Ground ice determinations along the Yukon coast using a morphological model

Nicole J. Couture
Geological Survey of Canada, Natural Resources Canada, Ottawa, ON, Canada
Wayne H. Pollard
Dept. of Geography, McGill University, Montreal, QC, Canada

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ABSTRACT
Permafrost in the Canadian western Arctic contains large amounts of ground ice and a geomorphological model is used to estimate ground ice content. The Yukon coastline was divided into 44 different terrain units based on geology, coastal morphology, and the presence of different types of ground ice. The overall volume of ground ice within a terrain unit was assessed based on the stratigraphic relationships between different ice types. Ice volumes in the various terrain units ranged from 0 to 74% and were a function of surficial material. Across the entire study area, ground ice accounts for 46% by volume of all earth materials. Pore ice and thin segregated lenses account for 76% of the total ground ice, massive ice accounts for 21%, and wedge ice for 3%.

RÉSUMÉ
Le pergélisol dans l'Arctique de l'ouest du Canada contient un volume important de glace de sol. Un modèle géomorphologique est utilisé pour évaluer la teneur en glace de ces sols. La côte du Yukon est divisée en 44 unités de terrain distinctes selon la géologie, la morphologie côtière, ainsi que les différents types de glace de sol retrouvé dans les unités. Le volume total de glace de sol est déterminé en se basant sur les relations stratigraphiques entre les différents types de glace de sol. Le volume de glace dans les différentes unités de terrain varie entre 0 et 74% et est influencé par la géologie des dépôts de surface. Le volume de glace de sol représente 46% du volume total des matériaux côtiers dans la région d'étude. Le volume total de glace de sol est constitué de: 76% de glace interstitielle et de lentilles de glace de ségrégation minces, 21% de glace massive et 3% de coins de glace.

1 INTRODUCTION

Ice in permafrost occurs when water freezes within the sediment or when surface ice is buried. Regardless of the origin of the ice, it is often the actual volume of ground ice that is of interest, since it is a major contributing factor in the response of the permafrost system to environmental changes or to human development. The Yukon Coastal Plain in the Canadian western Arctic is one of the most ice-rich areas of the country and, volumetrically, ground ice can constitute up to 70% of the upper portion of permafrost (French et al. 1986). Although several studies have general descriptions of ground ice contents along the Yukon Coastal Plain (Rampton 1974; 1982; Harper 1990; Harper et al. 1985) and a number of others give detailed assessments of ground ice volumes at specific sites (O'Connor and Associates 1986; Harry et al. 1985; 1988; Pollard 1990; 1991; Pollard and Dallimore 1988; de Krom 1990; McDonald and Lewis 1973), the research presented here provides a detailed assessment of ground ice volumes for the entire Yukon coast.

Determining the ground ice contents for Arctic coastal regions is important because of their susceptibility to environmental change and the potential for increased erosion. These areas are likely to be disproportionally affected by climate warming compared to other regions because they are at the interface of the land, the ocean and the atmosphere and are impinged on by changes on three different fronts. For instance, warmer air and sea temperatures will increase sensitivity to erosion, as will expected rises in sea level and the thermal expansion of the oceans (Shaw et al., 1998). Storms have been shown to be highly correlated with coastal erosion in some areas (Solomon et al.,1994) and an increase in their frequency is predicted (Lambert, 1995), as well as an increase in the open water period during which they exert the strongest influence on coastal retreat (McGillvray et al., 1993). Intensified coastal erosion will increase the amount of soil organic carbon being input into the Arctic Ocean from coastal sources, which in turn has implications for the

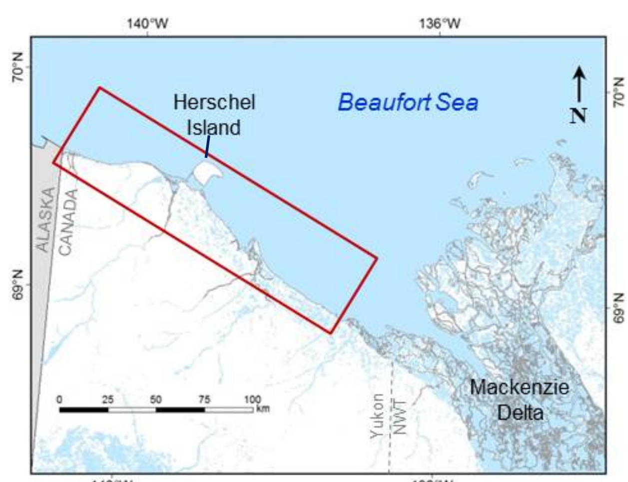

Figure 1. Location map indicating length of coast considered in this study (red rectangle).

ocean's ability to buffer atmospheric carbon dioxide.

The Yukon Coastal Plain is located along the Beaufort Sea west of the Mackenzie Delta (Figure 1). Most of the flat or gently sloping tundra landscape is covered by organic deposits, and peat beds are common, particularly in lacustrine basins (Rampton 1982). East of Herschel Island, surficial deposits consist of moraines, glacial outwash, and some lacustrine material. West of Herschel Island, deltas, alluvial fans, and lacustrine plains are observed. The region is within the continuous permafrost zone and permafrost reaches depths of approximately 300 m (Smith and Burgess 2000). Different types of ground ice are found, including pore ice, thin lenses of segregated ice, wedge ice, and large bodies of massive ice. This region is classified as having a low arctic climate, with a mean annual temperature of –11°C and mean annual precipitation between 200 and 300 mm. Beaches along the coast are generally narrow and are backed by coastal bluffs up to 60 m high, many of them comprised of unconsolidated and easily erodible sediments.

Coastal erosion in the Arctic is strongly influenced by the amount of ground ice present (Are, 1988) and several studies have shown correlations between erosion rates and ground ice content (e.g., Héquette and Barnes, 1990; Lantuit et al., 2012). The coasts of the Canadian Beaufort Sea currently have some of the highest erosion rates in the circum-Arctic, averaging 1.12 m/year (Lantuit et al., 2012). Along some parts of the Yukon Coastal Plain, however, long-term averages may be even higher (e.g., Harper et al., 1985; Forbes et al., 1995; Konopczak et al., 2014). By assessing the volume of ground ice in these deposits, this study will contribute to a better quantification of present-day carbon fluxes from this region and to improved projections of future erosion.

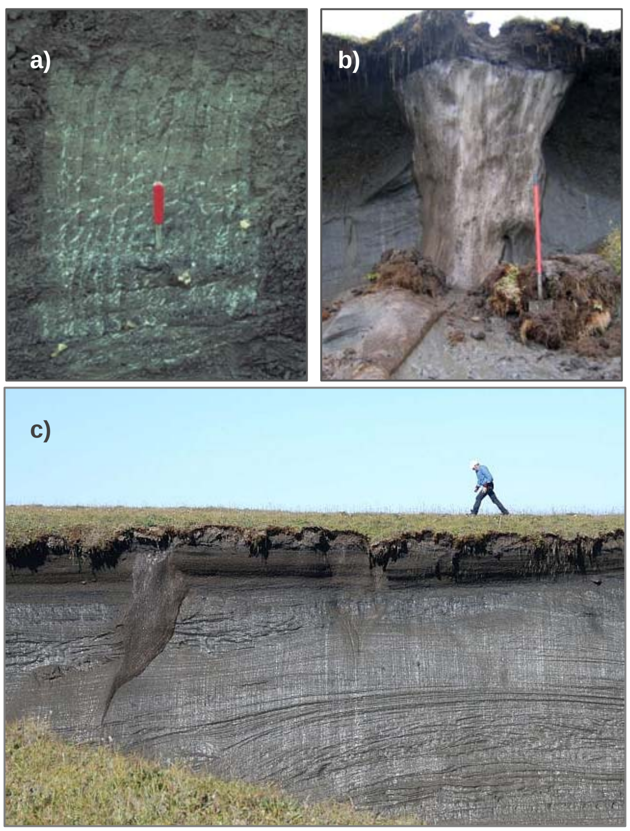

Figure 2. Different types of ground ice including a) pore ice, b) wedge ice, and c) massive ice (Photos: W. Pollard, H. Meyer, N. Couture).

2 METHODS

To assess ice content along the Yukon coast, a morphological model is used (Pollard and Couture 1999). The model calculates the total volume of ground ice for different terrain units along the coast by determining how much of each different type of ground ice is contained within that terrain unit. Terrain units were delineated using a detailed segmentation of the Canadian Beaufort Sea coastline that was conducted as part of the Arctic Coastal Dynamics (ACD) project, based on predominant landforms, surficial materials, permafrost conditions and coastal processes (Lantuit et al., 2012). This initial segmentation was then refined using direct field observations as well as data from the Coastal Information System (CIS) compiled by the Geological Survey of Canada (Couture et al., 2015), and studies by Rampton (1982), Wolfe et al. (2001), and Harper et al. (1985). The morphologic and geologic characteristics of each unit were used as input variables to the ground ice model. The thickness of material considered in the ground ice determination, depended on the height of the coastal bluffs. Heights were based on direct measurement or mean values from the ACD database. An average active layer thickness representative of the terrain unit was

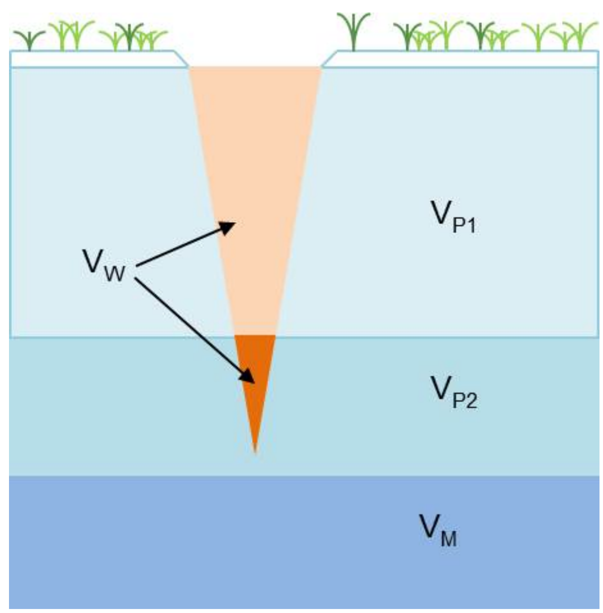

Figure 3. Diagram showing the possible stratigraphic relationship between different ice types in a profile. This terrain unit, for example, has two layers with differing amounts of pore ice and thin lenses of segregated ice (V_{P1} and V_{P2}), plus an ice wedge which penetrates into the second layer (V_W), plus a body of massive ice (V_M).

subtracted to obtain the actual thickness of materials used in calculations. In order to properly consider three dimensional variations in ice types, each segment was considered to extend 100 m back from the coast.

Three types of ground ice were considered in the model calculations: 1) pore ice and thin lenses of segregated ice, 2) wedge ice, and 3) bodies of massive ice (Figure 2). For each terrain unit, total ice volume was determined by examining the volume occupied by a given ice type and the percentage of volumetric ice content for each ice type. Using different model algorithms, ice volumes were adjusted to reflect the presence of wedge ice and massive ice in each horizontal layer, based on different geometric scenarios that account for the depths and stratigraphic relationships of the different ice types (Figure 3).

For the purposes of determining ice content due to pore ice and thin segregated lenses, the soil profile was separated into two horizontal layers (V_{P1} and V_{P2} in Figure 3) to account for the fact that ground ice contents are typically higher near the ground surface (Pollard and French 1980; Mackay 1970). Ice contents were measured in shallow cores and from the face of bluff exposures. For terrain units which could not be sampled, ice contents were extrapolated from units with similar characteristics or, where available, data from previously published site-specific reports were used. The volume of frozen material in each layer was then multiplied by the ice content to arrive at a volume of ice. This assumes that the permafrost materials consist only of sediments containing pore ice and thin segregated ice lenses, so this volume was later adjusted to account for the volume taken up by ice wedges and massive ice.

Wedge ice was quantified by estimating the length of wedges in a terrain unit based on the size of the polygons and therefore the spacing of the wedges. Size was measured directly or was from previous studies (Harry et al., 1985, 1988; Rampton, 1982; Solomon et al., 1994) The wedges were assumed to be triangular in cross-section and their volume was calculated geometrically using measured wedge dimensions. Because of the triangular shape of the wedges, they occupy different volumes in each of the horizontal layers being considered, so calculations were adjusted geometrically for each layer. Given the lack of volumetric ice content measurements for ice wedges in the region, a default of 88% was used, based on a measurement at one location within the study area.

Massive ice was considered to underlie a terrain unit only if a massive ice body or a significant number of retrogressive thaw slumps had been positively identified in a coastal unit. The mean depth to the top and bottom of massive ice bodies was directly measured or was estimated from published values. In several instances, the thickness of the massive ice body was difficult to determine since the lower part of the exposure was buried in slumped debris; in those cases, the massive ice was considered to extend to the base of the terrain unit. The calculated volume occupied by massive ice was adjusted if ice wedges extended down into the body of massive ice. The ice content of massive ice was from direct measurement or from site-specific published values. Where no values were available, a default of 80% volumetric ice content was used (based on massive ice, by definition, having a gravimetric ice content of 250%).

3 RESULTS

Based on the geomorphological characterization, the Yukon coastline was divided into 44 different terrain units. The terrain units ranged from 0.8 to 33.2 kilometers in length. Bluff heights for the different segments ranged from 0.9 m to as high as 60 m. Ice wedges were found in all units except for deltas and marine beaches, bars, and spits. Depths of the wedges ranged from 3.0 to 7.0 m (mean of 5.3 m), while the widths of the wedges were between 1.5 and 2.3 m (mean of 2.0 m). The mean spacing between wedges was 13 m. Massive ice was documented in 15 of the terrain units in either morainic or lacustrine materials. The thickness of the massive ice beds ranged from 2 to 9 m, with a mean of 4.3 m.

Total ice volumes for the different terrain units range from 0 to 74% and are a function of surficial material (Table 1). Mean volumes are lowest in the coarser grained coastal deposits in bars and spits (3%), while the highest ice volumes are found in more finely grained lacustrine deposits (54%). The distribution of the total ground ice for the different coastal segments is shown in Figure 4.

Model results show that over 180 million m^3 of ground ice is present in sediments along the Yukon coast. Volumetrically, this represents 46% of near surface earth materials (which includes sediments and ice). Across the entire study area, pore ice and thin segregated lenses account for 76% of the total volume of ground ice, wedge ice accounts for 3%, and massive ice for 21%. Figure 5 shows the percentages of the different types of ground ice per terrain unit from west to east (note that three units contain no ground ice).

Table 1. Ground ice volumes for terrain units with different surficial materials along the Yukon Coastal Plain.

Surficial material	Number of terrain units	Number of units with massive ice	Mean ice volume (%)	Range in ice volume (%)
Marine	10	0	3	1 - 6
Fluvial	5	0	13	0 - 39
Glacial outwash	3	0	46	42 - 57
Moraine	14	11	52	38 - 63
Lacustrine	12	4	54	30 - 74

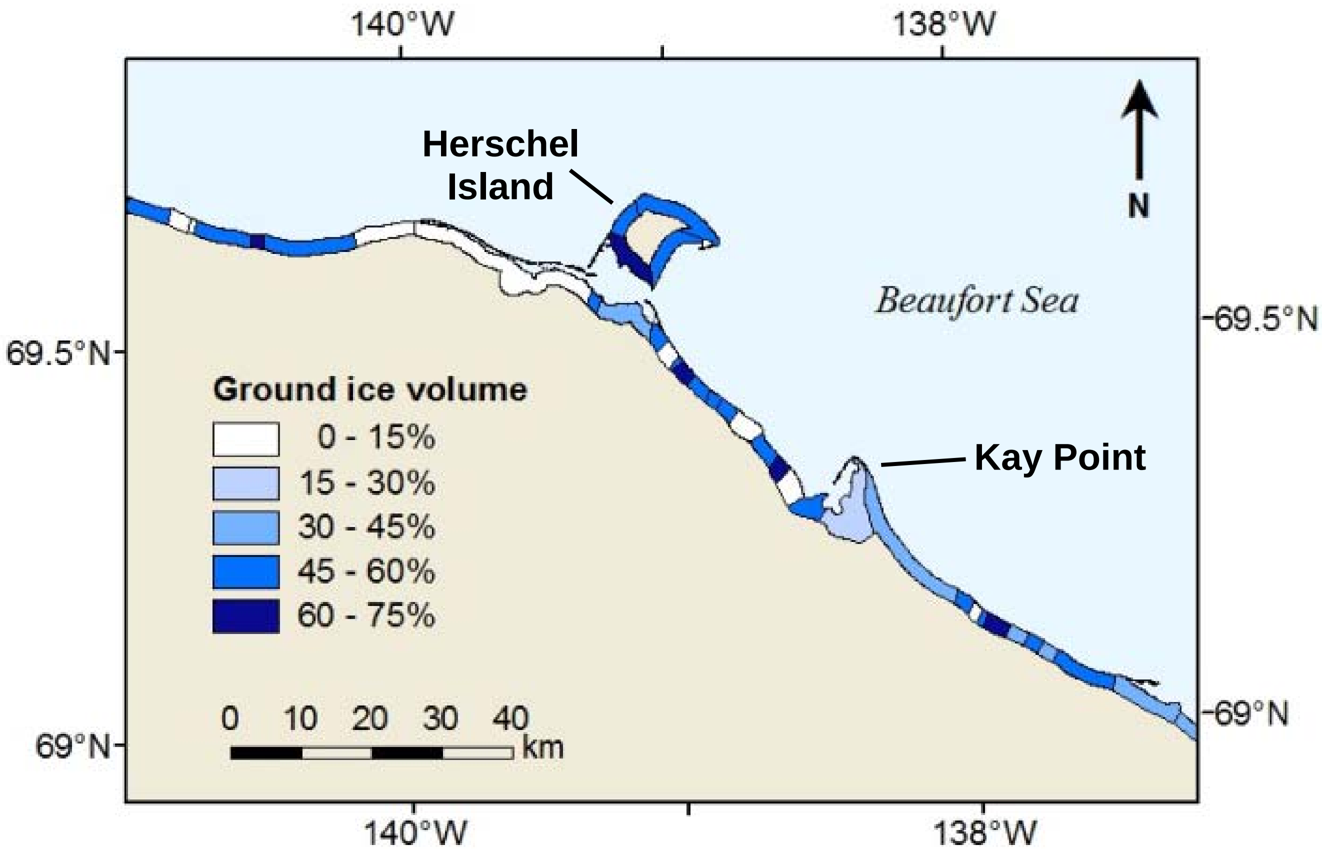

Figure 4. Ground ice content, by volume, for the different terrain units along the Yukon Coastal Plain.

4 DISCUSSION AND CONCLUSIONS

This study assesses ground ice volumes by accounting for the varying morphology and stratigraphy of terrain units along the Yukon Coastal Plain. The percentage of ground ice found here (46%) is similar to that calculated in other nearby regional studies. Pollard and French (1980) reported 47.5% ground ice in the top 10 m of permafrost on Richards Island (NWT) to the east of the study region. Along the Alaskan Coastal Plain, Brown (1968) found that ground ice comprised 46.6% of the upper 8 m of permafrost, while Kanevskiy et al. (2013) reported values of 77% for the top 2-3 m. Since ground ice volumes decrease with depth, the slightly lower values reported here may be explained by the fact that over a third of the Yukon coastline has bluffs higher than 10 m, hence, a greater volume of ice-poor material is included in this work. Lantuit et al. (2012) reported a volumetric ground ice content of 29.4% for the entire Canadian Beaufort Sea coast and included the entire bluff height in their calculations. The difference in ice content between the studies underlines the importance of considering morphologic variables (i.e., bluff height) in such assessments.

This study provides a quantification of ground ice at the landscape level for the entire Yukon coast. It illustrates how total ground ice volume and types vary in

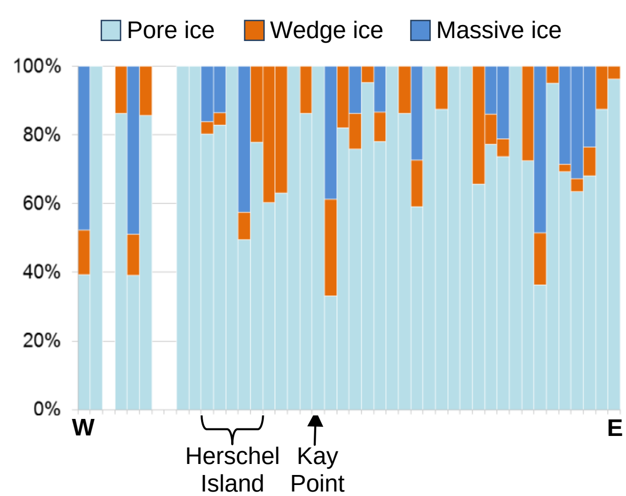

Figure 5. Ground ice types as a percentage of the total volume of ice for all terrain units, shown in geographic order from west to east. Three of the units contain no ground ice. The five units comprising Herschel Island and the Kay Point unit are indicated for reference with Figure 4.

terrain units with different geologies, coastal morphologies, and permafrost conditions. It considers the potential stratigraphic relationships between the different ice types and accounts for a variety of scenarios. The results allow us to draw the following conclusions:

1. Ground ice is an important component of sediments along the Yukon Coastal Plain, accounting for over 46% of earth materials. More than three quarters of this ice is pore ice and thin segregated lenses.

2. There is nevertheless considerable variation in total ground ice content among terrain units in the same region, much of it the result of differing surficial geology. Ice contents are lowest in coarse marine deposits and highest in morainal and lacustrine materials.

3. Because ice wedges are wider near the ground surface than at depth, wedge ice constitutes a greater percentage of the ground ice in low bluffs.

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