In 1973 a program of mapping and laboratory study was begun in order to define physical and chemical properties of the various sediment types that are associated with two distinct types of patterned ground, mud boils and frost cracks. One or the other of these varieties patterned ground occurs on virtually all unconsolidated deposits found south of Chesterfield Inlet, in the eastern District of Keewatin. Samples collected for project 700014 in 1970 and 1971 were analyzed in Ottawa; a field laboratory was operated in Rankin Inlet in 1973 to analyze selected physical properties of samples collected during the 1973 field season. The purpose of these studies is to ascertain relationships between surface patterns and properties of underlying unconsolidated sediment in order that reconnaissance mapping for terrain inventory may be improved. This report presents preliminary results for the ongoing program; however, most of the data presented relate to the properties of sediments forming mud boils.

Mud boils and frost cracks or tundra polygons rarely occur together (Fig. 1) and almost always indicate the textural and engineering properties of the unconsolidated sediment in which they are developed. Mud boils indicate poorly-sorted sediment with low liquid limit (<20%) and significant amounts of silt and clay, whereas frost cracks usually indicate either water-sorted sediments with high liquid limits, insignificant fine-grained component, and low pH or thick organic soil cover (in low, flat occurrences). Mud boils are common in areas underlain by till, marine silty clay, and colluvium containing significant fines; frost cracks are characteristic patterns on eskers, gravelly ribbed or De Geer moraine, marine or lake beaches or deltas, sandy shallow-water bottom sediments, and alluvium or alluvial plains along modern streams or adjacent to eskers.

Mud boils are referred to in the literature, by various names, such as frost boils, soil medallions, non-sorted circles, tundra craters, etc. Mud boil, a term with some current informal usage, has been chosen because neither permafrost nor frost are absolutely necessary to form mud boils and a muddy sediment is necessary. It should be emphasized, however, that seasonal frost and permafrost

Figure 1. Mud boils developed on a drumlin mantled by marine silty clay. Note frost polygons in surrounding sandy marine and/or fluvial sediment. Each of the two surface patterns is confined to a specific sediment type.
Selected physical and chemical properties of unconsolidated sediments from eastern District of Keewatin:

A. till carapace,
B. till,
C. marine silty clay,
D. shallow water lake-bottom sediment,
E. nearshore lake sediment or modified glacial sediment in subaqueous mud boil,
F. frozen marine and/or alluvial silty sand,
G. frozen grass-sedge peat,
H. frozen Sphagnum peat.

Atterberg Limits and Moisture Contents

Table 1 summarizes data from the Rankin Inlet laboratory and Figure 2 indicates Atterberg limits on sediments collected from mud boils in 1970, 1971, and 1973. From both displays it is apparent that liquid limits for Keewatin "muds" are very low with respect to other arctic or subarctic "muds" and that plasticity indices are low (<4%) or unmeasurable. This means that at very low moisture contents, Keewatin "muds" pass from a solid state possessing considerable shear strength to a liquid state shear strength, either directly or after passing through a very minor plastic phase. Thus, a very slight increase in moisture content or an increase in pore-water pressure may cause a seemingly solid soil to liquify or founder, or conversely, very slight decrease of these stresses may cause an
Figure 2. Liquid limit vs. plasticity index for various Arctic and subarctic sediments. Diagram after Cassagrande (1947); data from Alberta, Pawluk and Bayrock (1969), Inuvik, J. A. Heginbottom (unpubl.), Norman Wells, F. J. Kurfurst (unpubl.).

Keewatin' Till
Mudboils • Marine
Till near Inuvik, N.W.T.
Miscellaneous borehole samples, Norman Wells, N.W.T.
Till, Alberta (Pawluk and Bayrock, 1969)
Till, Quebec

apparently liquid, soft mud to become solid.

A dramatic example that illustrated these properties occurred on August 7, 1973 when a field assistant (C.I.D.A. student Aaron Villakazie) became trapped in a subaqueous mud boil (Type E, Table 1) on an island in Kaminak Lake (Figs. 7, 8). His foot sank in mud which, because of increased pore-water pressure caused by his weight, was above liquid limit (12.4% with a natural moisture content 11.9%) at and below the sole of his boot, but below liquid limit, or solid, above the toe of his boot. The liquid and plastic limits of the sediment are equal so that it could not behave plastically, only as a solid or liquid. Thus, in two hours and despite the efforts of seven men, he sank almost to the frost table and was extricated only after the rigid sediment around his leg was excavated hydraulically by a portable, high-discharge pump.

Texture

Figures 3, 4, 5, and 6 illustrate the relationship of texture to Atterberg limits for sediment from mud boils. Carapace samples on Figure 3 are clearly distinguished from their parent material (till) by their poverty of fine particles. This gives rise to liquid limits of 10-12% and a plasticity index near 0% for carapace materials. At its mean natural moisture content of only 60% of the liquid limit, however, the carapace is rigid and only under conditions of very high rain-fall or loading does the carapace absorb enough water to pass the liquid limit.

The finer texture of unmodified till and marine sediment (Fig. 3) allows for higher natural moisture contents, higher liquid limits, and greater plasticity indices. Moisture content averages 70 - 80% of the liquid limit, suggesting that these sediments would become mobile before carapace-type sediment would (i.e., at lower amounts of added moisture).

Figure 4 suggests that sediments forming mud boils have liquid limits and plasticity indices that both increase with decreasing mean grain size. The plasticity index increases with poorer sorting (Fig. 5) but the liquid limit is somewhat independent of sorting; marine sediments, particularly, show high liquid limits and good sorting. The plasticity index increases with increasing clay (2u-) content (Fig. 6) but the liquid limit varies widely at low clay contents (<10%). At clay contents >10%, liquid limits increase with increase in clay percentage.

It may be concluded from these data that textural parameters have a strong influence on the plasticity index but that only mean grain size consistently affects the liquid limit.

Moisture Contents and Excess Water

Moisture contents and excess water calculations shown in Table 1 are probably somewhat misleading,
Figure 3
Textural envelopes of three types of sediment found in mud boils.

Figure 4
Plasticity index and liquid limit vs. mean grain size. \( W_1 \) and \( I_p \) are expressed in weight per cent moisture; \( M_z \) is expressed in \( \phi \) units, higher numbers representing finer mean grain size. Samples from mud boils represented in Figure 3.
Figure 5
Plasticity index and liquid limit vs. sorting (graphic standard deviation). Sorting expressed in $\phi$ units. Increase in number indicates poorer sorting. Samples from mud boils represented in Figure 3.

Figure 6.
Plasticity index and liquid limit vs. percentage clay. Samples from mud boils represented in Figure 3.
but provide rough estimates for comparison with data from other areas. Samples were collected before August 15, 1973. From early May to that date, less than 1 in. (2.5 cm) of rain fell on the areas sampled (as opposed to 10 in. (>25 cm) in June-August 1970, and ~4 in. (~10 cm) in June-August 1971), and air temperatures and cloud-free periods were well above normal for this period. Thus, samples collected from the active zone were noticeably drier than in other years.

A second source of bias occurs in computation of excess water, which is an indirect measurement of excess ice. This value was derived from the ratio (free water volume/total volume), x 100 of a melted sample collected from below the frost table. Since most samples were within 6 in. (15 cm) of the frost surface, ice-lensing, which is always prominent near the frozen/unfrozen interface, was prominent in most samples; these figures cannot be extrapolated to conditions at depth.

It is interesting to note (Table 1) that frozen Sphagnum mosses with very high visible ice contents produce little or no excess water when melted because of the very high absorptive capacity of Sphagnum. Peats derived from grasses or sedges, on the other hand, may produce significant amounts of excess water on melting.

Conclusions

Preliminary data on Atterberg limits and natural moisture contents of unconsolidated sediments from Keewatin support the artesian concept of mud boil formation. Because of the low liquid limits and small plasticity indices of sediments forming mud boils, slight increases in pore-water pressure due to loading, small amounts of precipitation, cryostatic pressures created during fall freeze-up, or moisture increases during spring-summer thaw could all be causes of temporary liquefaction of the active zone with resulting hydrostatically driven diapirism or mud boiling. This seasonal activity would destroy other features, such as incipient frost polygons, so that these features are incompatible with sediment that form mud boils. Organic growth would also be disrupted seasonally so that no persistent organic cover could be established.

In dry sands and gravels of ridged or hummocky stratified drift, organic cover is slight because the moisture content of the well-drained active zone is low, the liquid limit of the sediment is very high; because of these factors, the thawed zone is stable enough to perpetuate seasonal growth of vertical ice wedges that are expressed at the surface as frost cracks. Only locally, where moisture from spring thaw builds up temporarily behind snow banks, is the liquid limit likely to be exceeded and slumping or flowing take place.

Frost cracks or polygons also occur where sediments derived from marine reworking or alluvial or lacustrine deposition have partially filled depressions that existed on the glaciated surface after retreat of the ice. These pockets of sediment have flat surfaces and occur in strips along major rivers and eskers, in post-glacial lake basins, and in numerous, smaller, random pockets at all altitudes up to marine limit (560±20 feet a.s.l. higher on the hill between Rankin and Chesterfield Inlets). These factors may cause mud boils to be
absent and frost cracks to predominate in these areas: 1) the flatness of most basins would not allow for significant hydrostatic head to develop; 2) the sedimentary fill is commonly sandy or gravelly so that liquid limits are too high to cause flow at normal moisture contents; 3) where the sedimentary fill is very wet, organic growth is lush, and a thick, insulating cover of peat develops on the sediment. In such areas the maximum depth of thaw is slight (15-30 cm) so that the active zone is never thick enough to develop the artesian system necessary for mud boil formation, no matter what the properties of the underlying mineral sediment might be.

References


REPORT OF ACTIVITIES
Part A. April to October 1973