[Proceedings of the Iowa Academy of Science](https://scholarworks.uni.edu/pias)

Volume 70 | Annual Issue Article 55

1963

Preliminary Investigation of Thermokarst Development on the North Slope, Alaska

Gary S. Anderson
Iowa State University

Keith M. Hussey
Iowa State University

Recommended Citation

Anderson, Gary S. and Hussey, Keith M. (1963) "Preliminary Investigation of Thermokarst Development on the North Slope, Alaska," *Proceedings of the Iowa Academy of Science, 70(1),* 306-320.
Available at: https://scholarworks.uni.edu/pias/vol70/iss1/55

Norton, W. H. and others, 1911: Iowa Geol. Survey 21, p 29-1214.
Peltier, L. C., 1950: Annals Assoc. Am. Geographers 40, p 214-236.
Rhoades, R. and Sinacori, M. N., 1941: Jour. Geology 49, p 785-794.
Savage, T. E., 1905: Iowa Geol. Survey 16, p 565-648.
Scobey, E. H., 1938: Jour. Geology 46, p 207-217.
Shaffer, P. R., 1954: Geol. Soc. America Bull. 65, p 443-456.
Soloviev, L. N., 1961: Akten des Dritten Internat. Kongresses für Speläöl. A, p 70-71.
Sweeting, M. M., 1950: Geographical Jour. 115, p 63-78.
———, 1960: Zeitschr, Geomorphologie, supp. 2, p 81-89.
Swinnerton, A. C., 1932: Geol. Soc. America Bull. 43, p 663-694.
Tester, A. C., 1937: Geological Map of Iowa: Iowa Geol. Survey.
Tri-State Geological Field Conference, 1948: Guidebook, 12th Ann. Field Conf., p 1-28.
Trowbridge, A. C., 1921: Univ. of Iowa Studies in Nat. History 40, p 1-127.
Turyshev, A. V., 1961: Akten des Dritten Internat. Kongresses für Speläöl. A, p 39.
Tuttle, S. D. and Northup, R. C., 1955: Iowa Acad. Sci. Proc. 62, p. 366-372.
Udden, J. A., 1898: Iowa Geol. Survey 9, p 247-388.
Visher, S. S., 1945: Geol. Soc. America Bull. 56, p 713-736.
White, E. L. and White, W. B., 1963: NSS News 21, p 17.
Wilson, A. G., 1896: Am Geologist 17, p 364-371.

Preliminary Investigation of Thermokarst Development on the North Slope, Alaska[1]

GARY S. ANDERSON[1] AND KEITH M. HUSSEY[2]

The North Slope of Alaska is extensively featured by a characteristic form of morphology designated "thermokarst". Briefly, thermokarst is a term applied to a "karst-like" topography formed in permafrost regions that have had extensive thaw. Aerial photographs of the North Slope reveal many thaw features that have forms analogous to karst areas.

GENERAL DISCUSSION AND LITERATURE REVIEW

Since the phenomenon of thermokarst has not been extensively studied and a majority of people without experience in the Arctic or Subarctic are not acquainted with the term, it seems warranted to summarize some of the problems associated with limitations imposed by definition of the term and the classification of thermokarst features; and also to discuss the developmental features and the work that has been done in the field to date. The term thermokast was proposed by M. M. Ermoleav in 1932 (Mukhin, N. L., 1960) as ". . . a form of relief having a certain similarity to karst formation but resulting from the action of heat." At the time of Mukhin's work (1960) he consid-

[1] Formerly, Iowa State University, Ames, Iowa, now University of Alaska, College, Alaska.
[2] Iowa State University, Ames, Iowa.

ered the current popular concept of the definition to be ". . . a process of differential settling or caving of the soil surface." He doubted the quality and validity of this definition since it did not properly describe its true nature and may also include relief caused by factors other than temperature. Mukhin (1960) re-defined the term as "the process of thawing of ice in the ground (except in bedrock) which is accompanied by the local settling of the soil surface and the formation of negative relief." In view of previous work on thermokarst and the classical work on normal karst, this definition is inadequate since it doesn't include the positive relief forms resulting from the formation of negative relief such as residual mounds remaining after thaw of ice-wedges around the centers of polygons. These have been discussed by previous investigators of thermokarst and are analogous to the "hums" of Jugoslavia, "pepino hills" of Puerto Rico and the "mogotes" of Cuba. (Thornbury, 1957, p. 334). Essentially, thermokarst is a topography comparable to karst topography of limestone regions but results from thaw in areas of perennially frozen ground or permafrost. The term has been defined, discussed and summarized by many authors, a few of whom are: Frost (1950, p. 36), Hopkins, Karlstrom and others, (1955, pp. 140-141), Muller (1947, pp. 83-84), Péwé (1954, pp. 329 338), Tsytovich and Sumgin (1959, p. 215).

The current literature describes a number of features that are characteristic of thermokarst topography. Most commonly accepted are: surface cracks, cave-ins, funnels, sinks, saucers, shallow depressions, "valleys," gullies, ravines, sag basins, cave-in lakes, windows, and sag-ponds (Muller, 1947, p. 84). It is anticipated that there are yet many more features to be classified as thermokarst. Presently, much of the literature consists of a resummarization of the earlier work and certain terms have become ingrained in the literature as true thermokarst, but as more extensive studies are initiated new nomenclature must be developed for other previously unrecognized thermokarst features.

Thermokarst is restricted to areas of permafrost, or frozen ground, which is widespread in Eurasia and North America, and which occupies an area considerably larger than the entire U. S. A. (Muller, 1947, p. 1). The precise extent of permafrost is unknown due to inadequate field data, but figure 1 shows a generalized distribution based on the work of Tsytovich and Sumgin (1959, p. 192), Brown, R. J. E. (1960, p. 166), and Hopkins, Karlstrom and others (1955, p. 136).

The major prerequisite for thermokarst development is that the ground contain massive embedded ice or be oversaturated with interstitial ice, and that the thermal regime be so disturbed as to produce a net input of heat into the ground. The thermal regime is usually disrupted by the action of nature or man destroying the natural insulation of vegetation, or by a climatic change tending toward warmer conditions as Halicki, 1951, has suggested (Péwé, 1954).

The rate and degree of thermokarst development depends on a number of factors which have been discussed in the words of: Hopkins and Karlstrom (1955), Muller (1947), Péwé (1954), Tsytovich and Sumgin (1959), and others. Muller (1947, p. 83) has summarized the factors related to the intensity of thermokarst processes to be: composition of the regolith, structural relations of ground that is susceptible to the thermokarst processes, climate factors, hydrologic and hydrogeologic factors, conditions of the soil, geomorphic factors, and human activity.

Thermokarst development is very dependent on the thermal properties of the soil and surface insulation. Muller (1947) and Tsytovich and Sumgin (1959) have described these properties in detail as related to permafrost engineering. The effects of deforestation in permafrost areas on thermokarst development have been discussed by Péwé (1954), and Rockie (1942). Recently, Drew, Tedrow, Shanks, and Koranda (1958) have described how rate and depth of thaw is related to the soil and vegetation in natural conditions at Barrow, Alaska. Theoretical soil physics is another discipline where much of the work in thermal properties of soils has been done by: Bouyoucos (1913, 1920), Crawford (1952), Crawford and Legget (1957), Kersten (1948, 1949, 1952), Legget and Peckover (1949), Misener (1952), and others.

The majority of the work on thermokarst to date has been done by Russian authors, some of whose contributions in this field are: Baranov (1958), Bakulin (1958), Kachurin (1938, 1955), Korzhver and Nikolaev (1957), Kosov (1959), Mukhin (1960), Pchelintsev (1946), Tikhomira (1956), Grave and Nekrasov (1961), and Tolstov (1961). American authors have discussed thermokarst and related phenomena in Alaska. Rockie (1942) and Péwé (1954) have reported on the thermokarst in the Fairbanks area and its relation to agricultural development. In areas where there is abundant ground ice, thermokarst mounds develop in 2 or 3 years, and thermokarst pits develop in 3 to 30 years after a field is cleared for cultivation. The mounds obtain their maximum relief where ice-wedge melting has been the most intensive. Where irregular masses of ice are extensively melted, large pits develop which are often accented by running water. These pits are sometimes very "cave-like" and enlarge with depth. Péwé (1954, p. 337) reports a pit that is 8 feet wide, 15 feet long, and 20 feet deep. At the base of the pit, two passageways 3 feet wide and 2 feet high branch out and extend horizontally. Another feature quite similar to the thaw pit described by Péwé is the thaw sink in the Imuruk Lake area, Seward Peninsula. Hopkins (1949, p. 119) describes them to be "closed depressions with subterranean drainage, believed to have originated as thaw lakes." The bottom of the sink opens into a subterranean passage and, in case the sink receives surface water from streams, the entire volume of water passes underground. In one situation, Hopkins (1949, p. 130) estimated that at least 8,500 cubic yards of material were removed from the original flat lake floor to form the sink and all of this material was redeposited in subterranean channels without preventing them from receiving surface water. The openings apparently were produced by the thaw of ground ice.

Thaw lakes are probably the most predominant thermokarst feature in many Arctic areas where they are geographically widespread. The common thaw lakes and cave-in lakes are found both north and south of the Brooks Range. Wallace (1948) describes cave-in lakes in the Nebesna, Chisana, and Tanana River valleys, in eastern Alaska, and Hopkins (1949) describes thaw lakes in the Imuruk Lake area, Seward Peninsula. Livingstone, Bryan, and Leahy (1958) studied a typical thaw lake in the coastal plain-foothills transition area, on the North Slope. Oriented lake basins of the Arctic Coastal Plain are another thaw phenomenon. Their morphongeny, which is dependent on factors in addition to thaw, will be discussed later in the text.

Wallace (1948) describes cave-in lake basins as those which result from a collapse of the terrain after a volume loss of ice, due to a disruption of the thermal regime. The basins he studied were in fine grained sediments, and he considers this to be characteristic of most similar features. He designates four stages of development: youthful, characterized by small circular lakes; early mature, when the small lakes grow by melting of their margins until they are aggregated; late maturity, when integrated drainage has formed between them; and old age, when the drainage channels have constructed sufficient natural levees to divide the lake basins into sections. By dating tree rings he has established the rate of shore line retreat to be 2.3 to 7.5 inches per year (Wallace, 1948, p. 181).

Hopkins' description of thaw lakes is quite similar to Wallace's. He describes the lakes as being initiated by a disruption of the thermal regime resulting in a net input of heat to the ground. They grow by ice loss beneath their basin and around their margin, especially along icewedge intersections, and by bank erosion of the margins. Eventually, some of the lakes are pirated by surface drainage, drained, or partially so, and vegetated to form a flat marsh surrounded by high banks. Other lakes develop internal subsurface drainage and proceed from a thaw lake to a thaw sink, as previously described.

Livingstone, Bryan, and Leahy (1958) studied East Oumalik Lake, and decided its development to have been caused by alternate periods of rapid growth and quiescence. During rapid growth, the wedges deteriorate fast and the result is ice-wedge holes in the lake bottom; during quiescence, the holes are smoothed out. At the present time, the lake is expanding northward (Fig. 4). By assuming that there has been no loss of permanently solid materials, the authors calculated the present partial volumes of mud, water, and air in the basin and that between the present water surface and the surrounding surface of the general terrain to derive the figure of 70% as the amount of space previously occupied by ground ice.

Among the most striking features on the Alaskan Arctic Coastal Plain are the longated and aligned thaw basins. These have received considerable attention by several authors: Black and Barksdale (1949), Brewer (1958a and 1958b), Britton (1957), Carson and Hussey (1959, 1960, and 1962), Livingstone (1954), Rex, (1958 and 1961), and Rosenfeld and Hussey (1958). The most recent and what appears to be the most logical explanation for these lakes is by Carson and Hussey (1962). The basins are initiated by increased thaw in local areas of water accumulation. Almost as soon as the basin is initiated, the predominant magnitude of east-west winds creates sublittoral shelves on the east and west sides of the lake and increases scouring on the north and south ends. The east and west sides are shaped by wave action which is limited by depth of the lake. Thus shore profiles are developed along the east and west sides which subdue thermal and hydrologic degradation; the ends are shaped by currents strong enough to erode the banks and bottom. Hence, they have relatively increased thermal and hydrologic erosion. With time, the lake expands faster to the north and south than to the east and west.

The center of the lake basin is relatively deep (usually less than 6 feet) and elongated. These features are frequently even more strikingly oriented than the surface expression of the basin. If the basin is less than 3 feet deep, the lake thaws in June and the rate of basin subsidence is relatively fast. Deeper basins which thaw three to six weeks later have more bottom insulation and deepen relatively slowly. Lakes less than 6 feet deep freeze to the bottom during the winter and are subject to conditions similar to the surrounding tundra. A lake greater than 6 feet deep does not freeze to the bottom. therefore, the permafrost table continues to be slowly depressed throughout the year. Brewer (1958-b) reports that under Lake Imikpuk, which is 10 feet deep, the permafrost table is depressed 190 feet. Nevertheless, lakes greater than 6 feet deep still have reduced subsidence because water volume and increased insulation of bottom sediments. Present studies are inconclusive, but indicate a decrease in ice with depth. This would mean that even though the permafrost table were considerably depressed, there would not be a comparable subsidence of the basin.

Even a cursory study of aerial photographs of the Alaskan Arctic Coastal Plain reveals the temporal nature of the thaw lakes. The surface is almost entirely covered by old basins that have been drained by headward erosion of streams, accelerated thaw along ice-wedges, extensions of basins across drainage divides, and by human activity such as heavy machinery disrupting the thermal regime around lakes and creating thaw gullies. Britton (1957) has extensively discussed the "thaw lake cycle" from the initiation of the lake, through its growth and development, until it is eventually drained and finally revegetated. Usually, not the entire volume of water is lost, as the outlet does not extend to the deepest part of the basin. The ponds that remain initiate another "thaw lake cycle."

It has already been pointed out that ground ice is a prerequisite for thaw relief development. By analyzing the data from a number of drill holes in the Barrow area, Hussey and Michelson (1961) have determined ground ice variations in four topographic locations: primary surface, anciently-drained basin, in a recently-drained basin, and in the bottom of a present lake basin. As would be expected, the ground beneath a primary surface has the greatest ice content. That beneath the drained basins has less, as a result of lost from previous thaw. From the information on ground ice, it is then possible to predict potential thaw and settlement on the respective surfaces. It was found that the absolute minimum settlement expected from the removal of ground ice in the upper 20 feet of the surface would be: 10.6 feet under the primary surface; 3.5 feet under the ancient drained basin; 2.2 feet under the recent drained lake basin; and, 0.2 feet under the present lake basin.

Thermokarst Features of the Northern Foothills, Alaska

In addition to the omnipresent thaw lake basins, both oriented and non-oriented, of northern Alaska, there are a number of thermokarst features present that have not been studied as extensively as the lakes. During the summer of 1962, the first author was a member of a two-man party that traversed by boat almost the width of the Northern Foothills section, Arctic Alaska, along the Meade and Ikpikpuk rivers. The lateral extent of the Northern Foothills section was surveyed by airplane and ground spot-checks. Previous to the 1962 field season, the entire Northern Foothills section was investigated by means of aerial photographs.

During the investigation, considerable attention was given to the environment and distribution of thermokarst features in these areas. Features that were found to be common included non-oriented lake basins, both drained and presently occupied, thermokarst ravines, beaded streams, and ice-wedge intersection ponds.

The Northern Foothills section is located completely within the zone of continuous permafrost (figure 2) and is subject to a Tundra Climate.

Climatic records from Umiat (U. S. Weather Bureau, 1952) show a monthly mean temperature of about 10°F, a daily maximum exceeding 70°F for about two weeks during the summer, and daily minimum exceeding -50° during extended periods of the winter. Precipitation is less than 10 inches per year, the greater portion of which is in the form of snow.

The region is underlain by east-west trending Appalachian-type folds of Cretaceous strata. Bedrock exposures are numerous at the southern portion of the section, but less common toward the north due to the regional dip in this direction and a mantling of marine Quaternary silts in the northern portion of the section.

In the southern portion of the section, the physiography is typified by east-west trending cuestas, while toward the north the hills have less relief with broad, flat uplands containing numerous thaw lakes and displaying extensive evidence of drained lake basins.

In the Northern Foothills, the thermokarst features are best developed in the alluvial valley fills and on the upland silt surfaces in the northern portion of the section. Most features are related to thaw and drainage of ice-wedges. Once the ice-wedge network starts to melt and is removed, the remaining highs are subsequently lowered by the removal of interstitial ice.

Scattered throughout the tundra of the Northern Foothills are small ice-wedge intersection pools. Figure 3 shows a typical feature of this type has formed at the intersection of six ice-wedges; depth is 2 feet. The water temperature was 18°C at the time of observation, but the bottom and sides of the pool were insulated with organic muck, so that the heat from the water was not noticeably effective in promoting further thaw.

It is feasible that once an ice-wedge pool is formed it could persist for extended periods as an individual feature, but normally it coalesces with other pools to form one of three types of larger thermokarst features. If the pool is in close proximity to

FIGURE 1

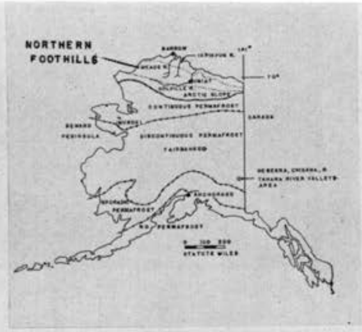

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

Figure 1. Map showing generalized distribution of permafrost in the Northern Hemisphere. The map is based on the work of Tsytavich and Sumgin (1959, p. 192), Brown (1960, p. 166), and Hopkins, Karlstrom, and others (1955, p. 136).

Figure 2. Map of Alaska showing the location of the North Slope, and the distribution of permafrost in Alaska (Hopkins, Karlstrom, and others, 1955, p. 136).

Figure 3. Small thaw pond formed by the melting of an ice-wedge intersection, Ikpikpuk River.

Figure 4. Oumalik Lake, a typical thermokarst lake in the Northern Foothills section.

Figure 5. Head of thermokarst ravine showing its initiation by thawing of ice-wedges and slumping of the tundra mat.

Figure 6. Well vegetated ravine, intermediate in size, and not showing further evidence of enlargement.

good drainage, such as along river banks, the thaw will be extended along ice-wedges and eventually a good drainage net will be established. Subsequent thaw and removal of water plus slumpage and removal of the adjacent regolith will cause the rapid development of thermokarst ravines. In areas of moderate

FIGURE 7

FIGURE 10

FIGURE 8

FIGURE 11

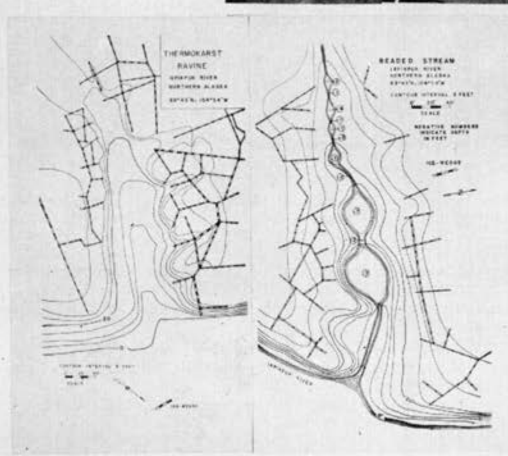

FIGURE 9

Figure 7. Actively forming ravine, currently enlarging by thaw and water can be seen running out from the bottom.

Figure 8. Aerial shot of a beaded stream which was partly mapped, figure 9.

Figure 9. On the left is a sketch map of a thermokarst ravine, area E, figure 10, showing the correspondence of ravine morphology and ice-wedge orienta-

tion. On the right is a sketch map of a beaded stream, area F, figure 11, showing the relationship of ice-wedges to stream morphology.

Figure 10 Composite aerial photograph from the Ikpikpuk River in the Northern Foothills section.

Figure 11 Composite aerial photograph from the Meade River in the Northern Foothills section showing the typical speckled topography.

drainage, such as along minor drainage valleys, the ice-wedge intersection pools will gradually connect by preferentially thawing along the ice-wedges having a common orientation with the valley. Improved drainage conditions will cause the areas of intersection to increase in size but only moderate thaw is continued in the connecting wedges. The result is a beaded stream.

In the Northern Foothills, thermokarst ravines are extensively developed along the banks of the major rivers. Figure 9 is a composite aerial photograph showing thermokarst ravines adjacent to the Ikpikpuk River. Ravine E, figure 9, was mapped in detail to show the correspondence of thaw directions and ice1wedge distribution and orientation (figure 10). Major relief appears to be formed by thaw of ice-wedges and removal of minor amounts of sediments. Presently the large channels shown on the map are well vegetated and show little evidence of further enlargement. At the heads of some of these channels further development of relief is forming by the thaw of ice-wedges and slumping of material into the channels. Figures 5, 6, and 7 show relative degrees of development of thermokarst ravines from the initial melting of ice-wedges to one of the larger ravines that was observed. Figure 7 is an oblique aerial photograph of an actively forming ravine in a bluff approximately 100 feet high. At the time of photographing, the sides of the ravine were covered with sludge and a sizeable stream was flowing from the base of the ravine. Dimensions of the ravine are only approximately since it was viewed from the air.

The maximum size of thermokarst ravine development noted was the badlands area, figure 9. It covers an area of approximately one-half square mile and has a maximum relief of 200 feet. The relation of the badlands morphology to a pre-existing polygonal net is evident from the rectangular drainage pattern in the area and the remnant polygonal outlines seen on the highs of the area.

Figure 9 shows a typical beaded stream, formed in a moderately drained area, and figure 8 is a low altitude photograph of it. The pools or beads of the stream form at the intersections of two or more ice-wedges and of those studied, the deepest was 7 feet. The channels between pools, or the links, follow ice-wedges and are much more shallow than the pools. Maximum depth observed was less than 2 feet, and often during the summer when discharge is low the links are nearly dry. Figure 10 is a sketch of the stream showing the relationship of morphology to ice-wedges. The beaded streams cannot be entirely considered as thermal relief features since they do have a large discharge at times and consequently have the ability to erode, although the water is usually clear and only minor amounts of bedload are in the stream bottoms.

In areas of poor drainage typical of broad flat uplands, the pools gradually interconnect, but the water resulting from thaw of ice has limited opportunity to drain. The end result can either be a broad flat surface of irregular minor relief with interconnected pools, or if thaw is extensive enough, a lake can form.

Figure 11 shows extensive flat areas with local irregular minor relief and a variety of vegetation associations estblished in the differing edaphic environments. The mosaic of minor relief, differing vegetation associations, and pools of water create a characteristic surface expression in this area, here termed "speckled topography". Although the speckled areas of figure 11 have a similar appearance on the aerial photographs, they occur in a variety of topographic positions, possesses minor differences in their edaphic environments, but, as a whole, express the same general terrain conditions. Some of the differing areas were studied to determine their relation with regard to terrain conditions.

Area E is a basinal feature with a drainage outlet to the north. Morphologically, it appears very much like a drained lake basin, but the regolith does not appear to be a lacustrine deposit. The basin contains a typical polygonal net of both high and low-centered varieties. There are numerous ice-wedge intersection pools and the extensive areas of poor drainage contain ice mounds and bog ridges. A typical high-centered polygon in the basin contains a regolith profile of layered peat, 0-9″; brown silt loam, 9-12″; and, permafrost, at 12″. In a ponded low-centered polygon the profile is: layered peat, 0-10″: brown silt loam, 10-15″; and, permafrost at 15″. With respect to the above described profiles and others investigated that were similar, it appears that they are not lacustrine due to the fact that the silt is not organic nor does it show banding or bedding. Furthermore, the peat is layered rather than the characteristic chunky and/or pulverized peat that commonly occurs around the basinal margins of thaw lake basins. It seems entirely possible that the basin could have formed by localized thaw and subsidence of the basin with penecontemporaneous removal of excessive water through the northern drainage route.

Area F is a typical upland speckled area, characterized by high-and low-centered polygons and ice-wedge intersection pools. Highs are cottongrass covered and have less than 2 feet relief; the lows are very moist and contain hydrophytic plants.

The highs consist of: vegetation mat, 0-6″; variegated blue-gray, reddish brown silt, 6-22″; and permafrost at 22″. The lows have: vegetation mat, 0-8″; blue-gray silt, 8-20″; and permafrost at 20″.

Area G, another upland speckled area, displays extensive minor relief formed by high-centered polygons elevated 1-5 feet above the ice-wedge lows which commonly contain water with large pools at intersections. The regolith o fthe highs consists of a firm blue-gray slightly red-brown variegated loam with permafrost at 20″.

Area H is a lowland speckled area formed by high- and low-centered polygons and ice-wedge intersection pools. Maximum minor relief is 1-3″ between the high-centered polygons and ice-wedge lows. The lows contain hydrophytic plants, whereas the highs have sedges and small shrubs. A profile from a high is: peat, 0-5″; variegated blue-gray, reddish-brown silt loam, 5-15″; and permafrost at 15″.

Area I is a basinal feature with drainage routes out both the east and west ends, although it is occupied by standing water. The basin contains numerous ice mounds but limited visible polygonal development. Regolith is: pulverized peat, 0-8″; very organic muck, 8-22″; and permafrost at 22″. This appears to be a typical Arctic lacustrine deposit, although no micro-fossils were found to prove this.

In general, the speckled areas are associated with poorly-drained broad-crested uplands, upland basins, and low basins. Their pattern is due to the contrasting mosaic of polygonal ground and associated vegetation assemblages and standing pools of water. In some cases the local drainage, especially basins with outlets, appears to be moderate as indicated by minor relief and regolith showing variegated colors.

The basinal depressions of figure 11 do not contain quantities of water now, but some of them probably did at one time. There also seems to be evidence that they could evolve without containing a lake. Further north of the area covered by figure 11, speckled topography is still extensive and many of the basins contain thermokarst lakes. Figure 4 is a photograph of Oumalik Lake, a typical lake in the northern portion of the Foothills section, which was studied by Livingstone, Bryan, and Leahy (1958). A summary of their work has previously been discussed in this text.

CONCLUSION

The study of thermokarst features and processes has been rather neglected in North America, but before we can effectively utilize our "far northland", studies related to these problems must be seriously considered. A number of associated disciplines, such as botany, pedology, physics, meteorology, engineering, geophysics, and geology have established the basic trends of research related to thermokarst processes and now it is time for investigators equipped with the basic ideas of these disciplines to directly relate them to more intensified studies of thermokarst development. Studies of this nature will aid in more effective planning and performing of engineering construction problems in Arctic regions. From the theoretical standpoint, thermokarst development is a process operating in a large area of the world, the Polar regions, yet this process of land denudation is poorly understood and completely neglected in the textbooks of general geology and geomorphology. Also, since the nature and rate of thermokarst development is related to climatic conditions, it is an indicator of present and past climatic trends, and detailed studies should benefit climatologists.

The North Slope of Alaska is one area of extensive thermokarst development. This study, and the previous studies in this area, is limited in its scope, but is intended to describe the features present here. The work that has been done indicates that thermokarst development is the major denudation process operating on the North Slope; but details are not well understood concerning the interrelationship of the geomorphic processes involved, and rates of development, both past and present, plus speculations into the future rates.

Literature Cited

Bakulin, F. G. (1958). Ice content and settling on thawing of permanently frozen Quaternary deposits in the Vorkuta region. (translated title) Moscow, Izdat. Akad. Nauk SSSR. Original not available for examination, abstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment Report Twelve 14:50 (1962).

Baranov, L. A. (1958). Fossil thermokarst in the Cisbaikal. (translated title) Materialy k Osnovam Ucheniia o Merzlykh Zonakh Zemnoi Kory, Vyp. 4:5-19. Original not available for examination, abstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment Report Twelve 15:101 (1961).

Black, Robert F. and Barksdale, W. L. (1949). Oriented lakes of northern Alaska. Jour. of Geology 57:105-118.

Bouyoucos, G. J. (1913). An investigation of soil temperature and some of the most important factors influencing it. Michigan Agriculture College Experiment Station Tech. Bull. 17:168-180.

——— (1920). Degree of temperature to which soils can be cooled without freezing. Jour. of Agriculture Research 20:267-269.

Brewer, Max C. (1958-a). Some results of geothermal investigations of permafrost in northern Alaska. Am. Geophys. Union Trans. 39:19-26.

——— (1958-b). The thermal regime of an arctic lake. Am. Geophys. Union Trans. 39:278-284.

Britton, Max E. (1957). Vegetation of the arctic tundra. In Hansen, Henry P., ed. Arctic Biology: Biology Colloquium 1957, pp. 26-61. Oregon State College, Corvallis, Oregon.

Brown, R. J. E. (1960). The distribution of permafrost and its relation to air temperature in Canada and the U. S. S. R. Arctic 13:163-177.

Carson, Charles E. and Hussey, Keith M. (1959). The multiple working hypothesis as applied to Alaska's oriented lakes. Iowa Acad. of Sci. Proc. 66:334-349.

——— (1960). Hydrodynamics in three arctic lakes. Jour. of Geology 68:585-600.

——— (1962). The oriented lakes of arctic Alaska. Jour. of Geology 70:417-439.

Crawford, Carl B. (1952). Soil temperatures, a review of published records. In Frost action in soils: a symposium. Highway Research Board, Spec. Rept. No. 2:17-41.

Crawford, Carl B. and Legget, K. F. (1957). Ground temperature investigation in Canada. Engineering Jour. 40:1-8.

Drew, J. V., Tedrow, J. C. F., Shanks, R. E. and Koranda, J. J. (1958) Rate and depth of thaw in arctic soils. Am. Geophys. Union Trans. 39:697-701.

Frost, Robert E. (1950). Evaluation of soils and permafrost conditions in the territory of Alaska by means of aerial photographs. Vols. 1 and 2. St. Paul District Corps of Engineers, U. S. Department of the Army. St. Paul, Minnesota.

Grave, N. A. and Nekrasov, I. A. (1961). Some observations on thermokarst in the vicinity of the settlement of Anadyr. Problems of the North (Problemy Severa), National Research Council, Ottawa, Canada, No. 4:165-172.

Hopkins, David M. (1949). Thaw lakes and thaw sinks in the Imuruk Lake area Seward Peninsula, Alaska. Jour. of Geology 57:119-131.

———, Karlstrom, Thor N. V., and others (1955) Permafrost and ground water in Alaska. U. S. Geological Survey Prof. Paper 264-F.

Hussey, Keith M. and Michelson, Ronald W. (1962). Tundra relief features near Point Barrow, Alaska. Mimeographed. Department of Geology, Iowa State University of Sci. and Tech., Ames. Iowa.

Kachurin, S. P. (1938). Instructions on the study of thermokarst. (translated title) Akad. Nauk SSSR, Moscow. Original not available for examination, abstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment Report Twelve 11:261 (1952).

——— (1955). Thermokarst as an index of permafrost degradation. (translated title) Materialy k Osnovam Ucheniia o Merzlykn Zonakh in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Zemnoi Kory 2:25-33. Original not available for examination, abstracted Establishment Report Twelve 10:123 (1956).

Kersten, M. S. (1948). The thermal conductivity of soils. Highway Research Board Proc. 28:391-409.

——— (1949). Thermal properties of soils. Univ. of Minn. Bulletin 21.

——— (1952). Thermal properties of soils. In Frost Actions in soils: a symposium. Highway Research Board, Spec. Rept. No. 2:161-166.

Korzhuev, S. S. and Nikolaev, S. S. (1957) Karst types in permafrost regions and features of their occurrence. (translated title) Izvest. Akad. Nauk SSSR, Ser. Geograf. No. 6:33-46. Original not available for examination, abstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establisment Report Twelve 13:98. (1959).

Kosov, B. F. (1959). Ravine erosion in tundra zones. (translated title) Nauchnye Doklady Vysshei Shokoly, Geologo-Geograficheskie Nauk, No. 1:123-129. Original not available for examination, abstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment Report Twelve 14:167 (1960).

Legget, R. F. and Peckover, F. L. (1949). Soil temperature studies — a progress report. Highway Research Board Proc. 29:434-445.

Livingstone, D. A. (1954). On the orientation of lake basins. Am. Jour. of Sci. 252:547-554.

———, Bryan, K., jr. and Leahy, R. G. (1958). Effects of an arctic environment on the origin and development of freshwater lakes. Limnology and Oceanography 3:192-214.

Misener, A. D. (1952). An absolute method of determining thermal conductivity and diffusivity of soils. In Frost action in soils: a symposium. Highway Research Board, Spec. Rept. No. 2:51-57.

Mukhin, N. I. (1960). Definition of the concert "thermokarst". (translated title) Trudy Inst. Merzlotovedeniia im. V. A. Obrucheva, 16:108-110. Original not available for examination, adstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment Report Twelve 15:78 (1961).

Muller, Siemon William (1947). Permafrost or permanently frozen ground and related engineering problems. J. W. Edwards, Inc., Ann Arbor, Michigan.

Pchelintsev, A. M. (1946). A morphological description of the thermokarst process in Yakutia. (translated title) Merzlotovedenie, 1:95-105. Original not available for examination, abstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment Report Twelve 12:209 (1958).

Péwé, Troy L. (1954). Effect of permafrost on cultivated fields, Fairbanks area, Alaska. U. S. Geological Survey Bulletin 989-F.

Rex, R. W. (1958). Orientation of lakes on the northern Alaska Arctic Coastal Plain. Unpublished manuscript. Scripps Inst. Ocean., Univ. of Calif.

Rex, R. W. (e1961). Hydrodynamic analysis of circulation and orientation of lakes in northern Alaska. In Raasch, Gilbert O., ed. Geology of the arctic: First International Symposium on Arctic Geology, pp. 1021-1043. University of Toronto Press, Toronto, Canada.

Rockie, W. A. (1942). Pitting on Alaskan farm lands: a new erosion problem. Geograph. Rev. 32:128-134.

Rosenfeld, G. A. and Hussey, Keith M. (1958). A consideration of the problem of oriented lakes. Iowa Acad. Sci. Proc. 65:279.287.

Thornbury, William D. (1957). Principles of Geomorphology. John Wiley and Sons, Inc., New York.

Tikhomirov, B. A. (1956). Frost-mound formation in relation to thermokarst and vegetation dynamics in northern Siberia. (translated title) Tezisy i plany dokladov . . . k soveshchaniiu 1956 g. po merzlotovedeniiu, Inst. Merzlotovedeniia AN SSSR. Moscow, Vyp. 2. Original not available for examination, abstracted in U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment Report Twelve 14:11 (1960).

Tolstov, A. N. (1961). The region of intensive erosion and thermokarst. Problems of the North (Problemy Severa), National Research Council, Ottawa, Canada, No. 4:157-163.

Tsytovich, M. A. and Sumgin, M. I. (1959). Principles of mechanics of frozen ground. U. S. Army Corps of Engineers Snow Ice and Permafrost Research Establishment. Translation 19.

U. S. Department of Commerce. Weather Bureau (1953) Local climatological data, Umiat, Alaska. Kansas City, Missouri.

Wallace, Robert E. (1948). Cave-in lakes in the Nabesna, Chisana, and Tanana River Valleys, eastern Alaska. Jour. of Geology 56:171-181.