Permafrost Features under Arctic Lakes, District of Keewatin, Northwest Territories

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In the District of Keewatin, west of Hudson Bay, numerous shallow lakes occupy depressions on the perennially frozen, glaciated terrain north of the treeline. Many lakes in the vicinity of Kaminak Lake have extensive shallow areas that are characterized by features of probable periglacial origin. Some features, such as polygonal patterns, frost-heaved boulders, and mudboils, are similar to those of the subaerial landscape.

Digitate, cobble-covered ribs and boulder-filled troughs that commonly form a crenulate pattern on the shallow shelves adjacent to till-covered shores are thought to be the subaqueous equivalents of mudboils that are common on the adjacent till plains. They are composed of till and are underlain by an undulating frost surface that is raised beneath troughs and depressed under ribs.

Holes with or without raised rims often occur singly or in clusters on loose, sandy silt bottoms in water depths less than 2.5 m. A frost table underlies the bottoms of these holes at depths of 30 to 50 cm in early August. Holes may be either sites of strudel scour or sites of final points of attachment of winter ice to the frost table, just before the buoyancy of the ice caused it to break free from the bottom in the spring, extracting frozen sediment from the surrounding unfrozen sediment, leaving a hole.

The features described are restricted to water depths that are probably equivalent to the average maximum thickness of winter ice. Thus, they represent areas where the lake is seasonally frozen to the bottom, and may be restricted to portions of lake basins underlain by perennially frozen ground.

Introduction

The glaciated surface of the Canadian Shield is underlain by deep, continuous permafrost west of Hudson Bay. North of the treeline, where the surface thaws to depths of only 15 to 200 cm during the summer, many lakes lie in glacially scoured bedrock basins or in basins dammed by glacial sediments or raised nearshore marine
sediments. Patterned ground, consisting mostly of ice-wedge polygons and mudboils (nonsorted circles), is characteristic of terrain between lakes. Distinct types of patterned ground also occur in the shoal areas of lakes of all sizes. The purpose of this paper is to point out the existence of these subaqueous patterns and to suggest that they may be related to permafrost that has been found in the shoal areas of many lakes. If the periglacial nature of the patterns can be demonstrated, they may prove to be a useful tool for mapping the areal extent of shallow, perennially frozen sediments in eastern arctic lake basins.

**Location and Climate**

The features described in this report are common between Chesterfield Inlet and the treeline (Fig. 1). Similar sublacustrine patterns are also common above marine limit and have been observed on low altitude air photographs of areas near Contwoyto Lake in the western part of the Shield. A. N. Boydell and J. Terasmae (pers. comm. 1974) report that similar features are present on the Boothia Peninsula and in northern Quebec, respectively.

Detailed observations were made in the Kaminak Lake area (Fig. 1). Kaminak Lake is located near the 'cold pole' of continental North America (Ahrensbrak 1968), an area where mean January temperatures range from a high of \(-29^\circ\text{C}\) to a low of \(-36^\circ\text{C}\). Total precipitation averages only about 20 cm per year. Lake levels are generally highest in June, during spring runoff, and drop 0.5 to 1.0 m over the summer. Freeze-up occurs when lakes are near their lowest stages, and water depths cited for patterns described in this paper are approximately those of the low water stage. In the Kaminak area, freeze-up usually occurs in early to mid-October (McFadden 1965) and ice thicknesses attain their maximum of about 2.0 m \pm\ in the period from late March to mid-May (Billello 1961). Ice break-up usually occurs during the first week in July. Lake water temperatures in 1973 ranged from 14 to 18°C from July 10 to August 20, the period of observation. These temperatures were relatively constant to water depths of about 12 m in all sizes of lakes (Klassen et al. 1974), but are considered to be exceptionally warm because of an abnormally warm summer (75% of the days had maximum temperatures in excess of 21°C).

**Glaciation and Glacial Sediments**

The Kaminak Lake area lies southeast of the Keewatin ice divide (Lee et al. 1957) and can be described as a gently rolling till plain with varying amounts of outcrop of Precambrian intrusive, extrusive and metasedimentary rock types. The till plain was flooded up to altitudes of about 170 m (560 ft) a.s.l. by the Tyrrell Sea (Lee 1960), but marine sediment deposited during this episode is common only below altitudes of about 60 m (200 ft) a.s.l. Esker and other ice-contact gravel deposits, and marine nearshore sand and gravel deposits are scattered over the till plain.

The surface till was deposited by ice flowing east to southeast, as evidenced by fluted till plains, striations, roches moutonées, indicator trains, and ribbed moraine (Ridler and Shilts 1974). Till in the vicinity of Kaminak Lake is red due to its content of red clasts and finely divided hematite derived from Precambrian red beds (Dubawnt Group) that crop out in the lower reaches of Kazan River, west and northwest of the study area (Wright 1967). Red till tends to lose the finely divided hematite when physically modified by water or frost-sorting processes, becoming grey. Active-layer structures stand out as a result of the color contrast between red, relatively unmodified till and physically modified grey till.

The physical properties of till and associated or derived glacial and postglacial sediments reflect the crystalline texture of the Precambrian bedrock. In the Kaminak area as well as elsewhere on the Canadian Shield, till is sandy with a moderate silt and low clay content. This texture causes tills to have very low liquid limits (10–20%) and very low plasticity indices (0–10%) (see Shilts 1974a). With these low limits, till in the active layer is very fluid during the thaw season and flows readily in response to slight increases in hydrostatic or cryostatic pressures.

**Previous Studies**

Very few studies of patterned ground in the subaqueous environment are known to the authors. Mackay (1958, p. 51; 1967) described sublacustrine frost cracks and stone circles, and studied other patterns similar in many respects to those described in this paper. In artificially drained lakes on Gary Island (north of the Mackenzie River delta), he noted sorted circles.
and stripes formed in stony mud in protected bays with water depths of less than 1 m. The circles consisted of a one-stone-thick cover over stony, silty clay surrounded by boulder-filled depressions. The stones in the centers looked as if they had been pressed down into the underlying mud. Although he did not reach any specific conclusions as to their genesis, he observed: (1) that they were similar in form to subaerial features, (2) that the lake bottom underwent a frost heave of several inches during winter, (3) that an area from which all stones had been removed
during one summer was again covered by stones, apparently frost-heaved to the surface, the next summer, (4) that these features must have formed in the subaqueous environment and not subaerially during a shoal phase of the lake, and (5) that permafrost was present under the shoal areas of the lakes.

Sublacustrine Patterns

Polygonal patterns, rib-and-trough structures, and single or clustered shallow holes with raised rims have been observed in water depths of less than ca. 2 m during the summers of 1970, 1971, and 1973. Permafrost is thought to be necessary to form ice-wedge polygons, and has been found at shallow depths beneath the rib-and-trough structures and shallow holes. Discussion of the general characteristics of the three types of patterns is based on low-altitude aerial photography, aerial observation, and on data from several excavations, probes and shallow dives made during the summer of 1973.

Polygonal Patterns

Subaqueous polygonal patterns (Fig. 2), similar to subaerial ice-wedge polygons, have occasionally been observed in the sandy shallow portions of lakes. They appear to have formed beneath the lakes because recent rises in lake levels are rare or they occur in sites of active sedimentation. None of these areas of subaqueous polygons was probed to test for the presence of permafrost, but, because of their similarity to subaerial polygons, they are considered by the authors to prove, where present, the extension of a shallow permafrost table beneath lakes.

Rib-and-Trough Patterns

Rib-and-trough patterns are by far the most common shallow-water features in lakes in southeastern Keewatin. This pattern forms a fringe of varying width along much of the shoreline and around many of the islands of most lakes. The rib-and-trough pattern (Figs. 3, 4, 5, 6, 7, 9) consists of a series of 2 to 3 m wide, cobble and boulder-covered ridges that stand 0.5 to 1 m above intervening 2 to 3 m wide troughs. Troughs are commonly filled with boulders larger than 50 cm in diameter. Near shore, the ribs usually trend at right angles to the shoreline, or directly down the steepest slope of the lake bottom. They occur at regular intervals with spacings from ridge crest to ridge crest of 4 to 6 m. Offshore, the ribs may bifurcate, turn obliquely or parallel to the slope or pass into individual, cobble-covered lumps surrounded by boulder-filled depressions (Fig. 6). Where ribs have been subaerially exposed by a permanent drop in lake level, they appear to have evolved into mudboils (Shilts 1974a, p. 229) or sorted circles (Washburn 1973, p. 108). Terrain adjacent to rib-and-trough patterns is usually a till plain. The patterns are rarely observed adjacent to the sandy, gravely sediment of eskers or raised nearshore marine sediments. They are also uncommon offshore from terrain containing ice-wedge polygons. Where excavated, both ribs and troughs were underlain largely by till, or by till modified by solifluction. The ribs are overlain by a one-clast-thick mantle of cobbles, and troughs are filled with a similar mantle of boulders (Fig. 7). As described by Mackay (1967, p. 37), the cobbles on the ribs appeared to be pressed into the underlying sediment. Near shore, where ribs are submerged to depths of less than 1 m, or where they are exposed during low water stages, the till is covered by 40 to 50 cm of well sorted, grey, medium to fine-grained sand, which is in turn overlain by cobbles or small boulders (Fig. 8). At two sites this sand covering was observed to be pierced by diapiric structures extending upward from the underlying red till. The sand appears to pinch out offshore so that portions of ribs lying more than about 1 m below the water surface consist of till directly covered by cobbles. Small, fresh-appearing mudboils were noted on the offshore portion of ribs. In some parts of Kaminak Lake, boulders in the troughs are partially or completely submerged by lacustrine silt or sand.

Excavations and probing to permafrost at several nearshore locations revealed that the frost table was undulating. Where probed, the frost table had a relief of 10 to 20 cm, rising...
slightly beneath troughs and being slightly depressed beneath ribs. Permafrost depths at the water's edge ranged from 60 to 140 cm below the rib-and-trough surface in early August 1973.

Rib-and-trough patterns have not been observed along portions of shoreline where the lake bottom has a steep slope. Although there seems to be a critical bottom slope beyond which these features do not form, no slope measurements have been made. The patterns have not been observed in the marine or estuarine environments of the present coast of Hudson Bay even.

Fig. 5. Rib-and-trough pattern on submerged drumlins, Kaminak Lake area. Drumlins are 100–200 m wide. Note mudboils on adjacent land surfaces (GSC #202653-G, portion of EMR Photo A19396-226).

Fig. 6. Irregular rib-and-trough pattern in small lake; photo from altitude of ca. 50 m (GSC #202653).

Fig. 7. Cobble-covered rib (foreground) and boulder-filled trough (background) in ca. 1.5 m water depth, Kaminak Lake. Boulders in trough average 50–60 cm diameter (GSC #202653-E).

Fig. 8. Excavation (40 cm deep) in sand cap of nearshore portion of rib. Note the armour of cobbles (GSC #202445-H).
though several tens of miles of marine shoreline were examined on low-altitude aerial photographs.

Sublacustrine Holes

Holes are circular (Fig. 9) to irregular (Fig. 10) in plan. They are 1 to 4 m wide, 0.3 to 1.3 m deep depressions with or without raised rims up to 0.6 m high. They occur singly or in clusters in very loose silty sand with contents of organic carbon from 0.5 to 1.5%. Holes appear to be restricted to water depths of less than 2 m and, where probed, are underlain by permafrost at 30 to 40 cm below their bottoms (ca. 140 cm below the general lake bottom surface). Thin layers often stand out as horizontal microledges on the walls due to differential erosion of sediment layers.

Where clusters of such holes occur, they appear to be of different ages. The walls of the most recent are grey in contrast to the yellow-brown oxidation color of the walls of older holes and of the general sediment surface. The bottoms of holes generally contain a thin mat of algal growth mixed with dark ferric hydroxide precipitate, which causes them to appear deeper than they really are when viewed from the air.

On the bottom of one hole, two small boulders, apparently frost heaved from below, were found covered by a thin cap of slightly disturbed bottom sediment with a surface oxidized to a depth of about 1 cm. Although small boulders were observed in some other holes, the sediment in which the holes are formed is generally boulder-free.

Some holes seem to have furrows extending offshore from one side (Fig. 11). These furrows fade out offshore and give the appearance of an object of about the same width as the hole dragging or excavating the soft bottom.

At one site on the Boothia Peninsula and at another near Kaminak Lake, very dense concentrations of holes were noted near the mouths of major inlet streams (Fig. 12). However, dense clusters of holes also occur in bays where no obvious surface drainage enters a lake.

Discussion

Of the three types of features described, only one, polygonal patterns, can be confidently associated with the presence of subaqueous permafrost. Permafrost has been found beneath rib-and-trough patterns and holes, but establishing a causal relationship between permafrost and genesis of these features is more difficult.

Rib-and-Trough Patterns

Rib-and-trough patterns are similar in many respects to mudboils or sorted circles, which usually occur on adjacent terrain. Both types of features are composed of till or other poorly sorted silty sediment with low liquid limit and low plasticity index; both are underlain by an undulating frost table; diapiric structures have been observed in both; and the rib-and-trough structure sometimes assumes the form of a sorted circle, a feature thought by the authors to be a form of mudboil. Because of these similarities and the common occurrence of the features side by side, we have inferred that the genesis of the rib-and-trough pattern must be similar in at least some respects to genesis of mudboils. Shilts (1974b, p. 545) has described the genesis of mudboils as follows: "Mudboils are round to elongate, 1- to 3-metre diameter, bare soil patches that form on till, marine silty clay, or colluvium, poorly sorted sediments (muds) with significant silt-clay content. Thawed muds with LL (liquid limit) <25% and M (natural moisture content)/LL near 1.0 form mudboils and associated solifluction features. When M/LL is slightly less than or equal to 1.0, rapid, liquid flow can be triggered by slight increases in moisture content or porewater pressure. During the thaw season, liquefied sediment is confined between a 1 to 2 metre deep frost table and a rigid desiccated or sandy surface layer. Artesian pressures proportional to the hydrostatic head between the top of a slope and any point on the slope cause the liquefied sediment to burst or boil to the surface at points of weakness in the surface layer, forming mudboils and associated mudflows. Cryo-

Fig. 9. Holes with raised rims on lakeward side of rib-and-trough pattern, Kaminak Lake area. Note that rib-and-trough pattern appears to pass into sorted circles in very shallow bays (GSC #202653-B, portion of EMR photo A19396-226).

Fig. 10. Irregular holes in small bay in Kaminak Lake. Diameter of holes about 3 m (GSC #202653-F).
static pressures during fall freezeup may accelerate the process”.

Build-up of cryostatic pressures during freezeup is thought to cause sublacustrine diapirc extrusion similar to that described for mudboils. When lake ice forms and freezes to the bottom, the frost table descends through the rib-and-trough structure, contacting the highest parts of the permafrost table (under the trough) first (Fig. 13). This creates an unfrozen cell in the core of the rib, similar to that depicted graphically by Schmertmann and Taylor (1965, pp. 53, 54, 62) for sorted circles. As the freezing front advances from the top, sides, and base of the ribs, water is driven in front of it into the unfrozen core. This increase in porewater pressure liquefies sediment in the core and builds up cryostatic pressures that cause the sediment to move toward areas where pressure can be released. The most likely place for pressure release, presumably accompanied by extrusion of the liquefied sediment, would be just lakeward or downslope from the contact of the lake ice with the bottom (Fig. 13). As lake ice thickens, this contact moves downslope and points of extrusion move with it until ice attains its maximum thickness of about two meters. Thus, the rib is a site of yearly sediment extrusion, which gives it its positive relief. The sediment that is extruded is replaced by similar sediment that enters the lake by solifluction from the active layer on shore.

The original irregularities in the sublacustrine permafrost table may have been caused by tongues of sediment entering the lake from mudboils, by varying thicknesses of lake ice caused by varying thicknesses of snow cover or drifting (Bilello 1961, p. 1), or by flooding of a surface with mudboils with their underlying, irregular permafrost table already developed. Thus, the regular rib spacing may be a function of the average spacing between mudboil centres, 4 to 6 m. Any such irregularities that occur at the shoreline at its freeze-up position would be perpetuated lakeward as rib formation progressed.

The hypotethsis advanced above for the formation of rib-and-trough patterns is probably oversimplified, but explains most of the observations made on these features to date. It does not explain ribs that do not trend downslope, the cobble-boulder cover, the nearshore cap of sand, and the evolution of ribs to sorted circles after prolonged subaerial exposure. Ribs trending obliquely to the apparent bottom slope may be the result either of shove by drifting lake ice that physically diverted sediment during their formation or of presently inexplicable topographic irregularities of the permafrost table. The cobble-boulder cover is undoubtedly formed by frost heaving (Mackay 1967, p. 37) and a combination of frost and water sorting of the frost-heaved clasts. The nearshore, sandy capping can probably be attributed to winnowing of fines by wave action combined with frost heaving of larger clasts to the surface. Since ribs owe their linearity largely to the progression of the lake-ice/bottom contact downslope, we assume that once subaerially exposed, they would evolve to the circular forms of genetically similar mudboils.

Holes

The holes that occur on sandy silty bottoms are difficult to relate to permafrost, but the observations that they seem to occur exclusively in water shallower than mean annual ice thickness and are underlain by permafrost suggest that permafrost may be essential to their formation. We have considered six hypotheses for the genesis of holes: (1) ice-rafted boulders dropped into soft sediment during spring break-up. This is
Fig. 13. Diagrammatic cross and longitudinal sections through rib-and-trough patterns illustrating hypothetical freezing fronts after ice cover is established on lake. Cryostatic pressures caused by excess water being driven into unfrozen core of rib are thought to cause extrusion of mud saturated to or above its liquid limit (10-18% for Kaminak area). Frost table depicted represents maximum depth of thawing during ice-free conditions. Sediment between frost table and bottom of lake ice or sand cap is till or other stony mud.

untenable because boulders are usually not found in the holes and holes are restricted by water depth; (2) partially buried boulders plucked from bottom by lake ice; boulders are only rarely observed in the sediment making this mechanism unlikely; (3) springs issuing from the lake bottom; the nature of the sediment and permafrost underlying the holes make this origin unlikely; (4) thermokarst depressions beneath the circular algal growths that are common on the lake bottoms. The configuration of the frost table, small size of the holes, and raised rims argue against this; (5) Strudel (Reimnitz and Bruder 1972; Reimnitz et al. 1974), or vortices caused by subaerial drainage over anchored ice pans, or by ice pans rising to the surface, causing water standing on the surface to be forced downward through holes or cracks in the ice. This process is common in the marine and estuarine environments of the western Arctic and seems to be a reasonable mechanism for forming holes. Although the vortex mechanism (strudel scour) might explain the round shape and raised rims of the holes, it does not totally explain their restriction to water depths of less than 2 m or their occurrence on a particular type of sediment. Boydell (pers. comm. 1974) reports typical strudel-like holes in lake ice on the Boothia Peninsula during break-up in 1974 (Fig. 14). He did not observe drainage passing through the ice holes and could not definitely relate the ice features to depressions in underlying sediment. Holes with angular or irregular shapes (Fig. 10) are difficult to explain by the scour mechanism. (6) Holes may be the last points of attachment where lake ice was anchored to the permafrost table during spring break-up. Frozen columns of sediment would have been plucked from the unfrozen sediment as the marginal shelf ice rose when buoyancy of the submerged ice exceeded the tensile strength of the shrinking points of attachment to permafrost. This hypothesis would explain the obvious removal of sediment from the hole, the grooves extending lakeward from some near-shore holes, which would be formed by the frozen sediment columns dragging through soft sediment (Fig. 11), and the restriction of the holes to <2 m depth, the average
annual ice thickness and assumed limit of near-surface permafrost. However, this hypothesis does not explain their generally round shape. Nichols (1967, p. 213) describes blocks of submerged, shorefast ice breaking from the bottom of Pelly Lake (66°05'N, 101°04'W) in Spring of 1966. He described the ice as "... quite dark, being impregnated with sand and mud, and seemed to contain a large portion of lake sediments".

We consider the last two hypotheses for origin of the holes to be the strongest in light of data presented earlier in the paper. Further research is needed to establish whether both mechanisms form holes or whether they are all formed by a single mechanism.

Conclusions

We have attempted to bring to the reader’s attention three types of shallow water patterns that seem to be typical of lakes in the zone of continuous permafrost in a glaciated area on the Canadian Shield. Based on our observations we consider polygonal patterns, rib-and-trough patterns, and, possibly, holes to be periglacial features, the first two features probably requiring a perennially frozen substrate for their formation. We also conclude that the low liquid limits and limited plasticity indices typical of till and associated glacial sediment derived from the crystalline rocks of the Shield are major factors in formation of the rib-and-trough patterns and explain why these features may not be common in Arctic areas underlain by Paleozoic and younger bedrock. The rib-and-trough structures are similar in genesis to mudboils, their linearity being caused by the offshore progression of the contact of thickening lake ice with sub-lacustrine permafrost surface. If some or all of these features are truly periglacial, their areal distribution may be a good indicator of the extent of a shallow permafrost table beneath lake bottoms.

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