Planetary and Space Science 58 (2010) 472–481

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Electromagnetic characterization of polar ice-wedge polygons: Implications for periglacial studies on Mars and Earth

Alaura C. Singleton [a,*], Gordon R. Osinski [a,b], Claire Samson [c], Marie-Claude Williamson [d], Scott Holladay [e]

[a] Department of Earth Sciences, University of Western Ontario, 1151 Richmond Street, London, ON, Canada N6A 5B7
[b] Department of Physics and Astronomy, University of Western Ontario, 1151 Richmond Street, London, ON, Canada N6A 5B7
[c] Department of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, ON, Canada K1S 5B6
[d] Canadian Space Agency, John H. Chapman Space Centre, 6767 route de l'Aéroport, St-Hubert, QC, Canada J3Y 8Y9
[e] Geosensors Inc., 66 Mann Avenue, Toronto, ON, Canada M4S 2Y3

ARTICLE INFO

Article history:
Received 20 February 2009
Received in revised form
20 August 2009
Accepted 14 September 2009
Available online 30 September 2009

Keywords:
Ploygonal terrain
Ice-wedge polygons
Mars analogs
Electromagnetic induction
Canadian Arctic
Geophysics

ABSTRACT

Polygonal terrain is found in a variety of polar environments on Earth and Mars. As a result, many areas of northern Canada may represent ideal terrestrial analogues for specific regions of Mars – in particular the northern plains. In the Canadian Arctic, polygon troughs are commonly underlain by wedges of massive ice, with rare examples of other wedge types. If the same is true for Mars, this raises interesting implications for the processes that concentrate H_2O at the Martian poles. This study uses an electromagnetic induction sensor to investigate the electromagnetic characteristics of terrestrial polar ice-wedge polygons. Surveys were conducted in two regions of the Canadian Arctic using a DUALEM-1S dual-geometry electromagnetic induction sensor, which measures electrical conductivity in the first 1.5–2 m of the subsurface. At locations where strong geomorphological evidence of ice was found, polygon troughs corresponded to local conductive anomalies. Trenching confirmed the presence of ice wedges at one site and allowed ground-truthing and calibration of the geophysical data. Previously unknown bodies of massive ice were also identified through the use of this geophysical technique. This study shows that an electromagnetic induction sounder is a useful instrument for detecting and mapping out the presence of subsurface ice in the Canadian Arctic. Taking together with its small size, portability and ruggedness, we suggest that this would also be a useful instrument for any future missions to Mars' polar regions.

1. Introduction

Polygonal terrain is common throughout the higher latitudes of both the northern and southern hemispheres of Mars (e.g., Seibert and Kargel, 2001; Mangold, 2005; Mellon et al., 2008; Levy et al., 2009) (Fig. 1a–d). On Earth, polygonal terrain is common throughout the Arctic regions of North America (Fig. 1e,f), Europe and Asia, and is an expression of the ground's response to seasonal temperature variations and freeze–thaw cycles. In Arctic environments the trough-like depressions that form the polygon boundaries commonly represent the surface expression of ice wedges, which form through the process of thermal contraction and expansion related to seasonal temperature variations (Mackay, 1990; Burn, 2004; Fortier and Allard, 2004). In some cases, the troughs can be underlain by sand wedges, primarily in locations where dry active layer conditions dominate, of in which no active layer is present. (e.g., Pewe, 1959; Marchant et al., 2002; Marchant and Head, 2007). It has been suggested that the polygonal terrain observed on Mars could also have been formed by thermal contraction cracking (Mellon, 1997), raising interesting questions about the distribution and history of near-surface water and ice on Mars (Levy et al., 2009).

This study explores the electromagnetic characteristics of polar ice-wedge polygons as analogues for Martian landforms through data acquired with an electromagnetic induction sounder. To the knowledge of the authors this technique has not been used before to study such periglacial landforms; although it has been used to successfully study Pleistocene-age ice-wedge pseudomorphs (Cockx et al., 2006). Previous studies have shown the use of ground-penetrating radar and electrical resistivity for studying polar ice-wedge polygons (e.g., Fortier and Allard, 2004; Guglielmin et al., 1997). The polygons surveyed for this study are located in two regions of the Canadian Arctic Archipelago, Nunavut. The first region is located on Axel Heiberg Island with

* Corresponding author. Tel.: +1 519 639 3363.
E-mail address: asingle2@uwo.ca (A.C. Singleton).

0032-0633/$ - see front matter
doi:10.1016/j.pss.2009.09.013

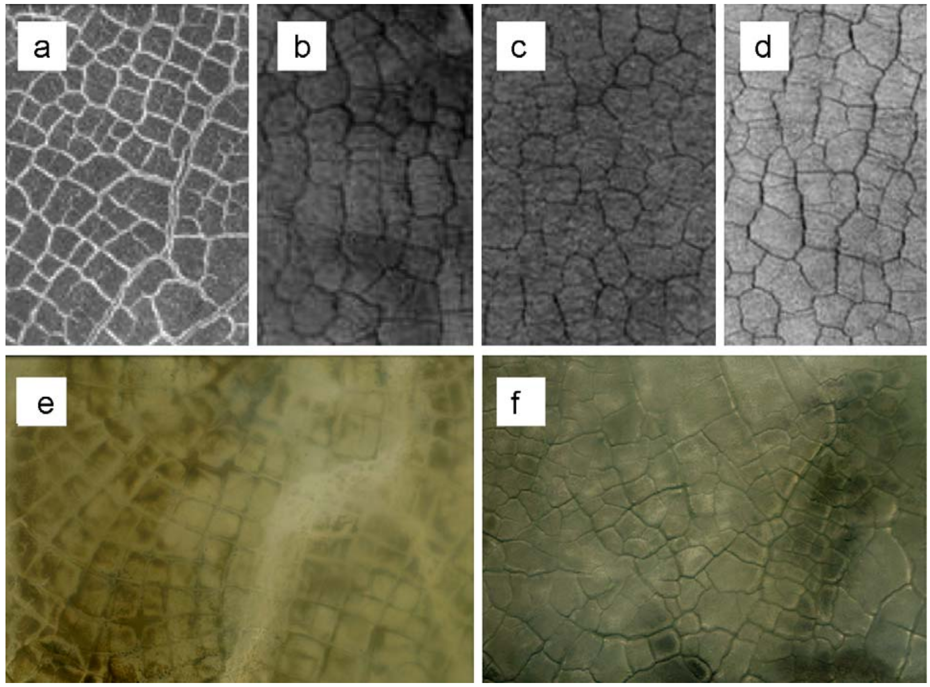

Fig. 1. Satellite and aerial photographs showing the morphological similarities between polygonal terrain on Mars (a–d) and on Earth (e and f). The top row are HiRISE images and are ~500 m across; the bottom row show regions that are ~300 m across. (a) Polygons first seen in MOC Image M01-00204 (HiRISE image PSP_007372_2475). (b) Polygons in Utopia Planitia (PSP_007173_2245). (c) Polygons in HiRISE image PSP_006962_2215; (d) Polygons in Utopia Planitia (HiRISE image PSP_007674_2240); (e) Polygons at Thomas Lee Inlet on Devon Island. (f) Polygons on Axel Heiberg Island. Martian images courtesy of NASA/JPL/MSSS.

the majority of surveying being done near the McGill Arctic Research Station (MARS) (79°26′N, 90°46′W) (Pollard et al., 2009). The second region is located just outside the Haughton impact structure (75°22′N, 89°41′W) on Devon Island (Lee and Osinski, 2005). The primary objective of this study was to assess whether an electromagnetic induction sounder can be used to detect and locate ice wedges in polar polygons and its suitability for future Mars missions. At the same, our aim was to develop a better understanding of polygon formation in a polar desert environment. This study will also briefly outline the operational advantages and challenges associated with using the DUALEM-1S dual-geometry sensor in the polar environment and explore its strengths and weaknesses for this type of survey, both on Earth and Mars.

2. Polygonal terrain and ice-wedge polygons on Earth

Polygonal terrain refers to a geometrical network of surface patterns bounded by trough-like depressions. Often indicative of subsurface ice presence, these features are some of the most common landforms found throughout terrestrial polar regions (e.g., Black, 1976; Pollard and French, 1980; Couture and Pollard, 1998). During the winter, if the tensile stress induced by rapid and severe falling air temperatures exceeds the tensile strength of the ground, a "thermal contraction crack" opens to relieve the stress (Lachenbruch, 1962). The cracks are typically up to 2 cm wide (Mackay, 1974), can be up to 10 m deep (Mackay, 1975), and extend laterally along planes of weakness until they intersect, forming enclosed polygonal shapes tens to hundreds of metres across.

The three main types of polygonal terrain found on Earth – sand-wedge, ice-wedge, and sublimation polygons – can be distinguished based on a combination of surface morphology and subsurface properties. While the thermal contraction cracking process is common to each, the substrates in which they form and the materials infilling the contraction cracks can vary (Levy et al., 2008). In ice-bonded materials that contain volumes of pore ice equal to or less than available pore space, open cracks in the summer can be filled with – depending on availability – wind-blown sand or draining meltwater, forming an initial sand- or ice-wedge, respectively. Thermal expansion processes during this warmer period cause local sediments to redistribute, forming raised shoulders bounding the trough that overlies the wedge materials (Mackay, 2000). Over hundreds or thousands of years of development, cracking reinitiates, the sand and ice wedges continue to grow in volume, and the sediment shoulders and troughs become increasingly pronounced (Sletten et al., 2003).

Ice wedges may be classified as epigenetic, syngenetic, or anti-syngenetic depending if they occur in areas of no change, accumulation, or erosion of the ground surface (Burn, 2004; Mackay, 1990). Based on field observations of the environments where they were found, this study deals only with epigenetic wedges, which grow in pre-existing permafrost beneath a ground surface that is neither aggrading nor eroding and are typically much younger than the host material (Burn, 2004). This type of wedge tends to crack near the centre of the existing ice. The veinlets are V-shaped thus they tend to grow progressively wider rather than higher or deeper (Mackay, 1990).

In regions where subsurface ice content greatly exceeds available pore space and surrounding air temperatures rarely, if ever, exceed the 0 °C, sublimation of ground ice exposed by the thermal contraction crack leads to localized terrain subsidence along the cracks (Marchant et al., 2002). Fine sediments immediately surrounding the crack can then fall into the crack, forming a modified type of sand wedge (Levy et al., 2006). As the sublimation process continues over time, the troughs that follow the cracks become deeper and increasing amounts of sediment fall in, resulting in a characteristic morphology displaying concave relief where the polygon centres are markedly higher than the troughs and the raised sediment shoulders bounding the troughs are typically absent (Marchant and Head, 2007).

3. Polygonal terrain on Mars

Large polygonal patterns on the surface of Mars were first displayed in images returned from the Mariner missions (Lucchitta, 1983). Originally, these were thought to be analogous features to polygonal terrain on Earth and were believed to be indicative of subsurface ice deposits (e.g., Carr and Schaber, 1977). However, later analysis demonstrated that – with diameters of kilometres to tens of kilometres – these features were too large to be caused by thermal contraction cracking, and are now thought to be formed as a result of various other geological processes (Hiesinger and Head, 2000; Lane and Christensen, 2000). These polygons range in size from 2 to 32 km with troughs sometimes over a kilometre wide dividing them (Hiesinger and Head, 2000). The inconsistency in polygon size between the two planets posed problems for drawing parallels between these features. In an attempt to explain this phenomenon the difference in size was originally attributed to the deeper propagation of cracks on Mars, explained by colder permafrost, larger temperature variations, and the lower Martian gravity (Mangold, 2005; Mellon et al., 2008; Levy et al., 2009).

Subsequent imagery from the Mars Orbiter Camera on NASA's Mars Global Surveyor mission revealed the presence of small-scale polygonal terrain, comparable in size and morphology to those observed on Earth. Moreover, numerical simulations (Mellon, 1997) and spatial coincidence with elevated hydrogen quantities in the upper metre of the subsurface (Mangold et al., 2004) suggested that polygons on Mars may, indeed, be indicative of subsurface ice, potentially in the form of ice wedges (Seibert and Kargel, 2001; Mangold, 2005).

Polygonal terrain is mainly found widely distributed between the high and mid-latitudes (North and South Hemispheres) on the Martian surface but they can be found in many other locations as well (e.g., Seibert and Kargel, 2001; Mangold, 2005, Mellon et al., 2008; Levy et al., 2009). Some of the locations include the Utopia Planitia and Elysium Planitia regions of the Northern plains. Polygons are typically found in geologically recent deposits, ranging in age from $\sim$1 My (Mangold, 2005; Levy et al., 2009) to $<$0.1 My (Kostama et al., 2006; Levy et al., 2009), and are thought to contain large amounts of interstitial water ice; however, this does not necessarily indicate that they are active at the present time (Mangold, 2005).

Most recently, detailed analysis of images returned from the HiRISE camera (McEwen et al., 2007) has produced evidence suggesting that ground ice sublimation may be the dominant formational process for Martian polygonal terrain. Citing the apparent relatively young age ($<$5 Ma) of polygons in the mid- to high-latitudes of the planet, Levy et al. (2009) argue that orbitally induced wet active layer processes during periods of high obliquity (Kreslavsky et al., 2008) could only have taken place well before the formation of polygonal terrain, and thus it may be more likely that sublimation of an extremely ice-rich substrate is responsible for the landscape patterns observed. Although this growing consensus points toward similarities with terrestrial sublimation polygons, the presence of ice wedges on Mars (perhaps due to localized microclimatic effects) has not been ruled out definitively and thus warrant further investigation.

It is important to note that seasonal thaw is not a necessary part of the contraction and expansion process. The thawing is necessary, however, for building of ice wedges and this can only occur in specific environments (Marchant and Head, 2007). In terrestrial polygons, the thaw melting water is what fills the cracks and allows for the creation of ice wedges (Mangold, 2005). This means that wedges and polygonal terrain may form through the contraction and expansion process without ever containing ice. This has been observed on Earth in the cases of sand or soil-wedge polygon systems, which show ground patterns with similar geometries to ice-wedge polygons (Black, 1976). Thus, locations on Mars that may contain ice in wedges must be locations that could have supported a thaw in the past. The current climate conditions on Mars are not suitable for seasonal thaws to occur at any latitudes. However, it is thought that the climate may have changed significantly in the last 10 million years so it could be that at some point the average daily temperatures were above freezing at the latitudes containing polygons (Head et al., 2003). Any search for ice-wedge polygons may, therefore, be confined to relict ice wedges, which may have formed sometime between 5 and 10 My ago. In addition, studies have shown that this could have been possible in specific microenvironments such as craters interiors or poleward-facing slopes (Mangold, 2005).

Aside from freeze–thaw cycles, there are other hypotheses on the origin of the polygonal terrains. All of the models that have been suggested involve cracking in response to tension. Some processes that generate tension are: the cooling of lava flows, desiccation of wet sediments, thermal contraction, loading of sediments with volatile-rich lavas, coalescence of smaller polygons, and tectonic processes (Hiesinger and Head, 1999).

4. Geology of study areas

4.1. Devon Island and the Haughton impact structure

The Haughton impact structure is a well-preserved complex impact structure situated near the western end of Devon Island (75°22′N, 89°41′W). The impact that created the structure is believed to have occurred 39 ± 2 million years ago in the late Eocene (Sherlock et al., 2005) and in a practically flat-lying, predominantly sedimentary target sequence (Osinski et al., 2005). This Lower Paleozoic sedimentary sequence unconformably overlies a crystalline (gneissic) Precambrian metamorphic basement, which forms part of the Canadian Shield. The Haughton structure has an apparent crater diameter of 23 km, with an estimated final (rim-to-rim) diameter of 16 km (Osinski et al., 2005). Since the impact, Devon Island has remained tectonically stable and Haughton remains well preserved despite being subjected to several ice ages. The excellent preservation of the structure is largely due to the primarily cold and relatively dry environment that has existed in the Arctic since the Eocene. Modern modification of the crater's landscape is dominated by seasonal regional glacial melting and periglacial processes. These processes include the formation of patterned and polygonal ground, gullies, and debris flows. The surficial material at the two locations surveyed on Devon Island was very different (Fig. 2). At the Thomas Lee Inlet site (Fig. 2a), the local sediments were very fine-grained clays and silts deposited as deepwater proglacial silt blankets. In contrast, the sediments at the Lake Orbiter site were pebble- and cobble-size proglacial outwash sediments. All surfaces were generally devoid of organic material. All the ice wedges surveyed in this study had a trough as their surface expression, and in most cases the trough was bordered by two symmetrical ridges. In a few cases, the ridges were absent.

4.2. Axel Heiberg Island

Axel Heiberg Island is located in the Sverdrup Basin, a northeast-trending, intracratonic basin that extends along the

Fig. 2. Series of field photographs showing the variations in the properties of surficial material present at the study sites. (a) Fine-grained marine or glaciofluvial sediments at Thomas Lee Inlet, Devon Island. (b) Pebble- and cobble-size glaciofluvial sediments at the Lake Orbiter site, Devon Island. (c) and (d) Fine-grained but vegetated sites on Axel Heiberg Island.

Canadian Arctic continental margin from the northern tip of Ellesmere Island, to Prince Patrick and Melville Islands spanning an area of approximately 313,000 km^2 (Pollard et al., 1999). The Sverdrup Basin Magmatic Province is located in the east-central part of the Sverdrup Basin. It consists of flood basalts, hypabyssal intrusive sheets and dykes, and volcanoes (Williamson, 1998). Igneous rocks from the Sverdrup Basin Magmatic Province have been dated with ages ranging from 129 ± 2 to 59 ± 1 Ma (Villeneuve and Williamson, 2006). Near the head of Expedition Fjord, where the study sites were located, a rugged profile of asymmetrical ridges are formed from breached anticlines, with scarp faces reaching angles of 70–80° and dip slopes measuring 25–35° (Pollard et al., 2009). Large domed structures cored by rock salt are common throughout the island, appearing as diapirs caused by the intrusion of Upper Paleozoic evaporites composed of an anhydrite ~500 m thick residing above a layer of rock salt (Stephenson et al., 1992). The surficial material found on Axel Heiberg Island showed much less variation than on Devon Island. Here the sediment mostly consists of fine organic soil mixed with gravel and larger sized rocks. Much of the ground is hummocky and is sparsely vegetated.

5. Instrumentation and methodology

Geophysical surveys were conducted in July 2007 using a DUALEM-1S electromagnetic induction sensor, which measures electrical conductivity in the first 2 m of the subsurface. The DUALEM-1S induction sounder features a sensor package, which was designed and manufactured by Geosensors Inc. of Toronto, Ontario (http://www.geosensors.com/) and is marketed by DUALEM of Milton, Ontario (http://www.dualem.com/). The DUALEM-1S induction sounder is contained in a rigid cylinder that is approximately 1 m long. The cylinder contains one transmitter loop antenna, located at the "front" of the instrument, and two receiver loop antennas located at the "back" of the instrument, a receiver lying in a plane parallel to the ground surface (Z-oriented receiver) and a vertical receiver (X-oriented receiver). The system's electronics are located in the middle portion of the cylinder. Terrestrial versions of the sensor use about 2 W at 12 V nominal, and weigh about 5 kg.

The instrument measures at 9 kHz (sinusoidal signal, very stable frequency) in the inphase and quadrature for two receiver geometries, with a single vertically oriented transmitter. Apparent conductivity measurements for low conductivity soils are obtained from the quadrature data, while the inphase data provide information on the magnetic susceptibility of the soil. The dual-receiver, single transmitter capability of this unit, its geometrical simplicity, factory-set internal calibration, fully digital electronics and high degree of thermal stability set it apart from other commercial sensors of this type. In addition, this instrument is an example of a sensor, which has a low induction number. For a sensor with a low induction number like this one, the signal recorded at the receiver is proportional to apparent conductivity. This makes data analysis very simple.

For this study, the instrument was deployed on the ground and mounted on a small sled. The instrument was operated using a handheld interface and was powered by an external battery. Fig. 3 shows a field image of the instrument being operated, with the various components labelled. Normally conductive soils range from a few mS/m for sandy, relatively dry soil up to hundreds of mS/m for moist clays and soils with saline groundwater. Very saline soils can exceed 1000 mS/m. (e.g., Reynolds, 1997). For normally conductive soils in the region (conductivity on the order of mS/m per metre to 100 mS/m per metre), the depth of exploration of the DUALEM-1S is approximately 1.5 times the distance between the transmitter and the Z-oriented receiver, and equal to the distance between the transmitter and the X-oriented receiver. Since the separation between the transmitter and receivers is 1 m, this makes the two depths of exploration approximately 1.5 m (Z-oriented receiver) and 1.0 m (X-oriented receiver). This study involved surveys being done over 21 separate polygon troughs. For most of these surveys, data were acquired along three parallel transects running perpendicular to the polygon trough (or set of troughs). Over polygon interiors the spatial sampling interval is 50 cm and over the troughs the sampling interval is increased to every 10 cm. In total, measurements were acquired for 21 sites, each over a separate trough (or set of troughs).

The instrument was visually levelled before each reading was taken. Not levelling the instrument can result in errors in the acquired data. Error will increase as the microtopography increases. The degree of error is relatively low in the horizontal coplanar (ZZ) data, and higher in the perpendicular array (ZX) data, due to the sensitivity distributions of the two configurations.

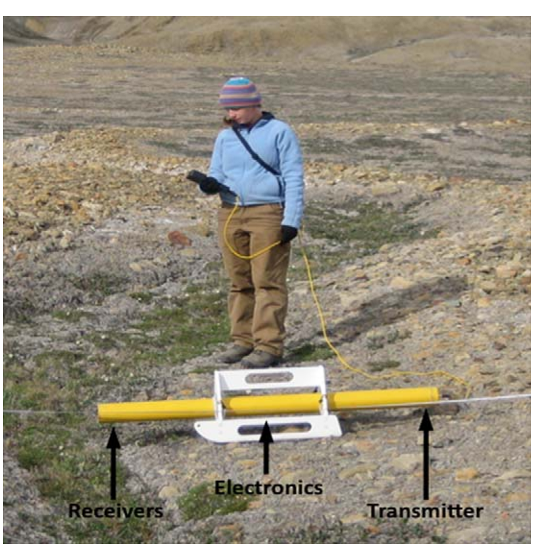

Fig. 3. DUALEM-1S induction sounder. The instrument is operated with a handheld interface and the external battery is carried by the operator in a camera bag over the shoulder. The instrument is being carried in a small sled that makes it easier to keep level.

These errors can be minimized by keeping the instrument as horizontal as possible. The instrument records its pitch-roll orientation, and this can be used as an input for more sophisticated inversion-based data analysis.

6. Results and discussion

6.1. Ice detection

At locations where strong geomorphological evidence for subsurface ice wedges was observed, the polygon troughs often corresponded to local conductive anomalies. Pure ice has a conductivity on the order of 0.02 mS/m (Reynolds, 1997). The conductivity of ice in nature depends on a number of factors. One of the main factors is the amount of impurities frozen in the ice such as soil, rock and organic material. Other factors include the acidity of the water and the temperature and density of the ice (Wolff et al., 1997). Ice in permafrost is more variable as it is likely to include some salts, clays, etc. that will tend to increase the bulk conductivity of permafrost relative to that of pure water ice. Values of 0.07 mS/m would tend to suggest the presence of some liquid water with some salts and or clays, at least as a fraction within the permafrost or at its surface. Note that there was no meltwater in any of the troughs surveyed in this study. To establish ground truth for this study, wedge ice was excavated on Devon Island at a depth of approximately 60 cm, and its apparent conductivity was measured with the induction sounder. Fig. 4 shows the trough that was excavated for this purpose and Fig. 5

Fig. 4. Trench dug to establish ground truth on Devon Island. The trench shows a contact between permafrost (top of image) and wedge ice and then a contact between wedge ice and massive ice (dark, bottom of image) as marked by the tip of the pencil. The depth to the wedge ice is approximately 55 cm. The depth to the permafrost is 66 cm. A geologic hammer provides scale. Closer view of this contact may be seen in Fig. 6.

shows a closer view of some of the excavated ice. Averaging results from five excavations, the overall ice conductivity range was found to be from 3 to 7 mS/m (X-oriented receiver) and 0 to 5 mS/m (Z-oriented receiver).

Fig. 6 shows conductivity measurements for three transects crossing a trough on Axel Heiberg Island. The shaded portion shows the conductivity range for ice. The anomalies fall into this range, supporting the presence of ice. This range of values for ice was used for the data from both Devon and Axel Heiberg Islands because no suitable location on Axel Heiberg Island was found that allowed excavation of ice to serve as a reference value.

6.2. Comparison of the study regions

The various sites on Axel Heiberg and Devon Islands showed a wide variety of ground material (see Fig. 2), trough characteristics and geophysical responses. On Devon Island, the geophysical data from some of the sites showed data that supports the presence of ice in wedges under the troughs. This was confirmed by trenching at the Thomas Lee Inlet site on Devon Island, where foliated wedge ice was detected at ~75 cm depth (Fig. 5). Geophysical data combined with ground truth also strongly suggest the existence of several bodies of previously unknown massive ground ice at the Thomas Lee Inlet site, and it is suspected for other sites.

Fig. 5. Enlarged view of the contact between wedge ice (bottom) and massive ice (top) at Thomas Lee Inlet on Devon Island. Note the foliated texture of wedge ice. Both types of ice were mostly pure with fine soils included in the form of foliations (wedge ice) and blebs (massive ice). A mechanical pencil provides scale.

Fig. 7 shows examples of data profiles from Devon and Axel Heiberg Island. Generally, troughs (locations with finer spatial sampling interval) fall into the ice conductivity range. However, in the case of the profiles from Devon Island, it may be seen that extending laterally from the troughs on either side the signal continues to be within the ice range. Because of the large number of excavations done at this particular location also showing ground ice, it is clear that there is extensive massive ground ice in the near subsurface in this area; ice is not only confined to beneath ice wedges. It is important to note that massive ground ice had not previously been discovered in this region of Devon Island so this is an important discovery made possible through this geophysical technique. In addition, the strong peak between 2500 and 3300 cm in these profiles shows the presence of wet clay along the transects. These results lead to the conclusions that various types of ground ice (discrete bodies of massive ice and wedge ice) can be detected using the DUALEM-1S induction sounder.

On Axel Heiberg Island only one of the sites shows data that supports the presence of ice in wedges under the troughs. The best plot obtained in this area may be seen in Fig. 7. There are several possible explanations for this lack of evidence:

(a) There is no ice in the subsurface at this site and perhaps the troughs are the surface expression of another process, or that they represent sand wedge polygons or ice-wedge pseudomorphs,.
(b) There is ice in the subsurface but it is too deep to be detected by the DUALEM-1S (i.e., >1.5 m); this is possible as we were unable to dig or core to greater than 1 m depth at these sites.
(c) The conductivity of the ground material is very similar to the conductivity of the ice resulting in no apparent anomalies.

It is not possible without drilling to conclude which of these factors is responsible for the lack of ice detection at these Axel Heiberg Island sites; however, it should be taken into account for any future Mars mission that seeks to sample ground ice (i.e., drilling to several metres depth may be required). In summary, the polygon systems on both islands exhibit features by the thermal contraction and expansion process necessary to produce ice-wedge polygons. At one location Devon Island, the presence of wedge ice was confirmed through trenching (Fig. 5).

6.3. Expected response of sublimation and sand-wedge polygons

How do our results of EM signal response to ice wedges compare with those we would expect from a similar survey conducted over sublimation-type or sand-wedge polygons?

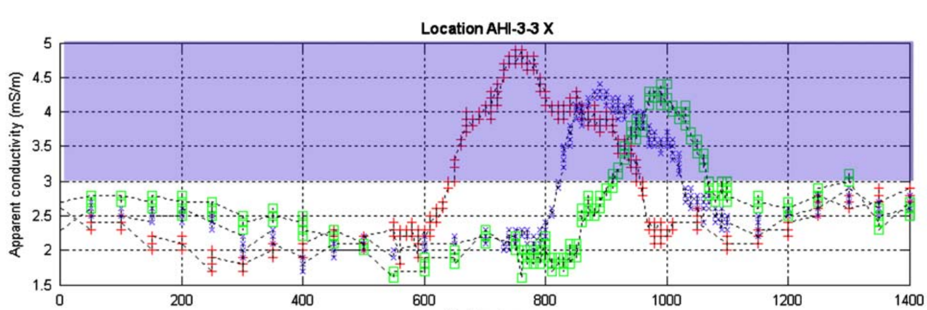

Fig. 6. Data acquired from the X-coil of the DUALEM-1S electromagnetic induction sounder along three parallel transects over the same 190–300 cm wide trough on Axel Heiberg Island. Note that the survey lines were not directly perpendicular to the trough, which accounts for the offset peaks. The prominent anomaly between 560 and 860 cm (line one – cross markers), 730 and 920 cm (line two – x markers), and 770 and 980 cm (line three – box markers) corresponds to the trough on the ground. This example shows how the conductivity range for ice was applied to infer the presence of ice. The shaded area represents the expected conductivity range for ice.

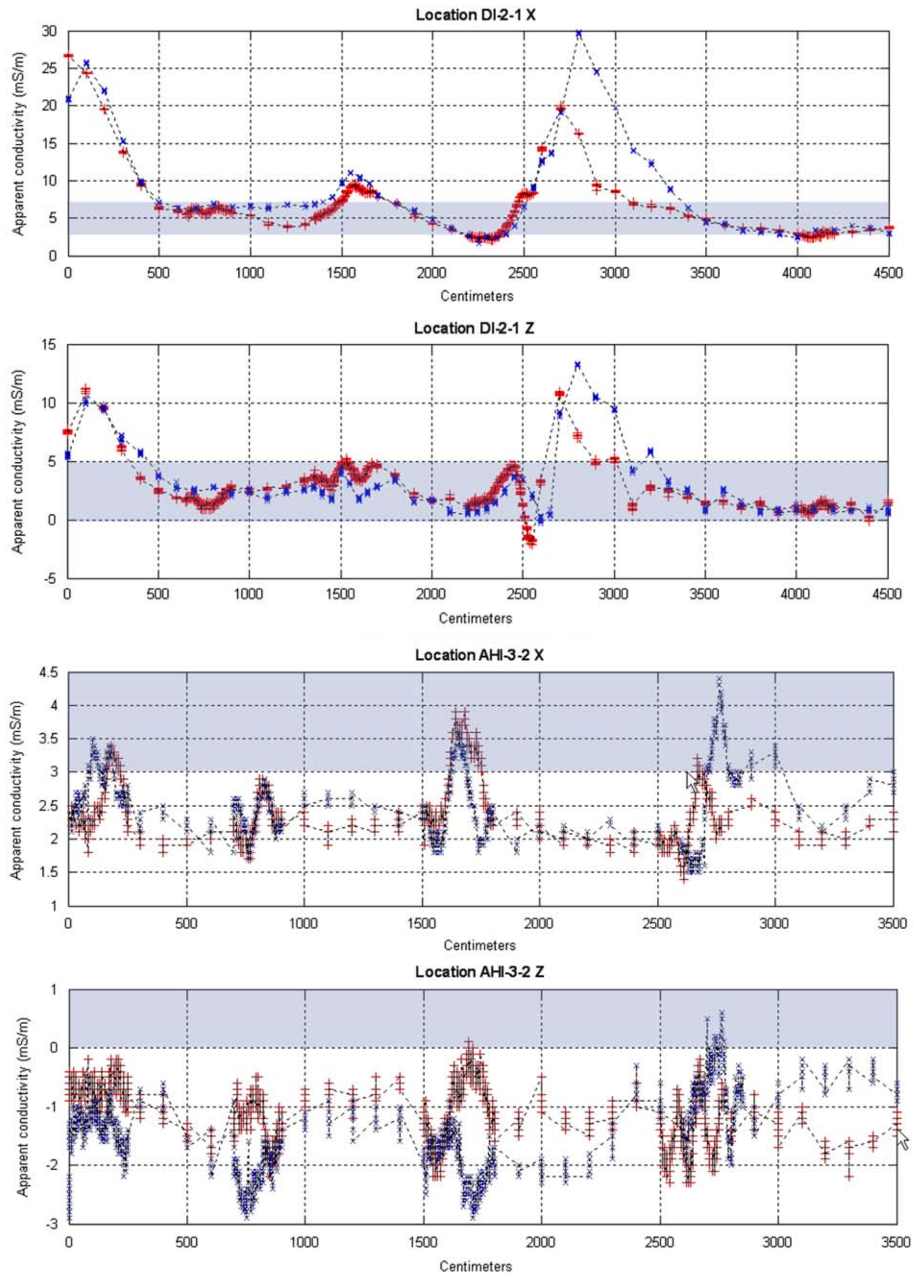

Fig. 7. Example of data acquired with by the X-oriented and Z-oriented receivers of the DUALEM-1S electromagnetic induction sounder. The top set of two shows data collected at Thomas Lee Inlet, Devon Island. The bottom set of two show data collected at Ridge Side, Axel Heiberg Island. The portions of the lines showing finer spatial sampling represent the areas over the troughs. The two lines represent the two transects done with the instrument. The shaded areas represent the expected conductivity range for ice. The inconsistency in the lower Axel plot is likely due to base-level error.

Insight may be gained from a more detailed description of the respective morphologies and processes responsible for the formation for each.

As noted in Section 2, the major difference between sublimation polygons and ice- or sand-wedge polygons pertains to total ice content and the location of ice of the shallow subsurface. Whereas the former develop in areas where a thin lag overlies an ice deposit well in excess of available pore space (Levy et al., 2006; Marchant et al., 2002), the latter typically form in regions where pore ice acts primarily as a cementing agent for the substrate materials (Black, 1976). With respect to ice-wedge polygons, excess ice will thus only be found within the wedge material beneath polygon troughs and not beneath polygon centres. Regarding sand-wedge polygons, excess ice will be entirely absent in both the wedge material and the surrounding substrate.

Fig. 8 depicts schematically the respective morphologies of the three polygon types and the expected behaviour of an induced EM signal for each. For sublimation polygons, the ‘background’ readings over polygon centres will be markedly greater than those for ice- and sand-wedge polygons due to drastically increased near-surface ice content. Above the trough, however, a noticeable drop in conductivity would be evident due to a lack of ground ice within the modified sand wedge material. Background measurements over the centres of ice- and sand-wedge polygons would be roughly equal due to the presence of pore ice cement, but variations would be evident above the troughs. Specifically, excess ice within the ice wedge would result in a demonstrable

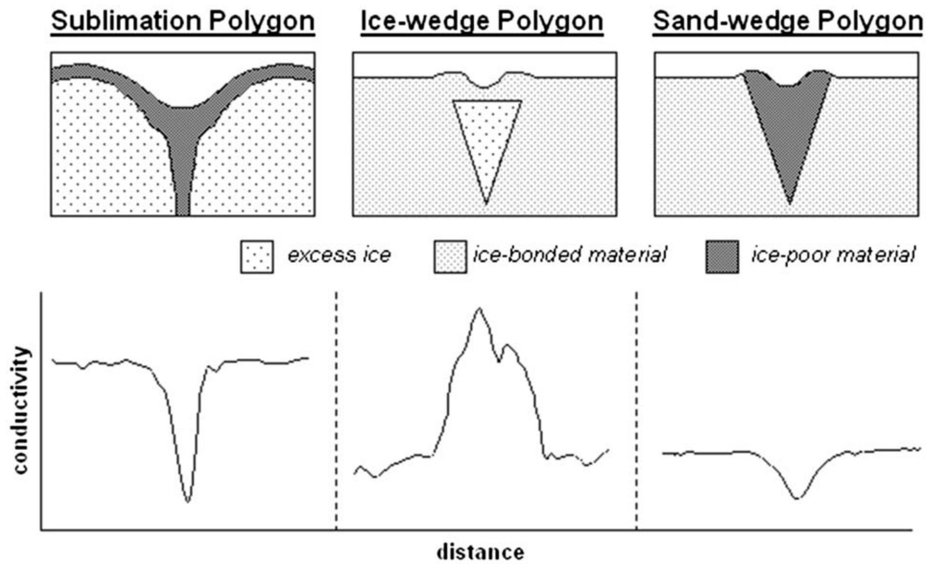

Fig. 8. Schematic depiction of the respective morphologies of the three polygon types and the expected behaviour of an induced EM signal for each.

peak in signal response (as evidenced by field data presented in Figs. 6 and 7), but the virtually ice-free materials comprising sand wedges would likely result a slight depression compared to readings taken over the polygon centre.

Certainly, additional field studies should be conducted to examine systematically the variations in EM signal response over sublimation, ice-, and sand-wedge polygons. By performing such investigations, a more complete understanding of terrestrial ground ice responses to shallow geophysical surveying techniques could better be used to calibrate and prepare for data returned from a robotic mission to ice-rich areas of Mars.

6.4. Suitability of the instrument for detecting ground ice on Earth and Mars

This study found that the DUALEM-1S electromagnetic induction sounder had a number of advantages and disadvantages for this type of survey. One of the main advantages is that the instrument is relatively small and compact making it very easy to transport in a helicopter or on the back of an All-Terrain Vehicle. It is also light enough to be run by a single operator. Another advantage is that the construction of the instrument is very rugged and contains no exposed delicate or mobile parts. These factors are especially important in the Arctic, and for planetary missions, where most machinery is affected by blowing dirt and dust.

The main disadvantage that was encountered during operations in the field is the difficulty in keeping the instrument levelled on rough Arctic terrain. This is especially true on very hummocky and rocky ground. Because of the instrument's sensitivity to being tipped, this issue may lead to unreliable data. This could be avoided by using an instrument that is not deployed on the ground. Some of the longer DUALEM series instruments may be carried with a strap over the shoulder during the survey. This would solve the levelling issue but would not be a reasonable option for the DUALEM-1S because of the inevitable loss in sampling depth. The disadvantage to the operator carrying the instrument is that any metal within approximately 1 m of the instrument can interfere with the instrument's signal. While possible, this is difficult to accomplish while wearing cold weather clothing and boots. Overall, this study has found that the DUALEM-1S induction sounder is suitable for carrying out research involving shallow surveys in the Arctic environment. It is recommended that a version of the instrument with longer coil spacing should be considered for future surveys depending on the desired results. A longer instrument would be able to sample deeper in the subsurface. Field experience shows that this instrument is well suited to shallow surveys that are carried out on fairly flat ground. It was found to be less suitable for some of the rougher Arctic terrain that was encountered.

These conclusions can be used to help predict this instruments' suitability for inclusion on a future Mars mission. Based on this study, we suggest that this instrument would be well suited to Mars missions focusing on the polar regions, either manned or unmanned. In the case of an unmanned mission, the instrument would be mounted on a rover. The use of a tiltmeter would allow levelling the instrument resulting in more accurate data. In addition, because ground electromagnetic geophysical surveys are fairly time intensive, having the instrument on a rover would negate the need for a human to spend large amounts of time on that project. One fundamental drawback to the instrument is the issue of not having anything made of metal close-by that would interfere with the instrument's signal. Any metal closer than the distance equal to the instrument's coil spacing has a possibility of influencing the reading. This issue would be the same if the instrument were to be mounted on a rover. This would also present a difficult engineering problem for a rover-mounted instrument on a planetary mission. Possible solutions to this issue include deploying the instrument on a non-metal boom or towing it behind the rover on a sled or cart. Because the data from this instrument is often not conclusive on its own it is recommended that this instrument be used as part of a suite of geophysical experiments, including, for example, ground-penetrating radar.

7. Conclusions

This study used a DUALEM-1S induction sounder to investigate the electromagnetic characteristics of polar ice-wedge polygons. The study areas represent terrestrial analogues for high-latitude regions of Mars where polygonal terrain is commonplace. Strong geophysical evidence – confirmed by trenching – for the presence of ice confined in ice-wedge polygons has been found at the Thomas Lee Inlet site on Devon Island. At the same site, the use of this geophysical technique also resulted in the serendipitous discovery of large bodies of massive ground ice, not previously indentified in this region of the Arctic. On Axel Heiberg Island only one of the sites showed data that supports the presence of ice in wedges under the troughs. This may be due to a lack of subsurface ice or that the ice is too deep to be detected by the DUALEM-1S (i.e., >1.5 m), and/or that the conductivity of the ground material is very similar to the conductivity of the ice resulting in no apparent anomalies. Despite this, the instrument was capable of detecting the presence of shallow ice wedges. The DUALEM-1S induction sounder was found to be an excellent instrument for this study, with its main advantages being its portability and its very high degree of base level stability and calibration accuracy. Future work with a version of the instrument with a longer coil spacing should be considered for future surveys in order to be able to sample deeper in the subsurface. Overall, these features make an induction sounder an attractive potential instrument for future missions to Mars' polar regions, such as a follow-on rover mission to the Phoenix landing site.

Acknowledgements

This study represents a component of the work done for the undergraduate thesis of A. Singleton in the Department of Earth Sciences at Carleton University, Ottawa, Canada. It was funded by the Northern Scientific Training Program, the Canadian Space Agency, and supported by the Polar Continental Shelf Project. We would like to thank Dr. Alain Berinstain, Dr. Pascal Lee, Dr. Wayne Pollard, and everyone at the Haughton–Mars Project and the McGill Arctic Research Station in the 2007 field season for their support of the fieldwork component of this project. We thank Timothy Haltigin for his field collaboration, helpful discussions, and his contribution of Fig. 8 to this manuscript. Finally, we would like to thank our reviewers Joseph Levy and John Bradford for their detailed and constructive comments. This is Polar Continental Shelf Project contribution 03809.

References

Black, R.F., 1976. Periglacial features indicative of permafrost: ice and soil wedges. Quaternary Research 6, 3–26.

Burn, C.R., 2004. A field perspective on modelling 'single-ridge' ice-wedge polygons Permafrost and Periglacial processes 15, 59–65.

Carr, M.H., Schaber, G.G., 1977. Martian permafrost features. Journal of Geophysical Research 82, 4,039–4,054.

Cockx, L., Ghysels, G., Van Meirvenne, M., Heyse, I., 2006. Prospecting frost-wedge pseudomorphs and their polygonal network using the electromagnetic induction sensor EM38DD. Permafrost and Periglacial Processes 17, 163–168.

Couture, N.J., Pollard, W.H., 1998. An assessment of ground ice volume near Eureak, Northwest Territories. In: Lewkowicz, A.G., Allard, M. (Eds.), Permafrost, Seventh International Conference, 23–27 June, Yellowknife, Canada. Universite Laval, Centre d'etudes nordiques, Collection Nordicana, pp. 195–200.

Fortier, D., Allard, M., 2004. Late Holocene syngenetic ice-wedge polygons development, Bylot Island, Canadian Arctic Archipelago. Canadian Journal Earth Science 41, 997–1012.

Guglielmin, M., Biasini, A., Smiraglia, C., 1997. The contribution of geoelectrical investigations in the analysis of periglacial and glacial landforms in ice free areas of the Northern Foothills (Northern Victoria Land, Antarctica). Geografiska Annaler Series A, Physical Geography 79, 17–24.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., Marchant, D.R., 2003. Recent ice ages on Mars. Nature 426 (6968), 797–802.

Hiesinger, H., Head, J.W. III., 1999. Polygonal Terrain of Utopia Planitia, Mars: The First MOLA Results. Abstracts of Papers Submitted to the Lunar and Planetary Science Conference, 30, unpaginated.

Hiesinger, H., Head, J.W., 2000. Characteristics and origin of polygonal terrain in southern Utopia Planitia, Mars: results from Mars Orbiter Laser Altimeter and Mars Orbiter Camera Data. Journal of Geophysical Research 105 (E5), 11999–12022.

Kostama, V.-P., Kreslavsky, M.A., Head, J.W., 2006. Recent high-latitude icy mantle in the northern plains of Mars: characteristics and ages of emplacement. Geophysical Research Letters, 33(L11201), doi:10.1029/2006GL025946.

Kreslavsky, M.A., Head, J.W., Marchant, D.R., 2008. Periods of active permafrost layer formation during the geological history of Mars: implications for circum-polar and mid-latitude surface processes. Planetary and Space Science 56 doi:10.1016/j.pss.2006.1002.1010.

Lachenbruch, A.H., 1962. Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. Special paper to the Geological Society of America 70, 69pp.

Lane, M.D., Christensen, P.R., 2000. Convection in a catastrophic flood deposit as the mechanism for giant polygons on Mars. Journal of Geophysical Research 105, 17,617–17,627.

Lee, P., Osinski, G.R., 2005. The Haughton-Mars Project: overview of science investigations at the Haughton impact structure and surrounding terrains, and relevance to planetary studies. Meteoritics & Planetary Science 40, 1755–1758.

Lane, M.D., Christensen, P.R., 2000. Convection in a catastrophic flood deposit as the mechanism for giant polygons on Mars. Journal of Geophysical Research 105, 17,617–17,627.

Levy, J.S., Marchant, D.R., Head, J.W., 2006. Distribution and origin of patterned ground on Mullins Valley debris-covered glacier, Antarctica: the roles of ice flow and sublimation. Antarctic Science 18 (3), 385–397.

Levy, J.S., Head, J.W., Marchant, D.R., Kowalewski, D.E., 2008. Identification of sublimation-type thermal contraction crack polygons at the proposed NASA Phoenix landing site: Implications for substrate properties and climate-driven morphological evolution. Geophysical Research Letters 35 (L04202).

Levy, J.S., Head, J.W., Marchant, D.R., 2009. Thermal contraction crack polygons on Mars: classification, distribution, and climate implications from HiRISE observations. Journal of Geophysical Research 114 doi:10.1029/2008JE003273.

Lucchitta, B.K., 1983. Permafrost on Mars: polygonally fractured ground. Permafrost: Fourth International Conference Proceedings, pp. 744–749.

Mackay, J.R., 1974. Ice-wedge cracks, Garry Island, Northwest Territories. Canadian Journal of Earth Sciences 11, 1366–1383.

Mackay, J.R., 1975. The closing of ice-wedge cracks in permafrost, Garry Island, Northwest Territories. Canadian Journal of Earth Sciences 12, 1668–1674.

Mackay, J.R., 1990. Some observations on the growth and deformation of epigenetic, syngenetic and anti-syngenetic ice wedges. Permafrost and Periglacial Processes 1, 15–29.

Mackay, J.R., 2000. Thermally induced movements in ice-wedge polygons,Western Arctic Coast: a long-term study. Geographie Physique et Quaternaire 54 (1), 41–68.

Mangold, N., 2005. High latitude patterned grounds on Mars: classification, distribution and climatic control. Icarus 174, 336–359.

Mangold, N., Maurice, S., Feldman, W.C., Costard, F., Forget, F., 2004. Spatial relationships between patterned ground and ground ice detected by the Neutron Spectrometer on Mars. Journal of Geophysical Research 109, E08001.

Marchant, D.R., Lewis, A.R., Phillips, W.M., Moore, E.J., Souchez, R.A., Denton, G.H., Sugden, D.E., Potter Jr., N., Landis, G.P., 2002. Formation of patterned ground and sublimation till over Miocene glacier ice in Beacon Valley, southern Victoria Land, Antarctica. Geological Society of America Bulletin 114, 718–730.

Marchant, D.R., Head, J.W., 2007. Antarctic Dry Valleys: microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars. Icarus 192 (1), 187–222.

McEwen, A.S., Eliason, E.M., Bergstrom, J.W., Bridges, N.T., Hansen, C.J., Delamere, W.A., Grant, J.A., Gulick, V.C., Herkenhoff, K.E., Keszthelyi, L., Kirk, R.L., Mellon, M.T., Squyres, S.W., Thomas, N., Weitz, C.M., 2007. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). Journal of Geophysical Research 112, E05S02, doi:10.1029/2005JE002605.

Mellon, M.T., 1997. Small-scale polygonal features on Mars: seasonal thermal contraction cracks in permafrost. Journal of Geophysical Research 102, 25617–25628.

Mellon, M.T., Arvidson, R.E., Marlow, J.J., Phillips, R.J., Asphaug, E., 2008. Periglacial landforms at the Phoenix landing site and the northern plains of Mars. Journal of Geophysical Research 113 doi:10.1029/2007JE003039.

Osinski, G.R., Lee, P., Spray, J.G., Parnell, J., Lim, D.S.S., Bunch, T.E., Cockell, C.S., Glass, B.J., 2005. Geological overview and cratering model for the Haughton impact structure, Devon Island, Canadian High Arctic. Meteoritics & Planetary Science 40, 1759–1776.

Pewe, T.L., 1959. Sand-wedge polygons (tesselations) in the McMurdo Sound region, Antarctica: a progress report. American Journal of Science 257, 545–552.

Pollard, W.H., French, H.M., 1980. A first approximation of the volume of ground ice, Richards Island, Pleistocene Mackenzie Delta, Northwest Territories, Canada. Canadian Geotechnical Journal 17, 509–516.

Pollard, W., Haltigin, T., Whyte, L., Niederberger, T., Andersen, D., Omelon, C., Nadeau, J., Ecclestone, M., Lebeuf, M., 2009. Overview of analogue science activities at the McGill Arctic Research Station, Axel Heiberg Island, Canadian high arctic. Planetary and Space Science doi:10.1016/j.pss.2009.01.008.

Pollard, W.H., Omelon, C., Andersen, D.T., Mckay, C.P., 1999. Perennial spring occurrence in the Expedition Fiord area of western Axel Heiberg Island, Canadian High Arctic. Canadian Journal of Earth Sciences 36, 105–120.

Reynolds, J.M., 1997. An Introduction to Applied and Environmental Geophysics. John Wiley & Sons Ltd.

Seibert, N.M., Kargel, J.S., 2001. Small-scale Martian polygonal terrain: implications for liquid surface water. Geophysical Research Letters 28, 899–902.

Sherlock, S.C., Kelley, S.P., Parnell, J., Green, P., Lee, P., Osinski, G.R., Cockell, C.S., 2005. Re-evaluating the age of Haughton impact event. Meteoritics & Planetary Science 40, 1777–1787.

Sletten, R.S., Hallet, B., Fletcher, R.C., 2003. Resurfacing time of terrestrial surfaces by the formation and maturation of polygonal patterned ground. Journal of Geophysical Research 108 (E4), 8044, doi:10.1029/2002JE001914.
Stephenson, R., Van Berkel, J., Cloethingh, S., 1992. Relation between salt diapirism and tectonic history of the Sverdrup Basin, Arctic Canada. Canadian Journal of Earth Sciences 29, 2640–2652.
Villeneuve, M., Williamson, M.-C., 2006. ^{40}Ar–^{39}Ar dating of mafic magmatism from the Sverdrup Basin Magmatic Province. In: Scott, R.A., Thurston, D.K. (Eds.), Proceedings of the Fourth International conference on Arctic Margins, OCS Study MMS 2006-003, US Department of the Interior, pp. 206–215.
Williamson, M-C., 1998. The mantle source of flood basalts from the Sverdrup Basin Magmatic Province, Nunavut, Canadian Arctic. International Volcanological Congress IAVCEI'98, Cape Town, South Africa 70pp.
Wolff, E.W., Miners, W.D., Moore, J.C., Paren, J.G., 1997. Factors controlling the electrical conductivity of ice from the polar regions – a summary. Journal of Physical Chemistry B 101, 6090–6094.