GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES, OTTAWA

PAPER 74-53

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V.N. RAMPTON
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Energy, Mines and Resources Canada
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Catalogue No. M44-74-53

Price subject to change without notice

Information Canada
Ottawa
1975

CONTENTS

Illustrations

ABSTRACT

Tuktoyaktuk is situated on a part of the Arctic Coastal Plain that lies below 100 feet in elevation and that has many lakes. Mean annual ground temperature is $-8^{\circ}C$, permafrost reaches a depth of 1200 feet on undisturbed sites, and the active layer is from 3 inches to slightly more than 40 inches in depth.

Near Tuktoyaktuk, a diamicton (till and reworked till) overlies thick outwash, generally sand. Massive ground ice commonly is found along the contact between the two deposits, especially where the till is thick. Outwash is also extensive on the surface. Fine-grained lacustrine sediments are found in areas of till and reworked till: coarse-grained lacustrine sediments are present in areas of outwash. Peat occurs on poorly drained areas, especially lacustrine flats. Intertidal sediments cap low areas that are periodically inundated by the sea; beach and spit deposits are common along exposed coasts. Excess ice is most common in lacustrine, intertidal, and organic deposits, and in the upper 2 to 5 feet of permafrost in other deposits.

Coastal retreat is rapid where massive ground ice or ice-rich sediments are near sea level and vulnerable to exposure by wave erosion. Retreat proceeds either through thermal niching and slumping or through ground-ice slumping. Spits are also moving rapidly landward across drained lake basins.

The Tuktoyaktuk area was last glaciated in early Wisconsin time. Following 11 500 B.P. the climate warmed, initiating extensive thermokarst activity that continued until about 3600 B.P., when the climate again deteriorated and the terrain stabilized except for minor ice slumping and erosion along the coast. Peat growth was probably greatest between 11 500 and 3600 B.P. and has decreased since.

Care should be taken in the Tuktoyaktuk area to avoid surface disturbance that will lead to thermokarst. Also, coastal erosion will continue at Tuktoyaktuk unless man constructs protective structures along the coast which forms its western edge.

RESUME

Tuktoyaktuk est situé sur une parties de la plaine côtière de l'Arctique dont l'altitude est de moins de 100 pieds et qui possède de nombreaux lacs. La température annuelle moyenne du sol est de $-8^{\circ}C$: le pergélisol atteint une profondeur de 1200 pieds aux endroits où le sol n'a pas été remué et la couche active a une forfondeur de 3 pouces à un peu plus de 40 pouces. Près de Tuktoyaktuk, un "diamicton" (till et till remanié) recouvre un épais dépôt fluvioglaciaire, généralement composé de sable. On trouve communément de la glace dans le sol sous forme massive le long du contact entre les deux dépôts, spécialement aux endroits où le till est èpais. Les dépôts fluvioglaciaires en surface est également considérable. Dans les régions de till et de till remanié, on trouve des sédiments lacustres à grain fin, par contre, dans les régions de dépôts fluvioglaciaires l'on trouve des sédiments lacustres à grain grossier. On trouve de la tourbe dans les régions mal égouttées, spécialement sur les replats lacustres. Des sédiments de la zone de balancement des marées couvrent les régions basses qui constituent l'estran; les plages et les flèches ne sont pas rares le long des côtes découvertes. Un excédent de glace est très commun dans les dépôts lacustres, les dépôts de la zone d'estran, les dépôts organogènes et dans les 2 à 5 pieds du sommet du pergélisol dans les autres dépôts.

Le recul de la côte est rapide là où les terrains où se trouve la glace dans le sol sont près de niveau de la mer et peuvent facilement être érodés par action des vagues. Le recul est causé par des niches d'ablation glaciaire et des glissements causés par réchauffement, ou par des glissements de terre et de glace. Les flè ches se déplacent également vers la terre rapidement par le traverse des bassins lacustres drainés.

La région de Tuktoyaktuk a connu sa dernière glaciation au début de periode Wisconsin. Ensuite, en 11 500 B.P. le climat s'est réchauffé, ce qui a provoqué des phénomènes thermokarstiques considérables qui se sont poursuivi jusqu'à il y a eviron 3600 B.P. alors que le climat s'est de nouveau refroidi et que le sol s'est stabilisé à l'esception de petits glissements de glaces et un action réduite de l'érosion de long des côtes. La formation de tourbe a probablement atteint son sommet entre 11 500 et 3600 B.P. et a diminué depuis.

Dans cette région, il faudrait prendre soin d'éviter toutes perturbations du sol ce qui pourrait déclencher l'action de phénomènes thermokarstiques 2. De même, l'érosion de la côte se continuera à Tuktoyaktuk à moins que l'homme n'érige des ouvrages protecteurs le long de la côte.

INTRODUCTION

The increased tendency of local peoples during the last 25 years to concentrate in settlements in the Arctic and recent developments in the petroleum industry have led to an expansion of Tuktoyaktuk. Further developments in the oil and transportation industries within the area point to continued expansion. It has become obvious that a description of the surficial geology near the hamlet is necessary for future planning. This need has led to an investigation of the surficial geology of the area as described in this report.

Tuktoyaktuk lies about 70 miles north-northeast of Inuvik on the southern shore of Kugmallit Bay, which adjoins the Beaufort Sea (Fig. 1). The hamlet is located on the west side of a deep-water inlet on the northwest coast of the northeast-trending Tuktoyaktuk Peninsula; although the water depth within much of the harbour ranges between 20 and 80 feet, boats entering the harbour are limited by nearshore depths of 12 feet in Kugmallit Bay.

Climate and Vegetation

Tuktoyaktuk has an arctic climate and lies well north of the tree line. Although the mean daily temperature is 12.8°F, extreme maximum temperatures in the summer exceed 80°F. Winter mean daily temperatures and extreme minimum temperatures (-58°F), are generally higher than for nearby meteorological stations located farther inland. Precipitation is low (Fig. 2), but up to 1.16 inches of rain has been recorded during a 24-hour interval; fog is common (Mackay, 1963). The prevailing wind directions are northwest and east, with mean wind speed of about 10 mph throughout the year (Dep. of Transport; Mackay, 1963).

Tuktoyaktuk lies in a zone where birch-heath tundra and sedge-cottongrass tundra are the predominant vegetation types. Birch-heath tundra, which generally includes *Betula glandulosa* Michx., *Ledum decumbens* (Ait.) Lodd., *Arctostaphylos alpina* (L.) Spreng., *Empetrum hermaphroditum* Hagerup, *Vaccinium vitis-idaea* L. var. *minus* Lodd, *V. uliginosum* L., *Robus*

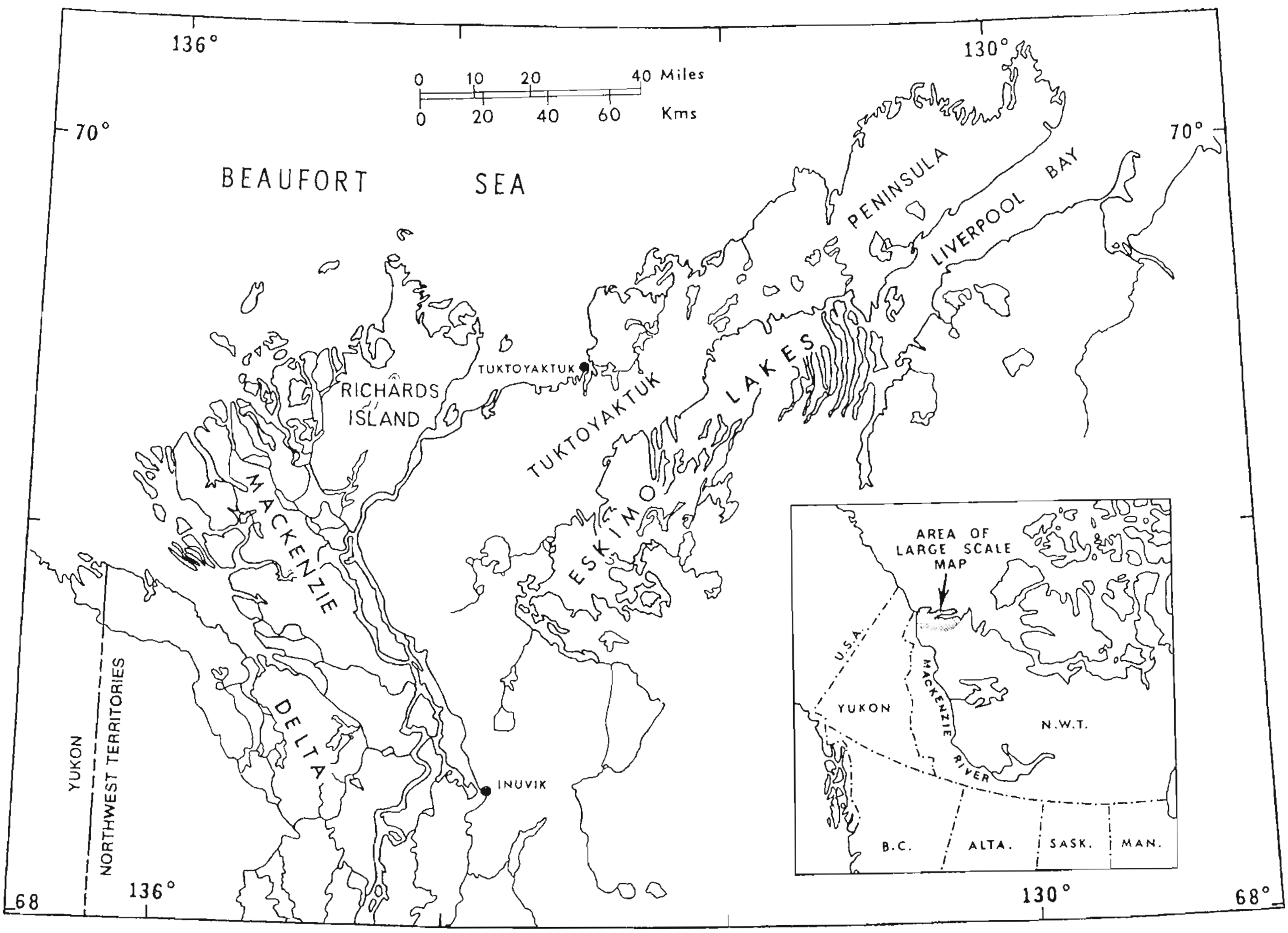


Figure 1. Index map.

Date submitted to division: February 15, 1974
Date approved for publication: July 3, 1974

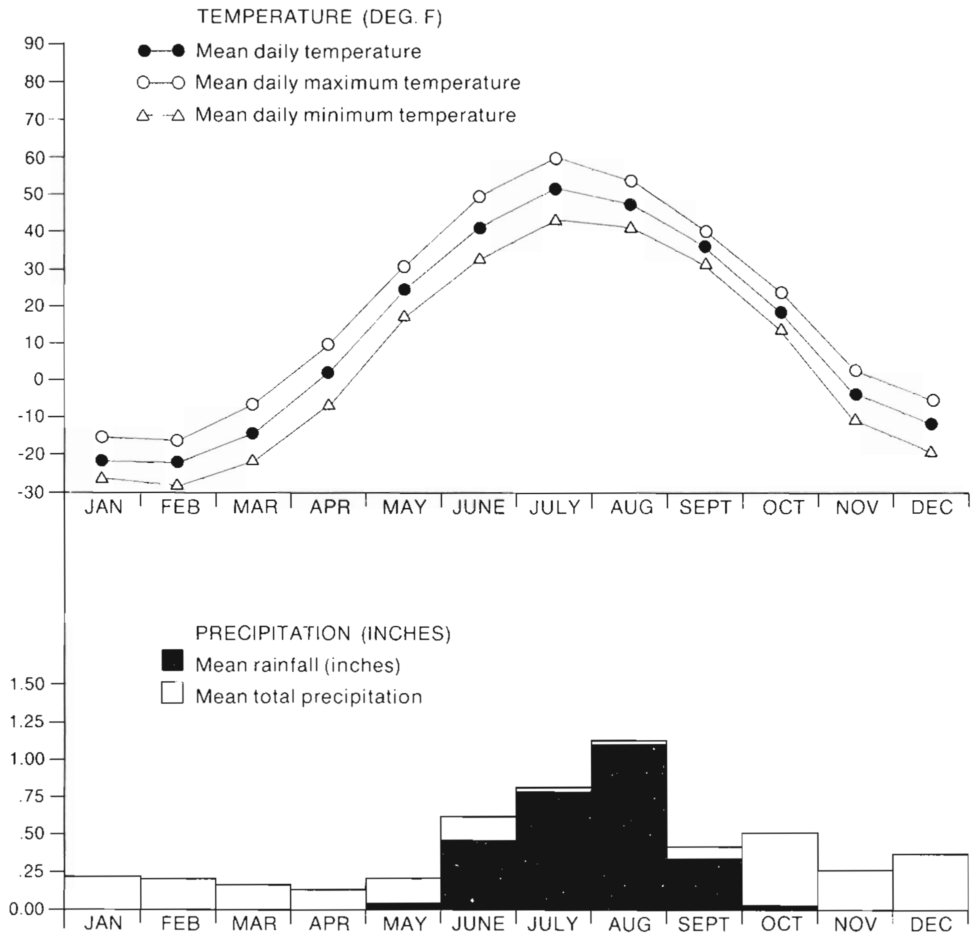


Figure 2. Temperature and precipitation records for Tuktoyaktuk (Dep. of Transport).

chamaemorus L., *Salix reticulata* L., and occasionally *Salix glacua* L. (Ritchie, 1972; K.L. MacInnes, pers. comm., 1971), dominates most moderate to well-drained sites. The sedge-cottongrass community, which generally includes *Eriophorum vaginatum* L., E. *angustifolium* Roth. and a variety of *Carex* sp., is present on moderate to poorly drained areas (Ritchie, 1972; K.L. MacInnes, pers. comm., 1971). More poorly drained areas and marshy areas generally are covered by sedge meadows, which typically include *Carex* sp., *Eriophorum Scheuchzeri* Hoppe, and the mosses *Drepanocladus* and *Sphagnum*. (K.L. MacInnes, pers. comm. 1972; Lambert, 1972.)

The vegetation present is largely a function of surface drainage, which in turn depends not only on type of subsurface material, but also on the slope and thickness of the active layer. For example, because of the regionally thin active layer, flat areas of sand can be covered by vegetation types similar to those on lacustrine clay and silt.

Areas periodically flooded by saline water and abandoned beaches have unique plant associations. Periodically flooded areas are characterized by sedge and grass meadows; predominately *Carex suppathacia* Wormskj., are common on those areas frequently flooded whereas meadows dominated by *Dupontia Fischeri* R. Br. and *Elymus* are common on areas flooded less frequently (K.L. MacInnes, pers. comm., 1961). The vegetation of abandoned beaches varies according to moisture conditions: *Arctophila-Hippuris* meadows are common where standing water is present; *Carex stans* Drej. meadows are common where the substrate is saturated. Mixed dwarf-willow-herb meadows are common on abandoned beaches. Alder-willow scrub *(Alnus crispa* (Ait.) Pursh, *Salix glauca* L., *Ledum decumbens* (Ait.) Lodd. ex Steud., *Vaccinium vitis-idaea* L. var. *minus* Lodd., *Luzula paruiflora* (Ehrh.) Desv.) and tall willow scrub *(Salix alexensis* (Anderss.) Cov., *Betula glandulosa* Michx., *Salix reticulata* L., *Artemesia borealis* Pall.) are present on older, coarse-textured, abandoned beaches protected from the wind.

Physiography

The Tuktoyaktuk Peninsula lies within the Arctic Coastal Plain of Bostock (1970). Mackay (1963, p. 136) has called the Tuktoyaktuk Peninsula and adjacent similar areas the "Pleistocene coastlands" and described them as follows: "most of the area lies below an altitude of 200 feet, with about 50 per cent below 100 feet...

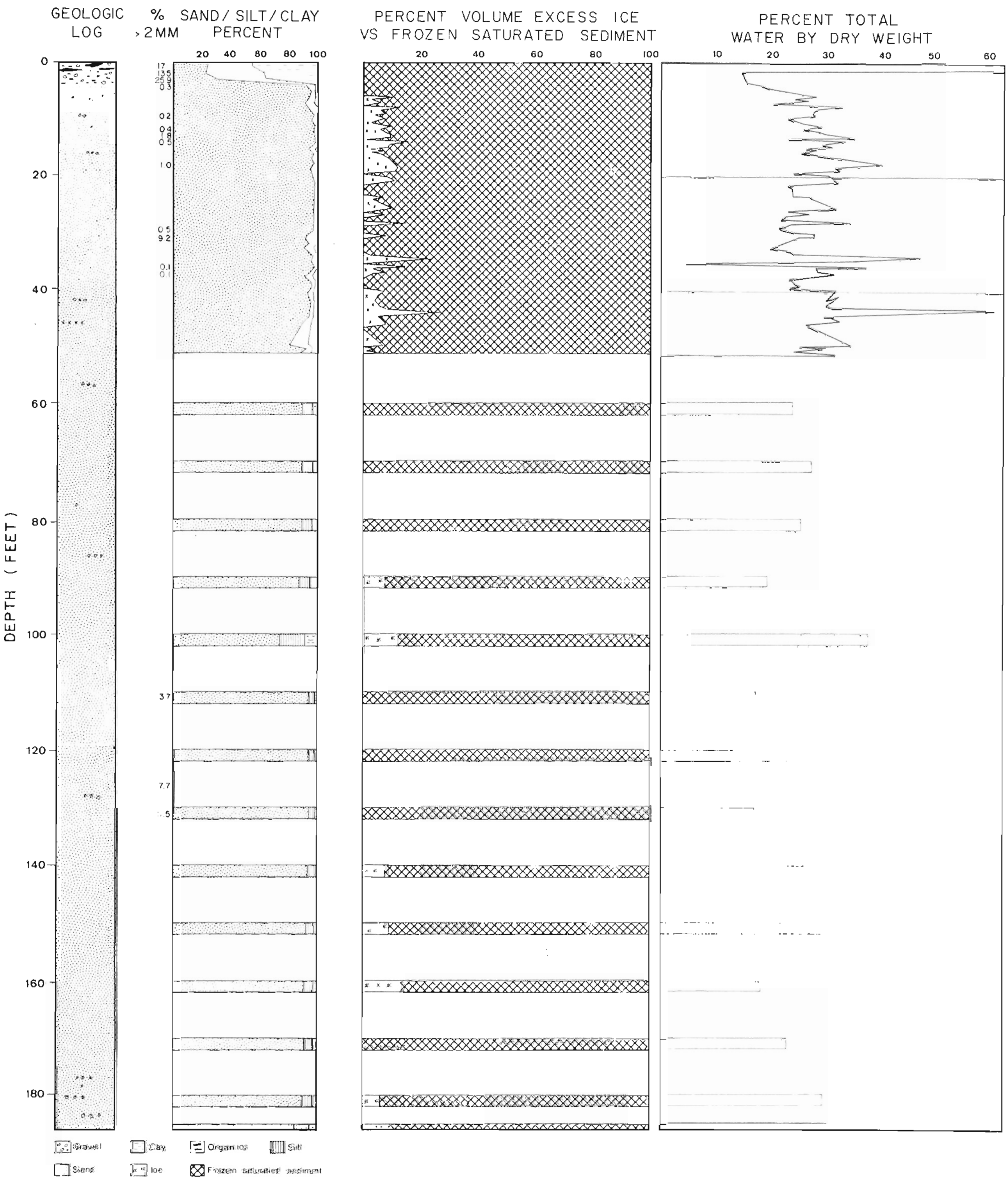


Figure 3. Geologic log from borehole near east end of airstrip (adapted from Wyder *et al.*, 1972).

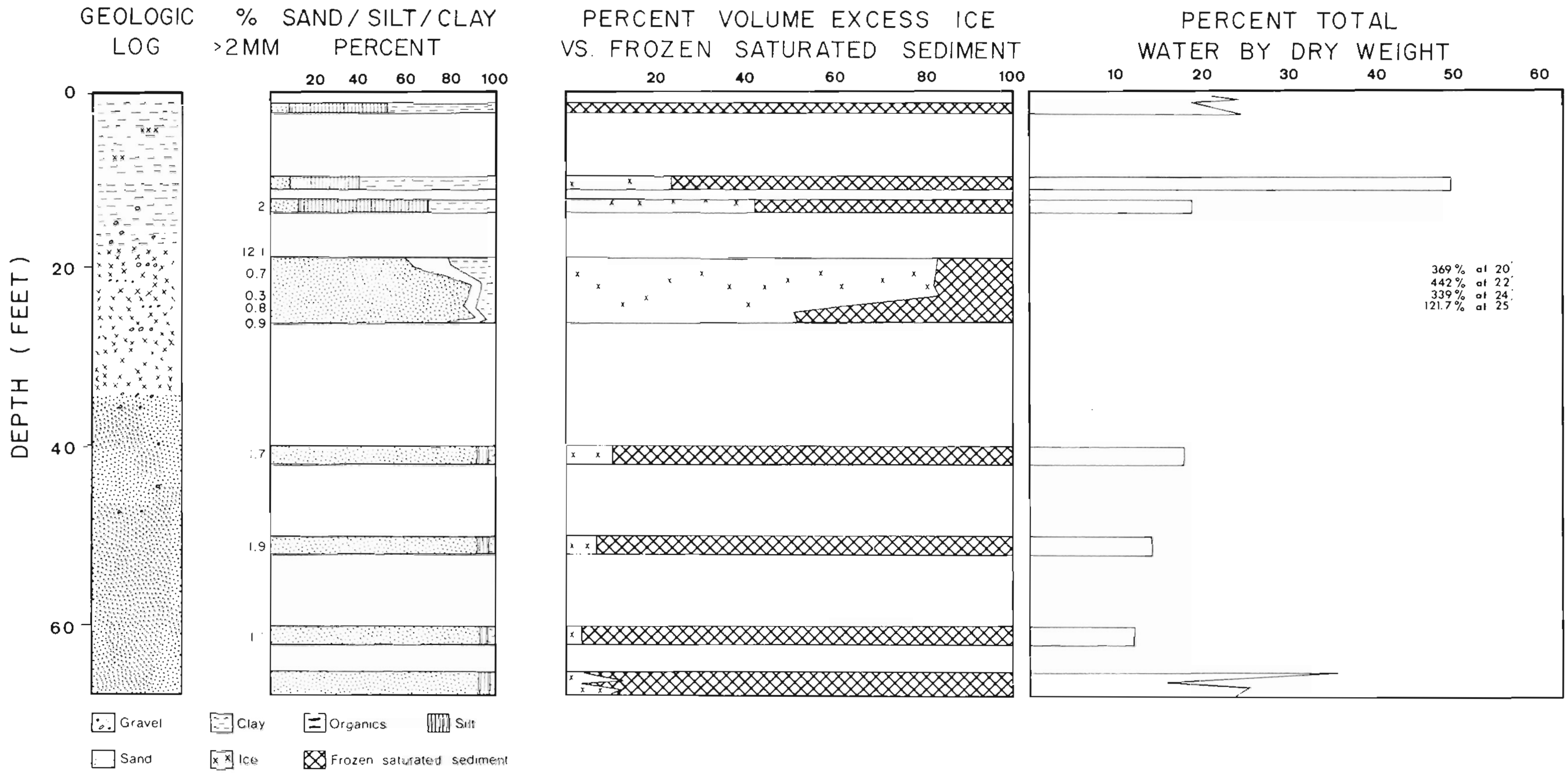


Figure 4. Geological log from borehole located on lacustrine terrace east of Tuktoyaktuk Harbour (adapted from Wyder *et al.*, 1972).

numerous lakes cover over 15 per cent of the surface. With minor exceptions, pingos are found throughout the entire area." The hamlet of Tuktoyaktuk lies in an area which is nearly half covered by lakes (Mackay, 1963). Near the coast many former lake basins and most inlets now are inundated with saline water.

Most of the map-area lies within Mackay's "undifferentiated coastlands" and "involuted hills" subdivisions. The former consists of flat to gently rolling terrain, with relief rarely being more than 50 feet except where large pingos are present. The margins of the map-area lie within the involuted hills, which "resemble on air photographs, the wrinkled skin of a well-dried prune. The wrinkles are curving branching ridges, ranging up to several hundred yards in length, several scores wide, and 20 feet in height. When seen from a lower altitude ... some involuted slopes appear to rise in a succession of terraces." (Mackay, 1963.) Near Tuktoyaktuk relief in the involuted hills ranges from 50 to 120 feet with the edges of the hills generally having steep slopes.

Permafrost

The mean annual ground temperature at Tuktoyaktuk is near -8°C (Mackay, 1974), and the depth of permafrost is probably in excess of 1200 feet in areas that recently have not been covered by lake waters or whose surface has not had a mean annual ground temperature of above -8°C in the recent past the base of permafrost is 1200 feet in a well at the south end of Richards Island (Jessop, 1970).

The average thickness of the active layer is about 23 inches, and exceeds 40 inches only where coarse-grained materials are bare of vegetation (R.J. Barnett, pers. comm., 1972). The active layer is thinnest in peat (3-6 inches) and in poorly drained, fine-grained deposits covered by peat.

General Geology

Stratigraphy

Thick sands probably of a glaciofluvial origin underlie most surface units throughout the area (Figs. 3 and 4). The sands are generally fine to medium grained, although beds of coarse and pebbly sand, and silty beds are present (Appendix A). A few crossbeds within the sand are pebbly. The upper parts of the glaciofluvial sands commonly are oxidized. Occasionally the sands may be contorted, with faults and recumbent folds at shallow depths. At Peninsula Point a 10-foot-thick bed of fine brown sand within the unit (Fig. 5) may be the equivalent of a sand unit, present to the east and west of Tuktoyaktuk, that is thought to be part of a delta built into the sea (Mackay, 1963; Rampton, 1971). The fine brown sand however could not be identified in drillholes near Tuktoyaktuk (Wyder *et al.*, 1972) or in the sands exposed at Ibyuk Pingo. Although drillholes in the immediate vicinity have not completely penetrated the above sands, a sequence of interbedded sand and marine clay that is exposed in surrounding areas (Fyles *et al.*, 1972; Rampton, 1971) probably underlies them.

In most places the glaciofluvial sands are overlain by clayey diamicton consisting of till or colluvium derived from till. In the central part of the map-area this diamicton is generally less than 5 feet thick, whereas in peripheral areas it ranges up to 25 feet thick. Elsewhere younger glaciofluvial gravel and sand or lacustrine sediments directly overlie the glaciofluvial sands. Commonly lacustrine sediments form a veneer on the clayey diamicton. Materials in depressions and on poorly drained flat areas generally are covered by peat. In areas periodically inundated by the sea, all of the above deposits may be covered by intertidal sediments.

Ground Ice

Massive segregated ice bodies, sediments containing an abundance of excess ice in the form of ice lenses, vein ice and pore ice, pingo ice and associated tension-crack ice, and ice-wedge ice are common within the mapped area (ground ice classification after Mackay, 1972a). Nearly all types of ground ice are exposed in the ice cellars and tunnels in the hamlet of Tuktoyaktuk (Rampton and Mackay, 1971). The abundance and former abundance of ground ice is also shown by the presence of patterned ground, which reflects underlying ice wedges, and the numerous depressions caused by thermokarst.

In general the massive segregated ice bodies are localized between thick clayey diamicton and glaciofluvial sand. A drillhole on the east side of Tuktoyaktuk Harbour encountered a typical sequence of about 18 feet of lacustrine sediment and clayey diamicton over some 15 feet of massive segregated ice, in turn over glaciofluvial sands (Fig. 3). In a coastal exposure 3.5 miles southwest of Tuktoyaktuk, 15 to 20 feet of clayey diamicton overlie massive ice (Fig. 6), which is probably more than 50 feet thick (Rampton and Mackay, 1971); if the stratigraphic sequence under this involuted hill is similar to that beneath a recently drilled involuted hill about 8 miles east of Tuktoyaktuk, sand directly underlies the massive ice. Massive segregated ice or numerous thick ice lenses also occur within sands, but are uncommon except in sand underlying massive ice bodies. For example, the hamlet's ice cellar shows a thick sequence of wide ice lenses in sand that has been folded as a unit subsequent to formation (Rampton and Mackay, 1971 and Fig. 7).

Ice lenses and vein and pore ice are present in fine materials and organic deposits and to a lesser degree in coarse materials. A zone abounding in ice lenses and veins commonly occurs near the base of the active layer; this is a result of a recent thinning of the active layer due to climatic cooling. As the active layer thins, ice lenses forming along its base during the annual freeze-back are incorporated into the permafrost. Mackay (1972a) calls this type of ice aggradational.

Ice wedges are ubiquitous in the area. Their volume and geometry, however, largely depend upon the

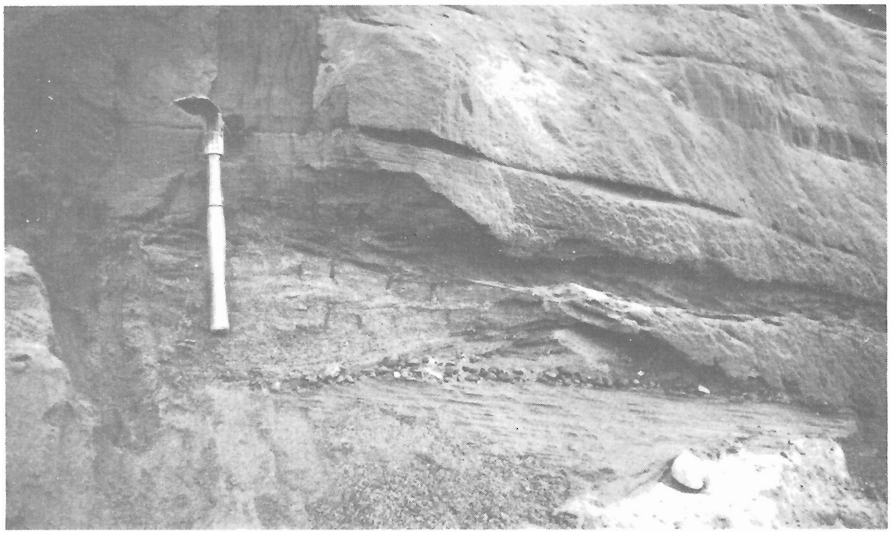


Figure 5.

Lower, pebbly glaciofluvial sand and possible fine-grained deltaic sand exposed at Peninsula Point. Contact is at head of mattock. (GSC photo 159010).

Figure 6.

Scarp at head of ice slump found southwest of Tuktoyaktuk. Note the exposed ice wedges in the debris flow overlying the massive ice, and the partly stabilized debris flow in foreground. (GSC photo 159012).

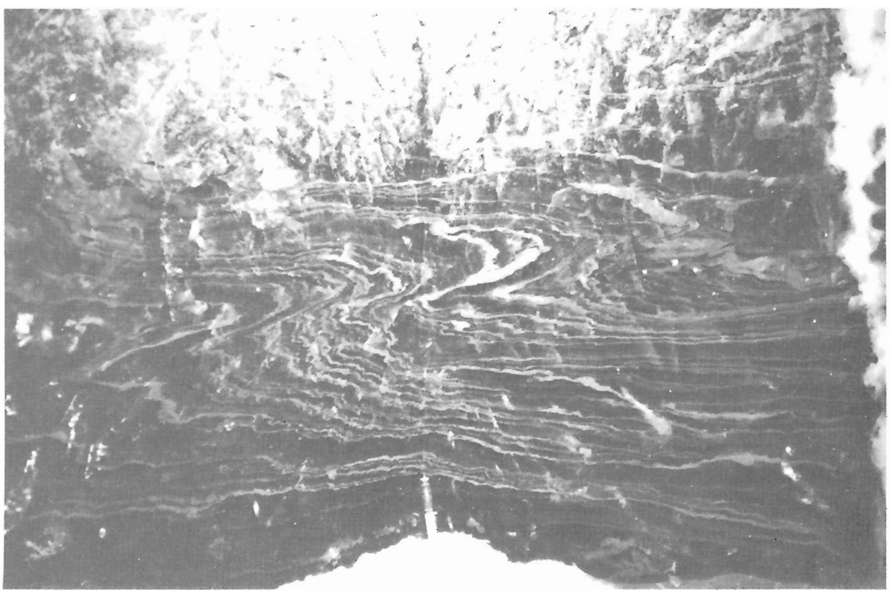
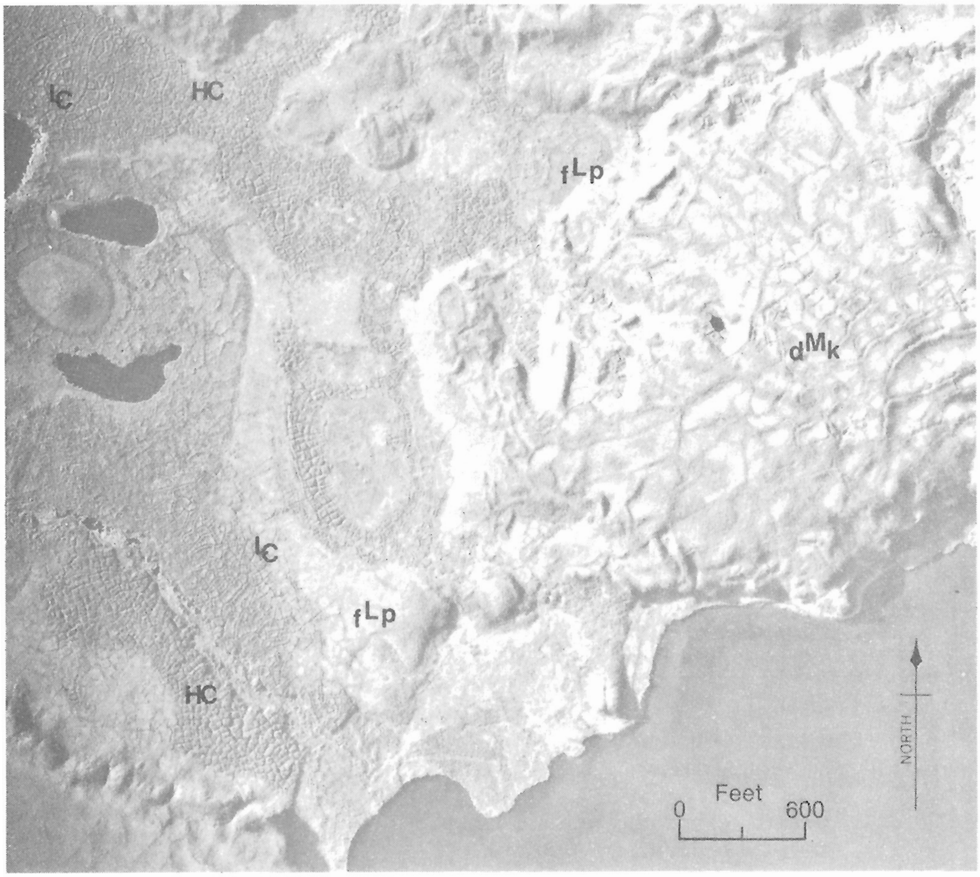


Figure 7.

Folded ice and sand in ice cellar in hamlet; dark bands are ice, light bands are sand. (GSC photo 158963).

Figure 8.

Airphoto showing typical patterned ground on morainal deposits ($_dM_k$), fine-grained lacustrine deposit ($_fL_p$), and organic deposits – low-centred (L_E) and high-centred (HC) peat polygons. (EMR airphoto A-22535-145).



enclosing sediment type. As can be seen in Figure 8, the polygonal ground indicates that they are closer together in organic deposits than in fine-grained lacustrine deposits or in clayey diamicton. Ice wedges are not always reflected on the surface by troughs, for downslope movement can prevent troughs from developing. Ice wedges are rare in surface sand and gravel.

Ice forms the core of every pingo. The depth of the ice core varies; for example, the ice cores of Ibyuk Pingo (Müller, 1962) and the tunnelled-out pingo at Tuktoyaktuk (Rampton and Mackay, 1971) are at shallow depths, whereas the ice core of the pingo at Peninsula Point is deeper. Also a 60-foot-deep borehole in another pingo near the hamlet did not reach ice. Tension-crack ice traverses most pingos in the area; occasionally it is exposed in fresh faces of the dissected pingo at Peninsula Point.

Ice wedges and ground ice in all cases are younger than the material they are contained within. Thus, the outer part of ice wedges developed in morainal deposits will be older than those developed in most lacustrine deposits; those developed in lacustrine terrace deposits will be older than those developed in recently drained lacustrine basins.

SURFICIAL DEPOSITS

The surficial deposits as indicated on Map 5-1974 are described in chronological order from oldest to youngest.

Morainal Deposits

In the vicinity of Tuktoyaktuk two types of morainal deposits have been mapped, according to their relief: (1) Morainal deposits modified by thermokarst – generally steep-sided hills with ice slump scars common along their flanks. Low ridges superimposed on the hills give an involuted appearance from the air. (2) Morainal deposits with gently rolling topography. The morainal deposits modified by thermokarst are generally 15 to 25 feet thick, whereas the gently rolling morainal deposits are commonly less than 5 feet thick and never exceed 10 feet in thickness. The diamicton that forms the morainal deposits is similar in both subdivisions: it contains 5 to 15 per cent clasts greater than 2 mm in diameter; the remainder is 12 to 24 per cent sand, 30 to 40 per cent silt, and 40 to 50 per cent clay (Fig. 9 and Appendix B).

The term diamicton has been used to describe the above material because its complex origin at many localities precludes use of a genetic term. In some localities it is till that has not been subjected to mass movement since deposition; elsewhere, it has been subjected to mass movement and genetically would be classified as mudflow debris or colluvium. In areas of thick diamicton, as in the involuted hills, the lower part of the unit is undoubtedly till; however, the upper part of the thick diamicton in the involuted hills and possibly the complete thickness in areas of thinner morainal deposits have been reworked through debris-flow activity, solifluction, or some other form of downslope creep.

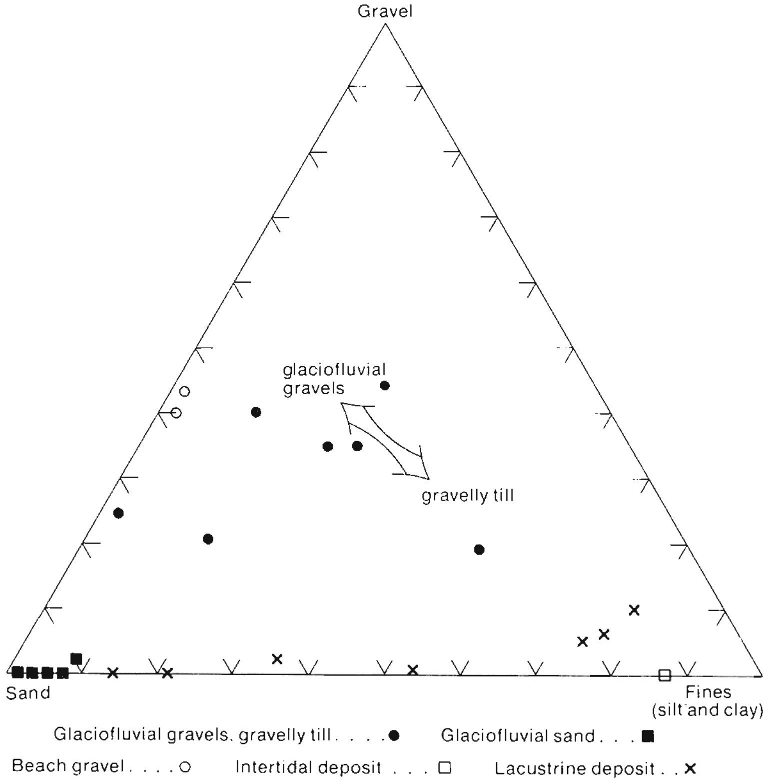


Figure 9. Gravel, sand, clay and silt ratios of samples collected in map-area.

The formation of mudflow debris can be seen at the ice slump 3. 5 miles southwest of Tuktoyaktuk, where till and associated sediments along with the underlying ground ice have been exposed by wave erosion. The removal of the vegetation covering these materials has caused them to thaw rapidly during the summer. The till and associated sediments that thaw then slide down the scarp, mix with water from the ice at the base of the scarp, and move farther downslope as a mudflow until the mixture loses enough water to stabilize. The redeposited till resembles the original material; occasional alluvial bedding structures, formed by water flowing from the area, and incorporated loose peat in the redeposited material are the only clues to its origin (c.f. Fig. 13 *in* Rampton and Mackay, 1971).

In relatively thin diamicton, pebbles oriented parallel to the slope indicate that solifluction or creep has affected much of the material. Also the diamicton consistently is thicker in depressions than on hills. Beds and lenses of sandy, stony, diamicton occasionally occur within this unit where it abuts against or is underlain by gravel. In fact, some of the poorly sorted outwash shown in Figure 9 may have been incorporated by an overriding glacier, and as such should be considered as till.

The upper part of the diamicton of both map-units contains much peat and organic silt because of frost action, solifluction, and downslope creep. It also contains, typically, much more ice than the lower part. The moisture content in any peat present is generally 40 to 500 per cent of the dry weight of the peat. Where the upper part does not contain organic material, it generally contains 10 to 25 per cent excess ice by total volume. Patches of pond silt and clay are common, and generally contain 25 to 40 per cent excess ice by volume. The lower part of the diamicton is generally free of excess ice.

Glaciofluvial Deposits

Glaciofluvial deposits near Tuktoyaktuk have distributions indicating deposition as outwash fans and valley trains. Depressions within them are probably the result of thermokarst. The surface of the unit is generally flat, but where depressions are common, it has a rolling or hummocky topography.

Gravel in this unit ranges from well sorted to dirty, with crude stratification. Generally, silt and clay are present (*see* Fig. 9). Where gravel is the surface material it is usually 4 or 5 feet thick, but ranges from 2 to 8 feet in thickness. Gravel beds 1 to 5 feet thick occur within the upper 10 feet of predominantly sandy units. Most of the glaciofluvial sand is medium to coarse grained, crossbedded, contains rare pockets and lenses of fragmented coal and driftwood and a few silty and gravelly beds.

In general the sand contains 5 to 20 per cent excess ice by volume, but in places excess ice is absent. Though the gravel is generally free of excess ice some of it contains up to 20 per cent excess ice by volume.

A thin layer of fine material, presumably a lacustrine or a pond deposit, locally overlies glaciofluvial materials. This is common on the peninsula terminating at Kiktoreak Point, where the lacustrine deposit covering the glaciofluvial materials averages 2 feet, but can reach 6 feet, in thickness.

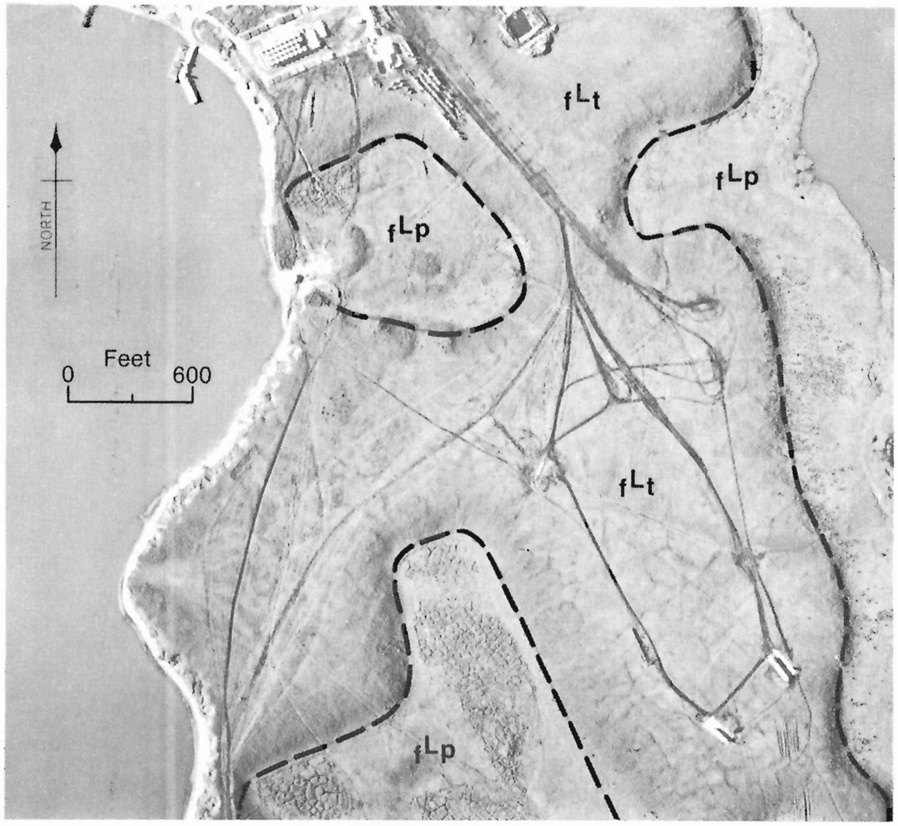
Lacustrine Deposits

Most lacustrine deposits in the Tuktoyaktuk area occupy basins that initially developed through thermokarst subsidence and that subsequently drained. In some areas ground ice has regrown in the drained depression and heaved the surface. Locally this has caused topographic reversal, with the lacustrine deposits standing above the surface of adjacent deposits; these areas are mapped as lake terraces. A good example of this is found between Mayogiak Inlet and Tuktoyaktuk Harbour, where Imperial Oil has its staging area. Local melting of ice under terraces there has formed younger lacustrine basins within this unit (Fig. 10).

Lacustrine deposits in areas of moraine, or surrounded by morainal deposits, are typically fine, because the morainal deposits supplied fine material to the expanding thermokarst basins. The lacustrine deposits are generally thinly bedded clay, silt, and fine sand and commonly are high in organic content (Fyles *et al.*, 1972). In many places their base grades into colluvium and contains a large number of stones and fragments of wood and peat. Of course, the shore zones generally have a concentration of stones, although well-sorted gravel beaches are the exception. The more

Figure 10.

Airphoto showing thermokarst lacustrine basins (fL_p) that have been incised into a lacustrine terrace (fL_t) underlain by massive ground ice. Stabilized ice slumps are present along the shore in the southwest corner. Tracks on the lacustrine terrace are due to vehicle travel. (EMR airphoto A22535-12).



stony beaches can be recognized by the willow *(Salix Alexansis)* shrubbery on them (K. MacInnes, pers. comm., 1971).

Lacustrine deposits generally contain 10 to 20 per cent excess ice by volume, but commonly they contain up to 80 per cent in the upper 3 feet and negligible amounts at greater depth. At the tunnelled-out pingo in Tuktoyaktuk, most of the lacustrine silts run 15 to 30 per cent excess ice, but some contain 45 per cent (Rampton and Mackay, 1971). With the exception of lacustrine terraces and ice cores of pingos, which are always located in former lake basins, massive segregated ice is rare under lacustrine deposits.

Coarse lacustrine deposits are common in areas of glaciofluvial deposits. Their ice content resembles the ice content of glaciofluvial deposits, although the occasional silt bed may induce ice lensing. Beaches in these areas are better sorted than in other areas because of the nature of the parent material.

The vegetation on some abandoned lacustrine basins indicates that they were drained within the last 200 years. Undoubtedly, whereas unfrozen zones exist within 100 feet of the surface in many of these depressions, permafrost may have closed in under some of the smaller depressions. For example, drillholes in a drained lake basin immediately east of the map-area showed the base of the permafrost to be within 150 feet of the surface; vegetation indicates that this depression drained more than 100 years ago (Mackay, 1973a). The water below the permafrost under these lakes is generally under artesian pressure.

Colluvial Deposits

Colluvial deposits veneer most slopes, but they have been mapped only where they constitute stabilized or partially stabilized mudflows associated with ice slumps that can be identified on airphotos or in the field. The material in the debris flows resulting from the ice slumps is almost identical in texture to the morainal materials, as most ice slumps develop in morainal deposits. The colluvial deposits in the debris flows vary in thickness from a few feet to more than 10 feet and are often underlain by massive ice, although they are generally free of excess ice themselves.

The surfaces of the ice slumps are generally sloping, often with a series of concentric ridges or steps parallel to the lower edges of the slumps (*see* Fig. 6).

Marine Deposits

Two types of marine deposits are common in the Tuktoyaktuk area: fine-grained intertidal deposits and coarse-grained beach and spit deposits.

Intertidal Deposits

The fine-grained intertidal deposits are found in (1) former lacustrine basins that have been inundated, and still are periodically inundated, by marine water and in (2) beaches that adjoin areas of fine-textured material and are protected from intense wave action. Intertidal deposits are generally high in organic

Figure 11.

Airphoto showing types of patterned ground developed in organic deposits: low-centred peat polygons (L_E) high-centred peat polygons (HC), and "pitted" peat (PIT). (EMR airphoto A2253-53).

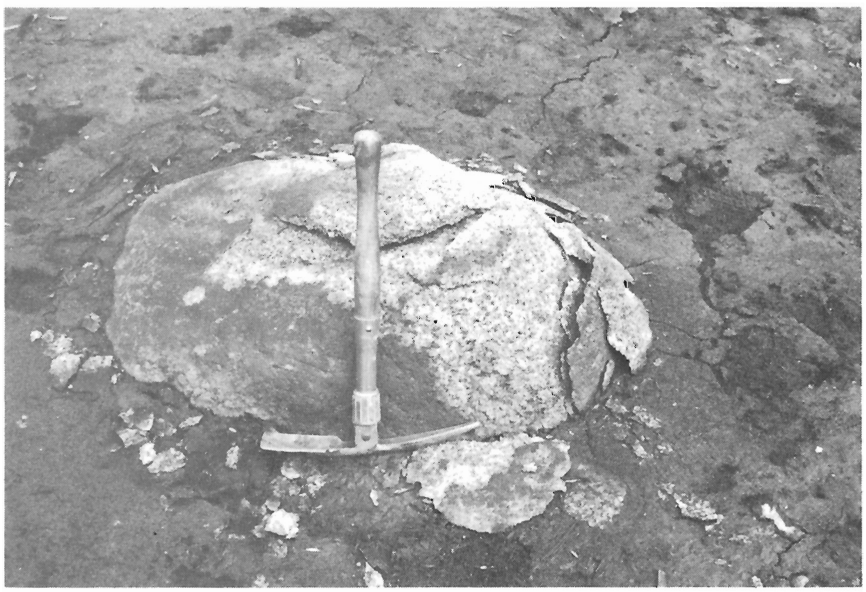


Figure 12.

Exfoliated boulder in the intertidal zone near Tuktoyaktuk. (GSC photo 158982).

Figure 13. Airphoto mosaic showing position of shoreline in 1935, 1950, 1969, and 1971 in vicinity of Tuktoyaktuk based on comparison of airphotos by Mrs. G. Mizerovsky. (EMR airphotos A21019-40, 46). Plot is on 1969 photos.

content, and the nearshore facies contain sand, gravel lenses, isolated stones, and fragments of driftwood. In some bays, driftwood has covered large areas, which are outlined on the map. Most fine-grained marine deposits probably contain much ground ice; presumably the permafrost table rose as sediment accumulated – a condition favourable for ice lensing. At one drillhole in the intertidal zone, excess ice contents of greater than 50 per cent were common in the marine sediments; however the bottom of the sampled interval may have included lacustrine sediments. Intertidal deposits are generally less than 5 feet thick.

Beach and Spit Deposits

Long, narrow spits form a protective barrier along much of the coastline; where they are absent, coastal bluffs are present. The beach materials generally range between 4 and 8 feet in thickness, but as they are commonly underlain by glaciofluvial sand it is not always easy to define their base. Where the spits are migrating across intertidal silts, which are resistant to wave erosion because of their vegetation cover, the gravels are 3 to 5 feet thick. In Tuktoyaktuk Harbour itself the beach deposits are generally only 2 to 3 feet thick. The ground under beaches probably thaws to depths of 4 to 5 feet in the summer (Mackay, 1970).

Gravel and sand in the spits along the coast accumulated through the erosion of till and glaciofluvial deposits as the sea advanced. Very little of the sand and gravel could have been brought in by longshore drift, because of the nature of the coast with its many inlets that act as sediment traps.

Organic Deposits

Most organic deposits are located on lacustrine and pond deposits, and in small areas of poor drainage on morainal and glaciofluvial deposits. Most areas mapped as organic deposits have peat thicknesses of between 3 and 6 feet, with the base grading into the underlying material. Although many boundaries of organic areas are sharp, others are not and peat less than 3 feet in thickness occurs outside the mapped organic areas. It is especially common in areas of lacustrine and intertidal deposits.

Most organic deposits in the Tuktoyaktuk area have a surface pattern: the most common pattern is high-centre peat polygons; less common are low-centre polygons. High-centre peat polygons generally have smaller diameters than low-centre polygons, 35 feet on the average as compared to 60 feet or more. Whereas high-centre peat polygons only have standing water in the trenches outlining the polygons, low-centre peat polygons commonly contain water in the central depressions.

An oddity of the Tuktoyaktuk area is found in the intertidal zone (Fig. 11), where holes 4 to 5 feet deep and 5 to 10 feet in diameter give the ground a pitted aspect. It is unclear whether these features result from the thawing of ice in peat that is inundated by brackish water or whether they develop on peat that is building up in intertidal flats in permafrost areas that periodically are inundated.

Peat has a high ice content and commonly will yield up to 60 per cent free water when thawed in an uncompressed state. The amount of free water (excess ice) is determined by the number and thickness of ice lenses that the peat contains – sampled profiles tend to be consistent in ice content. Peat generally has ice contents that range between 200 and 500 per cent of the dry weight of the peat, but occasionally exceeds 2000 per cent.

DYNAMIC PROCESSES

Frost-related Processes

Permafrost-related processes, such as solifluction and soil creep, ice-wedge formation, frost shattering of boulders (Fig. 12), pingo formation and the heaving of areas formerly covered by water bodies, have a major effect upon the landscape. Mackay and his associates have carried out studies on the rate at which such processes act in the surrounding region. For example, Kerfoot and Mackay (1972) found that solifluction is proceeding at an average rate of one centimetre per year at Garry Island – this is probably a maximum rate for the Tuktoyaktuk area, as solifluction lobes are few and deep snow accumulates only on sheltered slopes. Mackay (1972b) found that between 15 and 40 per cent of the ice wedges cracked up to 2 centimetres in width each year but that the annual growth of ice wedges is as little as one order of magnitude less. Mackay (1973a) also found that pingos initially may grow in height at a rate of 1.5 metres per year, but that the rate decreases with time. The rate of heave of former lake bottoms is smaller, but it is spread over a broader area.

An obvious feature related directly to permafrost is the ice slump (or retrogressive-thaw flow slide). Ice slumps generally occur along coasts or along shores of large lakes where wave erosion either bares massive ground ice directly or causes the ground to fail and expose massive ground ice. Once exposed, the ice and sediment overlying the ice tend to thaw rapidly. Supersaturated debris flows out from the base of the newly exposed face until loss of water causes it to stabilize at a low angle of repose. The process continues until the slope in front of the retreating face or scarp intercepts the surface above the scarp. If the mudflow debris is then removed from the base of the debris flow, ice may be re-exposed and a new cycle of melting and scarp retreat may ensue; this has occurred at the ice slump 3.5 miles southwest of Tuktoyaktuk. Active scarp faces generally retreat between 5 and 15 feet per year (Mackay, 1966). Active ice slumps and their scars are common on the east side of Tuktoyaktuk Harbour, south of the Imperial Oil storage area, and at the northern edge of the map-area.

Coastal Retreat

Coastal retreat is occurring as headland erosion and landward movement of spits and bars, which lie

Figure 15.

Beach, looking north from the Tuktoyaktuk curling rink. (GSC photo 202580).

either offshore or between headlands, occurs. For example, Flagpole Point, one of the most exposed headlands, retreated about 450 feet between 1935 and 1971 (Fig. 13) or an average of 12.5 feet per year; the seaward side of Tuktoyaktuk Island has retreated a similar distance. At the ice slump near Peninsula Point the coast retreated 800 feet between 1935 and 1967, or an average of 25 feet per year. Variation from the mean yearly retreat is large; for example, airphotos taken in 1966 and 1969 of the Tuktoyaktuk area show that negligible coastal retreat occurred during that interval. However, during a particularly intense storm on September 14, 1970 when winds gusted to over 70 miles per hour, the coastal bluff near Flagpole Point retreated 45 feet in one day (Department of Public Works, 1971). Obviously, major erosion of coastal bluffs requires a certain critical wind velocity and height of water. Wind velocity and water height, however, do not have to reach the magnitudes of the 1970 storm at Tuktoyaktuk because in excess of 100 feet of erosion occurred at Flagpole Point and Tuktoyaktuk Island between 1950 and 1969, even though the only storm that approached the intensity of the 1970 storm occurred previous to 1950, in 1944. (Father Lemeur, pers. comm., 1971.) These retreating coastlines have ice-rich sediments or massive ice at a level that is exposed when waves wash the colluvium from the face of a scarp. Erosion then may proceed rapidly through thermal niching and block slumping, or through ice slumping.

Generally, spits are the next most rapidly changing part of the coastline (Fig. 14), especially where they cross former lacustrine basins inundated by the sea or where they are attached to a rapidly retreating coastal scarp. Rapidly moving spits are present at Beluga Point, where much of the spit moved landward between 180 and 450 feet in the years from 1950 to 1971 (9 to 21 feet per year), and southwest of the airstrip towards Peninsula Point where some spits advanced inland as much as 1600 feet between 1950 and 1971 (48 feet per year). The tips of many spits are also extending rapidly; e.g., the spit forming Topkak Point has extended 250 feet between 1950 and 1971 (12 feet per year) and the spit at the eastern side of the ice slump 3.5 miles southwest of Tuktoyaktuk has extended 550 feet in the same period (26 feet per year). Other spits have remained fairly stable.

Coastal retreat is slower where beaches abut against small scarps, against scarps containing sediments with low ice contents, or against land with a gentle seaward slope. In these situations the seaward beach profiles may steepen during storms and allow some erosion of underlying material or material in the coastal scarp behind it, but the rates of erosion do not approach those described above. Also in areas where the sea abuts against ground with a gentle seaward slope, such as near the curling rink (Fig. 15), the beach may gradually aggrade inland during storms. Between 1950 and 1971 coastal retreat near the curling rink was only 50 feet (2.4 feet per year) as compared with up to 200 feet at Flagpole Point (9.5 feet per year).

Protected scarps, such as those in Tuktoyaktuk Harbour, and the edges of intertidal flats are generally fairly stable, although isolated occurrences of erosion occur through wave erosion or ice slumping.

QUATERNARY HISTORY

The lower glaciofluvial sand is the oldest deposit exposed at Tuktoyaktuk. If, as Mackay *et al.* (1972) claim, the only till on this part of the Tuktoyaktuk Peninsula is early Wisconsin or pre-Wisconsin in age, this unit would be at least early Wisconsin in age as it is older than the till. The age of these materials was determined not only from regional stratigraphic relationships (Mackay *et al.*, 1972), but also from attempts to obtain radiocarbon dates on wood from the sand at Ibyuk Pingo (Fyles *et al.*, 1972); the wood was beyond the range of radiocarbon dating. The regional extent of this sand or similar sand units indicates that much of the area was a large outwash plain during their deposition. If the sandy deltaic unit found in surrounding areas is missing at Tuktoyaktuk because of nondeposition or erosion, the lower glaciofluvial sand may represent two phases of outwash deposition.

The till seems to represent an early Wisconsin glaciation. Radiocarbon dates in the area indicate that it, too, predates the middle Wisconsin (Mackay *et al.*, 1972). The lack of any thick peat beyond the range of radiocarbon dating or of weathering zones on the till indicates that the till has not been subjected to interglacial climatic conditions, and that it postdates Sangamon time. The upper glaciofluvial deposits were formed during the same glacial interval as the till. The gravel and sand underlying the till would have been deposited in front of an advancing glacier, whereas the surface gravels would have been deposited in front of the retreating glacier.

The massive, segregated ice under the till formed subsequent to glaciation, for indications are that it is not of glacial origin (Mackay, pers. comm., 1973; Rampton, in press). For ice to form in the base of the till or under it, the underlying porous sediments must have been unfrozen so that water could flow to the advancing permafrost table. Rampton (in press) has proposed that much of the ground underlying the glacier indeed was not frozen during the glacial maximum, and that the hydraulic gradient due to the weight of the overlying glacier forced water to an aggrading permafrost zone near the glacial terminus where till was being deposited.

During a postglacial warm period starting about 11 500 B.P. (Ritchie and Hare, 1971) when spruce forest spread north of the present treeline, extensive thermokarst development led to the deposition of colluvial and lacustrine materials in thermokarst basins. Most datable materials from the base of those basins are between 11 500 and 8000 B.P. Dates of 8160 ± 140 B.P. (GSC – 1676) on peat in a lacustrine beach complex and 9460 ± 140 B.P. (GSC – 1458) on lacustrine silts in the tunnelled pingo (Rampton and Mackay, 1971) are typical of deposits in thermokarst depressions. A date of 12 800 ± 180 (GSC – 1214) at the base of clayey diamicton on Peninsula Point and dates of 14 130 ± 440 (GSC – 485) and 17 860 ± 260 (GSC – 481) from peat near the base of a clayey diamicton at Ibyuk Pingo (Fyles *et al.*, 1972) indicate earlier thermokarst development.

A deterioration in the climate at about 3600 B.P. (Ritchie and Hare, 1971) caused most slopes to stabilize and allowed the erosion of lake outlets to proceed without hindrance from ice slumping and solifluction. Once the lakes were drained, permafrost began to aggrade in the lacustrine sediments, segregated ground ice and ice wedges formed, and pingos developed.

Development of thick, organic deposits has been confined to the last 12 000 years. As organic deposits develop mainly in poorly drained depressions and lake plains, in many cases they are related to thermokarst activity. Peat growth is probably low at present in comparison to the relatively warm period between 11 000 and 3600 B.P.

Surface and near surface marine deposits near Tuktoyaktuk are all youthful. The beaches and spits are reworked almost every year and new sediment is added to the intertidal areas annually. The high parts of all areas, however, may only be affected during exceptionally high storm tides, which apparently occur about every twenty years.

ENGINEERING AND ENVIRONMENTAL CONSIDERATIONS

Tuktoyaktuk, being in an area of ice-rich permafrost, is vulnerable to (1) thermokarst subsidence and erosion caused by surface disturbance and (2) coastal retreat hastened by the presence of icy sediments. Either stripping of the surface vegetation or removal of the underlying substrata generally is undesirable, for this leads to thawing of the underlying material, further lowering of the surface, and in some cases ponding of water. Eventually sufficient material accumulates in the depression to prevent further permafrost degradation. Permafrost degradation is a serious possibility in all ice-rich sediments and in deposits with shallow ground ice (usually aggradational). In general most marine beaches and glaciofluvial gravels, some glaciofluvial sand, and rare morainic deposits will not have high, near-surface, ground ice content.

Stripping on slopes where the underlying material has much ice is unwise, for running water may remove the incoherent thawed material to induce further melting with resultant deepening of the trench. If a massive icy body underlies the slope, the result can be even more disastrous, for a ground-ice slump will develop and alter the landscape significantly. Such massive ice bodies generally are restricted to morainal deposits altered by thermokarst and in terraced lacustrine deposits.

Because of these hazards all structures should be placed on piles, a gravel pad, or some other structure to prevent a thickening of the active layer. Roads should be built without significantly altering drainage as damming of water can cause significant thermokarst activity. The presence of ground ice, specifically massive ice, will cause major subsidence if the ground thaws to any depth; any object that would act as a heat source should not be buried where massive ice is present.

Unless man intervenes, coastal retreat at Flagpole Point and on the seaward side of Tuktoyaktuk Island undoubtedly will continue at an average rate of 12.5 feet per year, even though yearly rates may vary from 0 to more than 45 feet. Other parts of the coast probably will retreat at rates similar to those between the years 1950 and 1971 (Figs. 13 and 14). Undoubtedly some areas will be more stable and others less stable than they were during that period due to changes in coastal configuration and the type of sediment eroded as the coastline retreats.

Removal of sand and gravel from spits will speed coastal retreat, for removal of material from a spit reduces the energy required to move it landward. Adjacent areas probably will be affected only inasmuch as irregularities in the coastline tend to be removed by erosion, thus, if a spit moves rapidly inland, adjacent headlands will be subjected to slightly increased erosion until the coastline is brought back to a form of near equilibrium. The numerous indentations along the coast appear to impede the interchange of material from spit to spit, and therefore removal of material from one spit system will not necessarily affect the sand and gravel supply of adjacent spit and beach systems seriously. Mining of the spits and beaches likely should terminate as soon as a road to the south is constructed, for more than adequate supplies of aggregate are available about 15 miles south of Tuktoyaktuk.

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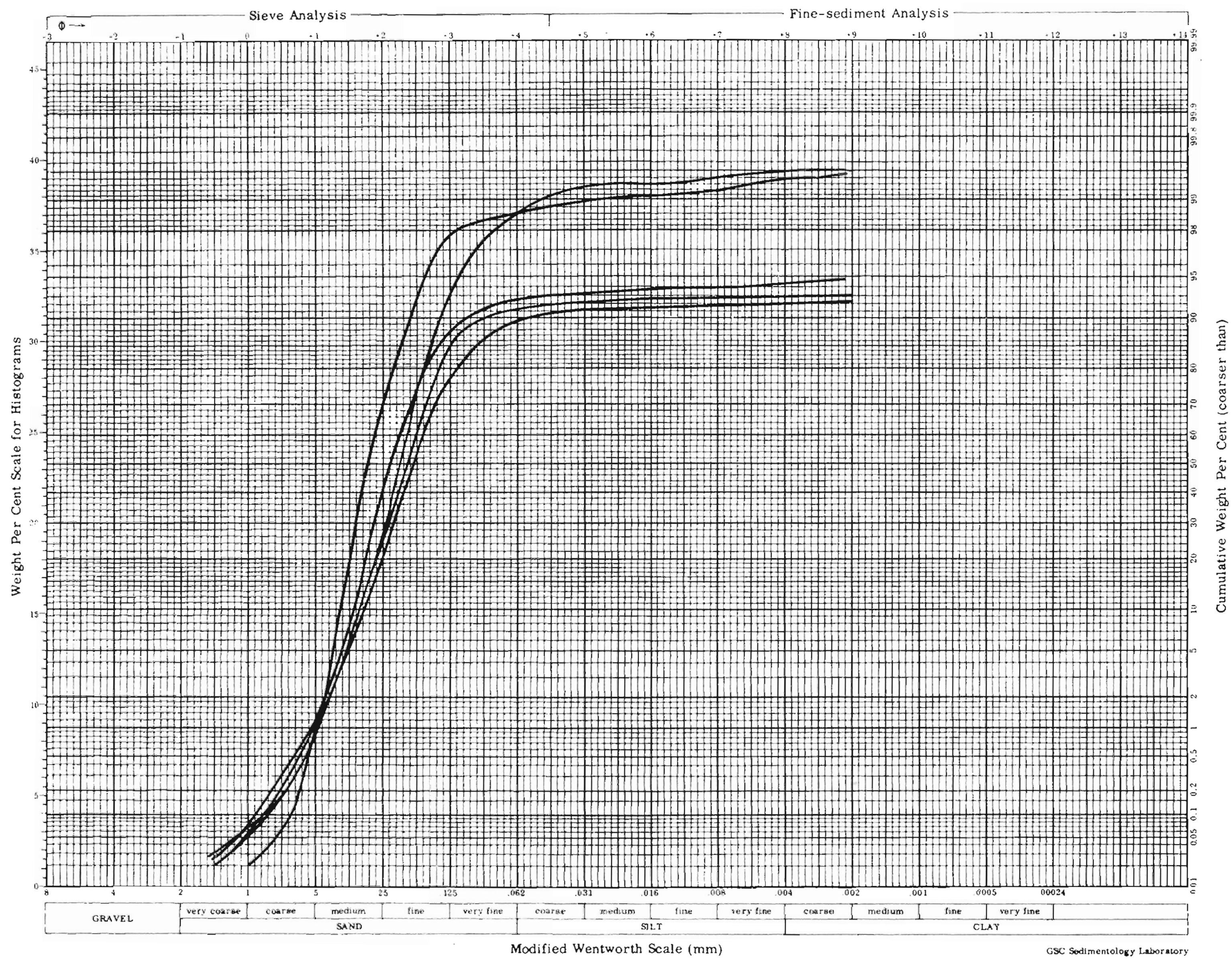
Appendix A.

LOGARITHMIC-PROBABILITY GRAPH OF GRAIN-SIZE DISTRIBUTION OF SANDS AT TUKTOYAKTUK

Field No.________ Lab. No ________



Appendix B.

LOGARITHMIC PROBABILITY GRAPH OF GRAIN-SIZE DISTRIBUTION OF DIAMICTONS AND LACUSTRINE DEPOSITS

Lab. No. ______