Estimation of Ice Wedge Volume on the Fosheim Peninsula, Ellesmere Island, Canadian High Arctic

Bernard-Grand'Maison, C.[1], Pollard, W.[2] & Copland, L.[1]

[1] Department of Geography, Environment and Geomatics, University of Ottawa; [2] Department of Geography, McGill University

cbern085@uottawa.ca

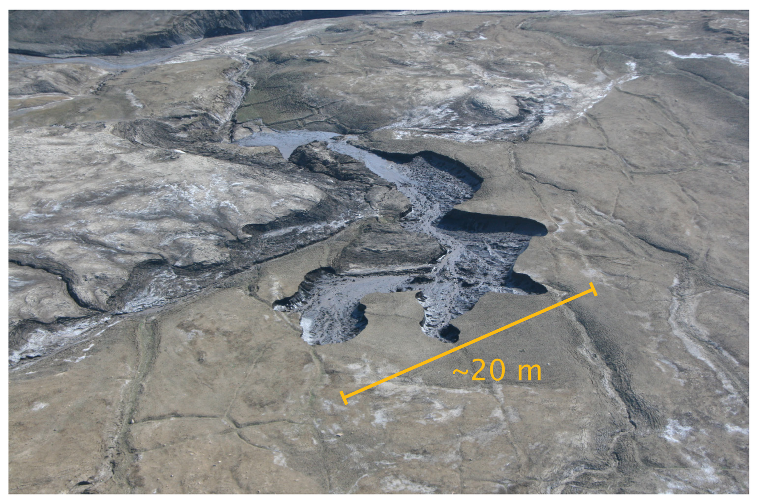
uOttawa McGill UNIVERSITY

Introduction

Estimating ground ice volumes is necessary to predict the sensitivity of permafrost terrain to temperature increase (Gilbert et al., 2016) (Fig. 1). This study focusses on estimating the volume of ice associated with ice wedges (Fig. 2) using a novel GIS-based approach on the Fosheim Peninsula (Fig. 3). Our goal is twofold:

1. **Ice wedge polygons delineation:** build upon the methodology introduced by Ulrich et al. (2014) to delineate ice wedge polygons on high-resolution satellite imagery using GIS by testing two semi-automated methods, namely *Thiessen Polygons* and *Watershed Segmentation*, and compare them with manual delineation;

2. **Ice wedge volume estimation:** perform a rough estimate of ice wedge ice volume of the Fosheim Peninsula by determining the potential coverage area of ice wedges from surficial geology data.



(a) Rapid melt out of ice wedges where massive ice is present, Fosheim Peninsula July 2017.

(b) Retrogressive thaw slump headwall with an exposed ice wedge (~6 m length) with no surface expression, Axel Heiberg Island, July 2016. Helicopter and person for scale.

Figure 1. Examples of thermokarst, i.e. processes related to permafrost degradation resulting from thawing of ice-rich permafrost (van Everdingen, 1998). The Canadian High Arctic permafrost is highly vulnerable to a slight temperature increase because it lacks strong insulation from vegetation and snow cover (Pollard et al., 2015).

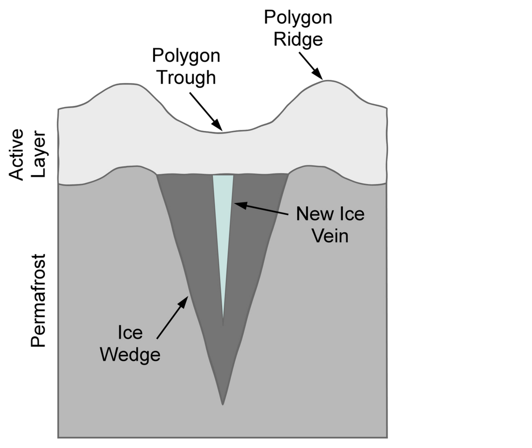


Figure 2. Representation of an ice wedge and its surface expression. Omnipresent in the Artic, ice wedges are wedge shaped bodies of nearly pure ice. They are created and grow from freezing of melt water infiltrating permafrost cracks (Lachenbruch, 1962). Intersections of ice wedge troughs create recognizable surficial polygonal patterns visible in satellite imagery.

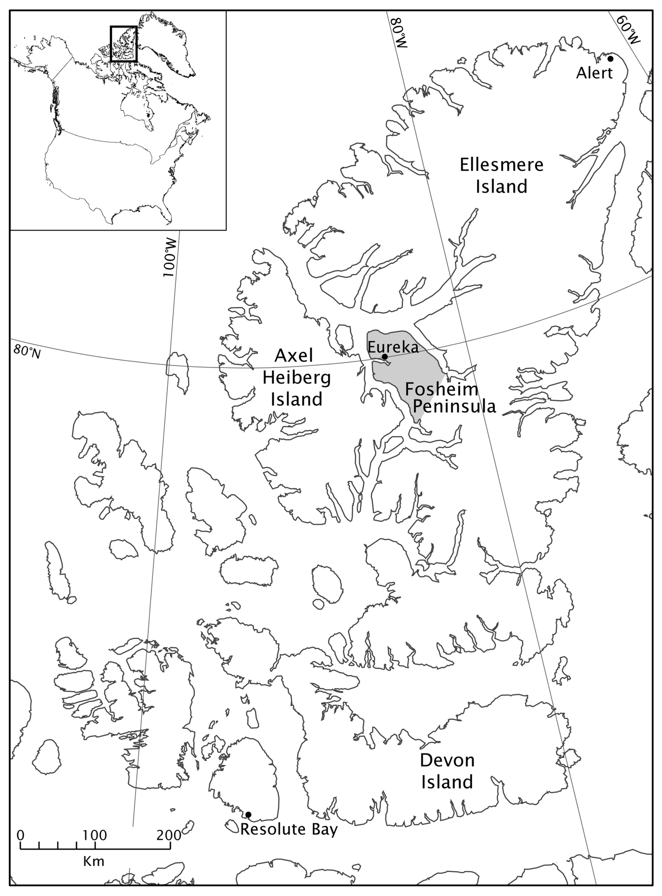


Figure 3. Location of the Fosheim Peninsula within the Eureka Sound Lowlands in the Canadian Arctic.The area is flat to gently rolling with mostly ice-rich silty-clay marine sediments and underlain by continuous, ~500 m deep permafrost with a thin active layer (30 – 100 cm) (Couture & Pollard, 2007).

Methodology

Main steps of our methodology, performed using ArcGIS (Version 10.3.1, ESRI):

1. Choice of four sample areas (250 m x 250 m) in the Eureka Sound Lowlands with various ice wedge polygon morphologies on *WorldView* 2 and 3 high-resolutions images (0.5 m/pixel)

2. Test/Adapt different techniques to delineate ice wedge polygons on each sample area:

   - **Manual delineation:** create a line dataset of trough centerlines manually to assess the accuracy of semi-automated method.Main delineation method used in Ulrich et al. (2014).
   - **Thiessen Polygons:** create Thiessen polygons from approximated center points of ice wedge polygons chosen by the analyst. Used at few sites in Ulrich et al. (2014).
   - **Watershed Segmentation:** interpretation of the pixel values as a height function and use of "Hydrology tools" to create watersheds representing each ice wedge polygon. Inspired from an image segmentation software algorithm used in Barraud et al. (2006) for petrographic analysis.

3. Create 3D subsurface models at each sample area for each technique: following the Ulrich et al. (2014) methodology, use of mean ice wedge width (1.46 m) and depth (3.23m) from field data, here from Couture & Pollard (1998).

4. Calculate the percentage of ice wedge volume at each sample area for each delineation technique using the "Surface Volume tool": consider only the top 5.9 m of permafrost to compare results with Couture & Pollard (1998).

5. Determine the potential coverage area of ice wedges on the Fosheim Peninsula from the digitization of the surficial geology map of Bell (1992)

6. Estimate the volume of ice wedge ice for the Fosheim Peninsula using the mean percentage ice wedge volume of the four sample areas obtained from the manual delineation technique

Results

1. Ice wedge polygons delineation

The Thiessen polygons technique is the least time consuming but simplifies polygon shapes as it cannot output curved lines and underestimates the ice wedge ice volume (Fig. 4). The Watershed Segmentation technique is the most accurate in trough localization and in ice wedge ice volume but requires supplementary manual editing to delete watershed boundaries over segmenting polygons. Implementation of both techniques in ArcGIS Model Builder greatly accelerated polygon delineation and demonstrates their potential to be applied to much larger areas in a time efficient manner.

2. Ice wedge volume estimation

Half of the Fosheim Peninsula surface area is potentially covered by ice wedges (±3,000 km^2, Fig. 5). Considering only the top 5.9 m of permafrost, this is equivalent to a volume of frozen material of 17.7 km^3. The total ice wedge ice volume is 0.67 km^3, when assuming an ice wedge volume of 3.81% by averaging the results from the manual delineation at the four sample areas. Our results are comparable to the study by Couture & Pollard (1998) in the Eureka Sound Lowlands region. From delineating ice wedge polygon on air photos, they defined low polygon density as 1.8% of volume and high density as 3.5%. Our sample areas EL1 and EL3 have a much higher ice wedge ice volume percentage, redefining "high density" polygonal terrain on the Fosheim Peninsula (Fig. 6).

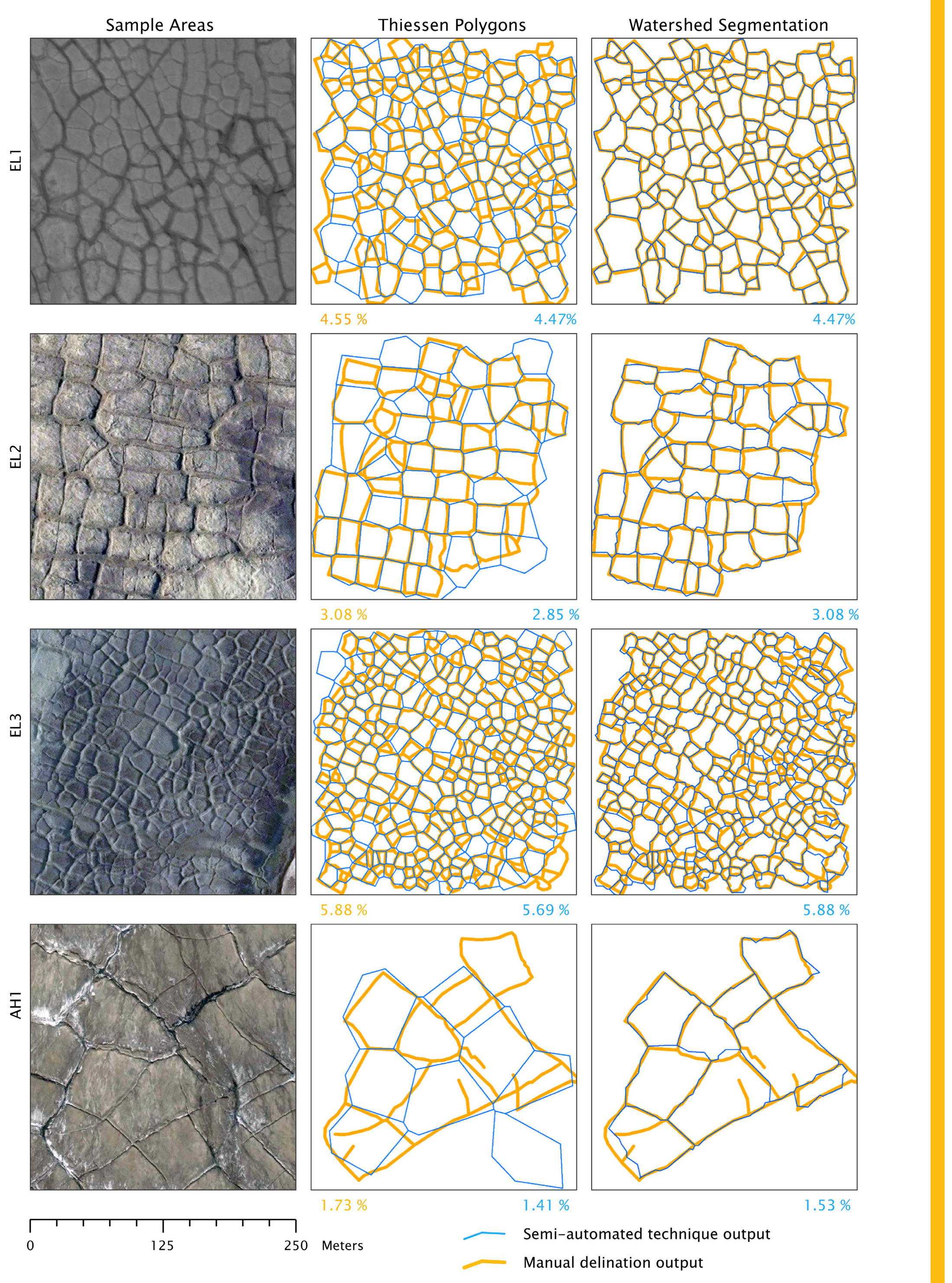


Figure 4. Original satellite image, delineation outputs and corresponding percentage of ice wedge volume for each delineation technique and sample area.

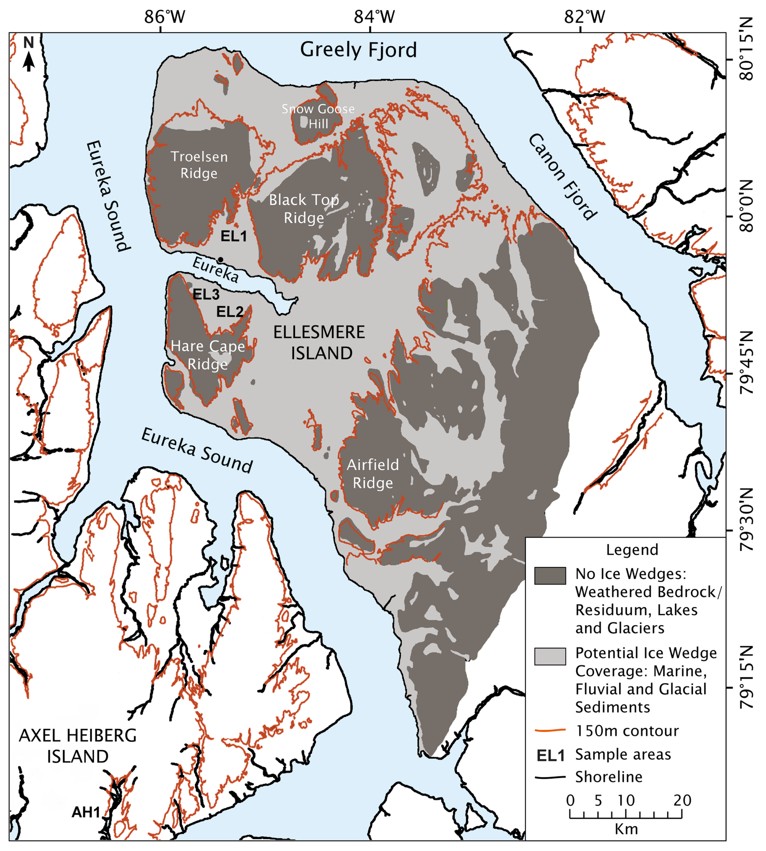


Figure 5. Potential coverage area of ice wedges on the Fosheim Peninsula. The 150 m contours are a proxy for the Holocene marine limit: massive ground ice and ice wedges are ubiquitous below this limit (Bell, 1996).

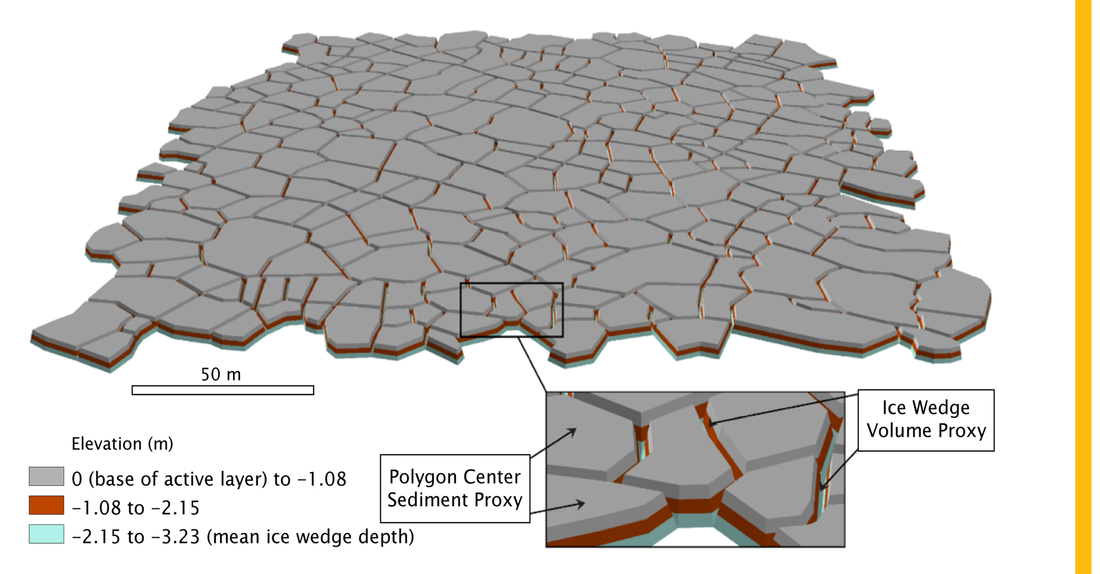


Figure 6. Example of a 3D subsurface model as a Triangular Irregular Network (TIN). The surface represents the entire EL3 sample area. Ice wedges are assumed to be isosceles triangles and composed of pure ice.

Future Work

Time constraint and required level of precision in the estimation of ice wedge volume are two criteria to be considered when choosing one of the delineation techniques presented above. Other promising remote sensing methods to detect topographic and subsurface change and to map ground ice distribution include LiDAR, InSAR and structure-from-motion technology (Jorgenson & Grosse, 2016). High resolution digital terrain models can be derived from these methods on which our watershed segmentation delineation technique could be applied with more confidence.

Fieldwork in the Eureka Sound Lowlands region could improve the ice wedge volume estimates by linking surficial geology and physiographic units with ice wedge polygon characteristics. The widespread nature of ice wedges will contribute to significant permafrost instability and ground subsidence once thermokarst processes are initiated. Associated with other ground ice estimates, large scale ice wedge volume estimations will help to assess the vulnerability of permafrost to climate change in the High Arctic and wherever they are present.

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