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THAW DEPRESSIONS AND THAW LAKES
A REVIEW

Contents: Introduction — Historical perspective — Synopsis of principles — Ice content of permafrost — Thaw depressions — Thaw lakes — Oriented lakes of northern Alaska and northwest Canada — Vegetation and thaw depressions and thaw lakes — Thermal aspects of thaw lakes — Other limnological aspects of thaw lakes — Suggestions for future study — References cited.

INTRODUCTION

In permafrost regions thaw of ground ice which comprises more volume than pore space in unconsolidated sediments results in thaw depressions that may become lakes. Both thaw depressions and thaw lakes are circum-Arctic and exceedingly abundant. Many thaw lakes are large striking features characterizing the coastal plains and lowlands with continuous and discontinuous permafrost. The concept of their origin is relatively simple, but in North America quantitative data on the factors involved are meager — only a few specific case studies are available. The better known areas are in northern Alaska and northwest Canada.

This paper reviews the present status of knowledge in North America of the thaw depressions and thaw lakes of the permafrost regions, as requested by Jan Dylik, President of the International Commission on Periglacial Geomorphology. This paper arbitrarily excludes kettles and kettle lakes, even though they are common in permafrost regions, because the mechanism of emplacement of ice in the ground specifically results from the work of glaciers. However, kettles resulting from thaw of buried glacial ice may well be identical to true thaw depressions in form, in process, and in implications regarding heat exchange.

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Details of the physical description of the thaw depressions and thaw lakes are not presented here, but can be found in the various references. Little information is new. However, a complete listing of the more important, widely scattered, more recent literature is attempted. Papers with simple reference to phenomena without new description or discussion are not listed unless needed to follow the trend of the times.

Thaw depressions are discussed after short sections provide an historical perspective, a statement of some principles, and a review of the ice content of permafrost. Thaw lakes arbitrarily are under a separate heading, and the oriented lakes of northern Alaska and northwest Canada are emphasized because they have been studied more than any others. The relationship of vegetation to thaw depressions, the thermal aspects of thaw lakes, and other limnological aspects follow. Suggestions for future study terminate this review.

HISTORICAL PERSPECTIVE

Prior to the introduction by Muller (1945) of the well-established Russian concepts of thermokarst, few papers in North America even mentioned the pitting of the surface by thaw of buried non-glacial ice. (In contrast concepts of the origin of kettles from thaw of buried glacial ice goes back more than a century — Whittlesey, 1860; White, 1964). Muller (1945, p. 84) listed the most common land forms produced: (1) surface cracks, (2) cave-ins and funnels, (3) sinks, saucers, and shallow depressions, (4) „valleys", gullies, ravines, and sag basins, and (5) cave-in lakes, windows, and sag-ponds. In the next few years other personnel of the U.S. Geological Survey working in Alaska contributed the results of various studies of Alaskan thermokarst features (Cabot, 1947; Wallace, 1948; Hopkins, 1949; Black and Barksdale, 1949).

In the 1950's the Geological Survey personnel continued to study thermokarst phenomena, but interest had spread to university personnel and others throughout arctic North America. The literature expanded many fold. Now most regional studies of unconsolidated sediments in permafrost areas at least mention the thaw depressions and thaw lakes present (e.g., Fernald, 1964). The orientation of the thaw lakes of the Arctic Coastal Plain became the subject of considerable discussion. Case histories of the thermal regime of a few arctic lakes were compiled. Summaries of certain aspects of the thaw lakes have appeared, but no definitive monograph of the thaw depressions and thaw lakes has been attempted. Clearly some thaw lakes span considerable time, but the distribution and history of the lakes in various places are imperfectly known. Dating of events and physical, biological, and chemical limnological studies are largely in formative stages. We are still in a data-gathering period, but time is ripe to bring the various approaches together.

SYNOPSIS OF PRINCIPLES

During the freezing of unconsolidated materials to make permafrost, water is attracted to the freezing surface. Water commonly fills all pores with ice, when it freezes, and also segregates onto growing ice crystals to form all sizes of irregular masses, veinlets, and dikelets of relatively clean ice, depending on various combinations of factors like size and shape of pores, texture, amount of water, and rate of freezing. The numerous laboratory experiments and discussions of the freezing process need not be reviewed here. Suffice it to say that the upper 5 to 10 meters of permafrost, where fine-grain materials are present, commonly contain 30 to 90 percent of ice by volume. The permafrost is supersaturated, i.e., the mineral and organic matter are a suspension in ice.

After permafrost has developed, ice can be added to the upper few meters of the ground by the growth of ice wedges in polygonal networks. As the moisture comes year by year from the atmosphere, such growth ultimately can replace all mineral matter with ice. Hence, the originally supersaturated permafrost can continue theoretically to increase its ice content up to 100 percent in the upper 10 m, the maximum depth of penetration of most ice wedges. No area with that much ice is known, probably because thaw is initiated which brings on thaw depressions that destroy the ice-wedge system. When ground is once again exposed, new ice wedges must grow to start the cycle again.

Supersaturated permafrost is unstable when exposed to solar radiation and warm air and water during the summer. It melts.

The resulting liquid "sludge" has low viscosity. It flows readily or the water can drain and evaporate away. As a consequence, the thawed grounds has less volume, and commonly a much smaller fraction of the volume, than the permafrost from which it was derived. Underground cavities and surface depressions result. Thaw continues as long as the ice can gain enough heat during the summer to raise its temperature to the melting point and overcome the latent heat of fusion. Organic matter and the soil "waste" from the thawed permafrost may thicken sufficiently to prevent the ice from gaining enough heat during the summer to melt. The growth of the cavity or depression then ceases. If water is trapped in the depression, of course, a small pond forms which can continue to grow into a lake. To form large thaw depressions and large thaw lakes the permafrost requires a paucity of mineral matter. Otherwise the remaining ice in the ground is quickly covered and protected from further thaw.

This overly simplified outline underlies our concept of the formation of thaw depressions and thaw lakes. The process can be looked upon as a simple heat budget. Stability of the permafrost requires that a negative temperature balance be maintained between the winter's heat loss and the summer's heat gain. The total heat exchange is not the problem, it is the summer gain of heat to the ground. A large winter heat loss may be compensated for by a greater summer heat gain so thawing is initiated just as easily as in a situation wherein a small winter heat loss is compensated for by only a slightly larger summer heat gain. The thermal balance is, of course, more easily upset where the annual temperature approaches the melting point.

Thaw of permafrost can start a depression in almost any climate, including the high Arctic. The nature and thickness of the active layer and the characteristics of the vegetal cover largely determine the heat flow and the stability of the underlying permafrost. Without protection ice thaws during a brief interval in summer even in extreme northern North América. Less protection is needed than in areas further south in warmer climates. Disruption of the vegetal mat or active layer by gravity movements, wind or water work, or even animals is commonly sufficient to induce thaw. The thaw continues until an insulating blanket of material is reestablished or until the supersaturated permafrost is destroyed.

ICE CONTENT OF PERMAFROST

In 1949—1950 Black measured the percentage of moisture by weight in 36 samples of permafrost, excluding ice wedges, from the Barrow area of northern Alaska. It ranged from 9.6 percent in clayey-silty-sand to 91 percent in peat. Deposits of gravel and sandy gravel were supersaturated when the ice content was 16 to 18 percent by weight. Deposits of sand were supersaturated with about 10 percent or more of moisture by weight — the samples contained from 9 to 40 percent. Deposits of silt were supersaturated with 13 percent or more moisture by weight — they contained from 13 to 65 percent. Deposits of silt, clayey silt, silty peat, and peat contained the most moisture, generally between 75 and 91 percent, not counting the massive ice in ice wedges.

The volume of ice-wedge ice present in local natural exposures in various places through Alaska was estimated. In northern Alaska the oldest areas contain ice wedges averaging about 5 m wide and comprising locally 50 percent of the upper 6 m of the ground. Such places are rare. Wedges 1 to 3 m wide and comprising 10 to 30 percent of the upper 6 m are more common. Many areas have even less. Total volume of ice in the upper 10 m of ground in most parts of the coastal plain is sufficient to produce thaw depression 3 to 6 m deep and locally even deeper.

Hussey and Michelson (1966) cite moisture contents of the permafrost at Barrow, both laterally and vertically, for (1) initial surface, (2) ancient drained-lake basin, (3) recent drained-lake basin, and (4) present lake bed. In the upper 6 m of permafrost the ground ice content is considerably less for the ancient drained-lake basins and recent drained-lake basins than for that of the initial surface residual. Average potential settlement as a percent of the 6 m was calculated as 55, 19, 12, and 2 respectively for the four areas listed above. Thus, it was concluded that most depressions could have formed by thaw of the permafrost.

On the assumption that the lake basins in northern Alaska are the result of thaw of ground ice, Livingstone, Bryan, and Leahy (1958) used the volume of the water and air in a basin to compute the volume of ice that must have melted. Their value of 68 percent for a total basin depth of 28 m is more than double that for any area of comparable depth in northern Alaska seen by the writer, and if true, must involve special conditions. Ice wedges normally do not grow to depths of more than 6—10 m so a special mechanism or unusual freezing conditions with abundant water must have been available during the formation of the deeper permafrost. Only the upper 5—10 m of permafrost has such high content of ice.

Ice content of permafrost has been measured in many areas for engineering purposes and is expressed as percent of ice to dry soil on a weight basis. For example, Pihlainen and Johnston (1954, fig. 10) at Aklavik, N.W.T., Canada, in the delta of the Mackenzie River, plotted the moisture content of 153 samples from 16 bore holes against depth. These showed in general, but with wide variations, a decrease in ice from the surface to a depth of 3 m and a relatively constant value from 3 m to 8 m of 54 percent. In the same delta area Mackay (1966) describes one section about 7 m high in which ice makes up almost 80 percent of the total volume of material, but other areas had much less. At Fort Simpson, N.W.T., on an island at the junction of the Liard and Mackenzie Rivers, permafrost was encountered in 20 of 30 bore holes, at depths of 1 to 6 meters (Pihlainen, 1961). Ice in 101 samples was considerably less than in permafrost at Aklavik. The number and distribution of thaw depressions in the Arctic seem to reflect the variation of ice content of the permafrost.

THAW DEPRESSIONS

Irregular hummocky topography associated with ice-wedge polygons has long been recognized, but earlier concepts considered only primary bulging upward by growth of ice rather than settling by thaw of the ground ice (Leffingwell, 1919, p. 211—212). Rockie (1942) seems to have been first to discuss specifically and in some detail the pitting and settling of ground in central Alaska caused by thaw of ice wedges. Péwé (1954) followed up Rockie's study, adding considerable detail in description and genesis of the phenomena. Péwé cited pertinent literature (not here listed to save space) and gave discrete definitions of the terms involved. Thermokarst mounds and pits in areas cleared for agriculture were given special attention. It is clear that the mounds are the centers of former ice-wedge polygons left by the destruction of the ice wedges. The pits are in cultivated or formerly cultivated fields near the boundary between permafrost-free slopes and slopes underlain by large ice masses. Permafrost in thin isolated masses and the low water table, 5 to 30 m below the surface, localized the pits. Water from melting ice and surface water funneled down from above and circulated freely through the passageways in loess, on its way to the water table. Where the water table is close to the surface, cave-in lakes form. Cavities probably formed within 3 years, and pits appeared within 3 to 30 years after clearing.

In Seward Peninsula, Alaska, Hopkins (1949) described thaw depressions, small thaw lakes that occupied some of those depressions, and thaw sinks which seem to have evolved when thaw lakes pierced the permafrost and drained into subterranean openings. The depressions are started by locally deep thaw resulting from (1) disruption of the vegetal cover by frost heaving, (2) accelerated thaw beneath pools occupying intersections of ice-wedge polygons, and (3) accelerated thaw beneath pools in small streams.

Anderson and Hussey (1963) reviewed the literature of thermokarst phenomena and, among others, discussed thermokarst ravines, beaded streams, and ice-wedge intersection ponds in northern Alaska. Most of the features are related to the thaw of ice wedges. However, "badlands" topography with maximum relief of 65 m surely cannot be attributed to melting of ice wedges alone, as seems to be implied. Anderson and Hussey conclude that thermokarst development is the major denudation process operating on the North Slope of Alaska. This, if true, must surely be a very recent and temporary condition because the destruction of ice wedges once started proceeds rapidly to depressions. Once the supersaturated permafrost is destroyed, it must be rebuilt before thaw and collapse can reoccur. This takes several thousand years.

THAW LAKES

Thaw depressions grade into thaw ponds and thaw lakes, and the distinctions, largely arbitrary, are based on the size of the basin and the amount of water present. A basin many meters in extent is generally needed for current and wave action to become a factor in shaping the basin. Texture and ice content of the material, vegetation, climatic factors, and others determine the rate of thaw and shape of the depressions.

Of the initial group from the U.S. Geological Survey who were introduced to permafrost phenomena under Siemon W. Muller, Wallace (1948) deserves credit for publication of the first specific field study of cave-in or thaw lakes. In eastern Alaska he found from tree-ring counts that bank recession was 6 to 19 cm per year. A sequence of development divided into four stages was recognized, based on the size and shape of the thaw depressions — from youth to old age. Hopkins (1949) followed shortly thereafter with his study of thaw lakes on Seward Peninsula. The largest thaw depressions are occupied by lakes which rarely exceed 300 m in diameter and are 0.3 to 2 m deep. Gullies cut into the lake banks mark the positions of ice wedges rapidly melted. More than one cycle of thaw lakes was noted. The thaw depressions, lakes, and sinks are recorded by maps and photographs. An idealized cycle is shown.

Ice-cored mounds of various sizes are produced in the active layer and in permafrost throughout the Arctic (Bird, 1967, p. 201—208; Mackay, 1966; Holmes, Foster and Hopkins, 1966). On thawing many produce thaw depressions and thaw lakes. During initial destruction of the mounds, it is relatively easy to recognize the nature of the source of the ice, but once entirely melted out, this is rarely possible. Most active layer phenomena are less than a few meters in diameter and only some centimeters to a meter deep. In tundra the thaw depressions may be dry, but ice laccoliths in marshy areas commonly produce small circular ponds. They are especially common in marshy lake beds in the Arctic Coastal Plain of northern Alaska. Most survive only a few years.

The large permafrost mounds, generally called pingos, are commonly many tens of meters in diameter and several tens of meters high. They range in age from some decades to many thousands of years. On thawing they can produce lakes. Only one pingo lake has been studied in detail (Likens and Johnson, 1966). It is 205 m long, 165 m wide, and 8.8 m deep. As the pingo is the open system type, whereby ground water is continuously supplied to the lake, its chemistry reflects the source of the water. The lake is chemically stratified and unusually high in strontium and lithium. Its age is less than 5720 radiocarbon years, and may be as recent as a few hundred years (Krinsley, 1965).

ORIENTED LAKES OF NORTHERN ALASKA AND NORTHWEST CANADA

In 1946 Black and Barksdale (1949) jointly studied the oriented thaw lakes of northern Alaska and completed a paper which Black presented orally on January 22, 1947. That paper was published without incorporation of later literature or of data from studies by Black in 1947—1950. Most of the lakes were considered to be true thaw lakes. Some resulted from the uplift and segmentation of lagoons, and the origin of others was not known. Later studies by Black, by Carson and Hussey (1962), and by Hussey and Michelson (1966) confirmed that sufficient ice was in the upper part of permafrost to form the lake basins less than about 5 m deep; Black doubts that sufficient ice is present to permit the lakes many tens of meters deep to form by simple thaw. In the first place, the unconsolidated sediments of the Gubic Formation (Black, 1964) are too thin over most of the Arctic Coastal Plain to permit such collapse unless they are essentially solid ice. Although the units of the Gubic Formation do not all have the same ice content, none is solid ice. Exposures up to 40 m of caving banks of lakes and streams do not show such large amounts of ice in the lower parts. Moreover, the underlying bedrock is commonly saturated, but not supersaturated with ice, and does not collapse when thawed. Thaw of ice can account for only a part of the depth of some deep lake basins — particularly those near the southern margin of the Coastal Plain.

The large number of oriented lakes and their extension into Arctic Canada has been documented by other studies (Bird, 1967, p. 211—216). These also seem to confirm the initial description by Black and Barksdale (1949) of the physical features of the lakes. The major concern has been with the possible cause of the orientation of the basins. The initial thought that the orientation was by wind oriented at right angles to that of today is disputed by all who have dealt with the problem (Anderson and Hussey, 1963; Carson and Hussey, 1959, 1960a, 1960b, 1962; Hussey and Michelson, 1966; Livingstone, 1954, 1963; Mackay, 1956, 1963; Price, 1963, 1968; Rex, 1961, Rosenfeld and Hussey, 1958).

Livingstone (1954) first called attention to a possible mechanism whereby currents account for the elongation of the lakes at right angles to the present winds. Rosenfeld and Hussey

(1958) point out rightly that the problem is more complicated than the simplified approach of Livingstone, and that his hypothesis cannot apply equally to those lakes only a few meters long or many kilometers long. They point to the possibility of fault and joint patterns controlling the orientation. It should also be mentioned that the Livingstone's hypothesis cannot be applied equally to these very shallow lakes and those with a deep central elongate basin.

Carson and Hussey (1959) reviewed five possible hypotheses for the lake orientation and concluded that each alone was not enough, but that a composite would suffice. The five are: (1) wave action from winds parallel to elongation during earlier time, (2) present winds which produce wave-current systems which scour at right angles, (3) present winds which distribute sediment on east and west shores, insulating them from thaw, (4) orientation produced by thaw during maximum insolation at noon, and (5) lakes controlled by north-south trending ice wedges which formed in the north-south components of a right-angle fracture system. They conclude that oriented ice-wedges might develop in the fracture system; that maximum insolation would be more effective in melting the north-south trending wedges than the complementary set; that the depressions so oriented would be perpetuated and enlarged by thaw and wind (wave) oriented sediments deposited on the east-west shores. Carlson, *et al.*, (1959) also suggest that preferentially oriented ice wedges play a role in the orientation of the lakes.

Carson and Hussey (1960a) reviewed the hypothesis of Livingstone (1954) and an unpublished one by R. W. Rex and then presented some current measurements from lakes near Barrow, Alaska. Their field data suggest Livingstone's hypothesis is not applicable, but that the approach of Rex merits further study. Carson and Hussey (1960b) provide additional data on the hydrodynamics in three of the lakes near Barrow, including conditions when the lakes are ice free and when an ice cake is present. Their measurements show that erosion is going on at the ends of the elongated lakes by long-shore currents as predicted by the hypothesis later published by Rex (1961). In an important summary paper Carson and Hussey (1962) bring together their field data on the lakes near Barrow in support of the circulation hypothesis of Rex (1961) and reject their earlier postulations of structural control by ice wedges. They point out that circulation in the smallest oriented ponds resembles that suggested by Livingstone (1954), but is too slow to erode. However, wave action on lee sides of those ponds is sufficient to erode. As lakes increase in size, a gradual change in circulation systems was observed by Carson and Hussey (1962), approaching that of the hypothesis of Rex (1961).

Rex's hypothesis is inadequate to account for the orientation of small basins, and also according to Carson and Hussey (1962), for the lack of erosive currents at the ends until after the basin is elongated. They develop briefly the concept of lake-basin orientation as an expression of a basin morphology controlled through interaction of slow basin subsidence by thaw and wind-oriented wave action. "These combine to produce a preferred pattern of morphology through all phases of basin development, with orientation accentuated during later stages by other processes, chiefly thermal and circulatory". Variations in natural conditions are considered to be instrumental in affecting changes in the shapes and depths of the lakes. Coalescence of lakes particularly leads to complex forms. The wind-resultant problem was raised by Price (1963), but Carson and Hussey (1963) concluded it would not change materially their earlier conclusions.

Mackay (1963, p. 51—55) attempted to analyze the equilibrium forms of lakes that might be produced by winds of today. "If it is assumed that winds from each of the 16 compass directions recorded in climatic records tend to develop curved bays, approximately cycloidal, than an oriented lake may be viewed as the summation or integration form of 16 cycloids, each of different size." He assumed that the diameter of the generating circle of the cycloid is equal to the resultant for a given wind direction. The computed shapes and actual shapes of lakes from the Mackenzie Delta and the Barrow, Alaska, regions agreed nicely. However, Mackay emphasized that the precise mechanism of lake orientation remains unexplained.

Mackay (1963, p. 44) also writes of a "ribbed pattern of north-east-southwest trending ridges in hundreds of large shallow lakes of the Mackenzie Delta. The sedgy ridges are minor features, 30 cm or so in height and several hundred to a thousand meters long. The ribs are perpendicular to prevailing winds and are believed to be formed primarily by wave action.

Mackay (1963, p. 47—50) categorized the shapes of the lakes and their central deeper basins into precise geometric forms in four categories: (1) lemniscate, (2) oval, (3) triangle, and (4) ellipse. Equations were set up for each.

Bird (1967, p. 210—216) most recently has summarized the occurrence of thermokarst and thaw lakes in Canada, including the oriented lakes. Price (1968) most recently reviewed the entire subject of oriented lakes, regardless of origin of the initial lake basin. Few originated as true thaw lakes, but they may be equally well oriented (e.g. Plafker, 1964). Photo interpretation of thaw lakes is summarized by Hopkins, Karlstrom, and others (1955).

A photographic map of the Barrow, Alaska, area on a scale of 1 : 25,000 has a 1-meter contour interval and local 1/2-meter contours (Brown and Johnson, 1966). The thaw lakes are portrayed beautifully. Cross-cutting age relationship of lake basins is brought out clearly by the omnipresent ice-wedge polygons. Maps showing lake basins of different ages are included in Carlson, *et al.* (1959) and Carson and Hussey (1960 and 1962). Other views and a summary of the lakes are given by Wahrhaftig (1965).

Dating of the oriented lakes has been a particularly difficult problem. Livingstone, Bryan, and Leahy (1958) by tree-ring dating showed that the gentle shore of one oriented thaw lake was exposed during the last 150 years. All observers of the lakes have witnessed shore erosion of several meters during single storms. Lateral migration can be very rapid. The truncation of existing ice wedges by lateral migration demonstrates that some lakes or parts of them must be only some decades or a few centuries in age. Radiocarbon dating of organic matter in two drained lakes suggests ages of several thousand years (Brown, 1965, p. 44—45). Other dates suggest most surface features near Barrow are not older than about 8,000 years, yet several older dates imply complicated events going back much farther. At 14,000 radiocarbon years ago pollen analysis shows vegetation that reflects climate somewhat colder than now (Colinvaux, 1964, 1965). The Pleistocene—Recent changes of sea and of climate that affected the permafrost and thaw lakes of the Arctic Coastal Plain in western and northern Alaska are reviewed fully by Hopkins (1967).

VEGETATION AND THAW DEPRESSIONS AND THAW LAKES

Collections and classification of vegetation associated with thaw depressions and thaw lakes have been made since the early 1800's in North America, although not until recently identified specifically with those features. Spetzman (1959) from 1946 to 1951 set up six major plant communities in the tundra of northern Alaska and mapped the vegetation in the vicinity of Barrow, Alaska. Wiggins and Thomas (1962) compiled the most complete report of the flora of northern Alaska from their work during the 1950's. Britton (1957) reviewed the vegetation of the Arctic tundra and included a brief outline of a "thaw lake cycle". The age of the tundra surfaces is related to the time of emergence of the coastal plain from the sea, but more importantly to the reworking of the surface by repetitive thawing of ground ice. The colonization of the drained lake basins and development of the tundra vegetation is mentioned.

Drury (1956) builds on unpublished field studies of Troy L. Péwé and presents a detailed analysis of the bogs in central Alaska. The relatively little publicized alluvial flats have amazing concentrations of treeless bogs and small ponds cutting into small islands and peninsulas of forests. Many, but not all, bogs and ponds result from thaw of ground ice. Depressions up to 5 m are common in the Upper Kuskokwim River Valley. Thawing seems to start from many centers to produce the anastomosing bogs. Active caving and collapse of trees into the ponds is widespread. Idealized cycles are presented and related to successional sequences of the vegetation. Maps and photographs of the plant communities show typical examples. Drury also speculates on the nature of the periglacial vegetation in eastern United States, using the associations from central Alaska as a guide. Drury, however, was not aware of the alleged periglacial frost-thaw bassins in New Jersey (Wolfe, 1953) which have yet to be substantiated. Brunnschweiler (1962, fig. 1) shows thermokarst on the Atlantic Coastal Plain from the glacial border south into Georgia. These are the Carolina Bays which are not accepted as periglacial phenomena, nor can they be accepted as pits resulting from the melting out of icebergs as proposed by Drabbe (1952?).

THERMAL ASPECTS OF THAW LAKES

MacCarthy (1952) showed that near Barrow, Alaska, the 0°C isogeotherm increases in depth as the distance from a large body of water (ocean or lakes) increases. Brewer (1958a) gives thermal profiles beneath two lakes in northern Alaska and concludes that lakes having a diameter of about 900 m or more and a depth of at least 2 m may be expected to have unfrozen basins beneath them to a depth of 60 m or more. Brewer (1958b) provides the first detailed description of the thermal regime of a thaw lake in North America. The lake, at Barrow, Alaska, is typical of the oriented lakes. The water, a maximum of 3 m deep, is in an essentially isothermal state during the ice-free period that lasts from late June until September. A peak temperature of 12°C was reached one summer. Ice accumulates up to 2 m thick in winter. The thawed basin below the lake is 58 m deep. Other lakes in the vicinity have similar thermal regimes. Clearly the bulk of incoming heat in summer is used to melt ice from the previous winter.

Livingstone, Bryan, and Leahy (1953) quantified the effects of the arctic environment on the origin and development of the northern Alaska lakes. Some lakes are glacial in origin and others are true thaw lakes. The morphology of the lakes in part was used to distinguish thaw lakes from kettle lakes. None of the arctic lakes examined showed summer stratification. Only a quarter of the annual heat budget was wind distributed. Heat flows to the underlying ground in all those lakes too deep to freeze to the bottom.

Johnston and Brown, (1964, 1966) show the distribution and temperature of permafrost around a small thaw lake in the Mackenzie Delta, N.W.T., Canada. The circular lake with a maximum depth of 1.5 m and a diameter of 275 m has thawed through the permafrost in the alluvium 70 m thick to bedrock and warms the adjacent permafrost. With the observed data, Brown, Johnston, and Brown (1964) used an electronic computer to estimate the thermal regime under and around the lake.

None of the above studies report or suggest the formation of bottom ice such as has been found in other arctic lakes (Nichols, 1967; Schaefer, 1950).

OTHER LIMNOLOGICAL ASPECTS OF THAW LAKES

No attempt is made here to cover the various physical, chemical, and biological aspects of the thaw lakes. An excellent summary for arctic North America was prepared by Livingstone, Bryan, and Leahy (1958). Very few chemical or biological studies have or need to be concerned whether the particular lake studied is a true thaw lake or a kettle lake, but exceptions occur, e.g., Likens and Johnson (1966), because of posssible groundwater influx. Salt spray and influx of sea water modify some lakes rapidly (Boyd, 1959). Even in the permafrost environment solution of the soil materials into drainage waters takes place (Brown, Grant, Ugolini, and Tedrow, 1962).

Perhaps more importantly the paleolimnological aspects of thaw lakes are least likely to be amenable to easy solution (Livingstone, Bryan and Leahy, 1958). Collapse and reworking of the thawed permafrost into a thaw lake precludes the use of many standardized techniques of stratigraphic study of lake-bottom sediments. Dating of the deposits of organic material is subject to gross errors because of incorporation of transported organic matter, and ecologic inferences of fauna and flora are likewise. Especially in the oriented lake area, where one lake is migrating into the basin of another, two and more sequences of lake sediments can be superposed with little detectable break between to distinguish them.

SUGGESTIONS FOR FUTURE STUDY

Livingstone (1963) presented an "outlook" for limnological studies in permafrost regions in North America. This writer agrees that descriptive aspects must be covered more thoroughly. Even the current distribution of thaw depressions and thaw lakes in North America is very poorly known. No single map of their distribution is yet available. The distribution maps of such forms in Canada are very small scale (Bird, 1967). No one has attempted to compile a map of fossil forms in North America. Thousands of drained-lake basins are recognized in northern Alaska by their surficial expression and their characteristic sediments, yet economic incentive to map them is lacking. A rare fossil pingo lake or thaw depression is recognized; presumbly hundreds exist.

Mackay (1963, p. 54—55) states "...the precise mechanism of lake orientation remains unexplained. The amount of littoral transport, the aspect of two-cell circulation, the possibility of thermal effects in a permafrost region, the preference for vegetation growth under favored micro-climatic and topographic conditions, and the effect of lake ice on lake orientation need further study." This writer agrees that more data are needed in the study of lake orientation. At present it is difficult to distinguish between cause and effect in circulation patterns of the lakes. Too few data on wave and current effects on thaw versus transportation and deposition of sediment are in hand, and these are largely restricted to the elongate lakes of the Barrow area.

The subaqeous shelves are a particular problem because we do not know how much is cut and how much is fill. Some lakes clearly are developing shallow shelves by truncation of ice wedges and adjacent permafrost — they are erosional rather than depositional features as called for in most hypotheses.

The transition from small oriented ponds to lakes many kilometers in size still seems hypothetical. The circulation differences in lakes, long and narrow, triangular, ellipsoidal, rounded, and irregular are yet to be recorded. Waves and currents work differently in lakes uniformily less than 1 m deep than those with central basins or 2 m deep. Which came first? — the central basin or the shallow shelves?

How old are the various thaw features? Some small pits grow in 1 to 3 years; some present lakes must be several thousands of years old, and much older buried lacustrine sediments overlie truncated roots of buried ice wedges near Barrow. Few dates are available, and their significance equivocal.

The thermal budget of few thaw lakes is approximated. Fortunately principals from temperate lakes are applicable particularly in those lakes which lie in thawed basins in permafrost. Similarly, most chemical and biological aspects of the thaw lakes are affected more by climate and surroundings than by the nature of the origin of the lakes.

The history of the thaw lakes is perhaps the least known and among the most intriguing aspects yet to be deciphered. Paleolimnologic studies of thaw lakes hardly have been started. Where possible they should follow parallel studies in adjacent lakes of other origin than thaw of ground ice.

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Carson, Charles E., 1968 — Radiocarbon dating of lacustrine strands in arctic Alaska. *Arctic*, vol. 21; p. 12—26.

Carson concluded that transgressive expansion of the lakes reached a maximum between 4,000 and 8,000 years ago.