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

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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

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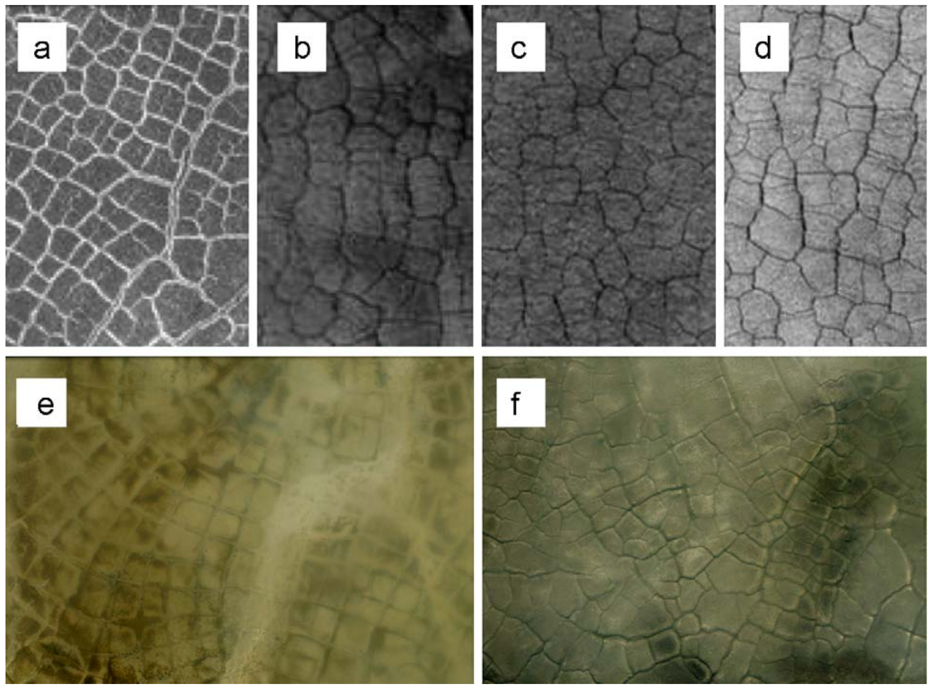

Fig. 1. Satellite and aerial photographs showing the morphological similarities between polygonal terrain on Mars (a–d) and on Earth (e and f). The top row are HiRISE images and are ~500 m across; the bottom row show regions that are ~300 m across. (a) Polygons first seen in MOC Image M01-00204 (HiRISE 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