abundant to produce, by melting, the relief existing in the Barrow area. Field data reveal that the quantity of ground ice varies with topographic setting. The effects of this variation on the major and minor relief features is not a simple problem. Therefore, one must determine the relationship between the geomorphic features and the ground ice conditions to find the significance of each.

Relief Characteristics

General Topography

The Arctic coastal plain is an emergent region with very low relief. Typical features are the numerous thaw lake basins and the polygonal ground. It is estimated that 50-75 per cent of the coastal plain is covered either by lakes or by marshes that occupy low areas or former lake basins (Fig. 2).

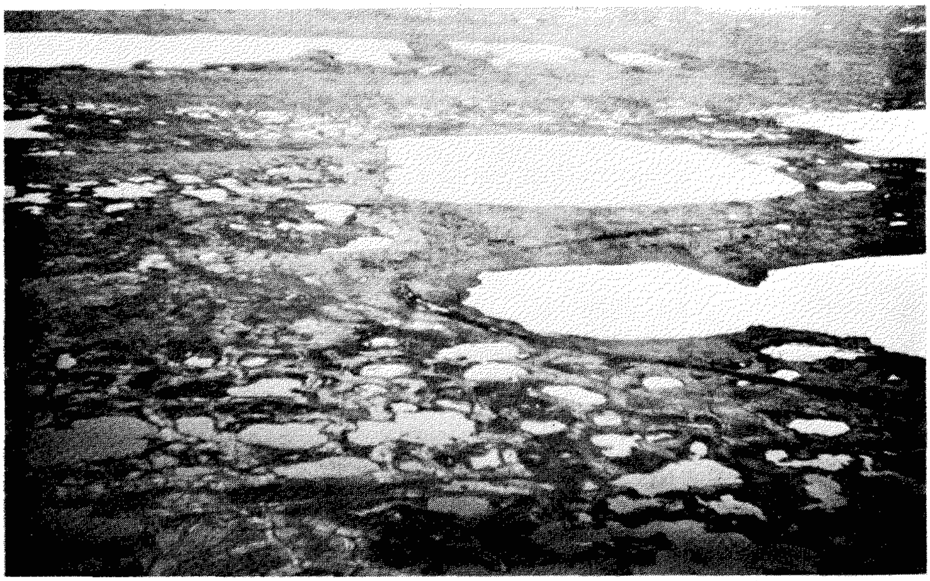


Fig. 2. Oblique aerial view of numerous lakes and ponds of the Arctic Coastal Plain.

The remaining 50-25 per cent is relatively higher and will be referred to as the initial surface residuals (see following section for definition). In the Barrow area, relief between the initial surface and basins is of the order of 10-15 feet. Relief of 10-20 feet, on the initial surface, and apparently not associated with lake basin development, will be referred to as initial relief (Figs. 7-9 and related discussion).

Both low and high relief surfaces show the polygonal ground characteristic of permafrost regions. This pattern is produced by contraction of the ground during extreme low winter temperature. Cracks form in which water and snow collect and turn into ice wedges. These gradually grow downward (Lachenbruch 1962a) and also surround the polygons. The processes associated with the accumulation and thaw of the ice are responsible for the important minor relief features that are so much a part of the polygonal ground.

The polygons can be classified into two types: those with high centres, and those with low centres. The distribution of each type is associated with a particular major relief feature. The high-centred type is generally confined to the relatively high and well-drained initial surface residuals, whereas the low-centred type features the basins. Basins that have been recently drained are the exception in that they show the development of high-centred polygons. It is believed that this is only a temporary stage, related to the draining of the basin with concomitant erosion along the ice-wedge troughs. The reasons for these associations are given in the following discussions of high- and low-centred polygons.

Other geomorphic features in the Barrow area include ice-cored mounds, drainage features peculiar to beaded streams, minor relief characteristics of slopes, and those features formerly described as beach ridges.

INITIAL SURFACE RESIDUALS

The initial surface residuals are defined here as including all areas failing to show evidence of thaw lake activity. While it is not concluded that these areas are "initial" in the sense of being original unmodified coastal plain, their ground-ice content indicates that the existing permafrost would have formed following a deep and extensive thaw that provided the necessary quantities of water. The surface morphology and sub-surface characteristics of the initial surface residuals are distinctly different from those of the basins. These differences will be discussed in later sections of this paper.

The initial surface finds expression in the Barrow region as irregular high, flat areas between basins, and adjacent to the northeast and northwest margins. It is featured by high-centred polygons and, in general, more than 70 per cent of the volume of the upper 20-foot zone of permafrost in these areas is composed of ice. The sediments consist of silts, fine sand, and gravel. There are local concentrations of beach-like gravels that are associated with the residual slopes that occur on the initial surface and, also in some local instances, the slope between the initial surface residuals and the basins. The residual slopes will also be discussed in a later section.

High-centred polygons. High-centred polygons, according to Black (1954), are characteristic of more or less integrated surface runoff areas underlain by rather coarse materials, and areas which are comparatively old. In the Barrow area, the only integrated surface runoff is found on the relatively elevated initial surface residuals. This obviously is the oldest surface. The underlying materials, however, with the exception of ice content, appear identical with those of the basins.

High-centred polygons are those in which the central portion is a mound, outlined by troughs (Fig. 3a) that, according to Britton (1958), and Black (1954), are initiated and deepened by the differential thaw and erosion of the peripheral ice-wedges. Soil and vegetable matter that slumps into the troughs must be, at least partially, eroded away to allow further thawing and deepening. This accounts for the fact that these polygons reach maximum expression in areas where a drainage system has developed along the troughs. Such areas are found where initial surfaces are near the boundaries of lakes and drained lake basins, and near drainages and sea-cliffs. There the relief ranges from less than 6 inches in the flat central portions of some initial surface residuals, to over 4 feet on the same surface near the boundary of a basin.

High-centred polygons are variable in size, ranging in diameter from 10-50 feet, which is only a fraction of that of the larger low-centred polygons. The smaller size of the high-centred polygons can be attributed partially to the division of first-order polygons by secondary and tertiary ice-wedge development. Another effect of this division is seen in the irregular shape of the high-centred polygons, as compared with that of the low-centred variety. The latter do not commonly exhibit division by secondary and tertiary wedges, and therefore

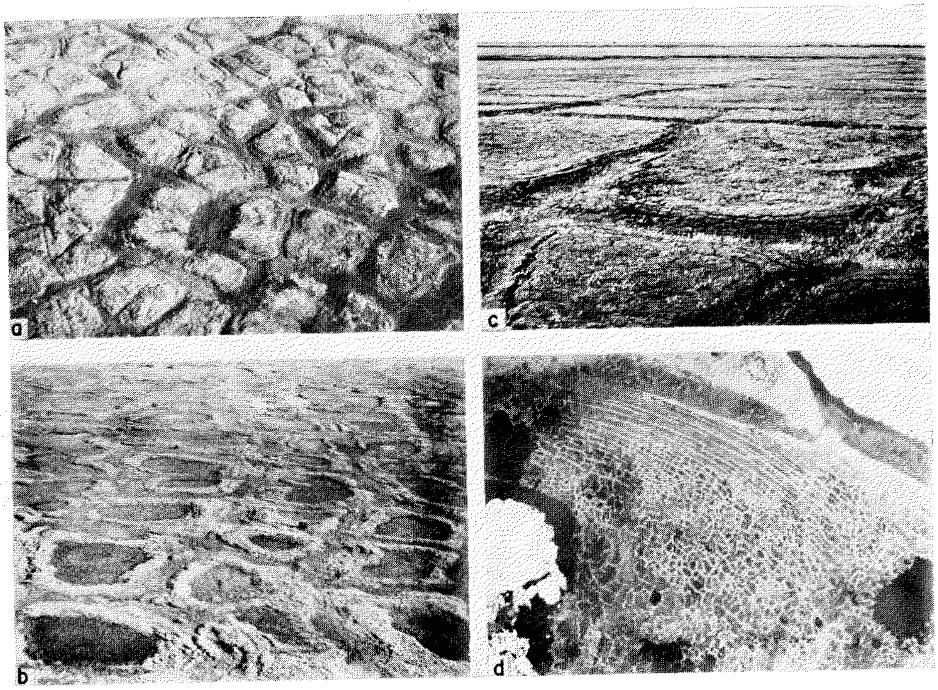


Fig. 3. (a) High-centred polygons; (b) Low-centred polygons; (c) Initially developed high-centred polygons in recently drained lake basin; (d) Controlled development of ice-wedges parallel to the margin of a drained lake basin.

locally show a greater homogeneity of size and shape. However, regionally, the low-centred polygons show the greater range in size, i.e., 30-200 feet.

THE DRAINED BASINS

The greater portion of the land area near Barrow is featured by drained elliptical oriented lake basins. These basins often form an overlap complex where several smaller basins occur in part or completely within larger, more ancient drained basins. Basins of several ages appear, in aerial view, to overlap in this manner. Carlson (1957) mapped the basins from aerial photos to show their relative ages (Fig. 4). Including the present lakes, this map shows seven generations of overlapping basins.

The ground-ice content of the upper 20 feet of the permafrost is considerably less for the ancient and recent drained lake basins than for that of the initial surface residuals. It is thought that the cyclic generation of the basins — wherein a lake develops, is drained, and a subsequent overlapping basin is formed — is in part a manifestation of the quantity and distribution of ground ice. This concept is supported by the differences in elevation between the basins and the initial surface, and in their respective ground-ice contents (Table I). Comparable data also include those concerning the depths of the present existing lakes (Table II), and the geothermal investigations of a lake in this area by Brewer (1958a, b). The origin and cyclic generation of the basins will be discussed in greater detail in a subsequent section of this paper which deals with the role of ground ice as related to the development of a thermokarst topography.

Table I. An example of the lateral and vertical distribution of ground ice content as it exists in the Barrow area, expressed as moisture content (m) per cent of dry soil (weight) and as ice (I) expressed as a percentage of the total volume of a permafrost sample.

Location	*Initial Surface Residual*		*Ancient Drained Basin*		*Recent Drained Basin*		*Present Lake*	
HOLE	P		B-I		B-II		L	
Depth Feet	m	I	m	I	m	I	m	I
1	58	63	104	75	74	68	38	53
2	140	79	40	54	8	18	27	44
3	146	80	93	73	63	65	22	39
4	98	76	86	72	63	65	26	43
5	233	87	61	64	70	67	30	46
6	198	81	64	65	141	80	24	41
7	285	89	73	68	18	34	19	36
8	75	69	58	63	20	37	19	36
9	76	70	26	43	19	36	20	37
10	109	75	22	39	19	36	19	36
11	104	75	32	48	18	34	19	36
12	118	77	33	49	17	33	19	36
13	67	68	29	45	26	43	18	34
14	77	70	23	40	23	40	18	34
15	62	65	23	40	21	38	17	33
16	92	73	21	37	20	37	17	33
17	79	70	17	33	15	30	—	—
18	81	71	17	33	11	24	—	—
19	78	70	18	34	—	—	—	—
20	—	—	18	34	—	—	—	—

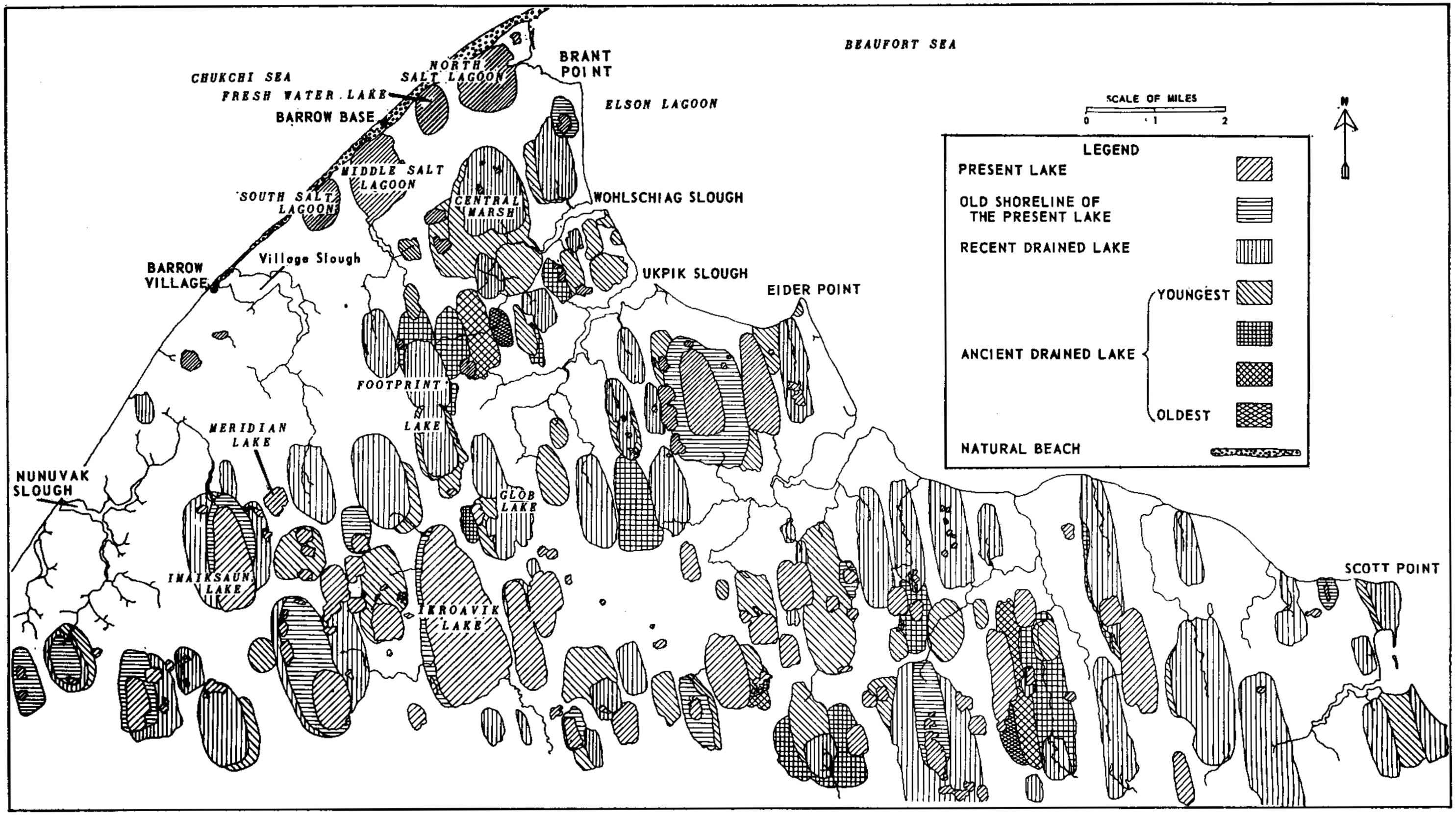


Fig. 4. Map showing the topographic and age relationships of the lakes and drained lake basins.

Table II. Length, width, and depth measurements of Barrow lakes, and their location with respect to the topography. Length is measured parallel to the general orientation of the lakes and the width perpendicular to this

Lake No.	*Length Yards*	*Width Yards*	*Depth Feet*	*Immediate Topographic Surroundings*
1	1,420	585	3.3	Basin
2	350	410	2.7	Basin
3	295	175	2.6	Initial Surface
4	295	585	3.5	Basin
5	2,640	1,000	7.4	Basin
6	645	585	2.0	Initial Surface
7	410	410	4.4	Basin
8	295	410	3.4	Basin
9	295	410	2.6	Basin
10	350	235	3.4	Basin
11	530	295	3.6	Basin
12	1,580	940	6.8	Basin
13	470	470	2.3	Basin
14	645	470	2.3	Initial Surface
15	950	800	3.1	Initial Surface
16	460	460	2.8	Initial Surface
17	940	820	3.8	Bas/I.S.*
18	2,660	1,650	4.7	Bas/I.S.
19	4,520	2,000	6.5	Bas/I.S.
20	2,820	765	4.1	Bas/I.S.
21	1,700	880	2.5	Initial Surface
22	1,350	950	9.0	Initial Surface
23	705	705	2.0	Bas/I.S.
24	2,230	880	4.0	Basin
25	2,560	760	2.9	Initial Surface
26	750	620	3.1	Basin
27	2,750	950	3.0	Initial Surface

*Situated partially as first generation lakes on initial surface residuals, but also overlapping on older drained lake basins. It was not determined whether the lakes originated in the basins or on the initial surface residuals.

The basins are oriented in a northwest-southeast direction. Several hypotheses have been proposed to account for this orientation. Among these are included the hypothesis of Black and Barksdale (1949) which suggests that ancient winds, parallel to the long direction of the basins, accelerated thaw and erosion in the same direction; those of Livingstone (1954), Rex (1958), and Carson and Hussey (1960, 1962), all of which suggest that current systems introduced by winds blowing perpendicular to the direction of orientation (as is the present prevailing wind direction), to be the active factor; and that of Rosenfeld and Hussey (1958) concerning the possibility that structural control might play a role in lake orientation.

Low-centred polygons. Low-centred polygons are the dominant minor relief features of the drained lake basins. These polygons have a centre that is enclosed by peripheral ridges. The ridges result from the thrusting, upward and laterally, of material on each side of a growing ice-wedge (Fig. 3b). The relief from the tops of the ridges to the centres of the polygons is generally 6 to 18 inches. Once the ridge has formed, the relief is enhanced by the accumulation of vegetal material upon it (Black 1954). In many cases the centres are ponded.

The poor surface drainage conditions typical of these areas results in little loss of water by runoff and hence little thaw of the ice-wedge. Extensive thaw of an ice-wedge would allow the ridges to slump into the deepened trough, promote drainage, and thus produce an elevated centre. According to Black, high-centred polygons might be developed from the low-centred polygons if the ridge material slumps backward into the depressed centre until the central portion is filled with soil and organic material (Fig. 3c). This may account for some of the polygons of this type which exist in the marsh areas. However, the usual development of high-centred polygons on the relatively elevated surfaces appears to result exclusively from the thaw and drainage of the ice-wedge trough.

Although, as mentioned before, low-centred polygons are generally much larger than their high-centred counterparts in any one particular basin, the size is relatively uniform. The first impression of the larger polygons might suggest that they are outlined by the primary wedges of the initial surface residuals, which were retained while the basin developed to its maximum depth, where the shallower secondary and tertiary ice-wedges would have been lost during thaw. This view might be supported by the ice-wedge patterns, that are visible from the air, on the bottoms of many present lakes. However, it is not believed that this is the case. Geothermal data collected by Brewer (1958b) indicate that under any lake with a water depth greater than 6 feet, the permafrost table would be so depressed that all of the initial wedges would be removed. Elevation differences between the basins and the initial surface residuals indicate, in most instances, a thaw-produced relief that would have permitted water depths greater than 6 feet. The lesser ground-ice content of the basin permafrost further indicates that such a deep thaw did in fact occur. It would have removed all traces of the original ice-wedge system. The ice-wedge pattern existing on the bottoms of present lakes is in all probability associated with the polygonization that would occur in the bed of any lake, in a permafrost region, that annually freezes to the bottom. It is also probable that the polygons that form after the basin would be larger, and would lack the secondary and tertiary ice-wedges simply because the tension stresses of the lesser amounts of groundice would not be sufficient to cause the development of the smaller contraction cracks. This view is further supported by the controlled, or oriented, polygon patterns which are common in some basins (Lachenbruch, 1962) (Fig. 3d). These show a definite rectangular periphery and only occur adjacent to drained basin margins. While the processes affecting this control are not known, their being parallel to the old shore suggests control of the contraction cracks by the water body.

THE PRESENT LAKES

The present lakes in the Barrow area occur either in the lower segments of old, partially drained basins, or on the initial surface residuals; or they extend across the boundary between a high and low area. They vary relatively little in depth, but greatly in shape and areal dimension. The lakes that were studied range in depth from less than 2 to over 9 feet, and in length from less than 300 to over 4,500 yards. Only larger basins are characteristically elliptical and oriented. The smaller basins in this area are irregular in shape and do not generally show the effects of an orienting factor. In some areas on the coastal plain, even the smallest basins have an elliptical shape and perfect orientation (Carson and Hussey 1962). The depths of most of the lakes in the Barrow

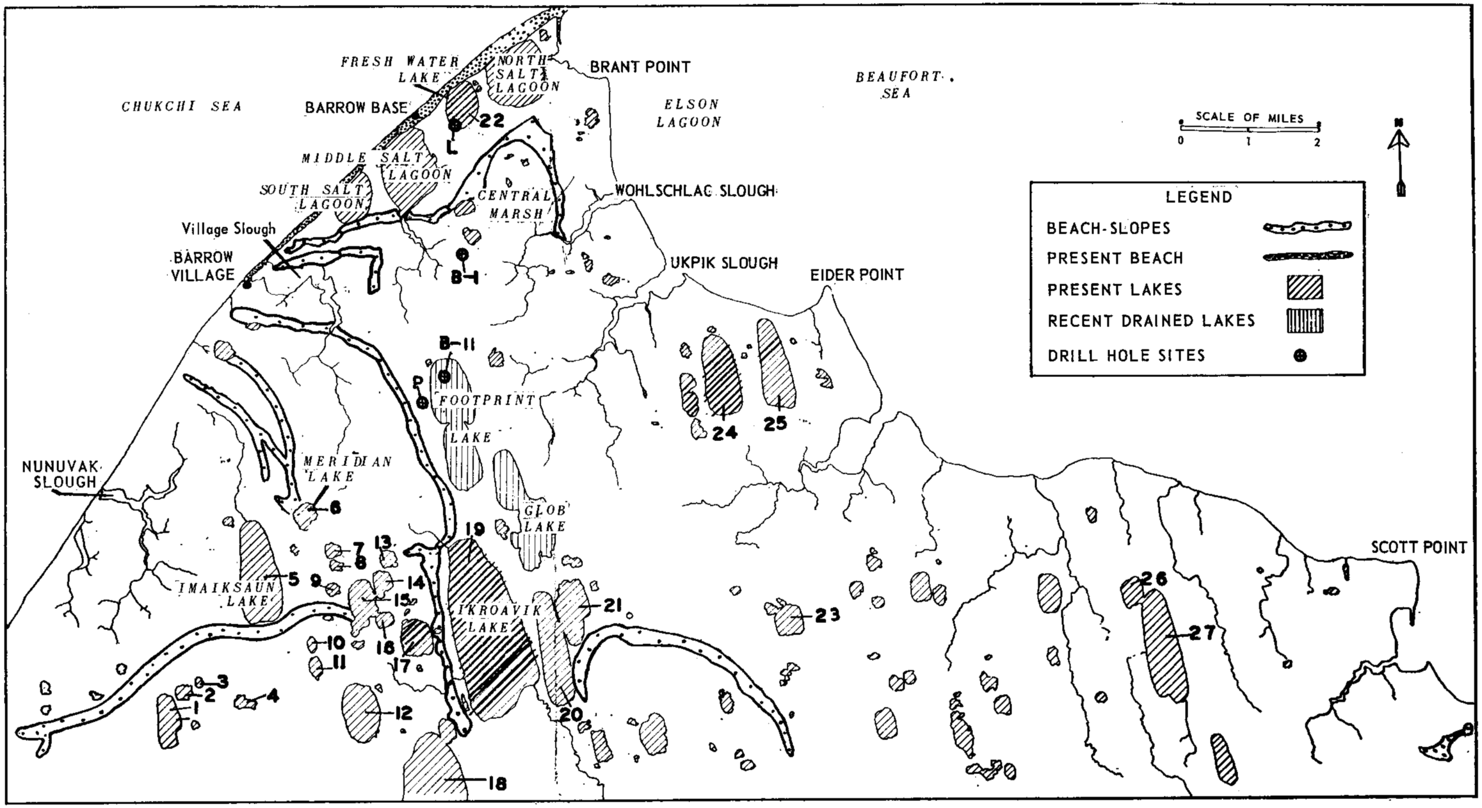


Fig. 5. Index map of lakes, residual slopes (referred to on map as *beach-slopes*), and drill hole locations.

area have been measured. The lateral dimensions are easily determined from the aerial photographs. These data are presented in Table II.

Fig. 5 shows the existing lakes, numbered so as to correspond with the data presented in Table II. These data indicate no definite relationship between lake depth and lateral dimension, except that the larger lakes tend also, with certain exceptions, to be the deeper. Lake depth plotted against width and length, for the lakes of each topographic setting, reveals no definite correlation. However, the problem of thaw lake development and orientation has been treated in detail by Carson and Hussey (1962). The view is presented that there is a characteristic relationship between shape, size, and depth in the initial development of an oriented thaw lake basin. The irregular distribution of ground-ice and various stages of drainage produce many exceptions to the ideal among the present-day lakes in the Barrow area.

The lakes are subject to grouping into two distinct categories on the basis of depth: those lakes which are over 6 feet deep, as opposed to those which are less than that in depth.

A lake which is less than 6 feet in depth will normally freeze to the bottom during the winter months. Summer thaw will melt the ice and an active layer at the bottom of the lake. The insulating effect of the sediments of the active layer controls the limit of thaw beneath an existing lake. The ice of the underlying permafrost is proven by the existence of a polygonal system on the bottom of the lake. Lakes which are over 6 feet in depth do not freeze to the bottom in the winter, and thus a layer of water is retained between the ice and the bottom. This results in a net input of heat into the ground from the lake water. The permafrost immediately beneath the lake is then thawed, and the permafrost table may be depressed several tens of feet. Brewer (1958b) reports the permafrost table beneath Fresh Water Lake (9 feet in depth) to be depressed 195 feet (*See also* Lachenbruch 1962b).

ICE-CORED MOUNDS

Among the less prominent of the geomorphic features are the many ice-cored mounds in the basinal marshes, on the initial surface residuals, and on the interconnecting slopes.

The mounds have a maximum relief of approximately 4 feet, and diameters ranging from 10 to 15 feet. They consist of a core, composed predominantly of ice, covered in some instance by silts and sands, or in others by moss peat. These are the soil mounds and peat mounds, respectively, as described by Black (1954).

A soil mound and a peat mound, were blasted open during the 1959 field season. The soil mound (Fig. 6a) had developed on the primary surface just south of Imaiksaun Basin. It was composed of nearly 2 feet of silt and fine sand covering a core of massive, bubble-rich ice (Fig. 6b). Soil particles were dispersed throughout the ice mass. The upper 6 inches of the soil material were organically enriched with owl droppings. The mound had a height of slightly over 3 feet and a diameter of 12 feet. An ice-wedge trough adjacent to the mound contained a small pond which, according to Black (1954) is commonly associated with these features. In this instance, it was not possible to determine whether the pond had genetic significance.

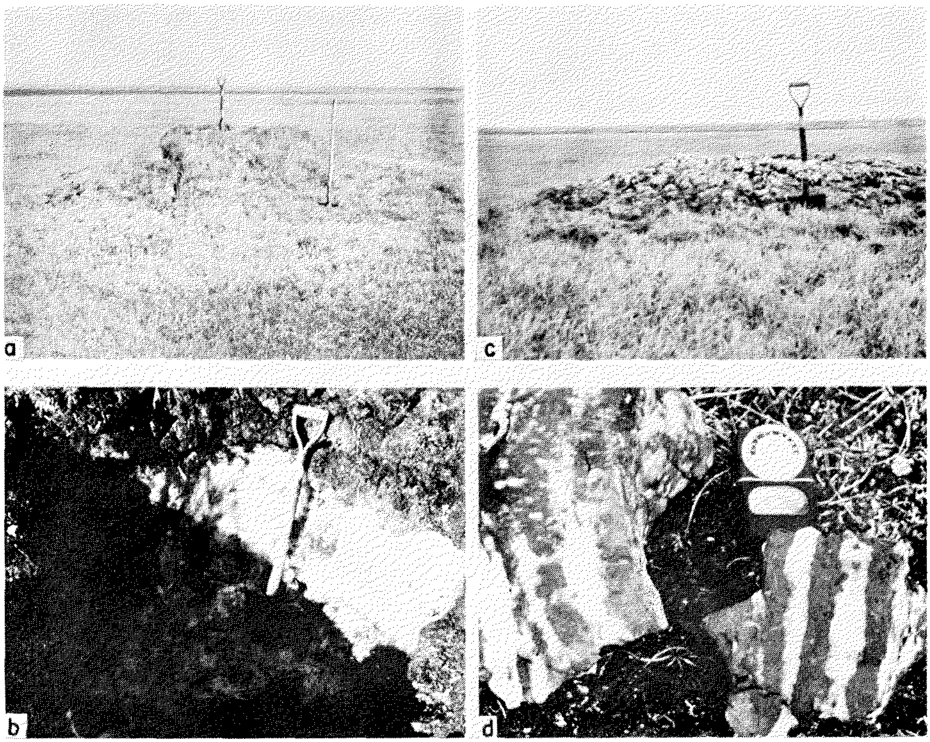


Fig. 6. (a) Ice-cored soil mound; (b) Exposed ice-core of mound shown in (a); (c) Ice-cored peat mound; (d) Layered ice from core of mound shown in (c).

The peat mound (Fig. 6c) was situated in the Imaiksaun Basin, on the east side of the existing lake. It was less than 1 foot high and about 10 feet in diameter. The core of this mound consisted of alternate layers of ice and soil. The layers were approximately 1 inch thick (Fig. 6d). The core was about 2 feet thick and was covered by about 18 inches of spongy, well preserved, bright yellow moss peat. Beneath the core was an air pocket about 8-10 inches across. The significance of this has not been established.

The processes by which the ice-mounds are developed have not been thoroughly investigated. Black (1954) states his belief that they are undoubtedly polygenetic, but points to ice-injection by cryostatic processes as a common factor in their development. Ice injected into horizontal contraction cracks, adjacent to a source of water, appears to be the most likely explanation; however, a much more detailed investigation must be conducted in order to determine which morphological characteristics have genetic significance.

A common characteristic of the ice-cored mounds previously described is that in each case the ice core is situated in the permafrost. Temporary features described by Black (1954) as ice-laccoliths differ from these mounds, in that an ice-core is developed within the active layer, covered only by the tundra vegetal mat. Black reports that these develop in a few hours, or a few days, during a fall freeze-up; most are destroyed by thaw in from 1 to 5 years.

The summer of 1958 was relatively very warm, and the fall freeze-up period was late and short. This may account for the fact that no ice-laccoliths were observed in the Barrow area in either the summer of 1958 or of 1959, though some excellent examples had been seen the two previous years.

RESIDUAL SLOPE FEATURES

A feature that looks like a ridge can be seen on the aerial photograph (Fig. 7). Rex and Taylor (1953) described this and similar features as old, uplifted beach ridges, and stated that they were composed of well stratified deposits of sand and gravel similar to that of the present beach. They added that the gravels were mantled by 12-18 inches of silt, which Black (1954) refers to as loess. It has been generally accepted by most investigators that an intermittent withdrawal of sea level left a series of beach-ridges at varying distances inland from the present coast, and that the ridges have subsequently been covered by loess and preserved on the landscape. This view is supported by the fact that the features show a tendency to conform generally with the present coastline (Fig. 5).

Field studies have revealed, however, that these features observed on the aerial photographs do not in fact represent ridges on the landscape, nor do they represent extensive surface or near-surface deposits of gravel. The features are actually slopes ranging from 2 to 4 degrees, that occur both on the initial surface residuals, and between the initial surface and an adjacent basin. The photo impression of those slopes that occur as relief on the initial surface is especially confusing because the ground pattern of minor relief features on either side of the slope is identical. This gives the impression of a level surface

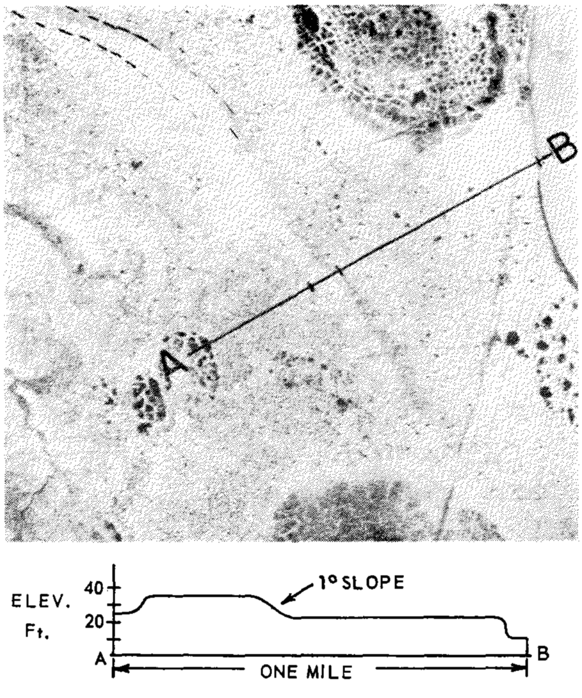


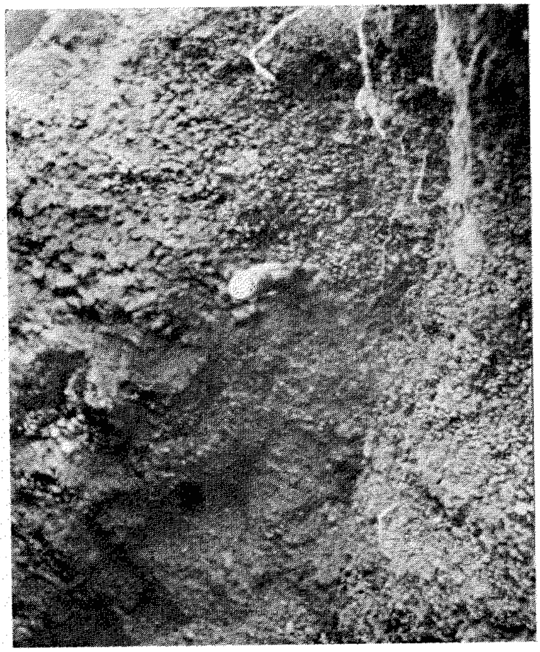
Fig. 7. Aerial photo of residual slope with profile A-B showing the actual topographic relationship.

divided by a ridgelike feature. Whereas, in fact, the surface on either side of the slope may differ in elevation by as much as 15 feet. This difference can be detected on the aerial photographs only when viewed stereoscopically. Fig. 7 shows the actual relationships.

Deposits of gravel, similar in appearance and in grading characteristics to the gravel of the present beach (Fig. 8), are exposed in several localities associated with the slopes. Mechanical analyses of this gravel show that it falls well within the range of grading variation for the gravels of the present beach and off-shore bar deposits. Immediately north of Central Marsh Basin, close to the present coast line, gravel is exposed at the edge of the basin near the surface, being covered by only about 2 feet of silt and organic matter. This agrees with previous descriptions of the beach-ridge features. However, the gravel associated with any of the more southerly slopes is found near the base of the slope, generally where a lake basin has thawed into it, or where it has been transected by drainage. Several holes blasted into the slopes reveal that the gravel is overlain by several feet of silt and sand containing only a scattering of pebbles. This in general is typical of the sediments of the area. The occurrence of the gravel deposits parallel to the present coastline suggest that they are probably buried beach or bar deposits. They differ from the deposit's reported earlier in that they are covered by several feet of silt and fine sand, and that the surface morphology is a slope rather than a ridge. The term beach-ridge was ascribed to these features largely because of their appearance on the aerial photos.

The residual slope features quite probably represent relict initial relief. However, where the residual slope of an initial surface joins that at the margin of a basin, it may be that the presence of the concentration of gravels controlled

Fig. 8. Gravel exposed in trench at the base of a residual-slope feature.



the shore erosion in the developing lake basin, and thus determined the location of the slope. The gravel may have been concentrated during erosion through removal of the sand and silt. They may in fact be gravel-defended residuals without having gravel under their entire length. The location and configuration of the slope may thus be due largely to basin development and not to the original distribution of beach gravels.

At this time, no explanation can be offered for the two-to-four degree apparent equilibrium of slopes in the area. It may be that this represents the lowest effective angle of significant mass wasting in the existing environment. This angle has been noted over extensive areas of the Arctic Coastal Plain Province.

The Role of Ground Ice in Thermokarst Development

The origin and distribution of the ground ice cannot be over-emphasized in this review, inasmuch as it is the accumulation and thaw of ground ice, more than any other factor, that determines the geomorphology of the area.

GENESIS OF GROUND ICE

Permafrost is defined as ground having a temperature continuously at or below 0°C. (Muller 1947). The definition calls for no specific amount of water (ice). In fact, the often-used term "dry permafrost" indicates that there may be no water (ice) present at all. However, ice is very commonly associated with permafrost, and its origin and distribution have been the subject of considerable investigation and debate.

The greatest concentration of ground ice occurs in a zone extending from immediately beneath the active layer to a depth of from 20 to 30 feet. In many areas, the ground is supersaturated with ice, sometimes to better than 80 per cent of its volume (Carson and Hussey 1962).

Ice in the ground occurs in nearly vertical ice-wedges, lenses, irregular masses, small grains and crystals, irregular particles, stringers, and films on the soil particles (Black 1954). The controversy concerning the origin of ground ice centres around the development of the ice-wedges. Taber (1943) proposes that all bodies of ice in the frozen ground originated from water below the freezing surface, and developed over a relatively short period. Black admits that this probably accounts for the smaller ice masses, crystals, lenses, etc. However, he agrees with Leffingwell (1915) that the ice-wedges grow over an extensive period by increments of water added from the surface into vertical contraction cracks. Water is made available to the cracks during the thaw season. Due to the effect of a geothermal lag in the frozen ground (Brewer 1958a), the cracks are open at depth at a time when the surface is thawed. Open vertical contraction cracks have been observed which extend from the seasonal thaw zone down into the ice in the frozen ground. It is the conclusion of most recent observers that the theory of Leffingwell, supported by Black and Lachenbruch is the correct one.

Taber's hypothesis for the existence of the ice content, exclusive of the wedge-ice, seems very probable and can be demonstrated in the laboratory. He states that ice layers and veins grow from the surface, downward, as a result of croyostatic processes which are operative during the development of the permafrost. It is difficult, however, to explain the origin of all forms of ground ice by one process, as he attempted to do.

DISTRIBUTION OF GROUND ICE

In this investigation of thaw lake development, quantitative ground-ice determinations were made for several topographically distinct locations in the Barrow area. It was found that there is a definite relationship between the ground-ice content and the topographic position of each area. A later section of this report will attempt to show how this variation in ground-ice content may both affect and be affected by the development of thaw basins. To determine the ground-ice content, with other pertinent data, holes 32 inches in diameter were drilled to a depth of approximately 20 feet. These holes were large enough to allow a man to climb into them to chip representative samples from the frozen side of the hole. Wedge-ice was avoided, but the samples were otherwise unbiased. The samples were placed in jars and allowed to thaw. If the soil was supersaturated with ice, it would settle beneath a column of free water. This settlement was measured, and the amount expressed as a per cent of the total sample height. The samples were dried to determine the moisture loss. The moisture content was determined as a per cent of the dry soil solids (weight). This value, rather than ice content, gives more easily a true percentage of the total sample. The ice content as a per cent of total volume is the best illustration of the ground-ice content, however, and is easily calculated from the moisture content [moisture per cent dry soil (weight)] by:

$$I = \frac{m}{m - \frac{100(0.91)}{G}} \times 100$$

Where:

I = ice, per cent of total volume
m = moisture content, per cent of dry soil (weight)
0.91 = assumed specific gravity of ice
G = specific gravity of soil solids; assumed for this area to be 2.65

In this calculation it is also assumed that the air-void volume of the permafrost is negligible, and that all of the water in the permafrost exists as ice; the latter assumption is admittedly not true, as in fact water does exist locally throughout the permafrost in the form of chloride brines. These brines may have been trapped in the permafrost as it developed, following the recession of the sea, when the sediment voids were filled with sea water (O'Sullivan 1963). However, observation has led to the belief that, for the calculations of the ice content, the amount of brine is relatively insignificant. The validity of these assumptions can be determined only by such basic permafrost studies as bulk density determinations and chloride analysis.

Moisture content and ice volume percentage data are given in Table I. These data are from four of the drill holes, one each located on the initial surface, in an ancient drained basin, in a recently drained lake basin, and beneath the bottom of a filled lake basin (in this case the hole was drilled and sampled while the lake was frozen to the bottom). The sites were chosen as being representative of their respective areas. The locations of these sites are shown in Fig. 5. In this paper, the analysis of the distribution of ice content is limited to a comparison of the ice content for the topographically distinct areas. The vertical variance in ice content cannot be accounted for at this time; however, the permeability, porosity, and capillary potential of the sediments, along with the availability of water at various depths, are probably among the significant factors.

THAW-RELIEF POTENTIAL

A major goal of this investigation was to ascertain the probable magnitude of relief that can be ascribed to the thawing of ground ice. The major relief in the Barrow area is between initial surface residuals and the floors of some lake basins. The belief of most investigators acquainted with this or similar areas is that the basins represent depressions resulting from thaw.

Observations indicate that the normal amount of surface runoff is negligible and that it could not have produced the numerous basins. Normal drainage conditions are such that maximum surface runoff occurs at a time when the ground is frozen, or protected from erosion by snow or ice. However, a condition that cannot be considered as a normal annual phenomenon exists during the spontaneous draining of a lake basin. Observations of a basin that was recently drained by induced drainage revealed that erosion of the drainage line, and the extension of the drainage back into the basin, was very pronounced. The bottom of the basin in general, however, appeared to be lowered very slightly, if at all, as a result of erosion.

At some localities in the Barrow area, the relief reaches magnitudes that are difficult to explain by thaw phenomena alone. In at least one area, that south of Imaiksaun Basin, the local relief is nearly 45 feet, as measured from the bottom of the present lake to the top of the initial surface residual, immediately south of the basin. On the west side of the basin, the primary surface steps off to an area of similar surface characteristics, also assumed to be initial. This surface is only 15 feet above the bottom of the present lake. The higher surface is joined with both the basin and the lower primary area by a three degree slope. The slope was formerly mapped as a beach-ridge, because of its appearance on aerial photos and the occurrence of gravel below its surface. The nature of the slope between the two initial surface areas, and between the high area and the basin, is sufficiently different from most such boundaries as to strongly support the concept that it is part of the initial relief. The character and magnitude of the relief between the low initial surface residual area and the basin is typical of that which can best be explained as being due to thaw processes. The relationship of the situation described above is schematically illustrated in Fig. 9.

Livingstone *et al* (1958), from the volume of a basin that he assumed had formed from settlement due to ground-ice thaw, calculated the volume per cent of ice in the permafrost necessary to account for the basin development. Ice-content determinations in the Barrow area make it possible inversely to determine the potential depth a basin might attain by thaw processes. However, there are variables other than ice-content involved in this determination. These include the air-void volume of the permafrost, the wedge-ice volume, and the void volume of the sediment after thaw. Since these have not been absolutely determined, assumed approximations must be employed, or the factor discarded if believed insignificant. This is allowable if, instead of trying to determine an

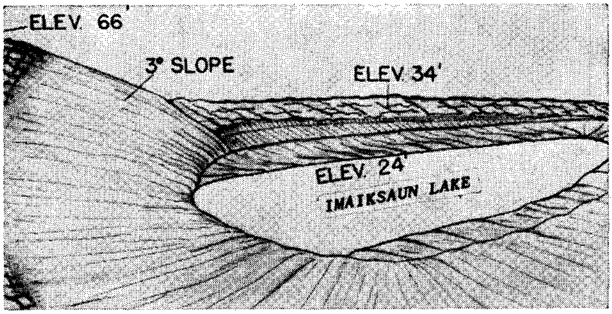


Fig. 9. Schematic diagram showing initial relief in the Imaiksaun basin area.

absolute value for potential thaw-settlement, an attempt is made to calculate the minimum amount that the ground will settle in an area by removal of the ground ice. On this basis, it is permissible to neglect the air-void volume of the permafrost. Observations indicate that this factor is negligible.

Thaw of the wedge-ice will definitely account for some settlement. The average widths and depths for the ice-wedges in most areas has been determined by drilling. In an area of intense ice-wedge development on an initial surface residual, the volume of wedge-ice in the upper 20 feet of permafrost is less than 5 per cent. This would account for less than 1 foot of settlement upon thaw. Thus, areas in which the polygons are over 25 feet in diameter would experience almost negligible settlement from thaw of the wedge-ice. Thus, these two factors, air-void volume and wedge-ice volume, can be eliminated from consideration in figuring minimum settlement.

The only settlement factors left to consider are the ground-ice content (exclusive of wedge-ice) and the void volume of the sediment after thaw. To calculate the potential settlement resulting from these factors, it is necessary only to express each in relation to a given quantity of soil solids i.e. the void ratio. It has been shown that a mathematical relationship exists between ground-ice per cent of volume of permafrost and the moisture content expressed as per cent of weight of dry soil solids. If one considers a column of permafrost in which there are 100 weight units of soil solids, the following relationship may easily be derived:

$$S = \frac{\dfrac{m}{0.91} - \dfrac{100}{G}(e)}{\dfrac{m}{0.91} + \dfrac{100}{G}} \times 100$$

Where:

S = settlement, expressed as a percentage of an original height of a column (or layer) of permafrost
m = moisture content
e = void ratio of the sediment
G = specific gravity of the soil solids
0.91 = assumed specific gravity of ice

For this calculation, the assumed specific gravity of the soil solids will be 2.65.

The void ratio of the thawed sediment is dependent primarily upon its grading characteristics and the amount of compaction to which it is subjected. The compaction of the sediment from overlying material decreases the void ratio. Therefore, since the settlement is inversely dependent upon the void-ratio value, it stands to reason that the void ratios from uncompacted samples which have thawed and settled would be a conservative figure to use when calculating the minimum settlement of materials which would definitely be subjected to compaction. Void ratios determined from the thawed samples fell generally near 0.7. This value is supported by void-ratio determinations from other soils having similar grading characteristics.

To calculate the minimum actual settlement which might occur in any area subjected to ground-ice thaw, it is only necessary to sum the percentages calculated from the 1-foot moisture content determinations from a drill hole in that area. The moisture content of samples collected from the drill holes listed in Table I were determined and the potential settlement calculated for each of the sites. These locations are considered to be representative of the different topographic surfaces of the area. The average minimum settlement, expressed as a percentage of an original depth, and the minimum actual settlement expressed in feet, which may be possible by ground-ice thaw, for the upper 20 feet of permafrost, is given in Table III.

Table III. Average potential settlement values that might result from the removal of the ground ice to a depth of 20 feet in topographically distinct areas (*see* Fig. 5 for locations of drill holes sites).

Area	*Drill Hole*	*Average Settlement Percentage*	*Minimum Actual Settlement*
Initial surface residual	P	55.4	11.1
Ancient drained lake basin	B-I	19.0	3.8
Recent drained lake basin	B-II	11.5	2.3
Present lake	L	2.0	0.4

These data show a great variation in calculated potential minimum settlement for the different surfaces. The greatest variation is between the initial surface residual and the bottom of the present lake. Lack of sufficient specific data prevents drawing of conclusions as to the reason for the variation in settlement values for the three basin areas. It appears to be a sound hypothesis, however, that the variation between the initial surface settlement potential and that of the basin areas is due to settlement already having taken place in the basins during their thaw development. This hypothesis may be tested in the areas of drill locations P and B-II. The location of drill hole P is on an initial surface residual having an elevation 10 feet above that of drill hole B-II, which is located in the adjacent drained lake basin. If all of the ice were removed from the upper 20 feet of ground in each of the areas, what is now the initial surface would be only about 2 feet above the basin. If it is acknowledged that it would take a 30-foot hole on the initial surface to correlate with the 20-foot hole in the basin, and if the additional settlement due to the greater concentration of wedge-ice in the initial surface residual were considered, then it is reasonable that this value would be slightly smaller. Thus, it might be supposed that in the past both areas were part of the same surface.

THE CYCLIC GENERATION OF THE THAW BASINS

While thawing of the ground ice is the most probable explanation for the initiation and development of a lake, the processes by which it is partially or completely drained and a subsequent lake is formed, wholly or in part within the original basin, are not clearly understood.

Obviously a lake can be drained by being tapped by a stream or a lower level expanding thaw basin. In either case drainage is probably started by thaw of an ice-wedge between the basin in question and a stream or lower basin. A basin whose potential development, towards some maximum depth possible by thaw, was interrupted by draining, would naturally continue to deepen by the additional thaw, and a lake would subsequently form. However, the relief characteristics of some of the more ancient basins, along with the ice content of the underlying permafrost, indicate that at one time these basins had attained the maximum depth. The fact that they subsequently also contained lakes or lake basins indicates processes considerably more complex than those mentioned above.

One can hypothesize that a lake originating on the initial surface would thaw until a layer of sediment formed thick enough to provide an insulating active layer over the permafrost table. Measurements have determined the thickness of this lake bottom active layer to be from 1 to 2 feet. As the depth becomes relatively static, there is nothing to prevent the lake from thawing laterally. An exceptionally warm summer would cause a further deepening of the lake through the removal of additional ice from the underlying permafrost, or by displacement of some of the active layer by wave erosion. The fact that such erosion does occur is illustrated by the benches of sediments observed adjacent to the margins of some recently drained basins. By the continual shifting of these sediments, the lake bottom would inch its way downward towards the significant depth of 6 feet. At this depth, the lake would no longer freeze to the bottom, and a net input of heat would result. This would accelerate the depression of the permafrost table to a considerable depth (Brewer 1958b) as the basin deepened to the maximum possible by thaw alone. At any stage, the development of this basin could be interrupted by drainage. A subsequent lake could then deepen by the same processes as outlined above.

While the lake is at the maximum depth, the thawed ground between its bottom and the depressed permafrost table will probably become saturated with water. As the basin is subsequently drained by one process or another, permafrost will return and ice will be injected into the freezing ground from below by the same cryostatic processes that were active during the formation of the original permafrost. The upper zone of new frozen ground will become supersaturated with ice, causing some uplift of the bottom of the basin. The net result will be a drained basin having underlying frozen ground with ground-ice quantities sufficient to enable a lake basin subsequently to develop within the older one. This hypothesis is consistent with the ice content distribution data listed in Table I.

Summary and Conclusions

The topography in the Barrow area, as in all similar regions of permafrost, results from the interactions of the usual geomorphic processes of erosion and mass wasting, plus the effects of certain regional processes that are associated with extremely low temperatures. These include: 1) fracture and movement of frozen ground material, as a result of thermal contraction and expansion; 2) surface uplift, resulting from the accumulation of ground-ice; and, 3) surface subsidence, resulting from the thaw of ground ice.

The sequence of geomorphic events that might explain ideally some of the relief characteristics of the Barrow area are as follows:

1. Emergence from the ocean.
2. Freezing with simultaneous injection of ground ice. Only the upper 20 or 30 feet becomes supersaturated with ice because the necessary water must move up from the material below.
3. The ground, frozen and supersaturated with ice, is subjected to thermal contraction during seasonal periods of extreme cold, so that a polygonal net of tension fractures is developed.
4. Additional ice is added to these cracks in seasonal increments, from the surface melt-water, thus forming a polygonal net of ice-wedges.
5. The addition of the ice to the wedges is accompanied by the upthrusting of material adjacent to them, both by the expansion of ice during the freeze-up, and of the ground during seasonal warm-up. This tends to form ridges of material on each side of the ice-wedge.
6. If drainage conditions are sufficient, the ice-wedges will be thawed, and troughs will be formed and perpetuated by the drainage. The ridge-forming material may slump into the troughs and develop the high-centred polygons. However, if drainage conditions are such that the wedge-ice is not eroded, the ridges can develop to where they stand in significant relief above the centres of the polygons, thus producing low-centred polygons.
7. Wherever water may become ponded (such as in the centres of the low-centred polygons) in such quantities as to facilitate the further thawing of ground ice, a lake basin starts forming. This basin may develop in depth until all of the excess ground ice has been removed, or until a layer of sediment builds up on the bottom through which seasonal thaw cannot extend.
8. Eventually the basin will become drained by one process or another, and two topographically distinct types of areas will have evolved: the basin areas; and the initial surface residuals.
9. The drainage on the relatively elevated initial surface will become integrated along the ice-wedge troughs, draining into the basins, and leaving the high-centred polygons as the predominant minor relief feature existing upon the initial surface residuals.
10. The drainage of the basin areas is confined and, therefore, these areas are characterized by the low-centred polygons.

11. Ice-cored mounds develop on both surfaces, most probably due to the injection of ice into horizontal contraction cracks.

The potential settlement evaluations, based on moisture-content determinations, lead to the conclusion that the basins existing in the Barrow area could have developed by the thaw of ground ice from the initial surface residuals, if one assumes that some of the greatest relief between the basins and the initial surface is due to initial relief upon the initial surface residuals.

Evidence for initial relief is found in the residual slope feature that exists at present both as relief upon the initial surface and between the initial surface residuals and some of the basins.

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