THE UTILITY OF 3D GROUND-PENETRATING RADAR IMAGING TO QUANTIFY SUBSURFACE ICE VOLUME: CONSIDERATIONS FOR POLYGONAL TERRAIN NETWORK DEVELOPMENT. C. N. Andres[1], G. R. Osinski[1], E. Godin[2] and A. Kukko[3]. [1]Department of Earth Sciences/Institute for Earth and Space Exploration, University of Western Ontario, London, ON, Canada, N6A 5B7 (candres5@uwo.ca), [2]Centre d'Études Nordiques, Université Laval, Québec, QC, Canada, G1V 0A6, [3]Finnish Geospatial Research Institute, FI-02430 Masala, Finland.

Introduction: Noninvasive 3D ground-penetrating radar (GPR) imaging was used to delineate the internal architecture and processes of the shallow subsurface in ice-wedge polygons. The GPR method records the two-way travel time of electromagnetic (EM) waves reflected at boundaries between subsurface layers with contrasting relative permittivity, which can be due to variations in sediment grain size, water content, and mineral composition [1,3,5]. Site-specific, comparative GPR allows for in depth analysis/interpretation of factors that may affect formation of subsurface features. Ice-wedge polygons are periglacial landforms of high interest as they house specific volumes of water-ice in the subsurface, which is a highly sought after resource in planetary exploration. Polygons are one of the most common landforms in the Arctic and on Mars formed via repeated freeze-thaw and meltwater infilling [2]. 3D GPR can provide great insight on the subsurface architecture and processes of these ice-rich features, that of which satellite imagery simply cannot provide.

Study Site and Methods: The objective of this research is to conduct a comparative study of subsurface ice in the Haughton Crater, Devon Island (75°22'01"N, 89°31'22"W) and in Strand Fiord, Axel Heiberg Island (79°09'43"N, 90°13'44"W), with implications to radar imaging and modelling of the shallow subsurface on high latitude regions of Mars (**Fig. 2**). These two sites are located in different types of substrate, climate, and latitude, however, they share similar features of polygonal patterned ground formations. More specifically, Devon Island is dry and cold (annual temp of -16°C/precipitation of <13 mm) and Axel Heiberg is relatively wet and cold (annual temp of -20°C/precipitation of 68mm) [8]. Using Sensors and Software Noggin 250MHz GPR, Ekko_Project software and MatLab 9.6 (R2019a), GPR models such as in **Fig. 1** were generated using several.

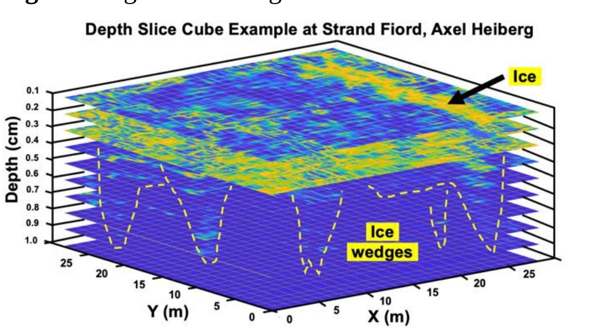

Fig 1. A depth slice cube of Strand Fiord showing concentrations of ice-rich radar returns in yellow/green correlating to ice-wedges in Model B **Fig. 3** (generated in MatLab 9.6).

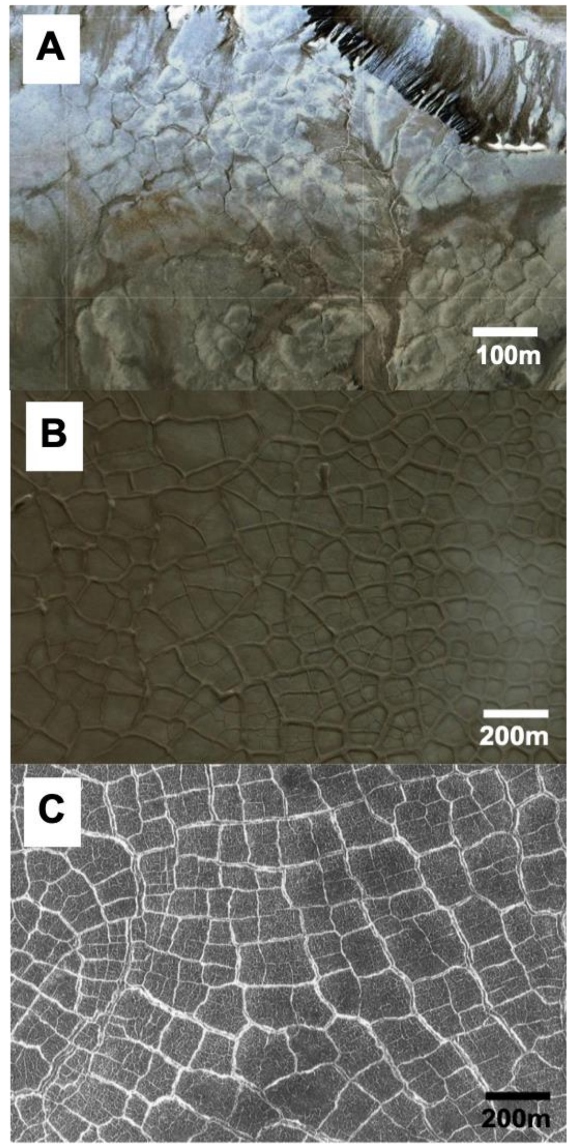

Fig 2. A localized mapping area of polygon networks on Earth, Haughton Crater **(A)**, Axel Heiberg **(B)**, and Utopia Planitia Mars **(C)**. Source: **(A, B)** Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community **(C)** HiRISE Image *ESP_56148_1145*.

processing techniques in order to filter the noise from the dataset and further extrapolate these line scans. Respectively, the processing elements that were used were the *dewow filter*, *background subtraction (total background), gain* (with a signal attenuation of 16db/m), *envelope filter*, and *migration* filter (frequency-wave number).

Radargram Profiles and Depth Slices. Horizontal slices (known as "depth slices" or "time slices") are essentially planview maps isolating specific depths. Time-slicing has become standard practice in GPR applications, because this patterning is often the most important indicator of varying signatures [3,4,5]. These planview maps (**Fig. 1)** are able to highlight surface structures and concentrations of ice at different depths.

3D GPR Model*: Ice Volume Calculation*. In order to model GPR data, an isosurface needs to be created in order to illustrate 3D shaded renderings from lattice files. They reflect the concept of a contour line (2D) and frames it in 3D space using matrices. Isosurfaces also display constant data values for a component that dissects a 3D volume, which in this case are the highest returns (filtered for ice-rich GPR signals).

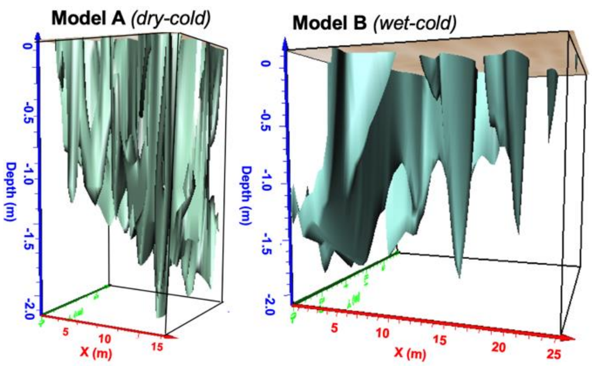

Fig 3. A snapshot of a 3D lattice video simulation, showing ice-wedge geometry and volume in (Model A) Haughton River Valley and (Model B) Strand Fiord.

Using the Voxler 4 software, a 3D simulation of ice-wedges can be modelled not only as a visualization tool but also as a calculator for subsurface ice volume. Volume calculations are generated from voxels (3D pixels) that are either partially or fully included in the isosurface. The total volume (isovalue) is the sum of the individual volumes from these voxels. In the Haughton River Valley, the volume of the ice-rich isosurface within the 15 m x 15 m GPR survey grid has been calculated to contain 32.7m^3 of water-ice (**Fig. 3; Model A**) as opposed to Strand Fiord, which has been calculated to house 43.28 m^3 of water-ice in a 25 m x 25 m GPR survey grid (**Fig. 3; Model B**).

Discussion: By comparing these two study sites, we are able to delineate two different periglacial environments – wet and cold (Strand Fiord) vs. dry and cold (Haughton). After 3D modelling of GPR data, it can be seen that the ice-wedges in the subsurface of Strand Fiord (**Figure 3; Model B**) are more well-defined and morphologically distinct. On the other hand, the ice-wedges in the Haughton River Valley (**Figure 3; Model A**) are more sporadic and not architecturally defined. This however, could be due to some limitations as well as error in the raw data itself. 3D modelling of GPR data can be limited by several factors, two of which are near-surface water and mineral concentration. Due to the soil's conductive nature, the GPR signals get "scattered" before it can return to the antenna when travelling through damp or wet soils, especially when they have high salt content or have a diverse lithology. For example, Haughton Crater is located in a clastic impact melt rock deposit, which can heavily impact signal attenuation due to differential dielectric constants.

Therefore, the Strand Fiord Model (Model B) is an accurate ice volume calculation/representation of a "wetter" and cold periglacial environment since it is consistent to have bigger ice-wedges with a greater amount of ice volume. The next step could be a temporal 3D GPR experiment in order to see fluctuations in ice volumes seasonally, which can give insight to secondary polygon and ice-wedge initiation [6,7].

Future Work: GPR has significant applications to planetary exploration with specific relevance to the *Radar Imager for Mars' Subsurface Experiment (RIMFAX).* Although GPR is a powerful tool in subsurface modelling, high-resolution surface ground-truthing and correlation using other datasets, such as LiDAR (**Fig. 4**) and facies sampling is the ideal complimentary fit to validate these top-of-the-surface expressions with subsurface processes.

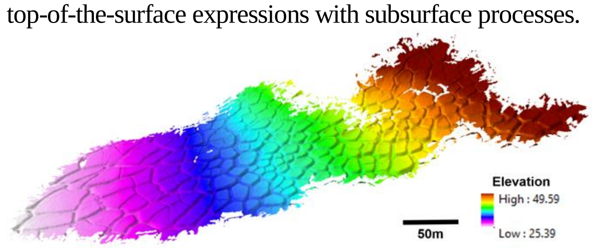

Fig 4. A digital elevation model of a portion of Strand Fiord, Axel Heiberg Island derived from the AkhkaR4DW backpack LiDAR instrument in 3cm resolution.

Since ice is one of the many potential subsurface signatures that can be seen on Earth and on Mars, it is important to expand on the broad capabilities of subsurface radar imaging not only for subsurface research but also in choosing sites that tend to be more ice-rich using periglacial geomorphology. This study begs to ask the questions: *Is it possible to tell if there is ice in a polygon network by simply investigating its morphology? If so, how much ice?*

References: [1] Grasmueck, M. et al. (2005) *Geophysics*, 70(1), 12-19. [2] Lachenbruch, A.H. (1962) *Geological Society of America.* [3] Brandt, O. et al. (2007) *Remote Sensing of Environment*, 111(2-3), 212-227. [4] Hinkel, K.M. et al. (2001) *Permafrost and Periglacial Processes*, 12(2), 179-190. [5] Munroe, J.S. et al. (2007) *Permafrost and Periglacial Processes*, 18(4), 309-321. [6] Godfrey, M.J. et al. (2008) *12th International Conference on Ground Penetrating Radar.* [7] Burn, C.R. and O'Neill, H.B. (2015) *Geotechnical Society*.[8] Government of Canada (2019) *Natural Resources Canada*