Contents

Author Index

Surficial geology, subsurface materials, and thaw sensitivity of sediments

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Abstract: The surficial geology of the Mackenzie valley and adjacent areas is presented in 1:1 000 000 scale compilation maps and is accompanied by geotechnical data from 56 boreholes chosen to represent typical stratigraphy of each major geological unit at several locations along the valley. For each of the representative boreholes, the potential for settlement of the ground surface as frozen ground thaws is determined, based on the thaw strain calculated for each soil layer of the borehole. Those geological materials most sensitive to thaw settlement are lacustrine and morainal, ice-rich, fine-grained sediments, and also the ice-rich and potentially highly compressible peat bogs. Much of the Mackenzie region is underlain by these materials; thus extensive terrain is susceptible to the impact of warming climatic conditions.

Résumé : La géologie des dépôts superficiels de la vallée du Mackenzie et des régions adjacentes est représentée sur des cartes de compilation dressées à l'échelle de 1/1 000 000. À ces cartes, s'ajoutent des données géotechniques provenant de 56 sondages choisis pour établir la stratigraphie typique de chacune des principales unités géologiques en différents endroits de la vallée. On a déterminé pour chaque sondage représentatif le tassement possible de la surface du sol suite à un dégel, en se basant sur la déformation causée par le dégel de chacune des couches de sol traversées par le sondage. Les matériaux les plus susceptibles de se tasser suite à un dégel sont les sédiments lacustres et morainiques à grain fin et riches en glace, ainsi que les tourbières oligotrophes à contenu élevé en glace qui affichent un potentiel de compressibilité élevé. Ces matériaux composent la grande partie de la région du Mackenzie; c'est pourquoi cette vaste contrée risque de subir les effets d'un réchauffement climatique.

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Contents

Author Index

INTRODUCTION

A thorough understanding of surficial sediments and their ice content in the Mackenzie valley is key to predicting the impact of climate change on geological processes such as ground subsidence and landsliding. In this paper, the surficial geology of the Mackenzie valley and adjacent areas is summarized, and geotechnical data are presented from selected boreholes chosen to represent typical stratigraphy of each major geological unit at several locations along the valley. For each of the representative boreholes, the potential for settlement of the ground surface as frozen ground thaws is calculated. Finally, general conclusions as to the thaw-settlement potential of the major surficial geology units are made.

SURFICIAL GEOLOGY

Methodology

Maps at 1:1 000 000 scale (Fig. 1a, b, in pocket) of the surficial geology of the Mackenzie valley, adjacent mountains, Mackenzie Delta, and adjacent Beaufort Sea coast were compiled from existing published and unpublished surficial geology maps. Of these, detailed geology at 1:250 000 scale of the northernmost area (68–70°N) was mapped by Rampton (1981a, b). The central area (64–68°N) was mapped at 1:250 000 scale by Duk-Rodkin and Hughes (1992a, b, c, d, e, f, g, h, 1993a, b, in press a, b). The geology of the area east of longitude 126°W and between 64°N and 66°N was compiled from various reconnaissance-level geology maps by Fulton (1970), Hughes (1970), Hanley (1973), and Hanley et al. (1975). For the southern area (60–64°N) the existing compilation map at 1:500 000 scale by Rutter et al. (1993) was augmented with peatland data derived from earlier 1:125 000 scale maps by Rutter and Boydell (1979, 1980a, b, c, 1981) and Rutter et al. (1980a, b, c, d, e, f)

At the 1:1 00 000 compilation scale, some details of the geology are lost due to the merging of geologically similar units and the disappearance of smaller units. Wherever possible, the maximum level of detail was retained. In a few areas, compilation was difficult because adjoining published maps were produced at different scales or different levels of detail. In these cases, some geological units end abruptly at the margin of the original map sheet (i.e. 64°N latitude or 126°W longitude); however, as the original sheets were mapped as part of large blocks using common legends, these boundary problems are limited.

A brief description of the origin, texture, thickness, morphology, drainage characteristics, permafrost, and ground-ice conditions of each map unit is provided in the legend accompanying the compilation map (Fig. 1a, b). This information is derived from legends accompanying the original surficial geology maps and the amount of detail, particularly with respect to permafrost and ground-ice conditions, varies accordingly. Thickness of permafrost is not included within permafrost conditions.

Surficial materials

Surficial materials are sediments deposited by ice, water, wind, and gravity during Quaternary time — the ice ages through to the present. The detailed glacial and deglacial history of the area is covered by Duk-Rodkin and Lemmen (2000). Permafrost currently underlies most of the Mackenzie valley; as a result, surficial deposits are generally frozen and frequently contain ground ice. A discussion of permafrost distribution and ground-ice types and conditions is presented by Heginbottom (2000). The general distribution and nature of surficial materials is summarized below.

Much of the Mackenzie valley has a thin and discontinuous to thick and continuous cover of glacial ground moraine (till) which, in places, blankets or veneers the underlying bedrock topography and in other areas imparts a hummocky, rolling, or streamlined morphology to the surface (Fig. 2). Till is a composite of clay-sized to boulder-sized materials; where the matrix is fine grained, ground ice is often present. Till underlies many of the other surficial units. Associated with the glacial sediments are more localized areas of glaciofluvial sand and gravel that were deposited by meltwater in, under, or near the glacier ice. These deposits either take the form of hummocky and ridged topography, or broad, commonly pitted, outwash plains and terraces. These coarser grained sediments, essential for construction, are usually well drained and less susceptible to ground-ice formation.

Thick deposits of glaciolacustrine and lacustrine silt and clay typify much of the central axis of the Mackenzie valley. They mark the position of temporary, large lake basins formed during deglaciation due to the combined effect of isostatic depression of the surface and the damming of drainage behind retreating ice margins. These fine-grained sediments are particularly susceptible to the formation of ground ice, and consequently thermokarst features are widespread. In places, the silt and clay deposits are covered by sand of raised deltas.

Following the drainage of the glacial lakes, the exposed lake beds were subjected to the action of wind and flowing water. In places, large dune fields, now stable, formed on the exposed lake bed. These dunes impede local drainage, creating conditions favourable to the accumulation of organic materials. Elsewhere, alluvial terraces were formed as the Mackenzie River and its tributaries eroded the lacustrine sediments in response to lower base levels. Alluvial sediments, locally ranging from silt to sand and gravel, cap many of these terraces. The Mackenzie River delivered sediments forming a delta on the Beaufort Sea — a process that continues to the present day. Modern alluvial deposition continues on the floodplains, and point bars and channel bars of the rivers.

Peatlands are thick accumulations of organic materials that overlie extensive areas of flat-lying, poorly drained lacustrine sediments. They are also found in depressions in ground moraine and, less frequently, other surficial geology units. In the Mackenzie valley, two classes of peatlands occur: fen, commonly unfrozen, and bog, generally frozen and ice rich (*see* Aylsworth and Kettles, 2000). Thermokarst is widespread in the latter.

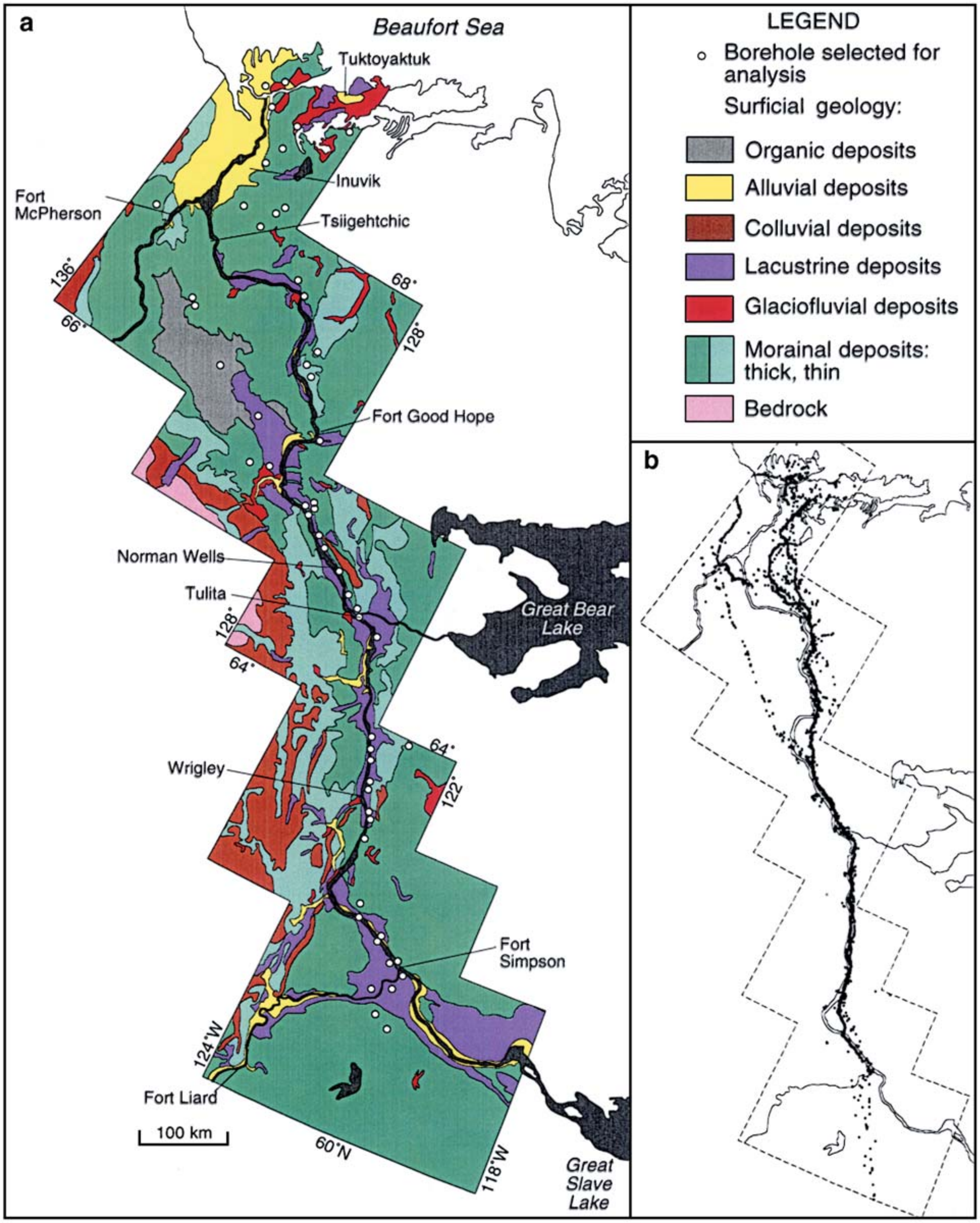

Figure 2. a*) Major surficial geology units in the Mackenzie valley and adjacent areas and location of the boreholes selected for analysis. For detailed geology see Figures 1a and 1b in pocket.* ***b)*** *Distribution of geotechnical boreholes in the Mackenzie valley.*

Contents

Author Index

Colluvial sediments characterize the surface of much of the mountainous areas, although they also occur on steeper valley sides cut into more subdued landscapes. These materials result from the downslope movement of material under the influence of gravity at speeds ranging from a slow creep to rapid landslides. Colluvium is derived from weathered bedrock as well as the entire range of surficial deposits; the texture and ice conditions of colluvium reflect the original deposit. Fine-grained colluvial material may contain segregated ice. In some instances it is the thaw of ice-rich sediments which induces the downslope movement of material.

Fine-grained till and lacustrine sediments characterize much of the Beaufort coastal plain. Both contain massive bodies of ground ice and are especially prone to thaw-induced slope failures and thermokarst development. Eolian dunes are associated with several extensive areas of hummocky glaciofluvial sand and gravel. Although marine sediments are known to underlie the surface deposits in a few locations within the coastal plain, marine deposits are, for the most part, restricted to beaches and tidal ponds along the modern coastline. Alluvial deposits are present along the alluvial channels of the Mackenzie River system and on the Mackenzie Delta.

SUBSURFACE MATERIALS

Methodology

Selected boreholes were chosen from the 'Mackenzie Valley Geotechnical Database' to represent the typical stratigraphy of surficial geology units for several locations along the valley (Fig. 2a). The database (updated from GSC Open File 350 by Lawrence and Proudfoot (1976)) contains records of over 12 000 boreholes drilled for route selection and design of pipelines and roads, either proposed or constructed, in the Mackenzie valley since the 1970s. The boreholes thus are concentrated in corridors aligned with these routes (Fig. 2b).

The main criterion in selecting a representative borehole was an examination of the soil description. In addition, an effort was made to select boreholes that also contained sufficient geotechnical data to allow an estimate of the response to thaw (when the unit is described as generally frozen). Depths of selected boreholes are typically less than 15 m.

Borehole data

Borehole information is presented on Figures 1a and 1b. Note that some boreholes were situated in small material units that have been lost in map compilation. Thus, on the compilation maps, these boreholes now seem to lie within a different material unit (i.e. number 3, a borehole in glaciofluvial sediments, lies within a moraine plain unit). Figure 3 provides details on the nature and layout of the borehole data; the borehole identifier is that from the geotechnical database. Material properties are plotted with depth. Beginning with the first two columns at the left are a simplified lithology (*see* legend on Fig. 1a and 1b) based on the field description of the major soil layers, and the USC code (Unified Soil Classification system). The USC system (American Standard Test Method, 1990) is widely used by engineers and geologists for soil classification of samples collected from geotechnical boreholes. The USC codes are positioned at the approximate depth where samples were taken. When a sample is coded the same as an overlying one, an asterisk appears in the column at the sample depth. Note also that since the simplified lithology is based on a field description, and the USC description is generally based on laboratory analysis, there may be discrepancies between these two columns.

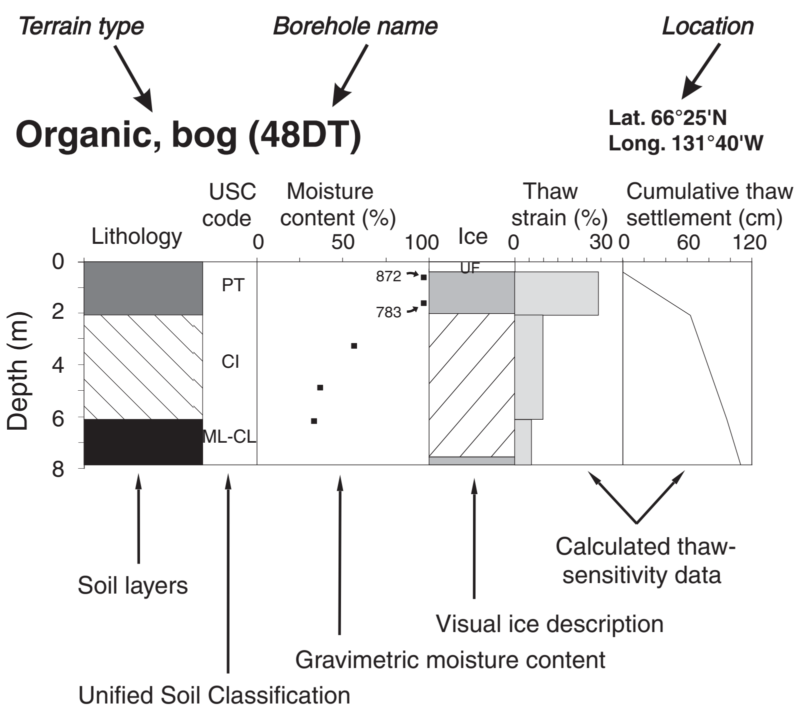

Figure 3.

Example of representative borehole log.

Contents

Author Index

Moisture contents (expressed as per cent of dry weight) from borehole samples are plotted in the third column. Where the moisture content is greater than 100%, the value is indicated at the correct depth. The borehole logs of frozen sites generally include a description of the ground ice, based on the National Research Council classification system developed by Pihlainen and Johnston (1963). A record of ice encountered is contained in the fourth column. An explanation of colours and codes is provided in the legend. For a detailed statistical analysis of the occurrence of visible ground ice within the entire geotechnical database, *see* Heginbottom et al. (1978). For a quantitative examination of the percentage of visible ice along the Norman Wells pipeline, see Burgess and Lawrence (2000).

None of the borehole data should be presumed to represent conditions outside the borehole corridors. This is particularly true where there is a difference in altitude, because of differences in climate and associated changes in ground temperature. For example, at the southern end of the Mackenzie valley, along the Norman Wells pipeline, permafrost occurrence increases with elevation onto the Alberta plateau (*see* Burgess and Lawrence, 2000). On the other hand, in the vicinity of Norman Wells, permafrost may disappear with increase in altitude; permafrost exists at a site in the valley floor, but is not present at a site about 250 m higher in elevation (*see* Burgess and Lawrence, 2000). Such a difference near Norman Wells may be related to pronounced winter air-temperature inversions in the region. As well, broad regional trends in permafrost conditions related to general climate trends while local variability exists due to differences in site specific conditions such as aspect, snow cover, vegetation, thickness of insulating organic mat, and shifting stream channels (*see* Burgess and Smith, 2000; Dyke, 2000).

THAW CHARACTERISTICS OF SUBSURFACE MATERIALS

Methodology

An estimate of thaw settlement for each borehole was determined using the thaw strain calculated for each soil layer. The thaw strain is a measure of the per cent change in height or thickness of a soil unit upon thaw, and is a function not only of the volume change involved in melting the ice, but also of the compressibility of the soil layer. The compressibility is generally one to two orders of magnitude smaller than the volume change due to thaw, particularly for the relatively thin thickness (less than 15 m) of unconsolidated material under consideration here, and therefore it has not been included in the calculations. Thaw strains were calculated using methods reported in the literature for major soil groups (Speer et al., 1973; McRoberts et al., 1978; Interprovincial Pipe Line (NW) Ltd., 1982). These methods require a knowledge of sediment type, and of one of the following properties: total moisture content, ice content, or frozen bulk density. Moisture content is most likely to be available. Calculated thaw strains for each frozen soil layer are provided whenever possible in the fifth column of the borehole data plots. (Note: thaw strains are 0 at low moisture contents, because there is no excess ice present).

The calculated thaw strains were then used to determine the cumulative thaw settlement at each borehole resulting from thawing to the bottom of the hole (or to bottom of permafrost if the permafrost was thinner than the total borehole depth). Regardless of the source or rate of thermal disturbance leading to thaw, this cumulative thaw settlement provides an indication of how settlement at the surface would increase as thaw progressed. The cumulative thaw-settlement plots begin at the depth where the borehole is logged as frozen, or from the top of the layer with sufficient data to calculate thaw strain. Since many boreholes were drilled in winter, this depth is often at the ground surface and hence includes the active layer (i.e. the zone that freezes and thaws annually). A discussion of active layers in the Mackenzie valley can be found elsewhere in this volume (*see* Nixon, 2000).

The abbreviation 'NA' appears in the thaw-strain and thaw-settlement columns whenever these calculations are not applicable, i.e. if there is no permafrost at the site, if the moisture contents are too low, or if the data is insufficient to allow a calculation of these parameters. Note also that the depth-scale increments are identical for all boreholes, but that the horizontal scales for moisture content, thaw strain, and thaw settlement vary from site to site.

Thaw sensitivity of sediments

The thaw sensitivity data represent actual calculations for specific sites and not the 'average' value from all boreholes in the corresponding terrain unit in the area. Despite this, several general and noteworthy trends can be seen in the data presented. Thaw strains generally decrease with increasingly deep soil layers for the borehole depth ranges presented here. In the north, however, the reverse is frequently observed, often as a result of buried massive ice (*see* for example boreholes for lacustrine and glaciofluvial units in the 68–70°N area).

The calculated cumulative thaw settlement that would occur at each permafrost site under thaw depth increases to 3 m and 5 m are given in Table 1. The warming causing the thaw is not linked to any particular source, be it natural, climatic, or anthropogenic, nor to any particular duration. For a discussion of the rate and magnitude of thawing at select locations in response to different rates of climate warming in the Mackenzie valley, *see* Burgess et al. (2000).

Organic, moraine, and lacustrine units show the greatest thaw strains. There is also a tendency towards increasing thaw strain with increasing latitude, especially for lacustrine and moraine units. For example, 5 m of thaw in moraine in the 64–66°N zone could lead to 10–25 cm of settlement, but could result in 50–80 cm of settlement in moraine of the northernmost areas between 68–70°N. Frozen organic terrain on the other hand has high thaw strains wherever encountered. For example, 5 m of thaw within frozen bog could result in 50 to 120 cm of settlement. Alluvial terrain is frequently thawed, but when frozen, thaw sensitivity is greater in the 64–66°N zone due to the finer texture of sediments there. Glaciofluvial terrains, commonly coarse-grained sands and gravel, show low thaw strains and thaw settlements of

Table 1. Calculated thaw settlement (in centimetres) for the representative boreholes at different zones of latitude, using a thaw depth of 3 m and a thaw depth of 5 m.

Terrain unit	60–62°N		62–64°N		64–66°N		66–68°N		68–70°N	
	3 m	5 m	3 m	5 m	3 m	5 m	3 m	5 m	3 m	5 m
Organic (fen)	uf	uf					***38***	***38***		
Organic (bog)	48	50	86	117	77 73	90 120	48 70	49++ 87		
Alluvial fan			uf	uf			17	18		
Alluvial plain			7	7+	55	80	uf	uf	20	38
Alluvial terrace	uf	uf	10	***16***	31	43			uf	uf
Colluvial complex			15	20++	uf	uf			9	25
Eolian ridges	uf	uf	uf	uf			13	22		
Lacustrine plain	uf	uf			19	21	49	66		
Lacustrine plain (fine-grained sediment)			8	17	23	26			20 33	150+ 50
Lacustrine plain (coarse-grained sediment)			uf	uf						
Lacustrine complex					52	64				
Glaciofluvial plain	uf	uf			2	7	2	8		
Glaciofluvial terrace			6	10++	10	25			6	12
Glaciofluvial, hummocky							0	0		
Glaciofluvial complex							0	5		
Moraine plain	uf	uf	18	20++	21	25	54	70		
Moraine, rolling							18	31	75 43	82 49
Moraine, drumlinoid plain			25	28++	8	11	2	3		
Moraine, hummocky			15	27	27+	I.D.	54	61		
Moraine blanket									38	52

Notes: Blank entries indicate this is not a major unit within the map zone or no borehole fell within this unit.
Values in ***bold italic*** indicate that this is a maximum value for the borehole, since no permafrost remains below that depth.
'+' indicates that the borehole is less than 5 m deep and therefore the settlement reported is a minimum value.
'++' indicates that the value has been extrapolated from the data, e.g. where the hole is slightly shallower than 3 or 5 m.
'uf' indicates the terrain unit is a major one on the map sheet, and the borehole is unfrozen.
'I.D.' indicates insufficient data to estimate, e.g. hole too shallow.

less than 25 cm for a 5 m thaw depth. However, should massive ice underlie glaciofluvial and lacustrine units, greater thaw strains and settlement would be anticipated.

SUMMARY

The response of terrain to changing climatic conditions has particular significance for the design, construction, and maintenance of infrastructure and buildings on permafrost soils in the Mackenzie valley. Thick deposits of glaciolacustrine and lacustrine silts and clays, fine-grained tills, and thick accumulations of organic materials (especially in the south), are characteristic of much of the surficial materials of the Mackenzie valley. These subsurface materials are generally frozen and frequently ice rich. The presence of this excess ice causes these soils to be sensitive to climate warming — when subjected to thaw they will undergo some amount of thaw settlement for a period of time. The subsurface data presented in this paper quantify the potential thaw settlement of the major terrain units, while the accompanying figures show the distribution of the most thaw-sensitive materials. Those regions most sensitive to thaw settlement will be extensive areas of lacustrine and morainal, ice-rich, fine-grained sediments, and the ice-rich and potentially highly compressible peat bogs.

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Author Index

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